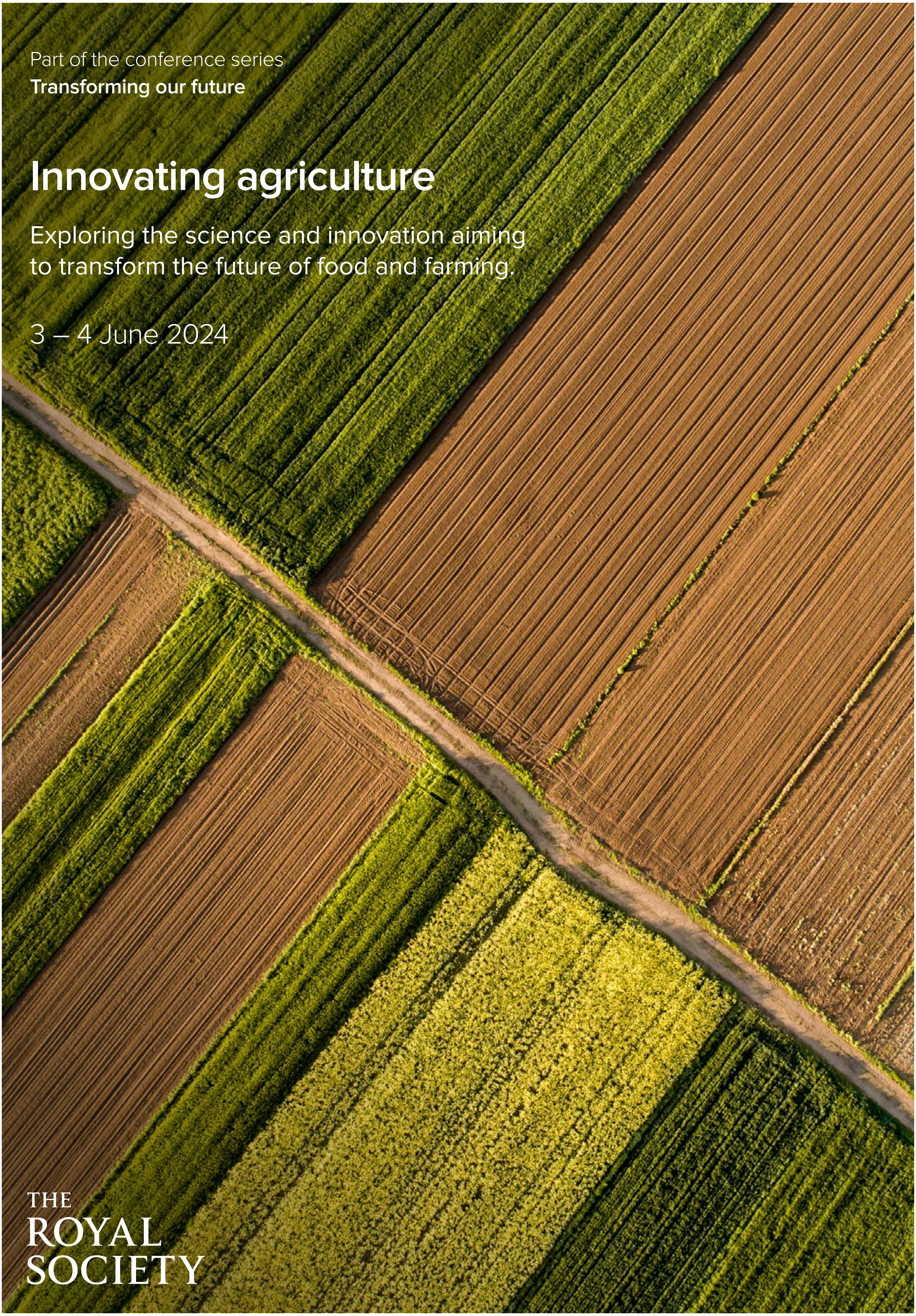
Part of the conference series
Transforming our future

Innovating agriculture

Exploring the science and innovation aiming to transform the future of food and farming.

3 – 4 June 2024



THE
ROYAL
SOCIETY

Introduction

Image: Professor Richard Flavell CBE FRS, International Wheat Yield Partnership and organiser of the *Innovating agriculture* meeting.

In the UK and globally, rising food production demands and ambitious environmental targets require the rapid development and scaling up of a breadth of new agricultural technologies and approaches. On 3 – 4 June 2024 the Royal Society hosted a hybrid conference, *Innovating agriculture*. This meeting explored aspects of cutting-edge science and innovation that are transforming or could transform the future of food and farming. Together, the examples provided during this meeting highlight the diversity of needs and opportunities across the wider agricultural sector.

Approaches to food production and patterns of consumption must be rethought and rebalanced with the need to respond to environmental challenges, including climate change, as soon as possible. Because all aspects of agriculture and the protection of the planet are interlinked across the world, innovations must be broadly integrated into policies and practices, which is yet another challenge for the sector.

There is clearly scope for the development and deployment of small innovations addressing discrete needs. Additionally, large-scale 'moon shot' approaches are required to refashion agriculture to reduce its impact on the planet and provide healthy and accessible diets for the peoples of the world. Better investment strategies and evidence-based national and international policies are needed to transform agriculture and the global food system.

The meeting took a broad approach to highlight the multiplicity of challenges embodied in the title of *Innovating agriculture*. Development of the meeting programme was led by Professor Richard Flavell CBE FRS (International Wheat Yield Partnership), Professor Sir Charles Godfray CBE FRS (University of Oxford) and Professor Angela Karp (Rothamsted Research).

This event was delivered as part of the Royal Society's *Transforming our future* conference series. Meetings in this series bring together experts from industry, academia, funding bodies, the wider scientific community and government to explore and address key scientific and technical challenges of the coming decade. These conferences are organised with the support of the Royal Society's Science, Industry and Translation Committee.

Summaries presented in this report are not verbatim records. They are intended to reflect the key points raised during presentations and discussions. Comments and recommendations included in this report are not necessarily those of the Royal Society.

> “There is a huge need for innovations and policies that can help us develop a new agriculture, a different agriculture, that is suitable and sustainable for our planet.”
>
> Professor Richard Flavell CBE FRS, International Wheat Yield Partnership.

Executive summary

The *Innovating agriculture* conference brought together stakeholders from industry, academia, government and the wider agricultural community to discuss five key challenges.

Highlights from the talks and panel sessions included:

Challenge 1: increasing yields sustainably

- Revolutionary genomics approaches (eg gene editing) can enhance and accelerate precision breeding to develop, for example, higher yielding crops with lower input requirements.
- Genomics approaches can also be used to improve plant disease management, for example by identifying and disrupting genes that make wheat more susceptible to fungal pathogens.
- An antibody-inspired novel technology platform can be used to create new crop protection products.
- Increasing photosynthetic efficiency in crops can enhance yields. A novel carbon-based nanomaterial product has shown promising results in enhancing photosynthetic efficiency.
- Sequences of cow microbiomes can enable the prediction of methane emissions and have the potential to underpin microbiome-based breeding for lower emission cattle.

Challenge 2: improving soil health and fertilizer production

- Soil management approaches and technologies that are reliable, improve productivity and offer a clear economic benefit to the farmer have a much greater likelihood of adoption.
- An improved understanding of how plants associate with beneficial microorganisms may enable better use of such microorganisms in agricultural systems to facilitate sustainable productivity.
- Soil nutrient levels and management approaches impact human nutritional outcomes, health and well-being.
- Improving soil health and reducing agricultural emissions is the responsibility of the entire supply chain, not just farmers.
- Ammonia for fertilizer is produced using the energy-intensive Haber-Bosch process, which is associated with high levels of greenhouse gas emissions. Incorporating carbon capture and storage technologies or using renewable energy sources have the potential to dramatically reduce emissions from fertilizer manufacture (but not from fertilizer use).
- Innovative alternatives to the Haber-Bosch process, including the use of electrocatalysis, are potential mechanisms for reducing agricultural emissions.

Challenge 3: developing novel food production systems

- Recent advances in vertical farming technologies are making use of cutting-edge science to improve the sustainability of high-value crop production.
- Foods produced by microbial fermentation can have health and environmental benefits, although taste and price may put off many consumers. Engineering biology techniques may help overcome these issues.
- Novel robotic and artificial intelligence technologies are helping to optimise the production of black soldier fly as a sustainable protein source.
- The use of cellular agriculture to produce cultivated meat has the potential to diversify and increase circularity within our existing food systems.
- Providing consumers with tasty, nutritious plant-based alternatives to animal products has the potential to reduce emissions associated with rearing livestock.
- Farmers' attitudes to cultured meats and their opinions on how this type of product might impact farm businesses are highly nuanced.

Challenge 4: funding agricultural innovation effectively

- The environmental issues facing agriculture and our planet are big, and agricultural entrepreneurs and the bodies that fund them need to think big.
- It is important to fund big high-risk, high-reward 'moon-shot' projects which, if they succeed, will have great potential benefits to society.

- Including end-users / customers as partners in R&D projects from an early stage can be an effective way to ensure their input is used in shaping an innovative idea and of accelerating adoption.

Challenge 5: supporting translation of new technologies and practices

- Innovations must work financially for farmers, particularly as they currently carry the bulk of the risk associated with food production.
- The system of knowledge exchange in the UK is highly fragmented. Joining up demonstration farms across the country, making it clear what resources and facilities exist and enabling broad access would make the system much more effective.
- Poorly defined regulatory frameworks (eg lack of clarity around carbon markets) are a huge barrier to uptake of innovation.

The programme of talks and panel discussions was bookended by two high-level keynote talks. Opening the meeting, Dr Lisa Ainsworth (USDA Agricultural Research Service) discussed lessons that can be learned from recent work on crop responses to changing atmospheric conditions, as well as the accelerating need for agricultural solutions to address the impacts of climate change. Professor Louise O Fresco (former President of Wageningen University) closed the meeting by sharing her reflections on the future of agriculture during a time of geopolitical tensions and changing climate.

Image: Sir Charles Godfray CBE FRS, University of Oxford and organiser of the *Innovating agriculture* meeting.

> “The derivation of the word ‘agriculture’ comes from the Latin ‘*ager*’, meaning ‘field’. This conference will explore both land-based food production as well as novel agricultural systems that are moving away from the field and using substantially less land.”
>
> Professor Sir Charles Godfray CBE FRS, University of Oxford.

OPENING KEYNOTE

Adapting crops to global atmospheric change

Dr Lisa Ainsworth, USDA Agricultural Research Service and University of Illinois at Urbana-Champaign, showcased recent work from the Soybean Free Air Concentration Enrichment programme and underscored the need for innovation to improve agricultural resilience.

Image: Dr Lisa Ainsworth, USDA Agricultural Research Service and University of Illinois at Urbana-Champaign.

Croplands are an essential part of our global food system. However, they are also a significant contributor to global climate change. Cropland expansion contributes to changes in the composition of our atmosphere, and long-term investigations seek to understand how these atmospheric changes will in turn impact crop production. This work highlights the critical need for innovations that can improve the resilience of our food system under changing climate conditions.

Cropland expansion and contributions to greenhouse gas emissions

Croplands occupy approximately 12.6% of the global land surface[1], and this area is rapidly expanding in response to growing food production demands. In the United States, the land area used for croplands expanded at a rate of over one million acres per year between 2008 and 2016, with most of these new croplands producing yields below the national average[2]. In addition to attendant losses of high-value natural habitats, cropland expansion is associated with an increase in greenhouse gas emissions from exposed soils, crop burning and deforestation to clear new agricultural land. Innovation and/or regulation is needed to limit and potentially reverse this expansion.

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1. US Geological Survey. 2015. Map of Worldwide Croplands. Available from https://www.usgs.gov/media/images/map-worldwide-croplands (accessed 12 June 2024).
2. Lark, TJ *et al.* 2020. Cropland expansion in the United States produces marginal yields at high costs to wildlife. *Nature Communications,* 11, 4295.

