UK PLANT SCIENCE RESEARCH STRATEGY

A GREEN ROADMAP FOR THE NEXT TEN YEARS

CONTENTS

FOREWORD

In many ways the idea of a national strategy is counterintuitive – science is global and more than ever we need to be working across national boundaries to solve the enormous environmental and societal challenges that we face. However, to collaborate more effectively in the international arena we first need increased investment and better co-ordination across the UK. In April 2020, following discussions with colleagues, I proposed a community-driven approach to develop a plant science research strategy for the UK. I engaged with no personal or professional agenda, no vested interest and an open mind[1]. Melanie Welham, Executive Chair of the UK Biotechnology and Biological Sciences Research Council (BBSRC), part of UK Research and Innovation (UKRI), was supportive of this endeavour and endorsed the proposal. Given that BBSRC is currently the largest funder of plant science research in the UK, this support and endorsement represented an opportunity for the community's collective experience to inform and help develop future priorities. I am grateful to Melanie and to UKRI for publishing the strategy document. However, this is not a BBSRC or UKRI strategy, it is much broader than that, bringing together all areas where plant science has a current and future role to play. Successful implementation will require co-ordinated engagement across a number of departments in both the UK Government and the devolved administrations, and a sustained long-term programme of investment.

Development of the strategy took place in three phases from April to December 2020, via online platforms and virtual meetings. In the first phase, I had one to one discussions with researchers and stakeholders across the field (>100), and I also held a workshop with twenty independent research fellows. I am extremely grateful to everyone who gave their time and thoughtful input during a very challenging period of national lockdown. The issues we discussed revolved around what plant science research can and should contribute to society, and what mechanisms are needed to ensure effective delivery of those contributions. After the consultation, I distilled many pages of informal notes into a two page summary of the core messages that would underpin the strategy. In the second phase, this summary was circulated to all consultees, with a request to consult more widely within their local constituency and to feedback any further comments. I then translated the overall direction of travel into a narrative. In the third phase, the strategy document was sent out for further consultation and feedback. At this point it was seen by a number of institutional committees, including BBSRC Council, by all of the original consultees and by additional interested parties who received it either directly from me or via other members of the community. I then incorporated comments from the third round of consultation into this final version. Appendix 1 lists everyone who agreed to be named as a contributor to the consultation. Not surprisingly there are different viewpoints around the relative importance of individual components of the strategy, but the strategy as a whole is enthusiastically supported by the overwhelming majority of the community.

I am indebted to the Policy Strategy and Evidence team at BBSRC, particularly Beverley Thomas and Joanna Jacklin for providing me with comprehensive data at short notice, and similarly to Gary Wilson at the Gatsby Charitable

[1] I currently receive research funding from the Bill & Melinda Gates Foundation and BBSRC; I am a paid advisor for the Gatsby Charitable Foundation's Plant Science Programme, a member of the John Innes Centre's Science and Impact Advisory Board and a core member of BBSRC's Committee B.

Foundation. Funding information for other organisations was gratefully received from Simon Kerley and Gladys Hodges (NERC), Andrew Millar (Scottish Government), Chris Quine (Forest Research), Nicola Spence (Defra Plant Health), Lisa Black (DAERA/AFBI), Clive Hayter (Kew) and Ken Norris (Natural History Museum). Cathie Martin, Ian Graham, Leon Terry, Iain Donnison, Johnathan Napier and Jan Chojecki/Dale Sanders/Simon Saxby kindly provided data in Boxes 1.1, 3.1, 3.2, 3.3, 3.5 and 3.6, respectively. I extracted ERC and Leverhulme funding data from their respective websites. Where relevant, I obtained permission to use data on protected characteristics that could be tracked back to individuals. I am grateful to Jonathan Jones, Celia Knight, Gail Preston and Alan Tollervey for comments on specific sections and to Tina Barsby, Ian Boyd, Belinda Clarke, Claire Craig, Dick Flavell, Ian Graham, Sue Hartley, Nick Talbot and Gary Wilson for critical input on the full draft. Any errors are mine.

A note on terminology. Although some would have preferred to see a reference to crops in the headline, I have used the inclusive term ‘plants’ to represent model organisms, green algae, seaweeds, crops and trees, because distinguishing between the groups did not help to convey the core messages. Most of the challenges ahead cross traditional boundaries and require a fresh outlook – a model plant, algal or tree species of today could be a crop of the future, and a new pest or pathogen could obliterate all. Whereas that decision was straightforward, deciding which terms to use to refer to the type of science that is carried out was more difficult. Basic and applied are still commonly used but the terms are not reflective of what we do and hinder progressive programmes. Basic science is far from basic with respect to the creativity required, and terms such as blue-skies, fundamental and discovery research seem more appropriate. Applied also fails to capture the complexity of some of the research it is associated with and the consequential need for innovation. Throughout this document I have therefore used the term fundamental to represent basic/blue skies/discovery research (technology readiness levels 1 & 2), and the term translational to represent any research with a long- or short-term goal to develop a new product or process (technology readiness level 3 onwards). Central to my thinking on this is that much of the research that will be carried out over the next decade will be focussed on long-term challenges that will require a mix of fundamental and translational research, balanced in different ratios as the project progresses, and depending on the nature of the challenge. Applied does not seem appropriate in this context and therefore I have used the term strategic.

Whether fundamental or translational, or both combined in a strategic programme, plant science research has a crucial role to play in safeguarding the future of our planet. To meet the expectations of both society and government, investment in the implementation of this strategy is essential and urgent.

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INTRODUCTION

Using energy harnessed from the sun, plants convert carbon dioxide in the atmosphere into the sugars and oxygen that sustain all life on earth. Trees in woodlands and forests, crops across agricultural landscapes, and microscopic green algae in garden ponds all contribute to the world's biggest manufacturing process. The silent machinery of photosynthesis produces food, fibre and fuel, and as part of the carbon cycle influences global weather patterns. In this way, plants underpin agricultural, ecological and climate systems. In order to live sustainably and protect our planet for future generations, we need to understand how plants function in the planet's wide range of environments.

It is perhaps the silence of plants and their lack of motility that leads most people to overlook both their importance and the need to understand how they work: the school curriculum allows qualifications in biology to be gained without a meaningful understanding of plant function; in 2018/19 less than 3% of UK Research and Innovation (UKRI) spend was on plant science research and development (R&D); and in 2017 the Life Sciences Industrial Strategy[2] report to government did not include any role for the plant science sector. It has taken a human health crisis to start turning the tide. The current COVID 19 pandemic has increased everyone's appreciation of the importance of a robust food supply chain, and of access to green spaces for human health and well-being. This increased societal awareness now needs to be harnessed to ensure that current and future generations understand, value and support a strategy that firmly embeds plant science R&D into the broader UK science and innovation landscape.

[2] www.gov.uk/government/publications/life-sciences-industrial-strategy

CONTEXT

The UK Government's Industrial Strategy (2017)[3] and 25 year Environment Plan (2018)[4], the Scottish Government's Climate Change Plan (2018)[5] and the Welsh Government's Climate Change Adaptation Plan (2019)[6] all pledge to introduce policies to incentivise the reduction of carbon emissions at individual, corporate and national levels. The target of achieving a net zero carbon economy has been set for 2050 in England and 2045 in Scotland. The ongoing Royal Society policy programmes on Living Landscapes[7] and Low Carbon Energy[8], and the Society's Greenhouse Gas Removal Report (2018)[9], emphasize the role that science must play in this endeavour. Critical for the delivery of 'Net Zero' is the implementation of the Clean Growth Strategy (2017)[10], Environmental Land Management Policy (2020)[11], Land Use Policies for Net Zero (2020)[12] and Farming for the Future Policy (2020)[13]. Without exception these programmes aim to reduce carbon emissions in agriculture and increase carbon sequestration in both cultivated and natural ecosystems, particularly forests and peatlands, and to increase the use of plants for bioenergy. These aims will only be achieved if strategic decisions are based on a mechanistic understanding of how plants grow, adapt and respond in different environments, and if that understanding is translated into commercial uses.

Discovering how genetic variation impacts on molecular, cellular and organismal processes, and how those processes are in turn modified by the environment, will allow predictions to be made about how plants are likely to respond to changing environments.

Recent technological advances in genome editing, advanced imaging, synthetic and structural biology, remote sensing, artificial intelligence and machine learning, provide an unprecedented opportunity to apply a systems approach to understand how plants function and interact with other organisms. The UK has a strong track record of world-leading plant science research delivered from a diverse high quality research base across public and private institutions. To ensure that knowledge gained is translated into public benefit, and to enable the transition to predictive plant biology, co-ordinated change is needed. This document outlines what change can deliver and suggests how it can be implemented. It considers fundamental (section 1) and strategic (section 2) research, innovation (section 3), people (section 4), infrastructure (section 5), and the UK's international role (section 6). Not surprisingly, many of the issues discussed converge with those highlighted in the 'Decadal Vision for Plant Science' that was recently published by the American Society of Plant Biologists following community consultation[14]. The recommendations presented here provide a strategic framework through which the UK research base can better support national and international endeavours to create more sustainable solutions for food production, land management and climate change mitigation, and to employ plants and plant products in biological, geochemical and physical engineering contexts.

[3] www.gov.uk/government/topical-events/the-uks-industrial-strategy
[4] www.gov.uk/government/publications/25-year-environment-plan
[5] www.gov.scot/policies/climate-change/
[6] www.gov.wales/prosperity-all-climate-conscious-wales
[7] https://royalsociety.org/topics-policy/projects/living-landscapes/
[8] https://royalsociety.org/topics-policy/projects/low-carbon-energy-programme/
[9] https://royalsociety.org/topics-policy/projects/greenhouse-gas-removal/
[10] www.gov.uk/government/publications/clean-growth-strategy
[11] www.gov.uk/government/consultations/environmental-land-management-policy-discussion-document
[12] www.theccc.org.uk/publication/land-use-policies-for-a-net-zero-uk/
[13] www.gov.uk/government/publications/the-future-for-food-farming-and-the-environment-policy-statement-2020
[14] https://plantae.org/wp-content/uploads/2020/11/DECADAL-VISION-2020-FINAL-sm.pdf

DELIVERABLES

Long-term investment in this strategic framework will deliver:

- **Landscapes that promote human health and well-being by sustainably balancing demands for agriculture, biodiversity, carbon sequestration, energy production and flood management. Achieved using predictive biology and digital twinning to inform and future-proof land use strategies, in combination with vigorous translational policies.**

- **Resilient agricultural systems to sustainably produce safe and nutritious food, accomplished by deployment of advanced plant breeding and crop management strategies**.

