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White Paper

Meat: the Future series

Alternative Proteins

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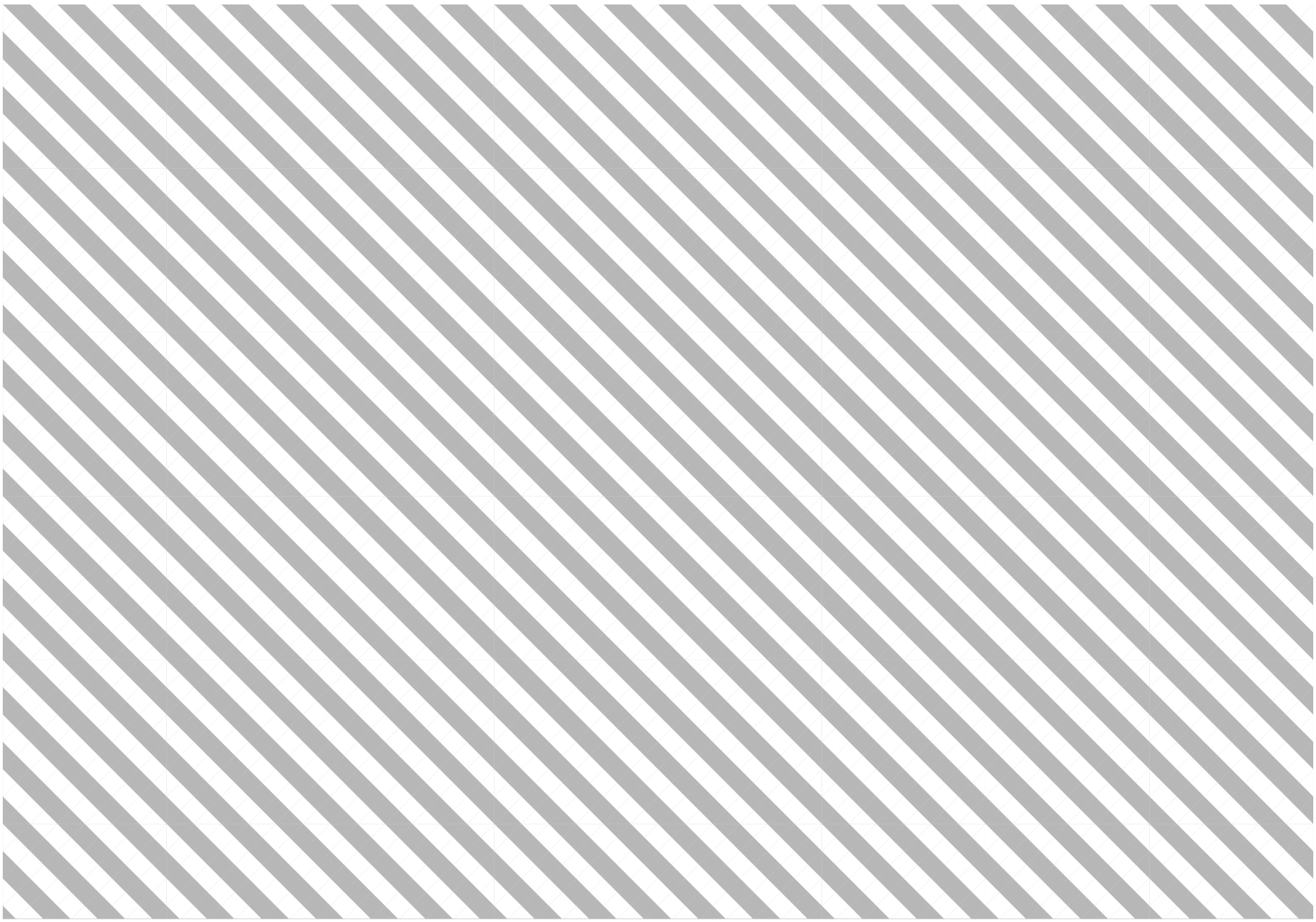

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Prepared by the Oxford Martin School, Oxford University for the World Economic Forum's Meat: the Future dialogue series

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Foreword

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Alternative proteins that can act as substitutes for traditional animal-based food are attracting considerable financial investment, research attention and interest in the media as a pathway to meeting the nutritional needs and food demands of a predicted mid-century population of 10 billion, in a healthy and sustainable manner. Many of these potentially disruptive alternatives are enabled by the Fourth Industrial Revolution and come with big promises – from reducing greenhouse-gas emissions to transforming nutrition and health.

This report investigates these claims using a food-systems lens. Employing quantitative models developed by the Oxford Martin School, the analysis shows that a wide range of protein alternatives can have important environmental and health benefits. The report illuminates sensitive intervention points at which multistakeholder discussions and new platforms for public-private collaboration are needed. It also notes gaps in knowledge, where further exploration will be required.

An important finding of this research is that showing the benefits of these products is not sufficient for consumers to adopt them. A much wider set of interventions will be required to accelerate uptake. To this end, the analysis in this report first uses social science techniques to look at a critical determinant of adoption: the interplay of *narratives* that are developing in regard to the costs and benefits of alternative proteins. Chiefly using information from North American and European markets, where alternative proteins are more advanced and available, the report seeks an understanding of which narratives have been most impactful or detrimental in affecting the acceptance and purchase of these products.

Next, the assessment focuses on the *political economy* and *regulatory environments* that can support such a transformation, recognizing the critical role these elements play in the food system.

Finally, the analyses are brought together to present recommendations on multistakeholder actions that may be required to accelerate adoption of beneficial alternatives, and to minimize the negative impact from the disruption of current protein delivery systems.

An important conclusion from the report is that for the foreseeable future the meat and protein alternatives industries will coexist and that, as a result, there are great opportunities for synergies. Indeed, it is unlikely that alternative proteins will achieve scale unless use is made of the production and marketing expertise of the traditional protein sector.

Alternative proteins represent a rapidly emerging new domain within the food system. The analyses in this report are not definitive and further work will be needed as the evidence base, technologies and production methods evolve, in order both to assess additional factors and to understand the full costs of transitioning away from traditional animal-based products in more developed countries as an important source of dietary protein. It is intended, however, that this research will open up further debate and discussion to help shape a more inclusive, sustainable, healthy and safe future.

This paper was prepared by the Oxford Martin School, Oxford University, as an input for the World Economic Forum's Meat: the Future, an initiative of the World Economic Forum launched in early 2018 to help accelerate the agenda for change in the world's protein systems. It specifically focuses on the role of alternative proteins as one of three pathways to accelerate the provision of universally accessible, healthy and sustainable protein to a growing population, in particular by encouraging multistakeholder collaboration.

I am grateful to my colleagues at Oxford who contributed to this report: Marco Springmann (who led on the modelling), Alex Sexton (who led on the social science analysis), John Lynch, Cameron Hepburn and Susan Jebb. We are grateful to Lisa Sweet (World Economic Forum) and to a number of external reviewers for incisive comments.

Introduction

By 2050, global food systems will need to meet the dietary demands of more than 10 billion people who on average will be wealthier than people today and will aspire to the type of food choices currently available only in high-income countries.[1] This food will have to be produced sustainably in ways that contribute to reducing climate change, and that address other environmental challenges.[2,3] At the same time, human health is influenced more by food than by any other single factor, and facilitating healthy diets is critical both for individual well-being and containing the costs of treating illnesses.[4] It is widely recognized that the current trajectory of the food system will not allow us to meet these goals.[5,6]

The food system needs to change radically to address these challenges,[7–11] and a very important part of this will be the adoption of new technologies, including the opportunities provided by the Fourth Industrial Revolution. The food sector has been relatively slow at capitalizing on recent technological advances: for example, the World Economic Forum's 2018 *Innovation with a Purpose* report[12] showed that cumulative start-up investments since 2010 are more than ten times greater for healthcare than for food. However, this does now seem to be changing and one of the areas attracting the greatest attention and investment is alternative proteins and meat substitutes.[13] How this sector will develop is far from clear, but there is a possibility of genuine disruption in the near future.

The Special Challenge of Meat

It would be impossible for a global population of 10 billion people to eat the amount of meat typical of diets in North America and Europe and keep within the agreed sustainable development goals (SDGs) for the environment and climate: it would require too much land and water, and lead to unacceptable greenhouse-gas and other pollutant emissions.[2] **In addition, excess meat consumption and current production have significant effects on human health, livelihoods and the economy. Meat thus poses a special challenge to the future development of the global food system.**[14]

Meat has a special place in human diets. Modern human beings have an innate preference for meat as it is both energy-dense and protein-rich and we evolved in an environment where energy and protein were scarce.[15,16] Meat has important social as well as nutritional functions, and in many societies the consumption and provision of certain types of meat signals status or hospitality. There is also a long history of meat abstinence in different societies, and complex taboos preventing people from consuming particular types of meat that probably have their origins in the avoidance of food poisoning. These strong cultural and biological drivers have a significant effect on efforts to change diets, as we have seen over time in relation to many public health campaigns designed to promote healthier consumption.[17]

In some low-income countries, the consumption of meat is important in providing a full and nutritious diet, and at least at present there are no viable alternatives with comparable energy and nutrient density. Often livestock production is also central to livelihoods and economic resilience. The importance of meat and livestock in these communities is explored in the 2019 International Livestock Research Institute (ILRI) report *Options for the Livestock Sector in Developing and Emerging Economies to 2030 and Beyond*, also prepared as an input for the Meat: the Future dialogues.[18]

Meat provides protein and a variety of micronutrients such as iron and B-complex vitamins. These are also available from other sources and most people in middle- and high-income countries who eat a reasonably varied diet consume sufficient quantities for good health,[19,20] though attention is needed on particular issues such as iron intake during pregnancy. The single greatest effect of diet on health is through energy intake and the world is currently experiencing an epidemic of the diseases associated with being overweight or obese.[21] Though meat is energy-dense, it typically comprises a relatively small fraction of energy intake and is not, per se, considered to be a specific risk factor for obesity in adults. There is evidence, though, that meat consumption is associated with the risk of contracting specific diseases. The evidence base is still limited, but most concern is with red meat and in particular processed meat.[22]

Much of the debate about meat production today centres on its environmental impact and in particular its greenhouse-gas emissions.[23] Impacts vary greatly between livestock types and production systems. Red meat (cow, sheep and goat) production is a particularly large source of greenhouse gases because of methane production in ruminant digestion. Approximately 15% of anthropogenic greenhouse-gas emissions come from livestock production (about 3% is due to dairy production), of which 40% are due to beef and dairy farming.[24–26] Livestock rearing can also be a source of dispersed and point pollution (including by nitrogen, phosphorous and pathogenic microorganisms), especially where rules on manure and slurry management are lacking or poorly enforced. The need for grazing land and for arable land to grow animal feed is the single most important driver of deforestation,[27] with consequences for greenhouse-gas emissions and biodiversity.[28,29] Where livestock are reared on land that cannot be used to grow arable crops, this can contribute to mitigating climate change by helping store carbon in the soil. However, the contributions are relatively small and often undermined by poor land management or overgrazing.[30] It is also important to think of the opportunity cost of using land for livestock rearing that might be used for other environmentally important functions such as carbon sequestration through reforestation.

