WECD
Warwick Economics & Development

Evaluation of the socio-economic impacts arising from BBSRC's investment in wheat research and innovation

Final Report

Biotechnology and
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Research Council

Contents

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Executive summary

This report presents the findings of the evaluation of the socio-economic impacts arising from the Biotechnology and Biological Sciences Research Council's (BBSRC) investments in wheat research and innovation between 2010/11 and 2021/22.

Context

Wheat is critical to global food security. It is the third most produced cereal (after rice and maize), and the second most produced cereal for human consumption (after rice); it provides the highest percentage of calories in the human diet (20%), and is the most significant source of vegetable protein.

With a growing world population, estimated at 10 billion people by 2050, and an increase in average incomes, global demand for food is predicted to increase by 56% by 2050. Global demand for wheat is growing by 1.7% per year. However, the current level of wheat production and productivity improvements are not enough to meet future needs – an additional 132 million tonnes of wheat is required annually by 2050 to meet current consumption levels, meaning that average yields will need to increase 40% in the next 30 years.

Wheat is particularly susceptible to climate change, especially heat. With a 2°C global temperature increase, wheat yields in the Global South are projected to decline by 10-15%.

Therefore, wheat yields must **increase at a rate similar to or higher than growing demand, alongside improving resilience in the face of changing environmental conditions**.

Wheat is the UK's most important staple crop, and the wheat market (supply, demand, and conditions) forms an integral part of the nation's sustainable economic and social infrastructure. **Average yields since 2000 have been broadly stable (at 7.9 tonnes per hectare) but fluctuate year on year as result of weather conditions; this is likely to be exacerbated by climate change.** For example, in 2020, wheat production and yields were at their lowest since 1981 (at 7 tonnes per hectare) due to unusually bad weather. However, in 2021, production and yield stabilised to long-term averages.

The UK is largely self-sufficient in production of grains, producing over 100% of domestic consumption of oats and barley and 90% of wheat. However, the 14 million tonnes of total domestic uses of wheat in the UK in 2020 was met by lower domestic yield (in tonnes per hectare of croppable planted area) due to unfavourable weather conditions for the crop, and increased imports, compared with 2018 and 2019. The UK imports also came at a higher price, with the value of imports of un-milled wheat higher by 55% in real terms to £409 million in 2020. Recent geopolitical events, such as the war in Ukraine, have pushed up global food prices. For example, wheat and maize prices were higher in 2022 than 2021, by 19.7% and 19.1% respectively.

With the UK population projected to grow from an estimated 67.1 million in 2020 to 69.2 million in 2030, a continuous trend of uncertainty around quantities of wheat for domestic uses and reliance on expensive imports to meet demand **would not be sustainable for the UK, as this will negatively impact upon the UK's food security ecosystem**.

Since its establishment in 1994, BBSRC has maintained and nurtured UK national capability in plant and crop science, as the key public funder of this work, through an evolving programme of Higher Education Institution (HEI) and Institute-led research programmes. Within this context, BBSRC is also the main national funder of wheat research, delivered across key Institutes and HEIs: recognising both the national food security and pre-competitive research needs, and the advent of technologies that have enabled the genetic characterisation of wheat, and accelerated genetically-assisted breeding approaches.

BBSRC published a 5-year Wheat Research Strategy in 2013, to recognise the changing wheat landscape of research capability and provide a framework for its future investments. This has included both Institute-led and internationally framed partnership approaches, the latter aiming to coordinate and maximise the value of national research investments to deliver a level of global impact that cannot be obtained by national approaches alone.

Aligned to this vision, **BBSRC invested £221.7 million in wheat research and innovation between 2010/11 and 2021/22**.

The evaluation brief and approach

The aim of the evaluation has been to conduct a socio-economic impact assessment of the BBSRC's investment in its wheat research portfolio between 2010/11 and 2021/22, supported by case study examples. The lines of inquiry for the evaluation were set out as follows:

- To what extent has BBSRC wheat research underpinned:
    - The development of new and improved UK wheat varieties with beneficial traits (e.g., increased yield, increased resilience, improved sustainability)?
    - Research in transformational technologies such as automation, sensing, farmer decision-support, and precision agriculture?
    - Improvements to agronomic practices?
- To what extent has collaboration and partnerships between researchers and relevant stakeholders facilitated the delivery of economic and societal impact?
- To what extent have BBSRC's investments in wheat research been successfully translated into practical and commercial application?
- What is the Return on Investment (RoI) from BBSRC's investment in wheat research over the past 10 years?

To address these questions, the evaluation methodology has involved a combination of primary and secondary research, including: desk-based research and thorough analysis of programme-related management and monitoring data; literature reviews to inform the context and the socio-economic impact quantification and analysis, as well as the case studies included in this report. The evaluation methodology included discussions with key BBSRC staff, alongside an extensive consultation programme with grant holders and external stakeholders. In total, 56 individuals were interviewed, including seven from BBSRC/UKRI, and 49 from other organisations. This programme of research was conducted between August 2022 and March 2023, and its main findings are summarised below.

Research outputs and outcomes

BBSRC investments in wheat research and innovation have produced a range of research and scientific outputs, that have underpinned the development of new and improved UK wheat varieties with beneficial traits (e.g., increased yield, improved resilience). These include:

- **Knowledge generation**, including publications, and the creation of genomic tools, techniques and datasets, e.g., CerealsDB database and website, and National Institute of Agricultural Botany's (NIAB) MAGIC population.
- **Development of germplasm with novel genetic diversity**, e.g., NIAB's re-synthesised wheats (also known as synthetic wheat), the John Innes Centre's Watkins landrace collection, and the University of Nottingham's wild relatives.

Feedback from stakeholder consultations indicates that BBSRC investments have been instrumental in:

- **'Game changing' transformations in wheat genomics** over the last 12 years, notably through contributions to sequencing the wheat genome, enabling researchers to make rapid advances in identifying the genes underlying traits, and generating accurate molecular markers for plant breeders to use. For example, **the Earlham Institute has developed an approach to identify genes in less than a month, instead of over the typical three to six years – accelerating the progress of wheat research**.
- Developing a significant **portfolio of 'phenomenal' resources**, including genetic material (germplasm), and genomic tools and techniques; for example, the wheat TILLING population , and genetic markers developed by the University of Bristol; and there is **strong evidence of take-up by commercial breeders**.

The BBSRC investments have also supported the development of transformational technologies, e.g., field phenotyping, gene editing, and speed breeding. Examples of these include the development of **expertise in precision agriculture and sensing technology**, with pockets of excellence at Rothamsted Research, NIAB, and the universities of Aberystwyth (National Plant Phenomics Centre), Bristol, Lincoln, and Nottingham.

BBSRC's investments in wheat research have been successfully translated into practical and commercial application. For example, there is strong evidence of germplasm, developed through BBSRC funding, flowing to larger and smaller commercial wheat/plant breeders.

Collaboration and partnerships have played a critical role in delivering these outputs. Collaborative approaches have enabled the **formation of longstanding research-industry partnerships**. These linkages are critical to the **translation of research into new commercial wheat varieties** (e.g., re-synthesised wheat), and the take-up of genomic tools. For example, one commercial wheat breeder commented that **90% of the genetic markers they use are from BBSRC research.**

BBSRC investments have also facilitated access to global knowledge, innovation and partners, through contributions to the Wheat Initiative and the International Wheat Yield Partnership (IWYP), both highlighting BBSRC's leadership **in amplifying its national investments by participating in international collaborations.**

The collaborative approach and knowledge sharing have been heralded an **'unquestionable success'** by stakeholders, and have **created a strong community in UK wheat research**; for example, through the Wheat Improvement Strategic Programme (WISP) and Designing Future Wheat (DFW) strategic programmes.

Collaborators have contributed **£30.3 million** in direct and in-kind contributions to BBSRC-funded research projects in wheat research and innovation. Collaborative work and partnerships have led to **further funding**, including for the continuation of BBSRC-funded projects from public, industry and charity partners, and for other research (not directly related to BBSRC-funded research): **£186.2 million in total**.

Overall, as stated by one stakeholder, UK wheat research is on a **'completely different level to five years ago'**, and this can be principally attributed to BBSRC.

Economic impacts and RoI

Economic impacts of publicly funded investments tend to be presented in terms of Gross Value Added (GVA). Facts and assumptions needed to monetise the socio-economic impacts of BBSRC investments in wheat research, and present these in terms of GVA were drawn from in-depth reviews of relevant literature, analysis of the BBSRC investment data; and detailed review of a sample of BBSRC-funded projects. The information gathered through these resources provided useful insights into the pathways from wheat research to different types of actual and potential impacts generated by BBSRC's investment portfolio, i.e., economic, societal and environmental impacts, including:

- productivity impacts, e.g., wheat yield improvements;
- business/market impacts, e.g., spinouts and job creation;
- health impacts, e.g., impacts on diet and nutrition; and
- environmental impacts, e.g., impacts on greenhouse gas (GHG) emissions.

It is customary that economic impacts of public investments in terms of GVA are presented over different periods of time, e.g., 10, 15 and 25 years. However, review of the grants in BBSRC's portfolio of wheat research and innovation (and feedback from the interviews) suggest that BBSRC investments relate to pre-competitive research, that could take relatively longer to materialise (i.e., closer to 20 or 25 years than 10 years). Therefore, it is recommended that the period over which benefits from the BBSRC investments in pre-competitive research are expected to fully materialise is **25 years**, i.e., investments in wheat research need to be treated as **patient capital** by both the private and public sector.

On this basis, it is estimated that the economic benefits that could materialise over a 25-year period from various research and innovation outputs generated by the BBSRC investments would create **£900 million GVA for the UK economy**, yielding **a return of £4 per £1 invested by BBSRC** in wheat research, between 2010/11 and 2021/22.

High-level estimates of economic impacts of BBSRC wheat research investments in the rest of the world have been also calculated on the assumption that 5% of the benefits generated globally from wheat research could be attributed to BBSRC funding. These economic impacts have only been calculated for impacts related to wheat yield productivity gains. Assessment of health and environmental impacts in the rest of the world will require further research (e.g., into health and environmental regulatory regimes in other countries) that falls outside the scope of this study.

Accounting for both UK benefits and benefits in the rest of the world, BBSRC wheat research investments between 2010/11 and 2021/22 could contribute **an additional £1.99 billion to the**

global GVA potentially generated from successful wheat research and innovation outputs, yielding **a return of £8.9 per £1 invested by BBSRC** in wheat research between 2010/11 and 2021/22.

These estimates of economic impacts represent a cautious approach. It has not always been possible within the scope of this research to collect, verify and monetise all possible benefits and impacts potentially arising from BBSRC-funded research in wheat research and innovation. For example, literature research and interviews have highlighted additional benefits that could lead to economic benefits. These include: monetisation of potential financial and economic impacts related to the behaviours and incomes of various economic agents along the value chain of wheat, including breeders, framers, flour millers and retailers; social and economic impacts generated through upskilling and career progression of researchers involved in BBSRC-funded wheat research projects; and additional health and environmental benefits not monetised as part of this research, as not all data is readily available to monetise the causal relationships between changes in wheat quality or productivity, and relevant health and environmental indicators. Further research will be needed to capture the additional impacts on UK/international economies that could be caused by changes in wheat production, productivity or quality.

As noted in the BBSRC Wheat Research Strategy, a range of crops and wider food sources are important for UK and global food security. This evaluation has found that BBSRC funding in wheat research and innovation in the last decade has strengthened wheat research capabilities in the UK and led to innovation and strong strategic partnerships. Benefits and lessons learned from wheat research and innovation funded by BBSRC in the last decade can inform research and operational models for other key crop species, and further strengthen the balanced range of BBSRC research investments within the context of BBSRC's sustainable agriculture and food priority areas.

1. Introduction

1.1. **Between 2010/11 and 2021/22**, BBSRC has invested **£221.7 million** in wheat research and innovation.

Evaluation brief

1.1. BBSRC commissioned WECD to evaluate the socio-economic impact arising from this investment portfolio in wheat research, with the evaluation questions set out as follows:

- To what extent has BBSRC wheat research underpinned:
  - The development of new and improved UK wheat varieties with beneficial traits (e.g., increased yield, increased resilience, improved sustainability)?
  - Research in transformational technologies such as automation, sensing, farmer decision-support, and precision agriculture?
  - Improvements to agronomic practices?
- To what extent have BBSRC's investments in wheat research been successfully translated into practical and commercial application?
- To what extent have collaboration and partnerships between researchers and relevant stakeholders facilitated the delivery of economic and societal impact?
- What is the RoI from BBSRC's investment in wheat research over the past 10 years?

1.3. The BBSRC 5-year Wheat Research Strategy (published in 2013) set out the drivers, opportunities and challenges for responding to pressing strategic priorities, and delivering impact from BBSRC investments in world-class scientific research relating to wheat. The strategy stated that its future wheat research investments would underpin the development of future generations of wheat crops, agronomic systems and industrial processes that would allow wheat to be grown and used more sustainably, whilst maintaining or improving yields and quality traits. BBSRC's current Strategic Delivery Plan also includes a focus on sustainable agriculture to produce safe, nutritious food to feed a growing population, while protecting the environment and mitigating and adapting to climate change. The Strategic Delivery Plan also highlights the importance of driving innovation through strategically supported institutes and campuses, and ensuring that impact is delivered though key national policy and industry partnerships as well as more internationalised partnership approaches. More detail about the BBSRC Wheat Strategy and its role in wheat research and innovation is provided in Section 2.

1.4. Within this broad context, the evaluation findings aim to provide evidence on the outputs, impacts and wider socio-economic benefits underpinned by BBSRC investment in wheat research and innovation in the last decade. In the light of wide-ranging issues surrounding global food security, the evaluation will also inform BBSRC and its stakeholders in forward planning, drawing on insightful information and evidence.

Evaluation methods

1.5. The following research tasks have been conducted to inform this evaluation study:

- **Literature review** – including government and UKRI strategies in this area, UK and global wheat production statistics, impact reports produced in this area to date, and literature discussing potential benefits/disbenefits and markets arising from related research activities.

- **Scoping consultations with BBSRC and UKRI teams** to support understanding of the context and developments around the wheat research portfolio.[1]

- Additional **stakeholder consultations** – interviews with **44 individuals from 28 organisations** were conducted between November and December 2022. A full list of organisations consulted, and the scripts used for these discussions are provided in Appendices A and B respectively.

- **An updated logic model depicting BBSRC's wheat investments portfolio and pathways to impact**, to reflect findings from the literature review and consultations with internal and external stakeholders.

- **Desk-based review of programme management information**, including funding and outcomes data collected through Researchfish, BBSRC internal reporting exercises (e.g., Institute Assessment Exercise) and other BBSRC information (e.g., Impact Showcase brochures).

- **Desk-based review of non-BBSRC databases** (e.g., commercial and market data and other publications (e.g., REF impact case studies).

- **Desk-based review of background information** relating to various projects that could be used to develop **case studies** that describe wider economic and societal impacts of BBSRC-funded wheat research; this research was followed by discussions with project Principal Investigators (PIs) and other stakeholders to discuss background, added value, impacts/benefits, and next steps. An initial list of 20 case studies was reviewed and nine case studies were selected to be included in the report, based on these discussions and desk-based research.

- **Quantification of economic and RoI** of the BBSRC investments in wheat research and innovation over the study period, drawing upon desk-based research and consultations with researchers and stakeholders.

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[1] Seven individuals from BBSRC (including the Global Food Security programme) and Innovate UK. In total, 56 individuals were interviewed including seven from BBSRC/UKRI and 49 from other organisations (including 44 as part of the interviews with stakeholders and additional five in selection and preparation of case studies). See a detailed list of all organisations that have contributed to this evaluation in Appendix A.

1.6. This Final Evaluation Report presents the findings from the evaluation research, including **nine detailed case studies** (see Appendix F).

Report structure

1.7. The remainder of the report is structured as follows:

- Section 2 provides an overview of BBSRC's portfolio of investments made over the assessment period (2010/11 to 2021/22), and the rationale behind investing in wheat research and innovation (including market failures and the intended pathways to impact as illustrated through the portfolio's logic model).
- Section 3 outlines the main research and scientific outputs from the BBSRC investments to date.
- Section 4 presents estimates of economic impacts and the RoI generated by the BBSRC investments in wheat research and innovation over the study period.
- Section 5 provides an overview of wider benefits, including policy-related and skills development.
- Section 6 concludes the report with a summary of the main findings and an outline of issues for further consideration in the future.

2. BBSRC investments in wheat research and innovation

Rationale for investment in wheat research

2.1. Wheat is critical to global food security. It is the third most produced cereal (after rice and maize), and the second most produced cereal for human consumption (after rice); it provides the highest percentage of calories in the human diet (20%) and is the most significant source of vegetable protein.[2]

2.2. With a growing world population, estimated at 10 billion people by 2050, and an increase in average incomes, global demand for food is predicted to increase by 56% by 2050.[3]

2.3. It is estimated that an additional 132 million tonnes of wheat is required annually by 2050 to meet current consumption levels, meaning average yields will need to increase 40% in the next 30 years (as current levels of wheat production are not sufficient to meet future demand).[4] However, wheat is particularly susceptible to climate change, especially heat. With a 2°C global temperature increase, wheat yields in the Global South are projected to decline by 10-15%.[5] Therefore, wheat yields must increase at a rate similar or higher than growing demand, alongside improving resilience in the face of changing environmental conditions.

2.4. Wheat is the UK's most important staple crop, grown on a larger area than any other crop,[6] **and the wheat market (supply, demand, and conditions) forms an integral part of the nation's sustainable economic and social infrastructure – the UK wheat harvest is worth £1.6 billion annually to the UK economy** (more, if processed wheat-derived products are included).[7] Average yields since 2000 have been broadly stable (at 7.9 tonnes per hectare), but fluctuate year on year as result of weather conditions, likely to be exacerbated by climate change. For example, in 2020, wheat production and yields were at their lowest since 1981 (at 7 tonnes per hectare) due to unusually bad weather; however, in 2021, production and yield has stabilised to long-term averages.[8] However, in general, changing climatic conditions (e.g., drier and hotter summers, and milder and wetter winters) have introduced more uncertainties and risks for the quantity and quality of wheat for domestic and industrial uses in the future.

2.5. The UK is largely self-sufficient in production of grains, producing over 100% of domestic consumption of oats and barley and 90% of wheat. However, the 14 million tonnes of total domestic uses of wheat in the UK in 2020 came at a higher price, with the value of imports of un-milled wheat higher by 55% in real terms to £409 million in 2020. **Geopolitical events,** such as the Russian invasion of Ukraine in February 2022, **pushed up food prices** including

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[2] Source: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7668007/

[3] Source: https://www.wri.org/food

[4] Source: Wheat Improvement: Food Security in a Changing Environment (2022), p.vii.

[5] Source: Source: Wheat Improvement: Food Security in a Changing Environment (2022), p.vii.

[6] In 2021, wheat was grown on 1.8 million hectares, representing 41% of the UK's total arable crop area. Source: Defra, Agriculture in the UK 2021: Wheat Production Statistics (2022).

[7] BBSRC, 5-Year Wheat Research Strategy (2013).

[8] In 2021, production was 13.9 million tonnes, and yield was 7.9 tonnes per hectare. Source: Defra, UK Food Security Report 2021 (2021).

wheat. Global wheat and maize prices were more expensive by 19.7% and 19.1% respectively in 2022, in comparison with a year ago. Ukraine supplies nearly 10% of global wheat exports (as well as 14% of corn and 17% of barley exports). Black Sea ports suspended operations, preventing the outflow of the 2021 harvest, whilst the 2022 harvest is dependent on Ukrainian farmers being able to access their land amidst the fighting (the main wheat and maize producing areas are in the east, south and north-east – areas hit hardest by the Russian invasion).[9]

2.6. The Agriculture and Horticulture Development Board's (AHDB) first official UK supply-and-demand estimates for the 2022-23 season indicate that imports are expected to fall by 39%, while there will be a 50% rise in the surplus available for export.[10] However, **reliance on expensive imports** to meet domestic uses would not be sustainable for the UK, as it would negatively impact upon the **UK's food security ecosystem** – particularly as the UK population is projected to grow by 2.1 million over the 10 years to 2030, from an estimated 67.1 million in 2020 to 69.2 million in 2030.[11]

2.7. For the past century, wheat has been subjected to some of the most selective breeding of any grain over time, given its importance to humans and the need to keep its yield as high as possible.[12] As stated in an historic scientific paper:[13]

> *'Breeders continuously strive to develop improved varieties by fine-tuning genetically complex yield and end-use quality parameters, while maintaining stable yields and adapting the crop to regionally specific biotic and abiotic stresses.'*

2.8. Traditional breeding efforts that cross elite lines with one another, and tend to focus on yield improvements, have resulted in the reduction and loss of genetic diversity. This in turn leaves wheat vulnerable to diseases and environmental shocks, particularly as chemical treatments are being phased out.[14]

2.9. To 'correct' these outcomes, breeding better crops (including bringing in resilience traits lost over time) is hugely important for food security globally. To achieve this, knowledge of wheat's genome is needed through sequencing, a method for determining the entire genetic make-up of a cell or organism. However, sequencing the wheat genome has been very complex, the main reason being that it is five times bigger than the human genome (and a hybrid of three different grass ancestors). Only relatively recently, in 2018, was wheat's

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[9] Algebris Investments, Impact of Ukraine-Russia conflict on food security and prices (March 2022); and The Conversation, How the war in Ukraine will affect food prices (March 2022).

[10] See: https://www.fwi.co.uk/business/markets-and-trends/crop-prices/high-uk-wheat-supply-and-recession-overhang-market-outlook

[11] Dates refer to the middle of the year, not decade (i.e., mid-2020, not mid-2020*s*). Source: ONS, National Population Projections (January 2022).

[12] See: https://doi.org/10.1007/978-3-030-90673-3_1 and https://doi.org/10.1007/978-3-030-90673-3_2

[13] See: https://www.science.org/doi/10.1126/science.aar7191; for non-paywalled version, see: https://core.ac.uk/reader/185511665

[14] E.g., in 2020, the EU banned chlorothalonil, the most widely used pesticide in the UK and the most popular fungicide in the US. See: https://www.theguardian.com/environment/2019/mar/29/eu-bans-widely-used-pesticide-over-safety-concerns

complex genome mapped, following nearly 13 years of research.[15] This knowledge enables the designing of genetic markers that can lead to breeding better crops.[16]

Market failures and rationale for public funding

2.10. Better wheat crops mean they are: highly productive, resistant to disease, thriving in soil without artificial fertilisers, minimum use of energy,[17] no environmental damage,[18] while remaining nutritious and safe. Ensuring delivery of these traits requires extensive and dedicated capacity and capabilities for scientific investigation, testing and subsequent exploitation, drawing on partnerships between research and industry, and mainly public funding to support these capabilities.[19] Public funders are in general more likely than commercial funders to focus on pre-competitive research that maintains the full range of genetic diversity, as many of these traits are beneficial in other growing conditions/climates, and provide other beneficial traits such as, for example, conferring resistance to pests, which are currently managed through agrichemicals. Such an approach reflects a long-term view, as these traits are not needed in current varieties, as they often result in a yield penalty; however, they are vital for future resilience in the crop overall. Differences between public and commercial priorities lead to a market failure, where public funding is required to ensure that **research exploring the full range of genetic diversity in wheat is maintained** for **future global food security.**

2.11. Sequencing the wheat genome took 13 years of research and over 200 scientists, proving that collaborative, transnational research and continuous committed investment was needed. Investment in wheat research and innovation from **private sources alone cannot be sufficient** to carry these scientific endeavours, which potentially can **have significant population/social benefits, or require years of trials and tests and may also take longer to deliver results and advantageous returns on investments**. Technology has now advanced considerably since the first efforts to sequence the wheat genome, and the cost of sequencing has declined dramatically – now researchers are focused on producing pan-genomes – for example, the Wheat 10+ Genomes Project (see also Wheat Genome Sequencing Case Study).

2.12. Achieving commercial benefits from the results of research related to wheat could take many years and **may not return the investment within the 8-12-year window typically expected**

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[15] See: https://www.science.org/doi/10.1126/science.aar7191; for non-paywalled version, see: https://core.ac.uk/reader/185511665

[16] A genetic marker is a gene or DNA sequence with a known physical location on a chromosome which controls a particular gene or trait. Genetic markers are points of variation (a 'flag') that can be used to identify individuals or species. Genetic markers are important developments in the field of plant breeding; for example, by accelerating crop breeding programmes through improved crossing selections e.g., see paragraph 3.16. See https://doi.org/10.1080/13102818.2017.1400401 and https://www.nature.com/subjects/genetic-markers

[17] Referring to both, energy required to produce Nitrogen fertiliser and other agri-chemicals, as well as less use of farm machinery in agricultural practices.

[18] Referring to reducing or minimising negative environmental impact such as fertiliser run-off into watercourses, which causes nutrification of the water, negatively impacting wildlife.

[19] See: https://www.nature.com/articles/nplants201518

by investors and shareholders.[20] Therefore, public investments are required to overcome this market failure, and ensure that both challenge-led and fundamental research are progressing.

2.13. Similarly, high research and development (R&D) costs and low profit margins in wheat may prohibit more commercial breeding and seed companies operating in this area. It could also be that RoI may not be as lucrative, or participation and engagement is regulated in a way that profit-making is constrained. For example, feedback from stakeholders as part of this evaluation (supported by background research) suggests that, whilst wheat is a globally important crop, it is not as lucrative as other investments, e.g., maize and soy. Maize and soy can be highly profitable for seed companies, as farmers must purchase new seeds every year for growing, whereas wheat growers are able to save their own seed and plant it the following year.[21]

2.14. Stakeholders also noted that, to date, the plant breeding sector has focused on improving traits related to increasing yields or quality of the final product. These characteristics are attractive to a producer, as they offer higher returns in an industry with tight margins and restrictive criteria on the quality needed to serve a particular market (e.g., quality wheat for flour milling). However, **there is less pull for other traits, like nutrition, sustainability, and resistance to diseases that are not present in the UK** (e.g., wheat blast). The focus on yield is partly due to how the current system is set up. AHDB's Recommended List[22] is the biggest route to farmers and getting varieties into the field – and the guaranteed way to get on the Recommended List is via yield. If a variety performs 2% better on yield than the control, then it is automatically included.

2.15. Therefore, it is highly likely that other traits will attract less private investment (at least, at this stage), with **public funding needed to signal and accelerate research related to issues affecting other traits and smaller segments of the population**. These are related to nutrition (e.g., fibre content), the environment (e.g., reduced chemical inputs), and resilience traits (e.g., heat tolerance). **There is also the consideration of generating benefits across the wheat supply chain**; for example, balancing the interests of farmers (e.g., yield), millers (e.g., processing quality), and consumers (e.g., nutritional quality), in a disaggregated supply chain where primary production and retail are disconnected, with poor market signals between them. Moreover, where commercial companies are not going to develop varieties suitable for the Global South (due to insufficient profit generated from selling into this market to justify investments in R&D), public funding is needed to support such research.

2.16. A further challenge is that **plant breeding is a slow operation, with a long route to commercialisation, if successful**. Developing a new variety may take 6-10 years, although it can take as much as 20 or 25 years. For example, one stakeholder noted that wheat crosses made in February 2023 are not expected to hit farmers' fields until 2030. This means that

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[20] Source: GRU annual reporting (2019).

[21] See: https://www.gov.uk/guidance/farm-saved-seed

[22] The AHDB Recommended List publications and resources provide information on wheat (and other crop) yield and quality performance, agronomic features, and market options to assist with farmers' variety selection. See: https://ahdb.org.uk/knowledge-library/recommended-lists-for-cereals-and-oilseeds-rl

investments in wheat research need to be treated as **patient capital** by both the private and public sector (i.e., neither impacts nor returns should be expected in the short term, although returns may be similar/as high as those expected from venture capital).

2.17. Stakeholder feedback and background research highlighted that the UK is widely regarded as having a **world-leading plant science research sector**, **particularly in wheat**, delivered from a diverse, high-quality research base across public and private institutions, including the John Innes Centre, Rothamsted Research, and NIAB.[23]

2.18. Given wheat's importance to global and UK food security, and combined with UK research excellence in wheat genetics, BBSRC's investments in wheat research support the UK's ambition to deliver world-leading wheat research and innovation;[24] for example, underpinning **sustainable wheat production, creating higher yielding and more resilient wheat crops in response to a growing population and a changing climate, and thereby ensuring national and global food security**. Much of this research is led by teams at BBSRC's strategically supported institutes.[25]

2.19. Since its establishment in 1994, BBSRC has maintained and nurtured UK national capability in plant and crop science. BBSRC has been the key public funder of this work, through an evolving programme of HEI and Institute-led research programmes.[26]

2.20. As noted in paragraph 1.3, BBSRC published a 5-year Wheat Research Strategy in 2013, to recognise the changing wheat landscape of research capability and provide a framework for its future investments. The strategy set out the drivers, opportunities and challenges for responding to pressing strategic priorities , **and delivering impact from BBSRC investments in world-class scientific research relating to wheat**. The strategy stated that research funded through BBSRC investments in wheat would underpin **the development of future generations of wheat crops, agronomic systems, and industrial processes that would allow wheat to be grown and used more sustainably, whilst maintaining or improving yields and quality traits**. For example, the strategy recognised that the yield and quality of the wheat crop would remain important, but there was a critical need to enhance a wide range of sustainability factors, including: resilience to climatic variation and disease; adaptations for different environments and soil types; positive benefits for the agri-ecosystem and reduction of negative environmental impacts; processing and usage qualities (for human and animal consumption and industrial biotechnology applications); waste minimisation, and recycling of nutrients. Furthermore, the strategy highlighted that a sustainable plan for maintaining and augmenting wheat research capability required the

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[23] E.g., see Langdale Report, UK Plant Science Research Strategy (2021); HM Government, UK Strategy for Agricultural Technologies (2013); and BBSRC, 5-Year Wheat Research Strategy (2013).

[24] See: BBSRC, 5-Year Wheat Research Strategy (2013); and, BBSRC, Strategic Delivery Plan 2022-25 (2022).

[25] These institutes include: Earlham Institute, Institute of Biological, Environmental and Rural Sciences (IBERS) at Aberystwyth University, John Innes Centre, Quadram Institute Bioscience, and Rothamsted Research.

[26] BBSRC was established by Royal Charter in 1994, by incorporation of the former Agricultural and Food Research Council (AFRC) with the biotechnology and biological sciences programmes of the former Science and Engineering Research Council (SERC). BBSRC's investments in wheat research and innovation build upon those of its predecessor organisations.

ensuring of a continued stream of innovation in the sector, and the supply of key skills to industry.

2.21. Within this context, **BBSRC is also the main national funder of wheat research, delivered across key Institutes and HEIs**, recognising both the national food security and pre-competitive research needs, and the advent of technologies that have enabled the genetic characterisation of wheat and accelerate genetically-assisted breeding approaches. Investments made by BBSRC have included both Institute-led and internationally framed partnership approaches; the latter of these aim to coordinate and maximise the value of national research investments, to deliver a level of global impact that cannot be obtained by national approaches alone. BBSRC also **aligns its strategic priorities in wheat with key government funders**.[27] In addition to BBSRC, organisations that invest in wheat research and innovation in the UK include:

- UK government funding: Defra (e.g., through the Wheat Genetic Improvement Network), and the Foreign and Commonwealth Development Office (FCDO).[28]
- AHDB.
- Plant breeders undertake their own research, as well as provide direct and in-kind contributions to UK institute and university projects.[29]
- European research funders, such as the European Research Council and Horizon 2020.
- Charities and not-for-profits, for example, Gatsby Foundation, Bill & Melinda Gates Foundation, The Morley Agricultural Foundation, and the John Innes Foundation.
- Universities, through contributions to research infrastructure (e.g., glasshouses, IT), and PhD student and post-doctoral researchers.
- UKRI, through Innovate UK and other UKRI research councils.

2.22. As highlighted by stakeholders, whilst other public funding does make important contributions (e.g., Defra co-funded the Wagtail project, and AHDB co-funded the Yellowhammer project with BBSRC), their investments are at a much smaller scale than BBSRC.

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[27] Within UKRI, BBSRC provides the vast majority of public funding for wheat research and innovation, principally under its 'Bioscience for sustainable agriculture and food' strategic challenge.

[28] Defra funds the Wheat Genetic Improvement Network (WGIN), one of four Defra long-term networks to improve major UK crop varieties, see: https://defracropgenetics.org/. The direct contribution of Defra to WGIN is £1.7 million for a 5-year programme, from 2018 to 2023 (extended to 2024), see: https://www.rothamsted.ac.uk/news/wgin-funded-2023. BBSRC also aligns its science calls with Defra and AHDB priorities e.g., on diseases.

[29] Including KWS, Limagrain, RAGT, and Syngenta.

Overview of BBSRC's wheat research investment portfolio 2010/11-2021/22

2.23. Between 2010/11 and 2021/22, BBSRC invested **£221.7 million** in wheat research and innovation, i.e., an **average investment of approximately £18.5 million per annum, through 485 grants.**[30] This BBSRC investment in wheat research and innovation represents approximately **6% of BBSRC's total research investments of £3.65 billion over the same period**.[31]

2.24. BBSRC investments in wheat research and innovation are grouped under four funding mechanisms:

a. **Strategic institute investments**, with funding distributed via **Institute Strategic Programmes (ISPs)** (i.e., John Innes Centre, Rothamsted Research, Earlham Institute, and Quadram Institute Bioscience) – this includes WISP, the Rothamsted Research 20:20 Wheat programme, and the DFW programme.

b. **Responsive mode funding**, including Strategic Longer and Larger grants (sLoLas).

c. **Initiatives**, including international and domestic initiatives such as: the IWYP; Sustainable Crop Production Research for International Development (SCPRID); various Newton Fund schemes, e.g., Virtual Joint Centre with Brazil, China and India in Agricultural Nitrogen; the Crop Science Initiative (CSI); and the Bioinformatic and Biological Resources Fund (BBR).

d. **Fellowships**, including Future Leaders Fellowships, which aim to develop the next generation of future research leaders, and David Phillips Fellows, which are designed to support outstanding early-career researchers.

2.25. The most notable examples of BBSRC's investments are described below:

- WISP ran from 2011 to 2017 and was a £16 million comprehensive pre-breeding programme – the first of its kind in over 20 years. The programme aimed to guarantee the sustainability of wheat production against the background of growing global population and changing environment. The programme brought together experts from five UK institutions: the John Innes Centre, Rothamsted Research, NIAB, the University of Nottingham, and the University of Bristol.
- The 20:20 Wheat Programme was a Rothamsted Research ISP that ran from 2012 to 2017. It aimed to more than double the yield in the UK to 20 tonnes per hectare in 20 years. Since the programme's first five-year phase concluded, its work has been incorporated into the Designing Future Wheat programme.

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[30] See graph of BBSRC investment over time in Appendix C. 485 unique grant references correspond to 331 unique project or work packages (WP) that could be broken down into further sub-projects.

[31] Investment in wheat research accounted for approximately one third (32%) of BBSRC total investment in crop science between 2017/18 and 2021/22: £109.8 million from a total crop science portfolio of £343.4 million.

- DFW is also an ISP, bringing together eight UK research institutes and universities, namely: the Earlham Institute, the John Innes Centre, Quadram Institute Bioscience, Rothamsted Research, the University of Bristol, EMBL-EBI, NIAB, and the University of Nottingham. The programme has provided genomic resources for the global wheat research community and focused on identifying and reproducing key wheat traits to breed the next generation of higher yielding, resilient wheat.[32]

- The Wheat Initiative brings together 14 countries, two international research organisations and six private companies. The Initiative nurtures collaborations between research and development programmes for wheat improvement in both developed and developing countries.

- IWYP is a major international programme catalysed through BBSRC leadership, which supports collaborative research between public and private organisations around the world to raise the genetic yield potential of wheat by 50% by 2035. The programme has already leveraged USD2.50 from other funders for every USD1 invested in IWYP by BBSRC.[33]

2.26. Table 2.1 shows the allocation of the BBSRC investment in wheat research and innovation among the four funding mechanisms (as described in paragraph 2.22).