- **Significant reductions in carbon emissions from the UK agricultural sector, contributing to the UK 2050 net zero goal, realized through biological replacements for chemical inputs, better management of plant-soil interactions, the use of perennial bioenergy crops and deployment of alternative farming systems.**

- **Proactive mechanisms to monitor, contain and deter plant disease, accomplished with remote sensing, biological interventions and engineered durable plant immunity.**

- **Completely new plant-based production systems for food and for the manufacture of novel products including vaccines, protein feedstocks and high value chemicals. Achieved through biological engineering and the development of innovative culturing technologies.**

1. SECURING A PIPELINE OF TRANSFORMATIVE DISCOVERIES

Curiosity driven fundamental research is essential both to understand the world we live in, and to sustain application and innovation pipelines. Unanticipated discoveries that emerge when hypotheses are tested with no presumed outcome can transform a research field and also underpin the development of disruptive technologies. However, the time between scientific breakthrough and invention can be decades, and applications can arise in unexpected contexts [Box 1.1]. **Sustained commitment to investigator-led fundamental research across the range of the discipline is therefore critical for the future viability of any research field, and for prospective innovation.**

Fundamental research in thale cress (Arabidopsis) and other model plant species has yielded step changes in our mechanistic understanding of plant biology. Long-term investment has produced a world-leading research community that is distributed across a diverse range of institutions, and many discoveries that were made in the UK are now textbook material. As these presumed canonical mechanisms start to be investigated in more diverse plant species, however, significant variation is being revealed. This genetic variation can be sufficient to explain differences in form and function but further complexity is often revealed when plants are grown in different biotic and abiotic environments. **Discovering the functional characteristics of genotype (G) by environment (E) interactions is the next frontier for fundamental plant biology [Box 1.2].** Understanding G x E requires a move towards more field-based experimentation, better utilization of natural genetic variation, and more effective collaboration with engineers and computational biologists to develop innovative robotic and machine learning technologies for phenotyping. **Provision of facilities to enable a shift in experimental approach will accelerate the transition from functional to predictive plant biology.**

Box 1.1: From mobile genetic elements in snapdragons to healthy fruit juice[15].

Time	1983	1985-2006	2003-2015	2014	2007-	2020 - 2021
Research Activity	Fundamental research on transposable elements in Antirrhinum majus	Fundamental research on genes regulating anthocyanin biosynthesis	Metabolic engineering of tomato for nutritional improvement	BBSRC most promising innovation of the year	Founding of spin-out Norfolk Plant Sciences; Patenting for Freedom to Operate	Notification of FDA for safety of purple tomatoes; USDA deregulation; commercialization
Financial Support	BBSRC John Innes Centre Core Funding	BBSRC John Innes Centre Core Funding & Plant Molecular Biology2 Initiative	EU – FP4 (ProFood) FP5 (FLORA) FP6 (ATHENA)	BBSRC John Innes Centre Core Funding & Institute Strategic Programme	BBSRC Follow-on Funding; EU (FP7 & H2020); Private investment	Private investment
Output						

Box 1.2: Examples of questions that could be answered with a better understanding of GxE.

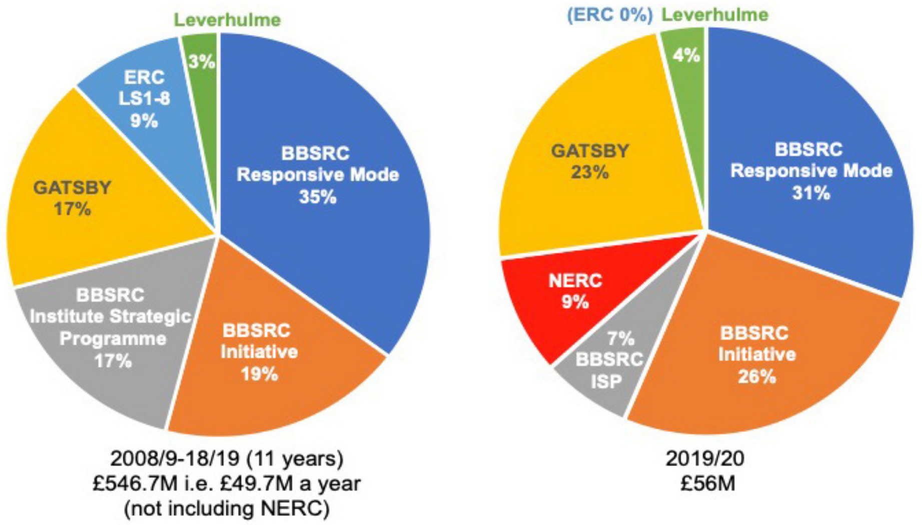
- How do genomes build phenotypes and how do phenotypes in particular environmental contexts influence genome evolution and adaptation?
- How do interactions between different plants, fungi and microbes influence soil composition?
- How does the plant immune system function?
- How does secondary metabolism generate the chemical diversity found in plant species?
- What mechanistic changes underpin land plant evolution and species diversification?
- How are developmental transitions from flowering to senescence to seed set regulated?
- How do plants utilize and allocate resources, and how does this differ in annuals and perennials?

***Recommendation 1a:** Co-ordinate activities between existing field research sites across the UK, as suggested in the UKRI Infrastructure Roadmap (2019)[16], to establish a National Field Research Platform with standard operating procedures for hypothesis testing experiments (including those around novel germplasm, natural variation, plant/microbe/soil interactions, robotics and machine learning). This will require identification of lead institutions, widespread participation of universities, research institutes and private organizations, and investment in appropriate facilities across field sites, including mobile phenotyping capabilities.*

[15] Research led by Professor Cathie Martin at the John Innes Centre, Norwich.
[16] https://www.ukri.org/wp-content/uploads/2020/10/UKRI-201020-UKinfrastructure-opportunities-to-grow-our-capacity-FINAL.pdf

UK Government support for fundamental plant science research is delivered primarily through ‘responsive mode’ grants awarded by a single BBSRC committee, with more ecological aspects funded by NERC[17] standard grants. Institute Strategic Programmes and Initiatives funded by UKRI also encompass components of fundamental plant science research. In 2008, establishment of the European Research Council (ERC) provided an alternative funding source for the very best high risk/high gain research across the EU, and UK plant scientists secured awards totalling more than €53M[18] over the following decade. Planned association[19] with the Horizon Europe Programme 2021-2027[20] should enable this funding stream to be maintained in the medium term. Funding from Charitable Trusts is primarily through the Gatsby Charitable Foundation’s long-standing investment in two institutes dedicated to fundamental plant science research (TSL and SLCU[21]). Notably, this source of private philanthropy will not be sustained indefinitely. Regular investment in project grants from the Leverhulme Trust adds another dimension to the funding landscape but the field has not benefited from Wellcome Trust investment, support that has been so important for sustaining excellence in UK biomedical sciences. Combined across investment routes, fundamental plant science research in the UK has received support of ~£50M a year over the last decade [Box 1.3]. **To sustain a pipeline of potentially transformative discoveries expected of the very best fundamental research, overall investment must be increased, evaluation criteria must be unequivocal, risk appetite must be high, project timelines must be flexible, and mechanisms must be implemented to avoid stochastic funding outcomes.**

Box 1.3: Funding for fundamental plant science research in the UK since 2008[22].



[17] Natural Environment Research Council.
[18] Number does not include €44.4M awarded by the applied life sciences panel LS9.
[19] https://www.ukri.org/our-work/collaborating-internationally/working-on-eu-funded-projects/
[20] https://ec.europa.eu/info/horizon-europe_en
[21] The Sainsbury Laboratory and Sainsbury Laboratory Cambridge University.
[22] BBSRC investment in fundamental research has been derived (as an estimate) based on its portfolio of plant science research classified as ‘orientated basic’ for other reporting purposes, e.g. to the Office of National Statistics. This portfolio includes research funded through responsive mode, strategic initiatives and institute strategic programmes (ISPs). The NERC figure reflects spend on standard research grants awarded via responsive mode. Research relevant to plant science in the NERC portfolio represents research where aspects of plant science are core activities within broader research programmes on ecosystem function and management. Historical data for NERC have not been retrieved. ERC funding has been classified as supporting fundamental research if grants were awarded by panels LS1-LS8. The lack of ERC funding in 19/20 most likely reflects reduced application rates during a period of uncertainty over post-Brexit arrangements. BBSRC, NERC and Gatsby Charitable Foundation figures are spend during the indicated time period, ERC and Leverhulme figures are awards made in the same timeframe.

***Recommendation 1b:** Evaluate fundamental research programmes on the basis of novel ideas or approaches that could to lead to a step change in the research field and deliver publications that stand the test of time, and on the track record of the investigator (taking into account career stage), to the exclusion of any other criteria. Mitigate against single point of failure for fundamental research funding by diversifying application routes and/or enabling resubmission of the top 10% of unsuccessful applications.*

2. STRATEGIC RESEARCH TO SOLVE GRAND CHALLENGES

Whereas the creativity of individual investigators feeds the fundamental research pipeline, the very best strategic research programmes are delivered by teams of researchers with synergistic skillsets and strong leadership, who combine fundamental and translational approaches in a seamless pipeline. The UK plant science community is currently fragmented both within and between sub-disciplines (model organisms, crops, soils, trees, biodiversity, biotechnology), and due to insufficient resources is often overly competitive and inward facing, leading to a lack of resilience. **Many of the long-term scientific challenges that are faced both nationally and internationally require urgent and sustained input from plant scientists but effective contributions will only be made if there is better co-ordination across the plant science research sector in the UK, if plant science is better integrated into the broader R&D landscape of engineering, computer and social sciences, and if there is a significant increase in investment.**

At least four of UKRI's current strategic priority areas[23] require plant science expertise and financial support from the Strategic Priorities Fund has already been approved for three focussed initiatives that streamline overlapping objectives of different research councils and government departments[24]. Further areas of plant science research that are needed to address existing and future challenges are highlighted in the UK Synthetic Biology Strategic Plan (2016)[25], the farming community's Feeding the Future Reports (2013[26] & 2017[27]), BBSRC's Strategy for Research in Agriculture and Food Security (2017)[28] and the John Innes Centre/ Sainsbury Lab's Healthy Plants, Healthy People, Healthy Planet Strategy (HP^3) (2020)[29]. The second part of the National Food Strategy[30] due to be released in 2021 and the developing England Tree Strategy[31] are likely to identify additional challenges. **From a plant science perspective there are four overarching questions that need to be answered [Box 2.1] to address the various scientific and societal challenges that have been articulated in these and many other documents that have been produced by government, industry, environmental and consumer bodies. To deliver answers to the four questions, multiple approaches need to be adopted, each of which represents a long-term intellectual and technical challenge [Box 2.2].**

Box 2.1: The Four Big Research Questions.