Agricultural impacts of climate change

Changes in atmospheric composition, including increasing levels of carbon dioxide and ozone from anthropogenic activities, have added a complicated new dimension to crop production. Improving our understanding of how crops respond to atmospheric changes and the interactions with temperature, drought and biotic stress is a critical step in enhancing the resiliency of our food production systems.

Soybean Free Air Concentration Enrichment (SoyFACE)

SoyFACE is a 32-hectare University of Illinois facility established in 2001 to examine how field crops respond to altered climatic conditions. Questions that can be addressed using this system include:

- What are the long-term responses of soybean, maize and other crops to global atmospheric change?
- What is the genetic, molecular and physiological basis for variation in response to global environmental changes?
- How do the combined effects of elevated carbon dioxide, elevated ozone, drought, temperature and biotic interactions impact crop function and yield?
- How do management practices interact with atmospheric change?

SoyFACE is one of a global network of FACE experiments, which are primarily located in northern, temperate regions. Using data from across this network, it was demonstrated that at current temperatures and with ample water and nitrogen, most key food crops exhibit a yield boost under enriched carbon dioxide conditions, although there is significant variation within crop type[3]. These different responses can be partly explained by genetic variation within crop types, which provides an opportunity to breed crops for the future atmospheric environment. Experiments have shown that there is a trade-off between yield increases under enriched carbon dioxide and the quality of the grain, particularly in terms of zinc, nitrogen and protein content[4]. Innovation is needed to accelerate high-throughput screening of seed collections to identify lines with desired traits (eg high yields in response to elevated carbon dioxide levels).

Future investigations

The FACE system can also be used as a testbed to examine how climate smart agricultural practices may fare in current and future environments. Recent work has focused on screening bioenergy crops for tolerance to ozone pollution to support high agricultural productivity in polluted areas. Other work using the FACE system is examining whether using basalt as a soil amendment increases carbon capture under elevated carbon dioxide conditions, and whether this soil amendment minimises the nutritional deficits associated with a high carbon dioxide growth environment.

> "To minimise agriculture's contribution to climate change, we need holistic innovations that improve agricultural outputs while reducing the environmental impacts. I'm very excited to hear more about climate change-ready germplasm, innovative crop management approaches, and ecologically and economically robust agroecosystems."
>
> Dr Lisa Ainsworth, USDA Agricultural Research Service.

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3. Ainsworth, EA & Long, SP. 2021. 30 years of free-air carbon dioxide enrichment (FACE): What have we learned about future crop productivity and its potential for adaptation? *Global Change Biology,* 27(1), 27-49.
4. Digrado, A *et al*. 2024. Seed quality under elevated CO_2 differs in soybean cultivars with contrasting yield responses. *Global Change Biology,* 30(2), e17170.

Breeding: why we need to start all over again

Dr Simon Griffiths, John Innes Centre, discussed some of the revolutionary approaches that should underpin future wheat breeding.

With humanity facing the interlinked existential challenges of climate change, biodiversity loss, declining soil health and food insecurity, there is a need to revisit the origins of wheat breeding to develop crops optimised for modern circumstances.

A brief history of wheat breeding

The foundations of bread wheat breeding were established 10,000 years ago in the Fertile Crescent, a historical region in the Middle East. Cultivation of bread wheat together with lentils, peas and barley supported the development of increasingly urbanised societies and supported a boom in population.

Up until the late 19th century, there were no institutional wheat breeding programmes. Farmers would exchange varieties with different traits. These domesticated, locally adapted and genetically diverse cultivars are known as landraces. However, as wheat breeding programmes became more mature in the 20th century, a small number of traits (eg yield) were prioritised and genetic diversity was reduced.

As challenges associated with climate change, reduced soil health and population growth become more urgent, there is a need to reintroduce diversity back into wheat breeding programmes to ensure we can select for traits that will enhance resilience.

The Watkins Landrace Collection

Landrace collections assembled prior to modern breeding are rare and are incredibly valuable due to the genetic diversity they contain. Modern landraces typically contain admixtures from modern varieties and are less heterogeneous than their more ancient predecessors.

Image: Dr Simon Griffiths, John Innes Centre.

In the UK, the Watkins Landrace Collection is a unique resource. It was assembled in the 1920s and 1930s to produce a global wheat survey, collecting over 827 bread wheat landraces from 32 countries via the London Board of Trade. Much of the plant material was collected from markets, and an effort was made to collect from multiple points around each country to take into account regional adaptation.

Advances made possible with genomics

To investigate genetic diversity within the Watkins Collection, whole genome re-sequencing was performed on the Watkins bread wheat collection and 208 elite modern varieties[5]. The data was used to produce a phylogenetic tree using 250 million SNPs. Modern wheat varieties appear to derive from just two of seven ancestral groups. Both of these groups are European. More than 50% of the genomes of modern wheat varieties can be reconstructed using just 26 landrace genomes from the Watkins Collection, suggesting that not many founder lines were used in the establishment of European breeding programmes.

To look for genes not present in modern wheat varieties, 73 landrace populations (more than 6000 lines) made from crosses with the Watkins Collection were grown as part of a field-based phenotyping study and 88 traits were examined (eg biotic stress, mineral content, etc). To link phenotypic data with genotypic data, quantitative trait locus analysis was performed. Using this gene discovery approach, hundreds of potentially useful novel genes and alleles were identified. Collaboration with commercial breeders is ongoing to backcross these genes into elite UK varieties and introduce them into company breeding pedigrees.

However, to truly harness the full power of genetic diversity, it would be hugely beneficial to start the breeding process from the beginning. New breeding programmes could maintain and develop each of the seven ancestral groups within the Watkins Collection. Key genes could be fixed at the start of the process (eg deleting the DELLA domain of of *RHT-1* to reduce lodging). Importantly, recent advances in gene editing and genomic selection can substantially enhance breeding precision and speed.

> “Incredible opportunities are possible with genomic selection, wheat genomics and gene editing. To apply these technologies properly, we need to go back to the start of the breeding process and use them to assemble/create wheat lines with the best compilations of variation from all that is now known.”
>
> Dr Simon Griffiths, John Innes Centre.

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[5] Cheng, S *et al.* 2024. Harnessing landrace diversity empowers wheat breeding. *Nature*, https://doi.org/10.1038/s41586-024-07682-9

Innovating agriculture at microscopic level: using nanotechnology to boost photosynthesis

Dr Imke Sittel, Glaia, described their unique technology that makes use of carbon-based nanomaterials to increase photosynthetic efficiency in crops and thus also increase yields.

Image: Dr Imke Sittel, Glaia.

Meeting growing demand for food production using sustainable approaches is a critical challenge for the agricultural community in the UK and across the world. Despite huge investment in breeding programmes for many crops, we are now starting to see plateaus in yield gains suggesting that other, more universal tools are needed. Glaia are proposing to enhance yields across a huge range of crop species by using carbon-based nanomaterials to tweak the ancient process of photosynthesis.

The basics of photosynthesis

Photosynthesis is nature's engine and is the driving force behind global food production. While it is a complex biological process, it can be simplified to the following equation:

$$6\ H_2O + 6\ CO_2 \rightarrow C_6H_{12}O_6 + 6\ O_2$$

Briefly, water together with carbon dioxide and a little sunshine produces glucose and oxygen. The process takes place in the chloroplast and involves many different enzymes, proteins, and molecules. However, it is hugely inefficient. Approximately 99% of available sunlight, required for catalysing the process, is not used. Notably, not all sunlight is photosynthetically useful as blue and red wavelengths are the most effectively utilised. If the 1% efficiency of photosynthesis could be increased to just 2%, it would double the amount of glucose and oxygen produced.

Photosynthesis includes light and dark reactions. In the light reactions, chlorophyll molecules absorb sunlight and release electrons. The flow of electrons through the electron transport chain along with subsequent reactions ultimately leads to the production of chemical energy in the form of NADPH and ATP. This chemical energy is then fed into the dark reactions, known as the Calvin Cycle, where carbon dioxide is used to produce glucose. As carbon dioxide is not typically a limiting factor, the amount of glucose produced is thus highly correlated with the amount of chemical energy produced in the light reactions. Photosynthesis is only as efficient as the electron transport chain.

The development of ‘sugar dots’

Modifying a plant’s ability to absorb sunlight is a possible means by which to improve photosynthetic efficiency. However, this requires subtle manipulation as absorbing too much sunlight can cause photodamage which reduces photosynthetic activity.

Gene editing could be used to address photosynthetic efficiency. However, this is a time-consuming process that would need to be undertaken independently for different crops, and also faces huge regulatory barriers in many regions around the world.

Inspired by naturally occurring carbon-based nanomaterials, the Glaia team have developed a more universal plant additive. Their ‘carbon dots’ increase the efficiency of the electron transport chain during photosynthesis. They are excellent electron acceptors and donors, can reduce photodamage in the plant and result in the production of more chemical energy and thus more glucose. Trials have shown that these ‘carbon dots’ increase wheat yields by up to 18% in the lab, and promising preliminary results have shown similar yield increases in a range of other crops in the field. The product is categorised as a biostimulant, which fortunately means there are low regulatory barriers to its commercialisation. However, because of this lack of regulation many growers are skeptical of claims made about biostimulants which can be a potential barrier to widespread adoption.

> “Photosynthesis is a fascinating biological process that has been evolving over billions of years… however, from a human point of view, it is surprisingly inefficient as a means to feed eight billion people.”
>
> Dr Imke Sittel, Glaia.

Data-driven approaches to reduce methane emissions from livestock

Professor Mick Watson, dsm-firmenich and Scotland's Rural College, presented several microbiome-based innovations with the potential to impact the greenhouse gas emissions produced by livestock.

For a long time, a major humanitarian problem has been 'How do we feed everyone?'. As the effects of climate change become ever starker, we must now also ask ourselves 'How do we reduce the impact of the food system on the environment?'. Agriculture is one of the biggest producers of methane, a potent greenhouse gas. An estimated 12% of human-caused greenhouse gas emissions come from livestock sector, and 65% of these emissions come specifically from farming cattle[6]. A range of approaches are being used in academia and industry in an effort to reduce methane emissions from cattle production.

Cows, methane, and the microbiome

Cows don't produce methane. Rather, archaea in their rumen produce methane. The microbial ecosystem within the rumen contains bacteria, viruses, fungi, protists and methanogenic archaea. It can be studied via metagenomics, which involves sampling the microbial ecosystem, extracting DNA, fragmenting then sequencing it. To examine species abundance, sequences are compared to reference microbial genomes. To explore the relative abundances of specific genes or metabolic pathways, sequences can be compared to functional databases. These two characteristics together help provide an understanding of the biological system at work.

A study comparing the microbiomes of low and high methane-producing cattle found that all enzymes involved in the methane production pathway had a higher abundance in high methane-producing cattle, and that these cattle had a higher species abundance of methanogenic archaea[7]. However, another study around the same time used a different data analysis approach and found no difference in microbial species abundance between high and low methane-producing cattle, although they did find differences in microbial behaviour[8].

Image: Professor Mick Watson, dsm-firmenich and Scotland's Rural College.

A caveat of the Wallace paper was that only 1 – 2% of sequence reads from the microbial ecosystem could be mapped to reference databases. To increase confidence in the results and explain the differences between these two studies, there was a need to improve the sequence mapping rate.

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6. FAO. 2023. Pathways towards lower emissions – A global assessment of the greenhouse gas emissions and mitigation options from livestock agrifood systems. Available from https://doi.org/10.4060/cc9029en (accessed 31 July 2024).
7. Wallace, RJ *et al.* 2015. The rumen microbial metagenome associated with high methane production in cattle. *BMC Genomics*, 16, 839.
8. Shi, W *et al.* 2014. Methane yield phenotypes linked to differential gene expression in the sheep rumen microbiome. *Genome Research*, 24, 1517-1525.

Metagenome-assembled genomes and cattle breeding

Microbial reference databases do not contain the genomes present in cow rumens, making the mapping process quite difficult. Metagenomics data from the rumen can be used to recreate these microbial genomes and update the reference databases[9],[10]. This work increased mapping coverage dramatically to 50 – 70%. When the datasets from Shi *et al*. were re-analysed, profound differences were observed in both microbial species abundance and enzyme abundance between high and low methane-producing cattle.