Table 2.1: Investments and projects by funding mechanism 2010-22

BBSRC investment in wheat research and innovation, 2010/11-2021/22		
Funding mechanisms	**(£m)**	**(%)**
ISPs	114.83	51.8
Responsive mode	52.48	23.7
Initiative	51.86	23.4
Fellowships	2.53	1.1
Total	**221.70**	**100%**

Logic model

2.27. BBSRC's investments in wheat research and innovations fund a variety of activities to deliver numerous scientific and socio-economic outputs and outcomes as set out in the portfolio's logic model – presented in Figure 2.1 and discussed in more detail in section 3.

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[32] Analysis of BBSRC investments over time shows that wheat research project spend peaked in 2017 at £25.9 million, coinciding with the start of the DFW ISP, and following the publication of the BBSRC Wheat Strategy in 2013. Further detailed presentation of BBSRC's funding over the evaluation time period is included in Appendix C.

[33] Source: BBSRC, Benefits to the UK from IWYP (November 2019) (BBSRC figures, not calculated by WECD).

Figure 2.1: BBSRC wheat portfolio logic model

CONTEXT: Wheat provides 20% of total calories consumed by humans daily. However, wheat is highly vulnerable to weather and climatic conditions. To address these vulnerabilities and keep yield as high as possible, wheat has been subjected over time to selective breeding, resulting in the reduction and loss of its genetic diversity, with the main impacts including a reduction in its ability to adapt and decreasing its resilience to new diseases. The relatively recent sequencing of the wheat genome (2018) provides opportunities to improve its traits and produce more productive and better-quality wheat for people and the environment. For this, an extensive infrastructure for scientific investigation and testing is needed.

RATIONALE for public investment in wheat research: Given wheat's importance to global and UK food security, combined with UK excellence in wheat genetics, BBSRC's investments support the UK's ambition to be a world leader in research underpinning sustainable wheat production, creating higher yielding and more resilient wheat crops in response to a growing population and a changing climate, and thereby ensuring national and global food security. In addition to BBSRC, other public funding sponsors in wheat research in the UK include: the Department for the Environment, Food and Rural Affairs (Defra), the Foreign, Commonwealth and Development Office (FCDO), the Agriculture & Horticulture Development Board (AHDB), and Innovate UK.

INPUTS

BBSRC funding

2010/11-2021/22: **£221.7m**
- Strategic institute: £114.8m
- Responsive mode: £52.5m
- Targeted initiatives: £51.8m
- Fellowships: £2.5m

Staff/researcher time

Facilities and infrastructure (e.g. glasshouses, labs)

Strategic advice and support from internal BBSRC resources and external partners

ACTIVITIES

High-quality fundamental research in wheat

Multi-disciplinary research around agricultural systems

Underpinning research in transformational technologies (e.g. field phenotyping, gene editing)

Engagement and collaboration between research and industry (e.g. Monogram, conferences)

Training and skills development
- PhDs and post-docs
- Support specialists (e.g. data analysts, technicians)
- Industry placements and other secondments

MAIN (RESEARCH) OUTPUTS

Development of germplasm with novel diversity

Creation of genomic tools, techniques & datasets

Development of transformational technologies

Increased resources (incl. publications) demonstrating new knowledge and insight

Collaborations with industry, policy and other organisations

Knowledge exchange between research and industry, and research and policy

Generation of intellectual property

Generation of further funding for research from public, industry and charity partners

Skilled wheat researchers with industry and policy knowledge

Research spin-outs

Processes

Committed public investment in wheat research (patient capital for revenue and infrastructure)

A national coordinator and a facilitator of wheat (non-medical bio-science) research activities, identifying opportunities, market failures and monitoring progress of investments and research outputs

OUTCOMES

Short-term (1-5 years)

New knowledge

Improved efficiency and reliability of gene and trait discovery

Development of wheat lines with improved traits

Development of strong partnerships with industry and others

Material, tools and technologies taken up and built upon by commercial (e.g. breeders) and other users

Delivery of national (and international) wheat capability

UK continues contributions to wheat genome sequencing and other international ontologies

Medium-term (5-10 years)

(New) wheat lines used in commercial and other breeding programmes

Exploitation and licensing of intellectual property

Improved crop management, development of novel agri-ecosystems approaches

Evidence-based policy influence in relation to sustainable varieties, agronomic practices, gene editing

UK is recognised as a world-leader in wheat research

Long-term (10+ years)

Increased wheat productivity (yield) and efficiency

Improved resilience to diseases and climatic conditions

Increase in the genetic potential of wheat by 50% by 2035

IMPACTS

Economic

Increased value of wheat crop to the UK and global economy

Maintaining UK's high levels of self-sufficiency for industrial and domestic uses

Retaining favourable trade conditions for the UK

Increased income for UK businesses (including farmers and growers)

Safeguarding of jobs

Creation of new businesses

Societal

Ensuring UK and global food security

Improved health through increased nutritional content of wheat (e.g. fibre)

Securing of rural economies (UK and global)

Environmental

More efficient use of resources (e.g. nitrogen, phosphorous, water)

Reduction in energy use and negative environmental impacts (e.g. CO_2 emissions, pollution of land and watercourses)

3. Main outputs and outcomes of BBSRC investments in wheat research and innovation

3.1. A range of research outputs have emerged from BBSRC's investments in wheat research since 2010. These are summarised in this section. Information on outputs and outcomes draws on analysis of BBSRC's wheat portfolio data (e.g., from the Researchfish outcomes collection system), stakeholder consultations, and desk-based research and analysis.

3.2. The Researchfish data presented in this section is accurate as of March 2022, as this represents the end of the most recent UKRI research outcomes submission period that could be used within the timeline of this evaluation. Note that: a) any data for 2022 represent a partial year (e.g., will only include January/February/March); and b) some projects are ongoing and expected to report additional outputs, outcomes and impacts as they progress, and contribute further information into the Researchfish system after they complete.[34]

3.3. Data drawn from the Researchfish outcomes collection system has also been de-duplicated to prevent double counting of outcomes and impacts. This means that raw data retrieved directly from Researchfish and without processing may differ from figures recorded here.[35]

3.4. Throughout this section, project examples refer to BBSRC grant references (e.g., BB/P010768/1) – **further details can be found on the UKRI Gateway to Research platform.**[36]

Overview of BBSRC-funded wheat research main outputs and outcomes

3.5. The main outputs and outcomes that have emerged to date from the BBSRC investments in wheat research and innovation are as follows:

- **Knowledge generation**, including **2,973 unique publications** between 2010 and 2022.
- **Creation of genomic tools, techniques and datasets**, e.g., CerealsDB database and website, NIAB's MAGIC population, the wheat TILLING population resources,[37] and University of Bristol genetic markers.

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[34] BBSRC only started using the system in November 2014 and it took several years for researchers to become familiar with using the platform. The trend seen here is therefore likely to be a result of: i) early grants not being reported on: ii) changes in reporting behaviour over time, including behaviour changes resulting from introduction of sanctions; iii) increased investment in wheat research over the period; iv) changes in academic output over the period. Prior to the introduction of Researchfish, BBSRC used the Research Outputs System and grant final reports – the data from these sources was not backfilled into Researchfish by BBSRC and researchers were not required to do so themselves.

[35] For example, raw data without processing would suggest that there has been further funding of over £560.2 million; however, with the data de-duplication process, this figure is more accurately closer to £186.2 million.

[36] See: https://gtr.ukri.org/

[37] Developed as part of a joint project between the University of California Davis, Rothamsted Research, the Earlham Institute, and the John Innes Centre.

- **Development of transformational technologies**, e.g., field phenotyping, gene editing, and speed breeding.

- **Development of germplasm with novel diversity**, e.g., the John Innes Centre's Watkins landrace collection, and the University of Nottingham's wild relatives.

- **Collaborations with industry, policy and other organisations, including international collaborations** with the International Maize and Wheat Improvement Centre (CIMMYT), and the Brazilian Agricultural Research Cooperation (Embrapa). Collaborators have contributed **£30.3 million** in direct and in-kind contributions to BBSRC-funded research projects.

- **Knowledge exchange between research and industry, and research and policy**, for example, through the Breeders Toolkit (BTK) and Breeders Observation Panel (BOP).

- **Policy influence**, including participation in national advisory committees providing scientific advice on a range of food and agricultural topics, and training practitioners (e.g., commercial breeders) and other researchers.

- **Generation of intellectual property** (IP), with 38 related outputs, including **five instances of IP being licenced**.

- **Further funding for continuation of BBSRC-funded projects** from public, industry and charity partners and **follow-on leverage and collaborations for other research** (not directly related to BBSRC-funded research) – **£186.2 million in total.**

- **Research spinouts** – six of which continue to be involved in wheat research and innovation.

3.6. More detail about these outputs and outcomes, including examples, are provided below.

Knowledge generation – publications and resources

Publications

3.7. BBSRC-funded wheat research has generated **2,973 unique publications** between 2010 and 2022. These have been published in high profile plant science and genetics journals.[38] Several landmark publications resulted from BBSRC investments regarding the UK's contribution to international efforts to sequence the wheat genome, through the International Wheat Genome Sequencing Consortium (IWGSC), including in 2012, 2014, and 2018.[39]

3.8. A bibliometric analysis conducted by BBSRC indicates that BBSRC wheat research is internationally competitive. For example, the 'category normalised citation impact' of

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[38] See: https://www.scimagojr.com/. Search categories 'Genetics' and 'Plant Science'.

[39] Grant references: 2012: BB/G012865/1, BB/G013985/1, BB/G013004/1, B/J004588/1 (GRO), and BB/H022333/1; 2014: BB/J003166/1; and 2018: BB/J00426X/1, BB/J004669/1, BB/P016855/1, BB/J003557/1, and BB/M014045/1.

BBSRC-attributable wheat research publications is more than twice the world average at 2.20, and 30% of BBSRC-attributable wheat publications are in the top 10% of the most cited documents globally. Bibliometric data were obtained from the Web of Science and InCites platforms (via Clarivate).

Tools and methods, models and databases, and software

3.9. BBSRC investments in wheat research have also **generated novel tools, methods, models, databases, and software**. As a few consultees involved in research noted, there has been an **'explosion' in genotypic and phenotypic data and the tools to analyse these over the past decade**. These outputs enable wheat researchers and plant breeders to be more effective and efficient; examples are given below.

Tools and methods

3.10. A total of **175 tools and methods** were reported. **Biological samples represented more than half the total tools and methods reported** (60%, 105 products). This covers wheat traits such as drought tolerance, resistance to wheat rusts, kernel size, and root structure, as well as biological samples of wheat wild relatives (e.g., goatgrasses), which could improve the genetic basis of wheat. New technology assay or reagents comprised almost one quarter of tools and methods reported (23%, 41 products). Examples of tools and methods include:

- The University of York's improved assay to describe the diversity of arbuscular mycorrhizal fungi within roots and in the surrounding soil, improving resource-use efficiency and yield performance through reduced inputs (BBSRC grant reference: BB/H014373/1).[40]
- NIAB's development of a physiological assessment, presented via a simple 'leaf colour chart', to change the way nitrogen fertiliser is applied in India to reduce input costs, improve profit margins and reduce environmental impact (BB/T012412/1).
- The University of Nottingham's high-throughput plant phenotype screening for ethylene sensitivity, which helps roots sense soil compaction. The method has been used to screen 1,000 wheat landraces in the Watkins collection and has applicability for tomatoes and rice[41] (BB/V00557X/1).

Databases and models

3.11. A total of **256 databases and models were reported**. In terms of data types, **89% (228) were databases or collections of data**. Examples of databases and models generated include:

- Nextstrain for wheat yellow rust: wheat yellow rust is the first plant pathogen to be added to the Nextstrain open-source platform. The website assists researchers investigating

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[40] Further details on individual grants can be found on Gateway to Research: https://gtr.ukri.org/

[41] E.g., 156 rice populations at the International Rice Research Institute (IRRI) have already been phenotyped.

how new pathogen strains emerge and spread – the addition of yellow rust provides researchers the ability to study the diversity of strains on a global scale (BB/M025519/2).

- The CerealsDB database and website was created by the University of Bristol to provide a range of facilities for the study of the wheat genome and has been designed with commercial breeders in mind. There have been over 1.5 million unique visits to the website (50,000 unique visits per month) and datasets have been downloaded over 48,000 times since the website launched in 2017 (to March 2022) (BB/N020421/1).

Software

3.12. A total of **154 software outputs were reported**. Most software outputs were pure (system) software (46%, 71 outputs), followed by webtools or applications (43%, 66 outputs). **75% of software outputs were made available under an open-source licence**. Examples of software reported through BBSRC wheat projects include:

- Earlham Institute's Wheat Data Portal: hosted on Grassroots, this portal has served over 7,100 page visits from users in 31 countries (from its launch in 2014 to March 2022), allowing researchers early access to full wheat genomes even before publication. Notably, this software was the main route of dissemination of the TGAC v1 Chinese Spring 42 wheat genome prior to its inclusion in Ensembl Plants (BB/L024144/1).

- The University of Bristol's Axiom® Wheat HD Genotyping Array – developed in collaboration with Affymetrix for large-scale, high-throughput genotyping of wheat, this is now a commercial product. Bristol also developed a unique array specifically designed for wheat breeders, which has been well received by industry (BB/I003207/1, BB/I017496/1 and BB/L020718/1).

- The Sainsbury Laboratory's AgRenSeq software is a pipeline to identify candidate resistance (*R*) genes in plants directly from a diversity panel. The team have received requests for collaboration from academia and industry (BB/J003166/1).

Creation of genomic tools, techniques, and datasets

Examples of transformations in wheat genetics and genomics

3.13. BBSRC investments have supported **'game changing' transformations in wheat genomics**[42] over the last 12 years – most notably UK efforts to sequence the wheat genome. The assembly and annotation of the wheat genome, combined with the computational power to scan sequences, has become a vital tool for UK and international wheat research and breeding efforts, enabling researchers to make rapid advances in identifying the genes underlying traits, and generating accurate molecular markers for plant breeders to use. For example, **Earlham has developed an approach to identify genes in less than a month,**

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[42] As best described by one research consultee but also reflecting the general feedback received from many stakeholders participating in this evaluation.

instead of the typical period of three to six years, accelerating the progress of wheat research.[43] As one research consultee commented:

> ***'Sequencing the wheat genome is transformative, leading to accelerations in breeding and the discovery of genes underlying key traits…BBSRC funding has enabled the UK scientist to play an important leadership role in delivering assembled wheat genomes.'***

3.14. Feedback from the interviews with stakeholders indicated that wheat research funding has resulted in the **creation of 'phenomenal' resources** for the UK wheat community.[44] These include the NIAB MAGIC population, NIAB re-synthesised wheat lines, John Innes Centre Watkins collection, and the wheat TILLING population. These resources facilitate gene discovery underpinning important traits, bring novel genetic diversity into wheat, and help breeders create improved wheat varieties.

3.15. These resources are made openly available through Ensembl Plants (wheat), hosted by the European Bioinformatic Institute (EBI), the Germplasm Resources Unit (GRU) at John Innes Centre, and through the Earlham Institute. For example, the wheat TILLING populations are well-used by researchers and industry. The resource helps researchers and plant breeders identify the effects of gene mutations in different copies of their target genes. Mutations can be used to improve nutritional value of wheat, increase the size of wheat grains, and/or generate additional variability in flowering genes to improve adaptation in the context of climate change. **The TILLING database has over 2,000 unique users across 5,000 sessions from 2017 to March 2022.**

3.16. BBSRC funding through WISP and DFW has supported the development of genetic markers, and there is strong evidence of take-up taken up by commercial breeders. Markers enable breeders to screen for phenotypes that might never appear in the field (e.g., yellow rust resistance), ensuring that important or interesting genes are not screened out and lost. One breeder commented that **90% of the markers they use are from BBSRC research**, with the University of Bristol being particularly successful in developing markers: one of the breeders interviewed for this evaluation uses the 'snip chip' marker developed by Bristol, and CIMMYT have also taken up Bristol's markers and added them to their own arrays, highlighting the international take-up of BBSRC-funded research.

3.17. Figure 3.1 provides examples of genomics tools and techniques, supported by BBSRC funding, which have enabled the transformation in wheat research over the last decade.[45]

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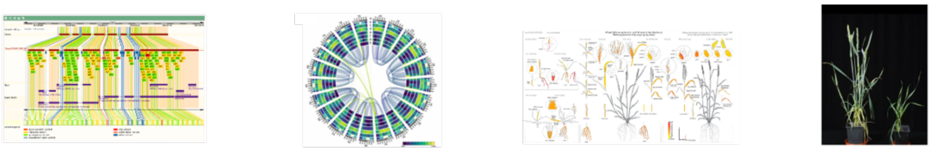
[43] Source: Brookdale Consulting, Earlham Institute Economic Evaluation (2018).

[44] As best described by one consultee but also reflecting the general feedback received from many stakeholders participating in this evaluation.

[45] Source: John Innes Centre.

Figure 3.1: Wheat genomics step-change – examples of tools and techniques



Mutations in every wheat gene *(Krasileva et al 2017)*

Wheat genome sequence *(Clavijo et al 2017, IWGSC 2018)*

Wheat gene expression atlas *(Borrill et al 2016, Ramirez-Gonzalez et al 2018)*

Speed breeding *(Watson et al 2018, Ghosh et al 2019)*

Quick cloning approaches (AgRenSeq, MutRenSeq) *(Arora et al 2019, Steuernagel et al 2016)*

Pangenome sequencing and haplotypes *(Walkowiak et al 2021, Brinton et al 2021)*

Wild wheat relatives sequencing and germplasm *(Gaurav et al 2022, Wingen et al 2017)*

Open access resources (data and germplasm) *EnsemblPlants, GRU, www.wheat-training.com*

Development of transformational technologies

Speed breeding

3.18. Scientists at the John Innes Centre, Earlham Institute, and Quadram Institute Bioscience, in collaboration with the University of Queensland (Australia), have developed protocols for rapid plant generation, dubbed 'speed breeding'.[46] By manipulating light conditions, they were able to achieve 50% shorter generation times in breeding conditions that permitted a faithful study of a range of adult plant phenotypes, allowing crossing efficiencies comparable to plants grown in glasshouses. The study and subsequent media coverage achieved international reach, and speed breeding has now been widely adopted as an enabling tool for crop research, including by breeders and CIMMYT.

Precision agriculture and sensing

3.19. Stakeholders noted that the **UK is strong at precision agriculture and sensing technology**, with pockets of excellence at Rothamsted Research, NIAB, and the universities of Aberystwyth (National Plant Phenomics Centre), Bristol, Lincoln and Nottingham. Phenomics **supports efficiency** in wheat breeding and data analysis; for example, researchers can monitor 10,000 trial plots per year – compared to 100 plots a decade ago.

3.20. For example, Rothamsted Research has developed a real-time wheat-head counting system, which uses machine learning to identify and count the number of wheat spikes in digital images taken under natural field conditions. The *DeepCount* technology could help predict yield and increase efficiency and save costs compared to labour-intensive and expensive manual counting. **One plant breeder has early access to this technology and is currently trialling it in their commercial breeding programme**.

3.21. However, according to the feedback received from stakeholders, **phenomics is lagging genetics, particularly in field screening, and how varieties perform in real-world**

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[46] See: https://www.earlham.ac.uk/news/space-inspired-speed-breeding-crop-improvement

conditions in the field. Moreover, outputs are more challenging to translate to breeders than genetic material and markers, and not all breeders have the capabilities to buy and scale-up expensive equipment.

Development of germplasm with novel diversity

The Germplasm Resources Unit and the Watkins Landrace Collection

3.22. The GRU at the John Innes Centre is a biological and seed conservation unit and has been part of National Capability infrastructure supported by BBSRC since 2012. BBSRC funding for 2017-2022 was £717,900.

3.23. The GRU aims to capture a broad genetic diversity of the UK's major strategic crops and wild relatives, to support plant science and crop improvement through breeding. A key focus is wheat, but the unit also holds pea, barley and oat germplasm. The germplasm-associated data is catalogued in an in-house-tailored management system and public database (SeedStor). Overall, the GRU custodianship spans 26 public collections, totalling 52,900 accessions.

3.24. The GRU provides critical national and international supplies of wheat germplasm. For example, over the last five years (2017-22), the GRU **has distributed more than 27,000 accessions to support over 1,700 scientists, breeders, educators and hobby growers from 49 countries.**[47] UK user requests represent the largest number; however, requests from international users comprise 34% of the total – **seeds were distributed to 34 countries globally.**

3.25. Stakeholder feedback noted that underpinning BBSRC funding for germplasm collections is very important, and the plant science community would face challenges if BBSRC were to reduce funding for such infrastructure.

3.26. The GRU is also well-respected and well-used by plant breeders; for example, 12% of requests for wheat TILLING mutants are from industry breeders.[48] Breeders also agreed they would send their varieties back to the GRU, increasing the number of lines with unique genes which are openly accessible. The GRU also coordinates the BTK, a key output from the DFW strategic programme, which translates discoveries from the programme to commercial pre-breeding (see also paragraph 3.26).

The A.E. Watkins collection of Landrace Wheat is a particularly significant collection hosted by GRU. In the 1930s, Watkins acquired 826 landrace cultivars of bread wheat which originated from local markets in 32 countries, covering Asia, Europe, and Africa. The collection houses a high level of genetic diversity – higher than in modern European winter bread wheat varieties. The increased knowledge regarding the diversity of the Watkins

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[47] Source: Germplasm Resources Unit: https://www.jic.ac.uk/research-impact/germplasm-resource-unit/

[48] Source: GRU IAE Review (2019).

collection was used to develop resources for wheat research and breeding through the WISP and DFW programmes.

Landraces are becoming increasingly important as a wheat breeding resource. An estimated 75% of the genetic diversity of crop plants was lost in the last century, due to the replacement of high yielding modern varieties. Landraces hold large genetic diversity and are locally adapted, so gene pools made of different landraces grown in different ecological conditions can be used in breeding to enhance wheat yield, quality, and resistance to biotic (e.g., diseases like yellow rust) and abiotic (e.g., heat, salt) stresses, particularly in response to climate change. Landraces are therefore a unique resource to improve wheat yields, to meet the demands of an increasing world population in the face of a global changing climate.[49]

The following abstract from a recent publication (6 January 2023) also demonstrates the use of the collection and potential outputs and benefits:

'Breeding for less digestible starch in wheat can improve the health impact of bread and other wheat foods. The application of forward genetic approaches has lately opened opportunities for the discovery of new genes that influence the digestibility of starch, without the burden of detrimental effects on yield or on pasta and bread-making quality. In this study we developed a high-throughput in vitro starch digestibility assay (HTA) for use in forward genetic approaches to screen wheat germplasm. The HTA was validated using standard maize and wheat starches. Using the HTA we measured starch digestibility in hydrothermally processed flour samples and found wide variation among 118 wheat landraces from the A. E. Watkins collection, and among eight elite UK varieties (23.5 to 39.9% and 31.2 to 43.5% starch digested after 90 min, respectively). We further investigated starch digestibility in fractions of sieved wholemeal flour and purified starch in a subset of the Watkins lines and elite varieties and found that the matrix properties of flour rather than the intrinsic properties of starch granules conferred lower starch digestibility'.

Breeders Toolkit (BTK) and Breeders Observation Panel (BOP)

3.27. BTK and BOP are two major outputs from the DFW programme and support the delivery of a pipeline of germplasm with novel traits to plant breeders developed through WISP.[50] The BTK is the DFW's own 'recommended list' of pre-breeding lines from academic experimental trials which have shown these lines contain an improvement compared to their elite parent. Based on this experimental data, the commercial breeding partners of DFW decide which lines are accepted into the BTK and multiplied for multi-site commercial testing. The material selected includes molecular markers, making it easier for breeders to pull in BBSRC-funded genetic material. As one commercial breeder commented:

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[49] See: https://link.springer.com/book/10.1007/978-3-030-77388-5

[50] Overall, the WISP programme developed 26,000 lines derived from landraces, re-synthesised wheats, and wild relatives. Source: John Innes Centre IAE Review (2019).

> ***'DFW has been extremely useful, as it distils down the best pre-breeding lines on offer…the lines come with markers, allowing the trait of interest to be quickly integrated and tracked through the breeding process.'***

3.28. The **BOP was an unintended output and benefit of the DFW programme** – researchers and breeders realised there was too much material to cover in just the BTK. The BOP provides access to wider material, enabling researchers and particularly breeders to screen DFW diversity panels for novel traits, such as disease resistance. **Without the BTK and the BOP, breeders would be overwhelmed by the amount of material and datasets**.

Development of new varieties

3.29. There is strong evidence of germplasm developed through BBSRC funding flowing from research to public breeding programmes, other University/research programmes and commercial plant breeders. This evidence includes:

- **Public breeding programmes:** Agarkhar Research Institute (India), Agricultural Institute Osijek (Croatia), Agroscope (Switzerland), CIMMYT (Mexico), ICARDA (International Centre for Agricultural Research in the Dry Areas, Lebanon), Indian Institute of Wheat and Barley Research (IIWBR), and the US Department of Agriculture (North Dakota, Kansas, North Carolina, South Carolina).

- **University/research programmes**: Hohenhiem University (Germany), Institution of Agricultural Research and Higher Education of Tunisia (IRESA), Kansas State University (USA), Lilongwe University of Agriculture and Natural Resources (LUANAR, Malawi), SRUC (UK), the University of Guelph (Canada), the University of Leicester (UK), and the University of Sydney (Australia).

- **Commercial wheat breeders:** Breun (Germany), Cerela Inc. (Canada), DSV, KWS, Limagrain, RAGT, Sejet Plant Breeding (Denmark), Sensako (South Africa, now part of Syngenta), and Syngenta.

3.30. These activities are facilitated by strong engagement and collaboration between research and industry, enabled through WISP and DFW strategic programmes, and tools such as the BTK and BOP (described above). Plant breeders are picking up new genetic diversity through BBSRC-supported wheat research; for example, through the Watkins collection, and the University of Nottingham's wild wheat relatives. Moreover, there is international exchange of germplasm through CIMMYT and IWYP.

3.31. There have been **two key successes** in this area. The commercial breeder DSV has developed a line including Watkins material which reached National List stage 1; DSV has also developed a re-synthesised wheat line from NIAB's programme which reached National Listing stage 2.[51] As DSV commented:

> ***'For lines to be good enough to be entered into National List testing is a big tick in the box for material coming through from BBSRC funding.'***

3.32. Stakeholders **anticipate the development of further wheat lines from BBSRC research in the future**. For example, one breeder estimated they will deliver derivatives from 5-10 wheat lines from the BTK in the next 2-3 years, and in the next 10-12 years, there will be 5-6 derivatives in their European programme.

3.33. Furthermore, stakeholders noted that disease resistance is a key strength of genetic material developed from BBSRC research. For example, **resistance to the Warrior race of yellow rust has been found in some landraces in the Watkins collection, and industry is now breeding this into elite wheat lines** – impact in the form of wheat varieties with built-in resistance will come in the next 10 years. This is particularly important as chemical treatments begin to be phased out. The NIAB and DSV Re-synthesised Wheat Case Study is presented in Appendix F.

Collaborations and knowledge exchange

Creation of a critical mass and community of practice

3.34. BBSRC funding has enabled the **creation of a critical mass and a community of practice in UK wheat research**, principally through the WISP and DFW strategic programmes, which cemented the foundations laid by the Monogram Cereals & Grasses Research Network (see also paragraph 3.42). The approach has been an **'unquestionable success'**[52], and highlights **BBSRC's leadership** in providing long-term strategic funding for a coordinated community of wheat researchers. Several consultees also noted the importance of including universities as part of building a wider wheat research community.[53]

3.35. BBSRC investment has also supported the international wheat community, through contributions to Wheat Initiative and IWYP. This approach enables **BBSRC** to **amplify its national investments by participating in international collaborations**, facilitating access to global knowledge, innovation and partners.

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[51] References: NL1: DSV321124:Wat110xRobigusxGerman; NL2: DSV3202105:SHWxGrahamxGraham. National lists are lists of varieties of agricultural crop and vegetable which have been approved for certification and marketing in the UK. Before a new crop variety can be placed on the market, it must undergo a statutory testing process. Successful varieties are placed on the National List or register of approved varieties. Official trials are conducted, in most cases for a minimum of two years, to test each candidate variety for a range of characteristics, which together determine its distinctness from other varieties, as well as its value to growers and end-users. See: https://www.bspb.co.uk/plant-breeding/regulation-testing-and-protecting-varieties/

[52] As best described by one research consultee but also reflecting the general feedback received from many stakeholders participating in this evaluation.

[53] The universities of Bristol and Nottingham were partners in DFW, whilst Imperial College London, and the universities of Lancaster and Leeds are new partners in the next ISP, Delivering Sustainable Wheat (DSW).

3.36. BBSRC wheat strategic programmes have also enabled the **formation of strong research-industry partnerships** – these linkages are **critical to translation** of research into new commercial wheat varieties with improved traits, like yield, nutrition, disease resistance, and quality. For example, the DFW programme's targeted approach through the BTK and BOP (see earlier paragraphs 3.27 and 3.28), coupled with screening lines and developing genetic markers, makes it easier for industry to 'plug in'. BBSRC funding in this case is important, as it gives industry relatively easier and less expensive access to resources generated by research that improves the genetic diversity of wheat.

Networks and collaborations

3.37. The BBSRC funding for wheat research has been successful at building strong research and innovation collaborations including: i) academic-academic collaborations; and (ii) academic-industry collaborations, both internationally and domestically.

3.38. Overall, **387 collaborations**, **leveraging £30.3 million in direct and in-kind contributions**, have been reported as the result of BBSRC funding for wheat research.[54] The majority of contributions (70%) were direct financial contributions, representing £21.2 million.[55]

3.39. Universities and academia provided £13.4 million in direct and in-kind contributions (44% of total contributions), followed by the public sector partners at £9.3 million (31%), and the private sector at £4.6 million (15%).

3.40. **Over half of collaborations (57%) were with international partners**.

3.41. Collaborations covered a wide range of projects, with different types (e.g., studentship, networking), partners (research, industry), length, and value. The examples of project collaborations listed below highlight the range of these collaborations:

- A collaboration between NIAB and the Centre for Crop Disease Management (CCDM) at Curtin University, Australia, which supported joint grant proposals to European funders and a visiting fellow to NIAB. A total in-kind contribution from CCDM to the value of £18,000 was reported (BB/E007201/1).

- The UK-China Phenomics-Metabolomics Network, a collaboration between Huazhong Agricultural University (China) and the Aberystwyth University focusing on plant phenomics, plant metabolomics, and the role of nitrogen in plant stress responses. The collaborators contributed travel and subsistence costs for a research trip to China to the value of £1,100 (BB/I016937/1).

- The University of Liverpool collaborated with BASF to sequence wheat cultivars – BASF directly contributed £20,000 for the sequencing and promoter capture. Following this,

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[54] As reported via Researchfish submissions.

[55] It should be noted that there is a possibility of financial contributions within collaborations also being reported as further funding – as such, **collaboration contributions and further funding leverage should not be combined.**

BASF funded an iCASE studentship on using open data and machine learning approaches to decode the regulatory regions of wheat (BB/N020871/1).

3.42. These collaborations, facilitated via BBSRC funding, have helped support advancements in wheat research and innovation in the UK and internationally, through, for example:

- Joint research projects, publications, and funding applications.
- Supporting improved skills and the development of the next generation of wheat researchers, through the supervision or funding of PhD studentships, and other research placements.
- New genetic markers and genotyping data, enabling faster mapping of traits and improved crossing selections for research and industry breeding programmes.
- Wheat lines with improved traits (e.g., enhanced iron content, improved resistance to mildew).
- Improved data interaction between UK and US storage systems, enabling quicker and easier movement of data.
- International transfer of germplasm with novel traits.

3.43. An example of networks and collaborations sustained beyond BBSRC inputs is described below.

The Monogram Cereals & Grasses Research Network was established in 2005, through BBSRC funding, as a cereals and grasses research community. Currently, it has 197 members from a variety of fields, including plant genetics, physiology, pathology, breeding, and bioinformatics. Its main aims are to act as a focal point for the UK cereals and grasses community, promote information exchange, and provide a link to help lower the entry barriers for new researchers. Overall, **Monogram started the process of creating a UK wheat research community – this was further cemented by the WISP and DFW strategic programmes**.

As part of the network, Monogram holds an annual conference, bringing together researchers and industry to discuss recent results and discoveries, exchange ideas, network, and collaborate. The 2021 Monogram conference was hosted virtually by the James Hutton Institute. It attracted 300 delegates from 30 different organisations, including participants from Germany, Australia, and India. The 2022 conference was hosted by the University of Leeds and attracted 120 in-person delegates alongside over 100 virtual participants. The 2023 conference was held at the University of Reading in April 2023.[56]

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[56] No details about number and country of participants were available at the time of the writing of this report.

Monogram provides a critical networking capability for UK researchers and industry in wheat and other cereal and grass crops, particularly for early-career researchers. For example, Monogram supports early career researchers through its Monogram Early Career Excellence Awards which recognise outstanding young researchers in the field of small grain cereal and grass research in the UK. The winners receive a £300 cash prize and the opportunity to present their work at the conference. As one organiser of Monogram 2021 commented:

'The meeting is an excellent opportunity for the more junior members of the community to give a talk alongside experts in the field, which is vital in encouraging the next generation of crop scientists in the UK'.[57]

Monogram provides a link to commercial scientists and plant breeders, supporting the translation of fundamental research and commercial exploitation. This is particularly useful for early-career researchers to support the development of industry contacts and framing of breeder challenges and priorities, but also supports general research-industry collaboration and partnerships, as well as secondments and career moves. The conference **is now entirely sponsored by plant breeders and other industry organisations**, and three industry representatives sit on the Monogram 13-member Steering Group, namely Limagrain, KWS, RAGT.

Secondments and career progression

Secondments

3.44. Researchers reported **162 secondments or placements** as part of BBSRC-funded wheat projects.[58] The reported secondments were hosted by **95 different organisations**. The majority of these secondments (68, 72%) were hosted by a research organisation or university (including in the UK and internationally), whilst 17 were hosted by public bodies (e.g., NERC, UK Government Office for Science), and seven by industry (e.g., ADAS, KWS, RAGT). Examples of secondments include:

- A four-month secondment to Syngenta for a PhD student from the University of Bristol, to facilitate knowledge exchange on wheat transformation and double haploid production (BB/N002628/1).

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[57] Source: https://www.hutton.ac.uk/news/monogram-2021-online-event-crop-research-and-plant-breeding-communities

[58] Defined as a secondment, placement, or internship that has taken place in connection with the research supported by the BBSRC award; this includes outgoing individuals (i.e., anyone delivering the research who goes on secondment at another organisation while engaged with the BBSRC-funded research), and incoming individuals (i.e., anyone coming to work with the team/organisation on research supported by the BBSRC award). This does not include students who are not funded by the award, and does not include career breaks. See: https://www.ukri.org/manage-your-award/reporting-your-projects-outcomes/additional-funder-questions/#contents-list

- Secondment of a researcher to from the University of Nottingham to CIMMYT to carry out field work in Mexico, analysing the photosynthetic responses of doubled haploid wheat lines (BB/N021061/1).

- A technician from NIAB secured a six-month secondment at AHDB to use the MAGIC population and undertake root phenotyping and QTL mapping. The individual went on to do a PhD in wheat genetics at NIAB, via the University of Cambridge DTP (BB/M008908/1).

- Professional placement for a PhD student from the John Innes Centre to work with the KWS pre-breeding team for four months, improving their knowledge of commercial breeding processes (BBS/E/J/000C0677).

3.45. International funding schemes were particularly valuable in enabling international collaboration, knowledge exchange, and learning. Examples of these include: IWYP-funded projects, the Virtual Joint Centres with Brazil, China & India in Agricultural Nitrogen programme, and the European Research Area (ERA-NET) on Coordinating Action in Plant Sciences (ERA-CAPS) programme. International host organisations include: CIMMYT, the Government of Thailand, universities in Brazil, Europe, the US, India and South Africa, and private industry (e.g., Secobra Recherches, Biogemma).