Overarching Question	Scientific/Societal Challenge
What species should be planted where and when, and how should they be managed?	Net Zero; Responsible Land Management; Biodiversity Maintenance; Food Security
How can yield and quality be increased with significantly reduced chemical inputs?	Food Security; Healthy Diet; Net Zero; Bioenergy; Responsible Land Management
How can plant health be sustainably protected?	Biosecurity; Food Security; Biodiversity Maintenance
How can plant products be used to improve human health & environmental resilience?	Healthy Diet; Fighting Disease; Bioenergy; Net Zero; Responsible Land Management

23 Animal and Plant Health, Energy, Global Food Security, and Technology Touching Life.
24 Bacterial Plant Diseases (£17.7M), Landscape Decisions (£10.5M), Transforming the Food System (£47.5M)
25 https://ktn-uk.org/news/a-pre-competitive-vision-for-the-uk-plant-and-crop-sector/
26 www.nfuonline.com/nfu-online/science-and-environment/science/science-team-reports/feeding-the-future-2013/
27 www.nfuonline.com/feeding-the-future-report-reduced-size/
28 https://bbsrc.ukri.org/documents/agriculture-food-security-strategic-framework-pdf/
29 https://www.hp3.org
30 www.nationalfoodstrategy.org/wp-content/uploads/2020/07/NFS-Part-One-SP-CP.pdf;
31 https://consult.defra.gov.uk/forestry/england-tree-strategy/

Box 2.2: What co-ordinated strategic research programmes could deliver and how.

Where and when

- Rational designs of sustainable and resilient cropping systems, woodland/forests and peatlands, by using genomics and computational systems biology to assess how genotype influences phenotypic variation in different environments and to predict how traits will perform in new environments.

- Land use schemes that will promote biodiversity, by using remote sensing and phenotyping technologies at canopy, field and landscape scales to discover how different plants contribute to biodiversity in various natural and managed ecosystems.

- Effective schemes for carbon sequestration, by characterizing soils and spatially modelling above and below ground carbon balance at different sites under alternative crop, microbiome and management scenarios.

More out less in

- Trait selection for high yield on low inputs and/or in disruptive farming systems, by developing modern technologies such as gene editing, speed breeding and genomic selection for translation into a broader range of species including vegetable, bioenergy and orphan crops, trees, algae and seaweeds.

- More resilient crops, by interrogating genotypic and phenotypic diversity in heritage varieties, landraces and crop wild relatives to identify traits such as disease resistance, nitrogen-fixing ability, drought tolerance or perennialism that can be transferred to elite varieties.

- Better soil management practices and/or the design of substrates for urban farming, by developing below-ground imaging and rapid species identification technologies to discover at field scale how interactions between different plants, fungi and microbes impact on soil health.

Plant health

- Non-chemical alternatives for plant protection, by screening libraries of both natural and synthetic biological compounds, including RNAs, for novel modes of action against weeds, pests and pathogens.

- Prompt containment and mitigation of disease outbreaks, by interrogating evolutionary dynamics in the genomes of hosts, pests and pathogens to develop diagnostic tools for the rapid identification of host resistance and the presence of both existing and emerging plant pests and pathogens.

- Durable genetically-encoded disease resistance, by predictively manipulating the plant immune system on the basis of data obtained from the informed deployment of multiple disease resistance genes and a knowledge of pest and pathogen biology.

Plant products

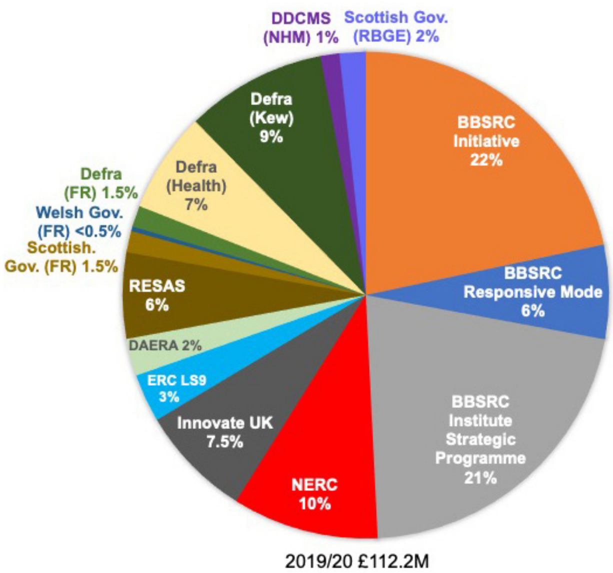
- New antimicrobials, biopesticides and biostimulants for human, animal and plant health applications, by using high-throughput assays to screen national plant collections for novel compounds.

- More rapid and sustainable production of vaccines, therapeutic antibodies, nutrient/protein supplements and animal feedstocks, by developing plant and algal systems as biological factories for production at scale.

- Rational design of sustainable buildings and new transport and energy systems, by using genomics, metabolic modelling and biomechanical assays at cellular and organismal levels to identify the most appropriate plant species to use for renewable energy, construction materials and carbon sequestration.

Publicly funded strategic research that focuses on plant science is currently supported by the aforementioned UKRI Strategic Priorities Fund, BBSRC's Institute Strategic Programmes to the John Innes Centre (JIC), Rothamsted Research (RRes), Earlham Institute (EI) and Institute of Biological, Environmental & Rural Sciences (IBERS); NERC funded programmes at the UK Centre for Ecology & Hydrology (CEH); Defra[32] funding for the Royal Botanic Gardens Kew (Kew) and for plant health research at FERA Science; DDCMS[33] funding for the Natural History Museum (NHM); Scottish Government funding to the Royal Botanic Gardens Edinburgh (RBGE), and through RESAS[34] to the James Hutton Institute (JHI) and Scotland's Rural College (SRUC); and Northern Ireland Executive funding through DAERA[35] to the Agri-Food & Biosciences Institute (AFBI). Forest Research (FR) is supported by separate grants from Defra and the Scottish and Welsh Governments. The involvement of University researchers in any of these institute programmes is limited and generally *ad hoc*, except where there is a joint governance arrangement between an institute and university e.g. IBERS/Aberystwyth, JHI/Dundee. Engagement with industry is also inconsistent, although the not-for-profit organization NIAB plays a significant role at the interface between research, farmers and growers (a role carried out by SRUC in Scotland and AFBI in NI). University contributions to strategic research challenges are primarily supported through BBSRC's Strategic Longer and Larger Awards (sLOLA) programme. **Combined across investment routes, strategic plant science research in the UK received support of over £100M in the last year [Box 2.3].**

Box 2.3: Funding for strategic plant science research in the UK[36].



[32] Department for Environment, Food and Rural Affairs.
[33] Department for Digital, Culture, Media and Sport.
[34] Rural and Environmental Science and Analytical Services Division.
[35] Department of Agriculture, Environment and Rural Affairs.
[36] BBSRC investment in 'strategic research' has been derived (as an estimate) based on its portfolio of plant science research classified as 'strategic and specific applied' for other reporting purposes, e.g. to the Office of National Statistics. This portfolio includes research funded through responsive mode, strategic initiatives and institute strategic programmes. The NERC figure reflects investment in strategic programme grants. Research relevant to plant science in the NERC portfolio represents research where aspects of plant science are core activities within broader research programmes on ecosystem function and management. ERC funding has been classified as supporting strategic research if grants were awarded by the applied life sciences panel LS9. The RESAS (Scottish Government) figure reflects total investment in plant science research, the vast majority of which is strategic or applied. Defra investment has been estimated on the basis of the proportion of annual budgets provided to Kew and to the Chief Plant Health Officer that were spent on plant science research. DDCMS investment has been similarly estimated from the proportion of the budget provided to the Natural History Museum (NHM) that was spent on plant science research. DAERA investment has been estimated on the basis of spend on grassland and plant science research at AFBI. Investment in Forest Research (FR) has similarly been calculated on the basis of the proportion of grants provided by Defra and the Scottish and Welsh Governments that were spent on plant science research. BBSRC, NERC, Innovate UK, Scottish Government (RBGE/RESAS) and Gatsby Charitable Foundation figures are actual spend; Defra, DAERA, FR and DDCMS figures are estimates of spend and ERC figures are awards made.

The move by UKRI to co-ordinate funding from diverse bodies and target strategic priorities is a step towards gaining better coherence, and examples such as BBSRC's Designing Future Wheat Programme[37] and Scotland's Plant Health Centre of Expertise[38] demonstrate how collaboration between organizations speeds up progress, brings together researchers from institutes and universities, and attracts industry engagement. Similar initiatives will presumably emerge as a result of the recent UK Government Science Capability Review (2019)[39] which unequivocally recommended a more co-ordinated and targeted approach to address scientific challenges of common concern across different government departments. The Bill and Melinda Gates Foundation's (BMGF) model of funding ambitious strategic challenges through long-term investment (>10 years) in teams of individuals with the required expertise, and in projects with clear milestones and stage gates could usefully inform future UK processes. The model is currently used by FCDO[40] to fund some of its long term overseas development research in agricultural technology[41]. Two of BMGF's agricultural grand challenge projects that have received FCDO funding over the last ten years are led by UK researchers[42] and a third has UK contributors[43]. **To more effectively address strategic challenges, procedures must be implemented to ensure that funding mechanisms are not constrained by administrative structures, that research teams comprise the most appropriate expertise from across institutions in all four nations, and that teams are well connected internationally.**

> ***Recommendation 2a:*** *Establish a framework to fund long-term strategic research programmes via a UK network of hub and spoke teams that are organized around specific biological or technological challenges [Box 2.2], and that operate in a non-exclusive pre-competitive arena to capture research capability and resources that exist in the private sector. Identify project leaders and key individuals to co-ordinate teams that can provide answers to the four over-arching research questions [Box 2.1] and invest in the infrastructure required at both hubs and spokes to ensure timely delivery.*

> ***Recommendation 2b:*** *Evaluate strategic research programmes on the basis of commitment by leadership to the end goal, team composition reflective of the best expertise from across the UK, balance of fundamental and translational research appropriate for the specific challenge, rationale of IP management strategy, and prospects for medium/long-term societal and/or economic impact.*

3. INNOVATION

UK plant science has the potential to make a substantial contribution to the bioeconomy, both through the development, commercialization and industrial uptake of new products and processes, and the creation of new companies and jobs. Recent examples of successfully commercialized products include the development of a cough suppressant production platform following fundamental research on plant secondary metabolism [Box 3.1] and the development of ethylene removal technology to reduce food loss [Box 3.2]. Both of these success stories stem from an academic/industry partnership that was formed at the start of the project. A similar example is close to delivering a commercial bioenergy crop for use in the UK and Europe [Box 3.3]. Public/private collaborations such as these enable commercial viability to be accurately assessed and experimental approaches to be co-designed in a way that ensures effective delivery of new products or processes. However, not only are such examples relatively rare but the model does not necessarily encourage a healthy pipeline for exploring more high risk and potentially disruptive innovations. **There is a pressing need to enable more effective input from plant science R&D across the innovation landscape.**

37 https://designingfuturewheat.org.uk/
38 www.planthealthcentre.scot
39 https://www.gov.uk/government/publications/government-science-capability-review
40 Foreign Commonwealth and Development Office (incoporates ex Department for International Development).
41 https://devtracker.fcdo.gov.uk/projects/GB-GOV-1-300728
42 www.ensa.ac.uk & www.c4rice.com
43 https://ripe.illinois.edu/

Box 3.1: New Supply Chain for Cough Suppressant from Opium Poppy[44] – Commercialized.

