A 5-Year Wheat Research Strategy for BBSRC

In 2012, BBSRC's Food Security Strategy Advisory Panel established a broadly-based, time-limited group to advise on the Council's future strategy and priorities for wheat research.

The working group considered a BBSRC portfolio analysis and the outputs of a web-based community consultation, to discuss and distil key strategic messages and to frame these in the context of a high level strategy document.

The main output of the group's independent advice comprises this suggested 5-year wheat research strategy together with a list of associated recommendations.

Vision

1. **This document aims to set out the key current drivers, opportunities and challenges for delivering impact from existing and future BBSRC investments in world-class scientific research relating to wheat. This research will underpin the development of future generations of wheat crops, agronomic systems and industrial processes that will allow wheat to be grown and used more sustainably, whilst maintaining or improving yields and quality traits.**

Scope

2. BBSRC has a substantial existing investment in wheat research that is in line with the pre-eminence of wheat as the UK's most important staple crop and UK research excellence in genetics and genomics of this crop. This document sets out a high-level strategy to guide future investment priorities for wheat research in the UK in the context of BBSRC's broader Strategic Plan[1].

3. A range of crops and wider food sources are clearly important for UK and global food security. The development of research strategy specific to wheat is not intended to undermine the importance of a balanced range of BBSRC research investments within the context of BBSRC's Food Security research priority area.

4. Although many of the research challenges articulated in this document will also be of importance to other UK and international funders, this document is intended to focus on wheat from a BBSRC strategic perspective, reflecting the Council's mission, remit and areas of influence. In delivering key objectives, the need for collaborative links to other key funders and wider stakeholders is acknowledged.

Global food security drivers and priorities for wheat research

5. **A wider food security challenge underpins strategic research on wheat**. The world needs more food to feed a growing population and, in many regions, to have more sustainable crop husbandry. Current practise may not recognise increasing pressures on land use, energy prices, fresh water and other natural resources and it may contribute to loss of biodiversity or degradation of the environment through soil erosion, aquifer depletion or pollution. Climate change is also likely to influence changes in crop husbandry.

6. **Globally, wheat has the third largest production of any cereal**, after maize and (almost matching that of) rice, and almost an order of magnitude larger than the next most produced crop, barley. However, wheat is grown on the largest area of land of any crop. It is also generally regarded as both the most important cereal for direct human consumption (rather than for livestock feed) and the most significant global source of vegetable protein.

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[1] http://www.bbsrc.ac.uk/news/planning/strategy/

7. **Wheat is a particularly critical crop for the populations most exposed to current and anticipated failures in global food security.** There are in the order of 1.2 billion[2] wheat-dependent poor and 2.5bn wheat-consuming poor, living predominantly in Africa and Asia where wheat yields are particularly threatened by climate change-induced temperature increases. These two regions will also host the majority of anticipated global population growth and are experiencing the most significant urbanisation shifts[3], pressures that will both greatly exacerbate existing vulnerabilities. Global food security is, therefore, dependent on expanded wheat production.

8. **On-farm wheat yields have started to plateau in developed nations, but it may be possible to overcome this through new research.** Wheat yields increased rapidly in the 1970s during the 'green revolution' but this trend has tailed off in recent years. The UK has championed research in wheat and, with access to the wheat genome sequence, new gene-based technologies and other advances in plant science and agricultural practice, there is potential to direct a further step change in wheat yields. We need to understand what yields may be possible 'in theory', and understand the key processes involved, to underpin the delivery of further yield gains 'in practice'.

9. **There is enormous potential to increase wheat yields in the developing world**. Yield in the developing world is much lower than in developed nations[4]. In part the difference is due to more favourable conditions and/or less constrained system inputs in developed nations. However the difference may also be because the widely used varieties and husbandry are not adapted to the local conditions. UK wheat researchers are well placed to make highly significant contributions towards improving food security for many millions of wheat-dependent people in the developing world.

10. **Yield gains generated through research will represent a 'hollow victory' in the long term unless they can be achieved sustainably.** The major successes in 20th Century agriculture, and crop breeding particularly, were in significantly increasing production. However, the gains have often been achieved within unsustainable farming systems[5]. The major challenge is to place past and future gains onto a more sustainable footing. This means making more efficient and sustainable use of resources and reducing environmental impacts (e.g. carbon footprints, biodiversity, soil quality, water table, pollution of land and watercourses). Increasing sustainability of wheat primary production will demand the minimisation of trade-offs with other services provided by rural landscapes (e.g. biodiversity, soil carbon storage, drought/flood mitigation, leisure and recreation). However, it is clear that there is much work to do to understand what sustainable maximised yields are achievable in the different regions where wheat is grown.