Career progression (next destination)

3.46. The next destination outcome tracks where researchers funded by BBSRC wheat projects move to during the lifetime or following the completion of a project. To date, there were **330 individuals reported as moving to other positions**. The majority of these positions were research-related, with the most common role being post-doctoral researcher (47%, 156 individuals), followed by Research Students (19%, 63 individuals).

3.47. **Approximately one quarter of next destination moves were reported as international** (27%, 90 instances): destination countries include the US, France, Australia, India, China, and Mexico – all important centres of wheat research and innovation. Host organisations include Orion Genomics (US), the National Research Institute for Agriculture, Food and the Environment (INRAE, France), Curtin University (Australia), Punjab Agricultural University (India), Sichuan Agricultural University (China), and CIMMYT (Mexico).

3.48. **The majority of researchers reported moving to another university/academic/research setting (57%), though a significant number moved to private companies (22%, 74 moves)**. This includes plant breeders (Bayer, Limagrain, KWS, Syngenta), but also other private companies where genetics and data skills are highly sought after, for example, IBM, Orion Genomics, and Tropic Bioscience, as well as sole trader consultancies.

Generation of intellectual property (IP)

3.49. BBSRC-funded wheat projects have generated **38 IP products** from 13 different organisations. Four of these patents were reported as having been licenced, as follows:

1. Method for increasing seed weight (patent number: EP1794302), generated by Rothamsted Research (BB/D019001/1).

2. As part of DARPA funding, the Earlham Institute's Air-seq technology, developed in collaboration with the Natural History Museum, detects, extracts and sequences the DNA of aerosol samples, and was licenced to Kromek to build devices for biological threat monitoring (BBS/E/T/000PR9818).

3. IP for an apparatus and method for determining spectral information (patent number: WO2019122891) – this has led to the creation of a new company (**Fotenix,** see also paragraphs 3.55 and 4.18) based on the patent (University of Manchester, BB/M005143/1).

4. Method of increasing seed yield (patent number: WO2018130828) – this has been licenced to several companies to test its effect in crops (John Innes Centre, BBS/E/J/000PR9787).

Further funding and leverage

3.50. BBSRC wheat research projects have secured **£186.2 million in further funding**.

3.51. **The majority of further funding comes from the public sector, representing £145.6 million** (78% of the total). BBSRC funding accounts for the majority of public funding (£108.8 million, 75% of the sector total). Researchers have also been successful in securing funding from European and international sources, highlighting the high regard in which UK wheat research is held. **Examples of funders** include:

- **UK:** AHDB, DSIT (formerly BEIS), Defra, Newton Fund, Scottish Government, UKRI (including BBSRC, EPSRC, Innovate UK, MRC, and NERC), and the Welsh Government.
- **European:** European Commission (including Horizon Europe), European Cooperation in Science and Technology (COST), European Research Council and the Independent Research Fund of Denmark.
- **International:** Australia (Australian Research Council, Grains Research & Development Corporation), Brazil (government, Agricultural Research Corporation, FAPESP), China (government), Mexico (government, CONACYT), and USA (DARPA, USAID, Department for Agriculture).

3.52. The charity and not-for-profit sector has contributed **£33.6 million**, with one grant from the Bill & Melinda Gates Foundation accounting for 72% of the sector total (at £24 million). Other charity funders include: the British Society of Plant Pathology, CGIAR, the Gatsby Charitable Foundation, the Global Crop Diversity Trust, The Royal Society, 2Blades Foundation, and the Wolfson Foundation.

3.53. Plant breeders (particularly Syngenta) **account for 85% of the £3.9 million private funding**. Other private sector funders include: Agrii, Aziotic Technologies, Betaseed, NVIDIA and L'Oréal.

3.54. **Further funding** goes towards the following costs:

- Research grant: £168.7 million (91%)
- Studentships: £8.5 million (5%)
- Fellowships: £5.7 million (3%)

- Capital/infrastructure (including equipment): £2.7 million (1%)
- Travel and consumables: £0.4 million (<1%)

3.55. Nearly **one third (29%) of private sector further funding was for studentships**, representing £1.1 million, highlighting the industry's contribution to generating the next generation of wheat researchers. This is a relatively low-risk investment for breeders, compared to other forms of collaborative research and development, and it can generate high value-added outcomes.

Research spinouts

3.56. BBSRC investments in wheat research have led to seven spinout companies in total over the assessment period (2010-2022). Of these spinouts, one has been dissolved, three are still directly connected to wheat research and another three are not exclusively conducting wheat research, but their research has an impact on wheat research and innovation. The spinout that was dissolved was **Mycoblade.** Mycoblade was established by the University of Exeter in 2017 and held a patent for a novel fungicide treatment for a pathogen that causes Septoria leaf blotch, a very important wheat disease. The company was dissolved in 2020.

3.57. The three spinouts that are still directly connected to wheat research are described below.

1. **Curtis Analytics provides** testing and analytical services for the measurement of asparagine, helping the food industry mitigate acrylamide in their products – acrylamide is a probable carcinogen and is formed when starchy foods are cooked at high temperatures. A spinout from Rothamsted Research in 2017, the company holds contracts major bread and breakfast cereal producers, farmers and crisp producers.
2. **Fotenix**, a spinout from the University of Manchester, was established in 2018 and aims to develop and deploy 3D multi-spectral imaging cameras for tractor and robotic mounting in order to identify disease threats and stresses on crops at an early stage. The company is already selling some of its products.
3. **SugaROx** was formed in 2018 to take forward research conducted at Rothamsted Research for a sugar signal that promotes growth and development in crops. Applied as a spray, it enhances yield, supports recovery from drought, stimulates flowering, and suppresses sprouting. The focus is on wheat, but it is likely to have wider application.

3.58. Economic impacts for the UK are generated by the wheat-related research and commercial activities of these businesses, and these have been accounted for in the assessment of the economic impacts by the BBSRC investments in wheat research and innovation.

3.59. The three spinouts that are not exclusively focused on wheat research, but whose research may have an impact on wheat research and innovation, are the following:

1. **Norfolk Plant Sciences**, which is a spinout from the John Innes Centre and The Sainsbury Laboratory, and was established in 2007 as the UK's first GM crop company to commercialise antioxidant-rich purple tomatoes. The spinout is involved in wheat research alongside research in crops like peas, potatoes and aubergines (with the potential, however, to translate beneficial traits from these plants into wheat).

2. **PulseON Foods** was formed in 2021 by Quadram Institute Bioscience and New Food Innovation to support the commercialisation of its unique, whole-cell pulse flour, which enhances the nutritional value of foods, particularly to support gut health.

3. **The Smarter Food Company** is a spinout from Quadram Institute Bioscience with a mission to prevent Type 2 Diabetes and other health conditions through developing food products incorporating a novel type of broccoli that could help lower high blood sugar. The company has recently launched its first product, a vegetable soup.

Other outputs – engagement activities and awards

Engagements

3.60. A total of **3,333 engagement activities** were reported by BBSRC-funded wheat research grants. Engagements include various activities such as presentations and workshops. The most common activity reported by researchers was giving a talk or presentation (42%), followed by participation in a workshop (23%). For example, researchers at NIAB gave a lecture to Limagrain's global wheat breeding team (approximately 40 staff) on wheat re-synthesis and pre-breeding, resulting in seed requests for distribution to various Limagrain breeding locations (see BB/E006868/1). Researchers from Rothamsted Research discussed gene editing and genetic modification with Defra Chief Scientific Advisor Gideon Henderson (for gene editing, see also paragraph 5.3), as part of the DFW programme work package on increased efficiency and sustainability.

3.61. BBSRC-funded wheat researchers also featured in national and international broadcast media and news (2% of total engagement activities, 67 instances). Examples include:

- Channel 4's *Food Unwrapped* series featured three BBSRC-funded researchers from Rothamsted Research (BBS/E/C/000I0280); the University of Sheffield's SoilBioHedge experiment, (BB/L026066/1); and the Quadram Institute Bioscience's research on developing bread with more resistant starch (fibre) (BBS/E/F/000PR9786).

- A TV interview with BBC *East Midlands Today* discussing the research conducted by the University of Nottingham (BBS/E/J/000PR9781).

- Radio interviews for: BBC Radio 4's *Farming Today* by John Innes Centre researchers; and Australia's ABC Radio *National Science Show* on crop diversity and new plant breeding methods by researchers at Aberystwyth University, BB/M009459/1).

Awards and recognition

3.62. Academic and civil awards and recognition demonstrate the high regard in which UK plant sciences (including wheat research) is held. Stakeholder consultations highlighted the strong reputation of UK research institutes.

3.63. Researchfish data also show that BBSRC-funded researchers have reported receiving **509 awards and recognitions** during the evaluation period. This includes academic recognitions such as being personally invited to be a keynote speaker at a conference (246 instances, 48%), appointments as an editor to a journal or book (11%, 57 instances), and attracting visiting researchers (24 instances, 5%).

3.64. It is also reported that UK organisations have attracted international talent from other parts of the world. **Impacts emerging from these collaborations include strengthened relationships between the host and visiting organisation, joint publications and funding applications, and novel research projects.** For example, as part of the NUCLEUS project, the University of Aberdeen hosted a Research Fellow from São Paulo State University (Brazil) to build on their research on the impact of grasses in Brazilian crop systems on resource acquisition (BB/N013204/1).

3.65. Notable awards include national honours (4 instances, 1%), research prizes (40 instances, 8%), medals (17 instances, 3%, and appointments to advisory positions of external bodies (12%, 60 instances). Examples of awards and recognitions include:

- An OBE for services to plant sciences for a researcher at the John Innes Centre, and an OBE for services to agricultural sciences and biotechnology to a senior manager at NIAB.
- The Jeanie Borlaug Laube Women in Triticum Award 2019 was awarded to post-doctoral researcher at the John Innes Centre and The Sainsbury Laboratory for their work on rapid resistance gene discovery and cloning.
- Rank Prize for Nutrition 2018 to researchers at the John Innes Centre and University of Bristol for pioneering research which has enabled plant breeders to exploit cereal genomics to develop improved wheat cultivars.
- A researcher from Embrapa (the Brazilian Agricultural Research Corporation) secured a fellowship to spend a year at Rothamsted Research working on the interactions between the Fusarium head blight pathogen and wheat, resulting in three joint publications with Rothamsted Research researchers.

4. Economic impacts of BBSRC wheat research investments and RoI

4.1. This section presents an overview of estimates of monetised economic impacts from the research outputs of BBSRC's portfolio of investments in wheat research and innovation, between 2010/11 and 2021/22. Estimates of RoI generated by BBSRC's investments in this period are also presented.

Overview of approach

4.2. Calculating the monetary values of socio-economic impacts relies on: a) facts about the outcomes and impacts of research and innovation projects (e.g., what the research is about, what has been achieved, and for whom); and b) assumptions about what would be the potential benefit, when benefits are expected to materialise, who is likely to be affected, and what would have happened in the absence of BBSRC's investments.

4.3. To establish these facts and assumptions, in addition to reviewing relevant literature and programme data (activities, outputs and outcomes), a sample of BBSRC-funded projects were reviewed in detail (descriptions of these projects are presented in Appendix F). The information gathered through these resources has provided useful insights into the pathways from research to different types of actual and potential impacts generated by BBSRC's investment portfolio, i.e., economic, societal and environmental impacts, including:

- productivity impacts, e.g., wheat yield improvements;
- business/market impacts, e.g., spinouts and new businesses and employment;
- health impacts, e.g., impacts on diet and nutrition; and
- environmental impacts, e.g., impacts on GHG emissions.

4.4. It has not always been possible within the scope of this research to collect, verify and monetise all possible benefits and impacts potentially arising from BBSRC-funded research in wheat research and innovation. For example, literature research and interviews have highlighted additional benefits that could lead to economic benefits. These include: monetisation of potential market, financial and economic impacts related to the behaviours and incomes of various economic agents along the value chain of wheat including breeders, farmers, flour millers and retailers; social and economic impacts generated through upskilling and career progression of researchers involved in BBSRC-funded wheat research projects; and additional health and environmental benefits not monetised as part of this research as not all data is readily available to monetise the causal relationships between changes in wheat quality or productivity, and relevant health and environmental indicators. Further research will be needed to capture these additional impacts on the UK economy and internationally.

4.5. Within this context, productivity, business, health, and environmental impacts have been monetised using data and assumptions drawn from the case studies and interviews, and verified through the literature review, as follows:

- The metrics used to assess **productivity-generated economic impacts** relate to: **yield, productivity, and value of yield**. The following assumptions were made in relation to outputs of wheat research[59] (such as tools to accelerated genetic improvement of wheat):
    - **Improving wheat productivity** – BBSRC-funded research supports ongoing wheat productivity increases of 1% per year[60] for 5 years then continuing at 5% without further increases.
    - **Improving crop health** (valued in terms of yield that would otherwise be lost) – with assumptions on the reductions of disease outbreaks such as yellow rust and periodic major disease prevention such as fusarium head blight (FHB).
    - **Improved crop quality** – it is assumed that this provides a transformational uplift in wheat value of 10% in the long term (in years 10 and 20 over 25 years).
    - Baseline data related to wheat crop such as: **croppable land (in hectares/ha), yield tonnes per ha, value/value per tonne,** are based on the information provided national statistics included in the publication *Agriculture in the United Kingdom 2021* (last updated in October 2022).[61] It has been assumed that the **proportion of UK and global wheat production likely to benefit:** 40%.
- **Health benefits** arising from research to improve the quality of wheat (for example, wheat high in resistance starch, a type of dietary fibre, that could boost fibre intake) have been monetised using data by the Department of Health and Social Care (DHSC) Calorie Model, and include: **health benefits arising from improvement of diets/reduced calorie intaking and impacts on obesity**; and savings for the NHS and for social care.[62] Resistant starch could also help tackle other health issues, including bowel cancer[63] (as high fibre content has been linked to reducing bowel cancer)[64]. Isolating the contribution of wheat quality on reducing these health risks or deaths, and therefore, estimating the contribution of BBSRC-funded projects on these benefits will require further primary and secondary research, to establish the monetary relationships between fibre intake, proportion made up of flour and wheat intake, and likelihood of prevention or reduction of bowel cancer. This research has not been conducted as part of this assessment.
- **Environmental benefits** have been calculated utilising information provided by HM Treasury guidance on the carbon prices per tonne of CO2e for each year that the CO2e

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[59] These assumptions are applicable to both wheat research in general and BBSRC-funded projects.

[60] Tadesse W, Sanchez-Garcia M, Assefa SG, Amri A, Bishaw Z, Ogbonnaya FC, Baum M., 'Genetic Gains in Wheat Breeding and Its Role in Feeding the World'. *Crop Breed Genet Genom*. 2019;1:e190005; see: https://doi.org/10.20900/cbgg20190005

[61] See: https://www.gov.uk/government/statistics/agriculture-in-the-united-kingdom-2021/chapter-4-accounts

[62] Department of Health and Social Care Calorie Model, August 2018.

[63] See:https://www.sciencedaily.com/releases/2013/02/130219140716.htm

[64] See: https://www.cancerresearchuk.org/about-cancer/causes-of-cancer/diet-and-cancer/wholegrains-fibre-and-cancer-risk

will be reduced. [65] These calculations are currently limited to known products/outputs and their impacts from research funded , e.g., a new variety of wheat with a 50% reduction in viscosity used in the distilling process for Scotch grain whisky). Further primary and secondary research will be required to establish any additional environmental benefits such as those arising from growing new wheat varieties' and the impacts on off and on-farm inputs in the form of fertiliser, chemicals, and irrigation.

- To estimate **business benefits**, assumptions have been made related to the generation of **spinouts from BBSRC-funded research** (described in paragraphs 3.54-3.57 in section 3). As mentioned in paragraph 4.4, additional research will be required to explore and verify the nature and extent of further economic and business benefits for various agents along the wheat value chain, including breeders and farmers.

4.6. It is customary that economic impacts of public investments on the economy tend to be presented in terms of **GVA**[66] over a period of time during which benefits are expected to materialise. Investments made to date would yield benefits into the future, and therefore, the monetary cumulative value of these future benefits (in £) will need to be calculated in terms of their net present value in £[67] (to enable assessment of the return to BBSRC investments over the study period).

Estimated economic impacts and RoI

UK Economy

4.7. Table 4.1 summarises estimates of economic impacts for the UK economy in terms of GVA. It is customary that future values are calculated over different time periods, i.e., benefits and impacts materialising in 10 years;[68] 15 years; and 25 years; this is the approach that has been followed in assessing economic impacts of the BBSRC investments. However, the evaluation research and interviews have shown that taking early stages of wheat research into the market (and also scaling these up) can be as high as 20-25 years (see paragraph 2.16). Therefore, it is recommended that the benefits from BBSRC investments in pre-competitive wheat research and innovation are presented over a 25-year. On this basis, it is estimated

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[65] See: https://www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal

[66] 'Gross Value Added' (GVA) measures the contribution to the economy of each individual producer, industry or sector. Simplistically, it is the value of the amount of goods and services that have been produced, less the cost of all inputs and raw materials that are directly attributable to that production – see https://www.gov.uk/government/statistics/rural-productivity/rural-productivity-and-gross-value-added-gva. The UK input-output analytical tables are used to estimate the proportion of GVA generated in different industries and sectors.

[67] 'Net Present Value' (NPV) represents the discounted total value of future sums of benefits discounted to the present. The Green Book sets out a framework for measuring benefits that arise in the future, and comparing them with those that arise today. To achieve this, benefits in future years are converted to a value in today's money. This is known as a 'present value' calculation. It requires a discount rate to be applied to future benefits. The green book applies a standard discount rate of 3.5% per annum to future benefits. A reduced rate of 1.5% per annum applies to policies that impact health or life outcomes.

[68] Impacts materialising earlier/within 10 years would be highly unlikely.

that **£897.9 million GVA could be generated by wheat research outputs for the UK over a 25-year period**.

4.8. Determining additionality[69] in complex environments that involve a large number of contributors and sponsors is not straightforward. Moreover, data related to funding of wheat research by the public sector in the UK is not systematically collected, and not readily available, except for BBSRC investments (and Defra contributions to specific programmes in the study period, such as WGIN)[70]. However:

- As noted in paragraphs 2.19-2.21, BBSRC has been the main (UK public) funder for dedicated early/pre-competitive wheat research. Drawing also on multiple sources of reported research expenditure by the main UK public funders of wheat research and innovation (e.g., Defra, AHDB and FCDO),[71] as well as feedback from stakeholders during this evaluation, it can be inferred that no more than an additional £20 million-£25 million in total could have been invested in wheat research and innovation in the UK by other UK public funders within the study period (i.e., between 2010/11 and 2021/22). This means that approximately 90% of UK public funding in wheat research and innovation in this period could be attributed to BBSRC (£221.7 million out of a total £240 million-£250 million).

- The interviews and desk-based research also suggest that attribution to BBSRC could be relatively high for wheat productivity-related benefits, i.e., between 80%-100%. The general feedback from stakeholders participating in this evaluation has been captured by one research stakeholder, who noted that wheat research is on a 'completely different level to five years ago', and this can be directly attributed to BBSRC. Industry stakeholders also recognised that BBSRC research delivered translational benefits; as one commercial plant breeder commented, 'I can see something I can use in 85% of BBSRC outputs'.

4.9. Within this context, Table 4.1 also presents the proportion of GVA/economic impact that could be directly attributed to BBSRC investments, at 80% and 90% attribution levels.

4.10. Table 4.2 presents the return on BBSRC's £221.7 million wheat investments, showing a return of **£4 per £1 invested by BBSRC** (meaning that, when accounting for attribution, an estimated £3.24-£3.64 would not have been generated without the BBSRC wheat research funding).

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[69] Additionality is the extent to which something happens as a result of an intervention or investment that would not have occurred in the absence of this intervention or investment.

[70] And more recently, wheat-crop-related research investments as part of the Farming Innovation Programme https://www.gov.uk/government/news/cutting-edge-farming-projects-to-get-share-of-30-million

[71] Including review of https://devtracker.fcdo.gov.uk, https://ahdb.org.uk/reports-reviews and additional various Government/Defra announcements and publications, e.g., https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/69574/pb13795-greenfoodproject-wheatsubgroup.pdf; https://www.ncl.ac.uk/cre/research/current/relu.html (the £27 million flagship Rural Economy and Land Use Programme (Relu), programme funded by ESRC, NERC, BBSRC, Defra and Scottish Government between 2003-2013); and https://www.parliament.uk

4.11. **These calculations are conservative**; as discussed in paragraph 4.4, it has not always been possible within the scope of this research to collect, verify and monetise all possible benefits and impacts potentially arising from BBSRC-funded research in wheat research and innovation.

Table 4.1: Estimates of economic impacts (GVA) from BBSRC investments[72]

Economic benefits to the UK	GVA (£ millions)		
	Net Present Value of GVA generated over 10 years	Net Present Value of GVA generated over 15 years	Net Present Value of GVA generated over 25 years
Productivity impacts	162.1	304.5	586.3
Health impacts	90.0	156.5	269.0
Environmental impacts	5.0	13.9	29.6
New business / job creation	4.0	7.5	13.0
Impact on the UK economy	**261.1**	**482.4**	**897.9**
Attribution to BBSRC at 80%	*208.9*	*385.9*	*718.3*
Attribution to BBSRC at 90%	*235.0*	*434.0*	*808.1*

Table 4.2: Estimates of RoI

Total impact on the UK economy (NPV of GVA over 25 years, £ millions)	897.9
BBSRC investment (£ millions)	221.7
RoI (£)	**4.05**
RoI attributed to BBSRC (£) – 80% attribution	*3.24*
RoI attributed to BBSRC (£) – 90% attribution	*3.64*

Global impacts – high level estimates

4.12. BBSRC investments are also **amplified internationally through collaborations and partnerships**, for example, with IWYP and CIMMYT, enabling the knowledge generated in the UK to be transferred globally. In the absence of information about the proportion represented by BBSRC investments in global wheat research and innovation, estimates of global economic impacts of BBSRC investments in wheat research and innovation have been calculated on the assumption of 5% contribution.[73]

4.13. Global economic impacts have been calculated for impacts related to productivity gains, as assessment of health and environmental impacts in the rest of the world will require further

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[72] Impact is calculated from 2022 onwards.

[73] This is a conservative assumption that draws on analyses conducted by BBSRC. This considers: (i) the share of global public research funding which can be attributed to BBSRC; (ii) the share of global wheat research publications that can be attributed to BBSRC; and (iii) the citation impact of BBSRC attributable wheat research publications relative to the global average.

research (e.g., into health and environmental regulatory regimes in other countries) that falls outside the scope of this study. The results of this analysis are presented in Table 4.3.

4.14. Accounting for both, UK and international benefits and (considering the additionality of BBSRC's funding), would generate **£1.985 billion GVA over a 25-year period** (as shown in Table 4.4), and lead **to a RoI of £8.9 per £1 invested by BBSRC** (as shown in Table 4.5).

Table 4.3: Estimates of economic impacts (GVA) to the rest of the world from BBSRC investments[74]

Economic benefits to the rest of the world	**GVA (£ millions)**		
	Net Present Value of GVA generated over 10 years	Net Present Value of GVA generated over 15 years	Net Present Value of GVA generated over 25 years
Productivity **impacts on the rest of the world economy**	**7,008.6**	**13,161.7**	**25,346**
Attribution to BBSRC at 5%	*350.4*	*658.1*	*1,267.3*

Table 4.4: Global economic impacts (GVA) – attributed to BBSRC

All economic benefits UK and the rest of the world	**GVA (£ millions)**		
	Net Present Value of GVA generated over 10 years	Net Present Value of GVA generated over 15 years	Net Present Value of GVA generated over 25 years
UK (Attribution to BBSRC at 80%)	208.9	385.9	718.3
Rest of the world (Attribution to BBSRC at 5%)	350.4	658.1	1,267.3
Global economic impacts attributed to BBSRC	**559.3**	**1,044**	**1,985.6**

Table 4.5: Estimates of Return on BBSRC Investment

Total impact UK and global economy attributable to BBSRC funding (NPV of GVA over 25 years, £ millions)	1,985.6
Investment to date (£ millions)	221.7
RoI attributed to BBSRC (£)	**8.9**

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[74] Impacts is calculated from 2022 onwards.

Overview of case studies

4.15. An overview of the case studies that have informed the economic impact assessment are provided below, and full case studies are presented in Appendix F.

Productivity impacts

Case Study 1: Using wild relatives to improve modern wheat varieties

Wild relatives of wheat provide a vast and largely untapped reservoir of genetic variation for desirable traits like disease resistance. Fusarium head blight (FHB) is a highly damaging fungal disease of wheat – as well as causing significant yield losses, the fungus produces mycotoxins which contaminate grain and pose a risk to human and animal health. Research at the University of Nottingham identified a wild relative of wheat (*T. timopheevii*) that is highly resistant to FHB. Using their new methods, Nottingham researchers **transferred FHB resistance genes from this wild grass to wheat** – these new lines showed significantly more resistance to FHB than the elite variety Paragon.

As there is very little variability for resistance to this disease in wheat itself, this resistance from a wild relative has a critical role to play in future global wheat production, improving yield for production in the UK and globally. A worldwide study of crop pests and pathogens in 2019 estimated a 21.5% global yield loss for wheat, with FHB as the second most damaging disease.[75] To capture the impacts of FHB in the economic impact assessment, it has been assumed that half of the 21.5% yield loss is avoided through wheat resistance to FHB, developed as a result of BBSRC-funded research.

In addition to economic impacts, health benefits could be generated from this research. For example, FHB produces mycotoxins which contaminate the grain. These toxins have negative effects on the immune, gastrointestinal and reproductive systems of animals (pigs are especially sensitive, whilst ruminants like cattle have higher tolerance).[76] In 2016, the International Agency for Research on Cancer (IARC) and the World Health Organization (WHO) reported that mycotoxin pollution seriously affects the economic development and health of residents in developing countries (Weber et al., 2023), with approximately 500 million individuals in developing countries directly and indirectly exposed to mycotoxins every day (Fellone, 2016).[77]

Case Study 2: Improving genetic resistance to Yellow Rust

Yellow rust is one of the most significant global diseases of wheat, and the past two decades have seen the rapid emergence of more aggressive and genetically diverse yellow rust races, which have infected previously resistant wheat varieties. Combined with the declining availability of chemical fungicides, this places an **increased burden on developing wheat with durable genetic resistance**. BBSRC funding has supported researchers to find novel

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[75] https://www.nature.com/articles/s41559-018-0793-y
[76] https://www.nature.com/articles/s43016-022-00655-z
[77] Source: https://apsjournals.apsnet.org/doi/epdf/10.1094/PDIS-03-12-0291-FE

resistance to yellow rust, generate genetic markers to help commercial breeders make appropriate crosses, and develop surveillance tools to track the movement of yellow rust across countries and globally. Further field trials are required to see if yellow rust resistance is transferred from genotype to phenotype. Successful lines will then need to be backcrossed into elite wheat varieties for commercial use in the UK.

Health impacts

4.16. Improved nutrition is a key health impact which could emerge from BBSRC-funded wheat research in the future. For example, wheat with improved fibre content could support the reduction of type 2 diabetes and obesity. BBSRC-funded researchers at the Quadram Institute Bioscience are currently undertaking clinical trials, to determine if white wheat bread with high resistant starch (a type of fibre) can help to boost fibre intake of healthy people.[78] Fibre helps reduce the risk of many common diet-related diseases,[79] but 91% of UK adults do not meet the recommended fibre intake; e.g., white wheat bread is one of the UK's favourite foods, but normally it has very low levels of fibre. In the long term, the research might be able to determine if high resistant starch bread can help reduce the risk of common chronic diseases.

Case Study 3: Nutrition – improving the quality of wheat starch to boost fibre intake

Dietary fibre is very important for human health and nutrition – but in the UK, only two-thirds of the recommended amount is consumed. Improving the quality of fibre in popular foods like white bread (which is low in dietary fibre) could boost fibre intake, and have some significant positive health impacts (e.g., obesity), as well as savings for the National Health System (NHS) and Social Care.

Researchers at Quadram Institute Bioscience have developed a new variety of wheat high in resistance starch (a type of dietary fibre) and have conducted a clinical study in humans to help understand whether bread that is high in resistant starch could help boost fibre intake. Further human trials will be undertaken to fully explore the potential of this novel wheat to improve fibre intake, whilst research is also required to test how this variety might perform in the field.

Assessment of economic impacts from improved health/reduction in diet-related diseases (e.g., obesity using Department for Health and Social Care data) shows that health benefits for individuals and savings for the NHS would amount to around £820 million over a 25-year period.

Environmental impacts

4.17. Society could benefit from improved environmental outcomes as a result of BBSRC-funded wheat research, including improved water quality and increased biodiversity through reduced

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[78] See: https://quadram.ac.uk/why-we-should-look-to-increase-our-dietary-fibre-intake/

[79] As noted in paragraph 4.5, resistant starch can also help tackle obesity, as well as bowel cancer (as high fibre content has been linked to reducing risks of bowel cancer). However, health impacts have been monetised only for diet-related improvements, i.e., reduction of daily intake of calories.

fertiliser and chemical use. As noted in paragraphs 4.4 and 4.5, at this stage, calculations are limited to known products/outputs and their impacts from research funded, e.g., a new variety of wheat with a 50% reduction in viscosity used in the distilling process for Scotch grain whisky), as described below.

Case Study 4: Developing low viscosity wheat for whisky distilling

Wheat is important to distilling, however it can be problematic for distilleries, as it causes sticky residues. BBSRC-funded researchers at Rothamsted Research, in collaboration with Limagrain[1] and the Scotch Whisky Research Institute, have developed a new variety of wheat with a 50% reduction in viscosity. Reduced viscosity of wheat reduces shut downs and cleaning within the distilling process for Scotch grain whisky. It has been estimated that these benefits will lead to an annual benefit/savings to industry of £7.5 million per year. Reductions in energy use will save a further industry £8.95 million per year in carbon emissions.

Over the next 5 years, Limagrain will breed the low viscosity trait into soft wheats rated good for distilling, and which meet the agronomy requirements of the Scottish distilling market.

Market impacts

4.18. As presented in section 3, BBSRC investments in wheat research have led to seven spinout companies over the assessment period (2010-2022). Of these spinouts, three are currently involved in wheat-related research; these three companies **employ 25 people** in total and have secured approximately **£1.4 million in further funding and investment**. Economic impacts for the UK are generated by the activities of the research and commercial activities of these businesses, and these have been accounted for in the assessment of the economic impacts initiated by the BBSRC investments in wheat research and innovation. An example of research and commercial activities by one of these spinouts (Fotenix) is presented below.

Case Study 5: Job creation

Currently, plant health diagnosis requires highly trained specialists to walk thousands of metres every day, to spot minute details that could be the difference between a high-yield harvest and a devastating loss. **Real-time identification of crop diseases could provide immediate feedback to farmers and growers, significantly reducing costly delays in rectifying actions**.

Fotenix is a spinout from the University of Manchester, that was established in 2018 and **develops and deploys 3D multi-spectral imaging technology to identify disease threats and stresses on crops at an early stage**.

The technology is suitable for a variety of crops; it can sense for a range of different stresses, and can be deployed on different platforms (e.g., tractors, robotics, greenhouses). Whilst pests and pathogens are a key focus, the technology can also sense for nutrient stresses, for example, nitrogen for grain protein content. Growers can use these insights to know what, where, and when to target treatments, be that nitrogen for grain protein content, or fungicides for yellow rust.

The research group that developed the company has been supported by BBSRC funding through the Agri-Tech Catalyst programme, co-funded with Innovate UK. Investment and support has also been received from ICURe, the EIT Food Accelerator Network programme, NVIDIA, AWS, Sony, Innovate UK, Innovation Factory, and Angel Investors alongside the ISCF Series A Investment Programme.

The company has a series of **patents on the apparatus and methods for determining spectral information from plants**. This is the technology underpinning Fotenix's products and services, for example, the INDIA integrated imaging platform (see image, right).

Fotenix is currently recruiting to triple its workforce to support its breeding and digital agronomy services to major agri-chemical companies.

The Fotenix INDIA mounted spectral imaging device. Credit: Fotenix.

5. Wider outcomes

Influence on policy and practice

5.1. Outcomes data from Researchfish shows **171 instances of BBSRC-funded researchers reporting influencing policy and practice**. Policy influence includes membership of guidance/advisory committees, contributions to consultations and reviews, contributions to the training of researchers or practitioners (e.g., wheat breeders), contributions to new or improved professional practice, or citations in government policy documents.[80]

5.2. **Almost one third (29%) of the policy impacts were classified as influencing the training of practitioners or researchers** (49 instances). This includes workshops and lectures to researchers, industry representatives, and government/policy delegates. For example:

- Visits from Government Office of Science (UK) and the Board of GenØk (Norway – biotechnology safety advisors to the governments of Norway and Finland) to the John Innes Centre to discuss genetic modification and genome editing (BBS/E/J/000PR9779).
- Researchers at the University of Nottingham trained Agrii staff on using neural network models to predict disease and yield in wheat (BB/M011550/1).
- Rothamsted Research researchers advised commercial wheat breeding companies on the effect that introgressions have on recombination, and why this may lead to difficulties in the future – this has resulted in some companies re-examining their breeding strategies (BB/N013360/1).

5.3. Researchers also **participated in national advisory committees, providing scientific advice on a range of food and agricultural topics** (39 instances). For example, researchers participated in Defra's public consultation on gene editing (alongside other discussions and meetings), as well as the Advisory Committee on Novel Foods and Processes, providing contributions on the safety assessment of novel and genetically modified foods .

5.4. Further examples of policy influence include:

- NIAB were cited as a case study in the government's UK Agri-tech Strategy, which highlighted its pre-breeding work and provision of community resources for wheat.
- Written submissions to the Parliamentary Inquiry into UK Soil Health and the Defra consultation on headline indicators to be used to deliver the UK Government 25 Year Environment Plan by the University of Sheffield (BB/L026066/1).

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[80] For a full list of policy sub-outcome types, see: https://rf downloads.s3.amazonaws.com/Outcome+type+map.pdf

- Researchers at the University of Reading supported plant breeders to take up assessment methodologies relating to flowering phenotype in wheat, with a particular focus on wheat production in Asia and other areas in a changing climate (BB/H012176/1).

- Researchers at the John Innes Centre and the University of Nottingham are members of the Science Board of the G20 Wheat Initiative, which coordinates wheat research across multiple countries, making more effective use of funding (BBS/E/T/000PR9785).

- Contribution to a Parliament POSTnote research briefing on sustaining the soil microbiome by researchers from Rothamsted Research (BB/N004418/1).

- Furthermore, 26 BBSRC-funded wheat researchers were cited as consultees in the recent UK Plant Science Research Strategy (2021).

5.5. Feedback from stakeholder consultations also suggests that gene editing could have policy impacts in the future, and may support changes in UK legislation.[81] For example, researchers highlighted that they have provided evidence to government from field research trails of genetically modified crops. Future impacts could relate to delivering more precise tools to enable more efficient and faster improvements in wheat, i.e., it has the potential to be a technology disruptor, and to bring substantial improvements to UK agricultural productivity.[82]

5.6. At the time of writing this report, the Genetic Technology (Precision Breeding) Act passed into law, potentially enabling the acceleration of breeding of wheat varieties with improved yield, disease resistance, and resilience to climate change. Researchers at NIAB were interviewed by the BBC for its report on gene editing, and commented:

> ***'When we look to how the population is growing and how much we are increasing our yields using traditional methods, we are lagging behind… we have to have an acceleration into how we can improve crops otherwise we are going to be struggling to feed the world'.***

Strengthening UK research and science capabilities and skills

5.7. Feedback from stakeholder consultations suggests that BBSRC investments have **contributed to strengthening the UK wheat/plant science skills base** in various ways. For example, early-career wheat researchers are benefiting from the recent transformational step-changes in wheat research (such as wheat genome sequencing), by working directly in wheat (rather than starting in Arabidopsis and transferring to wheat), thus accelerating both the transfer of fundamental research to improved varieties and authoring high-profile papers.

