Part of the conference series

Breakthrough science and technologies

Transforming our future

Future food: health and sustainability

Held on 12 December 2019

Conference report

THE ROYAL SOCIETY

Introduction

This conference held by the Royal Society brought together leading experts from industry, government and the wider scientific community to discuss the future of food sources and the human diet in decades to come.

Future food: health and sustainability focussed on three broad themes: the sustainability and health benefits of plant-based foods, alternative food sources and the application of synthetic biology in food production. The UK's current standing in terms of food research, changing consumer preferences and public perception, regulation, safety and ethical issues was also explored.

This conference is part of a series organised by the Royal Society entitled Breakthrough science and technologies: Transforming our future, which addresses the major scientific and technical challenges of the next decade. Each conference covers key issues including the current state of the UK industry sector, the future direction of research and the wider social and economic implications.

The conference series is organised through the Royal Society's Science and Industry programme which demonstrates the Society's commitment to integrate science and industry at the Society, promote science and its value, build relationships and foster translation.

This report is not a verbatim record, but a summary of the discussions that took place during the day and the key points raised. Comments and recommendations reflect the views and opinions of the speakers and not necessarily those of the Royal Society.

Image: A delegate tries food made from Camelina seeds – one promising vehicle for producing long chain omega-3 polyunsaturated fatty acids in a plant source, as in Professor Jonathan Napier's talk.

Executive summary

This conference considered three main topics: sustainability and the benefits of reducing animal-based food production, alternative food sources and synthetic biology approaches to food production. A panel discussion interrogated issues in regulation and ethics, changing consumer preferences and public perception.

- Public tastes are changing and there are now 22 million flexitarians in the UK – people who have primarily vegetarian diets but occasionally eat meat or fish. This demand for alternative food types is reflected in the increasing number of vegan products available, around 10,000 new products in 2018 up 52% on 2017.
- There are substantial health benefits to eating a mostly plant-based diet, including reduced LDL cholesterol and reduced likelihood of coronary heart disease.
- Transforming agricultural land use, food production and processing will allow us to stay within safe planetary boundaries with respect to global warming. Agriculture currently contributes 20 – 30% of greenhouse gas emissions.
- We are seeing increasing rigour in nutritional science, both of studies and how they are reported. However, consumers are confused and there is a need for clear product labelling of both the environmental impact associated with production of any food and its potential impact on human health.
- The size of the alternative meat industry is growing. While it is worth 1% of the global meat industry today (around $14 billion) it could grow to 10% (over $140 billion) within the decade.
- There is a range of methods to develop alternative protein sources, including engineering microbes to produce animal proteins via synthetic biology, CRISPR technology to improve the taste of fruits and vegetables, and producing meat by cellular agriculture. Plant-based protein sources are also being developed, and plants can be metabolically engineered to produce specific nutrients.
- SMEs and start-ups are finding success in the alternative foods space, partly due to increased public trust in small companies over large multinationals.
- Despite this technological progress and manifold environmental and health reasons for a mostly plant-based diet, without public trust, good flavour and affordability, there will not be widespread uptake of these new foods.

Image: Delegates networking at the conference.

Sustainability and the benefits of reducing animal-based food production

The role of plant-centric dietary patterns: the potential for a double win

The challenge of feeding the world's growing population a healthy and sustainable diet is substantial. Professor Walter C Willett, Harvard T.H. Chan School of Public Health, outlined work by the EAT-Lancet Commission to develop a target healthy diet, sustainable for an expected population of 9.8 billion in 2050.

Two billion people today lack key micronutrients and 155 million children have stunted growth. At the same time, two billion adults are overweight or obese, with implications in almost every health variable including diabetes, cancer and cardiovascular disease. In the USA, incidences of cardiovascular disease are increasing for the first time in 60 years and life expectancy is decreasing for the first time. Poor quality diets may be responsible for the reversal of many of the major health gains of the last century.

Meanwhile, we are on track to greatly exceed the 2°C limit of global warming set by the Paris Climate Agreement. As ice melts and releases trapped greenhouse gases, a feedback loop accelerates this warming with consequences for agriculture and health.

> "Feeding 9.8 billion people a healthy diet within safe planetary boundaries is possible and will improve the health and wellbeing of billions of people. In conjunction with green energy, this could allow us to pass onto our children a viable planet."
>
> Professor Walter C Willett, Harvard T.H. Chan School of Public Health

EAT-Lancet Commission study

The EAT-Lancet Commission addressed this challenge by identifying a target healthy diet and determining whether these foods could be sustainably produced within defined planetary boundaries for the expected population of 9.8 billion people by 2050. A global food systems modelling framework was applied to find the combination of diets needed to stay within food production boundaries while delivering a healthy diet. Parameters investigated to define a healthy diet included:

- **The ratio of polyunsaturated to saturated fat in protein sources.** Of protein sources studied, beef has the lowest ratio, and lentils the highest, with implications for health as polyunsaturated fat reduces blood cholesterol.
- **The effects of red meat on LDL cholesterol.** High-quality plant protein sources have a positive effect on LDL cholesterol, while animal protein sources have a detrimental effect.
- **Red meat and total mortality in prospective studies.** Increased red meat servings per day are associated with increased mortality including by heart disease and cancer, with a clear linear dose-response relationship. This included a long term epidemiologic study of 130,000 people for over 30 years. No sharp cut-off was found below which red meat causes no problems.

Recommended healthy diet and achieving it sustainably

A plant-based diet is closely linked to reduced coronary heart disease (CHD) with a linear relationship. Substantially lower risk (~20 – 30%) of CHD is observed by replacing one serving of red meat per day with nuts or beans. The target for red meat consumption was based on the development of Type 2 diabetes in a study of 204,000 people. A statistically significant increase in development of the disease was identified between 0.4 and 0.7 servings (85g) consumed per day.