11. **UK and global wheat production needs to become more resilient to the impacts of climate change**. Climate change is likely to result in sustained changes to mean temperature and water availability in agricultural regions. Perhaps more importantly, climate variability and the frequency of extreme weather events are also likely to increase, and new crop pest and diseases pressures will emerge. This will have significant implications for the profiles and productivity of agricultural landscapes in the UK and globally. There is likely to be considerable impact on the reliability of UK wheat yields and, perhaps more insidiously, quality of grain produced – even where yields may remain high, the quality of grain may be adversely impacted, preventing its use in higher value applications (e.g. bread making). In responding to climate change pressures, a sensible

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[2] [Reference/webpage no longer available – Feb 2016]
[3] Foresight. The Future of Food and Farming (2011) Final Project Report. The Government Office for Science, London.
[4] http://data.worldbank.org/indicator/AG.YLD.CREL.KG
[5] For example: http://www.foodsecurity.ac.uk/blog/index.php/2010/01/the-need-for-nitrogen/

ambition for the UK will be to seek to maintain, at least, current primary production quantities and qualities, whilst placing production on a more sustainable and resilient footing.

12. **To deliver impact, wheat research investments must underpin innovative products and practises that meet users' key needs and constraints.** Research must enable a better understanding of trade-offs between yield, sustainability of production and quality of produce, and underpin innovative solutions to balance and minimise these for different needs and contexts. Research must also deliver benefits that translate effectively to commercial farming and processing industries. For example, there is a particular need to maintain nutritional and processing qualities of grain when seeking to breed for other beneficial traits, including yield gains. Failure of research to enable the right balance of benefits to be obtained can mean impact is severely curtailed. Similarly, benefits must be reliably achievable outside of controlled research labs and idealised research farms. This is currently not always the case, and there are considerable research challenges in understanding why and how this issue might be addressed.

UK position in global wheat research

13. **The UK is a significant and highly efficient global producer of wheat.** We are amongst the international leaders in wheat production, obtaining mean yields of ~8 tonnes per hectare, in the context of a global mean yield of 2.8 t/ha. The UK's annual production is around 15M tonnes, of which up to 25% is exported[6]. These successes are built on a foundation of agronomic success; the UK-generated wheat variety 'Einstein' holds the record for highest ever recorded wheat yield of 15.6t/ha, in New Zealand. The UK record is 14.1t/ha, using 'Oakley' - another UK-generated variety.[7][8] However, it should be noted that these yields were reliant on heavy (unsustainable) application of nitrogen fertiliser.

14. **UK wheat research has underpinned the competitiveness of a valuable national industry.** The value of the wheat harvest to the UK economy is over £1.6 bn, and processed wheat-derived products are worth nearly an order of magnitude more. Research underpinning future UK wheat varieties and associated agronomic practices will have significant potential impacts in maintaining the competitiveness of the economic supply chain and associated wider societal benefits, and developing resilience to significant challenges for sustainability.

15. **The UK has a world leading track record in wheat research.** Five key strategic wheat research 'prizes' are based on the success of UK wheat research. They provide understanding of:

    (1) the genetic basis of bread-making quality;
    (2) the *Rht1* gene – a 'Green Revolution' gene that controls dwarfing;
    (3) the *Ppd1* gene, the primary gene controlling flowering time;
    (4) *Ph1*, the major chromosome pairing locus which stabilises wheat polyploidy;
    (5) common patterns of gene order in the chromosomes of wheat and other cereals. This concept of cereal 'synteny' allowed rice and Brachypodium to be used for positional cloning of wheat and barley genes for major traits.

    Most genes that have been identified for major traits in wheat to date have been done so through the synteny approach. A more detailed analysis of the importance of synteny, as an example of UK research success, is provided as **Case Study 1** (**appendix 1)**.