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[81] E.g., see government's Genetic Technology (Precision Breeding) Bill: https://bills.parliament.uk/bills/3167

[82] Note that according to one industry breeder, if approved, gene-editing technology will 'drip feed' into their work and will 'not have a massive immediate impact'. They also noted the biological barrier to speeding up wheat (and other plant) breeding; it is still taking several years to grow enough wheat to undertake the necessary trials (for Distinctness, Uniformity and Stability (DUS) and for Value for Cultivation and Use (VCU) – see https://www.gov.uk/guidance/vcu-protocols-and-procedures-for-testing-agricultural-crops), and then sell to growers/farmers.

5.8. The DFW programme has also supported the training of researchers in both academia and industry – for example, through the Wheat Training website, providing background information and practical resources to help both budding wheat scientists and experienced researchers who are looking to expand their work into wheat.

5.9. BBSRC funding in what research and innovation has also produced many highly skilled and highly trained staff, some of whom now work for commercial plant breeders, thus contributing to **knowledge transfer and diffusion** from the knowledge base to industry. For example, the head of one breeder's genotyping platform completed their PhD at the John Innes Centre, whilst the head of bioinformatics at another breeder completed their postdoctoral research at the Earlham Institute. As one research stakeholder noted: 'this keeps UK breeders at the top of their game'. In general, movement of individuals from research to industry helps strengthen research-industry relationships, supporting the transfer of fundamental research to commercial wheat varieties.

5.10. The enhanced knowledge base also strengthens the UK's position globally as one of the most attractive places for fundamental wheat research. For example, one breeder's genotyping platform HQ is in the UK and not France, where the breeder is located.

5.11. BBSRC funding has also contributed to widening the diversity of scientists in the field through, for example:

- The Women in Wheat Champions Programme is supporting women aiming for a career in wheat research through the provision of mentoring and training support. The programme pairs individuals at PhD and postdoctoral level with Group Leaders, who are experienced but hold no supervisory role over the mentee, and providing training sessions designed to develop the skills to help the mentees succeed in their chosen field (e.g., evaluating CVs, structuring presentations, preparing for interviews).

- The Women in Crop Science initiative is a global network which aims to create further opportunities for promoting and developing women as role models in crop science. The initiative hosts a global directory of female crop scientists, which to date has 426 members in 47 countries, covering 38 different crops.

5.12. Stakeholders also noted the importance of technician roles, which are essential in supporting the UK's world-class wheat science undertaken at research institutes and universities.[83] For example, one stakeholder commented that research institutes invest well in technicians, and that on ISPs each Group Leader has a 'plus one' role, by which they can secure a role for a key technician – this enables stable career paths for technicians. This relates to the BBSRC Equality. Diversity and Inclusion Action Plan and the Technician Commitment, the signatories of which include the majority of institutions undertaking wheat research in the UK.

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[83] E.g., see: https://www.jic.ac.uk/news/new-report-shines-light-on-challenges-faced-by-technicians-working-in-higher-education/

6. Conclusions

6.1. The main objectives of this study have been to capture the socio-economic impacts of BBSRC's investments in wheat research and innovation between 2010/11 and 2021/22.

6.2. BBSRC plays an important role as the main (public) funder for wheat research and innovation in the UK, and its funding and support have been instrumental in generating significant outcomes and benefits for the economy and society. Stakeholder feedback and background research has highlighted that the UK is widely regarded as having a **world-leading plant science research sector**, **particularly in wheat**.

6.3. BBSRC has supported the **creation of a critical mass and community of practice in UK wheat** through the WISP and DFW ISPs. This has facilitated **strong research-industry partnerships** and enables the transfer of genomic tools and germplasm to commercial and other pre-breeders (e.g., CIMMYT). According to stakeholders, this approach has been **'an unquestionable success'**,[84] and should be used as an **exemplar model** of institutions working together under one umbrella with a long-term, strategic goal. This is largely down to **BBSRC leadership** in bringing the community together.

6.4. The ISPs, alongside other funding mechanisms, have supported **'game-changing transformations' in wheat genomics**.[85] Wheat is no longer genetically intractable, thanks largely to BBSRC-supported contributions to the wheat genome sequencing and other fundamental research. This has led to the generation of a **portfolio of 'phenomenal' resources** [86] including germplasm with novel traits and genetic diversity, genetic markers, databases, tools, and software, all of which are being translated into applications for commercial breeders and international pre-breeding partners. Key examples include:

- The University of Nottingham is one of a handful of places in the world specialising in wild wheat relatives – this is important in bringing novel genetic diversity into modern wheat (e.g., resistance to Fusarium head blight, heat tolerance).

- The John Innes Centre's TILLING resources are widely used by research and industry, and the Germplasm Resources Unit provides essential national capability in seed conservation (including the Watkins collection of wheat landraces).

- NIAB's MAGIC wheat population and re-synthesised wheat programme, with significant productivity impacts (i.e., between 10-30% increases recorded in various trials) including improved disease resistance (biotic stresses) and environmental resilience benefits (abiotic stresses).

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[84] As best described by one consultee but also reflecting the general feedback received from many stakeholders participating in this evaluation.

[85] As stated by another research consultee but also reflecting feedback received by many researchers.

[86] As stated by a range of stakeholders in academia and industry.

- The Earlham Institute is highly regarded for its software and analytical tools, providing critical contributions to wheat genome sequencing and high-performance computing infrastructure.

- Rothamsted Research's work on agri-food systems and climate change, pathogens and phenomic technology supports efficiencies in wheat breeding programmes (for example, through the use of machine learning such as the *DeepCount* technology developed by Rothamsted Research, which helps to better predict yield and save costs compared to the labour-intensive and expensive manual counting).

- The University of Bristol's genetic markers are widely used by research and industry, with BBSRC funding playing an important role in addressing market failures preventing the private sector (in particular smaller wheat breeders) conducting expensive research (with uncertain results) in a relatively low-margin sector.

- Feedback from stakeholder consultations also suggests that gene editing is a key area of policy impact and may support changes in UK legislation; it also has the potential to be a technology disruptor, and to bring substantial improvements to UK agricultural productivity.

6.5. BBSRC has also supported the development of the next generation of skilled wheat researchers with industry knowledge – the UK is an attractive base for industrial R&D investment due to its expertise, and UK researchers are in high demand.

6.6. Whilst only two wheat varieties attributable to BBSRC funding have reached National List trials, and none are currently being grown in farmers' fields, it is likely that there will be such **impacts in the next decade**. For example, one of the breeders interviewed as part of this study estimated they will deliver derivatives from 5-10 lines from the DFW Breeders Toolkit in the next 2-3 years, and there will be 5-6 derivatives in their European programme within the next 10-12 years. The fact that **lines from BBSRC-funded genetic material have reached National List testing is a big achievement,** a 'big tick in the box', as stated by one commercial wheat breeder.

6.7. The study has also shown that the economic benefits resulting from various research outputs initiated, supported and generated by BBSRC investments in wheat research and innovation in the last decade would **create approximately an additional £900 million GVA for the UK economy** over a 25-year period, with a return on BBSRC's current investment **of £4 per £1 invested**. Assessment of economic impacts accounting for both UK and international benefits shows that the BBSRC investments in wheat research and innovation would generate **£1.99 billion GVA**, and lead to an **RoI of £8.9 per £1 invested by BBSRC** over a 25-year period.

6.8. These estimates represent a cautious approach. As discussed in section 4, it has not always been possible within the scope of this research to collect, verify and monetise all possible benefits and impacts potentially arising from BBSRC-funded research in wheat research and innovation. Further research will be needed to capture additional economic, health and environmental impacts on the UK economy and internationally.

Issues for consideration going forward

6.9. UK is widely regarded as having a **world-leading plant science research sector**, **particularly in wheat**, delivered from a diverse, high-quality research base across public and private institutions. Given wheat's importance to global and UK food security, and combined with UK research excellence in wheat genetics, BBSRC's investments in wheat research are supporting the UK's ambition deliver world-leading wheat research and innovation;[87] for example, underpinning sustainable wheat production, creating higher yielding and more resilient wheat crops in response to a growing population and a changing climate, and thereby ensuring national and global food security.

6.10. The long-term nature of breeding means that achieving commercial benefits and an RoI may take longer than the 8-12 years typically expected by shareholders. This means that investments in wheat research need to be treated **as patient capital** by both the private and public sector (i.e., neither impacts nor returns should be expected in the short-term, although returns could be similar/as high to those expected from venture capital).

6.11. Therefore, continued public investment is required to overcome this market failure. Public funding will be also needed **to signal and accelerate research related to issues affecting other traits and smaller segments of the population**. These relate to nutrition (e.g., fibre content), environmental (e.g., reduced chemical inputs), and resilience traits (e.g., heat tolerance).

6.12. Stakeholders and researchers also suggested a few specific issues for BBSRC to consider going forward, and these are summarised below:

- In terms of future research areas, the recent law change (in England) allowing the commercial development of gene editing in crops could impact on wheat research and breeding. At this stage, however, the extent of the impact is uncertain, and stakeholders noted caution as the regulatory environment in the rest of the UK and Europe could mean that gene editing may not have a huge immediate impact.
- Hybrid wheat is a key challenge, but could also have transformational impacts – not just in creating higher yielding wheat, but also in changing the wheat business model.
- The importance of disease resistance will increase in the future as chemical treatments are phased out and climate change brings new pathogens and pests to the UK. In addition, yield stability and resilience in the face of climate change will be critical, to create wheat varieties which yield well in drought, heat and saline conditions.

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[87] See: BBSRC, 5-Year Wheat Research Strategy (2013); and, BBSRC, Strategic Delivery Plan 2022-25 (2022).

Appendix A: List of organisations consulted

Scoping consultations with BBSRC and UKRI teams

Conducted between November and December 2022.

Organisation consulted		Number of stakeholders
BBSRC		4
Global Food Security programme (BBSRC)		1
Innovate UK		2
Total	**3**	**7**

Scoping interviews with stakeholders (conducted between November and December 2022)

Organisation consulted		Sector	Number of stakeholders
AHDB		Policy/other	1
Bayer Crop Science		Industry	1
Blackman Agriculture		Industry	1
CIMMYT		Research – SAF SAP	1
Defra		Policy/other	4
DSV		Industry	1
Earlham Institute		Research	2
Elsoms		Industry	1
IWYP		Research	3
John Innes Centre		Research	4
KWS		Industry	1
Limagrain		Industry	1
National Trust		Charity – SAF SAP	1
NIAB		Research	4
PepsiCo		Industry	1
Quadram Institute Bioscience		Research	1
RAGT		Industry	1
Rothamsted Research		Research	3
Scotland's Rural College (SRUC)		Research – SAF SAP	1
The Sainsbury Laboratory		Research	1
University of Aberdeen		Research – SAF SAP	1
University of Aberystwyth		Research	1
University of Bristol		Research	1
University of Leeds		Research	1
University of Lincoln		Research – SAF SAP	1
University of Nottingham		Research – SAF SAP (1)	3
University of Oxford		Research	1
Anonymous		Industry	1
Total	**28**		**44**

Additional consultations for completion of case studies (conducted between January and March 2023)

Nine case studies were conducted as part of the evaluation drawing on desk-based research and the scoping interviews with stakeholders, as listed in the previous table. To fill in gaps in information needed to complete the case studies, five more interviews were conducted between January and March 2023. Organisations consulted are listed below.

Organisation consulted	Sector	Number of stakeholders
Fotenix	Industry	1
Rothamsted Research	Research	1
Scotch Whisky Research Institute	Industry	1
University of Cambridge	Research	1
University of Manchester	Research	1
Total **5**		**5**

Appendix B: Stakeholder interviews script

a) Background/general information (about the participant and their organisations/research)

b) Research rationale and design, for example:

- What are the key applications of wheat research? (past, present, potential) Who are the main users/beneficiaries? (industry, consumers, other researchers)
- What are the main challenges/barriers to wheat research?

c) Achievements and benefits, for example:

- What are the main achievements/successes of BBSRC's wheat research to date/in the last 10 years?
- To what extent and how has BBSRC wheat research underpinned:
    a. The development of new and improved UK wheat varieties with beneficial traits (e.g., increased yield, increased resilience, improved sustainability)?
    b. Research in transformational technologies (e.g., automation, sensing, farmer decision support, precision agriculture)?
    c. Improvements to agronomic practices?
    d. New tools, processes, and technologies? Are these transferable to other crops/research areas/disciplines?
- To what extent and how has collaboration and partnerships between researchers and relevant stakeholders (e.g., industry) facilitated impact from BBSRC wheat research?
- To what extent and how have BBSRC's investments in wheat research been successfully translated into practical and commercial application?
- Has the research impacted upon policy? (e.g., provided evidence or influenced decision makers)
- Have there been any benefits to society? (e.g., increased public awareness, improving health and well-being, nutrition impacts of improved wheat)
- What is/will be the impact on growers (i.e., farmers), both in the UK and internationally?

d) Added value (science – funding – monetary), for example:

- To what extent are these benefits and contributions attributable to BBSRC funding? Are other parties involved (who and how)?
- What are the key features of BBSRC's investment in wheat research that have enabled these impacts/benefits?
- Do you think BBSRC's wheat research portfolio represents value-for-money?

Specific questions for industry

- Have any BBSRC-funded project outputs (e.g., new varieties, tools) informed/shaped your own (or organisation's) work in this area?

e) Future, for example:

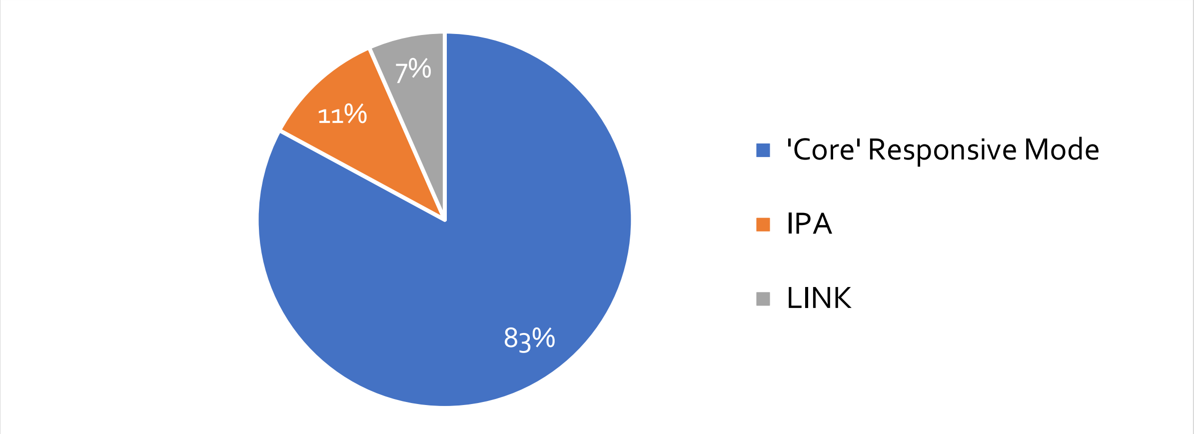
- How well aligned is BBSRC's investment in wheat research with other government and industry activities?
- Are there any notable gaps or 'market failures' in the funding landscape which are holding back the advancement of UK wheat research?
- How does the UK compare internationally, in terms of wheat research capability and capacity?

Appendix C: Analysis of BBSRC wheat research investments

Overview

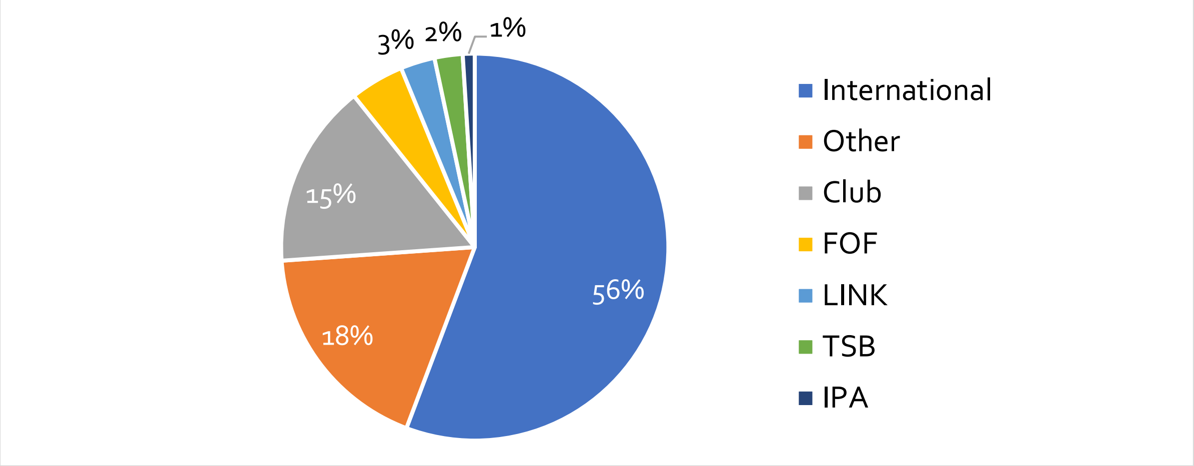
As Figure C.3 shows, the majority of funding (£43.5 million, 83%) delivered under the Responsive Mode were standard research grants, including Strategic Longer and Larger grants (sLoLas). Industrial Partnership Award (IPA) and LINK funding represent £5.5 million and £3.4 million of total Responsive Mode funding respectively. These schemes both support industry collaboration.

Figure C.3: Spend by funding scheme – Responsive Mode[88]



The 'Initiative' funding mechanism is represented by a number of different schemes. As Figure C.4 shows, **over half of funding is for international projects**, comprising £28.9 million.

Figure C.4: Spend by funding scheme – Initiative[89]



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[88] Note on acronyms: IPA (Industrial Partnership Award).

[89] NB: LINK and IPA projects could be funded under Responsive Mode or Initiative funding mechanisms (but the same project could not be funded under both). Note on acronyms: FOF (Follow on Fund); TSB (Innovate UK, previously Technology Strategy Board); IPA (Industrial Partnership Award).

International funding schemes include:

- IWYP.
- Global Challenges Research Fund (GCRF).
- Various Newton Fund programmes, for example, Virtual Joint Centres with Brazil, China & India in Agricultural Nitrogen programme.
- Joint Programming Initiative on Agriculture, Food Security & Climate Change (FACCE-JPI).
- Various European Research Area Network (ERA-NET) programmes.
- Sustainable Crop Production Research for International Development (SCPRID).

'Other' funding schemes include: Advanced Life Sciences Research Technology Initiative (ALERT), Bioinformatics and Biological Resources Fund (BBR), Crop Science Initiative (CSI), and the Tools and Resources Development Fund (TRDF).

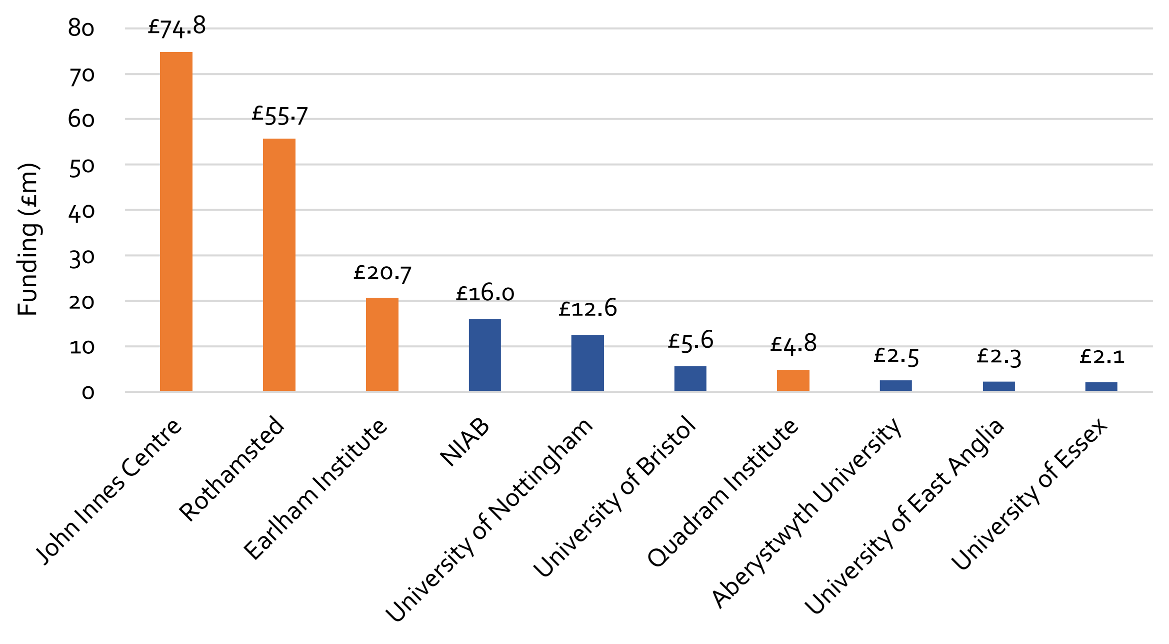
'Club' funding schemes comprise: Crop Improvement Research Club (CIRC), Diet and Health Research Industry Club (DRINC), Integrated Biorefining Research and Technology Club (IBTI), and the Sustainable Agriculture Research and Innovation Club (SARIC).

A number of schemes support industry collaboration, including the various club initiatives, LINK, IPA, and TSB (e.g., Agri-Tech Catalyst). Overall, **collaborative industry funding schemes represent one fifth of Initiative funding**, accounting for £10.9 million.

Organisations

As Figure C.5 shows, **BBSRC's strategically supported institutes received amongst the highest levels of investment in wheat research**, representing 70% of total BBSRC wheat research investment (£155.9 million). NIAB and the universities of Nottingham and Bristol also secured significant BBSRC support. The top seven organisations receiving the most funding were all participants in the DFW strategic programme.

Figure C.5: Total spend by organisation, 2010/11-2021/22 (top 10; BBSRC institutes highlighted)



Notable programmes

WISP

WISP was a comprehensive pre-breeding programme, running from 2011-2017. It brought together the John Innes Centre, NIAB, Rothamsted Research, and the universities of Bristol and Nottingham, with the aim of developing wheat strains which are resilient to future economic and societal pressures, with traits such as drought tolerance, yield growth, and disease resistance.

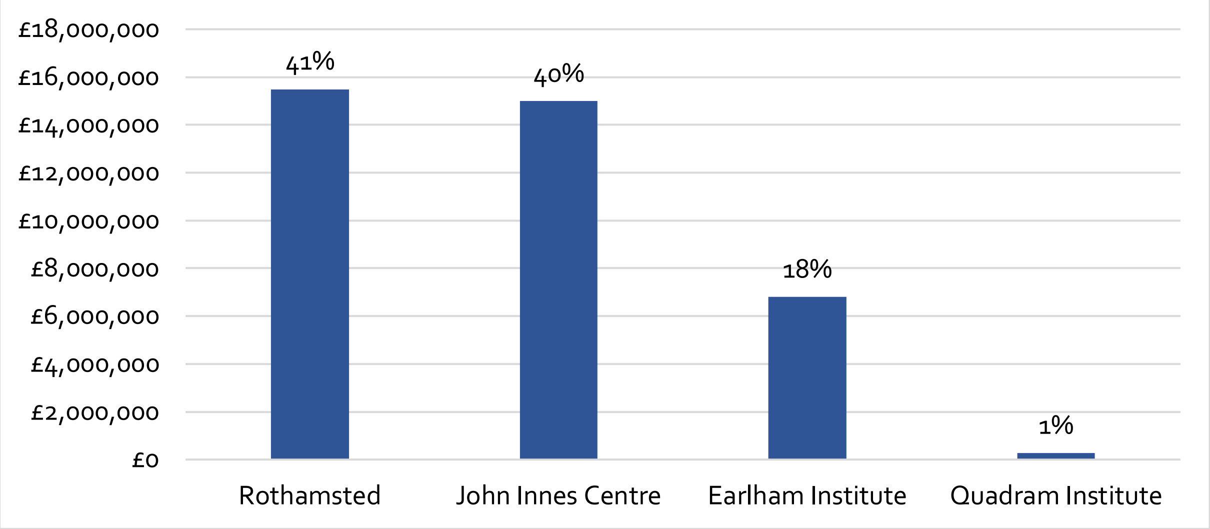
DFW

The DFW programme followed on from WISP, and included three new participants in the consortium: the Earlham Institute, Quadram Institute Bioscience, and EMBL-EBI. The programme aimed to develop the novel wheat germplasm generated through WISP, exploring wheat with increased yield potential, disease resistance, climate tolerance, and bread making and nutritional qualities. The programme was split into four work packages (WP):

- WP1: Increased sustainability and efficiency
- WP2: Added value and resilience
- WP3: Germplasm
- WP4: Data access and analysis

As Figure C.6 shows, Rothamsted Research and the John Innes Centre account for over 80% of DFW funding, with both organisations involved in all four work packages. Note that the funding to the John Innes Centre includes funding allocations to other partner organisations involved in the programme, i.e., NIAB, EMBL-EBI, and the universities of Bristol and Nottingham.

Figure C.6: DFW – funding by organisation[90]



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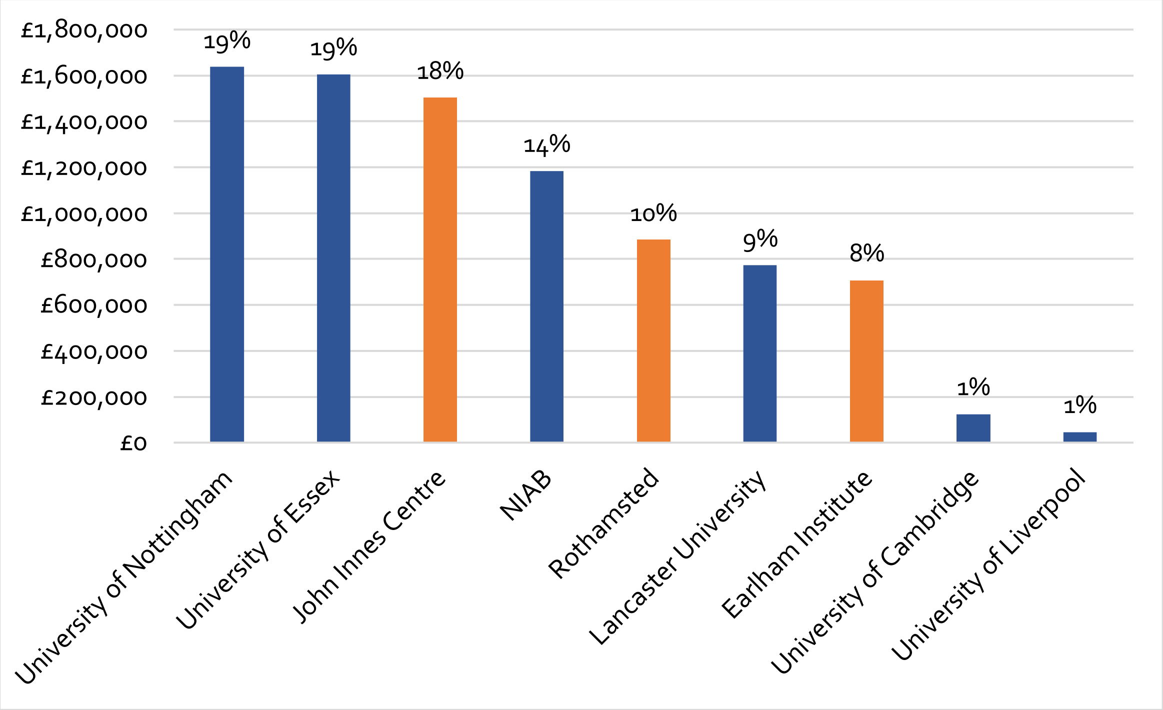
[90] As noted, the John Innes Centre funding also includes funding allocated to other partner organisations involved in the programme (i.e., NIAB, Bristol etc.).

IWYP

Established in 2012, IWYP is a collaborative public-private programme, aimed at raising the genetic yield potential of wheat by 50% by 2035. BBSRC contributes £2.1 million to the overarching management structure, as well as £10.6 million ($13.1m) to IWYP's research programme, and £2.8 million ($3.5m) to the IWYP hub at CIMMYT. The programme leverages $2.50 from other funders for every $1 invested in IWYP by BBSRC.[91]

Figure C.7 shows IWYP funding by organisation. Four organisations account for 70% of funding: the University of Nottingham (2 projects), the University of Essex (3 projects), the John Innes Institute (4 projects), and NIAB (1 project).

Figure C.7: IWYP – funding by organisation (BBSRC institutes highlighted)[92]



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[91] Source: BBSRC, Benefits to the UK from IWYP (i.e., BBSRC figures, not calculated by WECD).

[92] NB: The University of Liverpool grant was transferred to Earlham Institute following staff movement.

Appendix D: Analysis of BBSRC wheat research outcomes

This section provides **additional** information related to some BBSRC wheat research outcomes discussed in Section 3.

Publications

Figure D.1: Publications by sub-type

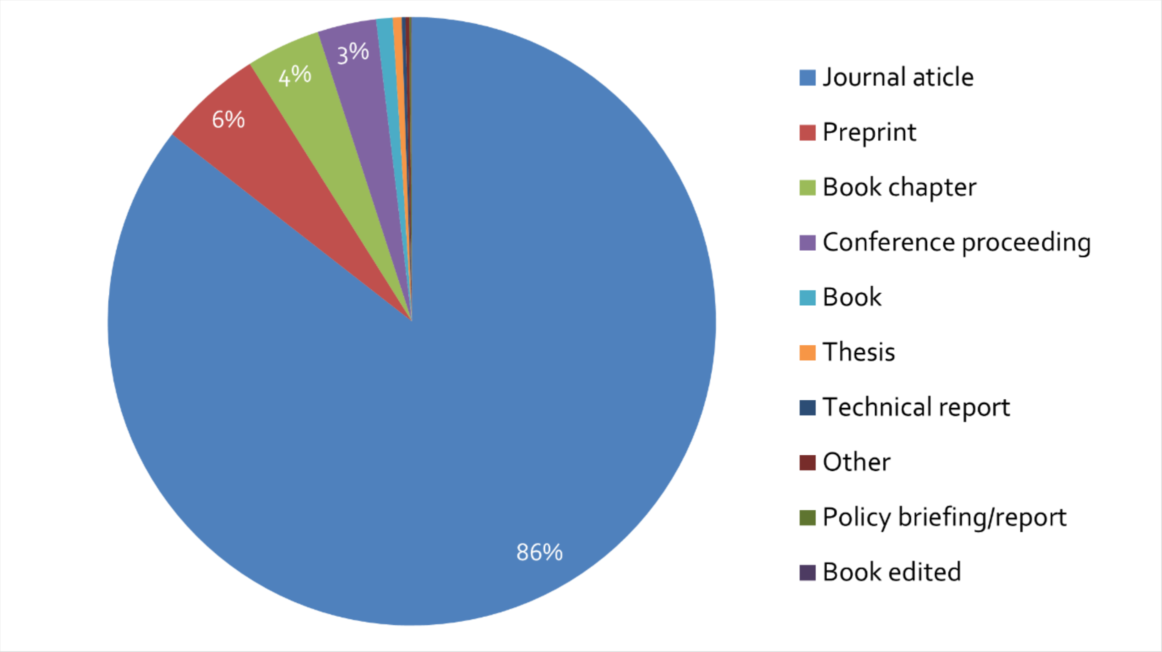
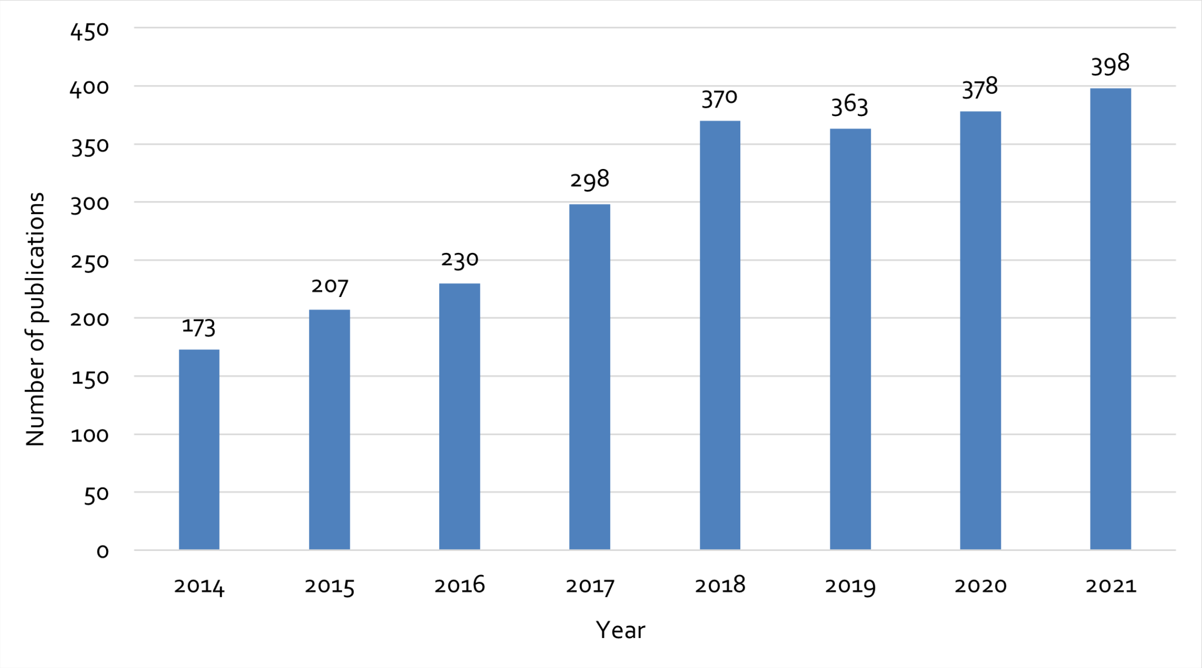


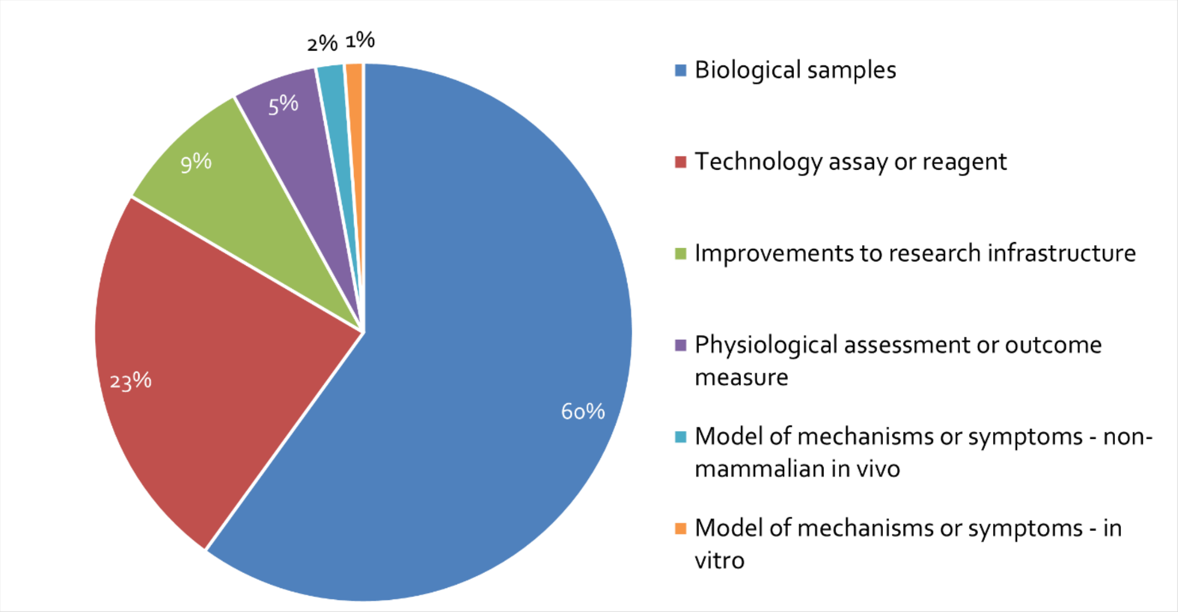
Figure D.2 shows that the majority of publications (58%) were published between 2017 and 2021. However, caution is needed in interpreting data on publications reported through Researchfish – see paragraph 3.2. BBSRC started using Researchfish in November 2014, and it took several years for researchers to become familiar with the platform. Interpretation of information presented here should take into account: i) early grants not being reported on; ii) changes in reporting behaviour over time, including behaviour changes resulting from introduction of sanctions; iii) increased investment in wheat research over the period; iv) changes in academic output over the period. Prior to the introduction of Researchfish, BBSRC used the Research Outputs System and grant final reports – the data from these sources was not backfilled into Researchfish by BBSRC, and researchers were not required to do so themselves.