This work enabled the prediction of methane emissions based on sequenced cow microbiomes[11] and underpins work on the potential for microbiome-based breeding for methane emissions[12]. A collaboration with the cattle breeder Genus is now being funded by Innovate UK to create a low-methane breeding programme using microbiome data.

Bovaer – a feed additive to reduce methane in cows

In 2008, DSM initiated its Climate Change Induced Innovation program. A potential feed additive to reduce methane emissions was discovered in 2010 as part of a high-throughput chemical screen. This was followed by years of on-farm trials in over 100 countries. As of 2024, the product (Bovaer) is commercially available in 58 countries. Data from trials and over 70 peer-reviewed publications indicate that Bovaer results in 46 – 90% methane reduction, works within 30 minutes of being consumed, and is completely reversible. It acts by targeting an enzyme (Methyl CoM Reductase) only present in the methanogenic archaea. There is no impact on traditional production parameters (eg milk or beef quality).

> “Fund curious scientists to do things they are interested in. We didn’t sit there back in 2014 thinking ‘We’re going to produce low-methane cattle through breeding.’ We just wanted to pursue our curiosity.”
>
> Professor Mick Watson, dsm-firmenich and Scotland’s Rural College.

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[9] Stewart, RD *et al*. 2018. Assembly of 913 microbial genomes from metagenomic sequencing of the cow rumen. *Nature Communications*, 9, 870.

[10] Stewart, RD *et al.* 2019. Compendium of 4,941 rumen metagenome-assembled genomes for rumen microbiome biology and enzyme discovery. *Nature Biotechnology*, 37, 953-961.

[11] Martinez-Alvaro, M *et al.* 2020. Identification of Complex Rumen Microbiome Interaction Within Diverse Functional Niches as Mechanisms Affecting the Variation of Methane Emissions in Bovine. *Frontiers in Microbiology*, 11.

[12] Martinez-Alvaro, M *et al.* 2022. Bovine host genome acts on rumen microbiome function linked to methane emissions. *Communications Biology*, 5, 350.

Safeguarding wheat yields from cereal fungal invaders

Professor Diane G O Saunders, John Innes Centre, explained how genomics-based approaches can be used to improve plant disease management.

Image: Professor Diane G O Saunders, John Innes Centre.

Wheat rusts are known colloquially as 'cereal killers' due to the scale of devastation they cause to wheat production every year. When we refer to the wheat rusts we are actually talking about three different fungal organisms that cause three distinct diseases of wheat (leaf rust, stem rust and yellow rust). Collectively it is estimated that these three diseases destroy over 15 million tonnes of wheat per year and result in a loss of $2.9 billion USD[13].

One major factor that contributes to the success of the wheat rusts is their ability to create vast quantities of spores that can catch a ride on wind currents to spread the disease long-distance between fields, countries and even continents. This is particularly challenging when new strains emerge with new abilities to overcome resistance, as they can move quickly. Therefore, there is a need for robust mechanisms to protect wheat crops against these constantly evolving threats.

What approaches are used to respond to disease outbreaks?

There are several tools used to prevent and respond to fungal infection. Good agronomic practices are important, as are fungicides. However, these chemicals can have ecotoxic and off-target effects and fungi can evolve resistance to them.

A key approach for managing disease outbreaks is the use of resistance-focused plant breeding. This involves the identification and integration of resistance genes which encode resistance (R) proteins. R proteins act like a surveillance mechanism, working to identify corresponding pathogen proteins that have been injected into the plant as part of the infection process. The plant's defense signaling pathway is then turned on. However, pathogens are under constant evolutionary pressure to evade recognition by altering or losing their proteins that are recognised by R proteins. Resistance is thus easily overcome, and breeders need constant new sources of R genes.

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13. CIMMYT. 2015. Tackling wheat rust diseases requires $108 million a year, study shows. Available from: https://www.cimmyt.org/news/tackling-wheat-rust-diseases-requires-108-million-a-year-study-shows/ (accessed 30 July 2024).

An alternate strategy is to focus on deleting or altering susceptibility genes. When the fungus infects a plant, it reprogrammes plant cells to obtain nutrients and turn off defense processes. By identifying what genes are impacted in this reprogramming, it may be possible to delete these elements, known as susceptibility (*S*) genes. Removing *S* genes that the pathogen fundamentally needs to survive and prosper can act as a more durable type of resistance that the fungus finds very hard to overcome.

How can gene targets for manipulation be identified?

To identify potential *S* genes, wheat cultivars with different levels of disease resistance were infected with yellow rust[14]. Samples were taken from the plants to investigate whether any link could be observed between disease susceptibility and altered gene expression. If a gene is only expressed during a susceptible interaction when the pathogen wins, it may indicate that the gene in question is being manipulated by the pathogen to aid its survival.

Once potential genes of interest are identified, researchers can make use of the extensive chemical mutant collections already in existence to order mutants where the gene of interest has been disrupted. These mutant wheat plants can then be immediately tested with the pathogen to see if disrupting the candidate *S* gene prevents fungal infection. If these trials prove promising, researchers may then invest in precision gene editing in elite wheat varieties.

Case study – TaICL

One *S* gene identified using the above approach is *TaICL*, which encodes isocitrate lyase in wheat. It is highly expressed during a susceptible wheat rust interaction, but not in a resistant interaction. Infection assays were performed on chemical mutants, and while wild type plants with functional copies of *TaICL* support the growth of fungal pustules, no pustules were observed on the mutants.

This suggests that this gene is essential for the pathogen to cause disease. How does a mutation in *TaICL* improve disease resistance? When *TaICL* is disrupted, aconitic acid builds up in the plant. Spraying aconitic acid on wheat plants also results in enhanced resistance to wheat rust. The fungus may be turning on this gene to stop the accumulation of aconitic acid that can prevent colonisation.

The next step is to work with commercial breeders to incorporate this finding into their breeding programmes and into farmer-preferred varieties.

> "Using precision genome editing, we can identify traits and get them out into the field within 2 to 4 years, which is a phenomenal acceleration in the breeding pipeline."
>
> Professor Diane G O Saunders, John Innes Centre.

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[14] Corredor-Moreno P *et al*. 2021. The branched-chain amino acid aminotransferase TaBCAT1 modulates amino acid metabolism and positively regulates wheat rust susceptibility. *The Plant Cell*, 33(5), 1728-1747.

The AGROBODY^{TM} Foundry: Biotalys' innovative platform to generate novel and sustainable biocontrols

Dr Carlo Boutton, Biotalys, described how some unusual features of camelid antibodies inspired the development of a novel technology platform that is being used to create new crop protection products.

Image: Dr Carlo Boutton, Biotalys.

There is a critical need for novel methods of crop protection that are more environmentally friendly and that have new modes of action. Increasingly stringent regulatory restrictions have dramatically decreased the number of synthetic pesticides available for use, and pest and pathogen resistance to traditional products is growing. Farmers are losing the tools they need to protect their crops.

Protein-based biocontrols

Biotalys was founded in 2013 in Belgium and went public in 2021. They are developing protein-based biocontrol products using an antibody-based foundry, a platform that has previously proven successful in human therapeutics.

The platform is nature-inspired. Over thirty years ago, researchers found that, unlike humans, camelids have two types of antibodies. All humans have just one type of antibody, termed conventional antibodies, with both heavy and light chains. For unknown reasons, camelids (eg camels, llamas, alpacas) have a second type of antibody that is structurally a bit simpler, as it only has heavy chains. Using Biotalys' technology platform, these heavy chain-only antibodies can be used to develop protein-based AGROBODY^{TM} biocontrols.

The development process starts with an in-depth analysis of the life cycle of the pathogen of interest. Biotalys' scientists look at which proteins are important for survival, infectivity, or pathogenicity, then purify these proteins from the pathogen and inject them into a llama. This is similar to a vaccination, and the llama then generates an immune response to these proteins via heavy chain-only antibodies. The llama will generate millions of these antibodies against the protein of interest. The scientists can then draw blood from the llama, isolate immune cells, put the heavy chain-only antibodies onto a phage and select for those antibodies that bind the protein of interest. Multiple different antibodies targeting different proteins of interest can be put on the same phage, resulting in the generation of biocontrol candidates with multiple distinct modes of action.

This pipeline of activity has initially focused on the production of biofungicides, although the technology is broadly applicable. Biotalys is also collaborating on the development of bioinsecticides.

The first product – EVOCA

EVOCA™, Biotalys' first AGROBODY™ product, is a contact active fungicide that shows preventative activity against powdery mildew and *Botrytis cinerea*, a necrotrophic fungus that infects wine grapes among other crops. More than 600 trials have been undertaken in disparate geographical locations to investigate the effectiveness of using EVOCA™ in place of a synthetic spray. When EVOCA™ is applied at the flowering stage in an integrated pest management programme, disease suppression is comparable to what is observed in a fully synthetic spray programme.

In terms of mechanism of action, treatment with EVOCA™ leads to rupture of *B. cinerea* cells. EVOCA™ disrupts the immature cell wall, making it unable to remodel. Spores start to germinate, but then burst, leading to spore collapse. EVOCA™ has been filed for registration in the US and the EU.

> "Twenty years ago in the pharmaceutical sector, all innovation was focused on chemistry. Pioneers began working on antibodies for therapeutics, and there was a lot of skepticism. There has since been a dramatic shift from chemistry to biological innovation, and the same could soon be for agriculture."
>
> Dr Carlo Boutton, Biotalys.

Soils! The heart and lungs of our food systems

Andrew Francis, Home Farm Nacton, explored the relationship between human nutrition, the water cycle and agricultural soils. He shared his personal on-farm innovation journey, and discussed how research and innovation can effectively plug into the farming sector.

Image: Andrew Francis, Home Farm Nacton.

Home Farm Nacton is a 1692-hectare farm in Suffolk. Just over 10% (205 ha) of the farm is dedicated to organic production, while the rest is farmed using more 'conventional' methods. They employ a complex rotation to produce 26 product lines including potatoes, leeks, onion, wheat and barley.

Context is king

Home Farm Nacton has over 200 fields. These differ substantially from one another in terms of size, microclimate, and soil physical and chemical parameters that impact food production. This diversity of field conditions means it is impossible to impose a one-size-fits-all approach to farm management. Instead, practices must be tailored to the hyperlocal environment.

Lessons in soil nutrition

To manage soil nutrition as part of a beet and root crop rotation, Andrew has previously used a rotational organic manuring approach with autumn and winter applications. After monitoring nutrient levels for a few years, he found that soil nutrient profiles were not following expected trends. Nutrient levels were heavily influenced by when and where samples were collected, and both potassium and magnesium levels were overall declining despite high application rates.

Following this analysis, the farm ran multi-decade trials to compare annual, rotational and no manure approaches to soil nutrition. Levels of organic matter, potash, phosphate and magnesium were monitored. As a result of the trials, they now use highly soluble fertilizer products applied just in time (as opposed to regular autumn and winter applications), which has led to improved soil nutrition and a 15% overall costs savings.

Cover crop trials

Cover crops are plants used to reduce the amount of soil left bare. They serve to prevent soil erosion and often improve soil nutrition. These crops are typically not harvested but are instead incorporated into the soil to increase the amount of organic matter. However, this incorporation can dry out the soil, thus it is important to consider soil type, soil moisture level and timing in terms of when the next crop needs to germinate as part of cover crop management.

In his previous position at Elveden Farms Ltd, Andrew explored the potential value of adding cover crops into the production system, initially using low maintenance grass. However, it did not grow well on their sandy soil type. Instead, they switched to using biofumigant crops (radish and mustard). These grew well and were easily integrated into the farming system. A key benefit of these crops is that their incorporation into the soil can help control nematodes, a highly problematic crop pest.

While there are some great potential benefits associated with cover crops, Home Farm Nacton found that they may increase the carbon footprint of agricultural operations when factors including the amount of diesel needed for their management are factored in.

