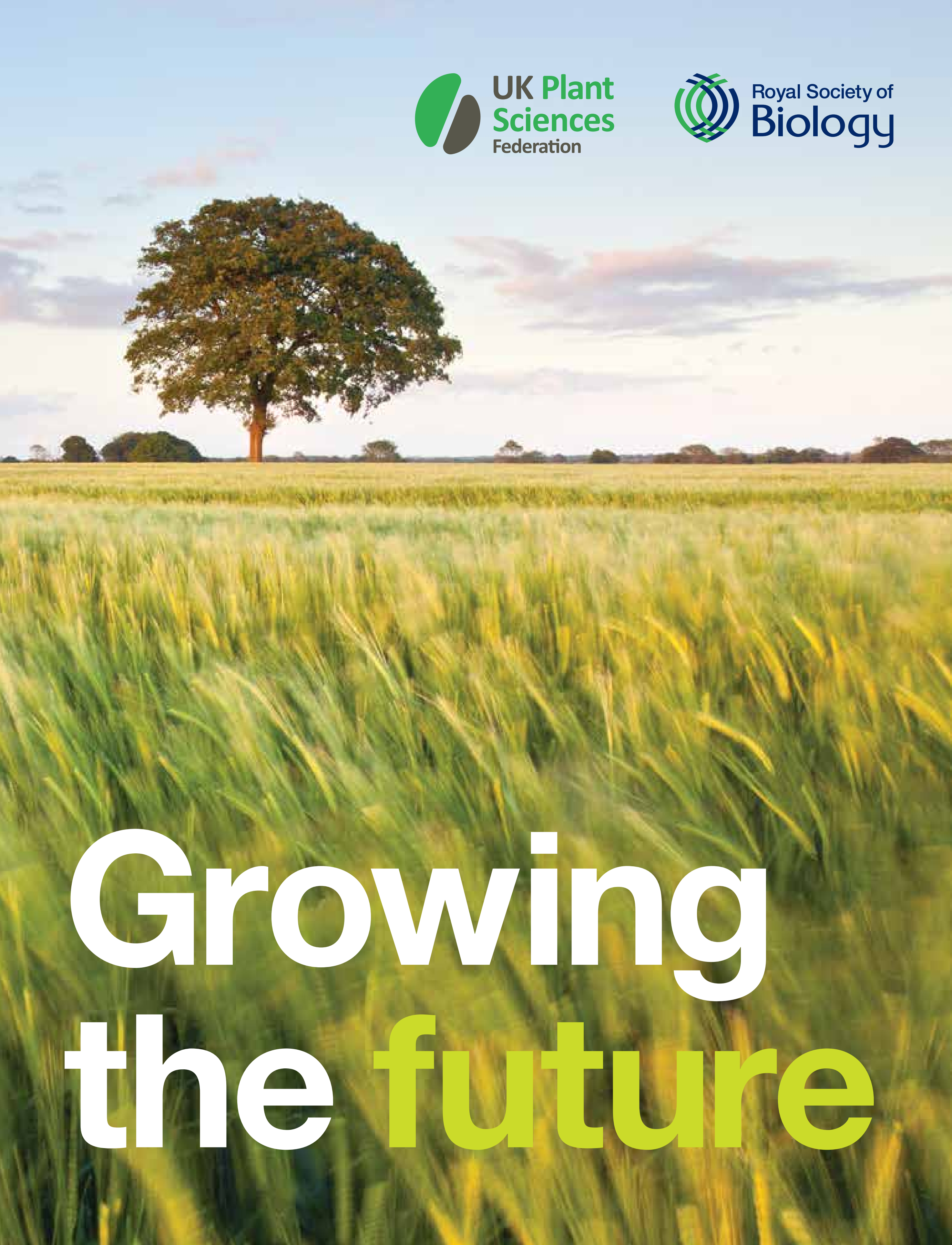
UK Plant Sciences Federation

Royal Society of Biology



Growing the future

About the UK Plant Sciences Federation

The UK Plant Sciences Federation (UKPSF) is a special advisory committee of the Royal Society of Biology. It brings together the UK plant sciences community to develop a coordinated approach to policy and practice in research, industry, funding, education and outreach, wherever possible.

The aims of the UKPSF are to:

1. Promote the importance of plant sciences for societal benefit.
2. Provide a forum for discussion, debate and information exchange that is independent and inclusive across the breadth of plant sciences.
3. Provide a focus and contact point for UK plant and crop science.

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About the Royal Society of Biology

The Royal Society of Biology is the leading professional body for the biological sciences – representing 18,000 individual members worldwide. The Society also represents a diverse membership of learned societies and other organisations.

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Foreword

Professor Sir John Beddington

There have been remarkable advances in the first two decades of this century that have revolutionised our understanding of the way plants work. Many of these fundamental discoveries have been made in the UK, and we are now in a position to exploit this understanding for the benefit of the UK.

There are huge opportunities to deploy this knowledge in areas that improve agricultural productivity and disease resistance, improve the agricultural environment, enhance the quality of the food we eat, produce new pharmaceuticals for the clinic, and use plants as cheap 'factories' in industries such as vaccine production. Furthermore the UK's leading position in plant science research will enable us to address the enormous challenges that underpin the United Nations Sustainable Development Goals (SDGs) and that include sustainable production of nutritious food and preservation of global biodiversity.

Growing the future is an admirable work, which correctly pinpoints the key requirements for plant sciences to mitigate the formidable challenges humanity will face as we approach the third decade of the 21st century. These challenges include, but are by no means limited to, human nutrition and health, mitigation and adaptation to climate change, and the preservation of ecosystems and biodiversity. These challenges are not going to go away, and if anything, are likely to become more pervasive. They are generated in part by rapid population growth, global urbanisation, and an increasingly unsustainable demand for natural resources. All of these will continue and exacerbate the difficulties faced by human populations as the century continues. Plant sciences alone cannot solve these problems, but they do offer significant potential to mitigate them.