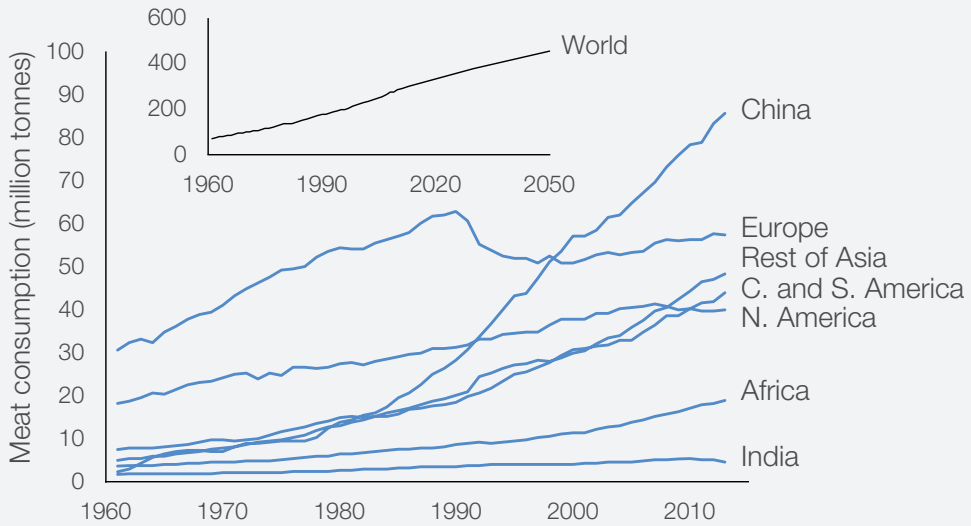
Rearing, distributing and selling animal-sourced food is responsible for the livelihood of millions of people throughout the world. It has been estimated that ~3% of gross global productivity (global GDP) is from agriculture, of which 40% is from livestock. It provides livelihoods for approximately 1 billion people, overwhelmingly concentrated in low-income countries, including some of the poorest countries on Earth.[18,31]

In discussing meat substitutes and the need to reduce global meat consumption, it is very important to ensure that no policies are enacted that negatively affect the health or livelihoods of some of the world's poorest and most disadvantaged groups that are dependent on meat and livestock. In a similar manner, there is also potential for disruption of the livelihoods of people in middle- and high-income countries, especially those with no other opportunities for employment, and these transition costs will have to be considered and planned for carefully, as has been seen in the transition away from fossil fuel-based jobs. In short, public support for alternative proteins will most likely be suppressed if the social costs of their adoption are seen to be too high.

It is because of the critical importance of meat to the sustainability of the food system that so much attention is paid to future trends in meat consumption (see Figure 1). Meat consumption in high-income countries is high, but relatively constant, while consumption is rising rapidly in China and less rapidly in most other regions (with India being

the main exception).[32,33] Overall, global meat consumption is rising with no sign of a plateau. Projections such as those discussed in the above-referenced ILRI report, *Options for the Livestock Sector in Developing and Emerging Economies to 2030 and Beyond*[18] show these trends continuing, with Asia in particular rapidly converging on "Western" levels of consumption. This pathway is incompatible with keeping global temperatures from rising more than 2 (let alone 1.5) degrees Celsius and with meeting several of the SDGs.[34,35]

Figure 1: Trends in the consumption of meat (data from FAOStat); regional data to date and global data to date and projections to 2050 [98]



Innovation and Alternative Proteins

The Meat: the Future initiative lays out three potential pathways to meet the needs of the world's growing population for protein in a sustainable and healthy way: alternative proteins; changes to current production systems; and consumer behaviour change. This report focuses on the first pathway: developing alternative-protein products. Here, there has been a burst of recent innovation involving new purely plant-based alternatives, products based on insects and other novel protein sources, and the application of cutting-edge biotechnology to develop cultured meat.

A continuum can be drawn from protein rich-plants that are used in unprocessed forms to substitute for meat in meals (lentils, for example) through more processed products such as soy-based tofu and wheat-based seiten to recent innovations seeking to make vegetable burgers and other products that are as indistinguishable as possible from real meat. Innovation is occurring across this spectrum from novel recipes and marketing to increase the desirability of the less-processed vegetable alternatives, through advances in food processing involving existing blends and flavours, to highly sophisticated biotechnology that combines products from multiple plant sources to create a "mouth-feel" and experience that closely mimics meat.[36,37]

A focus in the past decade has been to develop protein from sources other than traditional crops and livestock.[38] To date, the most commercially successful novel products are those based on fungi-derived protein (mycoprotein).[39] Insects have also received considerable attention, in particular because they can be reared on feed that is unsuitable for livestock and which otherwise would be wasted or have low economic value, thus contributing to a more "circular" agricultural economy.[40] Innovation in this area includes the discovery and investigation of new insect species of value for food production, and developments in how they may be produced economically at scale. Insects can be consumed in their natural state, although to increase acceptability in cultures where insect consumption is not traditional, there is also research into developing novel products that contain insects in a different form, for instance as flour.[41]

Producing meat in the laboratory without the involvement of living animals is a huge technical feat made possible by the Fourth Industrial Revolution.[42] Only in the past decade have technologies advanced enough to make this conceivable, with forms of meat that might be used in products which traditionally contain minced meat (such as burgers) already quite advanced and projected to be available to the public in the next few years. Furthermore, through more fundamental research into stem-cell technology and muscle development, and its medical applications in fields such as wound healing, there is a real prospect of rapid advances within the consumable meat sector in the next decade.[43] In addition to producing products that resemble meat, some "food futurologists" also envisage new products outside our current sensory experience that will create new food cultures.[44]

Another target of innovation is not to produce products that replace meat completely but to partially substitute or "extend" meat.[45] Any of the above protein substitutes could be used in this approach, though plant-derived mycoproteins and insect-derived proteins are especially suitable as they can be produced relatively cheaply today and can be incorporated with relatively minimal additional processing.

Most interest and investment in alternative proteins is currently in Europe and North America and it is from these regions that the report draws most evidence for its social science and political economy analyses. The modelling takes a more global perspective and in particular includes environmental and health benefits arising from diet change in middle-income countries. As underlined above (see also the World Economic Forum's *Options for the Livestock Sector in Developing and Emerging Economies to 2030 and Beyond*), the role of livestock and meat for the world's poorest people needs special consideration. The report focuses on alternative proteins and meat, while acknowledging the importance of and exciting recent developments in dairy and fish alternatives. It does not explore the possibility of substituting protein with fish: modelling this food type is especially complex because fish are particularly heterogeneous from a nutritional point of view (for example, different species of fish vary greatly in omega-3 fatty acids that have positive effects on health), and production methods vary significantly throughout aquaculture and capture fisheries.

Impacts of the Adoption of Alternative Proteins

What difference would it make to the global food system, and its effects on the environment, health and other areas, if the world made a transition from meat to meat substitutes, either traditional substitutes or novel protein alternatives – especially given that the global food system is complex with many feedbacks and non-linear effects?

In this section, a first pass at addressing this question is presented.

To model the food system, the research used a connected toolbox of models, the technical details of which have been described in the academic literature.[8,11,46–48] Thirteen types of food were explored that can be placed in four categories.

13 food types used for the modelling:

Types of meat	Fruits and vegetables	Processed non-animal substitutes	Novel alternatives
Beef (cattle meat)	Nuts	Tofu/soybeans	Cultured meat
Pork	Peas	Wheat-gluten/ seitan	Insects
Chicken	Beans	Mycoprotein/ fungus	Alga spirulina
	Jackfruit		

The first group contains different types of meat. The research focused on beef, pork and chicken.

The second class includes fruits and vegetables that can be consumed directly in an unprocessed state or as meat substitutes, or which can be processed to different degrees so that they begin to have the appearance and "mouth-feel" of meat. Here, the research looked at nuts, peas, beans and the tropical jackfruit. The latter is consumed relatively infrequently outside Asia, but is increasingly attracting attention as an export crop and a novel ingredient in other cuisines.[49] As discussed below, analysis of these cases provides some insights into the likely consequences of greater consumption of more sophisticated plant-based burgers.

The third category contains more processed non-animal products that are used as meat substitutes. Here, the research focused on: tofu, which is derived from legume soybeans and has been a part of Asian cuisines for millennia; wheat-gluten products (seitan); and mycoprotein, which is derived from fermented *Fusarium* fungus.

The final category includes the most novel alternatives. The research examined: cultured meat (beef was chosen as a focus, recognizing that excellent research and innovation is also underway using chicken and fish); insects in the form of flour made from crickets; and the blue-green alga spirulina (*Anthrospira*; technically cyanobacteria but below referred to as algae).[50]

How to interpret food system models

The function of this type of modelling exercise is not to try to predict *the* future but, in the first place, to help map out a space of *possible* futures. This is helpful as policy-makers concerned with, say, health, need to know whether encouraging the consumption of a particular meat substitute might have positive or negative effects, and whether there might be trade-offs with other areas of policy concern such as greenhouse-gas emissions. Second, quantitative modelling helps show what needs to be known to make better decisions. Constructing a model forces the quantification of a system and, as a result, reveals knowledge gaps. For example, the research found that there were some products, such as the most sophisticated plant-based burgers, that could not be included because sufficient relevant information was not available.