Technology Readiness Level	Dates	Funder	Indicative Investment	Output
3	2006-07	GlaxoSmithKline (GSK)	£100K	Proof of concept for gene knockout by mutagenesis in opium poppy.
2-5	2008-12	GSK	£2.5M	Discovery of gene cluster involved in noscapine biosynthesis; lab & field validation of breeding strategy to combine noscapine/opiate varieties[45].
2 & 3	2011-15	BBSRC Industrial CASE PhD with GSK	£100K	Gene candidates for improvement of chemical composition confirmed.
4-6	2013-14	BBSRC Flexible Interchange Fellowship Award with GSK	£200K	Academic/Industry partnership enhancement through technology validation and demonstration.
2-5	2014-18	BBSRC Industrial Partnership Award with GSK (14-15) and Sun Pharmaceutical Industries (SPI) (15-18)	£2.4M	Discovery of a novel gene encoding a cytochrome P450 fusion protein provided tools and know-how to develop noscapine only varieties.
5-9	2012-20	GSK until 2015, then SPI when it acquired GSK's Australia Opiates Division[46]	£3M	Validation of new plant varieties for field and factory based production.

Impact: By 2017-18 deployment of new varieties accounted for 100% of SPI's noscapine production (>25 metric tonnes, sufficient for 1.6 billion doses), representing ~80% of global demand for cough suppressants[47].

[44] Research led by Professor Ian Graham at the Centre for Novel Agricultural Products, University of York.
[45] IP was secured through a portfolio of patents assigned to GSK, with associated costs met by the company.
[46] Field trials, scale-up, extraction and processing were underpinned by academic R&D.
[47] Impact confirmed by Dr T. Tomaz, SUN Pharmaceutical Industries (Australia) Pty Ltd. Income not disclosed.

Box 3.2: Ethylene Remover Technology to Reduce Fruit Loss and Waste[48] – Commercialized.

Technology Readiness Level	Dates	Funder	Indicative Investment	Output
1-3	2006	Johnson Matthey Plc. (JM)	Not disclosed	Academic/industry partnership, proof of concept for ethylene adsorption using Palladium zeolite matrix[49].
2-4	2007-10	PhD studentship funded by JM	Not disclosed	Understanding of how ripening-related changes can be suppressed.
3-5	2010-13	EPSRC[50] Industrial CASE PhD with JM	£90K	Discovery of mechanisms for ethylene action in non-climacteric fruit systems.
5	2010	Defra and industry	£57K	Academic/industry partnership, efficacy trials through technology validation and demonstration.
6-8	2010-12	Two MSc studentships funded by Its Fresh! Ltd.	Not disclosed	Raw material formulated into wafer-thin membrane and efficacy tested[51].
8 & 9	2012	Rabobank	£10M	It's Fresh! enabled to increase overseas exports of the E+™ Ethylene Remover.
9	2018	Agrofresh	£7.6M	It's Fresh! enabled to accelerate global expansion.

Impact: Annual sales and exports of E+™ Ethylene Remover now total over £23M. It's Fresh! Ltd. and parent company Food Freshness Technology Holdings (FFTH) have secured over £26.5M investment from Anterra Capital, JRJ Group, AP Ventures and BXR Group to bring ethylene removal products to market[52].

[48] Research led by Professor Leon Terry at Cranfield University, Bedford.
[49] IP was secured through patent WO 2007/05207 assigned to Johnson Mathey with associated costs met by them.
[50] Engineering and Physical Sciences Research Council.
[51] Johnson Mathey licensed technology to It's Fresh!.
[52] Income not disclosed. https://itsfresh.com/about-us/

Box 3.3: Domestication of the Bioenergy Crop Miscanthus[53] – In Commercial Field Trials.

Technology Readiness Level	Dates	Funder	Indicative Investment	Output
3-4	2005	Defra	£10K	Evaluation of germplasm collected from UK and EU projects including wild accessions, breeder's lines & commercial hybrids.
1-3	2006-11	Defra, BBSRC, Ceres Inc.	£500K	Collection of wild germplasm in China, Japan, South Korea & Taiwan, with quarantine in UK, to extend genetic diversity with relevant agreements providing commercial freedom to operate.
3-5	2012-	BBSRC	£100K	Implementation of UN protocols on the Convention on Biological Diversity with Access & Benefit sharing agreements.
1-3	2008-	BBSRC, EPSRC, EU	£5M	Phenotypic characterization of key traits in wild germplasm and novel progeny.
2-4	2012-	BBSRC, Defra, Ceres Inc., Innovate-UK, Terravesta Ltd.	£10M	Development of methodology to perform wide interspecies crosses to generate heterosis. Development of seed-based (as opposed to rhizome-based) propagation to enable upscaling.
1-4	2014-	BBSRC	£500K	Development of genomic prediction techniques to accelerate rates of genetic improvement.
1-3	2010-	NERC, Energy Technologies Institute, EPSRC, BBSRC	£500K	Assessment of environmental impacts (GHG emissions, soil carbon and hydrology) of land use change involving Miscanthus.
4-7	2017-	Ceres Inc., Terravesta Ltd, EU H2020	£5M	Novel seed based and clonal varieties trialled in UK and Europe, in plots, field and commercial scale. Selected varieties[54] under registration trials from 2019, and licenced to Terravesta Ltd.

Potential impact: Assuming 50% of the 700,000 ha Climate Change Committee target for perennial biomass crops in the UK[12] was planted with Miscanthus, there would be 1 MtCO2e emissions savings in the land sector and an extra 5.5 MtCO2e from the harvested biomass (e.g. when used with carbon capture and storage).

[53] Research led by Professor Iain Donnison at the Institute of Biological, Environmental & Rural Sciences, Aberystwyth University.
[54] IP assigned jointly to IBERS and Ceres Inc.

Box 3.4: Factors limiting innovation, technology transfer and commercialization in the UK

- Lack of incentives and support for researchers to become innovators.
- Limited understanding of developer and end-user needs and requirements.
- Limited plant science technology transfer expertise in universities.
- Academic research outputs not often in a form that industry can readily take up.
- Lack of understanding amongst researchers of how to take an idea through to commercialization.
- Misalignment of expectations around the costs and timescales required to de-risk projects.
- Inadequate IP management strategies.
- Regulatory and consumer acceptance barriers.
- Complex value chains in industries operating on small margins.

Box 3.5: Omega-3 Fish Oils in Camelina[55] – Stalled at TRL5.

Technology Readiness Level	Dates	Funder	Indicative Investment	Output
1 & 2	2000-10	BBSRC	£800K	Molecular toolkit for the biosynthesis of omega-3 oils in transgenic plants.
2-4	2000-04	BASF Plant Sciences	£900K	IP assigned to BASF, research collaboration agreement funded.
3 & 4	2012-14	BBSRC Follow on Fund	£150k	Molecular characterization of elite events, Camelina IP filed.
3 & 4	2012-15	BBSRC Industrial Partnership Award with BioMar	£450K	First aquafeed trials using GM-derived oils for salmon feed, validation and de-risking of the technology.
2 & 3	2015-20	BBSRC Institute Strategic Programme	£200K	GM trials to evaluate the performance of elite camelina in the field.
3 & 4	2016-19	BBSRC	£250K	First studies using human subjects.
3 & 4	2017-19	BBSRC Super Follow on Fund with Marine Harvest	£467K	First open sea-loch aquafeed trials of salmon under commercial conditions.
3 & 4	2020-22	BBSRC Super Follow on Fund	£310K	Evaluation of novel GM oils as components of human foodstuffs.
4-5	2020	Yield10 Biosciences	£200K	Academic/industry partnership to improve the agronomic performance of camelina as a GM chassis for advanced metabolic engineering of traits.

Potential impact: The annual global marine harvest of ~one million tonnes of fish oils is worth ~two billion US dollars. The ability to produce a new, clean, sustainable and scalable source of fish oils would not only provide a new income stream for farmers and processors, but help aquaculture become greener. It would also deliver improved human nutrition via increased supply of omega-3 fish oils for direct or indirect nutrition.

[55] Research led by Professor Johnathan Napier at Rothamsted Research. Harpenden.

Box 3.6: Viral Based Technology for Protein Production in plants[56] – Licensed Commercially for Certain Uses (at TRL8 in Canada); UK Strategic Capacity Stalled at TRL6.

Technology Readiness Level	Dates	Funder	Indicative Investment /Income	Output
1 & 2	2004-08	EU	£393K	In planta transient protein expression system developed.
3	2006-	Plant Bioscience Limited (PBL)	£450K	Two patent families filed and maintained: one as a co-invention with Medicago Inc.
3 & 4	2009-11	BBSRC / EU	£436K	Proof of concept that virus like particles and capsids can be assembled in plants without polynucleotide content, and that they can be used to induce an immune response.
4-5	2008-	Medicago Inc. and others	>£1M	Licence income to PBL/John Innes Centre for various specific uses (e.g. flu vaccine).
4-6	2009-16	Medicago Inc.	Not disclosed	Flu vaccine progressed from animal models to Phase I and II clinical trials.
7-8	2017-20	Medicago Inc.	Not disclosed	Phase III clinical trials and new drug submission filed with Health Canada.
5 & 6 (UK)	2015	BBSRC, John Innes Centre, PBL	£5M	Leaf Expression Systems founded in Norwich as spinout for contract services and partnership development[57].