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[6] [Reference/webpage no longer available – Feb 2016]

[7] [Reference/webpage no longer available – Feb 2016]

[8] http://www.fwi.co.uk/articles/28/01/2013/137372/later-nitrogen-may-be-key-to-up-wheat-yields.htm

16. **The UK's wheat research success is built investment in both institutes and universities.** Between 2008 and 2011, BBSRC spent around £10M per annum on wheat research, out of around £50M on all crop research. This represents an increase from an annual investment of around £5M per annum in '04/'05. Historically, much of this spend has been in research institutes, and at present the John Innes Centre and Rothamsted Research receive a large share (£22M and £17M between '04-10', respectively) reflecting a strategic research agenda that requires long-term funding of coordinated programmes and infrastructure. However the HEIs also contribute significantly to wheat research. The recent expansion in funding for wheat research links to BBSRC's broader Strategic Plan. The strategy set out in this document aims to provide a framework so that the BBSRC spend on wheat links coherently with *Food Security* and *Industrial Biotechnology* priorities, supports sustainability of the research base and has an appropriate balance of support for Institutes and HEIs.

17. **There are exciting new opportunities for UK wheat research.** With a strong global track record of leadership in wheat genetics and genomics research, UK researchers are now in a good position to identify the next generation of important traits that will underpin the ability of UK agriculture to respond to the most pressing strategic challenges. This favourable position is based in part on the expertise in wheat within the research community and in part on the prospect that we can fully exploit the wheat genome sequence. The UK has been a major contributor to the global wheat genome sequencing consortium and the completion of the sequence will transform our ability to achieve strategic impacts in wheat improvement.

18. **A key future research priority will be to enable new traits and practices for improved sustainability.** Yield and quality of the wheat crop remain important but there is 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.

    A *whole cycle* consideration of sustainability will be needed, which will require multidisciplinary approaches and coordination of a wide range of research funded by BBSRC and others (e.g. engineering and social science). The Global Food Security Programme[9], as the top-level UK body coordinating key funders' relevant strategic priorities, will play a major role in promoting a more joined up approach to relevant research funding, to facilitate appropriately co-ordinated, multidisciplinary research activity and the translation of research into impact.

Research capacity and capability

19. **We need on-going, internationally competitive capability in a broad base of agricultural research and underpinning basic bioscience.** In order to deliver world-leading wheat research and innovation, the research base must be able to respond flexibly to strategic opportunities and challenges, and changing research opportunities and demands. It must have appropriate access to the necessary tools and resources, and

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[9] http://www.foodsecurity.ac.uk/

interact effectively with sector stakeholders to ensure maximised knowledge exchange and impact.

20. **Key areas of research need to be harnessed and integrated**. These flow from basic molecular-genetic plant science to genetics and 'omics-scale analyses through to the understanding of wheat interactions and responses in the field and in the context of farm-scale processes and the management of the wider agri-ecosystem. These areas are explored in more detail below.

Underpinning world class bioscience

21. **UK excellence and associated 'bedrock' investments in underpinning basic bioscience are essential to underpin strategic wheat research aims.** They will provide the foundation for the next generation of sustainable wheat crops. BBSRC-funded researchers require the capacity, resources and intellectual freedom to make discoveries and innovate in basic science, knowledge from which will continue to inform future strategic wheat research aims. Until now, the majority of such underpinning research has been conducted in model species, especially Arabidopsis, and then translated to wheat and other crop species. A key example of this is that of basic research on flowering time, described in **case study 2 (appendix 1).** There are still areas of plant science that can be undertaken only in other systems and tractable model species will continue to have an important role to play in informing and enabling wheat research and its strategic targets. These areas include the understanding of chromosome structure and its influence on recombination and gene expression, understanding and exploiting heterosis, and basic regulatory mechanisms affecting complex traits - including yield. However it is essential that there are clear routes to effective translation this basic research into wheat and other crops.

22. **Wheat will become a model crop system; we need to promote and enable an integrated approach with other plant models.** Although there will be a continued flow of underpinning research from other plant species that will inform wheat research, as for other key crop species, the tools and knowledge are increasingly available to allow wheat to become its own model system. The study of crops, classic model species and a diversity of related plant species can be expected to become increasingly integrated, with multi-directional flow of knowledge and research skills. We need to enable, and seek to remove any barriers to, a timely and effective transition to such integrated approaches.

Genetics, genomics and informatics

23. **We need 'omics and informatics resources tailored to wheat.** UK researchers have laid the groundwork for the next generation of wheat yield traits that will underpin new gains in productivity and sustainability; for example, they have identified 16 yield QTLs[10] that are sustainable over many generations through Mendelian selection and are ready for cloning. They now need access to appropriate genomics technology to unpick and understand the biology behind these QTLs. To exploit the wheat genome and integrate this knowledge with other 'omics and phenotypic datasets, we need to develop community-led UK resources in genomics, other 'omic and informatics that are tailored to wheat, as set out in paragraphs 24-27.