Modelling also allows a better understanding to emerge as to what factors are the most important in determining outcomes. This helps to show not only where future developments may have the greatest impact but also what parts of the food system will need to be understood in most detail to make good decisions. Finally, it is important to note that outputs of any such quantitative system models are approximations to be challenged: paradoxically, this approach can sometimes be most useful when it produces results that experts in the field think unlikely, with the process of working out why they occurred increasing the understanding of how the system operates.

Some of the analyses below explore the consequences of replacing beef with different alternatives. Beef is used as a base case for two reasons. First, of all the types of commercially available animal-based protein for the mass market, beef has the greatest effects on health and environmental outcomes and hence its substitution is likely to reveal the greatest consequences.[8] Second, research on cultured beef is in advance of culturing other types of meat, and consequently the sector has the best quantitative information to include in the models.[43,51]

When studying substitution, the research makes a calorie-for-calorie replacement. This is done because the single greatest effect of diet on health is through energy intake and weight, and the research did not want to conflate issues of meat substitution and obesity. In 2010, average beef consumption was 12–13 g d^{-1} (that is, per day) in lower-middle-income and low-income countries and 53–60 g d^{-1} in upper-middle-income and high-income countries, and hence the effects of the substitution will vary from one country to another.

Greenhouse-gas emissions

Switching from beef to alternative proteins can lead to significant reductions in greenhouse-gas emissions, especially for transitions to plant- or insect-based alternatives. While current estimates of emissions from cultured beef suggest only modest reductions, depending on how production of cultured beef is scaled up, there is the possibility of significant emissions reductions as well.

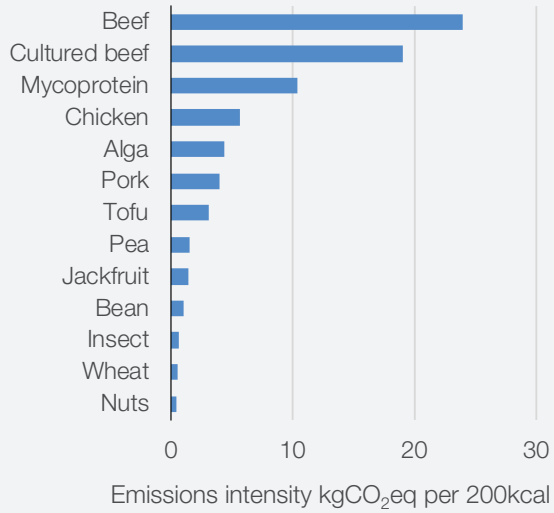
Greenhouse gases associated with the production of different types of food are estimated by "life-cycle analyses" (LCAs) that attempt to track the full range of emissions along the value chain (including such factors as the transport of animals and their feed). Meta-analyses of LCA estimates are available for beef, processed wheat, nuts, beans, peas and jackfruit; with that for beef taking into account the very different footprint from its various production systems.[52–55] The emissions intensities of the different food types are shown in Figure 2. Emissions are greatest from beef followed by cultured beef (modelled under current production methods) and then, some way behind, mycoprotein followed by alga. Emissions from insects and the plant-based foods are much lower. For cultured meat and to a lesser extent mycoprotein the electricity demands under current methods for production are largely responsible for the current emissions calculations.

In 2010, beef was responsible for about 2 GtCO2-eq [gigatonnes carbon dioxide equivalents] greenhouse-gas emissions. This is about a quarter of all food-related GHG emissions. Replacing beef in each region's diet with the different meat alternatives led to emissions reductions of 7–26%, least in the case of lab-grown meat under current production methods (7%; 0.5 GtCO2eq), more (16%) for mycoprotein, and close to the maximum attainable emissions reductions (23–26%) for the other meat alternatives. Currently, emissions from the agricultural sector are projected to grow, with more people demanding more beef as a significant contributing factor, and while it would of course be unrealistic to assume complete replacement, it is interesting to note the degree to which, if the best substitutes are adopted, they would bend the curve on future emissions growth.

It is important to note that this study's estimates of the emissions of cultured beef are based on the most recent research using a standard modern LCA approach.[54] Its estimate of emissions is markedly higher than an earlier study that would have placed cultured beef nearer to tofu in Figure 2 above.[56] It is felt that the more recent study with current methodology is the more reliable, but it is important to make two clarifying points. First, its significant emissions impact is based on the currently high energy requirement to make the culture medium, and there are clearly great opportunities to use renewable energy sources to substantially lower the emissions contribution from cultured meats. Second, the technology is still very much in its infancy, and depending on how production is scaled, there are substantial opportunities to reduce emissions from other parts of the life cycle. For instance, one important business model for cultured meats is that they could be produced in urban "breweries",[57] potentially collapsing global supply chains and bringing production closer to demand – thereby reducing the environmental impact of global supply chains such as shipping and trucking (including emissions from refrigeration). In general, the material and energy inputs from cultured meat are more flexible and substitutable than those involved in producing traditional meat. There is thus a greater opportunity (more dimensions) to optimize the production of cultured meat in ways that reduce greenhouse-gas emissions.

The types of purely plant-based meat alternatives that have reached markets in the past five years are not included in the analysis because of a lack of LCA data measured in a comparable way to the other food types. However, because the core ingredients are plant-based products such as beans and peas, the research would expect these alternatives to perform very favourably and to rank towards the lower end of the food types explored here. Some ingredients are more processed, for example, the heme iron that gives the appearance of red meat, and may require larger energy and other inputs, but because they are used at low concentrations they are unlikely to increase emissions greatly.

Figure 2 : Emission intensities of the different food types



Carbon dioxide equivalents metric

Carbon dioxide equivalents are used as a common metric to include different types of greenhouse gases on the same scale. Cattle and other ruminants produce relatively large quantities of methane. Compared to carbon dioxide, methane is a far more potent greenhouse gas. However, its half-life in the atmosphere is measured in decades, while for carbon dioxide it is measured in millennia. From the perspective of a policy-maker, it is the rate of methane release that affects future global warming, while for carbon dioxide it is the cumulative amount released. This important distinction is poorly captured by carbon dioxide equivalents. It is likely that most protein alternatives will have lower climate warming effects, but the extent of the advantage, and the relative performance of different substitutes, will depend quite subtly on the composition of the gases released. How and if regulators choose to assess this will affect the claims that can be made about environmental sustainability.[58–60]

The modelling provides a snapshot of the current understanding of emissions from alternative proteins and livestock.The rankings may change in the future, for example as innovation arising in part from the Fourth Industrial Revolution leads to improvement in different areas of agriculture including the livestock sector.[61] To give two examples, active research on reducing emissions from livestock directly (by manipulating their gut microorganisms)[62] or indirectly (by better pasture, manure and slurry management)[63] could improve the performance of traditional meat. Second, novel livestock feeds, for example based on insects – such as the black soldier fly – or algae, could lower the overall impact of meat production by reducing deforestation due to soy and other feed production.[64] In general, the movement towards sustainable intensification and climate-smart agricuture[65,66] – improving productivity while reducing emissions – will help reduce the footprint of traditional agriculture but it may not be enough, without the type of radical innovation discussed in this report, to achieve our climate goals. The research also notes that significant reductions in greenhouse-gas emissions can be obtained by switching from beef to non-ruminant meat such as pork or chicken, or to fish.

Studying the effects on water and land use

A molecule of carbon dioxide emitted in Beijing has the same effect on global warming as a molecule released in New York. This greatly simplifies the analysis of the greenhouse-gas emissions of meat and meat alternatives. To study other environmental effects of diet change is not so simple and depends much more on location. For instance, feedlot beef production requires a large and secure supply of water, which will have different consequences for the natural environment in wet Ireland and New Zealand compared to parched Australia and Texas. The effects on biodiversity may be even more local and depend on precisely which river gets polluted, or what specific forest is cut down for ranch land or to grow soy to feed cattle.[67,68]

It is always possible to treat changes in demand for meat as an exogenous variable and study pressures on water or land at any particular locality. It is harder to get a synoptic understanding of how significant changes in demand for meat and meat substitutes may affect global food, economic and biophysical systems. In order to provide evidence-based comparisons here, the research has not included these elements in the modelling.

There is currently ongoing work that aims to try to answer some of these questions, and as it is completed it should become part of the discussions. Researchers anticipate that for some alternatives the implications will be significant. For example, one study suggested that cultured meat might require just 2% of the land the global livestock industry uses today, though this assumes that none of the inputs would come from traditional agriculture.[56]

Diet-related mortality

Switching to many of the alternative proteins markedly reduced diet-related mortality in the model, an effect particularly due to increased consumption of dietary fibre. As expected, the research found switching from beef to cultured beef had little effect on diet-related mortality given the intent of creating the same end product through a different production means.

Given a particular diet and knowledge of its nutrient composition, it is possible to use epidemiological data to estimate consequent health effects (for methodology, see reference [46]).The research used the model to ask two types of question involving alternative proteins. First, what would the consequences be for an adult of consuming an extra 200kcal d^{-1} serving of beef or one of the 12 other food types? This addition analysis is undertaken in order to explore the marginal benefits of eating more of each food type given the diets consumed by people around the globe. Second, the research explored the consequences of replacing beef with one of the 12 other food types. This substitution analysis allows an exploration of the effect of diet switching. In this substitution analysis, the results will be more strongly influenced by regions with greater current beef consumption.

Diet-related mortality : risk factors

The model incorporates data on six risk factors:

1. Serum cholesterol levels associated with dietary fatty acid composition. The study used meta-analyses of studies linking dietary fat composition to cholesterol levels, and cholesterol levels to coronary heart disease to quantify this risk.

2. Blood pressure associated with sodium intake. The study estimated this risk from experimental studies of how sodium reduction affects blood pressure, and studies linking blood pressure to cardiovascular disease. Note that salt added as a condiment can counter any positive effects of low-sodium food.

3. Heme iron intake: there is evidence that increased consumption of animal-derived foods rich in heme iron is associated with increased coronary heart disease and stroke risk.

4. Fibre intake: increased consumption of fibre, typically from cereals, is positively associated with reductions in coronary heart disease, cancer and stroke.