"The UK has a proud history in the plant sciences, and if the recommendations of this report are followed, stands to have a comparable future"

Growing the future sets out conclusions to enable this potential to be realised in the UK. The conclusions address issues such as: international collaboration, skills and education, opportunities to strengthen UK plant science arising from changes to the research funding landscape, and the need for a broad debate on technologies in agriculture to inform decisions about regulation. These recommendations will catalyse the valuable intellectual capital embedded in the plant sciences community, and make it available to the wider UK research base, as well as to the economy. They are set against a background of a further revolution in the way plant biologists work, harnessing the power of big data – whether at the level of the genome or the field. This report highlights how investment in plant sciences research and development (R&D) will create opportunities for the UK economy, alongside how such investment will contribute to solving global challenges.

The UK has a proud history in the plant sciences, and if the recommendations and arguments of this report are followed, stands to have a comparable future. The importance of this future is manifest.

This report has been developed with the involvement of experts from across the bioscience community, to demonstrate to the UK Government, funders and other stakeholders the scale of the opportunities and ambitions emerging from the plant science sector – and offer proposals on how to realise them.

Executive summary

In this vision, the UK Plant Sciences Federation sets out opportunities and priorities within four key areas of plant science.

In addition, we offer four overarching conclusions, which are summarised below and set out in further detail at the end of the document.

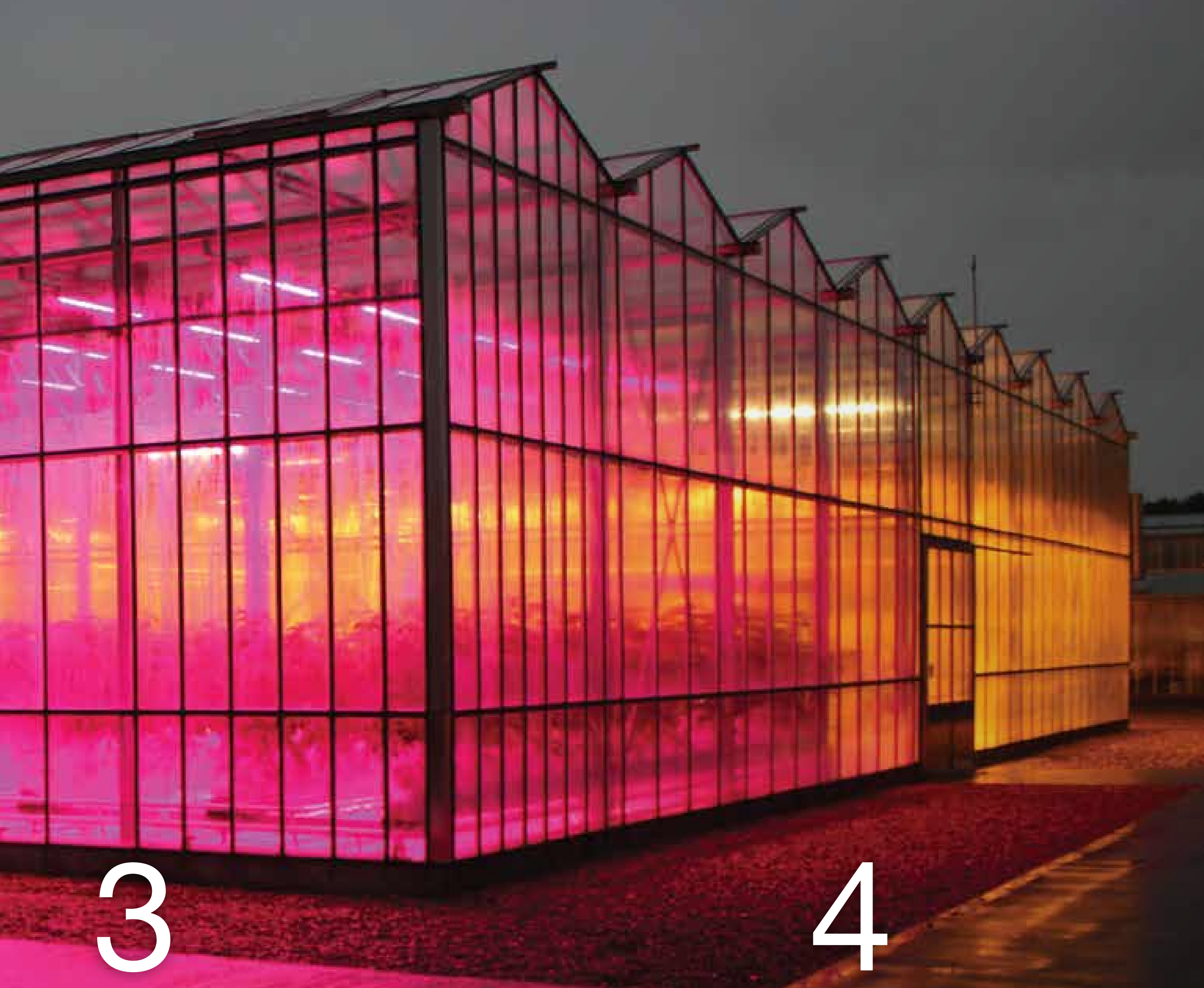
These conclusions apply across the discipline, and in some cases are relevant to other areas of science.

1

Changes to the research funding landscape provide compelling opportunities to strengthen UK plant science, and enhance its contribution to society. Plant science has the potential to deliver transformative benefits. Funders and research institutions should remove barriers and improve incentives for the movement of people and funding between public and private settings, in both fundamental and applied areas of research. Support to enable plant scientists to interact with colleagues across disciplines and research environments, with end-users of research, and with the public, will be extraordinarily beneficial.