Figure D.2: Publications by year (2014-2021)



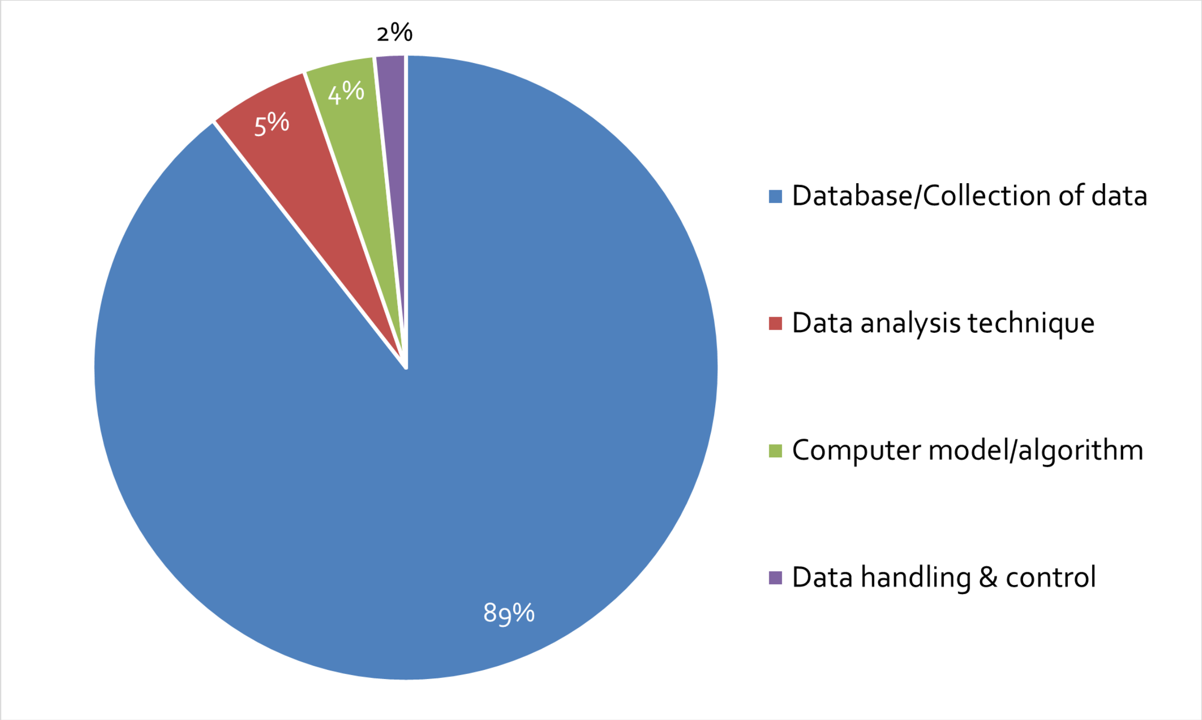
Tools and methods

Figure D.3: Tools and methods sub-types



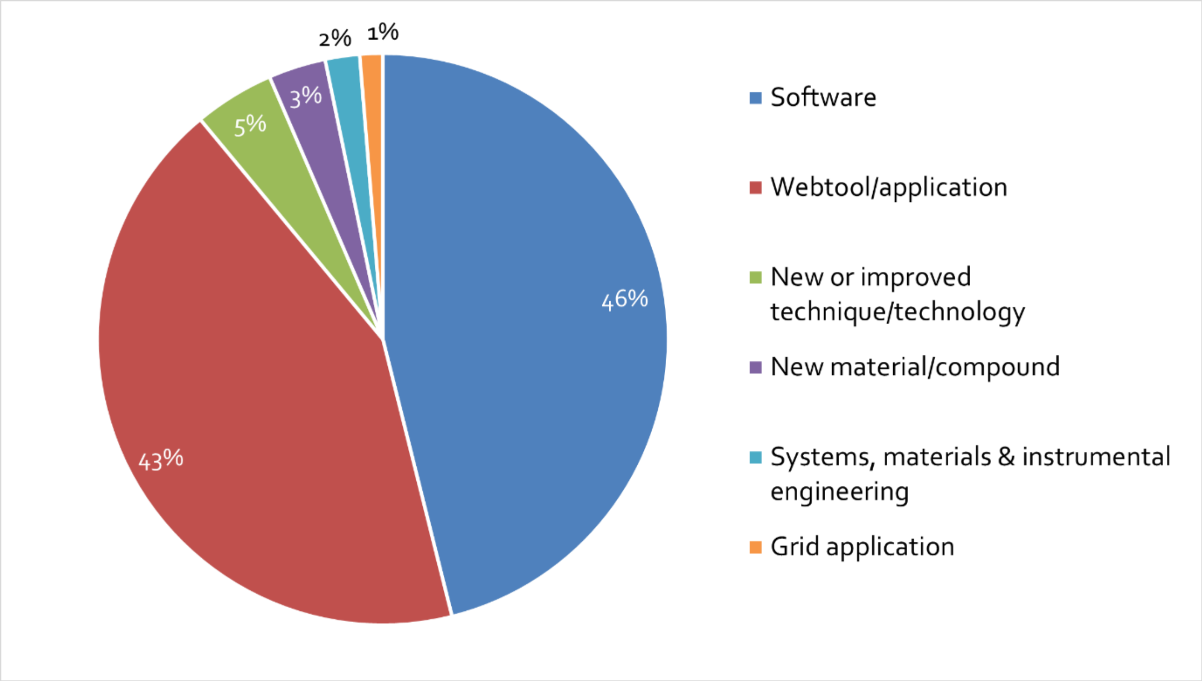
Databases and models

Figure D.4: Databases and models sub-types



Software

Figure D.5: Software sub-types



Networks and collaborations

Figures D.6 and D.7 show direct and in-kind collaboration contributions by sector.

Figure D.6: Direct collaboration contributions by sector

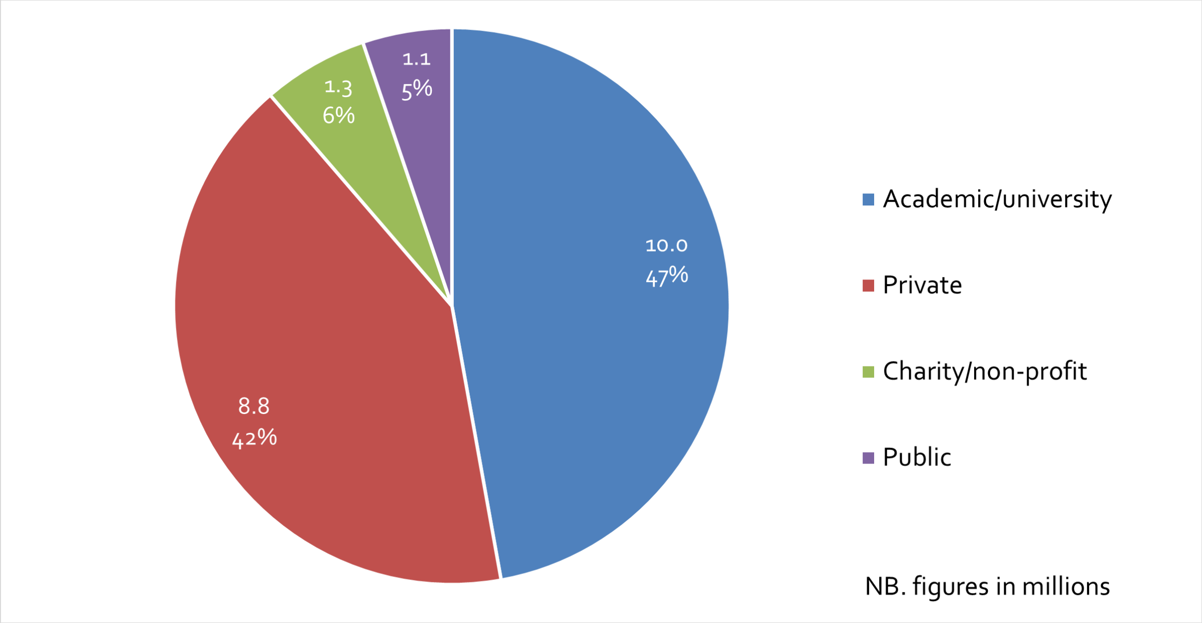
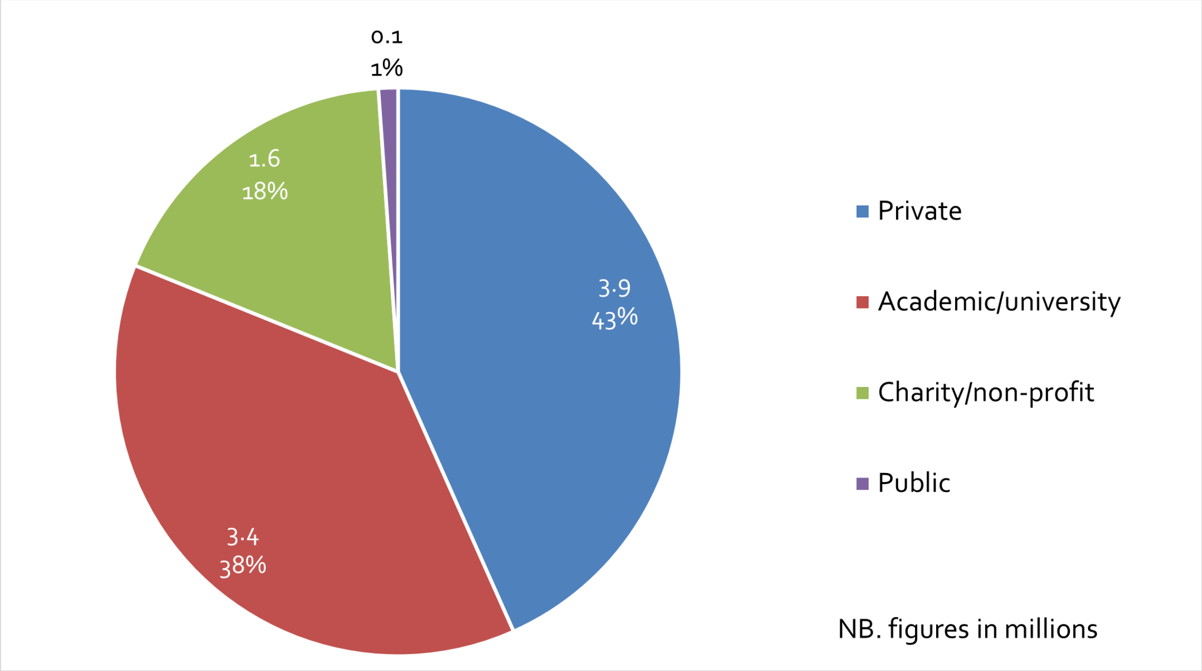
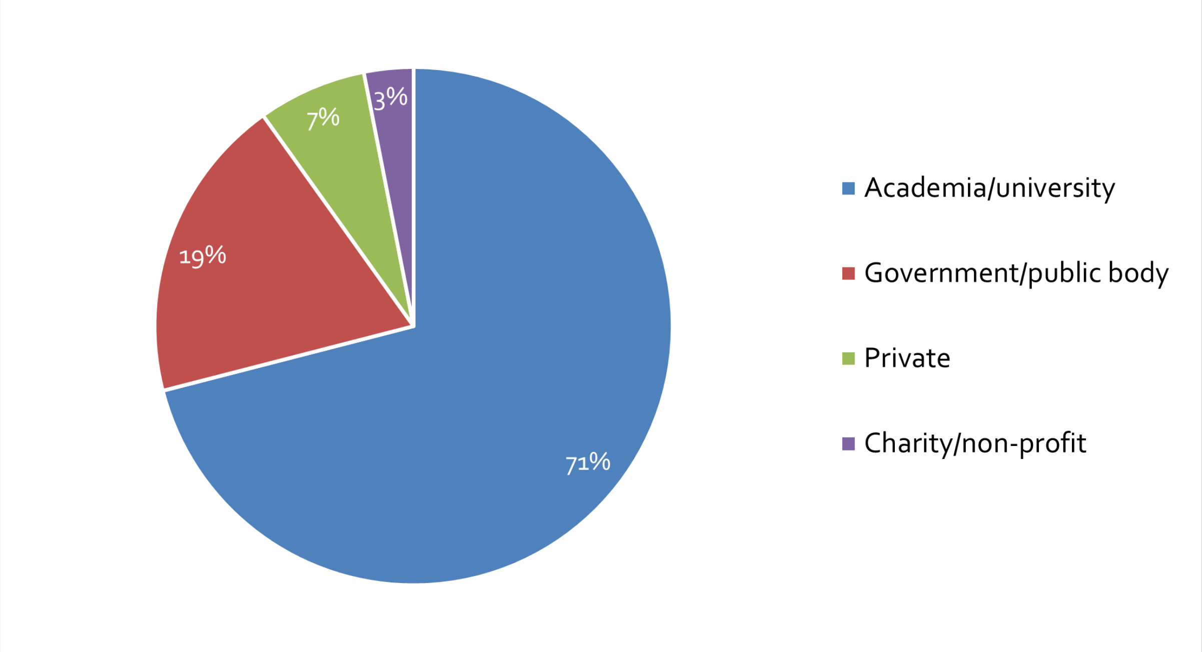


Figure D.7: In-kind collaboration contributions by sector



Secondments

Figure D.8: Secondment destination by organisation type (sector)



Career progression (next destination)

Figure D.9 shows the role of the individual moving position (i.e., the role they moved from to their next destination).

Figure D.9: Next destination – role in group

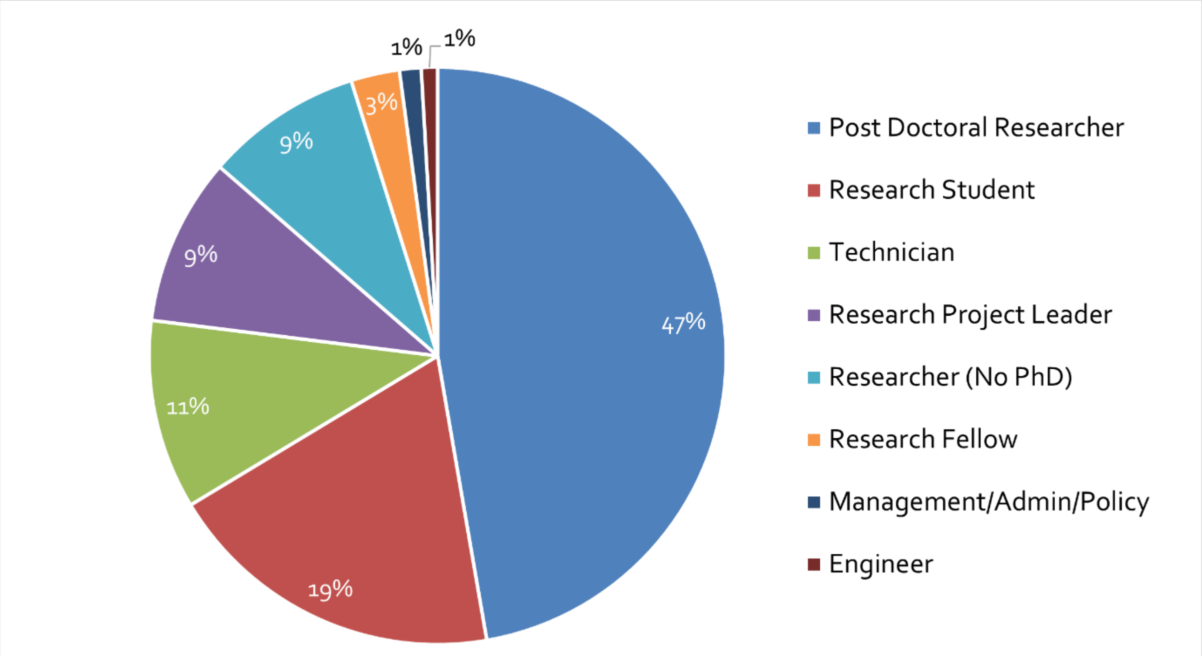


Figure D.10 and D.11 show the destination of the individual moving position, by country and sector respectively.

Figure D.10: Next destination – country destination

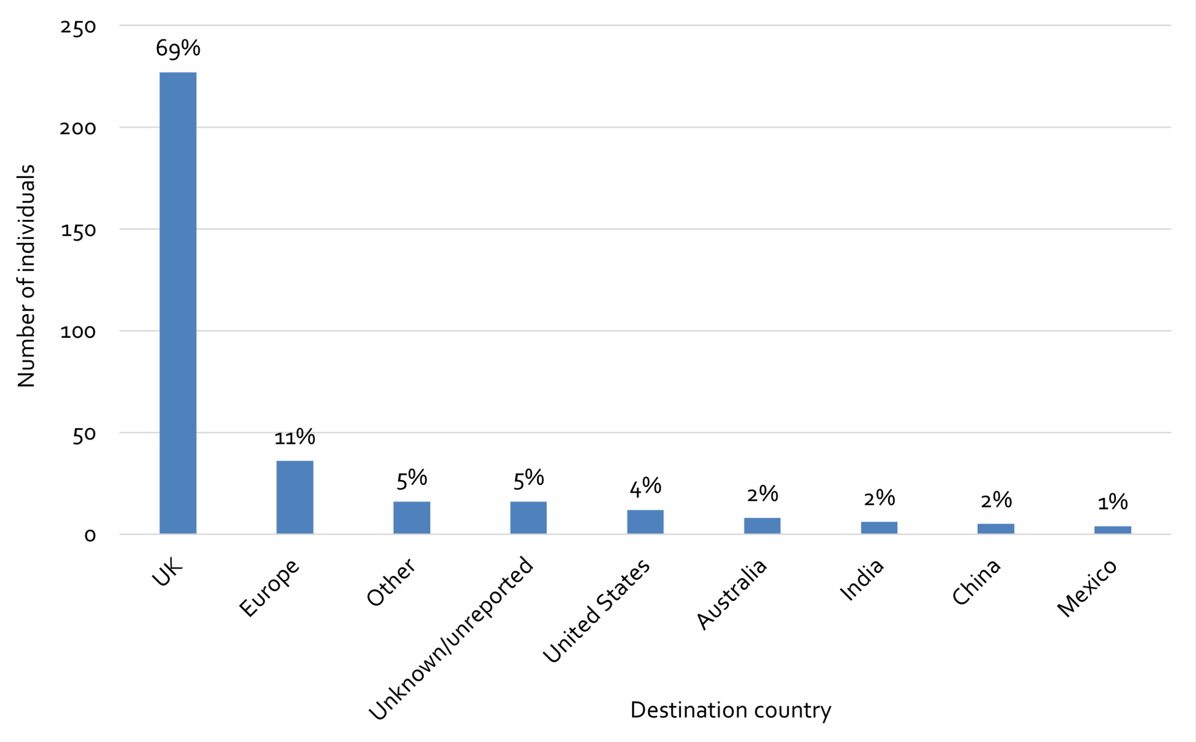
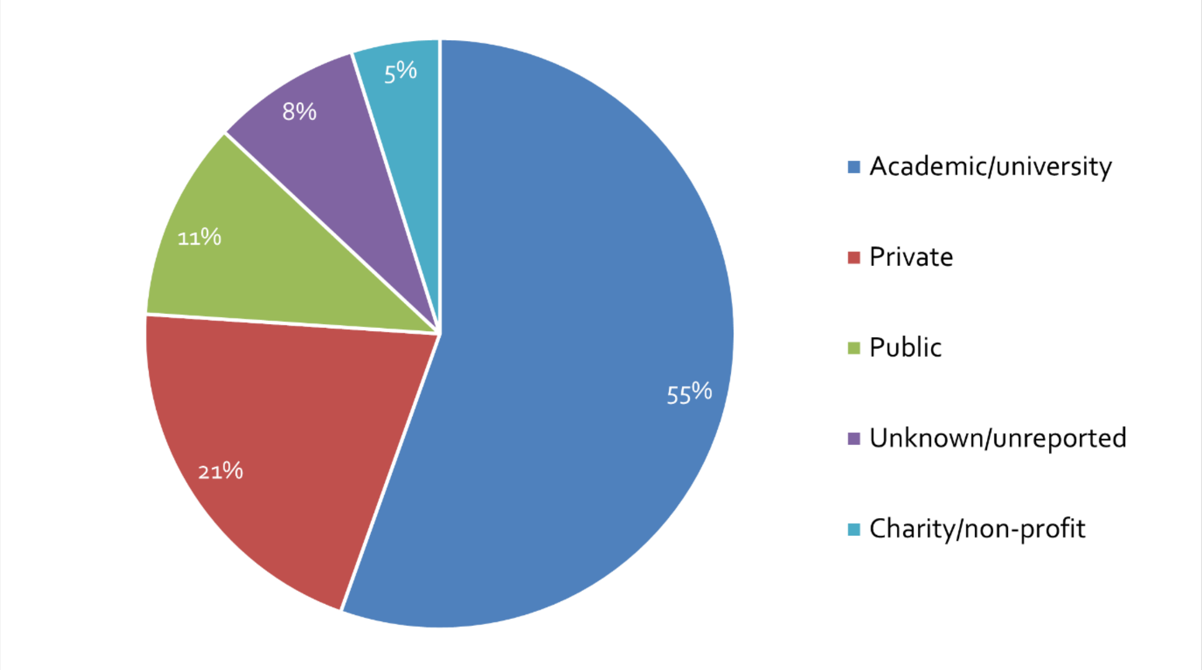


Figure D.11: Next destination – sector destination



Intellectual property

Figure D.12: IP by sub-type

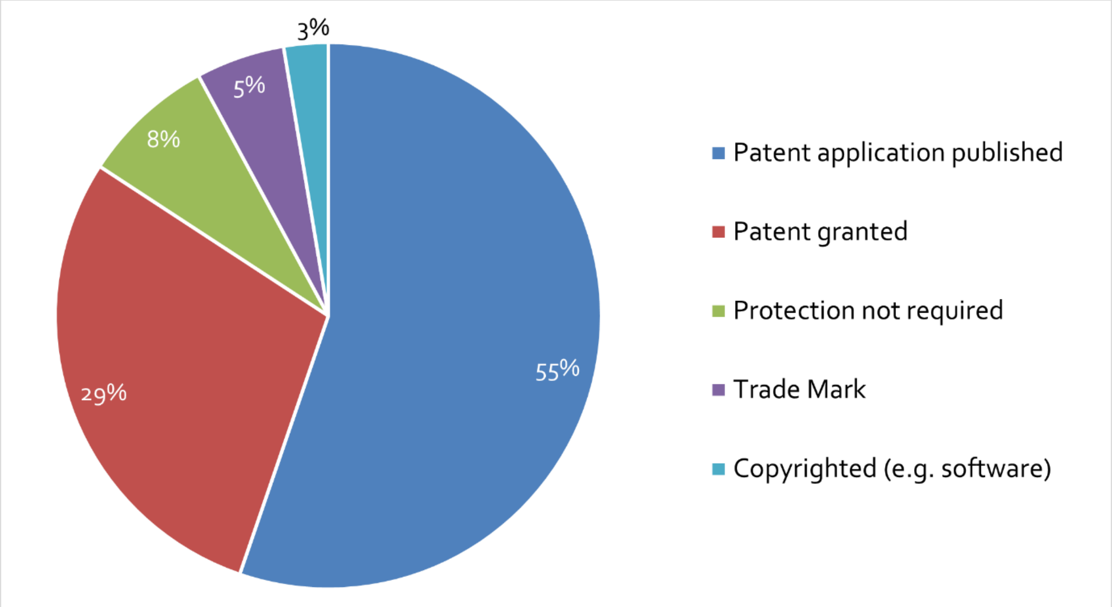
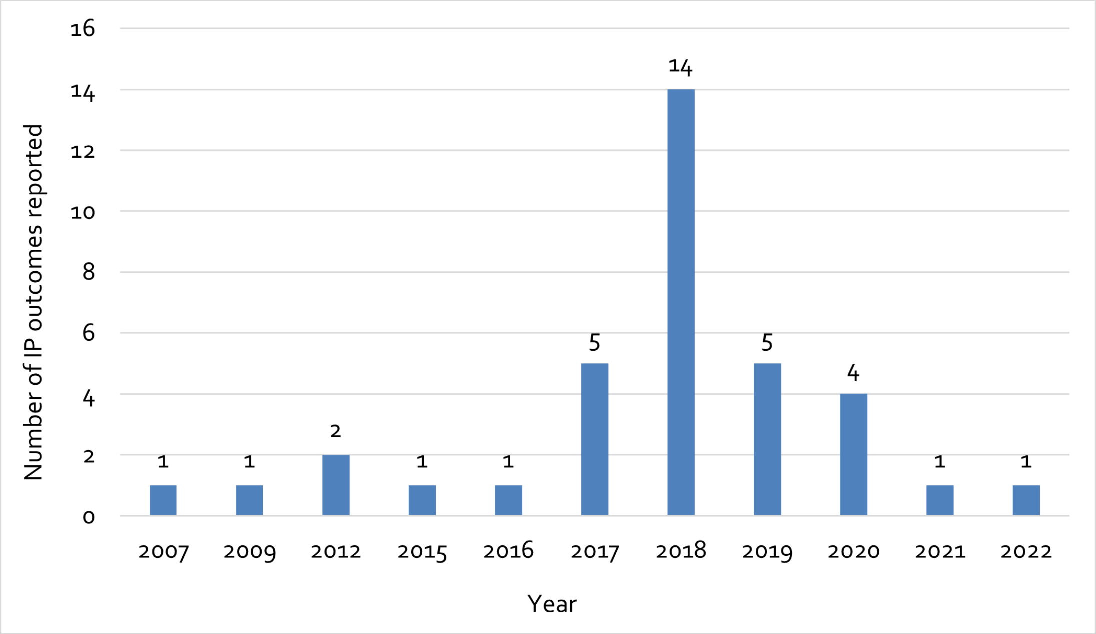


Figure D.13 shows IP outcomes by year. As with publications, caution is needed in interpreting this data reported via Researchfish – see paragraph 3.2. BBSRC started using Researchfish in November 2014, and it took several years for researchers to become familiar with the platform. Interpretation of information presented here should take into account: i) early grants not being reported on; ii) changes in reporting behaviour over time, including behaviour changes resulting from introduction of sanctions; iii) increased investment in wheat research over the period; iv) changes in academic output over the period. Prior to the introduction of Researchfish, BBSRC used the Research Outputs System and grant final reports – the data from these sources was not backfilled into Researchfish by BBSRC, and researchers were not required to do so themselves.

Figure D.13: IP by year



Further funding and leverage

Figure D.14: Further funding by sector contributor

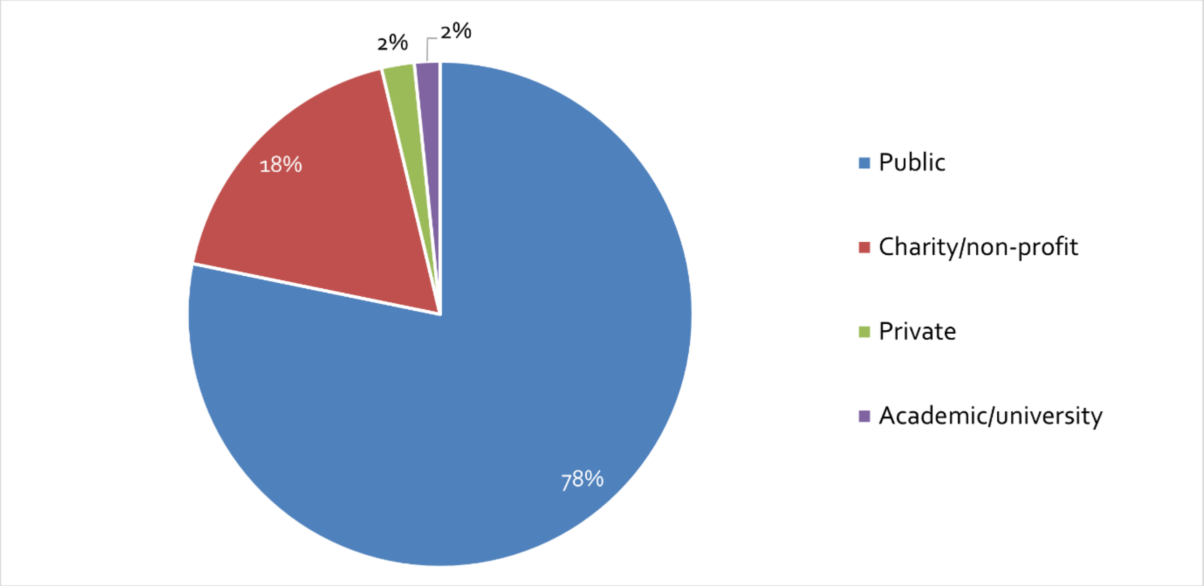
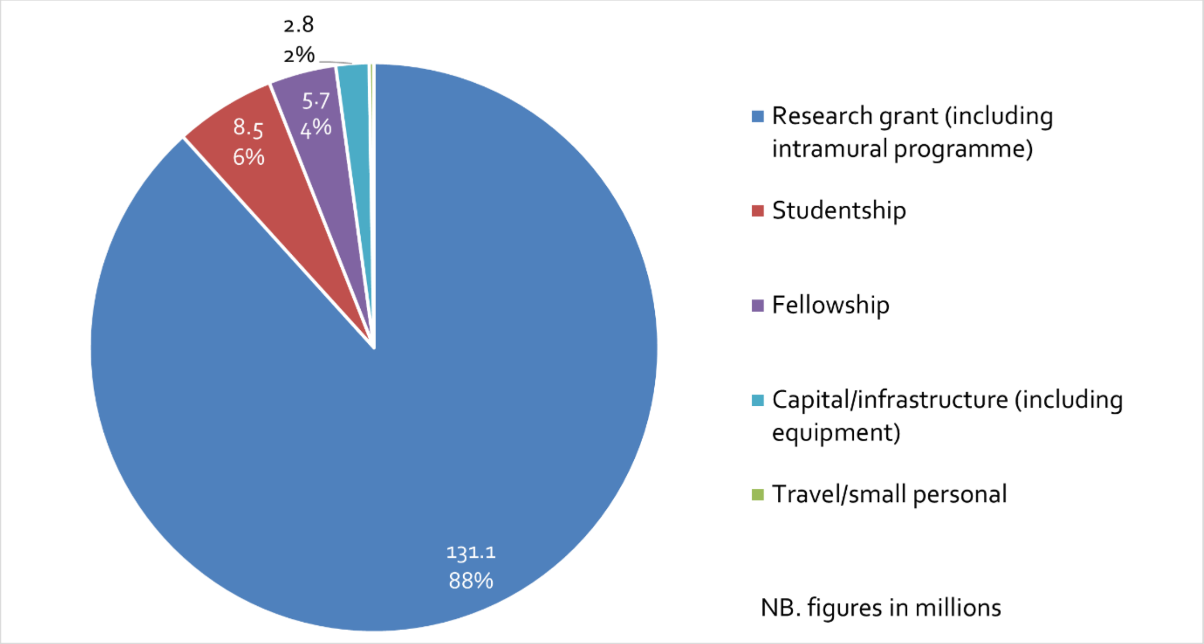
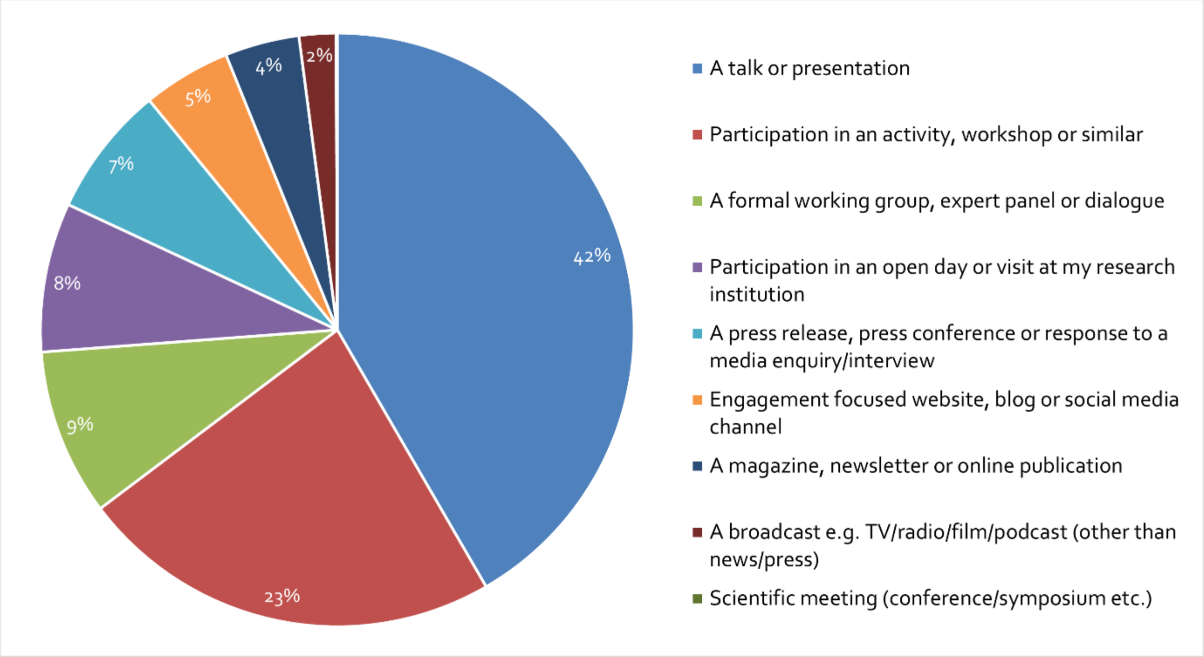