5. Low intake of polyunsaturated fats.

6. Low intake of potassium.

The results of this dietary addition analysis are shown in Figure 3, where the different diets are shown in rank order of increasingly positive effects on health. Consumption of more beef increases individual risk of diet-associated mortality by about 1.5%, chiefly due to higher heme consumption. Substitution with cultured meat is marginally better because of a more favourable lipid (fatty acid) profile, with heme consumption again being a main driver. It should be noted that some of the advanced vegetarian burgers that use artificial heme to create the impression of red meat, and which are not included here, may have similar negative effects on health. While most people in middle- and high-income countries get adequate iron (in heme and non-heme forms) from a varied diet, some individuals can suffer iron deficiency, which meat (though also other food types) can help to remedy.

The addition of all other meat alternatives into diets has positive effects on health, with a maximum predicted reduction in mortality rates of 5–7% for fibre-rich beans, peas and mycoprotein.

Foods rich in potassium and polyunsaturated fats also contribute to reduced mortality. Protein substitutes based on the alga spirulina have high sodium contents as they grow in alkaline water and this has a negative effect on health. Likewise, flour derived from insects contains relatively high levels of sodium and cholesterol, elements that partially mitigate other positive effects of this food type.

Substituting beef with any of the ten alternatives reduces diet-related mortality (Figure 4). The rank effects are similar to those for the diet addition analysis, with cultured beef having the smallest effect (a 0.1% reduction) and pea and mycoprotein the greatest (a 2.4% reduction). Breaking down these figures by country income status, the most positive effects are found in wealthier countries, where beef consumption is high and where there is a particular benefit of consuming more fibre. The effects are much less in low-income countries and may be lower still than indicated here if meat is providing nutrients missing in very poor diets.

In interpreting these results the study used current best epidemiological evidence, but clearly the evidence base is likely to change as more information becomes available. Additionally, any health gains at the population level assume people have access to the alternative proteins at prices they can afford (pricing is explored further below). For many people living in the poorest countries, there are no alternatives to meat and restricting access would be detrimental to their health.

Figure 3 : The health effects of consuming an additional portion of different alternative proteins

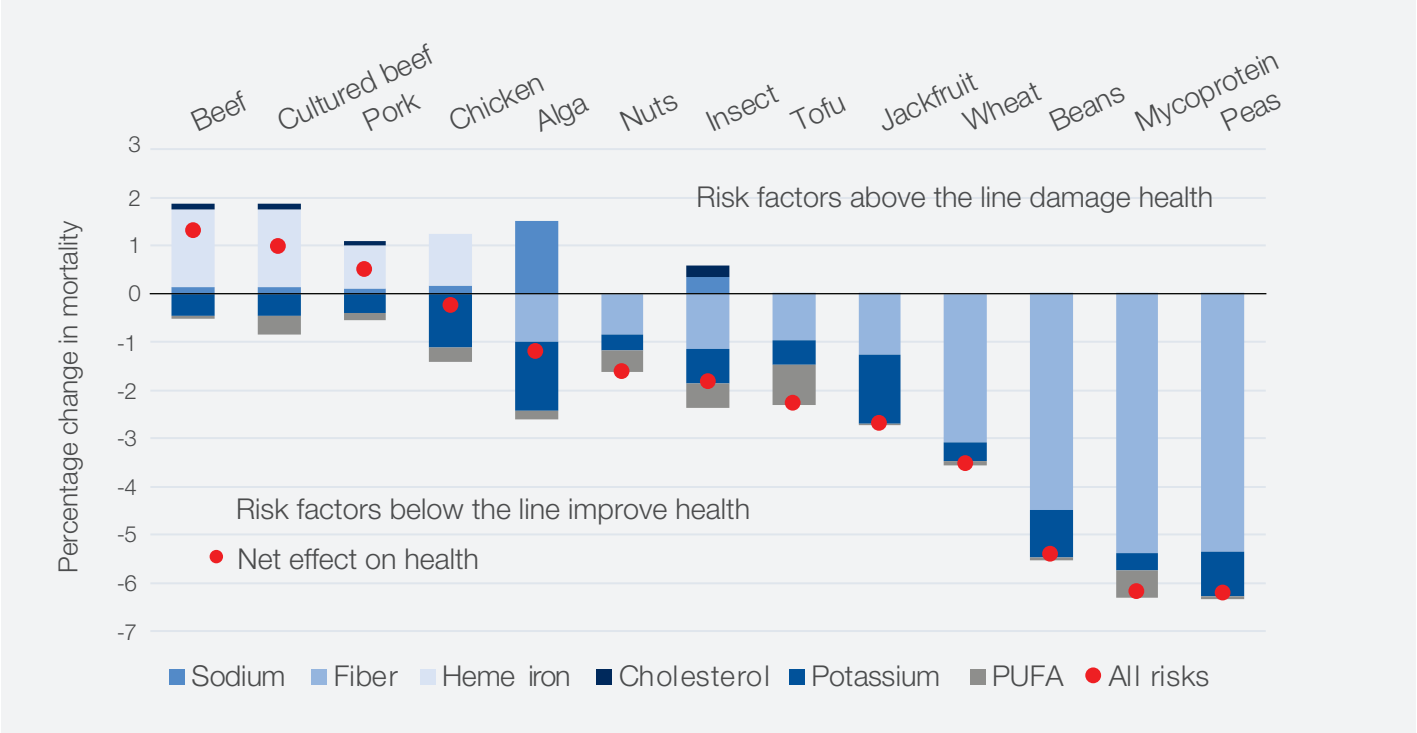
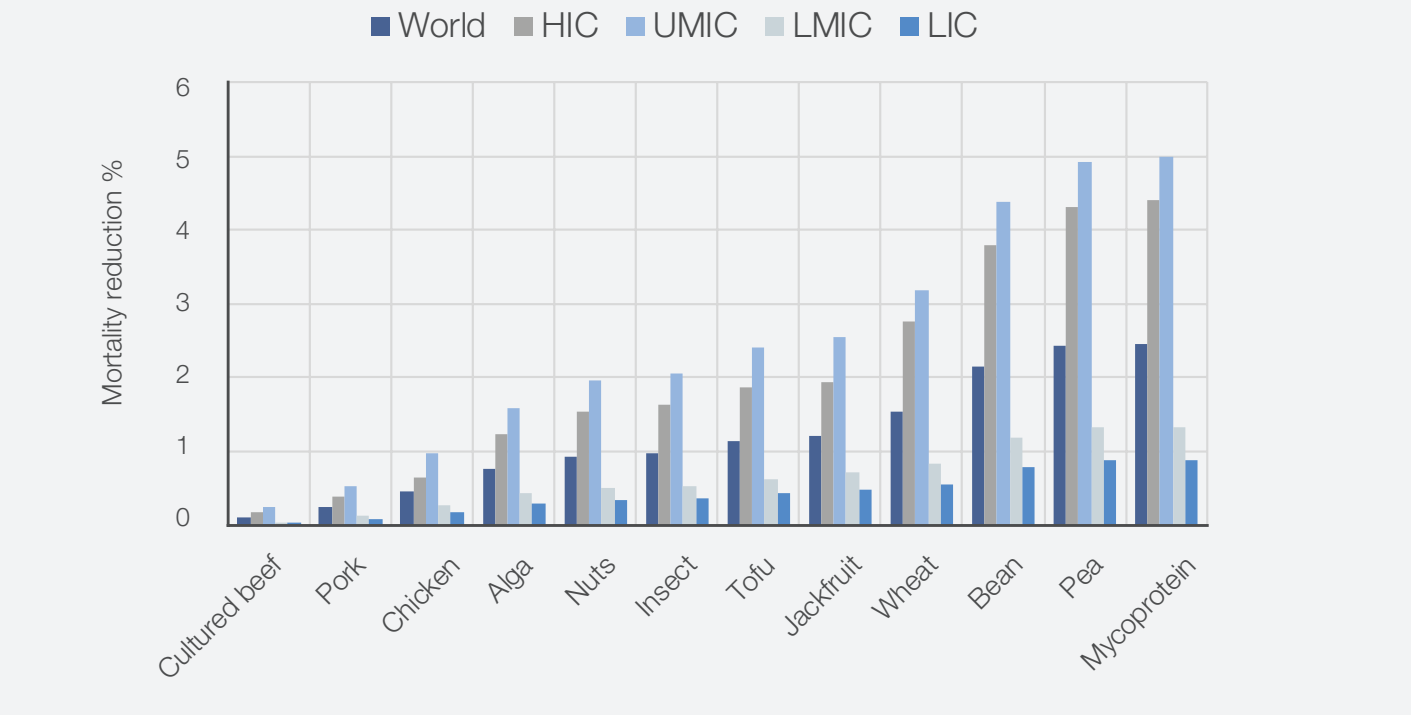
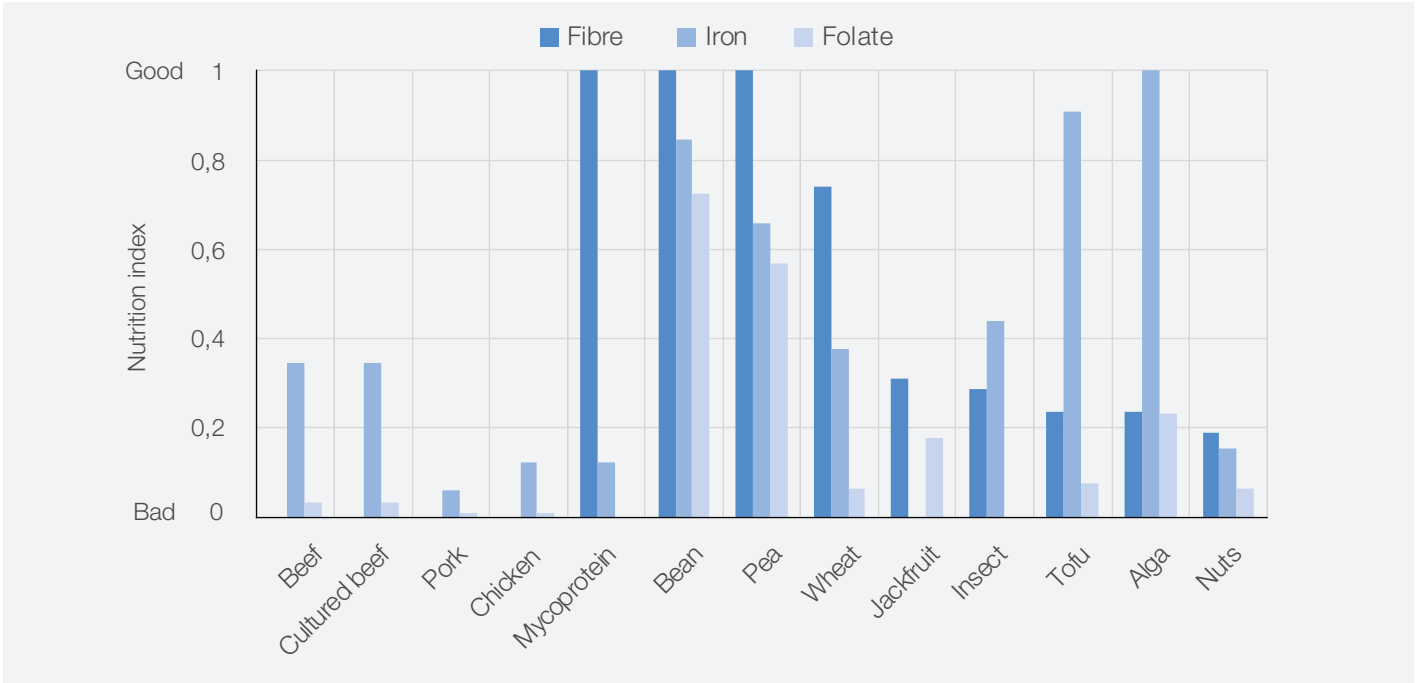