Potential impact: US$1M (~£750K) per annum in 2020 rising to US$16M (~£12M) before patent expiry in 2029 if used to produce a seasonal flu vaccine[58].

Multiple contributing factors currently limit the extent to which the full value of UK plant science research is captured and exploited [Box 3.4]. For example, late blight resistant potatoes developed in the UK[59] have been deregulated and commercialized in the US[60] but product development is stalled at Technology Readiness Level[61] (TRL) 5 in the UK, primarily due to investor concerns over regulatory issues. Similar concerns are hampering the commercialization of a plant based production platform for omega 3 fish oils, despite nearly a decade of BBSRC funded research to validate and de-risk the product in animal, human and field trials [Box 3.5]. Even in the absence of regulatory issues, examples can be found where technology that has been developed in the UK is commercialized overseas before any economic benefit is realized in the UK. A case in point is the development of virus based methods for protein production in plants (e.g. for rapid response vaccine manufacture) [Box 3.6]. **To ensure that outputs from publicly funded plant science research over the next decade not only contribute to food production, the environment and to human health, but also more directly to the UK economy, the factors that are limiting innovation, translation and commercialization, and investment therein, must be overcome.**

[56] Research led by Professor George Lomonossoff at the John Innes Centre, Norwich.
[57] Strategic UK opportunities lost to competitors because of the lack of a Good Manufacturing Practice (GMP) facility. An estimated £40M is needed for scale up and development of a GMP facility.
[58] Economic valuation by Brookdale Consulting for the John Innes Centre.
[59] Research led by Professor Jonathan Jones at The Sainsbury Laboratory, Norwich.
[60] https://www.federalregister.gov/documents/2015/09/02/2015-21747/jr-simplot-co-determination-of-nonregulated-status-of-potato-genetically-engineered-for-late-blight
[61] https://nerc.ukri.org/research/funded/programmes/technologypoc/tech-readiness-levels/

In 2013 the UK Government's Strategy for Agricultural Technologies[62] aimed to rebuild connections between fundamental and translational research[63], seeing the disconnect as the reason for a lack of innovation in the sector. The strategy led to £80M investment in four Agri-Tech Centres[64] plus £70M in an Agri-Tech Catalyst Funding scheme (2013-2016). The Agri-Tech Centres were established in 2015/16 with a view to attracting industry investment, and five years on it would be timely to critically evaluate and publish progress towards that goal. In 2017 the UK Industrial Strategy[2] committed further investment of £90M in a 'Transforming Food Production' initiative. Coincident with this, the Plant Sector Advisory Board for Innovate UK's Knowledge Transfer Network (KTN) published a pre-competitive vision for the plant and crop sector[65]. The KTN report comprehensively documents the contributions that plant science can make to deliver new products and processes for sustainable agriculture, covering three of the overarching questions in Box 2.1 and including roles for robotics, artificial intelligence and machine learning. Detailed scope for the commercial exploitation of natural and synthetic plant products, covering the fourth question in Box 2.1, is due to be outlined in the forthcoming report from the Engineering Biology Leadership Council[66]. **These recent reports reveal a growing appetite for innovation and the enormous potential for plant science research to fuel economic growth. Examples of products that could be delivered are indicated in Box 3.7.**

Box 3.7: Examples of high value products that could be delivered.

- Predictive simulation tools such as digital twins for farm and landscape management (where and when).
- High performing crop varieties for both traditional and novel farm systems (more out less in).
- Biological crop protection compounds (plant health).
- Algal platforms for bioengineered protein production (plant products).

As research projects travel through the TRL pipeline from fundamental research to commercialization, the public funding landscape changes. Currently, the research councils fund TRL1-3, with relatively small (~£100K) Proof of Concept Awards easing the transition from TRL2 to 3. Innovate UK starts funding between TRL3 and 4, with the expectation of cash investment from industry at that stage. This expectation does not fit well in the UK seeds and plant breeding sector, primarily because proof of concept (TRL3 & 4) can take 10-15 years, particularly in the development of new germplasm/varieties, but also because the seeds business operates on tight profit margins. Despite these drawbacks, the international Agbiotech companies do interact with UK academia to test early stage crop biotechnologies (e.g. through BBSRC Industrial Partnership Awards). Compared to other countries, however, the UK is seen as expensive for direct industrial funding. Another disincentive for early stage cash investment is the prohibitive cost of deregulation of GM traits (including – at present – gene edited traits). In the future, similar regulatory concerns could also embroil the development of innovative alternatives to chemicals for crop protection and the development of natural plant products for pharmaceutical benefits. The challenges are different in other areas of the sector such as precision agriculture, data handling and disruptive farming technologies, where the difficulty is introducing innovations in a new and rapidly evolving industry area that is currently both fragmented and capital light. In these cases, as with the use of plants as production platforms for novel industrial compounds [Box 3.6], identifying the right industrial partner(s) and securing cash

[62] www.gov.uk/government/publications/uk-agricultural-technologies-strategy
[63] Referred to as basic and applied in the original strategy document.
[64] Agrimetrics, Agri-Epi, CIEL & CHAP; https://www.agritechcentres.com/
[65] https://admin.ktn-uk.co.uk/app/uploads/2018/03/KTN-Pre-Comp-Plant-and-Crop-Booklet-Digital.pdf
[66] The Synthetic Biology Leadership Council has been renamed Engineering Biology Leadership Council (EBLC). The Sustainable Food & Agriculture Working Group (Anne Osbourn, Dale Sanders, Jason Vincent & Dieuwertje van Esse-van der Does) of EBLC have already submitted their recommendations. The final report is expected to be published at https://ktn-uk.org/programme/synthetic-biology-leadership-council/ in 2021.

investment through to scale-up stage (TRL4-8) is the most challenging aspect. In all cases, Innovate UK's requirement for early stage cash investment from industrial partners can result in opportunities to leverage expertise and other in-kind resources being overlooked, and independent innovation being disincentivised. **The major constraints for the translation and commercialization of UK plant science research are the lack of effective mechanisms to sustain public/private partnerships through critical stages of the TRL pipeline, limited opportunities for industry and other stakeholders to communicate the challenges that need to be addressed, and the absence of well-designed initiatives to stimulate innovation. For the UK to reap economic benefit from public investment in plant science research, these constraints must be removed.**

> ***Recommendation 3a:*** *Instigate a root and branch review[67] of how innovation in plant science research is stimulated, incentivised, funded and implemented in the UK, with the goal of developing a sustainable mechanism through which universities, institutes and industry can work together in both pre-and post-competitive frameworks (as appropriate) with a long-term view. This should involve a critical assessment of the impact of current Agri-Tech initiatives, together with a deep comparative analysis of best practice in other countries that have distinct strengths and weaknesses in harnessing the potential of plant science to drive economic growth.*

> ***Recommendation 3b***: *In line with a pledge in the UK R&D Roadmap (2020)[68], to ensure that the UK has a regulatory system that enables R&D to meet societal needs, conduct a review of procedures that govern the introduction of new plant varieties and of new plant protection products and systems. The review should consider the criteria for evaluation and critically assess whether the current system is fit for purpose when new breeding technologies are included, and when/if rapid product delivery timelines become necessary. A cost/benefit analysis of 'process' based assessment methods versus 'product' based alternatives should be included.*

4. DIVERSE PEOPLE AND SKILLS

The successful implementation of this strategy requires a professional workforce with diverse skillsets and mindsets. Although the last round of curriculum reform expanded plant science content in the Biology GCSE specification[69], plant science teaching in the core UK curriculum is minimal beyond Key Stage 3 (S3 in Scotland). As a consequence, a void in the skills pipeline is created at an early learning stage. Over recent years, a lack of awareness of why and how plants are important has also stifled enthusiasm for practical careers in plant science, with a subsequent decline in the availability of high quality vocational training courses. Added to the fact that student numbers and the types of course on offer at Further Education (FE) Colleges are generally driven by local drivers as opposed to individual or sector needs, there is a lack of strategic oversight to ensure that training opportunities align with predicted future need for skills. There are also limited opportunities for structured technical careers, likely because practical skills were devalued when many more people were encouraged to aspire to a university education. The Gatsby Charitable Foundation's 'Technicians Make it Happen Campaign'[70] aims to raise the profile of technical careers and the Agricultural and Horticultural Development Board has initiated a co-ordinated apprenticeship and training programme to address this issue for the agriculture and horticulture sectors[71], but more needs to be done to increase the appeal of careers in plant breeding, agronomy, forestry and horticulture. **To deliver this strategy over the long-term, mechanisms must be implemented to enhance general awareness of the importance of plants and plant science research, particularly in schools. Plant science and related careers must also become integral to policy discussions and developments in STEM education.**

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[67] This could be implemented by, or with, the new Innovation Expert Group (UK R&D Roadmap July 2020[68])
[68] www.gov.uk/government/publications/uk-research-and-development-roadmap
[69] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/800342/GCSE_single_science_updated_May_2019.pdf
[70] www.gatsby.org.uk/education/programmes/raising-the-profile-of-technicians
[71] https://ahdb.org.uk/skills

Recommendation 4a: *Provide incentives and support for organizations such as botanic gardens, museums, charitable trusts and learned societies, to launch a co-ordinated four nations campaign to raise awareness of why plants are important and why plant science research is essential for our future health and well-being. Ensure that campaign delivery mechanisms both encourage and enable engagement with diverse sectors of society.*

Recommendation 4b: *Continue to raise the profile and quality of plant science content in the school curriculum, highlighting links with other STEM subjects. Seek guidance from the Royal Society of Biology's Curriculum Committee[72], which is working with similar committees at the Royal Society of Chemistry and Institute of Physics[73], and which has input from education units at the Royal Society, Royal Society of Edinburgh, New Phytologist Trust, Society for Experimental Biology and Gatsby Charitable Foundation.*

Plant science research is currently represented in 48 UK universities[74], with ~50% having the critical mass (>10) to teach a broad range of plant sciences at undergraduate level. Very few research active universities offer vocation targeted courses such as agriculture, plant breeding and forestry[75], and in contrast to biomedical subjects, students rarely associate plant science with specific career paths. This in itself is not a bad thing, plants comprise one of the four eukaryotic kingdoms and as such should feature prominently in any biology degree course. However, when faced with alternatives, obscure or seemingly unattractive career paths can deter all but the most committed students from opting for plant science modules. Lack of demand then leads to fewer academic appointments in the area (particularly in large bioscience departments), a reduction in financial support for enabling facilities, and a consequential further loss of expertise and teaching capacity. **To raise the profile of graduate careers in plant science and thus to attract more undergraduate students into the discipline, more effort is needed to emphasize why the science is important and to illustrate the range of opportunities available. This approach has been validated over the last fifteen years by the Gatsby Plant Science Summer School[76], a national programme for first year undergraduate students from across the UK that has had a documented lasting effect on the attitudes of students toward plant science[77].**