The identified target diet was primarily based on plant protein sources, fruits, vegetables, whole grains, with the dairy and animal protein equivalents of one glass of milk a day and one beef burger a week. If everyone in the world adopted these dietary targets, it would prevent ~11 million premature deaths per year.

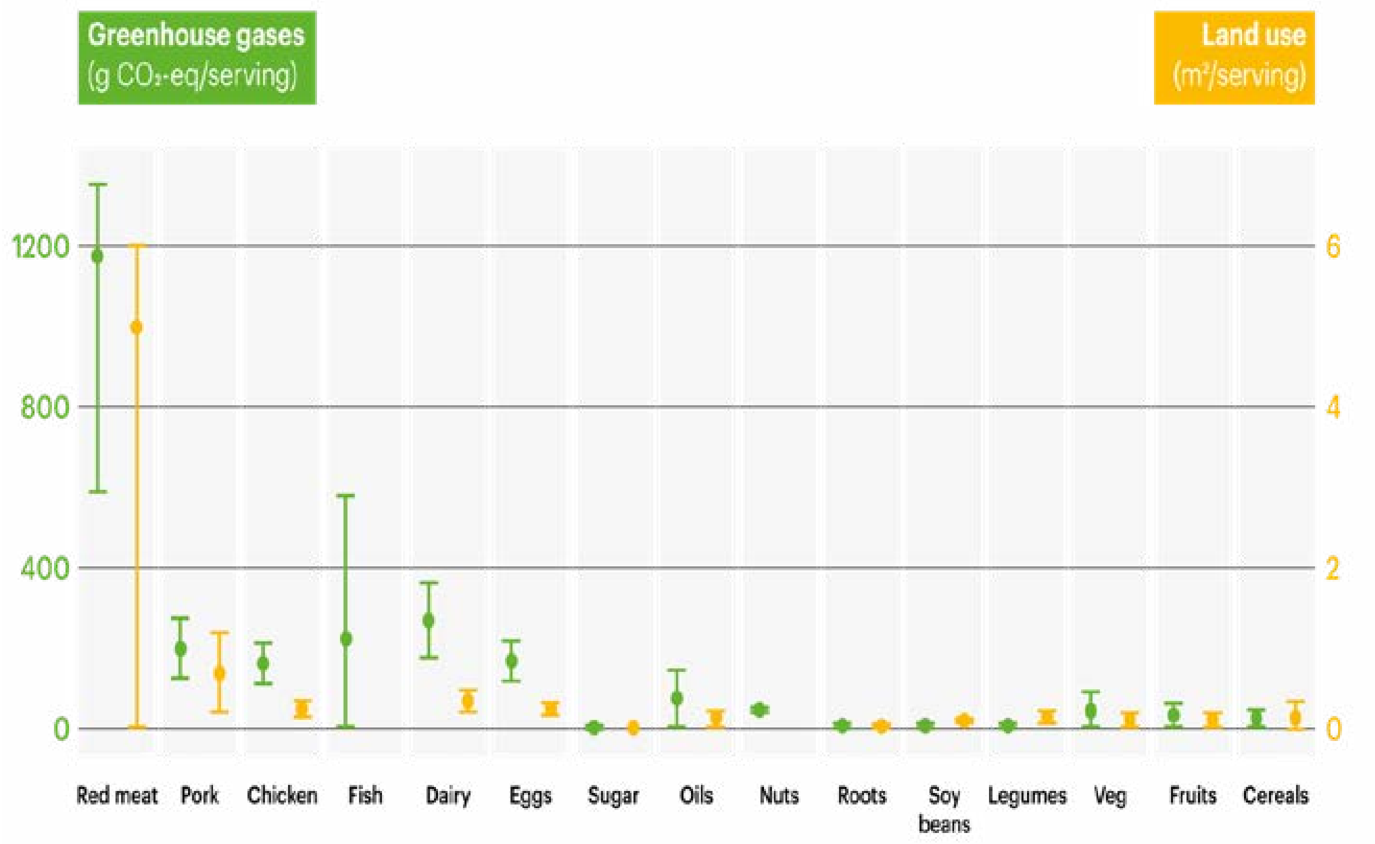
The environmental benefits of switching to a mostly plant-based diet are also substantial (figure 1). We are currently on track to exceed greenhouse gas emission limits set out by the Intergovernmental Panel on Climate Change (IPCC) for the agricultural sector by 2050. In conjunction with use of green energy sources, adopting a target diet will prevent us from overshooting this limit, while adding improvements in production and reducing waste allow us to undercut it.

Fake news

There have been examples of news articles that caught the publics' attention by countering this report by EAT-Lancet. These articles are based on academic research that concluded that there was no need to reduce consumption of red or processed meat. However, the researchers ignored randomised trials of cardiovascular disease (CVD) risk factors and discarded their own analyses of increased CVD risk. Such academic papers are influenced by the disinformation triangle of sensationalist media, Big Beef and 'evidence-based' academics, raising concerns that articles presented with flashy headlines gain more public traction than well-evidenced research.

FIGURE 1

Environmental effects per serving of food produced. Based on data compiled by M Clark and D Tilman.



Securing the food of the future: a foresight approach

"If we want to get to net zero carbon by 2050, business as usual is not an equation that adds up."

Sir Ian Boyd, University of St Andrews

Sir Ian Boyd, University of St Andrews, outlined key trends in population, climate and food production for the next century and the policy and technological changes required to plan for the future while mitigating against damage.

The UK is part of a global food system and decisions about its future food production and processing capacity should play to the country's strengths within this system. One of these strengths is science and technology in food processing: meeting the UN Sustainable Development Goals requires urgent structural and technical innovation in food production and manufacture.

Currently agriculture contributes 20-30% of global greenhouse gas emissions. However, transformation of agriculture and the food system is possible because of its current low production efficiency. There is a need to develop policies to incentivise the market and systematise technologies that are already available. This needs a conceptual transition from food produced by agriculture to food produced by manufacture. Many of the technologies for this transition already exist, but need to be joined together to develop new production processes. Without these changes, the environmental impacts of food production will eventually cause feedbacks that will lead to declining productivity.