2

International collaboration is a vital component of UK plant science. Maintaining close links with international networks, and enabling movement of skilled international workers, are essential to maintaining the UK's pre-eminent position in plant science research. UK plant science plays an important role in addressing global challenges, which involves collaborations with colleagues and communities overseas, requiring the smooth movement of people, ideas, and materials between countries, and policies that support these.



3

An ongoing, broad and balanced debate is needed on the UK's ambitions for agricultural production, taking into account new technologies, crop varieties and plant protection products, which can then inform decisions about regulation.

Our ability to produce nutritious food for healthy populations faces real threats, from changing climatic conditions to the spread of destructive pests and diseases. Technological innovations are available, including biopesticides, new plant protection products, and modern plant breeding methods such as genome editing. As regulators in the EU, Canada and the US take very different approaches, the UK must facilitate a robust debate on new methods in plant breeding and agriculture, and produce clear, sound policies, as its regulatory frameworks evolve. Well-informed public and policymaker views and workable regulatory systems are necessary for society to benefit from advances in plant science. Transparent and open dialogue between plant scientists and the public will be essential.

4

Engaging, inclusive and accessible plant science content is needed within biology curricula to realise the opportunities plant science offers to society.

It is essential to encourage interest in plant science, and to develop skills, in successive generations. Plants are an integral part of biology and the life sciences, relevant to us all, and not a niche subject. Engagement with plant science must begin in school and be nurtured in higher education and training to develop a plant science-literate workforce and society.

Introduction

Plant science is vital

Plants are essential to life on Earth. As crucial sources of food, medicines, materials and fuels, plants sustain people and societies, underpin ecosystems and drive economies. Plant science increases our understanding of life and expands our ability to utilise plants, contributing to maintaining healthy, productive societies and environments.

Plant science is central to tackling some of the biggest societal challenges and to meeting many of the UN Sustainable Development Goals (SDGs).[1] Plant research also contributes to meeting the ambitions set out by the UK Government in its Industrial Strategy, 25 Year Environment Plan and Clean Growth Strategy. Among many initiatives, plant scientists are developing:

- **Crops with improved yield and nutritional content** to help address food shortages and poor diet quality, which is a problem in both low- and high-income countries that can lead to undernutrition as well as obesity, creating a major burden on healthcare systems worldwide.[2]
- **Plants resistant to pests and diseases** to reduce the hunger, economic costs and environmental footprint associated with crop losses, and to reduce reliance on ecologically harmful pesticides.
- **Advanced crops for bioenergy, bioremediation, bio-based products and novel high value products**, tackling fossil fuel dependence, climate change, land degradation, health challenges, and plastic and other forms of pollution, with renewable, plant-derived alternatives.
- **More environmentally sustainable and resilient agriculture** with new plant varieties and practices that use water and other input resources more efficiently; reduce greenhouse gas emissions and harm to biodiversity, soils and waterways; and generate more consistent yields in varying climatic conditions.

As a fundamental area of the biosciences, plant research has led to an understanding of mechanisms profoundly important for all of biology and medicine. These range from revealing the genetic mechanisms of inheritance to demonstrating the importance of epigenetic controls of gene expression.

In addition to the amenity and ecosystem value provided by plants, the sector makes a sizable economic contribution. As one example, the food supply chain contributed £113bn or 6.4% of gross value added to the UK economy in 2016, and much of this, whether through crops or livestock, is underpinned by plant science.[3] UK production of wheat, our biggest crop, was worth almost £2bn in 2017, and fruit production was worth £765m.[4]

Opportunities for plant science

Advances in science and technology have created unparalleled opportunities for progress in the coming decades, through approaches such as genome sequencing and editing, computational genomics, metabolomics, speed breeding and the modernisation of agronomic practices using robotics and precision agriculture. For example, sequencing the genomes of greater numbers of individual plants and plant species, coupled with improved understanding about how genes and environmental factors interact to influence plants and their chemistry, will enable predictive approaches to enhance both breeding and the discovery of novel bioactive molecules.[5] Particularly promising opportunities for innovation exist where plant science meets other disciplines, such as engineering and robotics, data analytics and computing, soil and fungal science, and imaging technology. The UK is well placed to take advantage of these opportunities. Its vibrant landscape of universities, research institutes and companies are the sites of world-leading research, development and innovation in plant science.[6]

“Enhanced support for UK excellence in plant science will improve the entire life sciences sector and support economic growth”

The full potential of plant science to improve crop productivity, land management, environmental sustainability and quality of life cannot be delivered by plant scientists alone. Many challenges facing society involve complex, interacting issues that require multidisciplinary approaches. For instance, the problems of food and nutritional insecurity in many parts of the world are unlikely to be solved by increases in food production alone; biofortification and reducing post-harvest losses are beneficial, but broader issues must also be addressed, including economic disadvantage, and deficits in governance and infrastructure. Likewise, stewardship of the environment requires broad-based approaches that balance production technologies relevant to local soils, agriculture, ecosystems, climates and economies with new technologies, and take socio-political and cultural drivers into consideration. Entrepreneurs and innovators are needed to translate plant science ideas and transform discoveries into products or services that are effective and attractive to investors, users and consumers. To achieve this, good communication between research sectors and their stakeholder communities is crucial.

As this report aims to show, plant science has much to contribute to these essential endeavours. The Government’s commitment to achieve a total spend on research and development of 2.4% of GDP by 2027 is very welcome. Enhanced support for UK excellence in plant science will improve the entire life sciences sector and support economic growth. Encouragement for plant science is also needed in many forms, from education to the marketplace.