24. **A fully resolved and annotated wheat genome is needed.** Sequencing the wheat genome has presented an enormous challenge, due to its large size and complexity. A draft wheat genome (a 'survey sequence') is now available and has already been used for single-nucleotide polymorphism marker development to facilitate contemporary genetic approaches such as association mapping. Researchers are now in a position to begin to

[10] Quantitative trait loci: stretches of DNA containing or linked to the genes that underlie a quantitative trait (e.g. yield; grain protein content).

exploit this information in epigenetics, transcriptomics and metabolomics studies of wheat. However, much remains to be done; the planned releases of the wheat genome sequence have only limited capacity, for example, to facilitate forward and comparative genetics screens. There is pressing need for additional effort on the wheat genome sequence so that UK and other researchers can realise the full potential of this resource. The refined wheat genome sequence will also facilitate the flow of knowledge between wheat and model/other crop species.

25. **There is a leadership challenge and associated opportunities for key centres of informatics excellence.** A major component of the additional work on the wheat genome sequence is bioinformatic. There are major bioinformatics challenges in developing and integrating wheat-relevant 'omic tools and datasets. There is a clear opportunity for a UK centre(s) of bioinformatics excellence to be international leaders in this effort. In addition to the direct benefit – understanding of the wheat genome – there will also be associated benefits in research skills, capacity and tools to the UK.

26. **UK researchers require access to an on-going diversity of genetic information and resources.** Substantial BBSRC investments[11] are underpinning the production and curation of genetic material that can be used by the wider wheat research community to identify and dissect new QTL traits that will underpin breeding strategies for the future. Relevant genetic resources extend beyond wheat itself; as further information on other grass genomes becomes available, comparative genomics will reveal many key genes for control of durability, resilience to disease and maintenance of yield in variable environmental conditions. Sustained UK investment and research impetus is needed in a wide range of grasses, and the development of associated genetic/genomic resources, to underpin future research and, in particular, the development of desirable traits in both wheat and other key crop species.

27. **There is a need to emphasise excellent and sustained curation of genetic resources.** UK researchers need appropriate access to germplasm stocks produced by BBSRC funded research, and it is essential for these resources to be verified and validated to ensure they are *bona fide* and well tracked. Building on substantial current investments, there is a need to ensure enduring curation (quality assured maintenance and renewal) of genetic resources. This will ensure that the long-term value of a much larger body of public research investment can be realised, and this drives sustained benefits for UK taxpayers and industries.

28. **There is a need for improved multi-scale modelling of wheat.** There is huge scope for modelling to inform an improved understanding of crop biology and effective strategies to develop desirable traits; for example, the relative importance of, and relationships between, photosynthetic 'source' and grain 'sink' determinants on wheat yield. Improvements focussed on both metabolic sources and sinks may be necessary to significantly impinge on yield potential, but there is no agreed means of evaluating their relative importance and very few major genes involved in associated traits are so far known. Metabolic modelling approaches can inform the discovery of key genes, particularly as genome-scale metabolic modelling approaches are enabled by increasing knowledge of the wheat genome. However, there is much work to do to develop effective models based on contemporary understanding of the plant that would allow (for example) an objective prediction of the primary determinants of yield.

<u>Research in the field</u>

[11] 1) http://www.wheatisp.org/ ; 2) [Reference/webpage no longer available – February 2019]

29. **We need to be able to link greenhouse and field studies, enabling experimental validation and understanding of plant performance in the field.** This is an evolving topic, and it is not yet clear what is the most effective strategy for assessing performance of new and experimental genotypes in the field – is it linked to analysis under controlled conditions using sophisticated greenhouse-based plant phenotyping facilities[12] or should it be field-based and linked to new developments in imaging and high-throughput biochemical analysis? We need to explore and assess incoming technologies and techniques and be in a position to follow up the most promising approaches.

30. **There is a clear need for field capacity in wheat research.** Notwithstanding the possible need for controlled environment phenotyping, UK capacity and capability in field research will enable translation of research between laboratory and field conditions. The availability of *in situ* field phenotyping will facilitate interpretation of genotype in terms of field-condition phenotypes and will speed up plant breeding programmes. There is already a 'phenotyping bottleneck' where we can produce new genotypes faster than we can use them to identify useful traits. The UK is falling behind others internationally (e.g. INRA) in developing such facilities, and this should be reversed if we are to maintain UK wheat research competitiveness.