Transformation for rapid change

Planning for future food requirements can be tensioned against a number of population, technological and environmental trends. The trends include:

- Population growth to 11 billion by 2100 with 25% more people by mid-century and rising health problems of non-communicable disease, partly due to lifestyle and diet.
- Increasing climate stress, reducing our capacity to produce food as a result.
- The rise of disruptive green technologies not yet available within the agriculture sector.
- Very low resource efficiency of food production compared to other industrial sectors in the UK.
- Increasing adaptability of individuals to modern diets.
- Decreasing levels of agricultural innovation despite increasing levels of R&D investment.

If these trends continue, they will likely result in the systemic failure of the food system. Research currently focuses on conservative small-scale incremental changes, but transformation of food production is needed to meet sustainability goals and the requirements of a growing population. The resource efficiency of food production needs to improve five to ten times to align with other industrial sectors, while every unit of land needs to produce up to ten times as much by 2050. Without transformation, we will continue relying on chemical inputs that feedback on people, high energy tillage systems, and fossil fuels with the associated climate change.

Image: From left to Right: Sir Ian Boyd, Professor Walter C Willett, and Benjamin M Theurer answer questions from the audience.

The ‘transformational’ scenario applies advanced manufacturing methods including robotics, process engineering and genetics. However, while basic capabilities exist they are yet to be systematised. Transformation will involve closed loop manufacturing to reduce emissions to perhaps as little as 10% of current levels. Food will need to be produced close to consumption, reducing transport costs, while energy dense commodities will be produced proximally to the (renewable) energy they consume. We will likely see desert cultivation close to the ocean: for example, the Horn of Africa could provide a substantial source of solar energy, with water available after desalination.

> “This timely and educational conference generated huge interest among the general public, industry and academic communities. Together, we reflected on the current state of the planet’s human health and food supply, and derived courage from the speakers’ innovations and ideas to provide healthy, sustainably produced food, for a rapidly expanding global population.”
>
> Lucinda Bruce-Gardyne, Genius Foods

Position of the UK

The UK is similarly positioned to the rest of the world. Of UK farms, about 20% produce 80% of the agricultural output on 50% of the land. Therefore 80% of farms produce little, and 50% of farmland is unprofitable without subsidy, meaning that public funds are subsidising environmental damage.

The UK should reduce land use by farming and increase use for environmental protection such as reforestation and carbon capture and storage. To do this over the next decade while producing the same amount of food, we need to move 20% of food production to unconventional food manufacturing. The UK is in a good position to lead this transformative change, generating significant investor interest in an already significant food manufacturing industry and with a population sensitised to trade-offs between food production and environmental impact.

Alternative meat – future of food or just a fad? A commercial view on the potential market size

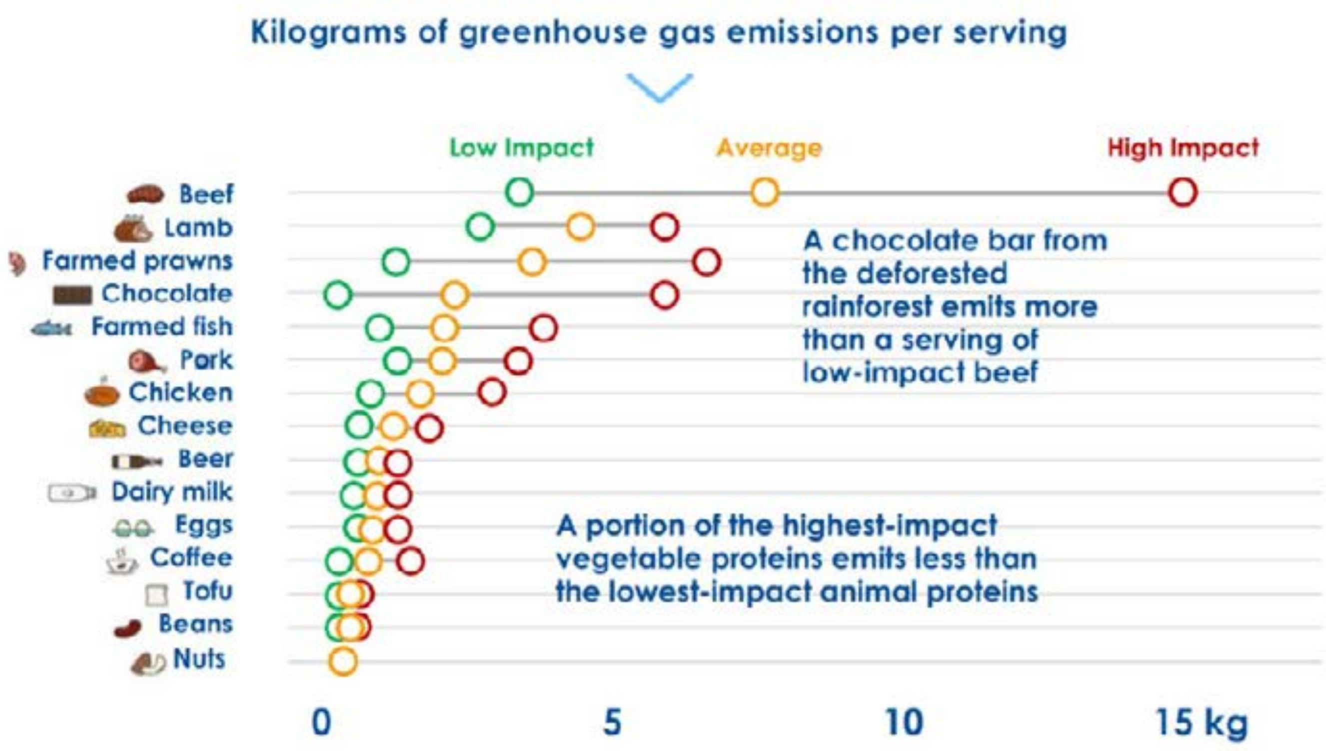
Benjamin M Theurer, Barclays, outlined motivators behind flexitarian consumption behaviour and the size of the meat alternatives market.