Cover crop trials are still ongoing at Home Farm Nacton as the team continue to strategise about how the overall management (eg timings of plantings and incorporation, methods of cultivation) could be modified to improve both the emissions profile and bottom line of the farm.

Making innovation work for farmers

- Farmers want to produce affordable food for consumers while also generating a profit. Technologies that improve productivity and / or offer a clear economic benefit to the farmer have a much greater likelihood of adoption.
- To be useful, new tools and approaches must be understandable and reliable. If a piece of equipment breaks down the first two times it is used, it is unlikely to be used a third time.
- Adapting existing tools (eg using soil moisture probes to measure nitrate levels) can save farmers time and money.
- With rotational food production system, it may take 15 – 20 years to produce convincing data to inform evidence-based changes in agricultural management. Can technologies be deployed quickly to provide emissions and economic benefits alongside these slower changes in management practices?

> “Today, we do the very best job we can using the best tools, people and technology available to us. But we recognise that tomorrow we must strive to do things differently.”
>
> Andrew Francis, Home Farm Nacton.

Achieving sustainable productivity in agriculture through beneficial microbial associations

Professor Giles Oldroyd FRS, University of Cambridge, discussed how an improved understanding of how plants associate with beneficial microorganisms may enable their use in agricultural systems to facilitate sustainable productivity.

Image: Professor Giles Oldroyd FRS, University of Cambridge.

In the last 60 years, farmers in high and middle-income countries have become increasingly dependent on inorganic synthetic fertilizers. Unfortunately, many of the nutrients in these fertilisers do not actually get taken up by crops. Instead, they are released into the environment where they cause eutrophication of aquatic systems, biodiversity loss and greenhouse gas emissions. To transform our current agricultural system into one that is more sustainable, we need another agricultural revolution equivalent to the Green Revolution of the 1960s, when the combination of plant genetics, chemical inputs and modern irrigation systems created huge increases in crop production.

The next agricultural revolution may be microbial

In the natural world, plants engage with a range of microorganisms to facilitate the uptake of nutrients. Legumes are particularly effective at forming these connections as they link with both beneficial arbuscular mycorrhizal fungi and nitrogen-fixing bacteria.

Arbuscular mycorrhizal interactions occur with most species of crops. The fungus colonises the soil at a level of complexity and density that the plant root cannot achieve. This complexity of hyphal networks, in addition to the release of acids that actively erode phosphate, makes the fungus much more effective at taking up macro and micronutrients. The fungus also colonises the plant root, making intrusions, arbuscules, into plant root cells, where nutrient exchange occurs.

Plant interactions with nitrogen-fixing bacteria appear quite different, with the emergence of nodules, that accommodate nitrogen-fixing bacteria and create the suitable environment for the bacterial enzyme nitrogenase to fix nitrogen.

Both arbuscular mycorrhizal fungi and nitrogen-fixing bacteria are accommodated intracellularly. That is, they are contained within unique compartments in plant cells and intentionally fed with lipids or sugars in exchange for mineral nutrients. This is different from associative interactions (eg with microorganisms on the surface of the root), as intracellular accommodation allows the plant to target lipids and sugars exclusively to beneficial microorganisms. In turn, arbuscular mycorrhizae can deliver up to 90% of the phosphate needed by a plant, and nitrogen-fixing bacteria can provide up to 100% of the nitrogen a plant needs.

The Enabling Nutrient Symbioses in Agriculture (ENSA) project

Crops have not been intentionally bred for enhanced associations with arbuscular mycorrhizal fungi. In fact, conventional breeding programmes are conducted using high nutrient soils. Associations with arbuscular mycorrhizae are absent at high soil phosphate levels, as the plant gains little benefit from the association with nutrients are not limiting.

Recent work has explored whether it is possible to break the link between phosphate availability and a plant's willingness to engage with arbuscular mycorrhizal fungi. A recent study found that, under low nutrient conditions, plants are primed to produce and perceive lipochitooligosaccharides, which then initiate symbiosis signaling and promote engagement with mycorrhizal fungi[15].

Constitutively expressing genes involved in this pathway increases the plant's ability to form fungal associations under high phosphate conditions. Preliminary data from two years of barley field trials show that engineered plants overexpressing these genes have a mycorrhizal colonisation rate of 20 – 30%, compared to just 2 – 3% colonisation of wild type plant roots.

Only a small number of plant species (eg legumes) can interact with nitrogen-fixing bacteria. Research has shown that when legumes evolved the capability to associate with nitrogen-fixing bacteria they utilised the pre-existing genetic platforms that allow interactions with arbuscular mycorrhizal fungi. This means that many of the genes required for interactions with nitrogen-fixing bacteria, already exist in cereal crops. It is possible to engineer cereals to produce root nodules that look convincing to a human; however they are currently unable to accommodate nitrogen-fixing bacteria.

> "Engineering nitrogen fixation is a moonshot, but better understanding of the evolutionary history tells us that it is more feasible than imagined 15 years ago."
>
> Professor Giles Oldroyd FRS, University of Cambridge.

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[15] Li, XR *et al.* 2022. Nutrient regulation of lipochitooligosaccharide recognition in plants via *NSP1* and *NSP2*. *Nature Communications*, 13, 6421.

GeoNutrition: exploring the roles of healthier soils to support improved nutritional outcomes

Professor Martin Broadley, Rothamsted Research, described how a greater understanding of the roles of soils, including soil health and management, can support more sustainable nutritional outcomes and improve human health and well-being.

Image: Professor Martin Broadley, Rothamsted Research.

Dietary deficiencies in minerals like zinc and iron have long been a global human health issue, particularly in low- and middle-income countries. In the 1990s, researchers began to explore the possibility of increasing the nutritional content of commonly consumed crops (eg wheat, rice, corn, etc) to address these pervasive micronutrient deficiencies. This led to the development of biofortified crops, in part through programmes like HarvestPlus. Efforts have also been made to increase the nutritional value of foods by improving soil nutrition.

However, as of the early 2010s it was still quite difficult to measure the impact of these activities on human health outcomes. Data on micronutrient deficiency severity could be obtained from reports produced by the UN's Food and Agriculture Organization, however these data gave high-level figures for countries and lacked granularity. Since 2017, the cross-sector Geonutrition team has been investigating how soils and landscape features affect human nutrition.

Micronutrient deficiencies correlate with grain nutrient composition

Funded by BBSRC and the Bill & Melinda Gates Foundation, early work by the team was conducted in partnership with the Ethiopian Public Health Institute, and with the Community Health Sciences Unit (Malawi). Using data from their National Micronutrient Surveys that came out in 2016, the GeoNutrition team looked at selenium deficiency risk rates across both countries and noticed structured variation (eg high risk in the west of Amhara region of Ethiopia). There was also regional variation in zinc deficiency. They then worked with colleagues across Ethiopia and Malawi to coordinate soil and crop sampling across both countries and found substantial geospatial variation in calcium, iron, selenium and zinc levels[16]. Regions with high levels of selenium deficiencies correlated with regions where crop selenium levels were low.

Improving agronomy to improve nutrition

Another study investigated what impacts zinc fertilisation might have on 'high-zinc' biofortified wheat varieties by running field experiments in different locations across Pakistan[17]. Although the study was not designed to specifically explore the effects of location on the performance of 'high-zinc' wheat, they did find that zinc levels in the grain varied across the trials. At all sites, foliar zinc fertilisation (applied to crop leaves) increased levels of zinc in the grain, although no significant effects of soil zinc fertilizers were observed, potentially because the trials were underpowered to detect these effect sizes.

A slightly different result was observed in maize field experiments in Malawi. In these experiments, which were powered appropriately, higher soil application rates of zinc-enriched fertilizers were correlated with higher grain zinc concentrations[18]. Taken together, these studies in Pakistan and Malawi demonstrate that both the environment and management practices (agronomy) influence the nutritional composition of crops.

To explore how agronomic approaches that aim to build soil health may affect crop micronutrient levels, a scoping review of published research from 2000 – 2021 was undertaken[19]. Analysis suggests that some approaches show promising links with improved crop nutritional content, although results are context dependent. For example, the use of high levels of organic inputs (eg composts, manures and cover crops) was associated with increased grain zinc concentration in 15 out of 16 rice-based studies.

To improve reproducibility and confidence in the data, appropriately designed large-scale studies are needed to explore the link between agronomic management approaches, site-specific conditions, crop nutrition and human health.

> "In terms of the agronomy of fertilizer use, there is great scope for informing practice and policy if we have the right data sets and analyse them in the right way."
>
> Professor Martin Broadley, Rothamsted Research.

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16. Gashu, D *et al.* 2021. The nutritional quality of cereals varies geospatially in Ethiopia and Malawi. *Nature*, 594, 71-76.
17. Zia, MH *et al.* 2020. Site-Specific Factors Influence the Field Performance of a Zn-Biofortified Wheat Variety. *Frontiers in Sustainable Food Systems*, 4, 135.
18. Botoman, L *et al.* 2022. Agronomic biofortification increases grain zinc concentration of maize grown under contrasting soil types in Malawi. *Plant Direct*, 6(11), e458.
19. Manzeke-Kangara, MG *et al.* 2023. Do agronomic approaches aligned to regenerative agriculture improve the micronutrient concentrations of edible portions of crops? A scoping review of evidence. *Frontiers in Nutrition*, 10.

The role of soils in supply resilience

Professor Debbie Sparkes, Diageo, showcased recent work on soils that aims to increase the resilience of key crops, decarbonise Diageo's supply chain and deliver positive outcomes in terms of biodiversity and water.

Image: Professor Debbie Sparkes, Diageo.

Diageo is a premium drinks company with over 200 brands sold in 180 countries. They have over 130 manufacturing sites spread across more than 30 countries.

They are committed to efficient and sustainable production. One of the key priorities in their *Society 2030: Spirit of Progress*[20] plan is to 'Pioneer sustainability from grain-to-glass', focusing on water, carbon, sustainable packaging and agriculture.

Crop resilience, soil health and decarbonising supply chains

Diageo rely on wide range of crops to make their products, including but not limited to barley, wheat, rye, sugarcane, sugar beet and aniseed. Their 2023 Annual Report[21] includes an analysis of the climate risks to agricultural ingredients within their supply chain, broken down by region. This analysis takes into account the volumes required of each ingredient, the types of climate risks (eg temperature, drought, etc) and the potential for replacement (eg barley is grown in multiple locations so there is some resilience, but only anise grown in Turkey can be used to produce *Raki*).

Like all businesses, Diageo are being encouraged to decarbonise. Most crops in Diageo's supply chains are bought in via procurement, thus emissions associated with their production are categorised as Scope 3 emissions for the company. This 'raw material' footprint accounts for 35% of Diageo's total Scope 3 carbon emissions, which they are aiming to reduce by 50% by 2030.

When thinking about how to improve crop resilience and reduce agricultural emissions, soils are an important factor. They have a major role to play in ensuring yield stability, especially in the context of a changing climate. Good soil structure acts as a buffer, supporting greater water infiltration rates, greater water holding capacity, and improved drainage. Diageo's work on soils also aims to support the growers who supply these raw materials into the company's supply chains.

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[20] Diageo. *Society 2030: Spirit of Progress plan.* Available from https://www.diageo.com/en/esg/society-2030-spirit-of-progress-plan (accessed 31 July 2024).

[21] Diageo. *Annual Report 2023.* Available from https://www.diageo.com/en/investors/results-reports-and-events/annual-reports (accessed 31 July 2024).

Examples of innovation

The Scotch Regenerative Agriculture Programme is a collaborative initiative between the James Hutton Institute, Agricarbon, Scottish Agronomy Ltd and SRUC. This science-led project is looking at the use of different mixtures of summer and autumn planted cover crops in advance of wheat and barley crops in combination with reduced application of nitrogen fertilizers. Impacts on soil carbon as well as physical, chemical and biological soil parameters will be examined.

Diageo are also working on a 'farm clusters' initiative with Scottish Agronomy, SAC Consulating, the James Hutton Institute and Agricarbon as a mechanism for encouraging growers in their supply chains to adopt regenerative agriculture practices. The twenty farms participating are currently at different stages of the regenerative agriculture journey. The first year of the programme is focused on baselining soil parameters and this will inform future activities.