31. **There is a need to understand better the interactions of wheat within the wider agricultural system ('agri-ecosystem')**. Such approaches will be necessary to underpin wheat production aims and to begin to place intensive production onto a more sustainable footing. They will be required to address key lines of research enquiry that require effective translation between laboratory and field, for example addressing the key question as to why some varieties perform more reliably in the field (often seemingly much more resilient to environmental fluctuations) than others. Agricultural systems research has been unfashionable and neglected, but is a key component of new approaches to sustainable and high yielding crop husbandry. We need integrated, multidisciplinary approaches to understanding and manipulating wheat-farming systems in a predictive way. Wheat is one of the best-characterised components of the agricultural ecosystem and it would provide a good platform to develop novel agri-ecosystems approaches for other crop species/systems.

32. **New approaches to agri-ecosystems will lead to better crop management and minimisation of agricultural trade offs**. Managing and mitigating trade-offs will be critical to delivering a range of key economic, environmental and societal services from wheat-growing landscapes, whilst optimising system stocks and flows and reducing inputs, in different agricultural contexts and climates (e.g. including higher/lower input scenarios for developed and developing world contexts), and at different scales of management (e.g. field to landscape)

<u>Research for a healthy supply chain</u>

33. **UK researchers and wheat processing industries must work together to better align strategic interests.** The UK is well placed to undertake excellent basic and underpinning research across the whole supply chain, and there are good examples of effective translation of UK basic research into impact for the food processing industry. For example, research into the genetic control of wheat glutenin composition has underpinned the development of varieties better optimised for bread and biscuit making. However there should be better two-way communication between industry and the wheat research base. The industry should fully understand what research can offer and the research community should better understand the needs of industry.

[12] [Reference/webpage no longer available – Feb 2016]

34. **Strategic gains in wheat production should not be at the expense of processing performance.** There is a significant challenge to maintain key grain quality traits in face of environmental extremes and other system pressures, often compounding, and a better appreciation and management of trade-offs in benefits is required. Key examples include:

- New high-yielding varieties that exhibit poor processing performance will not have high commercial value if higher quality grain is available to markets.

- New strategies for reducing nitrogen inputs must be cognisant of supply chain impacts; the UK presents an occasionally marginal environment for having the appropriate protein characteristics for bread making. Sub-optimal weather conditions and restricted nitrogen use can combine to significantly reduce harvest quality (resulting in protein levels below minimum requirements). This can impact both primary production and product consistency, as was seen in the UK's wet summer of 2012.

- The societal drive towards reducing salt in the food chain has a compounding effect on maintaining processing quality and consumer acceptability of products.

There can also be compound benefits; improving disease resistance can minimise the incidence of produce being rejected due to exceeding mycotoxin safety thresholds. Researchers need to be cognisant of the full range of contextual drivers and constraints for the supply chain, and research programmes should be well informed by key supply chain needs.

35. **Basic research can be channelled to different industry needs**. Research outputs that adversely affect some applications may be beneficial in other contexts and the strategic value of new 'all-purpose' varieties should be balanced against those with specialised applications. For example, high protein content is the key quality measure for bread making, whereas ethanol production favours a high proportion of fermentable starch. Similarly, non-starch polysaccharides are valued as a source of fibre for humans, but cause problems with nutrient release when used for poultry feed. Therefore there is an on-going need for basic research outputs to address a range of potential uses of wheat.

36. **There are opportunities for wheat research to underpin the development of innovative products and practises in the food chain:** changes to the quality of wheat grain should take account of nutritional effects (human or animal) and the potential for non-food applications. There are significant research challenges and opportunities for animal feed and industrial uses for which the needs are less well understood than for human food uses. Examples of possible opportunities for innovation include making better nutritional use of inherent soluble fibre in wheat, which can lead to issues of palatability in humans and digestibility of other nutrients in animal feed, and the development of wheat that lacks the gliadin proteins to which people with coeliac disease respond, whilst retaining gluten functionality.

People and skills

37. **There is a critical need for succession planning and 'new blood'.** Past success in UK wheat research is built on sustained investment and a platform of expertise and training over the previous 2-3 generations including that at the Plant Breeding Institute in Cambridge. It is evident that the UK wheat research community has sustained itself with a small central core of expertise since the closure of the PBI and changed emphasis of research at Rothamsted Research and in Aberystwyth. However there is a risk that this core will be lost as senior wheat researchers approach retirement age because there are few obvious successors to cover the broad spectrum of areas encompassing wheat research. A sustainable plan for maintaining and augmenting wheat research capability is required to ensure a continued stream of innovation in the sector and supply of key skills to

industry; we need to train and retain a cohort of researchers who understand and can work effectively with wheat.