Consumption habits change and we have a rising flexitarian population leading to growth of the alternative meat market. Plant-based meat substitutes currently form the majority of the market (soybean, mushroom, lentils), while lab-based meat from stem cells is not yet commercially viable but represents opportunity for the future. Flexitarian consumption behaviour is based on three drivers that should drive growth for the alternative meat market:

- **Health and wellness.** Consumers are concerned about animal-based meat due to the association with high cholesterol and heart disease, as well as antibiotic and hormone use, meaning meat-free alternatives are appealing. Consumers also prefer 'non-artificial' ingredients, including non-genetically modified organism ingredients. However, alternative meats are not necessarily healthier than natural meat due to significant processing and the higher sodium levels they often contain.
- **Sustainability.** There is increased consumer awareness about sustainability and the greenhouse gas footprint of agriculture worldwide. Currently, 26% of emissions come from food, of which 58% is from animal products: beef and lamb contribute half of this (figure 2). Alternative meat is a solution for sustainability as long as its production does not disrupt natural ecosystems or require a large amount of energy.
- **Animal welfare.** There are concerns around animal welfare and the use of hormones in raising animals. Only a third of consumers are fully aware of how animal-based meat is produced. Industrialising agriculture further in order to feed the population of 9.8 billion in 2050 would be worse from an animal welfare perspective, and alternatives could provide a solution to this.

Plant-based meat alternatives provide a clear solution to animal welfare issues, but the health and sustainability advantages are not yet guaranteed.

FIGURE 2



Credit: Danone, BBC adapted from Poore & Nemecek (2018), Science.

Image: Professor Cathie Martin FRS, John Innes Centre and University of East Anglia.

The market

A 10% share of global meat industry could be taken by alternative meat within the decade, from 1% today – from around $14 billion to over $140 billion. In the UK there are 22 million flexitarians and a third of Britons have stopped or reduced meat eating. Meanwhile ~10,000 new vegan products were introduced in 2018, up 52% on 2017. However, consumer adoption is critical for development of the alternative meat market, and this comes down to taste and price. A positive first sensory impression and a minimal or no price difference against animal protein is crucial. The price gap is expected to close over time, but currently the average cost per consumer trip can be 74% higher for someone on a plant-based diet. Eventually plant-based food should be cheaper due to the amount of resources needed to grow plants versus cattle or swine, and technological advances such as optimisation of production. Growth of the market needs to be driven by food producers, retailers and restaurants. Growth is driven mainly by large food conglomerates such as Kellogg's, Danone and Nestlé, rather than specialised companies. For plant-based foods to be an alternative to feed a growing population, they need to be adapted to emerging markets as well as in the developed world, where many products are currently emerging.

"Over 30% of diseases in urban environments are attributable to lifestyle, particularly diet. Health and sustainability are therefore both important aspects when considering innovation in the future of food."

Professor Cathie Martin FRS, John Innes Centre and University of East Anglia

"When large companies start getting involved in areas that others might call a fad, it's most likely not a fad."

Benjamin M Theurer, Barclays

Alternative food sources

The technical challenges of delivering vegan products in a meat-free environment in a sustainable manner

With the world's population estimated to reach more than 9 billion by 2050, there is a need to find ways of ensuring that we can feed people without severely damaging the planet in the process. Dr Muyiwa Akintoye, Quorn Foods, described the challenge of delivering a similar eating experience to those consuming meat-based foods using plant-based ingredients.

The effect of meat on the planet is receiving almost weekly coverage in the UK and we are at an inflection point for alternative meats, with more consumers choosing to eat vegan, vegetarian or flexitarian diets. As most of these products are targeted at people who have a predominantly meat-based diet, the challenge remains of trying to deliver a similar eating experience but using plant-based ingredients.

Veganism as a movement

Veganism is emerging as a significant subculture and Quorn is making a shift from predominantly vegetarian to vegan products. The main source of protein in Quorn is mycoprotein. To get the mycoprotein, which has a toothpaste-like texture, to be chewed like meat is no small feat and requires additional binder. The binding ingredient requires three key properties: irreversible heat gelation, high water binding for succulence, and a texture development. Hen egg albumen is one of the few native products that can do these things and finding a vegan alternative to egg white is challenging.

Potato protein provides an alternative binder, however, there is only one commercial supplier in the world at present, with limited output that is insufficient to meet Quorn Foods' projected use as the vegan market grows. Challenges with potato protein include low availability, occasional taste issues, and that it only has a sixth of the binding strength of egg. Meanwhile, any replacement binders need to fit existing factory technology, designed to cook with egg, in the short term. Finding alternative methods to produce the meaty texture from mycoprotein, including high pressure, temperature, shearing and melting, may remove the need for a binder, or offer the option to use much smaller quantities. As well as producing a vegan product, there is a major sustainability incentive to finding an egg alternative due to cost and availability (eg risk of avian flu).

Other challenges associated with producing vegan products include ensuring that product quality is not compromised by switching to the vegan alternative, and maintaining sustainability as vegan products sometimes require more processing as well as ingredients (with higher embedded carbon due to the energy used for heating and the additional ingredients).

To grow the meat alternative category requires ongoing collaboration between competitors to advance understanding of challenges and develop new food ingredients, process development and sensory experiences, to promote consumer understanding and adoption.