Diageo are also involved in the Landscape Enterprise Network programme in Yorkshire, a shared-cost initiative to facilitate the buying and selling of nature-based solutions. Yorkshire wheat goes into grain neutral spirit for Diageo brands, thus they have a vested interest in reducing emissions and improving the sustainability of agricultural approaches in the region. Diageo are working with Nestlé Purina and Yorkshire Water to support growers in their shared supply chains.

Diageo also has an open innovation platform, Diageo Sustainable Solutions. This programme aims to address key sustainability gaps in Diageo's supply chain and funds projects for up to six months with a budget of ~£150k. There have been three cohorts and a total of 12 funded pilot projects focused on different challenges. As an example of what these projects are hoping to achieve, a project in the third cohort is looking to develop and deploy internet-connected soil moisture sensors at a range of depths across Kenya and Uganda. They are looking to see if these probes are useful in supporting grower decision-making by helping farmers better understand their soil, how crops utilise moisture, and which practices support soil moisture retention and ultimately lead to higher quality and higher yields.

> "Like all businesses that rely on agricultural crops, we are keenly aware of the impact of climate change on supply chain resilience and sustainability."
>
> Professor Debbie Sparkes, Diageo.

New technologies to reduce the fertilizer product carbon footprint

Mark Tucker, Yara, discussed three technological developments that have the potential to reduce emissions associated with fertilizer production. He noted that the deployment of these tools will require new business models to ensure associated costs are not borne disproportionately by farmers.

Image: Mark Tucker, Yara.

Globally, we have transgressed the nitrogen and phosphorus 'planetary boundaries' (processes essential to maintaining the resilience of the Earth system), as human activities have dramatically perturbed these biogeochemical flows[22]. We now face the incredible challenge of feeding the growing global population while also getting our planet back to a 'safe operating space'.

It is not realistic to remove synthetic fertilizers from the food system in the short-term, as yields in agricultural systems that do not use these fertilizers face an upper yield[23]. To reduce emissions associated with synthetic fertilizers, two distinct areas must be considered: the product carbon footprint, which is the focus of this discussion, and in-field emissions, which are a challenge for any crop nutrition product. The carbon foot print of a fertilizer product is calculated using the Fertilizers Europe Carbon Footprint Calculator[24], which was developed jointly by the European fertilizer industry as an industry standard. The tool is independently validated by DNV-GL and the Carbon Trust.

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22. Richardson, K *et al.* 2023. Earth beyond six of nine planetary boundaries. *Science Advances*, 9(37), eadh2458.
23. Doring, TF & Neuhoff, D 2021. Upper limits to sustainable organic wheat yields. *Scientific Reports*, 11, 12729.
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Colour spectrum of ammonia production

The basis for mineral fertilizer is air, energy and minerals. These are used to produce ammonia, which can then be used to produce urea (the most-used fertilizer product globally) or ammonium nitrate (mostly used in Europe, including the UK).

There are different methods that can be used to produce ammonia, each of which is associated with a different colour. Grey ammonia is the most common type in European; it is produced by steam reforming from natural gas. Blue ammonia is produced by steam reforming from natural gas, but also includes carbon capture and storage as part of the process. Green ammonia is produced using electrolysis powered by renewable energies and thus has far lower associated emissions.

The first large volumes of low carbon fertilizers will be produced using blue ammonia. Yara and Northern Lights recently signed the world's first commercial agreement on cross border CO_2 transport and storage, with captured carbon to be buried under the North Sea. Yara and Enbridge are also planning a $2.9billion USD blue ammonia plant in Texas.

The 'holy grail' is to move towards green ammonia. Yara is building the first green hydrogen plant in Norway, which will be driven by hydroelectric power. The type of renewable energies used in future plants will be highly location specific (eg solar power in Australia, wind power in mainland Europe).

Summary

Ultra-low carbon fertilizers offer an 80% reduction in emissions associated with fertilizer production compared with today's best practice. They are now coming through the pipeline: in 2024, some crops are already being grown with these products, and production will continue to scale between now and 2030. Use of these products must go hand-in-hand with advances in fertilizer application and mapping technologies to ensure growers use as little fertilizer as possible to minimise in-field emissions.

The carbon reduction value associated with their use is substantial, with no impact on crop productivity. However, the cost to produce and transition to these ultra-low carbon products is high. For effective adoption, this additional cost should be shared across the value chain and not just result in farmers paying more for fertilizer.

> "New products must go hand in hand with better use of fertilizers – using as little as we can to manage in-field emissions."
>
> Mark Tucker, Diageo.

Ammonia and nitrate from air and water using plasma and electrocatalysis

Dr Mike Craven, Plasma2X Ltd and University of Liverpool, explored whether plasma and electrocatalytic technologies could offer a viable, economically feasible solution to nitrogen fixation in fertilizer production.

Image: Dr Mike Craven, Plasma2X Ltd and University of Liverpool.

Ammonia is a key intermediate product in fertilizer production. Demand for ammonia is growing in the agricultural sector, and it has potential uses as a transport vector for hydrogen and as a fuel in shipping. There is a need to reduce emissions associated with its production and ensure there is sufficient ammonia available to meet these competing demands.

Current standards in ammonia production

Ammonia is currently produced using the Haber-Bosch process, which uses hydrogen and atmospheric nitrogen and requires high temperatures and pressures to break nitrogen bonds. Conventional (grey) ammonia production uses fossil fuels, resulting in high associated emissions. Blue ammonia is an alternative production method that still uses fossil fuels in the Haber-Bosch process, but also includes carbon capture, utilisation and storage. The success of this type of production depends on cost-effective carbon capture and access to nearby areas for carbon storage. Green ammonia uses renewable energy to drive the Haber-Bosch process, and thus has ultra-low emissions. However, the cost of renewable energies is typically still very high, and the intermittent availability of many types of renewable energies does not work well with the Haber-Bosch process, which is most efficient with consistently high temperatures and pressures.

Electrocatalysis and the use of plasma

Unlike the Haber-Bosch process, electrocatalysis technologies activate nitrogen at low temperatures and pressures. The process can thus be stopped and started with very little to no loss in efficiency, facilitating easier integration with intermittent renewable energy sources.

Electrocatalysis uses electricity and a catalyst to form ammonia from nitrogen and hydrogen. This system uses an electrochemical cell with two catalyst electrodes and two compartments divided by partially permeable membrane. Hydrogen is fed into one compartment and is oxidised to produce H+ (protons), which pass via the permeable membrane into the other compartment. Nitrogen gas is added and reacts with the protons to make ammonia. To avoid the need to pre-make hydrogen, H+ can be produced directly via water electrolysis as part of the process.

Electrocatalysis technologies have a high theoretical energy efficiency and reduce overall operational expenses. However, they also have low yields and slow rates of ammonia production as it is difficult to get nitrogen gas to interact in a liquid with a solid catalyst surface.

One way to speed up this process is to use plasma, the fourth state of matter. Plasma is an ionised gas consisting of charged ions and electrons, formed by exposing a gas to high temperatures or strong electromagnetic fields. Plasma activates air to convert its nitrogen and oxygen molecules into nitrogen oxides. These can be dissolved into water to form aqueous nitrates and nitrites, which can then make nitric acid. This nitric acid can be reduced using electrocatalysis to produce ammonia more efficiently. This approach is more effective than using electrocatalysis alone because it circumvents the difficulty of getting nitrogen gas to react at a solid catalyst surface in a liquid.

Next steps

In terms of cost-effectiveness, electrocatalysis currently only competes with conventional production methods at a small-scale, making it suitable for decentralised production. The cost of making the reactors is low. However, operational expenses are high due to the comparatively low energy efficiency. If operational costs can be reduced by optimising the process and driving towards theoretical energy minimum requirements, it becomes much more competitive across a wider range of production scales. Decreases in the cost of renewable energy will also drive down the cost of this process.

> “Time is not on our side. We need to start reducing emissions now. There is no point in having a technology that can eliminate all CO_2 emissions in 20 years’ time, because by then the damage will already be done.”
>
> Dr Mike Craven, Plasma2X Ltd and University of Liverpool.

Translating UK agri-tech research

Professor Simon Pearson, Lincoln Institute of AgriFood Technology and Fruitcast.ai, discussed the challenges associated with commercialising agri-tech research. He emphasised the importance of access to funding as well as the need for diverse expertise within teams.

Image: Professor Simon Pearson, Lincoln Institute of AgriFood Technology and Fruitcast.ai.

Agri-robotics and artificial intelligence (AI) are useful tools with the potential to help address several grand challenges associated with our food system. These include:

1. Helping agricultural workers to do their jobs safely and productively. However, it is increasingly difficult to recruit skilled workers. Agri-robotics may be needed to help fill the gap in the workforce.
2. Driving up productivity. This is crucial to offset food price inflation and fair profit/cost sharing across the whole supply chain from farms to consumers. There is an obesity crisis in this country, and ensuring fresh produce and high nutrition foods are available at an affordable price is key to supporting consumers to diversify their diets and eat more whole foods.
3. Supporting informed farmer decision-making. This is particularly important in the context of climate change, which is increasing the frequency of extreme weather events.

However, the translation of cutting-edge science and technology from laboratories into commercial products that are then taken up by farmers remains a significant challenge.

The 'Valley of Death' – that old chestnut

Complexity increases several orders of magnitude as a technology proceeds from the lab bench towards an operational environment, and thus cost increases. There are several reasons:

- Diversity of operational environment – a robot may use crop images to navigate a field, however every day those crops grow and change.
- Testing and validation – it is a challenge and needs substantial investment.
- Ensuring reliability and safety – if a robot breaks down twice, a farmer won't use it again.
- Integration – new technologies need to work with existing tools and systems.

- Regulatory compliance – requires costly trials and testing.
- Manufacturing and scalability – it's challenging to produce things cost-effectively at scale.
- User interface – must be easy to use.
- Team – individuals must learn to work as part of a team.

Ceres Agri-Tech

A mechanism to support agricultural entrepreneurs in navigating the 'valley of death' has been developed over last five years. Ceres Agri-Tech was founded and based at Cambridge Enterprise and is supported by EPSRC and Research England's Agri-Tech Global program. It follows the model of Apollo Therapeutics, which supported the translation of medical therapeutics from lab into industry and has attracted substantial private investment.

In the Ceres Agri-Tech system, academics bid in to receive small aliquots of funding (£250k per project). They must pitch their idea to an external investment committee that includes representatives with significant industry track records, including Sainsbury's, Syngenta, Nestlé Purina and Barclays. Selected projects are funded against milestone-driven research, and they must deliver according to these milestones to keep receiving funding. The academics are mentored through the pitch process and project delivery. Following on from the Ceres-Agri-Tech system, academics may take their idea to an impact accelerator fund, initiate the patent process and/or start a spin-out.

In its first five years, Ceres Agri-Tech has had interest from 125 potential projects, met with 94 teams of which 49 received mentoring, and invited 37 pitches of which 31 were then selected to receive funding. The programme has generated 4 spinouts, invested £4.2 million and leveraged £6 million in investment.

Seed capital is difficult for early-stage companies to find. Particularly in the agricultural sector, these companies need patient, longer-term investment. There may be a role for government in helping innovators access this type of funding.

> "Complexity goes up several orders of magnitude as you go from a lab bench to an operational environment. As complexity grows, cost increases."
>
> Professor Simon Pearson, Lincoln Institute of AgriFood Technology and Fruitcast.ai.

PANEL DISCUSSION

How do we make the innovation pipeline more effective for food and agriculture?

Professor Angela Karp, Rothamsted Research, chaired a panel discussion exploring how private and public funding could be used to fund agricultural innovation more effectively.

Image: Professor Angela Karp, Rothamsted Research.

Dr Angie Burnett, Advanced Research and Invention Agency, and Dr Andy Cureton, Innovate UK, provided perspectives from public funding entities, while Dr Andrew Muir, Future Planet Capital, and Tom Ritchie, Cibus Capital, discussed the role of venture capital in supporting agricultural innovation.