38. **We must ensure that the best talent is appropriately developed and retrained at a range of career stages.** Creative use of available career development mechanisms is required to ensure the UK maintains an appropriate skills capacity in wheat research. There are slightly different challenges for developing mid-career researchers, who require on-going training in the latest technologies to be able to remain at the leading edge of research opportunities, and the younger researchers, who tend to be well equipped with relevant technical skills but need guidance towards the strategically important research targets. There are particular challenges for the integration of skills sets and the development of effective multidisciplinary research programmes.

39. **The newly recognised importance of agri-ecosystems research will require a new skill base.** There will be particular needs to 1) re-align and integrate research skills and expertise across currently disparate disciplines and communities, 2) develop appropriate strategic signposts, incentives and targets to encourage this process, and 3) develop national capacity and capability in appropriately configured and coordinated research facilities, including instrumented farm-scale platforms, to enable such approaches to be effectively developed and embedded.

Deriving impact

40. **Effective knowledge exchange will be essential to obtain impact from BBSRC investments.** Deriving value for money from strategic wheat research investments will require effective innovation, knowledge exchange and commercialisation of outputs. In achieving these aims, there is a clear need to better engage end users (e.g. milling and food processing industries) to promote and realise the potential of enabling research to underpin innovative and more sustainable products and practises. Conversely, we need to ensure that research programmes are informed by a good understanding of users' needs, drivers, constraints and challenges, to ensure that research outputs are appropriately targeted and tailored and can be readily taken up and built upon by commercial users. There is arguably a clear need for an organisation(s), whether existing or new, with a knowledge brokering remit to better link research and research users in an iterative process of synthesis, translation, promotion and feedback.

41. **Better funding of applied research will be needed to obtain impact from basic and strategic research investments.** Achieving appropriate impact from BBSRC's strategic investments is constrained by the gap that currently exists for the funding of collaborative and pre-competitive applied research. Defra LINK previously funded this but current mechanisms through the Technology Strategy Board focus on a model where competitiveness of individual companies is the driver. An impact of this has been considerably reduced cross-industry contact and engagement. There now exists a 'valley of death'; a lack of support for applied research that mitigates against an effective flow of new research knowledge, tools and products into application. This must be addressed if the UK is to see the full impact of public-funded strategic research such as that exemplified by wheat research. UK investment in an experimental breeding programme would be a valuable step in the right direction, as this would allow wheat researchers to extend the translational pipeline in testing and validating the outputs of, for example, new genomic selection techniques, population designs, yield QTLs, wild species introgressions, genomics and other technologies. This would also provide a mechanism for contributing to the training of the next generation of breeders.

42. **We need to understand the impact of previous research investments, and potential barriers to future impact.** We need to recognise the difficulty of directly translating/exploiting basic research 'in the field' and to seek effective ways to improve

translational impacts from publicly funded research. However, it is also difficult to quantify the level of impact that basic bioscience has had on the outputs of commercial breeding programmes to date; the value of underpinning investments is likely to be substantial but there is not a strong evidence base currently. We need to develop better measures of the impact BBSRC-funded wheat research is having, and to identify barriers to realisation of impact where they may exist. This will help to address community concerns that cutting edge academic research may not currently be deployed effectively by industry and, in particular, within commercial crop breeding.

43. **There is a risk of IP arrangements forming a barrier to effective KE**. Knowledge exchange and commercialisation can be constrained by close IP protection and the UK should strive to keep wheat genetic resources pre-competitive and freely available to all researchers, to maximise the impacts of relevant BBSRC investments and minimise timescales to deriving them. There is a need for UK leadership at an international level to seek to drive dialogue between funders, researchers and institutions towards a realistic international strategy. This is reflective of a more generic issue around open and timely access to bioscience research outputs, and genetic resources particularly, that will hopefully be addressed within the UK Government's forthcoming agri-tech strategy.