> "We have unprecedented opportunity to grow and the faster we do It the better the planet's future will be."
>
> Dr Muyiwa Akintoye, Quorn Foods

Image: Dr Muyiwa Akintoye, Quorn Foods

The potential and power of pea protein

There is a need to promote the use of plant-derived ingredients to enhance human health and reduce the environmental impact of food production by increased use of plant-based foods. Professor Claire Domoney, John Innes Centre, outlined the potential of pulse crops such as peas to achieve these goals.

Pulse crop seeds provide an excellent source of protein, starch, fibre and micronutrients, meaning they can be used as nutritious food ingredients and replace more energy-demanding components in animal feed. As nitrogen-fixing crops, pulses do not require the addition of nitrogen fertiliser. This reduces agricultural inputs and means the crops can be added in rotation or in inter-cropping with cereals to fertilise the soil. Pea has the advantage of having a higher protein digestibility-associated amino acid score than wheat and other cereals, which is important for maintaining muscle mass in humans.

> "Legumes and pulses not only bring excellent nutritional quality to our diet but also impact very highly on the inputs to agriculture by fixing their own nitrogen and providing nitrogen to the following crop."
>
> Professor Claire Domoney, John Innes Centre

Image: Professor Claire Domoney, John Innes Centre.

Improving peas and reducing unwanted characteristics

Research at the John Innes Centre (JIC) seeks to improve the nutritional profile of pea while addressing challenges in consumer acceptability. As a source of substantial natural and induced genetic variation, pea can be adapted to meet the diverse needs of food manufacture. *Pisum* germplasm is curated at JIC, and pea genome sequences are being interrogated to address questions about the synthesis of plant products. Besides natural variation, substantial changes can be made to pea protein profiles by selecting mutations in the genes that encode seed storage proteins. Examples include:

- Removing proteins with specific properties (eg vicilins) and enhancing those that contribute to desirable industrial processes.
- Changing the amino acid profile of the pea by increasing the content of limiting amino acids that could restrict the rate of growth. This had the negative side effect of increasing protease inhibitors.
- Identifying a valuable mutant line that lacked two functional trypsin inhibitor genes.
- Identifying the genes that control the amounts of particular metabolites negatively associated with consumer acceptability (eg raffinose) and mutant lines lacking such compounds.

In 2019, field trials of pea variants with altered seed product profiles yielded robust plants and seeds, while 'speed breeding' experiments showed the capacity to deliver commercially relevant materials in a shortened timeframe.

Swimming against the tide – optimising the accumulation of omega-3 LC-PUFAs in transgenic Camelina seed oils for use in aquaculture

Omega-3 LC-PUFAs (long chain-polyunsaturated fatty acids) are a key nutrient found only in fish. Professor Johnathan Napier, Rothamsted Research, described research at Rothamstead that aims to use genetic engineering to make omega-3 fish oils in different organisms, especially non-oceanic sources such as plants. This will create a new source of these fish oils to help deliver better nutrition to consumers, and help aquaculture reduce its reliance on oceanic sources of fish oils.

Consuming omega-3 fish oil is associated with human health benefits including reduced chances of cardiovascular disease and obesity. However, it is a limited natural resource with no available plant sources: the fatty acid composition of vegetable oils contains only short chain omega-3 oils, which lack these health benefits. More than 50% of fish consumed by humans is farmed by aquaculture. Fish do not produce LC-PUFAs: wild fish acquire them from marine microalgae in their diet, and farmed fish have to acquire them in aquafeed.

Aquaculture is a booming industry and a very efficient way to produce nutritious human food, yet farmed salmon now has less than 50% of the omega-3 fish oils of 10 years ago so less is going into the human diet. Around 80% of the fish oils harvested directly from the ocean are used directly in aquaculture rather than for human nutrition – removing a million tonnes of fish oil from the ocean annually. Algal fermentation in steel containers cannot yet be scaled up to this magnitude, and there is therefore a need for synthetic alternatives to ensure humans eating fish continue to receive the same quality of nutrition.

Mimicking the metabolism that algae undertake naturally to create omega-3 fish oils in plants is complicated. Research at Rothamsted attempts to engineer the metabolism of plants using the primary algal biosynthetic pathway for LC-PUFAs. This has been successfully carried out in a range of plant species, leading to the production of a transgenic[1] oilseed crop, *Camelina sativa*, which contains over 30% omega-3 LC-PUFAs in its seed oil. The genes are expressed only in the seeds and the rest of the plant remains unchanged.

Field trials carried out in Europe and North America evaluated the use of GM Camelina seed oil as a replacement for fish oil in aquafeed diets. The seed oil was an effective substitute in feeds for salmon and sea bream, confirming the potential of using transgenic plants to make omega-3 fish oils. However, many challenges beyond the laboratory remain to ensure this innovation delivers for the public good.

> "We are using agriculture to help aquaculture to help the consumer, while reducing the burden on the environment – from field to fjord to fork."
>
> Professor Johnathan Napier, Rothamsted Research

Image: Professor Johnathan Napier, Rothamsted Research, explains the problem of declining omega-3 content in farmed salmon.

1 Containing genetic material in which DNA from an unrelated organism has been introduced.

Synthetic biology approaches to food production

Using biotechnology to brew animal proteins and nutrients

Microbial fermentation of proteins for food processing and nutrition is vital to the global food system. Jason Kakoyiannis, Ginkgo Bioworks, described how this would allow us to engineer cells to produce the proteins we need without having to rear animals.

Recent advances in synthetic biology such as cheaply sequencing and synthesising DNA, combined with lab automation and data science, allows a greater variety of proteins to be produced including complex animal proteins useful in food and nutrition. These technological advances can help food creators and consumers reduce their dependency on animal agriculture.

As the technology to engineer biology becomes more accurate and efficient, cell based fermentation will become a more mainstream source of critical animal proteins. Synthetic biology allows direct production of the highest functioning single proteins for textural or nutritional properties, such as mouthfeel or antimicrobial activity. Initially this will be used to nutritionally enhance existing products, like plant-based milks and infant formulas; eventually, this may open up opportunities to source proteins from unconventional sources.