What plant science can deliver:

Improving crops and agricultural systems

Food is essential for everyone. The global human population is predicted to reach 9.7 billion by the year 2050,[7] placing many more people in danger from hunger and malnutrition. Preventing this outcome, by meeting projected global need, will require significant changes to food production systems and the development of effective and equitable distribution systems. These challenges are global, but have real impact on UK food security, due, for example, to unavailability or failure of crop protection chemistry; to reliance on food imports from regions vulnerable to climate change; or to uncertainties surrounding agricultural subsidy and trade post-Brexit, given that almost 60% of our imported food comes from the EU.[8] Technological innovations in plant sciences play essential roles in adapting both intensive and small-holder agricultural production. This will include developing crops with improved productivity and nutritional quality, resistance to existing and emerging pests and diseases, and resilience to extremes of weather, transport and storage. Underlying these factors is the imperative to drive down the significant environmental footprint of agriculture, which will otherwise exacerbate the climatic constraints on future production. UK plant scientists are already at the forefront of these endeavours, and with continued support they can generate the transformative plant-based technologies that can revolutionise agricultural systems at home and abroad, to support people and the planet.

Opportunities

UK scientists are world leaders in both discovery-led and applied plant science, leading global efforts that use multiple technologies to unlock the diversity across global crop populations and beyond.[9]

Strategies include:

- Harnessing the power of marker-assisted and speed breeding, together with advances in gene editing and genome sequencing, to produce resilient, resource use-efficient crops that deliver reliable yields and improved nutritional content year-on-year, with reduced use of agrochemicals and other inputs.[10] The genetic components that enable crop varieties to increase their yield, even under challenging environmental conditions, are already being identified and introduced to major food crops, for instance to produce drought-tolerant maize. Similar work is ongoing in 'orphan' crops (those that have received less attention from researchers, yet are critical in developing countries). Work to characterise and understand these genetic components is at an early stage; this approach has huge potential for crop improvement, and support for basic research is critical to provide further genetic targets.
- Informing the potential development of new farming systems and new crop varieties that reduce yield gaps across agriculture, horticulture and forestry.
- Developing multidisciplinary approaches that bring together advances in genetic technologies, analysis and insight from big data, and decision-support tools, robotics or digitally-connected farm machinery. This can enhance practical farm experiments and farmer engagement. Further, these approaches can address the challenge of sustainable crop productivity with strategies that maximise use of arable land while minimising environmental impact, such as intercropping, minimum tillage and other techniques based on agroecological principles.
- Combining advances in fundamental plant physiology with the engineering of closed-loop production systems, allowing the transition of agriculture and horticulture into new environments, such as urban areas in solar-powered greenhouses or LED-illuminated vertical farms. Such innovations bring food closer to populations centres, reducing reliance on imports and costs of transport and storage, and aiding urban regeneration and community engagement.

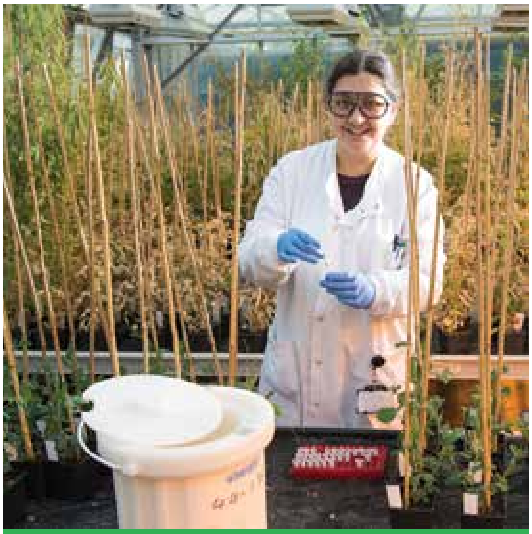
Priorities

Key actions needed for the realisation of these opportunities are:

- Provision of support to enable discoveries in fundamental plant science research that can help identify opportunities for crop improvement and improve basic knowledge of how plants work. To ensure that fundamental insights can inform future crop improvement, a long-term strategic vision and support are needed that will not be prey to short-term policy shifts. Examples from the UK of recent advances in fundamental plant science that have significant potential applications include: novel targets for increased crop yield and pathogen resistance;[11,12] the importance of epigenetic regulation in the control of plant phenotypes;[13,14] and the role of small RNAs in regulating gene expression.[15]

- Promotion of public-private partnerships and collaborations with consistent, long-term R&D policies, and support to bridge the gap between discovery science and commercial application. Interactions with experts in, for example, LED technology, UV penetrant materials for protected cropping, or renewable energy, will support innovative strategies to develop non-traditional agricultural and horticultural systems. These can provide the UK with new sources of productivity to buffer environmental and societal changes.
- Encouragement of promising forms of agri-tech innovation, including in areas such as precision agriculture and vertical farming, through investment and appropriate regulation. Impactful agricultural improvements can occur through the work of global consortia. UK plant science must collaborate internationally to lead and keep pace with other world centres of expertise, and to drive and absorb agricultural innovation to benefit society and the economy. The Global Challenges Research Fund (GCRF), which forms part of the UK's Official Development Assistance (ODA) commitment, is providing an increasing range of opportunities for plant research to benefit the least developed countries. Innovate UK and the Industrial Strategy Challenge Fund support the uptake of novel plant and crop science by industry to help bring innovations to market and deliver benefits.

"UK plant science must collaborate internationally to lead and keep pace with other world centres of expertise"



Case study: **Engineering Novel Crops**

UK scientists are leading members of three ambitious international collaborations across 35 institutions funded by the Bill and Melinda Gates Foundation, including the John Innes Centre, the University of Cambridge, the University of Oxford, the University of Essex and Lancaster University in the UK. These collaborative projects use engineering principles alongside genetic and genomic tools with the aim of re-imagining the possibilities of crops to meet critical goals for global agriculture.

Can rice be redesigned to grow in hotter climates?[16]

How can photosynthesis be made more efficient?[17]

Can cereals be engineered to take nitrogen out of the atmosphere, reducing fertiliser requirements?[18]

These challenges will be answered over decades and represent the type of ambitious, visionary scientific planning required to feed increasing global populations.

The solutions, if appropriately harnessed, will have a major impact on security and sustainability in food production.