Figure D.15: Further funding by grant type



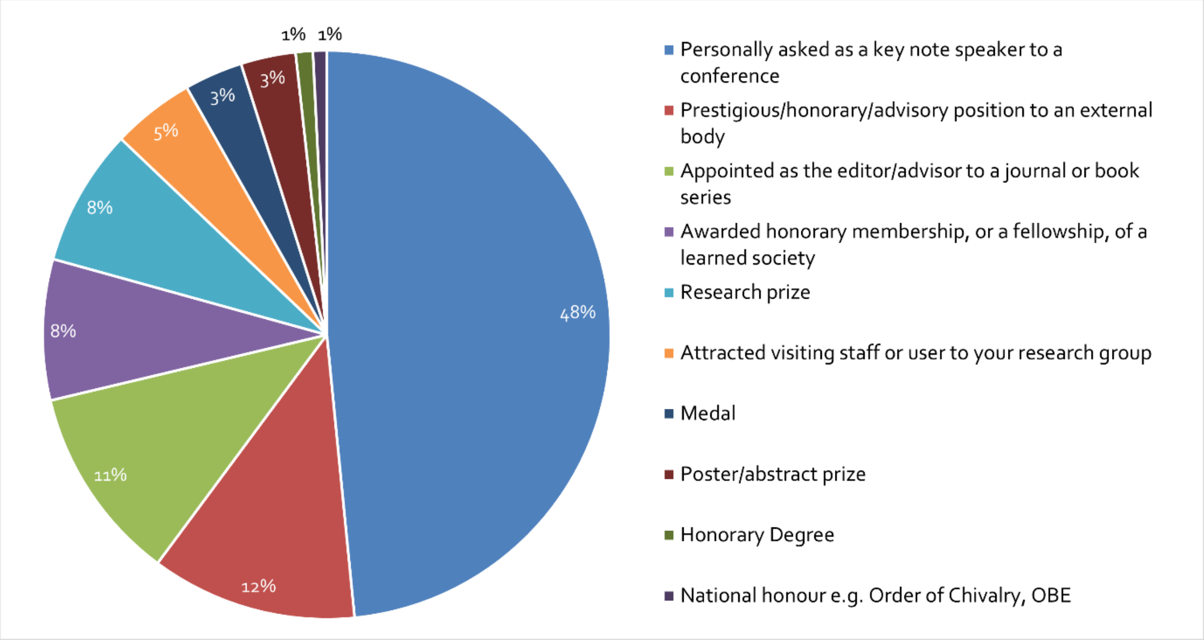
Engagements

Figure D.16: Engagement activities by type



Awards and recognition

Figure D.17: Awards and recognitions by sub-type



Policy outcomes

Figure D.18: Policy outcomes sub-types

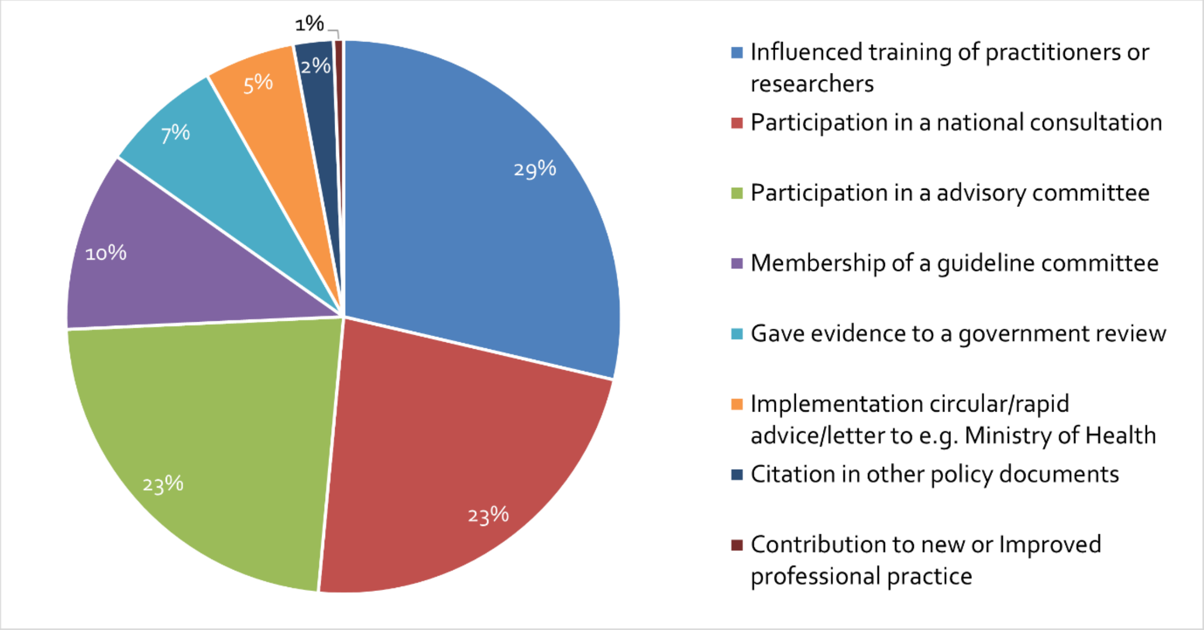
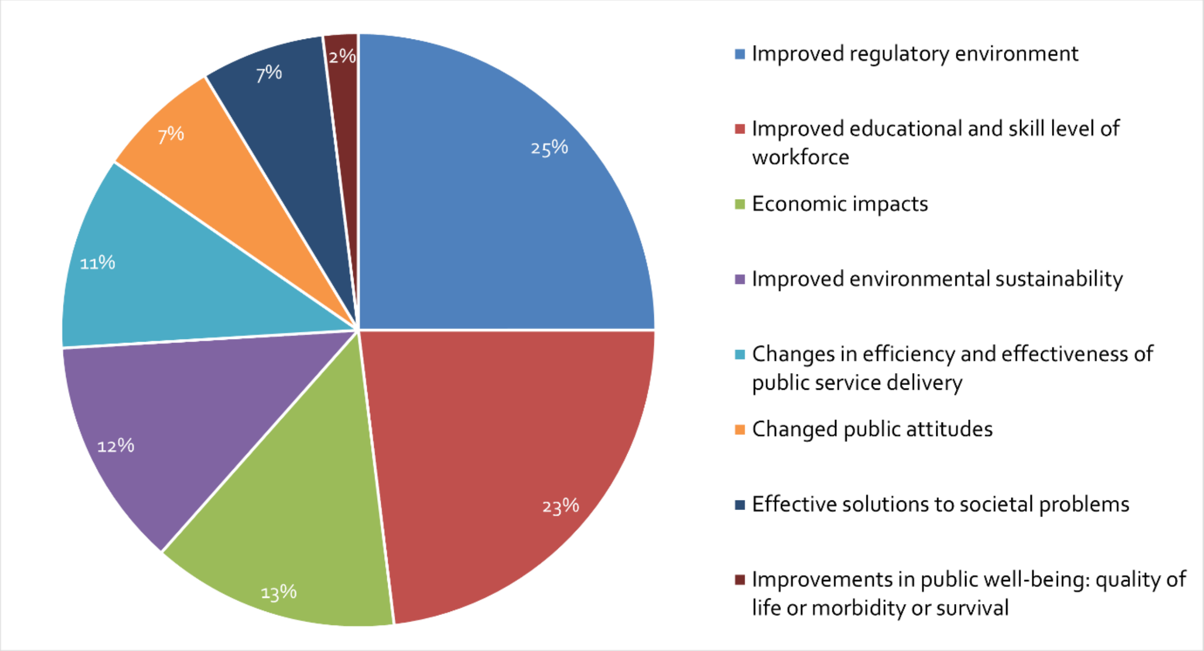


Figure D.19: Policy impact type[93]



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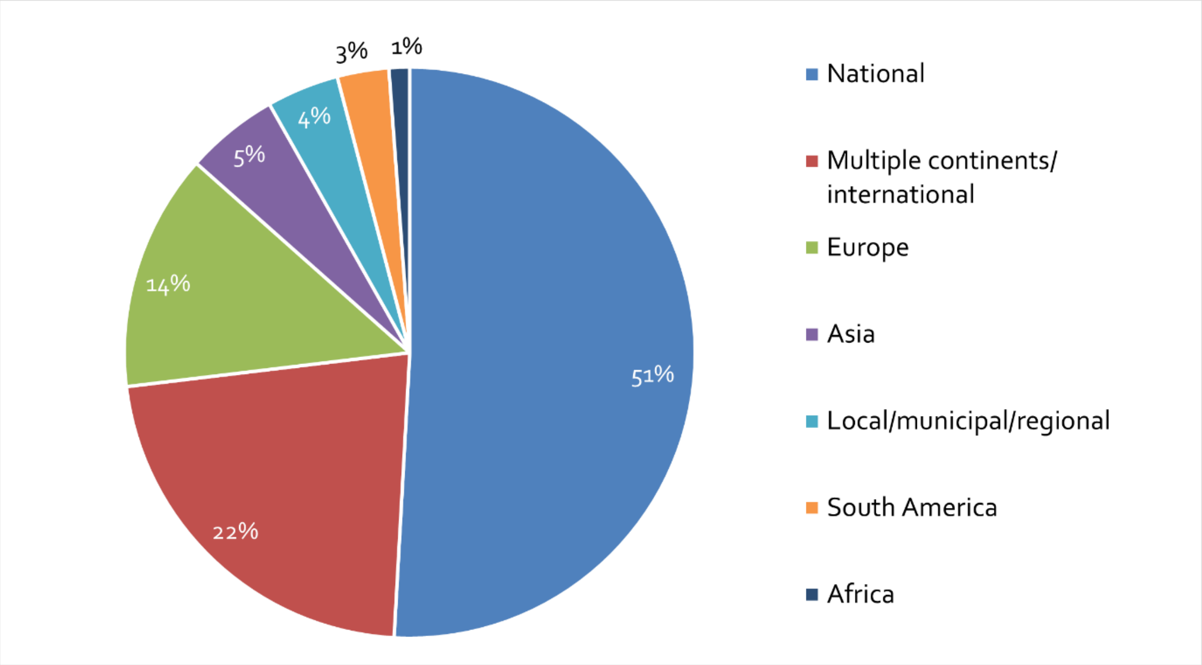
[93] Does not include 'Not known' and 'No Impact' responses.

Figure D.20: Policy impact geographic reach[94]



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[94] Does not include 'Not known' and 'No Impact' responses.

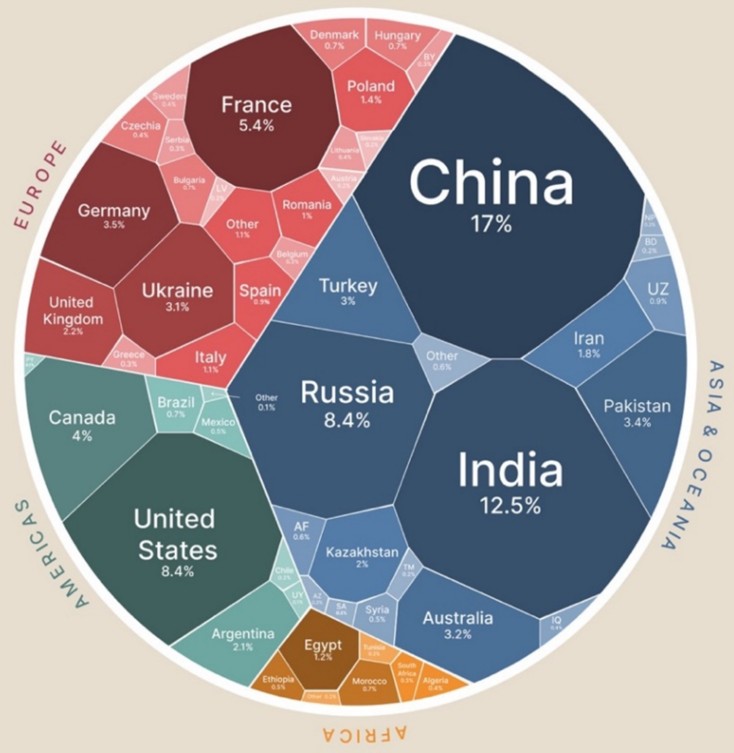
Appendix E: Wheat rationale and context

Global wheat context

Wheat is crucial to global food security. It represents the third most produced cereal (after rice and maize), the second-most produced cereal for human consumption (after rice) and supplies 20% of calories in the human diet.[95]

Asia dominates the production of wheat, with China, India, and Russia collectively accounting for 43% of world output in 2020 (see Figure E.1). Europe represents 34% of world output, with France, Germany and Ukraine significant producers.[96] The US, Canada and Australia are also major wheat producers.

Figure E.1: Global production of wheat, 2000-2020



Source: Visual Capitalist

Global wheat yields have increased steadily in the past two decades, from an average of 2.7 tonnes per hectare (t/ha) in 2000, to 3.5 t/ha in 2020. Asia and Europe – the two main wheat-producing regions – saw their yields increase by 32%, to 3.4 t/ha and 25% to 4.1 t/ha respectively, whilst Africa recorded the fastest increase, with yields rising 44% to 2.5 t/ha. This suggests there is scope to increase yields in lower performing areas – for example, Africa.

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[95] Gutiérrez-Moya et al, Analysis and vulnerability of the international wheat trade network (2021).
[96] FAO, Agricultural production statistics 2000-2020 (2021).

Wheat is the most globally traded cereal, with 25% of global wheat production being exported.[97] Russia, the third largest producer of wheat, is also the largest global exporter, accounting for 13% of total wheat exports in 2021 (worth USD7.3 billion). Other significant wheat exporters include USA, Australia, Canada and Ukraine.[98]

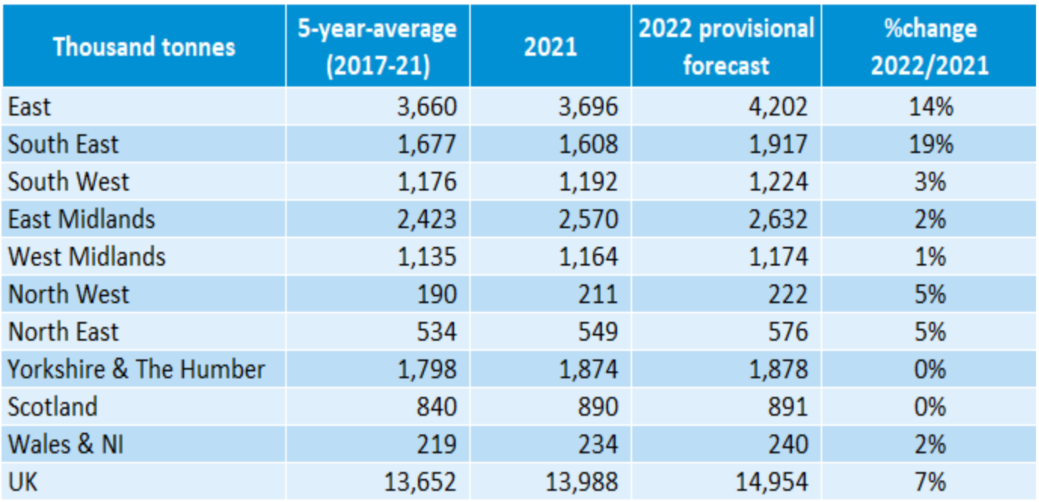
Wheat is critical to food security in the Global South, with countries like Indonesia, Nigeria, Turkey, Egypt, and Bangladesh amongst the largest importers. China, the world's largest consumer of wheat, is also a significant importer, accounting for 5% of total imports in 2021.[99]

UK wheat context

Wheat is the UK's most important staple crop. In 2021, 14 million tonnes of wheat was grown on 1.8 million hectares, representing 39% of the UK's total arable crop area.[100] Wheat performs very well in UK conditions, particularly in the East of England, with UK average yields amongst the highest in the world at 7.9 t/ha (2000-2020 average).[101] UK wheat production is valued at £2.7 billion, representing 25% of agriculture's contribution to the UK economy.[102]

The **East of England is the UK's highest wheat-producing region** – its climate, landscape, and soils are ideally suited for wheat growing (see Figure E.2). As such, the major commercial wheat breeders (e.g., Limagrain, RAGT, KWS) and research institutes (e.g., John Innes Centre, Rothamsted Research, NIAB) are located around Cambridge and East Anglia.

Figure E.2: AHDB UK wheat production outlook, June 2022



Thousand tonnes	5-year-average (2017-21)	2021	2022 provisional forecast	%change 2022/2021
East	3,660	3,696	4,202	14%
South East	1,677	1,608	1,917	19%
South West	1,176	1,192	1,224	3%
East Midlands	2,423	2,570	2,632	2%
West Midlands	1,135	1,164	1,174	1%
North West	190	211	222	5%
North East	534	549	576	5%
Yorkshire & The Humber	1,798	1,874	1,878	0%
Scotland	840	890	891	0%
Wales & NI	219	234	240	2%
UK	13,652	13,988	14,954	7%

Source: AHDB

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[97] Wheat Improvement (2022), p.59: https://link.springer.com/content/pdf/10.1007/978-3-030-90673-3.pdf

[98] World's Top Exports, Wheat Exports by Country (2021).

[99] World's Top Exports, Wheat Exports by Country (2021); Statistica, Wheat consumption worldwide, 2021/2022 (2022).

[100] Source: Defra, Agriculture in the UK 2021 (2022).

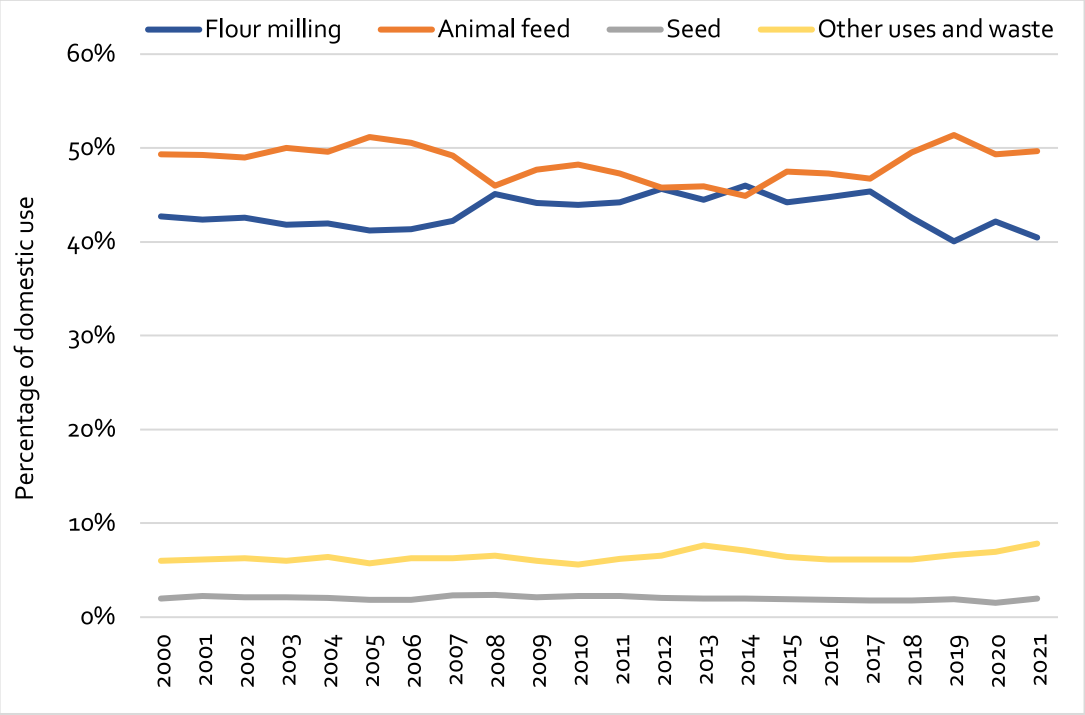
[101] FAO Statistics: https://www.fao.org/faostat/en/#data/QCL

[102] Defra, Agriculture in the UK 2021 (2022).

The UK generally produces around 80-85% of the wheat it requires for domestic use. This means the UK imports approximately 1.5-2 million tonnes of wheat annually, the majority of which comes from the EU, primarily Germany, Denmark, France, and Latvia. The UK exports approximately 1.5-2 million tonnes annually, with the majority to the EU.[103]

As Figure E.3 shows, the UK uses around 45-50% of its annual wheat supply for animal feed, representing approximately 7 million tonnes. Similarly, wheat for milling comprises around 40-45%, accounting for approximately 6 million tonnes.[104]

Figure E.1: UK wheat use, 2000-2021



Source: Graph produced by WECD from Defra data.

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[103] Defra, Agriculture in the UK 2021: Wheat Production Statistics (2022); Defra, Agriculture in the UK 2021 (2022), p.168.

[104] Defra, Agriculture in the UK 2021: Wheat Production Statistics (2022).

Appendix F: Case studies

Case study 1: Improving genetic resistance to Yellow Rust

Case study 2: Using wild relatives to improve modern wheat varieties

Case study 3: Genome sequencing – cracking wheat's genetic code to accelerate research

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CASE STUDY 1: Improving genetic resistance to Yellow Rust

Yellow rust is one of the most significant global diseases of wheat, and the past two decades have seen the emergence of more aggressive and genetically diverse yellow rust races. Combined with the declining availability of chemical fungicides, this places an **increased burden on developing wheat with durable genetic resistance**. BBSRC funding has supported researchers to find new and potentially more durable sources of yellow rust resistance, generate genetic markers for resistance loci (a specific, fixed position on a chromosome where a particular gene or genetic marker is located) to help commercial breeders track the loci in crosses, and develop surveillance tools to monitor the global movement of the fungal pathogen which causes yellow rust.

Context

Wheat is vital to global food security – it is grown on a larger area than any other crop and supplies 20% of calories in the human diet.[1] However, one fifth of the world's wheat yield is lost annually to pests and pathogens, accounting for 209 million tonnes worth £25 billion.[2]

Yellow rust, also known as stripe rust, is one of the most devastating diseases of wheat, accounting for 5.5 million tonnes in lost global production annually, worth £782 million.[3] It is a fungal infection caused by the pathogen *Puccinia striiformis* f. sp. *tritici* (Pst) which primarily affects the leaves (although it can also infect the ears), damaging photosynthetic tissue and leading to stunted and weak plants – this results in **significant grain yield losses and a reduction in quality**.[4]

The **UK is particularly prone to yellow rust**, with its temperate maritime climate being perfect for the pathogen's development. Whilst infection can occur across the UK, the disease is most prevalent in the East of England, the UK's most important wheat growing region.[5] However, yellow rust is also a problem globally, for example, in Europe, the US, China, and parts of Africa.

Fungal diseases such as yellow rust can be managed through genetic resistance and/or chemical fungicides. Breeders have predominantly used major "R" genes to build resistance to yellow rust, **but this type of resistance is relatively easy for the pathogen to overcome** – while the past two decades have seen the **global emergence of more aggressive and genetically diverse populations of the yellow rust pathogen**, for example, the Warrior group of Pst races.[6]

Recent EU regulation, for example, has resulted in the withdrawal of active ingredients used in key chemical fungicides used to counter yellow rust.[7] Moreover, these new Pst races are **more adaptable to environmental changes**, tolerating increased temperatures.[8] These races have been reported globally, with major outbreaks in south central United States and Australia. This places an **increased burden on developing wheat with durable genetic resistance to manage the yellow rust threat**.

Yellow rust symptoms in wheat. Credit: AHDB.

BBSRC-funded projects

BBSRC funding has supported a number of research projects into wheat genetic resistance to yellow rust, undertaken by, for example, the National Institute of Agricultural Botany (NIAB), the John Innes Centre, and the University of Nottingham. BBSRC-funded projects include:

- The Wheat Improvement Strategic Programme (WISP) and Designing Future Wheat (DFW) strategic programmes supported research on the Watkins landrace collection at the John Innes Centre, on wild relatives at the University of Nottingham, and re-synthesised wheat at NIAB, including work on the identification of new sources of yellow rust resistance.[9]

- Responsive Mode funding through the LINK scheme to NIAB and the John Innes Centre for the Wagtail project, and to NIAB for the Yellowhammer project.[10]

- Funding through the Bioinformatics and Biological Resources Fund (BBR) scheme to NIAB.[11]

- Responsive Mode funding through the Industrial Partnership Award (IPA) scheme to the Earlham Institute, the John Innes Centre, and NIAB.[12]

The research has been co-funded by Defra (Wagtail), AHDB (Yellowhammer), and DFID (SCPRID), and supported by commercial breeders, including RAGT, Limagrain, KWS, Saaten-Union (including Elsoms Wheat, DSV and LSPB), Lantmannen, SW Seed, Sejet Plant Breeding, and Syngenta.

Progress and achievements to date

Genetic markers for resistance

The Wagtail project – led by NIAB, in collaboration with the John Innes Centre and major breeders in the UK, Denmark and Sweden – evaluated 495 wheat lines popular across northern Europe in field trials with the aim of finding resistance to four fungal diseases, including yellow rust.[13] **Several genes were found that contributed to yellow rust resistance** and were thought most likely to be durable, rather than the R-type genes easily bypassed by the pathogen. The project **generated a database of genetic markers** associated with yellow rust resistance – these were then validated as being associated with resistance in breeders' material. Breeders have **adopted these markers** and have used the project's data to **inform selection and crossing schemes in their breeding programmes**.

The success of the Wagtail project led to a **request from the breeders for a project that focused solely on yellow rust**. This led to the Yellowhammer project, which aimed to further validate the resistance loci (a specific, fixed position on a chromosome where a particular gene or genetic marker is located) discovered in Wagtail, but also to determine the biological mechanisms underlying these yellow rust resistance loci.[14] An additional 460 wheat lines were genotyped and screened by breeders in fields in the UK, Denmark, Sweden, Germany and northern France. Aided by the sequencing of the wheat genome, which has enabled more detailed assessment to the genes underpinning each resistance locus, researchers **confirmed resistance loci identified in Wagtail** but also **uncovered additional yellow rust resistance loci not previously found**. Approximately **20 loci were taken forward for marker development and in-depth, biological and molecular analyses**. These markers have been **used and tested by commercial breeders**. As one commented:[15]

> ***'I have used a lot of the outputs from the Yellowhammer project.'***

The project ends in September 2023 and NIAB are currently running glasshouse trials, and undertaking gene expression analyses, to see how combining genes that have different biological functions and confer resistance in different ways may lead to more durable resistance.

In parallel, sources of durable adult plant resistance have been identified in NIAB's BBSRC-funded multi-founder advanced generation inter-cross (MAGIC) populations. Cross referencing results from MAGIC with Wagtail and Yellowhammer identifies strong sources of durable rust resistance in

MAGIC that is currently present at low frequency (~5%) in Northwest European germplasm, allowing these to now be specifically targeted for introgression into current breeding materials for assessment. Collectively, this will **help breeders decide what crosses to make for yellow rust resistance**. As Rachel Goddard, cereal pathologist at Limagrain, commented:[16]

> ***'Different genetic loci associated with resistance can change from year to year and location to location…It shows the importance of the [Yellowhammer] project's surveillance and monitoring of varieties over several sites and several seasons.'***

Pathogen surveillance and tracking

Researchers at the Earlham Institute and John Innes Centre have **developed new methods to assess the genotypic diversity of yellow rust races** – this has shown that one population of new lineages which has recently entered the UK (called 'Group 4') is the most dominant and diverse, and has replaced pre-2011 yellow rust races.[17] This and other data generated by the research has been **incorporated (for the first time) into the UK Cereal Pathogen Virulence Survey** (UKCPVS)[18] to **enhance the speed of diagnostics and surveillance**, and supported the long-running UKCPVS (undertaken by NIAB). As Professor Diane Saunders, project lead at the John Innes Centre, commented:[19]

> ***'New rust strains are constantly emerging and spreading across huge geographic space. Our best chance of tackling this threat is to know exactly which strains are present in a farmer's field so we can action the most appropriate control measures.'***

This method has led to the subsequent **development of the MARPLE (Mobile And Real-time PLant disEase) diagnostics platform**, a mobile nanopore sequencing technology for rapid diagnostics and surveillance of fungal pathogens in situ.[20] The technology **cuts yellow rust identification time from months to hours**, enabling increased surveillance of disease and more targeted methods of control. The platform is currently being **deployed in resource-poor regions such as Ethiopia, Nepal and Kenya** to enable tracking of individual genotypes for wheat yellow rust in real time. As Dr Dave Hodson, Senior Scientist at CIMMYT, commented:[21]

> ***'We believe we have a new race of yellow rust that has come into Ethiopia this year… MARPLE will allow us to rapidly diagnose this new race and determine its spread which has big implications in guiding control measures to where they are needed most.'***

Using this method, the researchers **identified the first case of wheat stem (black) rust in the UK for more than 60 years** – this fungal disease was largely eradicated in western Europe in the mid-to-late 20th century, but climate change is creating more favourable conditions for stem rust infection.

Novel genetic resistance

Novel genetic resistance to yellow rust, particularly to the new Warrior race, **has been found in the Watkins landrace collection** at the John Innes Centre. Researchers evaluated 500 accessions and found 3-4 genes present in the Watkins landrace collection that are not present in modern wheat – these are **now being bred into elite lines for trials**. As Dr Simon Griffiths, Programme Leader for DFW at the John Innes Centre, commented in a BBC interview:[22]

> ***'Within the [Watkins] collection, there are new resistances [to yellow rust]…which stand up against this disease, and that's being deployed by breeders right now to defend this really important threat to wheat production.'***

Researchers at the University of Nottingham have also **uncovered yellow rust resistance in wild relatives of wheat**, for example, in goatgrasses (*Aegilops caudata* and *Aegilops mutica*) and red wild einkorn wheat (*Triticum urartu*).[23] These lines are being **incorporated into locally adapted varieties in the UK, Kansas and Mexico** (CIMMYT).

Next steps

Further field trials are required to see if yellow rust resistance is transferred from genotype to phenotype. Successful lines will then need to be backcrossed into elite wheat varieties for commercial use in the UK.

CASE STUDY 2: Using wild relatives to improve modern wheat varieties

Wild relatives of wheat provide a vast and largely untapped reservoir of genetic variation for desirable traits like disease resistance. Fusarium head blight (FHB) is a highly damaging fungal disease of wheat – as well as causing significant yield losses, the fungus produces mycotoxins which contaminate grain and pose a risk to human and animal health. **Researchers at the University of Nottingham have found resistance to FHB in a wild relative of wheat**. The resistance genes are currently being transferred by breeders into elite adapted varieties in Mexico, Kansas (USA), and the UK to undertake field trials.

Context

The domestication of wheat has transformed a wild grass into one of the most important global crops – wheat is now grown on a larger area than any other crop and supplies 20% of calories in the human diet.[24] However, traditional breeding methods which cross elite lines with one another have led to a **narrow genetic base, leaving wheat vulnerable to diseases and environmental shocks**.

FHB is one such disease – it is a highly damaging fungal pathogen of bread and durum wheat (as well as other important cereal crops), and its impact is felt globally. As well as causing yield losses, FHB is particularly concerning as the fungus produces mycotoxins which contaminate the grain and pose a risk to human and animal health, particularly pigs.[25]

Fusarium head blight infection. Credit: Javier Segura/CIMMYT.

FHB incidence has risen dramatically in the UK over the last 20 years, with an estimated yearly increase of 1.8% – an epidemic in 2012 affected 96% of wheat crops.[26] Moreover, FHB thrives in humid, warm conditions; climate change may therefore increase the likelihood of FHB incidence, posing a further challenge to farmers in the UK and globally.[27] Farmers in the UK, Europe and the US may be able to control the disease with fungicides, but small-scale farmers in the Global South don't have the resources to buy such chemical controls, so need 'built in' disease resistance.

Wild relatives of wheat provide a vast and largely untapped reservoir of genetic variation for desirable traits like disease resistance, heat and drought tolerance, and improved nutrient use efficiency.[28] This variation can be exploited to develop new, high-yielding, disease-resistant, climate-resilient wheat varieties. As **there is very little variability for resistance to FHB in wheat itself, resistance from a wild relative has a critical role to play in future global wheat production**. As Hans Braun, former Director of CIMMYT's Global Wheat Programme (2006-2020), commented:[29]

> ***'With the exception of the dwarfing genes…genetic variability from wild relatives has probably had the greatest impact on wheat production. This is remarkable considering that only a tiny fraction of this variability has so far been exploited.'***

BBSRC-funded project

University of Nottingham researchers from the Nottingham Wheat Research Centre have

found resistance to FHB in a wild relative of wheat called *Triticum timopheevii* – this paves the way for breeding new varieties with improved resistance. This research has been supported by BBSRC funding through:

- Responsive Mode funding totalling £670,492.[30]
- The Wheat Improvement Strategic Programme (WISP).[31]
- The Designing Future Wheat strategic programme.[32]
- International initiative funding through the Sustainable Crop Production Research for International Development (SCPRID) programme, totalling £1.6 million.[33]
- The International Wheat Yield Partnership (IWYP) totalling £679,165.[34]

The research was also supported by the University of Nottingham through investments in research infrastructure (e.g., glasshouses, seed store).

Progress and achievements to date

Enhancing the transferability of wild relative genes to modern wheat

Historically, transferring genes from wild relatives into wheat has been very challenging. Many wild relatives have rearranged their chromosomes meaning they now can't align effectively and recombine when crossed with wheat – this means wild relative genes don't mix with wheat genes and aren't transferred to the new plant. Moreover, there has previously been a **lack of genetic markers to identify and track these introgressions**. This has made the process of transferring wild relative genes to wheat very time consuming and inefficient, which has hampered the exploitation of the genetic diversity held within wild relatives.

Researchers at the University of Nottingham have **identified a promoter which vastly increases the ability to transfer genes from wild relatives to wheat**, enhancing speed and efficiency.[35] Using these methods they have generated thousands of plants with genetic variability and also **developed diagnostic genetic markers** that tag the genes from the wild relatives, making it easy for other researchers and breeders to track the transfer of wild relative genes.[36]

BBSRC funding for underpinning fundamental research like wheat genome sequencing, as well as the supporting the development of genetic markers (e.g., the University of Bristol's work as part of WISP and DFW strategic programmes), has also helped overcome these technological barriers.

FHB resistant germplasm development and translation

Researchers at the University of Nottingham, in collaboration with pathologists at the John Innes Centre, identified a wild relative of wheat (*T. timopheevii*) that is highly resistant to FHB. Using their new methods, Nottingham researchers **transferred FHB resistance genes from this wild grass to wheat** – these new lines showed significantly more resistance to FHB than the elite variety Paragon. **As there is very little variability for resistance to this disease in wheat itself, this resistance from a wild relative has a critical role to play** in future global wheat production.

T. timopheevii. Credit: Andrea Moro, Università di Trieste

Researchers then developed novel germplasm based on these FHB introgressions, which have been **translated for public and commercial wheat breeders around the world**.

- **CIMMYT** are currently growing the FHB resistant lines at its centre in Mexico.
- The FHB resistant lines have been requested by **Kansas State University** and are already being incorporated into locally adapted Kansas varieties (e.g., KanMark, Bob Dole).
- The French breeding company **Florimond Desprez** specifically requested the FHB resistant lines, which are currently being incorporated into their breeding programme.
- The FHB resistant lines are also being incorporated into the breeding programmes of the following commercial breeders: **DSV**, **Elsoms**, **KWS**, **Limagrain**, **RAGT**, **LS Breeding** and **Syngenta**.

Furthermore, CIMMYT, the University of Saskatchewan (Canada), and Kansas State University (USA) have requested the FHB resistance introgression in a durum wheat background. Durum wheat is highly susceptible to FHB and the disease presents a major problem for durum production globally.[37]

Other traits

***T. timopheevii* has other desirable traits** which could be introduced into wheat, including **increased grain mineral content**. This is of particular significance to human nutrition in many parts of the world, and University of Nottingham research, through a BBSRC-funded PhD studentship, has identified introgressions from *T. timopheevii* and two other wild relatives (*Amblyopyrum muticum* and *T. urartu*) that result in **increased grain zinc and iron content** when introduced into adapted genotypes in Malawi.[38] These lines have also been **transferred into adapted varieties in Kansas and at CIMMYT** (Mexico).

Hybrid wheat could lead to yield increases of between 3.5% and 15%.[39] However, this requires cross-pollination between genetically different female and male parents; wheat is an in-breeder and therefore does not have the correct floral morphology required for out-breeding. Funded by IWYP, University of Nottingham research found that **two introgression lines of *T. timopheevii* which had smaller pollen grains** – this could support hybrid wheat production as smaller pollen could travel further than wheat's current heavy, short-lived pollen, which tends to self-pollinate.[40] **These lines are now at the IWYP translation hubs[41] for transfer into selected elite varieties** and have been **requested by UK breeding companies for incorporation into their own programmes**.

Next steps

The next steps with Nottingham's FHB work is to transfer the wild relative introgression carrying the FHB resistance gene into elite varieties in the UK, USA (Kansas) and Mexico (CIMMYT) – field trials are being undertaken to see if the resistance holds up in each country (this has already been found to be the case in Kansas) and to see if the introgression carries any genes which may negatively affect yield. If there are yield penalties, further manipulations will be undertaken at Nottingham to remove any deleterious genes. Researchers have also identified other sources of FHB resistance in wild relatives, which will be available for future exploitation.

CASE STUDY 3: Genome sequencing – cracking wheat's genetic code to accelerate research

Genome sequencing of cereal crops like rice and maize has led to improvements in yield and resilience. However, wheat's genome is exceptionally large and complex, and this has hampered research and breeding efforts to develop improved varieties. Moreover, the sequencing technology and methods available aren't suitable due to the wheat genome's size and complexity. **BBSRC funding supported the UK's contribution to international efforts** to sequence the wheat genome, which was first published in 2018 – this includes **sequencing, assembly and annotation**. This has already **accelerated wheat research and breeding to develop improved wheat varieties**.