Organisms such as yeast and fungi are being engineered to 'brew' animal proteins via fermentation, removing the need to source them from live animals. Ginkgo has built a platform to read and write DNA, allowing them to design cells to make compounds of interest. To make an animal protein, the animal genome is studied to identify which genes encode a specific compound. Changes are then made to the DNA of cells to make them overproduce that compound of interest, and those cells are brewed in a fermentation processes and purified. Gingko's Foundry model allows rapid production of a variety of animal proteins through heavy use of automation and ultra high throughput workflows. A large codebase of genome sequences and other biological assets allows rapid categorisation and reuse of previous work to deploy into new projects.

Access to genome sequences unlocks potential to test the properties of proteins from a range of animals that are not conventionally used in farming. This could be advantageous: proteins from the eggs and milk of animals from diverse climates may have nutritional benefits or unique properties (such as gelling and temperature resistance) compared to traditional protein sources. These proteins cannot easily be farmed but can be produced by fermentation. The ability to select food ingredients that are the best for a particular function could change farming from the historic paradigm that we eat is what is easy and cheap to grow at scale.

The clear consumer appetite for alternative protein sources is driving progress in biotechnology. Biotechnology has changed significantly in the last 15 years, however, while enzymes are relatively easy for cells to make, other proteins are harder. Remaining challenges include getting high enough expression levels of the protein in the cell, and the ability to explore protein space to find useful novel functional proteins from the animal proteome.

"We're no longer basing our food system on what tastes good and can be grown at scale, but by sourcing food ingredients that are best in class for that particular function. That's a completely different food sourcing system to that which we have now."

Jason Kakoyiannis, Ginkgo Bioworks

Image: Jason Kakoyiannis, Ginkgo Bioworks

How CRISPR technology can help us all eat more fruits and vegetables

"Gene editing technologies are predicted to bring dramatic benefits to human health. Early agriculture-based biotech efforts have mainly focused on increasing the efficiency and production of corn and soy, but improving specialty crops would also bring substantial societal benefits."

Haven Baker, Pairwise

Image: Haven Baker, Pairwise.

Haven Baker, Pairwise, explored the potential for gene editing technologies to improve the flavour and texture of fruit and vegetables, and increase the seasonal range in which crops can grow, to encourage people to eat more fruit and vegetables.

Diet is the single largest contributor to human health: currently over two billion people are obese or overweight and therefore at high risk of diet-related diseases. Increased snacking compounds the challenge of healthy diets. In the 1970s, 10% of Americans consumed one or more snacks a day, compared to 94% in 2019. Today, 25-30% of calories come from snacks and only 5% of snacks are fruit or vegetables. If healthy snacks can be promoted over sweets and crisps through greater marketing spend and improved produce this may help move consumers towards healthier eating habits.

Despite education and publicity, fruit and vegetable consumption has not increased between 1970 and 2016. Key barriers to fruit and vegetable consumption in US are accessibility, value and expense, family eating habits and negative experiences. Consumers want to buy healthy, convenient snacks and are happy to pay more for them. For example, pre-cut mango sells at 500% premium, while the unique, snack-able attributes of mandarins have doubled their consumption in the last five years despite being sold at a premium. Willingness to pay is an effective way to measure consumer interest in new traits and the likely increase in consumption if the new traits can be delivered.

One way to improve this is to develop more appetising produce. CRISPR technology can be a catalyst for improved diet and sustainability by making eating fruit and vegetables more convenient, flavourful, affordable and easier to eat.

Pairwise makes very few 'knock-outs' and mostly uses base editing or reproduces natural allelic variation. As well as health benefits, creating more desirable produce will make it easier to understand and communicate the benefits of CRISPR technology.

Products and market

Pairwise is working to domesticate the black raspberry using CRISPR. The fruit contains five times the antioxidants of blueberries and turns colour when ripe for ease of harvest. However, plants are weedy, thorny and produce fruit over a short timeframe. CRISPR can save decades of breeding for thornlessness, developing a product within a year. Other areas of development include caneberries, which have significant genetic diversity largely untouched by blackberry and raspberry breeders, and the development of pitless cherries that grow across seasons and climate zones.

Although gene editing is not regulated in the same way as genetically modified organisms in many places, countries have different regulatory systems and global regulatory packages for this technology are currently very expensive. This means that only very high value traits will come to market.

The 'Meat Machine'

Dr Joshua Flack, Mosa Meat described the process behind 'Meat Machine 2.0' and its potential and barriers to manufacture beef at scale through cellular agriculture.