Figure 4 : Net health effects of substituting beef with different food types globally and by national income class.



HIC: high-income country; UMIC: upper-middle-income country; LMIC: lower-middle-income country; LIC: lower-income country.

Figure 5 : The effects of diet substitution on the intake of three nutrients



Nutrient intake

Switching from meat to alternative proteins can have both negative and positive effects on nutrient intake and hence health, with the details depending critically on a person's overall diet. The judicious choice of alternative proteins, and potentially the incorporation of supplementary nutrients in these products, can avoid negative effects and help to improve nutrient intake.

To explore the health effects described above, the study modelled a series of scenarios in which beef was substituted with each of the different alternatives described above on a calorie-for-calorie basis. However, it is well known that current diets do not always provide for optimal nutrition. For example, in high-income countries, diets tend to be low in fibre and for some subgroups of the population low in iron, while they exceed recommended levels for saturated fat and sugar. At the other end of the economic spectrum, diets in low-income countries can be low in one or more of a range of nutrients, including iron and vitamin A. The data in the Annex shows the nutrient content of the different food types the research investigated.

It is possible to obtain an estimate of global nutrient deficiencies by comparing diets in different countries with recommended daily intakes.[69–71] Such estimates are only an approximation as they are calculated from population data and do not take into account variations in nutrient intake from individual to individual within the country; instead they provide a broad indication of the scale of the problem. Analysis can then recalculate the index, assuming beef has been substituted with one of the different alternatives, and look for any changes.

In Figure 5 the study explores the difference the diet substitution makes for three different nutrients – fibre, iron and folates. These are the nutrients for which the data is best and the effects of the substitution are greatest. The analysis finds that, because beef is low in fibre, substituting with mycoprotein, bean, pea or wheat leads to major increases in average fibre consumption, with the first three more than meeting recommended intakes. Cultured meat, pork and chicken similarly contain little fibre, while there is a modest improvement after switching to jackfruit, insect, tofu, alga or nuts. In the case of iron, beef and cultured beef provide roughly the same amounts of iron, more than chicken and pork. Iron consumption would be markedly lower for substitutes such as mycoprotein but much higher for bean, pea, tofu and algae. Finally, folate intake tends to be improved, sometimes markedly, by moving to alternative proteins.

These calculations indicate some potential benefits and costs of switching to alternative proteins. Further work needs to incorporate differences in the bioavailability of nutrients in traditional and alternative proteins, the topic of current active research. Nutrition is a function of whole diets rather than specific food types. Thus, the presence of meat as a source of vitamin B12 may be critical for a malnourished person in a low-income country with a very poor diet, but of little consequence for someone with a more varied diet. Similarly, a diet including only one type of plant-based alternative protein might have a poor amino-acid balance, while one with a broader variety of plant alternatives might be no different from meat.[72–74]

Food prices

On current prices, alternative proteins are not always competitive with meat. The most novel alternatives are expensive, but will undoubtedly fall in price as production is scaled up. Unless interventions are made, however, pricing will not necessarily align with the benefits for health, nutrition and the environment.

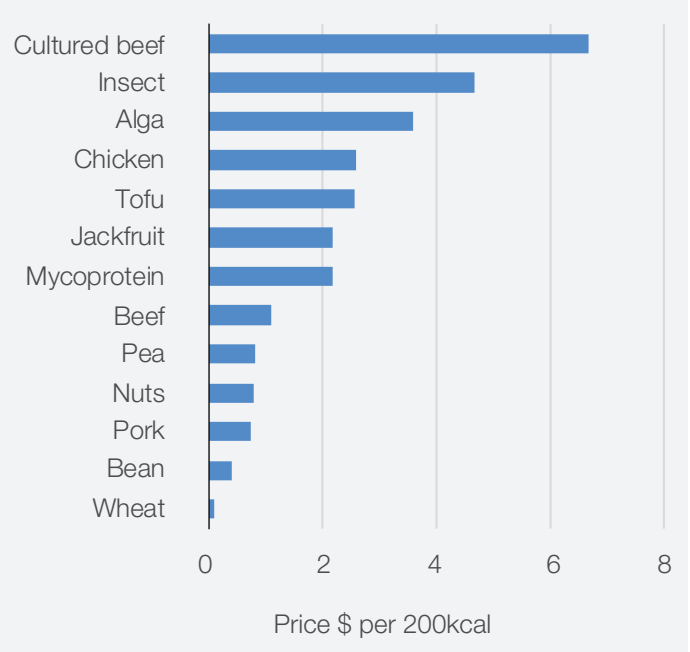
Many factors will affect whether consumers chose alternative proteins (see next section), although cost continues to be an important driver.[75] Most of the protein alternatives this study considers are already on the market, which allows current prices to be compared directly on a calorie-for-calorie basis. For others, the study uses published market projections, which are indicative but less accurate. Figure 6 compares prices using UK data.[76] For the three types of meat, the research has used ground (minced) preparations; relative prices obviously would be different for other cuts of meat and if the comparison was made by weight rather than energy.

The relatively low price of ground beef, the result of decades of industrialization focused on production efficiencies, is notable and likely anchors consumers' current expectations of what is a reasonably priced alternative protein. The costs of some established vegetable-based substitutes are lower than beef, sometimes considerably so, but tofu, novel vegetable substitutes (jackfruit) and alternative proteins were all costlier than ground beef. In the case of cultured beef (which has not yet reached market), the cost is over five times more.

The normal workings of the market will change the relative rankings of these products. Higher demand in the very short term might increase prices, but in the medium term it will stimulate competition and encourage research and investment that will lower production costs – both resulting in reduced prices. Technological advances exogenous to the food system – for example, in the biomedical study of muscle development – will also reduce production costs. Already, the costs of cultured meat have reduced dramatically over the past few years, from notional estimates of hundreds of thousands of dollars per kilo to $25, and that is before economies of scale are brought to bear.

This argument assumes that the economics of the food system continue as they are today, and in particular that any negative effects of the food system such as on the environment and on health remain as externalities. Internalizing these consequences would radically change the relative costs of the food items in the figure, and perhaps challenge the implicit assumption in much of the developed world that food prices should be as low as possible. Irrespective of internalization, the relative costs to the economy of different diets (through healthcare costs and lost productivity) will be of significant importance to public policy.

Figure 6 : Estimated current prices of the different food types



Framing the Future of Meat and Its Alternatives

Individuals choose which particular types of food to eat based on price and by their intrinsic beliefs about what is good or bad about them. These beliefs are partially determined by the interplay of a complex set of narratives – the stories we tell each other about food. Many stakeholders seek to influence these narratives; and understanding their dynamic interplay is essential to predicting how diets will evolve and how to encourage more sustainable and healthy food choices.

The models described in the previous section are helpful in showing how dietary change can lead to better environmental, health and economic outcomes, but the numbers themselves have limited traction in convincing individuals to eat different foods. The majority of food decisions made by most people are reflexive rather than considered, made on impulse rather than through rational choice.[77] Reflexive decisions are shaped by innate preferences, for example, for sweet or fatty foods, but also by personal beliefs shaped by exposure to current narratives.

Narratives, therefore, are ways of framing complex issues that have broad traction in society.[78] Narratives both draw on and contest the traditional corpus of science knowledge upon which "evidence-based" policy and individual consumer choice is made. Their evolution can be unpredictable and idiosyncratic, for instance, when an issue is taken up and amplified by social media.

It is particularly important to study the emerging narratives about alternative proteins for several reasons. First, alternative proteins represent to some degree a contested space, with some stakeholders enthusiastic about their prospects while others are less convinced by their worth or concerned that they may be a threat to livelihoods and other interests.[79] These narratives feed strongly into the political economy section, and the study consequently distinguishes between supportive and cautionary narratives.

Second, just as alternative proteins may be disruptive to the food industry, they are also psychologically disruptive, challenging society's very notion of what "meat" is.[80] There is tension between food as nutritionally sustaining and culturally valuable, and food as having potential for harm and ill health. Alternative proteins can be placed on both sides of this fault line.

This section presents an analysis of the main supportive and cautionary narratives based on qualitative social science investigation of digital data from the official public websites, social media accounts and related sources of important alternative protein companies and non-profit advocacy groups.[81] The focus is mainly on Europe and North America, where most innovation in this area is occurring.

The chief supportive and cautionary narratives that emerged from this analysis are described below in the form of clear statements (in bold). It must be stressed that these narratives are what were found in the material examined and are not necessarily supported by an evidence base. In other words, they are the building blocks of contemporary discourse, rather than statements that the study endorses.