Context

Wheat's genetic code is exceptionally large and complex. Made up of three closely related yet distinct sub-genomes, each from a different grass ancestor, it is five times the size of the human genome (and seven times that of maize) and highly repetitive.[42]

This **makes wheat much more challenging to work with** than smaller cereal genomes like rice and maize, which has **hampered research and breeding efforts to develop improved wheat varieties**. Sequencing the genome of rice in 2002, for example, increased breeding efficiency by generating molecular markers which can be used to quickly map desirable traits and identify genes within a region of interest – this has led to improvements in rice grain yield and drought tolerance.[43] Likewise, the sequencing of the human genome dramatically accelerated biomedical research.[44] A whole **genome sequence of wheat could be similarly transformative for wheat research and breeding**.[45]


The three ancestors of modern wheat (right), compared with modern wheat (left). Credit: CIMMYT.

However, **size and complexity of the wheat genome makes sequencing incredibly challenging**, with sequencing technology only able to produce short fragments which then needed to be assembled. Moreover, wheat's many genes are hidden among a sea of repetitive sequences which occur hundreds and thousands of times. This means it is hard to find the genes and assign them to the correct sub-genome and chromosome, and in the right order. As one plant genetics researcher commented:[46]

> ***'Imagine a giant heap of pieces from three puzzles, each made with identically shaped pieces and making very similar pictures, although you don't know what any of the pictures look like. That's what trying to sequence the wheat genome will be like.'***

BBSRC-funded projects

The size and complexity of the wheat genome meant an international collaborative effort was required, led by the International Wheat Genome Sequencing Consortium (IWGSC), established in 2005.[47]

UK contributions were led by the Earlham Institute (EI), and also included researchers from the John Innes Centre, Rothamsted Research, the Natural History Museum, and the universities of

Earlham Institute
Decoding Living Systems

Bristol, and Liverpool. This was **supported by BBSRC funding**, including:

- A Strategic Longer and Larger (sLoLa) grant to EI, the John Innes Centre, Rothamsted Research, and EMBL-EBI.[48]
- Strategic funding to Rothamsted Research as part of the Wheat 20:20 programme.[49]
- Fellowships to researchers at the University of Liverpool and the John Innes Centre.[50]
- Responsive mode funding, for example, to the John Innes Centre and the universities of Liverpool and Bristol;[51] and to EI, the John Innes Centre and the Natural History Museum.[52]

IWGSC is sponsored by public sector organisations like CIMMYT (Mexico) and INRAE (France), and private industry, such as BASF, Florimond Desprez, Illumina, Kansas Wheat, RAGT, and Syngenta.

Progress and achievements to date

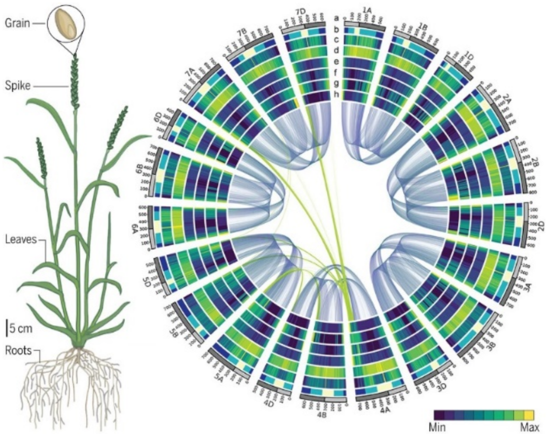
EI started work on wheat genome sequencing in 2009, and the first full reference sequence of the wheat genome was published in 2018. **EI played an important role in the assembly and annotation of the wheat genome**, contributing to each and every breakthrough using its genome sequencing capacity and bioinformatics tools developed on-site. The wheat genome has become a vital tool for UK and international wheat breeders and is already affecting the yield and quality of commercial varieties.

Knowledge generation – publications

UK researchers were **contributors to several landmark papers** on the sequencing of the wheat genome, notably the ground-breaking 2018 paper which identified the location of nearly 108,000 genes and more than 4 million molecular markers.[53] UK researchers also published early draft sequence fragments in 2012[54] and the first draft sequence for chromosome 3B (the largest of the 21 chromosomes) in 2014.[55] The latter paper was significant in establishing a proof of concept for sequencing the remaining genome.

Tools and software – assembly and annotation

Sequencing machines can only read very small parts of genomes, requiring assemblers to put the pieces together – when EI researchers started work on the wheat genome project they found a very fragmented analysis that needed to be brought together. **EI generated assemblies for all 21 chromosomes**, including developing the ground-breaking **W2rap software tool** which enables assembly of genome fragments.[56] A key benefit of W2rap is that it **produces results which are accurate enough to compare two wheat lines with each other**, something not previously possible.



The wheat genome deciphered, assembled, and ordered. The circular plot to the right shows regulatory sequences and the interaction network of expressed genes. Credit: IWGSC.

As part of the assembly work, EI researchers made modifications to the Broad Institute/MIT **DISCOVAR platform**, used to sequence the human genome, to help distinguish repeat sections (an estimated 85% of the wheat genome) – this enables a high-quality, precise assembly process. EI's assembly tool **support faster, more accurate breeding** as well as allowing pipelines of comparators for the first time, with applications beyond wheat. There has already been considerable interest from commercial companies for EI's sequencing work, reaching around £500,000 per year.[57]

Once sequenced and assembled, genomes need annotating to pick out the useful parts (i.e., the genes and their products). **EI researchers developed two tools to dramatically enhance genome annotation** to deliver the most comprehensive annotation of the 21 wheat chromosomes to date:[58]

- **Portcullis** enables researchers to better **distinguish between splice junctions in genes with 95-99% accuracy**. Improving accuracy can help with many downstream tasks such as transcript reconstruction and differential splicing analysis.
- **Mikado** helps genome assemblers correctly identify 'real' genes, which are sometimes lost in the process due to highly similar (sometimes almost identical) regions of DNA, by filtering out false positives and identifying where there might be false negatives. Mikado **enables EI researchers to integrate two alternative gene sets** created by IWGSC collaborators, ensuring a high-quality final wheat genome annotation.

Importantly, all these **methods and data are openly available on EI's Grassroots Genomics platform**.[59] This provides a versatile data repository, analytical services, and enables marker-assisted breeding that is freely available to researchers, breeders and the public.

Benefits of wheat genome sequencing

The assembly and annotation of the wheat genome is a vital tool as it **accelerates the development of new wheat varieties with improved traits**, like yield, heat tolerance, and disease resistance. For example, **EI has developed an approach to identify genes in less than a month, instead of the typical three-six years**.[60] As Professor Neil Hall, Director of EI, comments:[61]

> ***'Sequencing the wheat genome is transformative, leading to accelerations in breeding and the discovery of genes underlying key traits…BBSRC funding has enabled the UK scientist to play an important leadership role in delivering assembled wheat genomes.'***

The wheat genome sequence supports research efficiency through the following ways:

- **Gene discovery:** rapid identification and location of the genes responsible for desirable traits – these can then be isolated, and their function studied. For example, within months of the sequence being published, researchers at the John Innes Centre used the genome to identify genes contributing to grain size.[62]
- **Gene improvement:** identifying modified and improved versions of the genes into mutant collections and/or creating modified and improved versions by genetic engineering.
- **Marker-assisted breeding:** with a reference sequence, breeders have an unlimited source of molecular markers close to or within the genes of interest. They can use these markers to identify suitable parents containing the traits of interest for new crosses and track down the presence of the genes of interest in the descendants during the selection process.

Accelerating wheat research and new variety development could also help **overcome a market failure by increasing profitability throughout the wheat industry**. As wheat breeding becomes more efficient, it becomes easier for researchers and commercial breeders to transfer research discoveries into new and improved wheat varieties.[63]

Furthermore, the methods for wheat genome provide a **model for sequencing other large, complex plant genomes**, and the success of IWGSC efforts reaffirms the **importance of international collaboration and open access data and resources to advance global food security**.[64]

Next steps

It is impossible to capture the wide range of different genes from different wheat cultivars within a single genome, therefore, **additional genome sequences are required**. This will enable the full complement of wheat genes to be identified and provide insight into how breeders in different parts of the world have selected for different attributes (e.g., Australia and Mexico have selected for resilience to heat and drought). This information will be used to increase the speed of development of new wheat varieties and reduce the costs of bringing them to market.[65] For this work, **EI researchers are contributing to the 10+ Wheat Genomes Project**,[66] and have already **produced high-quality reference genomes for 16 elite global varieties** (including Europe, Japan, Mexico, USA and Australia). As Dr David Swarbreck, Group Leader at EI, comments:[67]

> ***'Sequencing multiple wheat genomes is revealing that wheat is a complex mosaic of bread wheat and wheat wild relatives. Identifying the full complement of wheat genes and provides the best resource for wheat researchers and breeders to continue to improve wheat quality and production.'***

CASE STUDY 4: Re-synthesised wheat – recreating the evolution of wheat to unlock the genetic diversity bottleneck

Traditional breeding has led to wheat having a narrow genetic base – this leaves it vulnerable to diseases and climate change. Moreover, yields need to improve to keep pace with increasing demand. **Researchers at the National Institute of Agricultural Botany (NIAB) have re-created a rare natural cross between an ancient wheat and a wild goatgrass which led to the evolution of what we know today as bread wheat.** This 're-synthesised' wheat (also called 'synthetic hexaploid wheat' or SHW) **introduces increased genetic diversity to modern wheat, as well as desirable traits**, such as improved yield, particularly under drought and high-temperature conditions, and disease resistance.

Context

The domestication of wheat has turned a wild grass into one of the most important global crops. Thousands of years of wheat breeding since has led to wheat varieties with improved yield, seed size, and nutritional content – wheat is now grown on a larger area than any other crop and supplies 20% of calories in the human diet.[68]

However, traditional breeding methods which cross elite lines with one another has led to a **narrow genetic base, leaving wheat vulnerable to diseases and environmental shocks**.[69] Moreover, **yields need to continually improve in order to keep pace with increasing global demand** for wheat.[70]

Around 10,000 years ago, in a rare hybridisation event, tetraploid durum wheat crossed naturally with a diploid wild goatgrass (*Aegilops tauschii)* to create the hexaploid wheat variety which forms the basis of modern bread wheat. **However, very little of the natural range of diversity in goatgrass was transferred during this crossing – as a result, modern bread wheat is low in diversity for the goatgrass genome**. Although inedible and considered a weed, goatgrasses have desirable traits, including disease resistance and tolerance to heat and drought.[71]

The goatgrass *Ae. tauschii*, an ancestor of modern wheat. Credit: CIMMYT.

This rare natural cross can be recreated through the development of so called 're-synthesised wheat' (sometimes also called 'synthetic hexaploid wheat' or SHW) which introduces more genetic diversity from goatgrasses.[72] The development of re-synthesised wheat contributes to unlocking the genetic diversity bottleneck, and introduces desirable agronomic traits, **including increased yield, particularly under drought and high-temperature conditions, and novel disease resistance**. As researchers have commented:[73]

> ***'Synthetic wheat, equipped with its broad genetic resources from wild donor species, is poised to play a bigger role in the race to meet upcoming environmental challenges.'***

BBSRC-funded project

NIAB has developed its own set of re-synthesised wheat lines – and researchers have recombined these re-synthesised genomes with elite UK varieties, enabling transfer to commercial breeding programmes. This research was supported by BBSRC funding through:

- The Crop Science Initiative (2007-2012) – this project established a crossing programme using re-synthesised wheats generated by CIMMYT (see below).[74]
- The Super Follow-on Fund (2013-2015) – this project took forward work undertaken under the Crop Science Initiative project.[75]
- The Wheat Improvement Strategic Programme (WISP, 2011-2017)[76] and the Designing Future Wheat (DFW, 2017-2023) strategic programme.[77] These programmes supported NIAB to create their own re-synthesised wheats.

NIAB has also received support from AHDB, the NIAB Trust, and commercial plant breeders (including KWS, Limagrain and RAGT) for this work, as well as from the French Wheat Research Fund (FSOV) for two projects based on NIAB's material developed in the early stages of WISP.[78]

Progress and achievements to date

The original SHWs were generated by CIMMYT in the 1980s, and varieties bred from these have been successfully used around the world, particularly in drought-prone, lower-yielding, extensive agricultural systems in China, Australia, India, Africa, and South/Central America. However, **the work undertaken by NIAB via the Crop Science Initiative was the first in-depth, systematic exploration of re-synthesised wheat in temperate, high-input cropping systems like the UK**. NIAB crossed the original CIMMYT SHWs with UK varieties, producing and evaluating 5,600 lines, with 1,000 taken forward for yield testing.

Whilst this project established that CIMMYT SHWs could deliver unexpectedly high yields and other beneficial traits, their provenance and pedigree history meant that they could not be used to directly follow ancestor species genes through into synthetic-derived pre-breeding lines. For this, it would be necessary to start a new programme of re-synthesis – this was undertaken by NIAB through funding from the WISP and DFW strategic programmes.

NIAB took two approaches to creating their own re-synthesised wheat. The first crossed 50 novel re-synthesised (hexaploid) wheat lines, each capturing a different goatgrass genome, into the 'Robigus' and 'Paragon' elite varieties, generating 9,000 pre-breeding lines. The second approach crossed durum wheat, emmer wheat, and wild emmer wheat (all tetraploid) into 'Robigus' and 'Paragon', generating 3,000 pre-breeding lines.

Via these crossing approaches, NIAB has **created a library of thousands of diverse wheat pre-breeding lines that harbour potentially game-changing ancestral genes**.

Ae. tauschii collection points which formed primary NIAB SHW. Credit: NIAB.

Although re-synthesis can help bring much-needed diversity to modern wheat, **it is a complicated process** that also introduces many undesirable traits, which must later be eliminated during the breeding process The process is very technically demanding and intensive, and it is **unlikely that a commercial plant breeder would do this on their own** – it is a risky, long-term venture, and exploiting this rich genetic resource requires specialised phenotypic screening tools and in-depth analyses to make it 'breeder-ready'.

Beneficial agronomic traits

The main aim of re-synthesis is to introduce 'left behind' genetic diversity from ancestral species into modern wheat to deliver beneficial traits. In 2022, NIAB conducted its largest ever winter wheat nursery to evaluate these lines, growing 4,000 of them in small plots in a single field trial alongside controls. The lines are currently being assessed for several traits, including yellow rust resistance, height, and flowering time.

In yield trials, several synthetic wheat-derivatives have outperformed their 'Robigus' elite parent, and in some cases yield higher than elite commercial varieties like 'KWS Santiago' and 'KWS Siskin'. The combination of high genetic diversity and competitive grain yields is very attractive to breeders and quite unique as a pre-breeding resource. However, few NIAB lines have been tested across multiple years, so further trials are needed.

Re-synthesised wheats can **improve disease resistance**. There is a lot of interest in NIAB's re-synthesised wheats as sources of resistance to Septoria tritici blotch and yellow rust, both of which are major targets for improvement by commercial breeders. For example, researchers have found the region of DNA for yellow rust resistance that are not widespread in UK elite wheat.[79] However, much of this is still at the 'pump-priming' stage or the focus of PhD studentships.

Re-synthesised wheats, due to their genetic diversity from hardy goatgrass, also have the potential to **improve resilience to environmental conditions**, like heat and drought – particularly in terms of maintaining or increasing yield under these conditions. As Dr Matt Kerton, Senior Wheat Breeder at DSV UK, comments:

> ***'It is traits yet to be discovered where the synthetics may prove useful…drought tolerance, stability, NUE [nutrient use efficiency], new disease threats. It is their diversity which is going to provide benefits.'***

Industry engagement and translation

NIAB's re-synthesised wheat resources are having a direct impact in breeding programmes. Commercial UK-based breeders have visited NIAB over the past five years to make selections on this material, which are then integrated into commercial breeding programmes and advanced for further testing. In 2020, approximately 60% of the material in NIAB trials were selected by at least one breeder. As these breeders also often have international testing networks, this material is also making its way into their overseas breeding programmes as well.

Early selections from NIAB's programme are already beginning to filter through to commercial programmes. Through its breeding programme, DSV UK has taken one SHW-derived line, dubbed 'Gandalf', to **National Listing**.[80] As Dr Matt Kerton, Senior Wheat Breeder at DSV UK, commented:

> ***'For lines to be good enough to be entered into National List testing is a 'big tick in the box' for material coming through from BBSRC funding.'***

NIAB have also worked with commercial breeders KWS, Syngenta, Limagrain, and CETAC (a loose coalition of several smaller breeders, including Secobra Researches, Saaten-Union, and Lemaire des Fontaines) through the two projects funded by the French Wheat Research Fund (FSOV).[10]

Next steps

The yield in DSV's synthetic-derived 'Gandalf' variety was not enough to compete with elite candidates so it did not progress to Recommended List testing. However, it is being recycled back into DSV's breeding programme, and may yet have a market depending on baking test results.

To continue this work, NIAB need to extract the traits and genes from its re-synthesised wheat material – this requires multi-location trials and specialised screening under e.g., heat and drought stress. Alongside this, NIAB are conducting a spring wheat 'mega-trial' of 5,000 lines in the field and 1,500 lines in the greenhouse to increase the quantity and purity of seeds – these will then be deposited in the gene bank for translation to partners.[81] For example, NIAB's re-synthesised spring wheat material is especially valuable for the Global South, as well as other countries e.g., Israel and Canada, whilst the winter wheat material is valuable for the UK and Europe.

CASE STUDY 5: Improving nutrient use efficiency

In many developing nations, particularly in sub-Saharan Africa, crop yields are very low due to poor plant nutrition. In contrast, farmers in the UK use large amounts of inorganic fertilisers – this underpins high yields but leads to significant environmental degradation. BBSRC-funded researchers at the University of Cambridge, in collaboration with seven other institutions, have set out to **transfer nitrogen fixation processes from legumes to cereals and to enhance the association with beneficial mycorrhizal fungi**. This **will improve a crop's ability to efficiently take up nutrients from the soil** and the air (nutrient use efficiency), leading to **enhanced crop yields in developing nations**, and **reduced inorganic fertiliser usage in the UK**. In the next 5-10 years, the project hopes to have genetic lines of crops with improved mycorrhizal symbiosis and association available to farmers.

Context

Cereal production is highly dependent on inputs of nitrogen-based fertiliser. However, farmers in developing countries neither have the resources to buy inorganic fertilisers, nor the infrastructure for their production and supply. Moreover, cereal production is limited to 20-40% of its potential yield due to nutrient depleted soils.[82] Improving nutrient take-up could enhance yields, helping to tackle global food security challenges.

In contrast, in the UK and in other developed nations, large amounts of fertiliser are used to sustain high yields. However, this leads to significant environmental degradation, for example, nitrate contamination of groundwater and problems of eutrophication, as well as emissions of nitrous oxide (N_2O), which is a significant greenhouse gas.

Legumes, such as beans and peas, form symbiotic interactions with rhizobial bacteria in the soil through the formation of root nodules – this supplies the plant with a source of nitrogen, and with mycorrhizal fungi to facilitate phosphate and other nutrient uptake. By transferring these symbiotic benefits to cereal crops (like barley, wheat and maize), farmers in developing nations could improve crop nutrient uptake and therefore enhance yields, whilst farmers in the UK could reduce their use of fertilisers and therefore limit their negative environmental impacts. As Professor Giles Oldroyd, project lead and Director of the Crop Science Centre at the University of Cambridge, comments:[83]

> *'Smallholder farmers in low-income regions like sub-Sahara Africa are only getting 20% of their potential yields because they cannot access or afford fertilisers. Nutrients, not water, are the limiting factor.'*

The BBSRC-funded project

Researchers at the University of Cambridge (and previously at the John Innes Centre), in collaboration with six other research institutions[84] as part of the **Engineering the Nitrogen Symbiosis for Africa (ENSA) project**,[85] are researching the potential for cereal crops to benefit from these symbiotic interactions in the way legumes do.

By understanding symbiosis signalling components in legumes, the project team is investigating which genetic components need to be transferred or edited to initiate nodulation in cereals to enhance uptake of nitrogen and enhance mycorrhizal associations for uptake of phosphorous, two important nutrients which contribute to crop yield. The project aims to engineer nitrogen-fixing cereals to sustainably improve productivity of smallholder farmers in sub-Saharan Africa without using synthetic fertilisers.

This research was supported by BBSRC funding through a Strategic Longer and Larger (sLoLa) grant totalling £2 million between 2013 and 2018.[86] The project was funded in parallel with a £6 million investment from the Bill & Melinda Gates Foundation.

Progress to and achievements to date

The project team has made some interesting and important scientific discoveries. On mycorrhizal symbiosis and association, the project has:

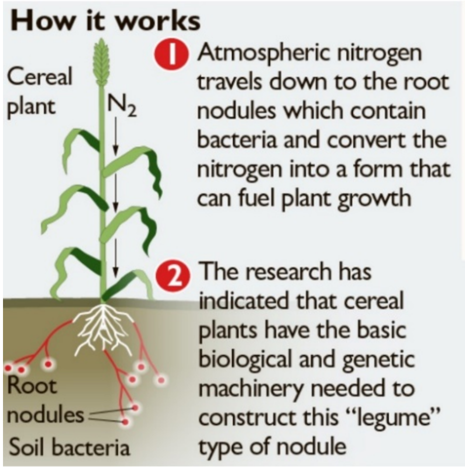
- Demonstrated it is **possible to optimise the symbiotic association between crops and mycorrhizal fungi to maximise their utility in agriculture**. This association is particularly important in obtaining phosphate, but also aids the uptake of nitrates and water.
- **Discovered a mechanism by which plants change their responsiveness to mycorrhizal fungi depending on whether the plant is starved for nutrients or not** – by overexpressing this factor they can enhance colonisation of the crop by mycorrhizal fungi, and therefore improve nutrient take-up and use efficiency.[87]

From this research, the project has **generated gene edited and genetically modified barley lines** with a variety of symbiosis engineering constructs, and **undertaken field trials** with these lines to evaluate whether improving crop interactions with mycorrhizal fungi can help them more efficiently absorb water, nitrogen and phosphorous from the soil – the initial results from the trial found high levels of mycorrhizal fungal colonisation in the soil at field trial plots.[88] **A patent for this method of increasing mycorrhizal association and symbiosis was published in 2021**.[89]

The project is initially working in barley as a model crop to prove the concept. The ultimate aim is to transfer these benefits to wheat and maize, important staple crops for farmers globally.

On nitrogen fixation, the project has:

- **Found that cereal crops have the basic biology and genetic machinery needed to construct nitrogen-fixing root nodules** found in legumes.[90]
- **Discovered the receptor structure crucial for initiating symbiotic signalling in legume plants** that engage in symbiosis with nitrogen-fixing bacteria – they have also identified cereal receptors with the same ability, meaning it might make it easier to engineer nitrogen-fixing cereals than first thought.[91]


How it works

① Atmospheric nitrogen travels down to the root nodules which contain bacteria and convert the nitrogen into a form that can fuel plant growth

② The research has indicated that cereal plants have the basic biological and genetic machinery needed to construct this "legume" type of nodule

Following the initial BBSRC and Bill & Melinda Gates Foundation funded project (2012-2017), the team received further funding from the Bill & Melinda Gates Foundation and the UK Foreign, Commonwealth and Development Office for Phase 2, totalling £28 million between 2017 and 2024. Phase 3 has recently been confirmed, totalling £28 million between 2023 and 2028.[92]

Whilst the project is now no longer funded by BBSRC, initial investment via the sLoLa was critical in facilitating co-investment from the Bill & Melinda Gates Foundation and enabling flexibility when the project had to switch the model crop from *Seteria* to barley in its second year. The project is also using wheat community resources developed through the WISP and Designing Future Wheat strategic programmes funded by BBSRC (e.g., NIAB's MAGIC population and TILLING resources)[93] – this highlights how BBSRC investment supports the wider wheat community.

In addition, Professor Giles Oldroyd, the project lead, provided expert witness evidence on gene editing for the Genetic Technology (Precision Breeding) Bill – the law has now changed in England allowing the commercial development of gene-edited crops.[94] This may accelerate the development of gene edited wheat with improved mycorrhizal symbiosis and association.

Next steps

The field trials of barley with enhanced capacity to engage with mycorrhizal fungi will continue, and in the next 5-10 years, the projects hopes to have genetic lines of crops with improved mycorrhizal symbiosis and association available to farmers. In 10-20 years' time, the project hopes to have generated nitrogen fixing cereals. However, further research and development is need, and the project teams still don't know if this is possible. The research is high risk, but if successful, could offer an alternative, more sustainable route to global food security away from dependence on synthetic fertilisers. As Professor Giles Oldroyd, project lead and Director of the Crop Science Centre at the University of Cambridge, comments:[95]

'Ultimately, if we have all of this working together, then you're looking at even higher yields than what we're currently achieving with a fraction of the fertiliser inputs.'

CASE STUDY 6: Nutrition – improving the quality of wheat starch to boost fibre intake

Dietary fibre is very important for human health and nutrition – but in the UK we consume only two-thirds the recommended amount. Improving the quality of fibre in popular foods like white bread (which is low in dietary fibre) could boost fibre intake. **Researchers at Quadram Institute Bioscience have developed a wheat high in resistance starch, a type of dietary fibre**, and have **conducted a clinical study in humans to help understand whether bread that is high in resistant starch could help boost fibre intake**. Further human trials will be undertaken to fully explore the potential of this novel wheat to improve fibre intake, whilst research is also required to test how this wheat might perform in the field.

Context

A major global challenge in health is the increasing prevalence of diet-related diseases, such as Type II diabetes, heart disease, bowel cancer, and obesity.[96] For example, bowel cancer is the fourth most commonly occurring cancer in the UK, accounting for 11% of all new cancer cases,[97] and costs the UK economy more than £1.7 billion per year.[98] Research shows that consuming **higher levels of dietary fibre reduces the risk of developing many of these diseases**.[99] For example, **28% of bowel cancer cases in the UK are caused by eating too little fibre**.[100]

However, **91% of UK adults do not meet the recommended 30g daily intake of fibre**, with most people only averaging 19g per day.[101] White bread made from wheat is one of the UK's favourite staple foods and accounts for 71% of total bread consumption.[102] However, it usually has very low levels of fibre, at around 1g per slice, compared to around 3g per slice for wholemeal bread.[103]

Increasing the quality of starch in bread wheat so it contains more dietary fibre could improve nutrition, and in the long term, reduce the risk of common chronic diseases and support overall population health. As Dr Ian Johnson, Emeritus Fellow at Quadram Institute Bioscience, stated:[104]

> ***'We can now be very confident that high consumption of fibre…particularly from whole-grain cereals, provide significant protection against the common diseases of later life that now place considerable strains on the NHS.'***

BBSRC-funded research project

Researchers at the Quadram Institute Bioscience have developed a wheat which is high in resistance starch, a type of dietary fibre, to help boost the fibre intake of people who consume wheat products like bread. This research was supported by BBSRC funding through:

- The Designing Future Wheat (DFW) strategic programme, which funded the Quadram Institute Bioscience,[105] and supported the creation of community resources used in this project, notably the wheat TILLING population.[106]
- The Molecules from Nature strategic programme, led by the John Innes Centre.[107]
- The Food Innovation and Health strategic programme, led by the Quadram Institute Bioscience.[108]

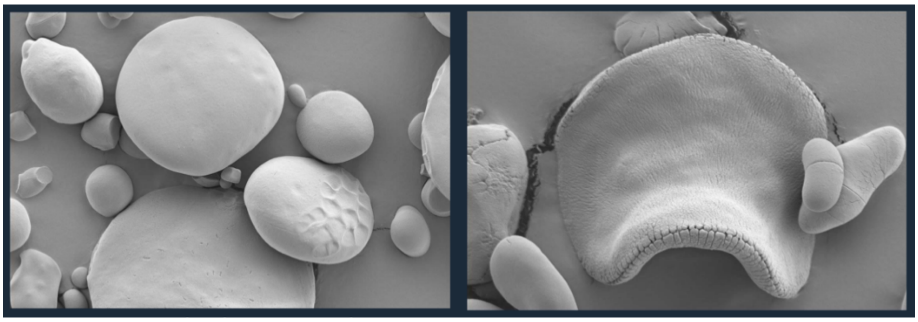
As Dr Brittany Hazard, Group Leader for Designing Future Wheat at the Quadram Institute Bioscience, commented:

> ***'Being part of a wheat-focused ISP like DFW is important for my research group, being the only one at Quadram solely focused on wheat…we have strong connections with the John Innes Centre and work closely with Rothamsted.'***

Progress and achievements to date

Researchers at the Quadram Institute Bioscience have **modified the starch in the wheat grain to make it behave more like dietary fibre**. The research found that **wheat with mutations in *starch branching enzyme II* (*sbeII*) genes have more 'resistant starch'** – this resists digestion in the small intestine and is instead digested in the colon, which increases feelings of fullness but also feeds the gut microbiome. The consumption of resistant starch is associated with improved gut health, reduced glycaemia, and increased satiety.

Using the wheat TILLING resources developed as part of the DFW programme,[109] researchers generated wheat lines carrying different mutations of *sbeII* genes. They also designed prototype wheat foods (semolina pudding and bread rolls) made with *sbeII* mutants to determine the resistant starch and starch digestibility of the foods (*in vitro*). These experiments showed that **bread rolls made from *sbeII* mutant wheat contained more resistant starch** and showed lower susceptibility to digestion than the control.[110]



Normal wheat starch (left) compared to *sbeII* wheat starch (right). Credit: Quadram Institute Bioscience

To help understand whether bread that is high in resistant starch could help boost fibre intake, the researchers **conducted a clinical study in humans**, in collaboration with Imperial College London and Norfolk & Norwich University Hospitals. The REST clinical study[111] measured blood sugar after participants ate high resistant starch bread and conventional white bread (which is low in resistant starch) – the study showed that ***sbeII* wheat flour had potential to lower blood sugar response compared to white bread**, meaning it resists digestion. The study has provided pilot data to inform the design of future studies and define the levels of resistant starch required to have an impact.

As Dr Brittany Hazard, Group Leader in Designing Future Wheat at the Quadram Institute Bioscience, commented:

> ***'Wheat is the most important staple food crop internationally and in the UK… any improvement in wheat could have a major impact on health and nutrition around the world.'***

The research team also **developed an assay to screen for natural variation in starch digestibility in the Watkins landrace collection** held at the John Innes Centre – this may uncover wheat lines which naturally have high levels of resistant starch. This enables Quadram Institute Bioscience researchers to utilise this genetic resource and make it more accessible to their needs.

In an unintended consequence, researchers also found that **bread that is high in resistant starch is less affected by staling in chilled storage** – bread texture is improved. This means that it might be suited to chilled sandwiches and other convenience foods. This has led to a **proof-of-concept study with an ingredients company** on bread storage.[112]

Next steps

Further acute and chronic intervention studies are needed to fully explore the potential use of novel wheat to improve the fibre intake from bread and other wheat-based foods.

Further research is also needed on how novel wheat lines with mutations in the starch structure might perform in the field – for example, whether this results in yield penalties, or how different growing conditions (e.g., heat, drought) might affect starch structure. Researchers at the Quadram Institute Bioscience are currently working with CIMMYT to investigate these aspects.

CASE STUDY 7: International Wheat Yield Partnership

Wheat is critical to global food security, supplying 20% of calories and protein in the human diet. **However, current annual increases in production are not on track to meet the estimated demand from rising population growth and counter the threat of climate change – wheat yields need to improve**. To address this twin challenge, the International Wheat Yield Partnership (IWYP) brings together global public research funders and private industry with the goal of increasing the yield potential of wheat by 50% by 2035.

Context

The domestication of wheat has turned a wild grass into one of the most important global crops – **wheat is grown on a larger area than any other crop and supplies 20% of calories and protein in the human diet.**[113] Thousands of years of wheat breeding has led to wheat varieties with improved grain yield, seed size, and nutritional content.

With a growing world population, estimated at 10 billion people by 2050, overall food demand is predicted to increase by 56% by 2050,[114] with **global demand for wheat growing by 1.7% per year.**[115] **However, annual increases in wheat production are not on track to meet future needs**. Moreover, wheat is particularly susceptible to climate change; with a 1°C global temperature increase, global wheat yields are projected to decline between 4.1% and 6.4%.[116]

Thus, wheat researchers and breeders are faced with an interlocking challenge: improving genetic gains in productivity, grain yield, and yield stability, whilst also increasing resistance and tolerance to disease and environmental threats and stresses. To address this global challenge, the **IWYP**[117] brings together public funders and private industry across the world to work towards a **common goal: to increase the yield potential of wheat by 50% by 2035**.

Wheat in the field in Kazakhstan. Credit: M. DeFreese/CIMMYT.

BBSRC-funded research project

IWYP is a public-private partnership, initiated by BBSRC, CIMMYT, USAID, GRDC, AAFC and SADER (Mexico) in 2012 – it is an associated programme of the Wheat Initiative.[118]

Between 2015 and 2020, IWYP had a total investment of $64 million (around £51.3 million), funded by 14 public sector partners from the UK, US, Australia, Canada, France, Mexico, and India,[119] and supported by 11 private sector partners, including Syngenta, BASF, Limagrain, and Mahyco (India).[120]

BBSRC investment between 2015 and 2020 accounted for £15.5 million, comprising:

- Overarching management structure: £2.1 million
- Research programmes/projects: £10.6 million
- CIMMYT Hub: £2.8 million

IWYP International Wheat Yield Partnership
Research to Deliver Wheat for the Future

The programme leverages $2.50 from other funders for every $1 invested in IWYP by BBSRC.[121] As the IWYP programme management team comment:

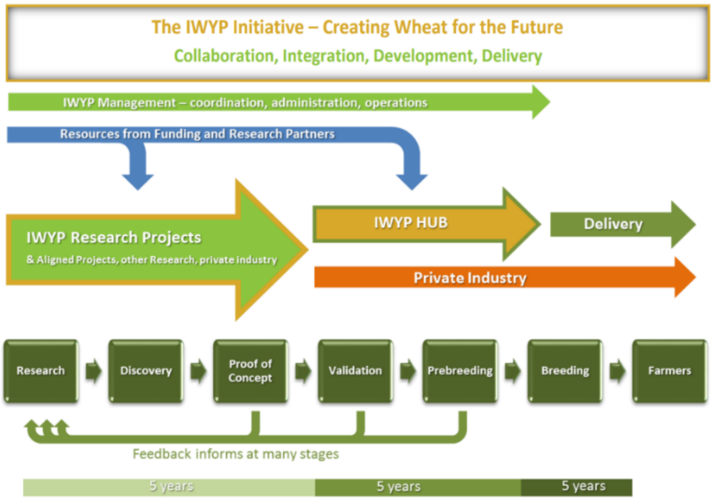
> ***'The value of BBSRC investment in IWYP is in leveraging the power of the collective. BBSRC are amplifying investments as they have access to more knowledge, technical platforms and innovation through international partners and networking.'***

Progress and achievements to date

Overall, **IWYP has supported an observed yield improvement of 2.5% year-on-year** where Wheat Yield Consortium Yield Trial germplasm was evaluated internationally. This includes a 2.8% improvement under optimal/high yielding conditions, and a 1.4% improvement under low yielding conditions.[122] Moreover, new lines at CIMMYT exhibit significant improvements over test varieties in several target traits, including **20% increased biomass**, **30% higher radiation use efficiency** (RUE), **10-15% higher photosynthetic efficiency**, **10% more grains** and **15% larger and heavier grains**.[123]

International coordination, collaboration and integration

IWYP is a unique partnership which maximises the value of research investment by **efficiently coordinating and integrating research and enabling international collaboration** across its partners and beyond. For example, public and private partners align strategies, research, pre-breeding development, and varietal breeding to address IWYP goals. Through alignment with research projects not funded within IWYP when they have related goals, allows the partnership to widen its scientific network and the chances of success.



The IWYP delivery model. From research and trait discovery to validation in field trails, and translation to breeding programmes – and ultimately to farmers' fields. Credit: IWYP

To date, IWYP has **created an international wheat research community of practice** involving over 150 scientists, working on 41 research projects across 60 institutions in 14 countries.[124]

Science and research

IWYP has supported scientific excellence through funded projects which aim to increase wheat yields through research in areas such as photosynthetic efficiency, flowering time, grain size and number, floral morphology (to support hybrid wheat), and root systems. To date, these projects generated ~200 publications, 108 molecular genetic markers, and 25 tools and protocols.[125]

IWYP's research community has **confirmed the association of grain yield with various traits**, including final biomass, harvest index, grain number, spikes per square metre, and canopy temperature. Data has also **validated the strategy that combining parents with complementary 'source' and 'sink' traits correlated with yield has the potential to achieve the level of genetic yield gains required** – this will help inform future breeding strategies.