Key themes that emerged from the wide-ranging conversation have been summarised below.

What makes an idea investable?

- Public funding is critical for early-stage research where IP cannot be captured or where risks are too high for private investment.
- Public funders are interested in ideas that might grow the UK economy and that address key societal challenges (eg helping reduce greenhouse gas emissions or increase biodiversity) that are under-provided by the market.
- As part of the assessment process, public funders want to see that innovators have considered how the idea will be implemented. How will it fit into an existing production system?
- For private investors, the value proposition is key. It must be clearly defined, and there must be clarity over whether the innovators have a clear competitive advantage.
- Both private and public funders want to see that innovators have thought about who stands to benefit from their idea and how it could be monetised. A lot of innovation is led by R&D but having an appropriate business model is key for commercialisation. Even early-stage projects may benefit from engaging with potential end-users / future customers (eg farmers) to ensure the idea is not being developed in isolation.
- Investors of all types want to see a strong team in place who have the necessary skills and expertise to advance the idea. Teams need to be flexible as ideas may need to be tweaked to be commercialised.
- Investors are particularly interested in companies that can make a convincing case for their ability to scale in the UK and globally in a well-defined timeline.

Image: (Left to right) Dr Andy Cureton, Innovate UK; Tom Ritchie, Cibus Capital; Dr Andrew Muir, Future Planet Capital; and Dr Angie Burnett, Advanced Research and Invention Agency.

Is the agricultural innovation community in the UK ambitious enough?

- The environmental issues facing agriculture and our planet are big, and agricultural entrepreneurs and the bodies that fund them need to think big. There needs to be a high-level vision of what the sector needs to achieve to drive meaningful innovation.
- Improving productivity on farm must be a key focus for future innovation alongside addressing environmental challenges.
- There are some very successful companies in the UK, but there are not enough of them. There is a need for a critical mass of innovative organisations so skilled people can move between them and so non-specialist investors can see what early-stage companies may become.
- There is a need for more risk capital in the UK, there is a dearth compared to the US. Many UK companies move to the US to access capital and a bigger market.

Investment in innovation often follows trends, with similar projects and companies receiving funding. Should this change?

- It is important to fund high-risk, high-reward ‘moon-shot’ projects if the benefits to society and potential financial returns are so promising that it is worth the risk.
- It is the nature of venture capital to fund projects with huge potential return on investment, but investors must still undertake thorough due diligence.
- When funding at an early stage where there is risk, public funders will often fund multiple projects on similar themes as it is unclear which idea is most likely to succeed.

Patient (long-term) capital – does it really exist, and how can it best be incentivised?

- It depends on the profile of the investor. If looking for 'patient' funding this requires a specific type of investor with a long-term investment horizon. This may mean approaching corporate venture capital funds. If there is an ability to raise capital without giving away too much ownership of the enterprise, then this is often compatible with attracting additional investors later.
- Deep-tech sectors in general require patient capital, agriculture is not necessarily unique in this respect.
- The government-driven Enterprise Investment Scheme (EIS) is a fantastic mechanism for supporting early-stage innovation through venture capital. It offers tax reliefs to individual investors who buy shares in a company and helps the company to raise money and grow its business.
- It would be valuable to get more institutional money (eg pension funds) involved in venture capital to support longer term investing and ensure there are larger pots of money available to support the commercialising of innovative ideas.

How can entrepreneurs engage with end-users?

- Including end-users / customers as partners in publicly funded R&D projects can be an effective way to ensure their input is received and used in shaping an innovating idea at an early stage.
- As an example, SugaROx are a biostimulant spin-out company that uses local distribution partners in countries around the world to coordinate field trials. This minimizes the cost to the company and means they have a ready-made distribution model in place if the trials are ultimately successful.
- The Agricultural Universities Council has started a programme of stakeholder workshops to bring together huge networks of farmer-led organisations to get their thoughts on what they need in terms of technology and other types of support.
- Defra's Farming Innovation Programme aims to fund both new technologies and new management approaches or changes in practices.
- Farmer-led innovations are key in addressing real on-farm needs. However, some of these ideas may not be suitable for venture capital funding as the potential return on investment may be small and / or the teams may not be ready to commercialise the idea. These innovations may instead need knowledge-exchange or dissemination platforms to create impact.
- Funding to enable farmers to participate in trials is an area that could be further explored. The Defra Farming Innovation Programme offers support of this type.

> "To address major agricultural challenges, we must commit to long-term and large-scale innovation and R&D funding. We cannot lose faith when results are not seen in the short timescales often desired by venture capitalists."
>
> Professor Angela Karp, Rothamsted Research.

‘Ungeography’: how vertical farming could help transform how we grow

David Farquhar, tech investor, serial entrepreneur and advisor to the board of the John Muir Trust, discussed the potential role for vertical farming in our future food system.

Image: David Farquhar, tech investor, serial entrepreneur and advisor to the board of the John Muir Trust.

Innovation in food and farming has not kept pace with other sectors, and agriculture is considered the least digitised of all major industries[25]. However, recent advances in vertical farming technologies are making use of cutting-edge science to improve the sustainability of crop production.

There are several environmental benefits associated with vertical farming. It is less land intensive than traditional farming by a ratio of up to 10,000:1 and requires substantially less water. Vertical farms generate fewer greenhouse gas emissions and less water pollution than conventional agricultural systems. Closed, fully automated systems can grow plants without the use of pesticides, herbicides or fungicides. Growing conditions can also be manipulated to maximise for crop features such as yield, taste and nutritional value. Finally, vertical farms can utilise almost any land type, including brownfields, and can be located near target consumers to minimise food miles.

The engineering

Intelligent Growth Solutions is a UK-based vertical farm technology company that designs and builds farms around the world. Their vertical farm machine operates using growth trays organised in automated racks. Advanced computing is used to replicate and deliver controlled weather, which can be broken down into a three-dimensional matrix of sun, wind, and rain. Each dimension can be further magnified into approximately 8 – 10 factors that all influence features of the plant such as its growth rate, nutritional value, taste, resilience to extreme weather, and appearance. Each factor can have an infinite number of values (eg the spectrum of light), which means that control requires very big maths.

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[25] Goedde, L *et al.* 2020. Agriculture’s connected future: How technology can yield new growth. *McKinsey & Company*. Available from https://www.mckinsey.com/industries/agriculture/our-insights/agricultures-connected-future-how-technology-can-yield-new-growth (accessed 31 July 2024).

Sunlight conditions are replicated using a cluster of five coloured LED lights that can be combined in various spectra, level of brightness and photoperiods to suit plant needs. Heating, ventilation and air-conditioning systems located at the bottom of the trays simulate wind conditions and a mobile frame running vertically between the racks houses the watering and monitoring systems.

Trays can be adjusted to accommodate various sizes of crops, and the planting setup can vary at the tray and tower levels, accommodating for different root types and plant species. This versatile system can grow plants through their full cycle or produce starter plants for greenhouse or hybrid operations, such as growing potatoes into seedlings before transferring them to a field.

The crop science

In vertical farming, as with all forms of agriculture, conditions must be varied throughout a crop's life cycle. Initially, conditions should be humid, dark, and warm to germinate seeds. Later, they should be cold, dry, and bright to enhance crop durability and shelf life. Additionally, diurnal cycles with approximately 18 hours of sunlight are ideal, allowing for the acceleration of the crop's life cycle by extending the perceived length of a day. Replicating winter conditions is not beneficial for yield; only summer, spring, and late autumn conditions are desirable for crop production. Climate variables can also be made to mimic local climate data from different geographies to more effectively grow crops adapted to those specific conditions. In addition, the 'weather' can be maintained such that plants such as chilli bushes don't mature, but flower and fruit and so can be harvested continually.

Next steps

Researchers at the Advanced Plant Growth Centre at the James Hutton Institute are using vertical farming to stress test plants, examining how varying growing conditions such as temperature, gas composition, and light type will affect crop qualities like taste, yield, nutrient content, appearance, and resilience to climate change. This research aims to identify the best possible growing conditions for different crops, enhancing their overall quality and climate resilience.

Vertical farming has potential applications beyond food production, such as producing crops for nature conservation initiatives (eg tree seedling production, mangrove reparation, the re-establishment of extinct species) and pharmaceuticals.

While the cost of energy to run a vertical farm is often cited as a major challenge, the economics vary dramatically according to how the energy required to run a vertical farm is produced. For example, co-locating a vertical farm with a locally effective power generation method (eg a solar farm in Dubai) has the potential to put most vertically-farmed crops into competitive price points.

> "If we bring the science and the machine together with the right government policy, we can have a significant impact on our ability to sustainably feed ourselves."
>
> David Farquhar, Tech investor, serial entrepreneur and advisor to the board of the John Muir Trust.

Micro-organisms as a sustainable source of next generation food and ingredients

Dr Rodrigo Ledesma-Amaro, Imperial College London, discussed how recent advances in engineering biology could help the microbial foods industry to address its existing challenges.

Image: Dr Rodrigo Ledesma-Amaro, Imperial College London.

There are three types of alternative protein according to The Group Food Institute: plant-based, cultivated, and fermented microbial food. Fermented microbial food can be divided into three groups:

1. Biomass: Growing microorganisms in a bioreactor which are then used as ingredients in alternative proteins (eg Quorn grows filamentous fungi for use in their products).
2. Traditional: Transformation of animal/plant feedstock through microbial fermentation into a different-tasting food (eg sauerkraut, kimchi).
3. Precision: Microorganisms are used to produce specific functional ingredients like proteins, enzymes, carbohydrates, vitamins, pigments, and fats.

The role of engineering biology

Health and environmental benefits associated with eating microbial food include that it can contribute to gut microbiome diversity, it can use waste products as feedstock, it has a low land footprint, and production is indoors and thus independent of climate. However, key challenges faced by the microbial food industry include taste, nutrition content, and price. Engineering biology technologies such as microbial strain improvement, biofoundries and bioprocessing engineering could help to overcome these challenges. Engineering biology approaches can be used to:

- Manipulate metabolic pathways to yield desired products, enrich high-value products and potentially enhance taste.
- Engineer microorganisms to use cheaper and more sustainable feedstocks like CO_2, methane, or lignocellulosic byproducts from traditional agriculture.

- Improve nutritional properties of microbial foods by engineering the microorganisms to express specific high-quality proteins or micronutrients.

The UKRI-funded Engineering Biology Mission Hub on Microbial Food will be developing novel tools, processes, and products that can help encourage wider-scale use of microbial foods. Examples of these tools, products and processes developed by the Rodrigo Ledesma-Amaro (RLA) lab are described below.

Tool innovation

CRISPR technology employs a guide RNA to direct an endonuclease to a specific DNA region. By cutting DNA at a precise location, this technology can be used to enhance or reduce the expression of a specific gene. CRISPR gene activation and inhibition (CRISPRai) uses multiple guide RNAs for simultaneous edits of DNA, enabling better manipulation of complex metabolic pathways. A recent study used CRISPRai to express 11 guide RNAs in the industrially relevant yeast, *Saccharomyces cerevisiae*, to produce a 45-fold increase in succinic acid, a precursor molecule in the production of a range of chemicals and food additives[26].

Product innovation

The RLA lab is currently using the biomass fermentation approach to produce food based on the *Yarrowia lipolytica* yeast. They are also exploring how to produce food ingredients in a more sustainable manner using yeast as a platform.

Process innovation

Traditional fermentation methods use a single engineered microorganism to produce a specific product, but overengineering can reduce performance. The RLA lab, as part of the Microbial Food Hub, is designing processes that rely on a range of microorganisms working together in a synthetic microbial community. For example, one project which is producing the antioxidant resveratrol using two yeast strains has achieved a three-fold yield increase relative to traditional processes[27]. The first strain produces the intermediate pathway, and the second produces the final product. Splitting the pathway and dividing the labour decreases energy requirements and increases yield. Furthermore, promoting cross-feeding and metabolic dependency between the strains ensures that they depend on each other and encourages them to grow together in a controlled ratio to further maximise production.