Communication and International Coordination

44. **The wheat research community must build effective networks and develop better outreach activities.** BBSRC and BBSRC-funded researchers must communicate regularly and iteratively to develop a common understanding of strategic aims and key challenges, and seek to improve dialogue with a full range of wheat research contributors, the wider plant science research community, policy makers, industrial users and a wider range of stakeholders. A range of approaches should be pursued to facilitate dialogue and information exchange, including physical networking and web-based tools. These should build on currently developing community programmes and initiatives, such as WISP and the International Wheat Initiative, and their associated community information resources.

45. **UK researchers cannot meet the challenges and opportunities for wheat research, or develop the impacts of the research, alone.** We need to ensure UK researchers are able to participate in key international initiatives and can collaborate effectively with international researchers, ensuring a flow of the best international skills and expertise, and promoting research standards and data sharing.

CASE STUDY 1 – Synteny; a success story for UK research investment and impact

Conserved synteny aids the genetic analysis of all the modern cereal species through the production of a composite map of the ancestral grass genome from which these cereals evolved. Ground-breaking papers by UK researchers described the concept of synteny first between rice and wheat[13], and then all of the major cereal genomes[14], revealing that the genes within specific chromosome regions of these species often occur in the same order. However, the sizes of the genomes can be very different. Large genomes are generally less tractable than smaller ones; the barley genome is large, and the allohexaploid wheat genome (a stably-inherited combination of three closely related diploid ancestral *Triticum* genomes), is enormous. Therefore researchers have been able use the genomes of rice and Brachypodium, which have much smaller and more readily characterised genomes, as models to identify parts of larger cereal genomes, particularly those of wheat and barley, that are responsible for important phenotypic traits, based on the conservation of gene positions.

This approach provides genetic markers for selecting phenotypic variation during breeding, for example by CIMMYT[15]. The products of these selections are now beginning to appear as new varieties, and hence in farmers' fields. This success has been built on twenty years of sustained strategic crop research investment, particularly at the John Innes Centre. Recent and on-going UK research investments are generating new positionally cloned genes and better-defined genetic markers for a wide range of potentially beneficial traits, resources which will underpin accelerated breeding programmes that seek to respond to the challenges of sustainably intensified wheat production and usage.

CASE STUDY 2 - Flowering time: why basic research in multiple plant species has been crucial for wheat research

Work in several plant species has contributed to elucidation of the mechanisms involved in determining flowering time in wheat, which is much more variable than for some other cereals, and is a trait of agronomic importance – the ability to control and optimise it for different environments and agricultural regimes is highly desirable.

In Arabidopsis, the 'classic' plant genetic model, the regulation of flowering time is via the circadian clock interacting with the Constans pathway (CO gene, regulating the FT gene). CO promotes flowering under long days (a 'long-day' plant). The vernalisation pathway links with this mechanism to ensure flowering only occurs following prolonged cold; this helps to ensure flowering in Arabidopis, a temperate-zone plant, only occurs after winter.

In rice, the same pathway regulates flowering. However rice has an additional novel pathway not found in Arabidopsis that means that the role of CO is reversed: it promotes flowering in short days but suppresses flowering in long days (a 'short-day' plant). The vernalisation pathway neither exists nor is required in rice.

In barley and wheat, relatively closely related species that are long-day plants like Arabidopsis, the gene *Ppd1* has been recruited to have a major role promoting flowering and

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[13] Moore G*, Gale MD, Kurata N, Flavell R (1993) *Molecular analysis of small grain cereal genomes*. Nature Biotech. 11 584-589.

[14] Moore G*, Devos K, Wang Z, Gale M (1995) *Cereal Genome Evolution: Grasses, line up and form a circle*. Curr. Biol. 5, 737-739. (One of the top 10 most cited papers on wheat research).

[15] William, H.M, Singh, R.P, Trethowan, R., Van Ginkel, M., Pellegrinshi, A., Huerta-Espin, A. and Hosington, D. (2005) *Biotechnology applications for wheat improvement.* CIMMYT. Turk J Agri. 29, 113-119.

it seems that the role of the CO gene has been bypassed[16][17]. Barley and wheat undergo vernalisation, but the gene pathways are mostly novel compared to Arabidopsis. It is thought that barley and wheat both evolved from an Asian ancestor to modern rice (and share a more recent ancestor with each other). To adapt to temperate conditions (long-day flowering, vernalisation), they have had to disable the role of CO in flowering time and re-evolve a vernalisation pathway that was absent in the common ancestor with rice[18]. In wheat, it appears that, in addition to the effect of polyploidisation, the copy number of *Ppd1* on individual homeologues also varies[19]. It has been proposed that this may explain the broad phenotypic variation in flowering time observed in wheat.