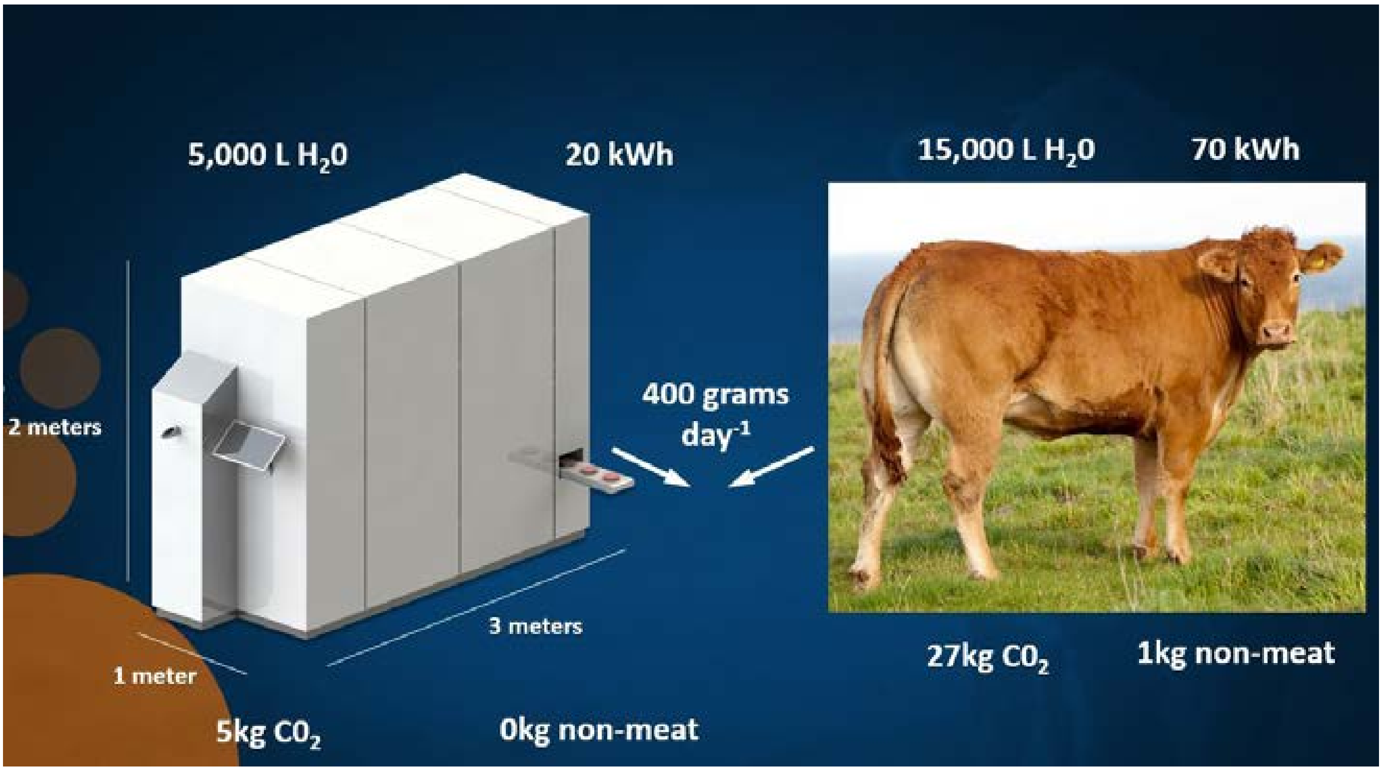
The first animals were domesticated for meat production over 10,000 years ago. Despite their inefficiency in turning energy into muscle tissue, animals remain our only source of meat. Companies in the field of cellular agriculture aim to change this.

Cellular agriculture is a very nascent field but companies are proliferating rapidly while investment in the area is growing. Cellular agriculture aims to produce real meat grown from animal cells, without the detrimental environmental and animal welfare consequences of our current food system. Mosa Meat aims to produce beef grown exclusively from muscle and fat stem cells taken from a small biopsy of muscle from a living cow. Through this method they expect to produce 20% of the carbon footprint of traditionally raised meat (figure 4).

Image: Dr Joshua Flack, Mosa Meat.

FIGURE 4

The relative inputs and outputs of Mosa Meat's 'Meat Machine 2.0' versus 'Meat Machine 1.0' – a cow. In a good case scenario using renewable energy, cellular agriculture has around 20% of the carbon footprint of traditionally raised beef.



Credit: Joshua Flack and Jonathan Breemhaar.

Cows are a very inefficient source of food, producing 400g of meat per day. They require water and energy inputs, and output greenhouse gases and non-meat waste. The five steps of tissue engineering could provide meat more efficiently.

- **Isolate the cells used to produce the meat.** Satellite cells – muscle stem cells – are present in all muscles. They remain in an inactive state until the muscle is damaged by exercise or injury, when the cells migrate to fill the gap in the damaged muscle.
- **Cell proliferation.** Satellite cells grow rapidly, with more than one doubling per day when given warmth and nutrients. This exponential proliferation is unusually fast for eukaryotic cells and allows production to compete with natural meat.
- **Tissue formation.** Edible scaffolds or hydrogels are used to align the cells with each other, such that they fuse into a functional unit of skeletal muscle or a myotube.
- **Tissue maturation.** The longest stage, in which the myotubes are allowed to develop tension – the equivalent of exercise. They develop the meat's texture, taste and colour, the latter being the most important for consumers.
- **Burger formation.** An analogous process is used to create fat tissue, which is then combined with the muscle tissue to create a meat product.

Substantial challenges remain before cultured meat becomes a reality. Taste is the most important factor and people will not buy the product if it does not closely mimic real meat. Scaling the process up is also challenging: most technologies are based on the medical industry, but for this process there is a need to produce millions to quadrillions of cells. Carrying out this process in an animal-free way suitable for vegans needs to be achieved – currently, getting satellite cells to reproduce requires foetal bovine serum. Lastly, to make the product commercially viable the costs must be reduced; the first burger made by this process cost a quarter of a million euros in 2013.

Image: Dr Stephen Chambers, Subsero.

"We now have the opportunity to engineer biology to produce a diet that is healthy for both humans and the planet."

Dr Stephen Chambers, Subsero

"The Royal Society's Future Food conference was an excellent chance to discuss crucial concepts and ideas with a wide cross-section of people. It was hugely encouraging to see such interest in cultured meat and other technologies with the potential to disrupt our ailing food system."

Dr Joshua Flack, Mosa Meat

Panel session: Regulation, ethical issues, changing consumer preferences and public perception

This discussion, chaired by Professor Wendy Russell, University of Aberdeen Rowett Institute, considered the position of the UK in food research and technology, the regulatory changes needed as more novel food products come to market, and the importance of honest communication to instil public trust. The panel comprised Ernesto Schmitt, The Craftory; Dr Andreas Sewing, BASF; Helen Munday, Food and Drink Federation; Professor Chris Elliott OBE, Queen's University Belfast; and Professor Alan Raybould, University of Edinburgh.