> ‘We aim to learn from nature, which doesn’t rely on one single organism doing everything, but communities of organisms working together. We are trying to bring this to the bioreactor.”
>
> Dr Rodrigo Ledesma-Amaro, Imperial College London.

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26. Shaw, WM *et al.* 2022. Inducible expression of large gRNA arrays for multiplexed CRISPRai applications. *Nature Communications*, 13, 4984.
27. Peng, H *et al.* 2024. A molecular toolkit of cross-feeding strains for engineering synthetic yeast communities. *Nature Microbiology*, 9, 848-863.

Developing the cutting-edge technologies required to accelerate insect farming as a global industry

Keiran Whitaker, Entocycle Ltd, described innovative technologies that optimise the production of black soldier fly as a sustainable protein source.

Image: Keiran Whitaker, Entocycle Ltd.

The process of raising animals and producing their protein-rich feed has resulted in the loss of natural resources and biodiversity whilst also contributing to deforestation and greenhouse gas emissions. The world's current protein demand is unmaintainable, with the United Nations predicting a shortage of 60 million tonnes per annum by 2050.

Entocycle aims to accelerate a global transition to the use of sustainable protein through utilising insects, innovation and technology.

Black soldier fly

Black soldier fly (BSF) larvae can be used as an all-natural challenger to soya. These non-disease, non-pest species are known to have an average production timeline of only 6 – 10 days and can be found on many continents all over the world. Not only is there a 98% reduction in the use of land and a 99% reduction in food miles compared to soya, BSF production can also save 4 – 6 tonnes of CO_2 compared to other protein production systems and act as carbon capture technology when using the right food waste to feed insects. While some companies use 40 – 50% of their grandparent stock to repopulate, Entocycle can make use of only 2%, leaving 98% of insects available to be used for protein.

Why farm insects?

British farmers are facing increasing pressure from the public and the government to help address agriculture's environmental impact. While this has paved way for more sustainable farming practices, the changes also come with high investment and financial burden for the farmers.

Through the use of insect farming, British farmers and UK businesses can become part of a rapidly growing industry. This would reduce the UK's reliance on imported protein for animal feed whilst simultaneously reducing its agricultural footprint. Additionally, insect farming results in the production of high volumes of frass (excrement of insect larvae), which is a highly effective organic fertilizer and could be a valuable co-product.

> "Every single animal eats insects, and that's the fantastic thing about it. There is no modification here, it's a 100% natural system that we are just applying into industrial scale."
>
> Keiran Whitaker, Entocycle.

Features of large-scale insect farms

By incorporating Entocycle's cutting-edge technology into BSF farms, new levels of productivity and sustainability can be attained. There are three main features offered by Entocycle:

- **Climate control**
  Insects are known to be exothermic creatures, and the biggest cost in insect farming stems from the need to cool them down. The UK's climate is poised to be a great solution in regulating temperature, humidity and airflow within BSF facilities. By bringing in cold air to cool the system down, the heat from production may then be used to breed flies in the other half of the facility.

- **Machine vision**
  Machine vision automation technology can be used to monitor insect populations in real-time to count and track insects over their lifecycle. Entosight^{TM} Neo enables precision counts at +95% accuracy for 3000 insects per second, ensuring that there is a consistent quantity and quality of larvae being provided with minimal labour costs.

- **Automation**
  A significant proportion of insect farming consists of the challenge of warehousing, and automation can be used to manage this. Entocycle's robotic arms can move boxes used to store insects quickly and for extended periods of time. They range from 5 to almost 500 tonnes of insect processing power per day, which helps with scalability.

Cellular agriculture: part of the whole systems approach for food security and net zero

Professor Marianne Ellis, University of Bath and Cellular Agriculture Ltd, focussed on the potential of tissue engineering-based cellular agriculture for cultivated meat to help diversify and increase circularity in our existing food systems.

Image: Professor Marianne Ellis, University of Bath and Cellular Agriculture Ltd.

Cellular agriculture is a collection of technologies seeking to produce consumables that are traditionally produced in livestock-based agriculture systems, through other means such as precision fermentation or tissue engineering.

One such consumable is cultivated meat, also known as cultured meat, which is a protein ingredient made up of muscle cells only. These muscle cells begin as stem cells from animals, which are grown in cell culture media, put into bioreactors, and put through a series of processing steps before they become product that can be used as food substance.

Developing and scaling the cultivated meat industry

The cultivated meat industry is nascent, and historically tissue engineering has only been used to produce a small number of cells for medical applications. Research is ongoing into manufacturing meat for wide-spread consumption.

While the technology to produce cultivated meat exists, key challenges relate to scaling. To feed a growing global population, operations must be able to scale rapidly and dramatically. A key difficulty in producing cultivated meat at scale relates to the sourcing and cost of cell feed at such quantities.

Scaling up cultivated food production could revolutionize the food industry in terms of reducing the land area used. For instance, a facility producing 60 tonnes of quality protein per week, equivalent to 12,900 head of cattle, would traditionally require around 738,100m^2 of land. However, cultured meat could feasibly only require 66,430m^2 for cell farming and a 6,000m^2 factory plot[28].

The EPSRC-funded Cellular Agriculture Manufacturing Hub (CARMA) aims to help develop an impactful cultivated meat industry, alongside other cellular agriculture products, through early consideration of sustainability, social responsibility, and public acceptance. There are a range of possible approaches to producing cultivated meat, so stakeholders and consumers should be engaged early to ensure that suitable technologies are chosen.

Furthermore, the environmental impact of cultured meat is significantly affected by the selected cultivation methods and technologies. For example, cell culture media typically contains serum from foetal calves or horses. Using serum-free media can reduce the environmental impact by 18% compared to the baseline[29]. Conversely, maturing cells for an extra week can increase the environmental footprint by 65%. Therefore, optimising these factors is vital for minimising the environmental impact of cultured meat production. Developing an impactful cultivated meat industry will require working with stakeholders across the value chain, and considering features such as local geography, culture, feedstocks, energy sources, and diets.

> ‘Cellular agriculture can be adapted for local, culturally relevant production based on feedstocks, energy sources and diets.”
>
> Professor Marianne Ellis, University of Bath.

Opportunities for incorporating cultivated meat into the existing food system

The cultivated meat industry could be integrated into existing food systems to:

- **Increase circularity between cellular agriculture systems**
  Unused sugars and nitrogen are generated when growing muscle cells for cultivated meat production. These could be used to feed yeast, which can then be processed to create another food product. Additionally, yeast can be hydrolysed to produce amino acids necessary for cultivated meat production.

- **Add value for existing food producers**
  The cultivated meat industry could help to provide added value or alternative product routes for farmers and food producers. For example, plant waste could be used as a scaffold structure or media ingredients to be used in bioreactors for growing muscle cells, or farmers could sell stem cells as an additional product from animal carcasses already being sold for human or animal feed.

- **Creation of valuable byproducts**
  A byproduct from cellular agriculture with potential alternative applications is lactic acid, which can be used to make compostable plastics or as a preservative.

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[28] Cellular Agriculture Ltd. Unpublished data.

[29] Tuomisto, HL *et al.* 2022. Prospective life cycle assessment of a bioprocess design for cultured meat production in hollow fiber bioreactors. *Science of the Total Environment*, 851, Part 1, 158051.

Escape from the planet of the cows

Professor Patrick Brown, Stanford University School of Medicine and Impossible Foods, argued for the need to replace livestock agriculture and support development of plant-based meat products over the next two decades to reduce greenhouse gas emissions.

Image: Professor Patrick Brown, Stanford University School of Medicine and Impossible Foods.

Animal agriculture currently exploits 45% of Earth's ice-free land surface[30]. In comparison, all crops for direct human food consumption occupy about 7% of the land surface. Expansion of animal agriculture has destroyed native ecosystems and replaced diverse plant and animal species with livestock and the few species that can co-exist with them. This habitat destruction and degradation is the principal cause of a precipitous decline in global populations of wild vertebrate animal species, which now average less than a third of their numbers in 1970[31].

Replacing animal agriculture can rapidly turn back the clock on global heating by unlocking negative greenhouse gas emissions on a massive scale. If animal agriculture was phased out over the next 15 years and the associated land was permitted to return to original ecosystems, it would create a 30-year pause in net human greenhouse gas emissions[32].

Prompt, fundamental change is needed to address these immense environmental concerns.

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30. Herrero, M *et al.* 2009. Livestock, livelihoods and the environment: understanding the trade-offs. *Current Opinion in Environmental Sustainability*, 1(2), 111-120.
31. WWF. 2022. *Living Planet Report 2022.* Available from https://www.worldwildlife.org/pages/living-planet-report-2022 (accessed 31 July 2024).
32. Eisen, MB & Brown, PO. 2022. Rapid global phaseout of animal agriculture has the potential to stabilize greenhouse gas levels for 30 years and offset 68 percent of CO_2 emissions this century. *PLoS Climate*, https://doi.org/10.1371/journal.pclm.0000010.

Replacing animals in the food system

Asking people to give up animal products is a non-starter, and any government that tries to compel people to make changes to their diet is going to be hugely unpopular. A more subversive approach is needed: innovation and market competition. That's the way things change.

The researchers behind Impossible Foods began by investigating why the taste of meat transforms so dramatically during cooking. Meat has much more abundant heme than vegetables, and this is the critical catalyst for reactions that transform simple nutrient molecules into flavour and aroma. If heme is added to vegetable broth, a similar explosion of flavour and aroma is achieved.

Heme can be produced at scale using precision fermentation. After a few years, the Impossible Foods team could make a plant-based meat that could compete with animal products and was preferred in both blinded and unblinded tastings[33].

Supporting farmers through the transition

If animal agriculture is to be reduced or replaced, farmers who make a living raising animals need to be supported in transitioning through this process. Subsidising farmers to transition away from raising cattle towards restoring ecosystems is a huge opportunity in terms of increasing carbon capture and restoring biodiversity. As the Swiss Re Institute estimates that global temperature rises could cut global GDP by up to 14% ($23 trillion USD) by 2050[34], paying farmers to reduce greenhouse gas emissions could be much cheaper than paying the costs associated with intensifying climate change.

Summary

Mechanisms to bend the curve on climate change and reverse the collapse of biodiversity include:

- removing anti-competitive obstacles to plant-based meat, fish and dairy foods;
- supporting and facilitating innovation in sustainable proteins with the same priority and urgency as renewable energy systems; and
- establishing and expanding programmes that pay farmers and other landowners who voluntarily commit land to ecosystem restoration.

> "The problem is not that people love meat, it is that we are producing it the wrong way."
>
> Professor Patrick Brown, Stanford University and Impossible Foods.

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33. Sogari, G *et al.* 2023. A sensory study on consumer valuation for plant-based meat alternatives: What is liked and disliked the most? *Food Research International*, 169, 112813.

34. Swiss Re Institute. 2021. *The economics of climate change.* Available from https://www.swissre.com/institute/research/topics-and-risk-dialogues/climate-and-natural-catastrophe-risk/expertise-publication-economics-of-climate-change.html (accessed 31 July 2024).

Is cultured meat a threat or opportunity for UK farmers?

Dr Alexandra Sexton, University of Sheffield, discussed UK farmers' attitudes to cultured meat and their opinions on what conditions might make on-farm production of cultured meat practical, economically viable and desirable.

Image: Dr Alexandra Sexton, University of Sheffield.

Agriculture is both vulnerable to and a driver of planetary climate change. Animal agriculture in particular is associated with large volumes of greenhouse gas emissions and has received considerable negative media attention. This has driven extensive work on better ways to produce meat and other animal products.

Alternative proteins

Many types of alternative protein production systems are being developed. Two of the most-discussed approaches are plant-based proteins, which remove the need for animals in protein production, and cellular agriculture (cultured meat), which removes the need for animal slaughter but does require animal cells.

Different arguments have been made as to how desirable a livestock-free planet might be, and predictions vary as to how quickly it could be achieved. There are still many economic hurdles for alternative proteins to scale up to become truly competitive with animal products. Notably, the direction of travel for the broad alternative protein sector has involved collaboration with traditional livestock companies, which are increasingly adding alternative protein products to their portfolios.