What plant science can deliver:
Plant health and biosecurity

Pests, pathogens and weeds have a massive impact on food security; they reduce global crop yields by an estimated 25-40%,[19] and are especially devastating in low- and middle-income countries. To take just one example, Asian soybean rust, which emerged in South America in 2001, causes losses of up to 80% in soy crops, with control costing around $2bn per year in Brazil alone.[20] Through globalisation and climate change, pests and pathogens can spread quickly to new regions of the world, affecting not only agriculture and horticulture, but also our natural ecosystems and forests. In Great Britain, 14 new pests and diseases have become established on trees since the 1990s.[21] New threats on our doorstep include *Xylella fastidiosa*, a potential pathogen of over 150 different plant species.[22] Our ability to control these threats is being reduced through the loss of effective chemical actives and increasing resistance to pesticides. For example, up to 80% of UK black-grass populations are now highly resistant to selective herbicides, significantly impacting production of the UK's most economically important crop, wheat.[23]

Opportunities

Despite these challenges, UK plant scientists have huge opportunities to reduce the negative impacts of plant pests and diseases, benefitting human health through enhanced food security and nutrition, and reducing costs for farmers. Even relatively small reductions in overall disease losses for some crops could improve the lives of millions, increasing yields and reducing waste, as well as creating economic returns.

- A paradigm shift is needed to change crop protection systems currently dominated by synthetic chemicals to a co-ordinated system that integrates chemical and biological controls with plant resistance – an area in which UK plant scientists have great expertise. Soil health can be improved by manipulating the microbiome, and plant health and productivity can be enhanced by utilising beneficial microbes and deploying biopesticides.

> **"Up to 80% of UK black-grass populations are now highly resistant to selective herbicides, significantly impacting production of wheat"**

- Plant natural products represent a tremendous untapped source of new bioactive molecules to identify and exploit – particularly molecules that are difficult to synthesise conventionally, using synthetic biology approaches available to improve scale, performance and reliability (see the following section on Plant Biotechnology for examples).
- Plant breeding and the development of varieties with improved and robust resistance, for instance through *R* gene stacking, will continue to underpin crop health systems (see case study: *Late blight resistance in potatoes*). Innovative genetic solutions and novel breeding methods such as gene editing also provide opportunities to enhance resistance to pests and diseases (see case study: *Tomelo*).
- Ensuring UK biosecurity requires the development of sensitive surveillance and monitoring systems integrated with remote sensing and citizen science. These need to provide early detection of new and emerging threats, such as newly introduced pests or resistance-breaking pathogens.

Priorities

We should build on the wealth of outstanding UK discoveries revealing how plants interact with pests, pathogens, their wider microbiome, and the environment. Developing smart, disease resistant crops, understanding and implementing biological crop protection and enhancement agents, and improved surveillance and disease forecasting are key to achieving the improved plant health and biosecurity the UK needs. Integrated 'omic' discovery platforms and continued plant breeding developments will be important in achieving this. Practical engagement with the end-users of research, for instance with farmers, will also be needed.

- Improved surveillance networks should be created and supported through investing in new technology, such as genome-based diagnostics,

Case study:
Innovation in plant health

Late blight resistance in potatoes

The UK is a global leader in the study of plant disease and immunity, including research on oomycetes. These fungus-like pathogens include the Irish potato famine agent, *Phytophthora infestans*, which causes annual losses of over £55m per year in the UK alone, and over US$5bn worldwide. A 30 year legacy of basic research has generated a widely recognised body of knowledge that set the stage for several practical applications. For example, researchers at The Sainsbury Laboratory (TSL) observed natural genetic variation for resistance to late blight in wild potato relatives. Genes underpinning resistance were transferred to cultivated potatoes,[27] and were shown to be effective in recent field trials. One resistance gene, *Rpi-vnt1*, has been licensed to US potato company Simplot and is the first cloned disease resistance gene to be deployed commercially, although currently only in the US. In recent BBSRC-funded collaborative research with Simplot and UK start-up Biopotatoes, the TSL team has developed Maris Piper lines that combine a stack of three late blight resistance genes with genes for improved tuber quality.

Tomelo

Another team at TSL recently demonstrated the power of new genome editing approaches for disease control. Using CRISPR/Cas9 genome editing, the researchers deleted 48 nucleotides from *MILDEW RESISTANT LOCUS O*, a 'susceptibility' gene. The edited tomato, named Tomelo, carried no foreign DNA, yet proved resistant to the powdery mildew fungal pathogen *Oidium neolycopersici*. It took less than 10 months to generate this resistant line,[28] although further development to bring a crop to market would take years. Images show infected wild-type plants (top row) and resistant Tomelo (bottom row).

remote sensing, bio-sensors and electronic noses, alongside data analytics/informatics and risk-based modelling.

- Mechanisms are needed to facilitate the rapid mobilisation of plant science expertise to effect coordination of research and response efforts to major disease outbreaks. For example, the Scottish Plant Health Centre is a virtual centre of expertise for Scotland that brings together interdisciplinary experts from across research organisations.[24] As a further example, CONNECTED is a network of international scientists and researchers addressing the challenges of vector-borne plant viruses in Africa, which is hosted by the University of Bristol.[25]

- UK plant scientists, government institutions, funding bodies, industry, educational and research institutions and other bodies such as learned societies must effectively engage with the public, enabling dialogue on issues such as biosecurity, genetic modification and other crop protection technologies – both existing (e.g. pesticides) and new (e.g. plant breeding innovation and biocontrol) – so that people can benefit from innovations.