Supportive narratives

Foods containing alternative proteins help you live a healthier life

Alternative proteins are free of the risk of food poisoning or contamination

Products based on alternative proteins taste excellent

Alternative-protein products are better for the environment

Alternative-protein products do not harm animals

Alternative proteins promote food security by releasing land currently used to grow animal feed for the production of human food.

Cautionary narratives

Alternative-protein products will always play just a minor role in the global food system

Alternative-protein products are not real food

Alternative-protein products are not as good as the real thing

Livestock is more than food

Supportive narratives

Foods containing alternative proteins help you live a healthier life. Much of this messaging centres on the desirability of good-quality protein and high-protein foods. Much marketing material suggests alternative proteins are sources of physical power – providing fuel for healthy and adventurous lifestyles, as followed by people with desirable body aesthetics. Emphasizing the benefits of protein per se has been particularly important for insect-based products such as energy bars, their main presence in the market to date. A similar concentration on protein has been used to promote protein-rich diets such as the "Paleo diet" and in general this has been part of a "nutricentric"[82] trend that in recent years has seen protein treated as a specific food category.

This emphasis on protein, a familiar nutrient category, also acts to blur the distinction between traditional animal-sourced foods and their possible substitutes. It can act to break down the assumption that protein must come from animal products (though narratives supportive of insect products may build on this assumption).

Alternative proteins are also positioned as avoiding the unhealthy components of animal-based proteins, especially the high content of saturated fatty acids, and as containing more fibre, which has positive health benefits. Explicit claims (not always justified by the epidemiological literature) are often made that their consumption reduces the risks of cancer and cardiovascular disease. It is also claimed that alternative protein is free of other negatives associated with livestock such as hormones and antibiotics (claims often coupled with the exclusion of other ingredients with negative connotations for some people such as soy, gluten and genetically modified organisms/GMOs).

Alternative proteins are free of the risk of food poisoning or contamination. Livestock production is often perceived as a messy business involving the management of animal waste and the slaughter of a living creature. There are many opportunities along the supply chain for food to become contaminated or spoiled, especial in countries where refrigeration is expensive and power supplies unreliable. Meat and animal products in high-income countries are probably safer today than at any time in history, yet periodic food scares involving meat and dairy do occur. The production of plant-based food involves fewer opportunities for contamination or spoilage, while cultured-meat production offers the promise of laboratory-level control of the whole process. The position of insect-based foods is less clear (in fact or perception); some production facilities approach laboratory levels of control while others make a virtue of using food waste as feedstock with less opportunity for close control.

The use of antibiotics as veterinary medicines, but particularly as growth promoters, is causing increasing concern as levels of antimicrobial drug resistance grow.[83] Producing food that largely avoids the use of antibiotics is occasionally employed as an argument in favour of cellular meat or plant-based substitutes. If some of the direr warnings about the rise of antibiotic resistance come to pass[84] then society and decision-makers can expect much more emphasis on this advantage.

The use of the word "clean" to describe meat produced in laboratory-like facilities has been particularly contested.[81] While clean denotes purity and the absence of contamination, those within the field worry about its association with the "clean eating" movement, which privileges unprocessed, over processed, foods. It has also raised criticisms from outside the alternative protein sector that it unfairly demonizes traditional meat as "dirty" or "unclean". Today, the terms "cultured meat" or "cell-based meat" are generally preferred.[85]

Products based on alternative proteins taste excellent. Two barriers to the uptake of animal-free alternatives, particularly among meat eaters, are a lack of familiarity and negative perception of their sensory properties. Building a narrative that promises the same taste, appearance and overall eating experience as conventional animal foods has consequently been a central goal of those supportive of alternative protein developers. Statements such as "*The revolutionary plant burger that looks, cooks and satisfies like beef*" and "*mouth-watering juiciness and chew*", supported by appropriate images and videos, are common on websites and promotional material associated with these products.[36,37]

Such strategies work to shift perceptions of alternative protein eating from "dull to desirable"[86] and emphasize that food which is "good" for us and the planet is also tasty to eat. This stress on pleasure can be further highlighted by including notions such as "treating" oneself to a "guilt-free guilty indulgence".

Alternative-protein products are better for the environment. The increasing realization that livestock animals are a significant source of greenhouse-gas emissions has underpinned the narrative of alternative proteins being good for the environment and in particular good for climate change mitigation. The coincidence of beef production having a particularly large environmental footprint and burger patties being the first products of the recent suite of novel alternative proteins has reinforced this. In addition to greenhouse-gas emissions, avoiding the conversion of rainforest for beef production (particularly in the Amazon) and reducing competition for water are sometimes listed as environmental benefits of alternative proteins.

As noted earlier, narratives do not always align with facts.[30] Some of the environmental claims made by supporters of alternative proteins are not always supported by scientific evidence, and the exaggeration of the negative effects of livestock on the environment can be common (one ascribed half of all anthropogenic greenhouse-gas emissions to livestock, the best estimate is about 15%).[26; 30]

Alternative-protein products do not harm animals. There has been a marked rise in the past decade in the numbers of vegetarians and vegans in high-income countries, especially among the generation of millennials.[87] The reasons for this trend are complex and still unfolding, but early research indicates that concern for personal health and the perceived benefits of non-animal diets for the environment and animal welfare are leading reasons for people under 25. Some animal welfare charities have embraced the prospect of artificial meat as a means to avoid livestock and especially intensive livestock production.

This narrative is mainly used by advocacy groups, and relatively infrequently by the alternative protein industry, where some material does talk of building a "kinder" food system and quotes the figure of 66 billion animals being slaughtered each year for food. As animal welfare, vegetarianism and veganism are associated in Europe and North America with more liberal political philosophies, there may be concern that emphasizing this narrative too heavily may put off some potential purchasers.

Alternative proteins promote food security by releasing land currently used to grow animal feed for the production of human food. At the global level, this is stated as helping address the challenge of meeting the food demands of a growing global population.

Messages broadly framed about global food security can have limited traction and yet the same narrative when reframed at a more personal level can be much more potent. An example of effective marketing material for a plant-based burger that encapsulates this story is: "*We make [our product] entirely from plants, without the destructive impact of livestock, so that you, your children, and your grandchildren's children will always be able to enjoy a good ol' fashioned burger*".[36] Here, alternative proteins are framed as a solution for the future that preserves the pleasures of the present.

Cautionary narratives

Alternative-protein products will always play just a minor role in the global food system. Especially in the earlier stages of the development of alternative proteins, a common narrative was to dismiss the new products as not being a serious threat to the status quo. In the case of more revolutionary products such as cultured meat, this was at least partly based on genuine scepticism about whether the technology could actually be developed at scale and at competitive prices, a standpoint that for some products such as cultured meat might still be defended today. The dismissiveness was also rooted in a belief that the consumer would reject the new products because they would never taste as good as the original, or because, in the case of more novel products, they would reject the underlying technology on principle or because of a "yuck factor". The rise of electric vehicles and the recent decline of the diesel combustion engine provide examples of the rapidity with which technologies and infrastructures can be disrupted.

Alternative-protein products are not real food. The characterization of artificial protein products as unnatural, artificial or synthetic in comparison with conventional animal foods is a common cautionary narrative. Targeted in particular at the most processed alternatives, the idea that these products are "not real food" challenges their controlled and safe image by highlighting the technoscientific nature of their production – specifically the use of biomedical techniques, laboratories and in some cases genetic engineering.

Alternative-protein products are not as good as the real thing. If "not real food" stresses the negatives of artificial protein, then "not as good as the real thing" stresses the positives of traditional animal-sourced foods. It highlights meat and dairy as energy-dense sources of protein and many micronutrients and often claims that natural foods provide a superior "balance" of nutrients, or simply just feel and taste better.

This and the prior account align with an overarching narrative found throughout the food system and particularly prevalent in North America and Europe, one that seeks to reclaim the natural from the artificial, the slow from the fast and the simple from the overly processed in the modern food system. It targets in particular ultraprocessed food, a category that is hard to define but is normally taken to mean the outcome of large-scale commercial processing.[88] At its heart is a distrust of the modern commercial food system and more generally a dissatisfaction with contemporary global capitalism as a viable mechanism for delivering a sustainable and socially just food system.

Livestock is more than food. The final cautionary narrative stresses the non-food contributions to society of the livestock industry and points out that livestock production can have positive as well as negative externalities. In particular, it highlights the importance of the industry's contribution to many countries' GDP, and also its special role in supporting local rural economies.[18]

For example, livestock production is the only viable form of agriculture in many European upland and North American dryland regions, and its disappearance would substantially affect jobs and the socioeconomic sustainability of local communities.[31]

This narrative is often expressed as a reaction to the "demonization of meat",[89] especially by urban as opposed to rural commentators, and people with a liberal as opposed to conservative worldview. It enlists the fact that many people in developing countries are reliant on livestock, not only for food but as stores of wealth. It can interpret rich-country concerns about livestock as neocolonial attacks on cultures in which livestock and livestock production are central.[90]

Regional variations – highlighting Asia

This report's discussion of the framing of alternative proteins has largely focused on North America and Europe, the main centres of current innovation. Here, we present a brief assessment of how narratives may develop in the wealthier countries of Asia such as China and India. This region has a very long history of using meat substitutes in its indigenous cuisine, but the new movement for alternative proteins is just beginning to gain momentum.[91]

Meat consumption is increasing in Asia but is still lower than in Europe and North America. Nevertheless, the latest Chinese dietary guidelines (2016)[92] encourage eating less meat and have a set a target of a 50% reduction by 2030. Traditionally, China has consumed more chicken and pork than red meat, and in whole (or cut-up) form rather than as minced meat. This suggests that companies innovating with chicken and pork substitutes, for instance, may find more ready markets than those developing plant-based and cultured-meat burgers.

A variety of factors will lead to a different development of supportive and cautionary narratives about alternative proteins in Asia compared with Europe and North America. Here are four:

- Asia has a far longer history of using plant-based and insect-based products as high-protein alternatives to meat, which would suggest people in this region may be predisposed to accept new non-animal alternatives.