Over the last five years, BBSRC funded 427 PhD studentships in plant science and there are currently 22 independent research fellows (IRFs)[78] working in the field, based at 14 different institutions. At face value these figures are encouraging for the future of the discipline, but there is no room for complacency. By comparison, MRC[79] awarded ~2000 PhD studentships for biomedical sciences over the same period and it is only a minority funder in the area. Notably, plant science research received 28% of total BBSRC spend over the last five years but only 18% of PhD studentships, suggesting either that there was insufficient opportunity in some institutional doctoral training partnerships (DTP) and/or that there was insufficient uptake. Given that ~18% of plant science DTP studentships were awarded to non-UK EU citizens during this period, and that overseas fees liabilities will deter applicants from the EU post-Brexit, the field is facing an imminent recruitment issue. Lack of diversity also needs to be addressed. Gender balance in plant science is good from undergraduate through to IRF stage (51% of the 427 BBSRC DTP studentships were awarded to individuals who self-identified as female and 55% of the current IRFs self-identify as such), but women are still under-represented at senior levels in both academia and industry. Ethnic diversity is poor at all career stages, with minority ethnic undergraduate students noticeably under-represented in biology, particularly in plant science, relative to biomedical sciences. Only 4.2%

[72] https://www.rsb.org.uk/images/SSR_September_2018_23-29_McLeod.pdf
[73] https://www.ase.org.uk/system/files/SSR_September_2018_19-20_Tomei.pdf
[74] www.garnetcommunity.org.uk/sites/default/files/newsltr/GARNish33_Online_Final_0.pdf
[75] www.ucas.com
[76] https://www.slcu.cam.ac.uk/outreach/gatsby-plants/GPSSS
[77] http://www.plantcell.org/content/24/4/1306
[78] Awarded since 2015 through the Royal Society URF, Leverhulme ECR, NERC IRF or UKRI FLF schemes.
[79] Medical Research Council; https://mrc.ukri.org/skills-careers/studentships/

of BBSRC PhD studentships over the last five years were awarded to students who self-identified as belonging to a minority ethnic group[80] (16% chose not to disclose), although 14% of the current IRF cohort identify as such, as compared to 13% of the UK population as a whole[81]. **There is an urgent need to increase the number and ethnic diversity of high quality UK students applying for vocational, undergraduate and postgraduate programmes in plant sciences**.

> ***Recommendation 4c:*** *Increase PhD studentship spend to align with the proportion of overall spend in the research field. Establish a high profile Centre for Postgraduate Training in plant sciences that spans multiple UK institutions, offers enhanced stipends, includes vocational MSc courses, embeds entrepreneurship training, and provides a conduit for internships and studentships targeted at under-represented groups. Align this programme with an apprenticeship scheme of relevance to production sectors (agriculture, horticulture, forestry and biotech), linking universities and institutes undertaking research in plant science with regional FE colleges, industry and other relevant providers such as botanic gardens.*

5. NATIONAL INFRASTRUCTURE

The UK has some of the most high-profile publicly funded research institutions in the world but more than a decade of austerity has left many with run-down buildings and out-dated facilities. The UK R&D Roadmap (2020)[68] pledges to provide long-term flexible investment for infrastructure in public sector research institutes and universities. That commitment needs to be realized to enable the successful delivery of this strategy and to ensure that plant science infrastructure and capabilities are commensurate with world-class R&D. The UK R&D Roadmap also pledges to consider place-based outcomes in decision making and to this end, investment in public sector research establishments must be enabling for research across the UK. **A National Field Research Platform (Recommendation 1a) that co-ordinates, upgrades and maintains experimental field facilities and support staff across all four nations, will simultaneously level up access across the UK and establish a new capability that could connect with similar platforms in other countries**. This platform would also link to ongoing activities in ASSIST[82], a long-term (but finite) national programme that aims to develop new crop management systems through co-ordinated research across a UK network of experimental study farms. **Investment in a distributed network of state of the art laboratory based and controlled environment facilities is also needed to enable researchers across the UK to deliver solutions to the strategic challenges that have been outlined [Boxes 2.1 & 2.2].** Crucially, capital investment in both field and laboratory based facilities must be accompanied by realistic strategies for long-term support. It is unfortunate that investment in the National Phenomics Platform at IBERS, which provided state of the art facilities for UK plant science research around a decade ago, was not associated with a long-term funding strategy. As a consequence the facility is now used mainly by local research groups and by overseas researchers who pay for access through the co-ordinated EU plant phenotyping programme EMPHASIS[83], rather than by researchers elsewhere in the UK. The recent £62M Tay City Deal investment in facilities at the James Hutton Institute[84] will provide critical infrastructure for Scotland's plant science, but without an ongoing financial commitment, similar issues may be faced in the future. **To deliver this strategy, infrastructure investments must be co-ordinated, capital expenditure should be aligned with realistic long-term plans for maintenance and upgrade of facilities, and any ongoing financial support should be conditional on provision of affordable access for plant science researchers across the UK.**

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[80] Includes all non-white groups
[81] 2011 UK census data
[82] https://assist.ceh.ac.uk/content/about-assist
[83] https://emphasis.plant-phenotyping.eu/
[84] www.hutton.ac.uk/news/james-hutton-institute-welcomes-tay-cities-deal-funding-boost

***Recommendation 5a**: Invest in a UK-wide network of specialized hubs, including the HP[3] project proposed for the Norwich Research Park[29], to provide world-class national capabilities that can be affordably accessed by researchers across all four nations, linking ongoing investment with an enablement strategy and associated accountability.*

Whereas buildings can be replaced, germplasm and preserved plant collections need ongoing maintenance to safeguard for the future. A number of UK institutions curate national and international plant collections, many funded by UKRI, Defra, RESAS and DDCMS via non-competitive National Capability grants. For example, the Millennium Seedbank at Wakehurst houses the greatest concentration of living seed-plant diversity in the world, preserved plant specimens in the UK herbaria collectively comprise the world's largest herbarium (with most at Kew, RBGE and NHM), and national germplasm collections (including potatoes, wheat, peas, forage grasses and legumes, willow, fruit and broad leaf trees) are curated by JHI, JIC, IBERS, RRes, NIAB, Forest Research and the Universities of Reading and Warwick. **The national plant collections are critical for current and future research capabilities, and as such ongoing funding for curation is essential, but they are not easily accessed. The genetic diversity that is captured in the UK plant collections represents a largely untapped resource that needs to be made widely available to accelerate the discovery of how plant form and function varies and evolves in different environments, and to allow predictions of how it might change in the future.**

***Recommendation 5b:** Harness phenotypic and genotypic information sequestered in the distributed plant collections by digitizing phenotype records through an expansion of UKRI's Strategic Priorities Fund initiative to digitize museum collections[85] and by strengthening existing collaborations between the Natural History Museum, Royal Botanic Gardens Edinburgh, Kew & the Earlham Institute to collect and annotate genomic data. Data should be linked to the Crop Genetic Improvement Platform[86] to further support the development of new crop varieties.*

6. INTERNATIONAL LANDSCAPE

UK plant science researchers participate in many international programmes. EU-wide projects that bring together complementary expertise to address strategic challenges of shared interest have made major contributions to the field and have boosted UK research capacity over the last twenty years with funding from successive EU programmes. Bilateral programmes between UKRI and Brazil, China, India and the US have also developed synergistic networks of researchers addressing both fundamental and strategic questions. The International Wheat Yield Partnership[87], which is funded by both public and private organizations, is a rare example of a multinational research programme. **Additional bi- and multi-lateral programmes with countries that have both a high quality research base and an economic dependence on agriculture/horticulture would accelerate research to develop plant varieties, methods and technologies for sustainable and resilient farming systems**.

***Recommendation 6a:** Maintain existing bilateral programmes with Brazil, China, India and the US, and explore opportunities for new bilateral programmes with Australia, Canada, Japan, Mexico, New Zealand and South Korea. Create and/or engage with funding opportunities for multinational consortia, to bring together novel ideas, ambitious approaches and complementary expertise from across the world to tackle questions of major fundamental and strategic importance.*

[85] Towards a National Collection: Opening UK Heritage to the World (£19M)
[86] https://defracropgenetics.org/
[87] https://iwyp.org

As with UK national goals[2-8], at least five of the UN's Sustainable Development Goals (SDGs)[88] – zero hunger, good health and well-being, responsible production and consumption, climate action, and life on land – require input from plant science research. Over the last five years, UK researchers have contributed to projects that address these issues, funded by FCDO, GCRF[89], Newton Fund[90] and the Darwin Initiative[91], with FCDO funding focussed on delivery of products and solutions to end-users as opposed to research towards product development. In 2018/19 BBSRC awarded over £25M for plant science research through these routes. Although it is too early to evaluate the lasting impact of GCRF research programmes (which were initiated in 2015), it is clear that there have been benefits in terms of fostering increased interdisciplinarity and enabling the development of effective partnerships with researchers in low and middle income countries (LMICs). However, short lead in times for funding calls (< six months) and short project timeframes (3 years) undoubtedly led to opportunities being missed. Given that a 2019 independent evaluation[92] of the CGIAR Consortium[93] led to major reform and integration into a single overarching 'One CGIAR' management board[94], and that most FCDO funding for plant sciences has been routed through CGIAR Centres, it is likely that opportunities for impact have been missed there as well. With the first tranche of GCRF funding ending next year, and the CGIAR governance being overhauled, there is an opportunity to reassess funding mechanisms to ensure that UK contributions to overseas development programmes are effectively deployed. **Because local institutions are better positioned to identify demands, and co-designing solutions is more likely to deliver impact, more meaningful contributions to the SDGs can be made if short term responsive projects that are driven primarily by the capacity and interests of UK institutions are replaced by long-term strategic collaborations between UK researchers and local institutions in LMICs.**