- To enhance our national plant health and biosecurity capabilities, the UK must invest in its science and research capabilities across all plant health disciplines, including rebuilding neglected areas such as nematology, weed science, entomology, plant physiology and applied plant pathology. Specialist taught MSc courses are needed to restore the pool of well-trained professionals, alongside upskilling of plant health professionals across all sectors through bespoke continuing professional development (CPD) training. The Royal Society of Biology is supporting skill development and recognition through its Plant Health Professional Register.[26]

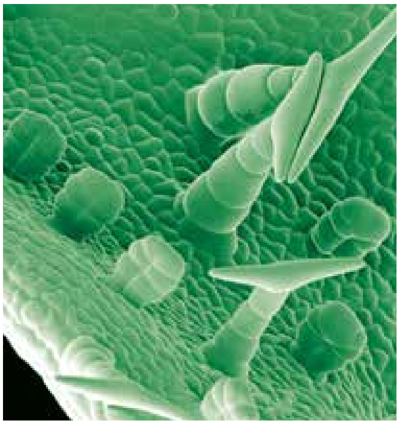
What plant science can deliver: Plant biotechnology

Biotechnology is the use of biological resources to make or modify products or processes for specific use. It is involved in the production of food, transport fuels, medicines, plastics and enzymes that enable more energy efficient manufacturing processes. Plants produce a vast array of secondary metabolites that give us a range of high value products including medicines, nutraceuticals, flavours and fragrances, and the potential for many more. Biotechnology can be used to realise this potential either by improving plant-based production platforms or by lifting the production pathways out of plants and putting them into new host platforms such as yeast or bacteria.

Opportunities

The UK has a real opportunity to implement plant biotechnology in mainstream manufacturing and production, increasing efficiency and helping to meet the objectives of the Industrial Strategy, Clean Growth Strategy and 25 Year Environment Plan.

- Through breeding and synthetic biology, plants can be tailored to particular uses, for example: delivering consumer products, medicines, greener energy production and novel products to meet the nutritional, health and other needs of an aging population.[29,30] Tailoring Plant Metabolism at Rothamsted Research,[31] and Molecules from Nature at the John Innes Centre,[32] are major BBSRC-funded programmes underway to deliver this.
- Agricultural by-products are potential feedstocks for producing a huge range of bio-renewable products. For example, plant biotechnology offers a means to address the accumulation of plastics in the global environment, through the energy efficient conversion of biomass into biodegradable materials with many of the positive properties of plastics but without the longevity and post-use disposal issues.



- Combining plant and microbial biotechnology can further add to the diversity of products, with plants providing unique building blocks that can be further refined through fermentation.
- Bioenergy with carbon capture and storage (BECCS) combines large-scale biomass energy applications, including electricity generation, with the capture and storage of CO_2.[33] BECCS provides the opportunity to remove CO_2 from the atmosphere, which is increasingly required alongside the urgent need to reduce emissions and meet the Paris Agreement commitments to keep global warming ‘well below’ 2˚C.[34] This approach is especially attractive where biomass derives from waste products or from marginal land where its production does not conflict with food crop production, but enhances biodiversity.
- Around 30,000 plant species produce compounds that are currently used medicinally,[35] but the majority are as yet untested. Genomics could facilitate the search for molecules valuable in health or industrial biotechnology. Plants can be engineered to produce treatments for globally important diseases. Monoclonal antibodies to prevent transmission of HIV, produced in tobacco plants, recently received regulatory approval and underwent the first clinical trials in humans.[36] The plant-based Hypertrans expression system enables rapid, large scale and cheap production in plants of diagnostics and vaccines to combat a range of animal and human diseases including blue tongue, zika and polio.[37] Hypertrans technology also provides a cheap alternative to fermentation systems for production of high value molecules.

Priorities

- The industry’s ‘National Industrial Biotechnology Strategy to 2030’[38] and the Government Strategy ‘Growing the Bioeconomy’,[39] both launched in 2018, should position the UK as a truly global player and ‘open for business’ for biotech research and innovation, delivering well-rewarded, high-skilled UK jobs in the biotechnology sector. There remain challenges to optimise new production systems and to communicate the opportunities achievable from clean, safe biotechnologies and their application.
- Those working in this area need to develop ways to engage with the public to champion the benefits that are available through plant biotechnology, such as in the PharmaFactory project[40] or as successfully implemented by the synthetic biology sector.[41]
- Funding and networking opportunities are needed that encourage academic and industrial innovators to take their technologies into the marketplace. For example, the BiopilotsUK alliance[42] has emerged in the industrial biotechnology sector to

help signpost where pilot scale-up and associated facilities and expertise are available. Innovate UK funding provides support, and the academic-facing BBSRC Networks for Industrial Biotechnology and Bioenergy are providing proof of concept funding to encourage interactions between universities and industrial partners.[43]

- Innovations bring together highly distributed technologies and specialisms such as data science, robotics, remote surveillance, plant breeding and genomics, as well as social science, and translation and production contributions. Innovation Voucher schemes, funded under EU Regional Development Funding schemes, and low-cost access to research and expertise, funded under EU Programmes (e.g. Interreg (Biobase4SME[44]) and H2020 (Superbio[45])), have been important mechanisms for supporting early engagement with spin-out and early stage plant biotechnology innovators. A potentially very different environment post-Brexit could have significant implications for access to EU-funded schemes, thereby impacting the UK's development of novel, high value bioproducts, unless the funding gap is redressed.