"No one imagines that we're going to be totally in a Star Trek world in which drinks replace 'real' food. This could have a place, but only if it's genuinely a better alternative to what's already out there, including nutritional delivery, but also in terms of carbon and water footprint, and biodiversity."

Helen Munday, Food and Drink Federation

"The science is broad and exciting around alternative foods, but how do you actually get consumers to adopt it and overcome the commercial barriers, the marketing barriers and the consumption barriers?"

Ernesto Schmitt, The Craftory

Position of the UK in food research and technology

- This is a time of considerable change in food technology, eating habits and agriculture. As the Millennium is seen as the time of the technology revolution, in 20 years this period will be seen as the time of the food revolution.
- UK industry is not in as strong a position for technological development and research as it could be. While some multinational companies have R&D centres in the UK, several have moved their R&D centres and associated funding elsewhere. For example, Unilever is setting up a research centre in the Netherlands. R&D tax credits are not as beneficial in the UK as in some other countries.
- World monopolies in the technology sector mean that competition between smaller companies is largely over, so research and optimism about change is shifting from technology to consumer goods. Greater availability of funds and skilled people means that research in food can now be carried out by start-ups as well as large multinational corporations.
- Investment by the Government in the UK's excellent academic institutions could help them fulfil their potential while increasing investment and innovation to support the Industrial Strategy Grand Challenge of transforming food production.
- Change will not necessarily be brought about by large companies but by entrepreneurs and collaboration with academia. The original nucleus of research might be academic and then rapidly amplified by the entrepreneurial world.

Regulation

- New technologies will challenge regulation. As many more novel food products come to market, we will need to adjust our regulatory frameworks to cope with them.
- Regulations should be developed following debate about policy and what we want to achieve and avoid with products, rather than starting by gathering data about the technology which could lead to public mistrust, as with GM crops.
- Europe and the US have contrasting regulatory frameworks. European regulation is based on a precautionary principal which can stifle innovation and lead to considerable differences in terms of uptake of technology.
- Farmers have been demonised, particularly in the meat sector, but will help form part of the solution in feeding people a healthy diet sustainably.
- The food system is complex and needs to be considered on a whole systems basis, not just food but culture and biodiversity. There is a need to develop better decision support tools to manage whole systems, then embed them in policy and decision making at all levels for policy makers and individuals.
- To be viable, future foods need to be better both nutritionally and environmentally, including reducing water consumption, carbon output and negative impact on biodiversity. A biodiversity tax may be introduced as well as the carbon tax, while energy will become more expensive. This will lead to complex decision-making that balances affordability with environmental sustainability.
- Different regulations may come in after Brexit. The UK is open to innovation and technology and there may be a reinvigoration of food policy which could have substantial impact on food production and manufacture.
- For public uptake, nutritional and environmentally sound food needs to be both affordable and taste good. The taxation system could be changed advantageously to make nutritional food more affordable, and this will hinge on industry engaging with government.

"I think we need to change regulations to deal with the new products coming along and I would advise us to pause and have a solid debate about policy and what we want to achieve and avoid with products, and regulations should follow from that."

Professor Alan Raybould, University of Edinburgh

Image (left to right): Panellists, Professor Chris Elliott OBE, Ernesto Schmitt, Professor Alan Raybould, Helen Munday, Dr Andreas Sewing and Professor Wendy Russell (Chair).

Communication and public trust

- There is a need for scientists to be better communicators. Honest communication to the public, even to explain that the exact impacts of food or diet are not known, will help restore public trust in the food supply system.
- Scientists as individuals have a responsibility to communicate openly with friends and family about new technologies, where what you say as a trusted contact will have greater impact, as well as telling the story from the perspective of a corporation.
- Communication to generations X, Y and Z needs to happen on new platforms including social media. While other sectors have moved onto these platforms, science is not moving quickly enough in this area. Science is also competing against misinformation on these platforms.
- Collaboration between scientists and entrepreneurs may help communicate to the public because entrepreneurs help pinpoint a particular industry problem and how a technological solution can help consumers. We should start with non-scientists outlining the problem to solve rather than scientists promoting the technology available, to ensure that we produce products and companies that connect with consumers.
- Consumers want to do the right thing, and have responded rapidly to efforts to reduce plastic straws and plastic bags. Similarly, people will acclimatise to not having as much meat on shelves in supermarkets.

> "The public needs to be convinced of the benefit we are delivering. If we can come from that end then maybe some of the risk might be accepted."
>
> Dr Andreas Sewing, BASF

> "Farmers have been demonised, particularly in the meat sector, but will be the solution to lots of the problems."
>
> Professor Chris Elliott OBE, Queen's University Belfast

> "Of the topics discussed today, communication to the public and how we as a collective get those messages about sustainability and the environment across will be really important"
>
> Professor Wendy Russell, University of Aberdeen Rowett Institute

- There is an issue of public trust in new food technologies and people scrutinise their food much more closely than other new products. This is partly the result of media scaremongering about technologies including genetic modification, genome editing and lab-grown meat. People want evidence about a new food being safe before eating something radically different, which scientists have to be prepared to give. However, the evidence-based approach of scientists may get less public attention than a less evidence-based study published with an attention-grabbing headline.
- The public is concerned about processed food. However, a food's nutritional value depends on what is optimised for during processing. A new paradigm for processed food could optimise for high nutritional value and flavour instead of cost, making the food more attractive to wider populations.
- Targeted surveys on plant-based alternatives identified a cultural association in the UK of meat with masculinity, while veganism is seen by men as effete. Developing new terms such as 'future food' and 'plant power' to replace 'vegan' will help include this disengaged portion of the population.
- Big corporations are trusted less by the public than smaller companies. The substantial success of challenger brands is partly due to this issue of trust, and challenger brands are for the first time seeing major success in consumer goods and are able to charge a premium.
- Introducing education starting in primary school on the food supply system, as well as the impact of food and production on the environment and health, will be important in prompting widespread change in diet.

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