Recommendation 6b: *Develop a more integrated, long-term and demand-led strategy for research and capacity building in LMICs by funding at least two stage-gated challenge programmes. Align an agricultural programme with the goals of the One CGIAR[95], engaging with the CGIAR Centres and National Agricultural Research Stations in LMICs, as well as larger agricultural organizations such as ICAR[96], CAAS[97] and EMBRAPA[98]. Focus on capacity building in countries where there is potential for sustained improvements in agricultural productivity and increased resilience of agriculture to climate change. Develop a conservation programme with both local and international research institutions in the tropics (e.g. the Smithsonian Tropical Research Institute[99] and South East Asia Forest Research Partnership[100]), to map and protect natural capital in important plant areas[101] and to identify mechanisms to mitigate the impacts of climate change and habitat loss on these vital ecosystems.*

[88] www.un.org/sustainabledevelopment/sustainable-development-goals/
[89] Grand Challenges Research Fund www.ukri.org/research/global-challenges-research-fund/
[90] www.newtonfund.ac.uk
[91] www.gov.uk/guidance/darwin-initiative-applying-for-main-project-funding
[92] http://www.mopanonline.org/assessments/cgiar2019/CGIAR%20Brief%20Web_.pdf
[93] Formerly call the Consultative Group on International Agricultural Research.
[94] www.cgiar.org/impact/one-cgiar/
[95] https://cgspace.cgiar.org/bitstream/handle/10568/110918/OneCGIAR-Strategy.pdf?sequence=1&isAllowed=y
[96] Indian Council of Agricultural Research
[97] Chinese Academy of Agricultural Sciences
[98] Brazilian Agricultural Research Corporation
[99] https://stri.si.edu/
[100] www.searrp.org
[101] www.kew.org/science/our-science/projects/tropical-important-plant-areas

LIST OF RECOMMENDATIONS FOR:

UKRI, UKRI/Defra/RESAS/DAERA/Welsh Government, UKRI/Defra, Defra/FSA, DDCMS, DfE, UKRI/DfE, UKRI/Defra/RESAS/DDCMS, UKRI/FCDO

1. Securing a pipeline of transformative discoveries

Recommendation 1a: *Co-ordinate activities between existing field research sites across the UK, as suggested in the UKRI Infrastructure Roadmap (2019)[16], to establish a National Field Research Platform with standard operating procedures for hypothesis testing experiments (including those around novel germplasm, natural variation, plant/microbe/soil interactions, robotics and machine learning). This will require identification of lead institutions, widespread participation of universities, research institutes and private organizations, and investment in appropriate facilities across field sites, including mobile phenotyping capabilities.*

Recommendation 1b: *Evaluate fundamental research programmes on the basis of novel ideas or approaches that could to lead to a step change in the research field and deliver publications that stand the test of time, and on the track record of the investigator (taking into account career stage), to the exclusion of any other criteria. Mitigate against single point of failure for fundamental research funding by diversifying application routes and/or enabling resubmission of the top 10% of unsuccessful applications.*

2. Strategic research to solve grand challenges

Recommendation 2a: *Establish a framework to fund long-term strategic research programmes via a UK network of hub and spoke teams that are organized around specific biological or technological challenges [Box 2.2], and that operate in a non-exclusive pre-competitive arena to capture research capability and resources that exist in the private sector. Identify project leaders and key individuals to co-ordinate teams that can provide answers to the four over-arching research questions [Box 2.1] and invest in the infrastructure required at both hubs and spokes to ensure timely delivery.*

Recommendation 2b: *Evaluate strategic research programmes on the basis of commitment by leadership to the end goal, team composition reflective of the best expertise from across the UK, balance of fundamental and translational research appropriate for the specific challenge, rationale of IP management strategy, and prospects for medium/long-term societal and/or economic impact.*

3. Innovation

Recommendation 3a: *Instigate a root and branch review[67] of how innovation in plant science research is stimulated, incentivised, funded and implemented in the UK, with the goal of developing a sustainable mechanism through which universities, institutes and industry can work together in both pre-and post-competitive frameworks (as appropriate) with a long-term view. This should involve a critical assessment of the impact of current Agri-Tech initiatives, together with a deep comparative analysis of best practice in other countries that have distinct strengths and weaknesses in harnessing the potential of plant science to drive economic growth.*

Recommendation 3b: *In line with a pledge in the UK R&D Roadmap (2020)[68], to ensure that the UK has a regulatory system that enables R&D to meet societal needs, conduct a review of procedures that govern the introduction of new plant varieties and of new plant protection products and systems. The review should consider the criteria for evaluation and critically assess whether the current system is fit for purpose when new breeding technologies are included, and when/if rapid product delivery timelines become necessary. A cost/benefit analysis of 'process' based assessment methods versus 'product' based alternatives should be included.*

4. Diverse people and skills

Recommendation 4a: *Provide incentives and support for organizations such as botanic gardens, museums, charitable trusts and learned societies, to launch a co-ordinated four nations campaign to raise awareness of why plants are important and why plant science research is essential for our future health and well-being. Ensure that campaign delivery mechanisms both encourage and enable engagement with diverse sectors of society.*

Recommendation 4b: *Continue to raise the profile and quality of plant science content in the school curriculum, highlighting links with other STEM subjects. Seek guidance from the Royal Society of Biology's Curriculum Committee[72] which is working with similar committees at the Royal Society of Chemistry and Institute of Physics[73] and which has input from education units at the Royal Society, Royal Society of Edinburgh, New Phytologist Trust, Society for Experimental Biology and Gatsby Charitable Foundation.*

Recommendation 4c: *Increase PhD studentship spend to align with the proportion of overall spend in the research field. Establish a high profile Centre for Doctoral Training in plant sciences that spans multiple UK institutions, offers enhanced stipends, includes vocational MSc courses, embeds entrepreneurship training, and provides a conduit for internships and studentships targeted at under-represented groups. Align this programme with an apprenticeship scheme of relevance to production sectors (agriculture, horticulture, forestry and biotech), linking universities and institutes undertaking research in plant science with regional FE colleges, industry and other relevant providers such as botanic gardens.*

5. National infrastructure

Recommendation 5a*: Invest in a UK-wide network of specialized hubs, including the HP[3] project proposed for the Norwich Research Park[29], to provide world-class national capabilities that can be affordably accessed by researchers across all four nations, linking ongoing investment with an enablement strategy and associated accountability.*

Recommendation 5b: *Harness phenotypic and genotypic information sequestered in the distributed plant collections by digitizing phenotype records through an expansion of UKRI's Strategic Priorities Fund initiative to digitize museum collections[85] and by strengthening existing collaborations between the Natural History Museum, Royal Botanic Gardens Edinburgh, Kew & the Earlham Institute to collect and annotate genomic data. Data should be linked to the Crop Genetic Improvement Platform[86] to further support the development of new crop varieties.*

6. International landscape

Recommendation 6a: *Maintain existing bilateral programmes with Brazil, China, India and the US, and explore opportunities for new bi-lateral programmes with Australia, Canada, Japan, Mexico, New Zealand and South Korea. Create and/or engage with funding opportunities for multinational consortia, to bring together novel ideas, ambitious approaches and complementary expertise from across the world to tackle questions of major fundamental and strategic importance.*

Recommendation 6b: *Develop a more integrated, long-term and demand-led strategy for research and capacity building in LMICs by funding at least two stage-gated challenge programmes. Align an agricultural programme with the goals of the One CGIAR[95], engaging with the CGIAR Centres and National Agricultural Research Stations in LMICs, as well as larger agricultural organizations such as ICAR[96], CAAS[97] and EMBRAPA[98]. Focus on capacity building in countries where there is potential for sustained improvements in agricultural productivity and increased resilience of agriculture to climate change. Develop a conservation programme with both local and international research institutions in the tropics (e.g. the Smithsonian Tropical Research Institute[99] and South East Asia Forest Research Partnership[100]), to map and protect natural capital in important plant areas[101] and to identify mechanisms to mitigate the impacts of climate change and habitat loss on these vital ecosystems.*

APPENDIX 1

Name	Position	Institution	Sector
Alexandre Antonelli	Director of Science	Kew	Non-Departmental Public Body
Duncan Barker	Livelihoods Advisor Agriculture Research; Lead Advisor DfID/ BBSRC programmes	FCDO	Government
Tina Barsby	Director and Chief Executive Officer	NIAB	Not for Profit Charitable Organization
David Baulcombe FRS FMedSci	Royal Society Research Professor	University of Cambridge	HEI
Charlie Baxter	Head Global Seeds, Traits & Regulatory	Syngenta	Private
Malcolm Bennett FRS	Professor of Plant Sciences	University of Nottingham	HEI
Alison Bentley	Global Wheat Program Director	CIMMYT	Institute (CGIAR)
Paul Birch FRSE	Professor of Plant Pathology	University of Dundee	HEI
Lisa Black	Head of Plant Testing Station	Agri-Food and Biosciences Institute	Institute (NI)
Mike Blatt	Regius Professor of Botany	University of Glasgow	HEI
Ian Boyd FRSE	Professor of Biology	University of St Andrews; ex CSA Defra	HEI; Government
Martin Broadley	Professor of Plant Nutrition	University of Nottingham; FCDO	HEI; Government
Richard Buggs	Professor of Evolutionary Genomics	Queen Mary University of London; Kew	HEI; Non-Departmental Public Body
Fiona Burnett	Head of Connect for Impact	Scotland's Rural College	Institute (Scotland)
Mario Caccamo	Managing Director	NIAB EMR	Not for Profit Charitable Organization
Duncan Cameron	Professor of Plant and Soil Biology; Co-director P3 Centre	University of Sheffield	HEI
Jonathan Carruthers	Senior Science Policy Officer	Royal Society of Biology; UKPSF	Learned Society
Jan Chojecki	Managing Director	PBL Technology	Technology Transfer
Belinda Clarke	Director	AgriTech E	Private
Martin Clough	Head of Crop Protection R&D Technology & Digital Integration; Chair KTN Plant Sector Advisory Board	Syngenta; Knowledge Transfer Network	Private; Innovate UK