Examples of UK institution-led IWYP-funded projects include:

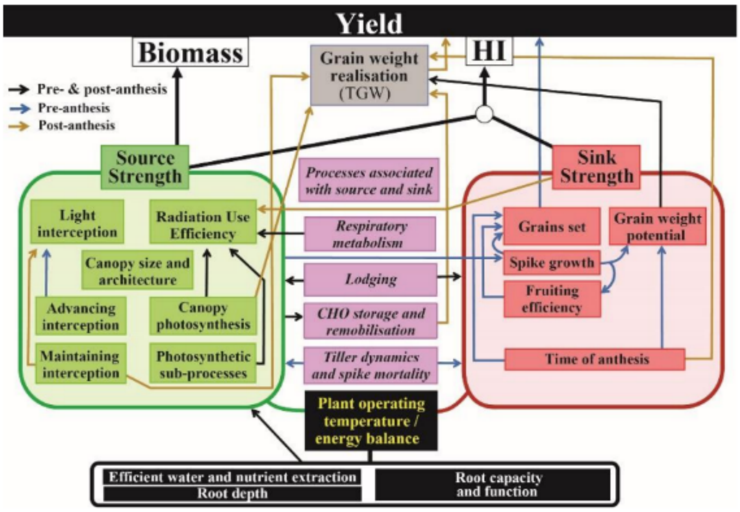
- Rothamsted Research found that spraying Trehalose-6-phosphate (T6P) precursors on wheat during early grain filling stimulates starch synthesis in grain, **increasing grain size and overall yield by up to 20%**.[126]

- The Earlham Institute found that **under heat stress, wheat crossed with wild relatives and landraces achieved a 50% higher yield** over wheat without this DNA (including reduced canopy temperature).[127] The project identified and developed genetic markers that could enable the targeted introduction of exotic DNA conditioning heat tolerance into elite lines – these markers are now being tested for integration into the CIMMYT breeding programme.

- NIAB is exploring how to **optimise wheat root systems to improve yield potential** (e.g., narrow vs. wide root angle, low vs. high root biomass). The project has generated genetic markers for root biomass and three novel seminal root angle DNA locations in durum wheat, which are currently undergoing yield and root trials in Mexico (CIMMYT).[128]

- The University of Essex is exploring how **reducing the sensitivity of stomata (leaf pores) to blue light could increase yield by enhancing photosynthetic rates and reducing water loss**.[129] The project has developed a high throughput thermographic screening protocol, and generated mutants – this may lead to the selection of wheat lines with improved yield potential through increased water use efficiency and photosynthetic rates.

Bringing together outputs and knowledge from across its portfolio (and several decades of previous research), IWYP have **created a tool which details the interactions and relationships between key yield 'source' and 'sink' traits**. The **IWYP Wiring Diagram**[130] is intended to make it easier to conceptualise and design changes in specific components of wheat with better understanding of the consequences of the changes on whole crop field performance, and thus **facilitate the generation of more impactful innovations in wheat breeding**. Moreover, by illustrating current knowledge gaps, the Wiring Diagram can be **used to prioritise R&D investments**, as well as a **teaching tool** for the next generation of crop physiologists, geneticists and breeders.

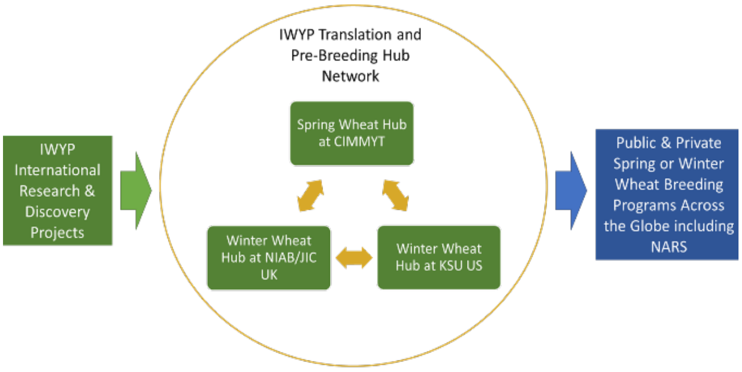


IWYP Yield Wiring Diagram. Credit: IWYP

Germplasm development and delivery

IWYP has supported the **delivery and exploitation of novel germplasm** to global pre-breeding programmes, chiefly through **three pre-breeding "Hubs" at CIMMYT** (Mexico – spring wheat), **Kansas State University** (USA – North American winter wheat), and **NIAB** (UK – European winter wheat).[131] In 2021/22 alone, IWYP research projects have generated 26 novel wheat lines with optimised traits, with a further 286 wheat lines generated from CIMMYT IWYP Hub, available to all breeding programs worldwide.[132]

Outputs and germplasm developed at these Hubs are **transferred and incorporated into public and private breeding programmes globally** for trialling to create new higher yielding wheat varieties for farmers to grow. In the 2021/22 cycle, **germplasm was distributed to 117 collaborators in 42 countries**, leading to **35 new potential high yielding lines being field tested**.



IWYP Translation and Pre-breeding Hub Network and Delivery Process. Credit: IWYP.

These Hubs are important as they broaden the utility of IWYP's discoveries and facilitate the critical steps of downstream validation and pre-breeding development, i.e., translation, that are typically lacking in most discovery research programmes. For example, the Hub at CIMMYT has implemented a new international trialling system, the IWYP Yield Potential Trait Experiment (IYPTE) network,[133] which enables the Hub to contract trials at specific locations, prescribe agronomic practices and collect specified phenotypic data on important yield potential traits.

Next steps

IWYP will continue to feed its pipelines with new discoveries that can fill gaps in knowledge or trait enhancement, including stimulating and aligning new research projects around the world. The IWYP Wiring Diagram will help identify gaps and high-value research targets that can add to or enhance existing yield potential traits, as well as guide research into which traits combine to result in the largest boost to yield. Linking this research with high throughput phenotyping (to support predictions of trait performance in different environments) and more detailed molecular markers will help make selection for yield traits as smooth as possible, particularly in varietal breeding programmes.

CASE STUDY 8: Fotenix – next generation crop disease monitoring and analytics

Currently, plant health diagnosis requires highly trained specialists to walk thousands of metres every day to spot minute details that could be the difference between a high-yield harvest and a devastating loss. **Real-time identification of crop diseases could provide immediate feedback to farmers and growers, significantly reducing costly delays in rectifying actions**.

Fotenix is a spinout from the University of Manchester which **develops and deploys 3D multi-spectral imaging technology** in order to **identify disease threats and stresses on crops at an early stage.**[134]

The technology is suitable for a variety of crops, can sense for a range of different stresses, and can be deployed on different platforms (e.g., tractors, robotics, greenhouses). Whilst pests and pathogens are a key focus, the technology can also sense for nutrient stresses, for example, nitrogen for grain protein content. Growers can use these insights to know what, where and where to target treatments, be that nitrogen for grain protein content, or fungicides for yellow rust.

The company was established in 2018 and the research group from which it spun out has been supported by BBSRC funding through the Agri-Tech Catalyst programme, co-funded with Innovate UK.[135]

Investment and support has also been received from ICURe, the EIT Food Accelerator Network programme, NVIDIA, AWS, Sony, Innovate UK, Innovation Factory, and Angel investors alongside the ISCF Series A Investment Programme.[136]

The company has a series of **patents on the apparatus and methods for determining spectral information** from plants.[137] This is the technology underpinning Fotenix's products and services, for example, the INDIA integrated imaging platform (see image, right).

The Fotenix INDIA mounted spectral imaging device. Credit: Fotenix.

Fotenix is currently recruiting to triple its workforce to support its breeding and digital agronomy services to major agri-chemical companies**.**

CASE STUDY 9: Developing low viscosity wheat for whisky distilling

Wheat is important to distilling, however it can be problematic for distilleries as it causes sticky residues. BBSRC-funded researchers at Rothamsted Research, in collaboration with Limagrain and the Scotch Whisky Research Institute, have **developed a new variety of wheat with a 50% reduction in viscosity**. Reduced viscosity of wheat reduces shut downs and cleaning within the distilling process for Scotch grain whisky. Over the next 5 years, Limagrain will breed the low viscosity trait into soft wheats rated good for distilling and which meet the agronomy requirements of the Scottish market for distilling.

Context

Whilst single malt Scotch whisky is made solely from malted barley, many whiskies are made from a mix of malted barley and unmalted cereals, such as wheat and maize – this is known as grain whisky. Over 800,000 tonnes of UK wheat is used in Scotch whisky distilling each year, around 5% of total UK wheat production.[138] Wheat accounts for 90% of cereal inputs in grain whisky, and grain whisky is regularly used as a component part of blended Scotch whisky, which accounts for around 90% of all sales.

However, **wheat can be problematic for distilleries as it causes sticky residues and deposits** – this blocks pipes and increases wear on pumps in the distilling process and impairs the efficiency of evaporator plates when using waste material to make syrup for animal feed. **This leads to regular downtime for cleaning** – effectively shutting down the distillery which usually work 24/7 – **reducing efficiency and increasing costs.**[139]

Scotch whisky is a hugely important sector, directly employing 11,000 people and providing £5.5 billion in GVA to the UK economy. Scotch whisky exports to key markets like India, the EU and China are worth £6.2 billion.[140] **Developing improved wheat varieties that do not leave such sticky residues could therefore be extremely valuable**. As the Scotch Whisky Association notes:[141]

> ***'The distilling industry will want to see more varieties coming through the AHDB system combining high alcohol yield and low viscosity.'***

BBSRC-funded research project

Rothamsted Research, in collaboration with Limagrain and the Scotch Whisky Research Institute (SWRI) have developed a new variety of wheat with a **50% reduction in viscosity**.

This research was supported by BBSRC funding as follows:

- Responsive Mode and Follow-on funding, totalling £1.3 million since 2009.
- The Designing Future Wheat strategic programme, which funded Rothamsted Research[142] and supported the creation of community resources like the Wheat TILLING population.[143]
- Joint BBSRC-Innovate UK funding via the Agri-Tech Catalyst (£62,000), which supported industry collaboration with Limagrain and SWRI.

Progress and achievements to date

Rothamsted Research **discovered the genes responsible for making Arabinoxylan (AX)**, an abundant molecule in grass cell walls which provides dietary fibre for humans. However, around 25% of AX in wheat grain is extractable in water, giving rise to these viscous, sticky residues.

This discovery **enabled 'reverse genetics' approaches to improve wheat traits.** This is where researchers start with knowledge of what a gene does, rather than screening for the trait in a plant first and then looking for which of its genes are responsible. **This new wheat line is one of the first wheat varieties in the world developed using reverse genetics**. This would have been impossible without BBSRC funding to support the sequencing of the wheat genome.

A patent on Rothamsted Research's method for reducing the viscosity of wheat flour through decreasing the soluble AX content in a wheat grain was submitted in 2012 and granted in 2014.[144]

Genetic modification (GM) methods were used to prove the principle that suppression of target genes greatly decreased extract viscosity from wheat grain. Subsequently, researchers set out to achieve the same low-viscosity trait using a non-GM approach so that it would be acceptable for commercial production. Using the John Innes Centre's wheat TILLING resources,[145] developed through the Wheat Improvement Strategic Programme and Designing Future Wheat programmes, Rothamsted Research were able to confirm their hypothesis (using the Super Follow-on Fund).[146]

Low viscosity wheat lines and controls in the field for distillery testing (August 2020). Credit: Limagrain.

Following this success, funding via the joint BBSRC-Innovate UK Agri-Tech Catalyst,[147] supported Rothamsted Research in their collaboration with Limagrain and SWRI to test this wheat variety. Initially a test using 50g of grain was successful; then a larger **pilot of 0.25 tonnes at a Diageo test facility successfully demonstrated the new wheat lines had decreased viscosity compared to controls.**[148] As the Scotch Whisky Association comments:[149]

> ***'Low viscosity will benefit process efficiency in the grain distillery.'***

A low viscosity wheat would also reduce reliance on imported maize for distilling, though this has not been quantified – maize has advantages over wheat in terms processability and energy savings.[150] As Limagrain comment:[151]

> ***'Low viscosity wheat would strengthen the continued use of UK wheat in distilling and offer a solution to those distillers still using maize.'***

Next steps

The pilot tests were undertaken on a hard milling/bread wheat (Cadenza); however, this variety is unsuitable for distilling. Over the next 5 years, Limagrain will breed the low viscosity trait into soft wheats rated good for distilling and which meet the agronomy requirements of the Scottish market. Limagrain will also supply collaborators with the trait in a soft wheat background to run further pilot scale tests. Within 10 years, the aim is to release commercial varieties into the market, and the longer-term hope is that this new wheat variety will transform the Scottish wheat market into only low viscosity types, as has been done for low/non-Glycosidic Nitrile (GN) spring barley.[152]

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[1] Source: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7668007/

[2] Source: https://www.nature.com/articles/s41559-018-0793-y

[3] Source: https://www.nature.com/articles/nplants2015132

[4] Source: https://link.springer.com/article/10.1007/s00122-021-03983-z

[5] See: AHDB: https://ahdb.org.uk/yellowrust

[6] The Warrior group of races arrived in the UK in 2011 and are thought to be derived via sexual recombination rather than asexual mutation (as the UK population had previously been) – this has led to high diversity within the population. See: https://www.cpm-magazine.co.uk/technical/disease-delve-the-dynamic-force-behind-yellow-rust/

[7] E.g., propiconazole, cyproconazole and epoxiconazole. See: https://doi.org/10.3389/fcimb.2021.730297

[8] Source: https://journals.plos.org/plospathogens/article?id=10.1371/journal.ppat.1009503

[9] The WISP programme partly supported this work through strategic funding to the John Innes Centre, Rothamsted Research, NIAB, and the Universities of Nottingham and Bristol. WISP ran from 2011 to 2017 and had a total budget of £16 million. See: https://www.cerealsdb.uk.net/cerealgenomics/WISP/Consortium/WISP.php.The DFW programme partly supported this work through strategic funding to the John Innes Centre, Rothamsted Research, NIAB, the Quadram Institute, EMBL-EBI and the universities of Bristol and Nottingham. DFW ran from 2017 to 2023 and had a total budget of £37.6 million. See: https://designingfuturewheat.org.uk/

[10] Wagtail ran from 2011-2015 and provided funding to NIAB (£383,151) and the John Innes Centre (£98,279); Wagtail was also supported by Defra and AHDB. See: https://gtr.ukri.org/projects?ref=BB%2FJ002542%2F1. Yellowhammer ran from 2018-2023 and provided funding to NIAB (£548,682), see: https://gtr.ukri.org/projects?ref=BB%2FR019231%2F1. Yellowhammer was also supported by AHDB.

[11] The project, titled 'The wheat Diverse MAGIC platform', ran from 2015-2019 and funding to NIAB totalled £517,796. See: https://gtr.ukri.org/projects?ref=BB%2FM011666%2F1

[12] The project, titled 'Using field pathogenomics to study wheat yellow rust dispersal and population dynamics at a national and international scale', ran from 2015-2018. BBSRC funding: Earlham Institute (2015-2017, £263,784), the John Innes Centre (2015-2018, £300,705 – includes transfer from the Earlham Institute), and NIAB (2015-18, £303,465). See: https://gtr.ukri.org/projects?ref=BB%2FM025519%2F1

[13] See: https://gtr.ukri.org/projects?ref=BB%2FJ002542%2F1

[14] See: https://gtr.ukri.org/projects?ref=BB%2FR019231%2F1

[15] Source: BBSRC Wheat Evaluation consultation undertaken by WECD (November 2022).

[16] Source: https://www.cpm-magazine.co.uk/technical/theory-to-field-yellowhammer-strikes-gold/

[17] See: https://gtr.ukri.org/projects?ref=BB%2FM025519%2F1

[18] See: https://ahdb.org.uk/knowledge-library/uk-cereal-pathogen-virulence-survey-ukcpvs

[19] See: https://www.jic.ac.uk/news/kenya-becomes-the-third-country-to-launch-marple-diagnostics-hub/

[20] See: https://www.jic.ac.uk/news/innovative-surveillance-technique-gives-vital-time-needed-to-track-a-cereal-killer/. The MARPLE project was funded by BBSRC and the CGIAR Big Data Inspire Challenge: https://bigdata.cgiar.org/inspire/inspire-challenge-2017/real-time-diagnostics-for-devastating-wheat-rust/

[21] Source: https://www.jic.ac.uk/blog/going-virtual-marple-diagnostics-training-in-the-covid-era/

[22] See: https://www.bbc.co.uk/news/science-environment-63457903

[23] See: https://doi.org/10.3389/fpls.2020.00606 and https://doi.org/10.1002/csc2.20120

[24] Source: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7668007/

[25] E.g., see: https://doi.org/10.1186/s40813-016-0041-2

[26] Source: https://doi.org/10.1111/ppa.13433. See also: https://doi.org/10.1038/s43016-022-00655-z

[27] Source: https://doi.org/10.3390/pathogens9060419 and https://doi.org/10.1111/ppa.13433

[28] Source: https://onlinelibrary.wiley.com/doi/10.1111/pbi.12606

[29] Source: https://www.nottingham.ac.uk/news/breeding-with-wild-relatives-to-produce-disease-and-climate-resistant-wheat

[30] The project, titled 'Developing tools for introgression into wheat where recombination is not possible', ran from 2011-2017; funding to the University of Nottingham totalled £670,492. See: https://gtr.ukri.org/projects?ref=BB%2FH012834%2F1

[31] WISP partly supported this work through strategic funding to the University of Nottingham, totalling £1.2 million. See: https://gtr.ukri.org/projects?ref=BB%2FI00260X%2F1. WISP ran from 2011 to 2017 and had a total budget of £16 million. The programme involved 5 institutions: John Innes Centre, Rothamsted Research, NIAB, and the universities of Bristol and Nottingham. See: https://www.cerealsdb.uk.net/cerealgenomics/WISP/Consortium/WISP.php

[32] The DFW ISP partly supported this work through strategic funding to the University of Nottingham, totalling £2.1 million (estimate provided by Nottingham). DFW ran from 2017 to 2023 and had a total budget of £37.6 million. The programme involved 8 institutions: John Innes Centre, Rothamsted Research, Earlham Institute, Quadram Institute Bioscience, NIAB, EMBL-EBI, and the universities of Bristol and Nottingham. See: https://designingfuturewheat.org.uk/

[33] The project, titled 'Exploitation of interspecific biodiversity for wheat improvement', ran from 2013-2017; funding to the University of Nottingham totalled £1,620,271. The then Department for International Development (DFID) was a co-funder. See: https://gtr.ukri.org/projects?ref=BB%2FJ011827%2F1

[34] The project, titled 'Isolation of genetic variation for flowering morphology for hybrid wheat production', ran from 2018-2022; funding to the University of Nottingham totalled £679,165. See: https://gtr.ukri.org/projects?ref=BB%2FH012834%2F1 and https://iwyp.org/wp-content/uploads/sites/34/2018/08/Julie-King-Project.pdf

[35] See: Project: https://gtr.ukri.org/projects?ref=BB%2FH012834%2F1; publication: https://onlinelibrary.wiley.com/doi/10.1111/pbi.13241

[36] See: https://onlinelibrary.wiley.com/doi/10.1111/pbi.13241

[37] Source: https://apsjournals.apsnet.org/doi/10.1094/PHYTO-03-19-0095-RVW

[38] See: https://www.nottingham.ac.uk/research/beacons-of-excellence/future-food/meet-the-team/rothamsted-phds/veronica-guwela/index.aspx

[39] See: https://gtr.ukri.org/projects?ref=BB%2FS012796%2F1

[40] See: https://iwyp.org/wp-content/uploads/sites/34/2022/01/IWYP140-IWYP-Science-Brief-FINAL.pdf

[41] See: https://iwyp.org/iwyp-research-breeding-hub/

[42] For comparisons, see: http://www.jamesandthegiantcorn.com/2010/08/27/wheat-genome-draft-sequence/

[43] Source: https://doi.org/10.1016/j.copbio.2013.08.019

[44] Source: https://doi.org/10.1038/nature09792

[45] See: https://www.earlham.ac.uk/news/earlham-institute-helps-finally-crack-wheat-code

[46] Source: http://www.jamesandthegiantcorn.com/2009/09/11/the-family-of-wheat/

[47] See: https://www.wheatgenome.org/

[48] 'Wheat/Triticeae Genomics for Sustainable Agriculture' (2012-2018). BBSRC funding: EI (£3.4 million), John Innes Centre (£1.3 million), Rothamsted Research (£36,662), and EMBL-EBI (£456,674), see: https://gtr.ukri.org/projects?ref=BB%2FJ003743%2F1

[49] The Wheat 20:20 strategic programme (2012-2017) partly supported this work through strategic funding to Rothamsted Research, totalling £14.6 million. See: https://www.rothamsted.ac.uk/wheat-to-feed-the-world

[50] University of Liverpool: 2010-2013, £253,779; see: https://gtr.ukri.org/projects?ref=BB%2FH022333%2F1. John Innes Centre: 2015-2018, £298,912; see: https://gtr.ukri.org/projects?ref=BB%2FM014045%2F1

[51] 'Mining the allohexaploid wheat genome for useful sequence polymorphisms' (2009-2012). BBSRC funding: University of Liverpool (£1 million), John Innes Centre (£293,306), and the University of Bristol (£206,951); see: https://gtr.ukri.org/projects?ref=BB%2FG013004%2F1

[52] 'Wheat Pan-Genomics' (2017-2021). BBSRC funding: EI (£129,431), Natural History Museum (£1 million – transfer from EI), and John Innes Centre (£47,695); see: https://gtr.ukri.org/projects?ref=BB%2FP010768%2F1
[53] See: https://www.science.org/doi/10.1126/science.aar7191
[54] John Innes Centre, universities of Bristol and Liverpool. See: https://www.nature.com/articles/nature11650
[55] EI and John Innes Centre (ref: BB/J003166/1), see: https://doi.org/10.1126/science.1251788
[56] See: https://www.biorxiv.org/content/10.1101/110999v1 and https://www.earlham.ac.uk/news/can-we-produce-better-wheat-crop-feed-world-single-multiple-wheat-genomics
[57] Source: Brookdale Consulting, Earlham Institute Impact Evaluation (2018).
[58] See: https://www.earlham.ac.uk/portcullis and https://www.earlham.ac.uk/mikado
[59] See: https://www.earlham.ac.uk/research-project/grassroots-genomics
[60] Source: Brookdale Consulting, Earlham Institute Impact Evaluation (2018).
[61] Source: BBSRC Wheat Evaluation consultation undertaken by WECD (November 2022).
[62] See: https://www.smithsonianmag.com/smart-news/sequencing-wheat-genome-could-lead-lead-breadier-future-180970063/
[63] Source: IWGSC: https://www.wheatgenome.org/
[64] See: https://www.earlham.ac.uk/news/earlham-institute-helps-finally-crack-wheat-code
[65] Source: Brookdale Consulting, Earlham Institute Impact Evaluation (2018).
[66] See: https://10wheatgenomes.com/. Includes the John Innes Centre, NIAB and the Natural History Museum.
[67] Source: https://www.earlham.ac.uk/news/earlham-institute-helps-finally-crack-wheat-code
[68] Source: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7668007/
[69] Source: https://www.sciencedirect.com/science/article/pii/S1631069110003021?via%3Dihub
[70] Source: https://www.annualreviews.org/doi/10.1146/annurev.environ.041008.093740
[71] See: https://www.cimmyt.org/news/extensive-use-of-wild-grass-derived-synthetic-hexaploid-wheat-adds-diversity-and-resilience-to-modern-bread-wheat/
[72] See: https://www.niab.com/uploads/files/NIAB_Superwheat_QA_2015.pdf and https://www.youtube.com/watch?v=M7bN2C1Pjso
[73] Source: https://doi.org/10.1016/j.eng.2018.07.001. See also: https://doi.org/10.1038/s41437-022-00527-z
[74] The project, titled 'Pre-Breeding at NIAB – Ppd alleles and markers QTL for earliness per se and novel variation from synthetic wheat useful to UK/EU wheat improvement', ran from 2007-2012; funding to NIAB totalled £646,318. See: https://gtr.ukri.org/projects?ref=BB%2FE006868%2F1
[75] The project, titled 'Wheat Improvement from Synthetic Hexaploids (WISH)', ran from 2013-2015; funding to NIAB totalled £262,283. See: https://gtr.ukri.org/projects?ref=BB%2FK020269%2F1
[76] WISP partly supported this work through strategic funding to NIAB. WISP ran from 2011 to 2017 and had a total budget of £16 million. The programme involved 5 institutions: John Innes Centre, Rothamsted Research, NIAB, and the universities of Bristol and Nottingham. See: https://www.cerealsdb.uk.net/cerealgenomics/WISP/Consortium/WISP.php
[77] The DFW ISP partly supported this work through strategic funding to NIAB. DFW ran from 2017 to 2023 and had a total budget of £37.6 million. The programme involved 8 institutions: John Innes Centre, Rothamsted Research, Earlham Institute, Quadram Institute Bioscience, NIAB, EMBL-EBI, and the universities of Bristol and Nottingham. See: https://designingfuturewheat.org.uk/
[78] See: https://www.fsov.org/exploitation-d-une-variabilite-genetique-nouvelle-issue-de-bles-synthetiques-pour-l-amelioration-de-la-stabilite-du-rendement and https://www.fsov.org/apport-des-bles-synthetiques-a-l-amelioration-conjointe-de-la-productivite-de-la-teneur-en-proteines-et-l-efficience-d-utilisation-de-l-azote
[79] Source: NIAB documents, shared via email. Yellow rust resistance has also been reported in other research and trials, e.g., see: https://www.sciencedirect.com/science/article/pii/S2095809917303880
[80] Reference: DSV Gandalf: DSV3202105:SHWxGrahamxGraham
[81] The NIAB spring wheat mega-trial was funded as part of a one-year 'bridging fund' from BBSRC following on from the completion of the DFW strategic programme.
[82] Foley et al (2011) Solutions for a cultivated planet. *Nature* 478, 337-342: https://doi.org/10.1038/nature10452
[83] See: https://www.thetimes.co.uk/article/excitement-grows-for-self-fertilising-crops-ks72x9hjb

[84] John Innes Centre, James Hutton Institute, NIAB, University of Oxford, Albert Ludwig University of Freiburg, Aarhus University, Wageningen University & Research, University of Toulouse III Paul Sabatier, and the University of Illinois.
[85] See: https://www.ensa.ac.uk/
[86] See: https://gtr.ukri.org/projects?ref=BB%2FK003712%2F1 and https://gtr.ukri.org/projects?ref=BB/K003712/2
[87] See: https://www.cropsciencecentre.org/news/discovery-new-mechanism-enhancing-symbiotic-interactions
[88] See: https://www.cropsciencecentre.org/news/first-crop-science-centre-trial-harvest
[89] See: https://worldwide.espacenet.com/publicationDetails/biblio?FT=D&date=20220608&DB=EPODOC&locale=en_EP&CC=AR&NR=121460A1&KC=A1&ND=4
[90] See: https://www.ensa.ac.uk/news/barley-orders-soil-bacteria-to-manufacture-ammonia-fertiliser/
[91] See: https://www.ensa.ac.uk/news/innovative-ensa-science-reveals-a-cereal-receptor-complex-that-can-initiate-root-nodule-organogenesis-in-legumes/
[92] See: https://www.cropsciencecentre.org/news/cambridge-led-consortium-receives-35m-boost-crop-production-sustainably-sub-saharan-africa. Partners for phases 2 and 3 include: John Innes Centre, James Hutton Institute, NIAB, University of Oxford, Royal Holloway University of London, Albert Ludwig University of Freiburg, Aarhus University, Wageningen University & Research, University of Toulouse III Paul Sabatier, and the University of Illinois.
[93] See: https://www.niab.com/research/agricultural-crop-research/resources/niab-magic-population-resources; and https://github.com/homonecloco/bioruby-wheat-db/wiki
[94] See: https://www.bbc.com/news/science-environment-64596453
[95] See: https://www.thetimes.co.uk/article/excitement-grows-for-self-fertilising-crops-ks72x9hjb
[96] Source: The Lancet: https://doi.org/10.1016/S0140-6736(19)30500-8
[97] Source: https://www.cancerresearchuk.org/health-professional/cancer-statistics/statistics-by-cancer-type/bowel-cancer
[98] Source: Bowel Cancer UK: https://www.bowelcanceruk.org.uk/news-and-blogs/news/bowel-cancer-costs-the-uk-%C2%A31.74-billion-a-year/
[99] Source: The Lancet: https://doi.org/10.1016/S0140-6736(18)31809-9
[100] Source: Cancer Research UK: https://www.cancerresearchuk.org/health-professional/cancer-statistics/statistics-by-cancer-type/bowel-cancer; citing: https://www.nature.com/articles/s41416-018-0029-6
[101] Source: Public Health England, National Diet and Nutrition Survey 2014/15-2015/16 (2018).
[102] Source: Federation of Bakers: https://www.fob.uk.com/about-the-bread-industry/industry-facts/market-snapshot/
[103] Source: Quadram Institute Bioscience: https://quadram.ac.uk/people/brittany-hazard/
[104] Source: https://quadram.ac.uk/why-we-should-look-to-increase-our-dietary-fibre-intake/
[105] The DFW ISP partly supported this work through strategic funding to the Quadram Institute Bioscience. DFW ran from 2017 to 2023 and had a total budget of £37.6 million. The programme involved 8 institutions: John Innes Centre, Rothamsted Research, Earlham Institute, Quadram Institute Bioscience, NIAB, EMBL-EBI, and the universities of Bristol and Nottingham. See: https://designingfuturewheat.org.uk/
[106] See: https://designingfuturewheat.org.uk/tilling-project-page/
[107] The Molecules from Nature ISP partly supported this work through strategic funding to the Quadram Institute Bioscience. The programme was led by the John Innes Centre, ran from 2017 to 2023, and had a total budget of £4.4 million. See: https://www.jic.ac.uk/research-impact/our-research-programmes/molecules-from-nature/
[108] The Food Innovation & Health ISP partly supported this work through strategic funding to the Quadram Institute Bioscience. The programme was led by the Quadram Institute Bioscience, ran from 2018-2023, and had a total budget of £2.9 million. See: https://quadram.ac.uk/research_areas/food-innovation-health/

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[109] See: https://designingfuturewheat.org.uk/tilling-project-page/. Developed as part of a joint project between the University of California Davis, Rothamsted Research, the Earlham Institute, and the John Innes Centre.
[110] See: https://pubs.rsc.org/en/content/articlelanding/2022/fo/d1fo03085j. See also: http://www.wgin.org.uk/information/documents/Stakeholders%20Meetings/SM_30Nov2017/15%20Brittany_WGIN%20-%20Nov2017.pdf
[111] See: https://quadram.ac.uk/reststudy/
[112] See: https://quadram.ac.uk/blogs/what-is-the-best-way-to-store-bread/
[113] Source: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7668007/
[114] Source: https://www.wri.org/food
[115] Source: https://onlinelibrary.wiley.com/doi/10.1111/pbi.12757
[116] Source: https://doi.org/10.1038/nclimate3115. See also: https://doi.org/10.1111/pbi.12757
[117] See: https://iwyp.org/
[118] See: https://www.wheatinitiative.org/
[119] For full list of public funders, see: https://iwyp.org/funders/
[120] For full list of private partners, see: https://iwyp.org/industry/. NB: Pioneer was a previous partner.
[121] Source: BBSRC, Benefits to the UK from IWYP (i.e., not calculated by WECD).
[122] Source: IWYP Annual Report 2021/22, p.14.
[123] Source: https://iwyp.org/wp-content/uploads/sites/34/2020/07/IWYP-Hub-Science-Brief-FINAL.pdf
[124] Of these figures, approximately 40 are UK researchers, and 11 projects are led by UK institutions (with UK institutions as partners in a further 18). Source: IWYP Annual Report 2021/22.
[125] Source: IWYP Annual Report 2021/22, p.5.
[126] Source: https://iwyp.org/wp-content/uploads/sites/34/2022/03/IWYP-Science-Brief-IWYP149_FINAL.pdf
[127] See: https://iwyp.org/wp-content/uploads/sites/34/2020/08/IWYP64-Science-Brief-FINAL.pdf. See also: https://www.earlham.ac.uk/news/exotic-wheat-dna-could-help-breed-climate-proof-crops
[128] See: https://iwyp.org/wp-content/uploads/sites/34/2021/11/IWYP122-IWYP-Science-Brief-FINAL.pdf
[129] See: https://iwyp.org\wp-content\uploads\sites\34\2022\01\IWYP123-IWYP-Science-Brief_FINAL.pdf
[130] See: https://iwyp.org/wp-content/uploads/sites/34/2022/05/IWYP-Wiring-Diagram-Science-Brief.pdf
[131] See: https://iwyp.org/iwyp-research-breeding-hub/ and https://www.cimmyt.org/news/international-wheat-yield-partnership-launches-european-winter-wheat-hub/
[132] Source: IWYP Annual Report 2021/22, p.5.
[133] See: https://iwyp.org/wp-content/uploads/sites/34/2022/06/IYPTE-Science-Brief_FINAL.pdf
[134] See: https://fotenix.tech/
[135] See: https://gtr.ukri.org/projects?ref=BB%2FM005143%2F1 and https://www.gov.uk/government/publications/agri-tech-catalyst/agri-tech-catalyst
[136] ICURE: £1.1 million grant funding plus £250,000 equity (2017); EIT: support and networking (2019); NVIDIA: £100,000 credit and networking (2019); Innovate UK: £1.1 million grant funding (2019-2024); ISCF Series A Investment Programme: £524,317 (2021/22).
[137] See: https://worldwide.espacenet.com/publicationDetails/biblio?DB=EPODOC&CC=WO&NR=2019122891&KC=A1
[138] Source: AHDB: https://ahdb.org.uk/cereals-oilseeds/uk-human-industrial-cereal-usage.
[139] Scotch Whisky Association, Cereals Technical Note (August 2021), p.23.
[140] Source: Scotch Whisky Association: https://www.scotch-whisky.org.uk/insights/facts-figures/
[141] Source: Scotch Whisky Association, Cereals Technical Note (August 2021), pp.23-24.
[142] The DFW ISP partly supported this work through strategic funding to Rothamsted Research. DFW ran from 2017 to 2023 and had a total budget of £37.6 million. The programme involved 8 institutions: John Innes Centre, Rothamsted Research, Earlham Institute, Quadram Institute Bioscience, NIAB, EMBL-EBI, and the universities of Bristol and Nottingham. See: https://designingfuturewheat.org.uk/
[143] The Wheat TILLING population was created at Rothamsted Research, funded by Defra's Wheat Genetic Improvement Network. This was then taken over by the John Innes Centre which did the sequencing work.

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[144] See: https://www.ipo.gov.uk/p-ipsum/Case/PublicationNumber/GB2503598

[145] See: https://designingfuturewheat.org.uk/tilling-project-page/

[146] See: https://gtr.ukri.org/projects?ref=BB%2FK010824%2F1

[147] See: https://gtr.ukri.org/projects?ref=BB%2FN019164%2F1

[148] Diageo produces 40% of Scotch whisky, and owns famous brands like Johnnie Walker, Talisker, J&B and Buchanan's. Scotch whisky represents 25% of Diageo total sales, worth £3.2 billion in 2018/19. See: https://media.diageo.com/diageo-corporate-media/media/uh3g3yrk/diageo_scotch_factsheet.pdf

[149] Source: Scotch Whisky Association, Cereals Technical Note (August 2021), p.23.

[150] Scotch Whisky Association, Cereals Technical Note (August 2021), p.30.

[151] Source: https://www.thedrinksbusiness.com/2020/05/scientists-create-designer-wheat-for-whisky-production/

[152] Ethyl carbamate is a barley-derived carcinogen present in a range of spirits, which has been a concern for distillers. The identification of the genetic marker for the barley precursor epiheterodendrin (Glycosidic Nitrile, GN) led to the development of low/non-GN barley for distilling. See: https://doi.org/10.1002/jib.192