Case study: Artemisinin production from plants

Artemisinin is the active ingredient in the most effective treatment for malaria currently available – artemisinin-combination therapies (ACT). According to the World Health Organisation, there were 216 million cases of malaria worldwide in 2016, with an estimated 445,000 deaths.[46] Artemisinin is produced by the sweet wormwood plant, *Artemisia annua*. The drug has saved millions of lives. However, poor *Artemisia annua* seed supply and low yielding varieties have meant artemisinin price and availability have fluctuated. Scientists at the Centre for Novel Agricultural Products (CNAP), a research centre based at the University of York, created a hybrid variety that combined high concentrations of artemisinin with robust growth. The variety has undergone extensive field trials in Africa and Asia, and has been registered as a variety in China. Hybrid seed uptake by commercial producers has led to a projected production of over 200 million treatments for malaria sufferers. Further work on the plant has identified that its trichomes – small hairs from which artemisinin is obtained – could be used as factories for production of new compounds with potential applications in medicine and industry.[47]

"The UK has a real opportunity to implement plant biotechnology in mainstream manufacturing and production, increasing efficiency and helping to meet Government objectives"

What plant science can deliver:

Biodiversity and ecosystems

Biodiversity is the diversity of all living things. Plant biodiversity underpins all terrestrial life, yet one in five plant species globally is threatened with extinction.[48] Threats to biodiversity include climate change, invasive non-native species and land-use change and intensification, particularly the intensive management of agricultural land. The UK is among the most nature-depleted countries in the world.[49] Land-use driven reductions in plant biodiversity are a likely cause of the global decline in pollinating insects, which further negatively impacts terrestrial plant biodiversity and food production.[50,51]

Ecosystems can be viewed from the perspective of the benefits they provide to people, such as food, air filtration and climate regulation. Ecosystems also provide positive effects on mental and physical health. These benefits are termed ecosystem services. Ecosystem services are often unrecognised in decision-making. One approach to illustrating their importance is through economic valuation of the benefits of ecosystem services, although not all values can be expressed in financial terms. For instance, the UK natural capital accounts[52] show that in 2015:

- carbon sequestered was worth over £1.5bn
- vegetation removing pollution was worth over £1bn
- timber production was worth £227m

Opportunities

Concerted action is urgently needed to halt the net degradation of natural capital and linked declines in biodiversity.

- Plant scientists can contribute to developing more sustainable agriculture and food production systems. Improving agricultural systems that produce more from a given area can avoid land being brought into production, thereby contributing to biodiversity protection. Studies on the effectiveness of intercropping, agroforestry, improved crop rotations and integrated pest and weed management are needed to improve agricultural sustainability without compromising productivity.[53] The emissions and biodiversity impacts of livestock farming could be ameliorated by better grassland management, deploying forage varieties and mixtures that require less fertiliser, and land management that supports insect pollinators and other wildlife.
- In urban areas, green roof developments, pollinator-friendly urban planting, wildlife corridors, bioremediation of contaminated land, flood alleviation planting and street planting can be used to improve air quality, well-being and urban resilience. Road verges, railway lines and other assets could be managed to enhance biodiversity and dispersal of plants and animals, allowing species to move in response to climate change.[54]
- Emerging tools and technologies for data collection provide opportunities to catalogue and understand the UK's natural assets, changes in condition, resilience, and to assess management interventions. Open-source, standardised methodologies allow plant scientists to collaborate and measure the effects of interventions at landscape scales, providing support for decision making to help policymakers and the public. Many local natural history societies have knowledgeable botany groups including county plant recorders, and, along with the Biological Records Centre,[55] offer valuable resources for assessing biodiversity.
- Genetic studies of threatened plant species can guide practical conservation efforts and reveal minimum population sizes to reduce the risks of local extinctions and guide ecosystem management.

Priorities

- Maintain and develop ecological monitoring programmes, such as the UK Environmental Change Network[56] and the Countryside Survey,[57] to collect data on biodiversity, natural capital assets and the delivery of ecosystem services that can help direct and support good use of plant science for beneficial management. Engaging citizen scientists enables biodiversity monitoring while utilising and enhancing public enthusiasm for conservation.[58]
- Incorporate evidence into decision and policymaking to empower and support long-term, sustainable management of natural capital.[59] This will require communication across sectors and borders.
- Embed systems thinking and the appreciation of biodiversity into education to ensure future professionals in all sectors understand the importance of ecosystem management.
- Implement and refine biodiversity and natural capital assessment methods to address the challenges described in this report, including the development of more sustainable agricultural practices and the control of exotic species and diseases through integrated pest management.

"The UK is among the most nature-depleted countries in the world"

Case study:
Conservation of crop wild relatives

Many crops have undergone centuries of repeated selection for desirable traits by farmers. More recently, scientific selection by plant breeders has significantly improved yield, but reduced the genetic diversity within modern crops, leaving little scope to adapt to climate change or to new pests and pathogens. Crop wild relatives are the ancestors and close relatives of our modern crops. They are genetically adapted to grow in a broad range of environmental conditions and therefore provide a large pool of variation that can enhance crops with new, useful traits.[60, 61]

Research led by the University of Birmingham has identified a global set of 1,392 priority crop wild relatives for 193 global crops,[62] and determined the off-site conservation action to ensure long-term genetic diversity genebank availability of these species.[63] Kew's Millennium Seed Bank Partnership is working on a 10 year programme with the Crop Trust to collect and conserve seed from the wild relatives of 26 priority crop plants in seedbanks.[64] Recently the University of Birmingham and its partners have identified a global set of 150 conservation sites where priority crop wild relative species can be conserved in nature. The aim is for these to form part of a global network of protected areas that underpin food security for the future.[65]

Nurturing UK plant sciences

To meet the opportunities and respond to the challenges outlined for UK plant science, a skilled and coordinated workforce, motivated students and engaged citizens will need to consider how plants and plant sciences impact society and individual lives. As such, we welcome the assertion in the Government's 25 Year Environment Plan that children and young people should be encouraged to engage with nature and give greater consideration to the environment; plants should be central to this.

Formal science, technology, engineering and mathematics (STEM) education in schools and colleges should inspire, with plant science, horticulture and agriculture integral at all levels. It is important that plants are not taught as a niche, avoidable module. Both in general and technical routes, students need a broad and balanced STEM curriculum, which delivers the fundamentals of science and explains the place of plants, agriculture and society within this. The next generation of learners, and indeed their teachers, cannot know all the technologies and skills that they may need in order to excel in the future, and so a concepts-driven curriculum that nurtures independent thought should be encouraged.[66] Engagement with plant scientists is needed to ensure school, college and university courses support the development of the required understanding and competencies. Plant scientists could beneficially engage with those amending curricula, producing the specifications for general and technical qualifications, developing educational resources, and delivering teacher training and continuing professional development.