What are farmers' attitudes to cultured meat?

Within the UKRI-funded collaborative project 'Is cultured meat a threat or opportunity for UK farmers?', researchers have assumed that conventional livestock systems will still be used widely in the short- to medium-term. The social science strand of the project is exploring what UK farmers think about cultured meat (if they think about it at all), and what they think it might mean for their farm business.

A series of six focus groups involving a total of 75 farmers were conducted both in-person and online[35]. Discussions covered three main themes: public acceptance, environmental implications, and socioeconomic considerations. Farmers engaged in complex and nuanced discussions on the topic and were keen to discuss both potential opportunities and threats associated with cultured meat.

Media analysis was undertaken to explore how cultured meat was being discussed in legacy agriculture media in the UK, including *Farmers' Weekly*, *Farmers' Guardian* and a popular online forum[36]. By examining 147 articles published between 2017-2023, the researchers found cultured meat was not being discussed often or in detail. In the online forum, a small but vocal minority of users including some public-facing farmers were keen to discuss cultured meat in detail and the conversation in some cases became quite polarised. Lab-based images remain the dominant visual representation of cultured media in the UK food and farming media, which may influence opinions.

How do farmers think cultured meat might impact their businesses?

The project team interviewed farmers from different regions of the UK with different types of farming businesses and varying attitudes to cultured meat. They asked farmers to think through possible risks to their business in the next ten years associated with two scenarios:

1. Business-as-usual. Farmers were roughly evenly split into optimistic and pessimistic camps. Discussions around economic insecurity, power within supply chains and challenging net zero targets were recurring themes.
2. Cultured meat-goes-mainstream. There was a lot of discussion around impacts on income, increased competition and rural livelihoods.

> "There is a general appetite amongst farming communities to continuing to engage with the cultured meat industry, and a perceived need for the cultured meat industry to learn more about conventional agriculture."
>
> Dr Alexandra Sexton, University of Sheffield.

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35. Manning, L *et al.* 2023. Threat or opportunity? An analysis of perceptions of cultured meat in the UK farming sector. *Frontiers in Sustainable Food Systems*, 7.
36. Goodman, M *et al*. Unpublished data.

Panel: How can innovations in food and agriculture be deployed at scale?

Professor Iain Donnison, Aberystwyth University, chaired a panel discussion on the challenges associated with the translation and adoption of innovative agricultural technologies and practices.

Image: (Left to right) David Exwood, NFU; James Evans, John Deere; Dr Katrina Hayter, HSBC; Professor Jo Price, Royal Agricultural University; and Professor Iain Donnison, Aberystwyth University.

Providing a diversity of perspectives, panellists included James Evans, John Deere; David Exwood, NFU; Dr Katrina Hayter, HSBC; and Professor Jo Price, Royal Agricultural University.

The discussion was guided by questions from both the chair and the audience. A synopsis of the conversation is included here.

How do we scale and commercialise technologies that are feasibly deployable in the near-term?

- To build a pipeline of agricultural innovation, we need to ensure that early-stage research questions are appropriately framed, address the big challenges society is facing and are focused on issues relevant to end-users.
- The agricultural innovation field requires future leaders in systems thinking who can help us understand the myriad factors that influence how new technologies can be developed and implemented.
- To support innovation that will help society meet highly ambitious emissions targets, large amounts of capital must be released and deployed at scale within the agricultural sector. The agricultural sector has huge untapped potential for low-cost carbon and climate action. HSBC have a number of financial tools (eg Sustainability Linked Loans, Green Bonds) to help clients invest in the low-carbon, nature-positive economy.
- Innovations must work financially for farmers, particularly as they currently carry the bulk of the risk associated with food production.
- Traditionally, farm machinery has continued to get bigger and more powerful. There is now a push to create products that deliver economic benefits to the end-user while also delivering a benefit in terms of improved sustainability. Collaboration with start-ups can keep larger companies agile and innovative.

- The choice agenda is important, there is no one size fits all. The rapid uptake of the Defra's Sustainable Farming Incentive (SFI), where farmers can choose from a menu of environmentally friendly actions for which they will be paid, speaks to the power of choice.

- Herbal leys (sown pastures made up of a diverse mix of grasses, herbs and legumes) are an interesting case study. A few years ago, there was a huge amount of skepticism about their use, which discouraged research. The availability of funding is changing things: charitable funding for field labs encouraged some farmers to try them, and recently SFI started paying farmers to use them and the economic benefits in addition to the SFI payments became obvious. A seed supplier reported that in the past few years herbal ley seeds made up 2-3% of overall sales, but since the SFI payments started this has shot up to 40% of sales. If you want innovation taken up quickly, financial incentives can work.

How can we best join up the agricultural innovation ecosystem?

- Terminology (net zero, regenerative agriculture) is often poorly defined and can be needlessly confusing and divisive.

- The system of knowledge exchange in the UK is highly fragmented. Joining up demonstration farms across the country, making it clear what resources and facilities exist and enabling broad access would make the system much more effective.

- Data sharing is and will continue to be important. Decisions around financial investment in innovation must be supported by relevant data. Farming produces huge amounts of data, and on-farm decision-making is increasingly data driven. Agricultural devices and apps used to produce and store farm data are typically not interoperable. Improving the ability to share data between different devices and apps, as well as between farms and between institutions, could support huge efficiencies and provide much-needed evidence for the effectiveness of different technologies and approaches.

How do we make translation work in the UK? Are there lessons to be learnt from other sectors? Other countries?

- There is a need for need to be bigger, 'moonshot' investments in the UK's agricultural innovation system. The funding available is often for short-term, smaller projects and it can seem like the 'jam is spread too thin'. Other countries (eg Israel) have historically been more willing to make large investments in riskier initiatives and have thriving innovation ecosystems as a result.

- Changing the perception of agriculture will be important to draw and retain skilled people in the sector. Agricultural innovation has the potential to help address big challenges around climate and biodiversity, and capturing the interest of young, talented people with skills in the STEM subjects will help support future advances in the field. A strong purpose can be very attractive.

- Route to market needs to be developed from the beginning of any innovative idea and clearly defined as part of the commercialisation process.

How can we get the balance right between agricultural productivity and farm economics, with other public goods including carbon and biodiversity?

- There are financial tools that can help with the delivery of public goods at scale and at pace. There are opportunities for blended finance (strategic use of public sources of capital to stimulate private investment), particularly in the agricultural sector in lower income countries but to some extent also in higher income countries like the UK.

- Land managers increasingly have access to income that is not linked to food production. This might be through SFI, or via nascent carbon and biodiversity markets.

- Regulatory signals are important. For example, deforestation regulations are about to shake up supply chains around the world. Regulation is an important part of pushing agriculture (and other sectors) to make changes to improve public goods.

- Poorly defined regulatory frameworks (eg lack of clarity around carbon markets) are a huge barrier to uptake of innovation.

What is agriculture going to look like in 25 years?

- The principles of farming have been the same for thousands of years, but the methods have evolved and will continue to change. Production of livestock and staple crops is likely to always be a key part of agriculture.
- Changes like the phasing out of boom sprayers, diesel gas and fertilizers produced using natural gas would be welcome.
- A movement from some automation to near-total autonomy in farm machinery is likely, as are alternative fuels (eg hydrogen) and possibly electrification.
- We will need even more from the land than we currently demand from it (nature, fuels, food, carbon, leisure, etc). We need to scale many technologies and approaches focused on improved agricultural sustainability and efficiency, using every tool in the toolkit.
- Systemic culture change in institutions is needed. Academic researchers are still primarily rewarded for publications as opposed to impact, although this is perhaps slowly changing.

> “When talking about interdisciplinary teams, people can be described as miners (those with a depth of knowledge in a specialised area) or bridges (those with a breadth of expertise). People working in agriculture are often bridges”.
>
> Professor Iain Donnison, Aberystwyth University.

Where are we in understanding agricultural innovations?

Professor Louise O Fresco[37], Former President of Wageningen University, discussed where we currently are in understanding importance of agricultural innovations / research and what we must do to lay the foundations for an ecologically healthy world.

Diversity is crucial for agriculture, not only in the sense of biodiversity but also in terms of ideas. Not one farmer or farm is exactly like another, thus there can be no universal solutions. However, there are overarching principles that we must collectively follow.

Learning from the past

The Green Revolution resulted in the widespread use of science-informed practices for plant breeding, water management, crop nutrition and overall farm management. These approaches saved an estimated one billion from starvation[38]. However, the long-term consequences of this transformation of the global agricultural system have included environmental damage from the overuse of mechanical and chemical inputs and many small farmers going out of business.

It is vital that we efficiently use our agricultural resources such that yields can be increased without expanding the amount of land used for agriculture. As the world population continues to grow over the next fifty years, so will the demand for food and animal products. Learning from the Green Revolution, there must be concerted policies to manage land use, markets and support for farmers.

Image: Professor Louise O Fresco, Former President of Wageningen University.

Innovation in agriculture

There is currently no premium for innovation within the Common Agricultural Policy in the European Union. There is no acknowledgement of how much farmers excel at taking up innovation, and how much they risk. It would be beneficial to introduce a funding mechanism that rewards bottom-up innovation in farming. We must strive for freedom for farmers and also freedom for companies to undertake for high-risk, high-reward work. In the UK, approximately 19% of research and development is funded by the public sector[39]. This is much lower than in many other parts of Europe. Public funding is a necessity, even more so for high-risk and long-term research.

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37. Louise O Fresco. Available from https://louiseofresco.com/louise-fresco-engels-nieuw/ (accessed 31 July 2024).
38. Easterbrook, G. 2019. Forgotten benefactor of humanity. *The Atlantic*. Available from https://www.theatlantic.com/magazine/archive/1997/01/forgotten-benefactor-of-humanity/306101/ (accessed 31 July 2024).
39. Panjwani, A *et al.* 2023. Research and development spending. *House of Commons Library*. Available from https://commonslibrary.parliament.uk/research-briefings/sn04223/ (accessed 31 July 2024).

Challenges faced today

The challenges facing agriculture are much more complex today compared to 50 years ago. The impact of climate change is increasing. Demographics are shifting, as many countries now have aging populations, which has knock-on effects in terms of labour productivity and nutritional needs. Globally, it is estimated that at least one billion people are deficient in at least one micronutrient (eg zinc, iron or vitamin A). Children under five and pregnant women are disproportionately affected.

To effectively respond to these issues, agriculture must be understood in holistic terms from farm to consumer, including the often-complicated supply chain in between these two points. The sector must be open to change. By 2050, global society will be looking to phase out the use of fossil fuels, which means we must develop and scale processes to produce valuable petrochemicals from biomass instead. We must also change the proportion of plant-based to animal protein consumption by 2050, however this will not happen overnight. Another area of science that should not be forgotten is photosynthesis, which is a highly inefficient biological process. As solar radiation is not a limited resource, improving the efficiency of photosynthesis could have enormous benefits in terms of achievable crop yields. High-risk and innovative research is needed in this area.

The future of agriculture

Industries such as information technology, business administration and artificial intelligence are becoming increasingly popular with young people entering the workforce. There must be a discussion on how to recruit more talented young people back into the agricultural sector. There is a lack of accessible information surrounding the industry and its importance. Dystopian views about the state of the world, particularly regarding food and agriculture, have exploded in recent years, and there is a widespread romanticised view of nature as an oasis of harmony and ease. Both inaccurate and extreme interpretations have roots in the lack of storytelling about the significance of food production. Food is important, not only for health but also culturally as food brings people together. There is enormous potential in the collective science and technology communities to be used for the betterment of mankind. With an open-minded and optimistic approach, many solutions can and will be implemented to address the challenges faced by agriculture.

> "I am quite optimistic about what the world will look like in 2100. None of us, here as we stand, are likely to live to see that day, but I think it is up to us to lay the foundations for a food and agriculture system that truly feeds and helps mankind."
>
> Professor Louise O Fresco, Former President of Wageningen University.

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