- In China (and other countries), there is a public preoccupation with food safety[93] and there have been several significant incidents, including the adulteration of milk products with melamine in 2008 that affected over a quarter of a million people and resulted in the deaths of six babies. Narratives that stress the safety and controlled production of meat substitutes are likely to resonate with these concerns.

- Some countries such as India have a long cultural history of religious vegetarianism. In these countries, abstinence from meat has an association with tradition and conservatism, which contrasts with its association with liberalism and the counterculture in the West.

- While environmental and welfare issues currently have less traction in Asia than in Europe and North America, there are signs of this changing among the increasing numbers of young, middle-class consumers.

Political Economy

Alternative-protein products have the potential to disrupt a major economic sector. Whether this will happen and at what speed will depend in part on how the alternatives benefit society and whether consumers chose to purchase them – topics that are discussed in the last two sections. It also depends on the political economy of the food system, the interactions between the different stakeholders who believe they will benefit or suffer from the transition, the narratives used and how governments respond to their arguments. However, this disruption should not be approached as a zero-sum game; constructing a future in which as many people as possible gain from the spread of alternative proteins can both maximize human welfare and deliver the best outcomes for global health and the environment.

Here, the study considers two issues: first, the implications for different industry sectors; and second, how the regulatory environment is responding to the challenge of novel food types.

Implications for industry sectors

The food industry

Alternative-protein products are already on sale, chiefly in high- and middle-income countries, although even here they occupy only a small fraction of the market. The next decade will see a potential tipping point, when they might move from being "niche food" to "mainstream food" in high- and possibly middle-income countries. The improved quality of novel products and possible intervention by governments are two factors that may accelerate the change.

For major food manufacturers and consumer brands, the study defines two contrasting scenarios for the future of different types of alternative protein. The first, "mainstream food", is one in which alternative proteins are taken up by major food companies, and – employing their strengths in production technologies and marketing – they achieve mass-market penetration and genuinely disrupt the ~$1 trillion per annum global meat market. The second is that alternative proteins remain "niche food", marketed at a relatively high price point to particular consumer communities.

Recent history shows only a small number of alternative proteins introduced in the past 50 years have achieved scale. The majority of these are based on soy, wheat or tofu and include vegetarian products such as Tofurkey (available from several manufacturers in Europe and the US)[94] or Boca Burgers (now owned by Kraft Heinz)[95] in the US. Of the non-plant-based alternatives, only the mycoprotein-based Quorn has achieved substantial market penetration, and chiefly in the United Kingdom.[39] Though sales are substantial (£205 million in 2017), they are dwarfed by meat and the product is largely viewed as a specialist vegetarian product.

There are several reasons why this history may be a poor guide to the future, however. First, significant technological advances in taste, texture and presentation make modern alternative-protein products considerably more attractive than their predecessors. Second, the demonstrable environmental and health benefits of some products may persuade some governments to facilitate or accelerate their uptake, through regulatory or fiscal intervention, rather than just leaving it to the market (an analogue might be government interventions in the 1990s and 2000s to promote solar power uptake, for example). Lastly, the increasing investment by major food and commodity companies in alternative protein start-ups (for example Cargill in Puris; Tyson Foods in Beyond Meat and Future Meat Technologies; both in Memphis Meats; Maple Leaf Food in Entomo Farms and Lightlife Foods; Nestle's in Sweet Earth)[96] clearly signals industry's belief in the potential for significant growth in this sector and brings their strengths in production, marketing and distribution.

Livestock sector

A major concern is that alternative proteins, were they to become generally accepted and relatively cheap, would lead to reduced livestock production, creating unemployment and causing farms to go out of business – with knock-on effects for the whole rural economy.[97] This is an understandable worry, but one that may be overstated for the foreseeable future, given the underlying trend for meat demand to increase globally.[98] Paying higher prices to farmers for producing high-quality, sustainable meat, and rewarding them for the provision of ecosystem services are two ways in which the alternative and traditional sectors can work together to maximize societal benefits.

Reducing the impacts on the livestock industry of the rise of alternative proteins is important in order to protect the livelihoods of the people concerned, especially as many live in regions with restricted alternative employment. It is also important as the livestock industry is politically active and influential.

Livestock is currently "mainstream food", but one might imagine that it could take on aspects of "niche food", producing conventional meat with very high welfare and environmental standards and sold at a high price point. The stated aim of some alternative protein start-ups is to replace intensive meat production (with implied negative welfare and environmental standards) rather than to replace more artisanal production. An argument against including economic externalities in the price of meat is that it is regressive and disadvantages those on low income.[48] This argument would have less force if alternative proteins had both price and taste parity with their animal-based counterparts.

There is a growing movement to understand and price the ecosystem services provided by the natural environment. Many of these services are provided by land currently used for livestock grazing, and rewarding these positive externalities of farming both provides societal benefits and supports rural economies. The UK government recently announced that after leaving the EU it would reallocate the money the UK farming sector receives as a direct cash transfer under the Common Agricultural Policy (CAP) to payment for the provision of public goods.[99] Some of this money will go to livestock farmers to reward them for managing their land more sustainably (probably with lower stock density).

Feedstock industry

Livestock currently consume about 1.5 billion tons of grains a year (out of about 2.6 billion in total), typically in the form of concentrates.[100,101] Were there to be a reduction in meat production, the feed industry would be strongly affected; however, it could at least partially recoup losses by switching to producing the inputs required for alternative protein production.

The production of alternative proteins at scale will require substantial inputs. For plant-based analogues, these are arable crops, which may or not be the same as those used for feeding livestock. For cultured meat, a wider variety of inputs are needed and though these conceivably might include novel raw ingredients derived from sources such as algae, without significant interventions plants are likely to be the most economic source. Insect-based alternative proteins also use plant inputs, but include parts of the plant that cannot be used as farm-animal feed. Thus, there will still be a demand for "feed" in the broad sense of the word, though it may be reduced and will almost certainly involve growing different types of crops at scale. The amount of feedstock required per unit of output will be less – part of the environmental efficiency argument in favour of alternative proteins – but not necessarily the total demand, which will depend on the consumption patterns of a growing global population.

A substantial fraction of the material fed to cattle is a by-product of food grown for human consumption. It will be important to understand the consequences of a reduced market for these products; for example, might it lead to an increase in the net costs of production and hence the price of food, or might it stimulate the production of renewable energy or novel bioproducts?

The regulatory environment

Regulatory agencies are being challenged to develop appropriate rules for the new wave of alternative proteins. Good regulation that protects the public from health risks and unsubstantiated claims is important and can both stimulate innovation and promote value creation. Clarity about which agencies have responsibility for regulation, and neutrality from the sway of any interest group, is critical to realizing the potential of alternative proteins.

Regulation to ensure that novel food substances have no negative effects on human health is necessarily complex. One set of regulations seeks to ensure food safety – that products do not contain toxins or pathogens which could potentially affect all consumers – and is relatively uncontroversial. Another set of regulations, however, concerns allergens that particular individuals react against. Most foods are allergenic to a small number of people, and a point of contention in the regulation of alternative proteins is the stringency with which novel proteins should be tested as rare potential allergens.

In some jurisdictions, certain classes of technology are subject to specific regulations. For example, in Europe there are specific rules for genetically modified (GM) foods that apply even if they are indistinguishable in their final form from non-GM alternatives. It is not yet clear how different regulatory authorities (including religious authorities) will treat cultured meat and whether it will be subject to specific regulations. Indeed, it was only in November 2018 that the United States decided cultured meat should be jointly regulated by the Food and Drug Administration (FDA) and the United States Department of Agriculture (USDA).[102]

Many alternative protein companies make bold claims about the environmental sustainability of their products, particularly in terms of greenhouse-gas emissions and water use. So far, relatively few independent assessments of these claims have been made and, as the report discussed in the modelling section, those that have should be treated as preliminary.

The possibility that future regulations prompted by increasing concern about climate change may reduce the value of current assets (so they become "stranded assets") has become part of mainstream thinking in the energy sector. Analysis of how this type of regulatory risk might affect the food industry, and in particular how it might influence the relative returns from investing in meat and alternatives to meat, is just beginning.

In May 2018, Missouri passed a law reserving the term "meat" for products derived from live animals. Around the same time, a farmer-politician in France successfully inserted an amendment into the nation's agricultural bill making it illegal for vegetarian products to be marketed using terms such as "meat", "steaks" and "sausages". The year before, the European Court of Justice declared illegal the use of "milk" and associated terms such as "cheese" to describe dairy substitutes.[103]

Behind these initiatives are concerns that the camouflaging and normalization of protein alternatives confuses the public and makes it easier for alternative-protein products to be associated with the positive attributes of traditional proteins. These arguments both refer to and feed into the development of the different cautionary and supportive narratives discussed above. The overall effect of these interventions is hard to gauge: they may delay adoption by causing alternative proteins to appear less familiar to the consumer, or perversely may accelerate adoption by providing extra publicity about the substitute products concerned.

Accelerating the Adoption of Alternative Proteins

The challenge of meeting the protein needs of a mid-century population of 10 billion people in an inclusive, sustainable, healthy and nutritious manner is enormous, but achievable. What is clear is that this will not happen on our current, business-as-usual trajectory. Significant transformation of the protein system is essential to achieve the SDGs and to meet the Paris Agreement climate change targets.

The new wave of alternative proteins and the vision of what they can deliver in the future provide an exciting set of options that can help with this transformation. The modelling in this report shows that different types of alternative protein can substantially reduce greenhouse-gas emissions and can contribute to a reduction in diet-related mortality.

To make a meaningful impact, however, it is clear that a combination of well-orchestrated public and private actions must be accelerated to drive transformative change at scale, both globally and in different regions and within different supply chains and markets. The analyses in this report identify a number of significant intervention points at which such actions may be most effective.

Avoiding unintended consequences of alternatives

Modelling highlights the benefits of change but is also valuable in identifying perverse or unintended outcomes. Once identified, and particularly if identified early, actions can be taken to confirm that a risk exists and then reduce or mitigate it. Our assessment has highlighted a few such areas – which, while preliminary, deserve further attention.