Name	Position	Institution	Sector
Enrico Coen FRS	Group Leader	John Innes Centre	Institute (BBSRC)
Holly Croft	UKRI FLF 2020	University of Sheffield	Independent Research Fellow
Richard Dale	Syngenta Fellow, Herbicide Bioscience	Syngenta	Private
Caroline Dean FRS	Group Leader	John Innes Centre	Institute (BBSRC)
Katherine Denby	Professor and Academic Director of the N8 AgriFood Resilience Programme	University of York; N8	HEI
Laura Dixon	UKRI FLF 2019	University of Leeds	Independent Research Fellow
Liam Dolan FRS	Sherardian Professor of Botany	University of Oxford; MOA Technology	HEI; Private
Claire Domoney	Group Leader	John Innes Centre	Institute (BBSRC)
Iain Donnison	Head of Department Biological Environmental and Rural Sciences; Professor	IBERS; Aberystwyth University	Institute (BBSRC); HEI
John Doonan	Director National Plant Phenomics Centre; Professor	IBERS; Aberystwyth University	Institute (BBSRC); HEI
Luke Dunning	NERC IRF 2020	University of Sheffield	Independent Research Fellow
Keith Edwards	Professor of Cereal Functional Genomics	University of Bristol	HEI
Rob Edwards	Head of School of Agriculture, Food and Rural Development	University of Newcastle	HEI
Richard Flavell FRS	Consultant	International Wheat Yield Partnership	Private
Rob Freckleton	Professor of Population Biology Head of Animal and Plant Sciences	University of Sheffield	HEI
Jim Godfrey	Director; President Royal Agricultural Society of England; Chair NIAB Board; Chair IRRI Board	RJ & AE Farming Company	Private
Ian Graham FRS	Weston Chair of Biochemical Genetics; Director of BioYork	University of York; CNAP	HEI
Murray Grant	Professor of Food Security	University of Warwick	HEI
Claire Grierson	Head of School of Biology	University of Bristol	HEI
Sarah Gurr	Professor of Food Security	University of Exeter	HEI
Neil Hall	Director	Earlham	Institute (BBSRC)

Name	Position	Institution	Sector
Claire Halpin FRSE	Associate Dean of Research & Professor of Plant Biology and Biotechnology	University of Dundee	HEI
Jake Harris	Royal Society URF 2020	University of Cambridge	Independent Research Fellow
David Harris	Deputy Director of Science	Royal Botanic Garden Edinburgh	Non-Departmental Public Body
Richard Harrison	Director of Cambridge Crop Research	NIAB	Not for Profit Charitable Organization
Stuart Harrison	Head of Seeds R&D Partnerships & Open Innovation	Syngenta	Private
Sue Hartley	Professor of Ecology; Vice-President for Research	University of Sheffield	HEI
Malcolm Hawkesford	Head of Plant Sciences	Rothamsted Research	Institute (BBSRC)
Yrjo Helariutta	Group Leader	Sainsbury Lab, Cambridge University	Institute (Gatsby Charitable Foundation)
Piers Hemsley	Principal Investigator & Senior Lecturer	University of Dundee/ James Hutton Institute	HEI/Institute (Scottish Government)
Gideon Henderson FRS	Chief Scientific Adviser	Defra	Government
Alistair Hetherington	Melville Wills Professor of Botany	University of Bristol	HEI
Sandy Hetherington	UKRI FLF 2020	University of Edinburgh	Independent Research Fellow
Julian Hibberd	Professor of Photosynthesis	University of Cambridge	HEI
Andrew Hitchcock	Royal Society URF 2019	University of Sheffield	Independent Research Fellow
Patrick Hussey	Professor of Plant Molecular Cell Biology	University of Durham	HEI
Rob Jackson	Professor of Tree Pathology	University of Birmingham	HEI
Dan Jenkins	Head of Gatsby Plant Science Education Programme	Science and Plants for Schools	Charitable Foundation
Ian Jepson	Head of Traits Technology Development & RTP Site	Syngenta	Private
Davey Jones	Professor of Soil & Environmental Science	University of Bangor	HEI
John Jones	Head of Department Cellular & Molecular Biology; Professor of Biology	James Hutton Institute; University of St Andrews	Institute (Scotland); HEI
Jonathan Jones FRS	Group Leader	Sainsbury Lab, Norwich	Institute (Gatsby Charitable Foundation)

Name	Position	Institution	Sector
Sophien Kamoun FRS	Group Leader	Sainsbury Lab, Norwich	Institute (Gatsby Charitable Foundation)
Rucha Karnik	Royal Society URF 2016	University of Glasgow	Independent Research Fellow
Angela Karp	Director	Rothamsted Research	Institute (BBSRC)
Steve Kelly	Royal Society URF 2015	University of Oxford	Independent Research Fellow
Stefan Kepinski	Senior Lecturer	University of Leeds; SEB	HEI; Learned Society
Paul Kersey	Deputy Director of Science	Kew	Non Departmental Public Body
Charlotte Kirchhelle	Leverhulme ECR 2017	University of Oxford	Independent Research Fellow
Sandy Knapp	Merit Researcher	Natural History Museum	Non-Departmental Public Body
Celia Knight	Education Consultant	Celia Knight Consulting	Private
Rachel Lambert	Senior Livelihoods Adviser Agriculture Research	FCDO	Government
Zach Lichman	UKRI FLF 2018	University of York	Independent Research Fellow
Keith Lindsey	Head of Department of Biosciences; Chair of New Phytologist Trustees	University of Durham; New Phytologist Trust	HEI; Charitable Foundation
Emily Lines	UKRI FLF 2020	Queen Mary University of London	Independent Research Fellow
Marjorie Lundgren	UKRI FLF 2020	University of Lancaster	Independent Research Fellow
John Mackay	Wood Professor of Forestry	University of Oxford	HEI
Ian Mackay	Senior Researcher in Plant Breeding	Scotland's Rural College	Institute (Scotland)
Luke Mackinder	UKRI FLF 2020	University of York	Independent Research Fellow
Cathie Martin FRS	Group Leader	John Innes Centre	Institute (BBSRC)
Aine McGowan	Partnership Liaison Officer seconded to Gates Foundation	FCDO	Government
Andy Meharg FRSE	Professor Global Food Security Institute	Queens University Belfast	HEI
Andrew Millar FRS FRSE	Chair of Systems Biology; CSA for Environment, Natural Resources and Agriculture, Scottish Government	University of Edinburgh; RESAS	HEI; Scottish Government
Laura Moody	Royal Society URF 2019	University of Oxford	Independent Research Fellow
Laila Moubayidin	Royal Society URF 2017	John Innes Centre	Independent Research Fellow
Jim Murray	Head of School of Biosciences	University of Cardiff; SEB	HEI; Learned Society

Name	Position	Institution	Sector
Naomi Nakayama	Royal Society URF 2015	Imperial College London	Independent Research Fellow
Johnathan Napier	Group Leader	Rothamsted Research	Institute (BBSRC)
Richard Napier	Professor	University of Warwick	HEI
Richard O'Hanlon	Head of Grassland and Plant Sciences	Agri-Food and Biosciences Institute	Institute (NI)
Giles Oldroyd FRS	Russell R Geiger Professor of Crop Science	University of Cambridge	HEI
Anne Osbourn FRS	Group Leader	John Innes Centre	Institute (BBSRC)
Bill Parker	Head of Technical Programmes	AHDB	Levy Board
Geraint Parry	Chair Plant Science Group; ex GARNET Co-ordinator	Royal Society of Biology; GARNET	Learned Society; Community
Simon Pearson	Professor of Agri-Food Technology	University of Lincoln	HEI
Andrew Plackett	Royal Society URF 2019	University of Birmingham	Independent Research Fellow
Wayne Powell FLSW FRSE	Chief Executive Officer	Scotland's Rural College	Institute (Scotland)
Gail Preston	Programme Director Interdisciplinary Bioscience DTP	University of Oxford	HEI
Adam Price	Professor of Plant Breeding	University of Aberdeen	HEI
Tony Pridmore	Professor of Computer Science	University of Nottingham	HEI
Chris Quine	Chief Scientist	Forest Research	Government Research Agency
Christine Raines	Professor; Pro-Vice-Chancellor Research	University of Essex	HEI
Jim Reay	Head R&D Crop Protection Infrastructure & Capital Management	Syngenta	Private
Sarah Robinson	Royal Society URF 2017	Sainsbury Lab Cambridge University	Independent Research Fellow
Ronelle Roth	Royal Society URF 2020	University of Oxford	Independent Research Fellow
Dale Sanders FRS	Director	John Innes Centre	Institute (BBSRC)
Diane Saunders	Group Leader	John Innes Centre	Institute (BBSRC)
Simon Saxby	Chief Executive Officer	LEAF	Private
Robert Scotland	Professor of Plant Systematics	University of Oxford	HEI
Maddy Seale	Leverhulme ECR 2019	University of Oxford	Independent Research Fellow
Alison Smith FRS	Group Leader	John Innes Centre	Institute (BBSRC)

Name	Position	Institution	Sector
Jim Smith FRS	Director of Science	Wellcome Trust	Charitable Foundation
Pete Smith FRS FRSE	Professor of Plant & Soil Science	University of Aberdeen	HEI
Nicola Spence	Chief Plant Health Officer	Defra	Government
Steven Spoel	Head of Molecular Plant Sciences; ex GARNet Chair	University of Edinburgh; GARNET	HEI; Community
Richard Summers	Head of Cereal Breeding & Research	RAGT	Private
Louise Sutherland	Project Development Director	Ceres Agritech Knowledge Exchange Partnership	Technology Transfer
Mark Suthern	National Head of Agriculture	Barclays Bank	Private
Nick Talbot FRS	Executive Director	Sainsbury Lab, Norwich	Institute (Gatsby Charitable Foundation)
Chris Tapsell	UK Research Director	KWS	Private
Leon Terry	Professor of Plant Science; Director of Environment and Agrifood	Cranfield University	HEI
Freddie Theodoulou	Group Leader	Rothamsted Research	Institute (BBSRC)
Iain Thomas	Head of Life Sciences	Cambridge Enterprise	Technology Transfer
Alan Tollervey	Head of Agriculture Research	FCDO	Government
Jurriaan Ton	Professor of Plant Environmental Signalling; Co-director P3 Centre	University of Sheffield	HEI
Lesley Torrance FRSE	Director of Science; Professor of Biology	James Hutton Institute; University of St Andrews	Institute (Scotland); HEI
Cristobal Uauy	Group Leader	John Innes Centre	Institute (BBSRC)
Dieuwertje Van Der Does	Open Plant Project Manager	John Innes Centre	Institute (BBSRC)
Jason Vincent	Head of Synthetic Biology	Syngenta	Private
Richard Williamson	Managing Director	Beeswax Dyson	Private
Kathy Willis	Professor of Biodiversity	University of Oxford; ex Director of Science Kew	HEI; Non-departmental public body
Gary Wilson	Head of Science Portfolio	Gatsby Charitable Foundation	Charitable Foundation
Zoe Wilson	APVC For Research & Knowledge Exchange Faculty of Science	University of Nottingham; Monogram	HEI; Community