"Formal STEM education in schools and colleges should inspire, with plant science, horticulture and agriculture integral at all levels"

Industry needs suitably skilled, innovative and inquisitive candidates entering the workplace, while plant scientists at all levels should aim to understand the needs of industry and other stakeholders. Guidance is needed, whether through apprenticeships or at undergraduate level, to raise awareness of the benefits that careers involving plant science can offer to people and the economy. Advice on careers in plant science and agriculture should be delivered within the framework of the UK Government's Careers Strategy,[67] and through schools and colleges statutory guidance on careers.[68] Greater support is required for young people to engage with workplace experiences, employment options and employers.[69] As part of this, a greater number and wider range of opportunities for industrial and employer-based placements are needed. Summer placement schemes, such as the Royal Society of Biology's Plant Health Undergraduate Studentships programme,[70] are effective in providing undergraduates with academic or industrial research experience and awareness of career opportunities, but places are limited. Beyond formal school education, support is needed for lifelong learning, CPD opportunities, and postgraduate level skill development, to meet the skills demands on the future workforce.

Together, these steps will help to ensure that the Government's ambitions for the Industrial Strategy, and future health and prosperity of the UK, are reflected in education and skills policy.

Case study:
The Gatsby Plant Science Education Programme

Supporting plant science education in secondary schools and universities,[71] the charitably-funded Gatsby Plant Science Education Programme develops inspirational teaching resources supporting over 6,000 UK teachers and technicians through the Science and Plants for Schools project.[72] The project works with current and trainee science teachers to enthuse the next generation with plant science. For high-achieving undergraduates, the Gatsby Plant Science Summer School is a chance to discover the challenge and opportunities offered by studying plant science. Over 14 years, the annual residential summer school has engaged more than 1,000 students from 28 UK universities, with inspirational speakers introducing active research areas in a relaxed setting that builds students' confidence to plan their own careers.[73] Each year, 70-85% of these undergraduates leave the summer school wanting to study more plant science at university.

In conclusion

Growing the future describes some of the huge potential that plant science offers our society, and considers some of the opportunities and priorities arising within four areas. In preparing this report we identified the following broad considerations that we believe are vital steps to nurture and grow a vibrant and resilient plant science sector in the UK.

Changes to the research funding landscape provide compelling opportunities to strengthen UK plant science, and enhance its contribution to society.

- It is essential that support for fundamental plant science research is maintained, both to help us better understand the world and to provide a constant source of discoveries and innovation. Plants provide model systems in which to study basic biological processes relevant across biology and medical science, for example epigenetics. Applied research is vital to deliver benefits, including improved crops and agricultural systems for a changing world, products and practices to protect plants from threats, biomanufacturing and protecting biodiversity and ecosystems. A funding system that recognises the importance and complementarity of both fundamental and applied research is necessary to achieve these goals.
- Multidisciplinary research can deliver exceptional value; encouragement and support is needed to link science communities and this could be delivered through UK Research and Innovation (UKRI), the Industrial Strategy Challenge Fund, and other mission-led approaches. Facilitating linkages across academic departments and industries could provide an innovation continuum of research through to delivery, leading to significant impact for researchers and end-users.
- Enabling effective engagement between plant scientists and the public is vital to enable understanding and dialogue about the options that plant science can provide to address challenges. Resources that facilitate engagement activities, including via independent specialists, can play an important part in this.
- There are complex demands on UKRI budgets but the plant science dividend, and capacity to address fundamental challenges in health, nutrition, environment and production should not be understated. It is important to stress that decisions made with integrated plant science in mind can provide preventions rather than cures to many threats to food, nutritional and environmental security.

International collaboration is a vital component of UK plant science.

- Plant science is highly international and UK scientists need well-supported opportunities both to collaborate, and to move freely between linked research projects in different nations.
- Continued involvement in multi-country research programmes is vital; they provide mechanisms for collaboration, funding and access to infrastructure that can deliver hugely ambitious plant re-engineering projects that would not be possible without global cooperation.
- Ease of movement for skilled people and trainees is an essential part of ensuring that science in the UK has the right mix of talents at any time, ensuring biosecurity and research continuity.
- The vast majority of calorific intake comes from plant products, so UK expertise in plant science has an important role to play internationally to secure long-term global food security, both directly through addressing relevant Sustainable Development Goals (SDGs), and indirectly through capacity-building projects.

An ongoing, broad and balanced debate is needed on the UK's ambitions for agricultural production, taking into account new technologies, crop varieties and plant protection products, which can then inform decisions about regulation.

- Technologies old and new can be combined to produce new plant varieties for agriculture and for use in biorefineries, relevant to both established markets and development needs. Well-informed public and policymaker views and workable regulatory systems are essential to avoid an innovation gridlock where desirable products are achievable but not realisable, or where research is pursued but not a societal priority.
- Ongoing and open conversation between plant scientists, social scientists and other stakeholders should be encouraged in order to engage with the public in discussions and decisions about innovation, and to interact with practitioners, including farmers, foresters and conservation managers. Recognition and reward for researcher activity beyond the publication of scientific articles is essential to achieve these broader benefits.

Government and governance mechanisms should be appropriately responsive and explicitly address scientific and other robust evidence when communicating decisions.

Engaging, inclusive and accessible plant science content is needed within biology curricula to realise the opportunities plant science offers to society.

- Education on plants, and the species that interact with them, is vital to learning about the life sciences. Good plant science education not only conveys appreciation for these complex organisms and systems, but also their potential to contribute across STEM specialisms.
- Accessible and inclusive representation of plant science careers and skills is needed, together with effective careers guidance for students and educators.

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