First, the analysis illustrates that increasing consumption of spirulina algae at scale could have negative health effects because of its high salt content, and the same for cricket flour in regard to sodium and cholesterol. Second, the use of heme iron derived from plants and used in vegetarian burgers will require further study to understand if it has the same health risks as heme iron in animal-derived foods. In both cases, these impacts might be mitigated by future changes in the way in which these alternatives are processed. An advantage of many of the new wave of alternative proteins, both plant-based and those involving cultured meat, is that their precise nutritional composition can be tailored to best meet the needs of human health.

Finally, the analysis highlights the current greenhouse-gas emissions of cultured meat not being significantly lower than standard meat production, mainly due to the sizeable energy requirements in its current production methods. Yet, there is great scope for mitigation of these impacts through the use of renewable energy, innovation in production and the co-location of production and consumption to collapse supply chains and reduce transport emissions (and costs). The relatively large emissions identified in this report should not be seen as a negative for cultured meat but as a call for action to where innovation is required to help accelerate the transformative potential of the cultured-meat sector.

Blending production realities and social science to drive increased conversion to alternative protein sources in middle- and high-income countries

Alternative proteins will become a major part of the food system only if people decide to consume them. Starting from a common evidence base and framing alternative proteins using narratives that are both honest and which resonate with peoples' aspirations, as well as frankly addressing and responding to those that are critical, will be essential if alternative-protein products are to be accepted.

Further efforts should be made to target narratives to different constituencies – within a country there is not one public but multiple publics. Insights from the food-processing and marketing industry could be hugely valuable in making messaging more sophisticated and the potential assistance they could provide in achieving societal goals for the food system is greatly underappreciated. Much more work is needed into how supportive and cautionary narratives vary between countries and this will be essential to achieving a global impact for alternative proteins.

Accelerating investment

Alternative proteins present opportunities for venture capital and the private sector, and have rightly attracted considerable recent investment. In addition to promising strong investment returns, they also have great potential – as shown above – to contribute significantly to the provision of public goods, including a healthier population and a stronger, more resilient environment. They therefore present a strong argument for joint public-private investment and new platforms for innovation acceleration and market development, similar to how the renewables industry was "pump-primed" by some key governments in the 1990s and 2000s, with a global public good benefit in mind. In particular, investment in technical and production methods that can be scaled in ways that maximize sustainability is critical, and may not be delivered purely by the market. There is, therefore, a substantial opportunity for a smart public-private intervention to help shape and accelerate a new protein economy.

Creating incentives

The interaction between alternative and traditional proteins is not a zero-sum game, despite some narratives that imply it is. There are enormous opportunities for multiple stakeholders and society in general to gain – particularly if decision-makers can look beyond single measures of success to a more systemic view of the food system: one that is inclusive, sustainable, healthy and nutritious, and productive.

Alternative-protein products do have the potential to disrupt the food system, which threatens established livelihoods. The sector is not alone in this regard, for this is a challenge currently faced by all industries experiencing the Fourth Industrial Revolution. A better understanding of how the political economy of the food system works can help reduce tensions and assist policy-makers identify groups that may be at risk of impact and proactively help them. For example, affected livestock producers might be assisted to produce higher-value but lower-volume products. The new approach the UK has announced of paying farmers for the provision of ecosystem services – "public money for public goods"– illustrates another policy option with potential multiple beneficiaries.

Innovation in traceability and labelling for both alternative- and traditional-protein products, for example, involving distributed ledgers and embedded microchips, present exciting opportunities to improve transparency and communicate to consumers the multiple impacts of different food types. This responds to consumers' increasing demands for knowledge about the food they eat, but also enables them to become powerful agents for change, providing a collective incentive for improvements in multiple dimensions of the food system. This topic – at the food systems level – is the focus of the second phase of the World Economic Forum's Innovation with a Purpose initiative.

Regulatory agencies have struggled to keep pace with the speed of innovation in this area. Regulation needs to be smart and designed not only to keep the public safe and protected from unsubstantiated claims, but also to facilitate innovation and value creation.

Finally, the study notes that researchers are increasingly hearing calls for a new social contract, one that places value on factors overlooked in the previous industrial revolutions. New metrics such as those based on environmental, social and governance (ESG) considerations have begun to put financial value on areas previously regarded as externalities. As this space evolves, it will present further incentives to support innovations such as alternative proteins, which look to deliver a variety of environmental and societal benefits.

Co-creation opportunities in regions with growing demand

A large focus of this report has been on alternative proteins in high- and middle-income countries where per capita meat consumption is at or above recommendations and where reducing consumption is of most importance. It is to be hoped that insights from these countries will help low-income countries avoid the food-system mistakes made in the past by today's wealthy nations as they increase in prosperity and move along their own development trajectory.

It cannot be assumed that all of the exciting alternative-protein innovations currently being developed, mainly in the West, will be appropriate for all markets and cultures. A strong spirit of co-creation is needed to identify and adapt the best ideas that address environmental and societal challenges to new markets – particularly those such as China, the rest of Asia and Africa.

Conclusion

To meet the protein needs of a projected population of 10 billion people by around 2050 in an inclusive, sustainable, healthy and nutritious manner is, as discussed above, a significant challenge. But it can be done. Transformation of the food system is essential to achieve the Sustainable Development Goals and to meet the Paris Agreement climate-change targets. Innovation and experimentation in both alternative and traditional proteins will be critical.

It is hoped that the figures presented in this paper will provide a starting point for further analysis, one that will need to evolve as new alternatives are developed and as production processes and technologies are scaled up. The discussion will need to respond to developments in how traditional animal-based protein is produced and to changes in what consumers believe is an equitable food system producing nutritious food.

This analysis is intended to facilitate further debate and dialogue between stakeholders, and to identify areas of opportunity and critical intervention points. It seeks to encourage a step-change in progress, in particular by harnessing the transformational possibilities of the Fourth Industrial Revolution. It argues for a systemic, multistakeholder approach – the building of new platforms of action to accelerate and scale this new protein economy – in order to help create the future we want and need.

For the foreseeable future, the meat and alternative-protein industries will coexist and have the opportunity to complement one other. Both incumbents and new players, and the various stakeholders who are involved throughout the protein supply chains, will gain from a nuanced debate about how to evolve and reshape regional and ultimately global food systems to provide healthy and sustainable diets. Only through dialogue and structured collaboration will society be able to transform the protein system, to create a future where safe, sustainable, affordable and healthy protein is provided to all.

Annex: Nutrient Content of 200kcal of Meat and Meat Alternatives

Nutrient (g)	Beef	Pork	Chicken	Wheat	Nuts	Bean	Pea	Tofu	Myco-protein	Jackfruit	Insect	Alga	Cult. beef
Calories (kcal)	200	200	200	200	200	200	200	200	200	200	200	200	200
Grams	83	67	140	60	33	157	247	241	235	211	43	69	83
Protein	20.89	17.30	24.39	5.79	6.43	13.65	13.38	24.05	25.88	3.62	27.49	39.63	20.89
Carbohydrates	0.52		0.06	44.87	7.39	35.91	35.68	2.84	7.06	48.95	2.89	16.48	0.52
Sugar				0.61	1.65	0.50	14.00	1.71	1.18	40.17		2.14	
Fibre				7.89	2.11	11.65	14.07	2.41	14.12	3.16	2.89	2.48	
Fat	12.11	13.99	11.33	1.17	17.63	0.79	0.99	12.67	6.82	1.35	8.68	5.32	12.11
Sat. fatty acid	4.67	5.20	3.22	0.26	2.64	0.11	0.18	2.21	1.41	0.41	2.89	1.83	2.33
Mon. fatty acid	5.33	6.23	5.05	0.17	11.38	0.06	0.09	3.18	1.18	0.33	1.47	0.47	5.33
Poly. fatty acid	0.41	1.26	2.11	0.70	3.25	0.43	0.46	6.40	4.24	0.20	3.97	1.43	2.74
Transfats			0.09		0.01								
Cholesterol mg	70.00	63.30									131.64		70.00
Calcium mg	20.83	14.81	8.39	19.88	28.67	44.09	61.73	679.52	100.00	50.53	65.10	82.76	20.83
Iron mg	2.23	0.87	1.15	2.23	1.23	4.63	3.63	4.92	1.18	0.48	2.54	19.66	2.23
Heme mg	0.78	0.44	0.52										0.78
Magnesium mg	18.33	16.16	29.37	70.48	74.79	70.87	81.48	84.34	105.88	61.05	52.08	134.48	18.33
Phosphorus mg	177.50	152.19	248.95	194.58	144.32	223.62	266.67	267.47	611.76	44.21		81.38	177.50
Potassium mg	294.17	243.77	730.07	237.35	211.86	634.65	602.47	313.25	235.29	943.16	438.34	940.00	294.17
Sodium mg	70.83	49.16	83.92	1.81	1.32	3.15	12.35	9.64	11.76	4.21	175.05	722.76	70.83
Zinc mg	5.16	2.16	2.06	1.78	1.34	1.69	3.06	2.58	21.18	0.27	7.59	1.38	5.16
Copper mg	0.07	0.03	0.09	0.29	0.50	0.38	0.43	0.48	1.18	0.16		4.21	0.07
Vitamin C mg		0.47			0.26	1.89	98.77			28.84	0.43	6.97	
Thiamin mg	0.04	0.48	0.15	0.18	0.10	0.25	0.66	0.12		0.22		1.64	0.04
Riboflavin mg	0.15	0.15	0.34	0.11	0.13	0.09	0.33	0.12	0.54	0.12	1.44	2.53	0.15
Niacin mg	4.74	2.83	7.80	3.22	2.05	0.91	5.16	0.58	0.82	1.94	3.25	8.84	4.74
Pantothen. mg	0.57	0.35	1.53	0.61		0.35	0.26	2.03	0.59	0.49	3.62	2.40	0.57
Vitamin B6 µg	0.32	0.26	0.72	0.12	0.12	0.19	0.42	0.20	0.29	0.69		0.25	0.32
Folate µg	7.50	4.04	1.40	16.87	19.77	204.72	160.49	21.69		50.53		64.83	7.50
Vitamin B12 µg	2.28	0.36	0.78								3.62		2.28
Vitamin A µg	5.83	1.35					93.83			10.53		20.00	5.83

Abbreviations: Cult., cultured; Sat., saturated; Mon., monounsaturated; Poly., polyunsaturated.; pantothen., pantothenate.

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