Therefore studies based on Arabidopsis, rice and barley have all contributed to developing an understanding of wheat flowering time variability. Arabidopsis work has provided insight into the photoperiodism and vernalisation mechanisms, and aided identification of a number (but not all) of the photoperiod genes in rice, wheat and barley, but not many of the vernalisation genes in wheat/barley and not the 'wiring' of the genes. Work on rice and barley has provided both the genes and the 'wiring' - but does not explain phenotypic variation for breeders in wheat - which can be due to copy number variation. Bringing these studies together developed a complete picture that resolved the wheat-specific elements, information that can feed into future breeding programmes.

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Specific recommendations of the wheat strategy working group for BBSRC

BBSRC research investment

1. **Strategic overview:** BBSRC should continue to fund wheat research as a substantial component of on-going crop research investments, in light of the strategic importance of wheat, and the excellent track record of strategic successes by UK wheat researchers. Responsive mode remains an effective mechanism for ensuring that a bedrock of underpinning plant and microbial science thrives.

2. **National investments:** BBSRC should guard against any complacency that might undermine the UK's leadership position in global wheat research. Current national investment levels are broadly appropriate but there is a need for tracking and monitoring and regular review. The UK has been and remains a world leader in wheat research, and this is an indicator that BBSRC's past and current investments have been appropriate in scale and direction, particularly acknowledging recent strategic investments in the area. There are some specific current needs around emerging opportunities that will require effective and timely investments to be made.

3. **International investments:** BBSRC has a major international leadership role to play. There is a threat of the international research effort being out of kilter with the global strategic prominence of wheat, and the scale of the research challenges. BBSRC should not reinvent activity on a national scale where there is relevant international initiative (e.g. wheat genome), rather seek to engage proactively to contribute to an overall global impetus and gain maximum leverage for UK research therein.

Key research needs

4. **Wheat genome:** There is a huge job to be done in unlocking and realising the potential of the wheat genome. BBSRC must seek to ensure that international wheat genome initiative delivers in a timely way, with appropriate participation of, and leverage for, UK research. There is an associated requirement for national capability in high quality wheat sequencing and annotation.

5. **Informatic resources:** In the development of 'omic and informatic resources tailored to wheat, there is a major informatics requirement and a need for the development of community-led resources. TGAC is probably best placed to lead this and, to facilitate further engagement, could be requested to lead on a position paper suggesting how comparative cereal genomics should be taken forward in the UK.

6. **Field phenotyping:** Technology in this area is improving rapidly and new approaches are currently being developed; it is yet not clear how and where major investment will reap greatest dividends. BBSRC should consider what the key capability needs are for UK research, and seek to enable the development of flexible, appropriate capacity to undertake phenotypic studies in a range of field conditions. A BBSRC-led community workshop would be an appropriate starting point.

7. **Experimental wheat-breeding platform:** BBSRC should engage with other key stakeholders to consider the strategic need for an experimental wheat-breeding platform for the UK. NIAB is ideally placed to lead such a development. This could also provide a mechanism for contributing to the training of the next generation of breeders.

8. **Agricultural systems and agronomy:** There is a real need to build capacity; many of the gains in terms of sustainable practice will probably stem from work in this area. However, the way forward is less clear than for some other areas. BBSRC needs to consider how to build capacity and integrate disparate infrastructure and expertise, and how to integrate genetics-led breeding approaches, agri-systems thinking and translational/applied research.

Research Skills Capacity

9. **Succession planning for wheat researchers:** BBSRC should be proactive in facilitating a continuity of UK wheat research capacity.

   There is an absence of wheat researchers aged between the late thirties and late forties, and an urgent need for succession planning. This could otherwise seriously impinge on the capability and capacity of the research community to deliver against the identified strategic wheat research priorities. Addressing this issue in a timely way will require early engagement. One possible mechanism to address would be via conversion fellowships for mid-career (tenured) researchers, with a track record of success. This would encourage re-alignment of able/tested researchers to fill an approaching leadership gap across a range of research areas in wheat. Fellowships would need to be funded for around 7 years to take into account the experimental constraints imposed by long crop growing times. Suitable incentivisation would also be necessary to acknowledge the career risks involved, and this would probably necessitate some institutional commitment towards these fellows upon completion of the fellowship; joint appointments may be feasible.

10. **Doctoral Training:** BBSRC should consider enhanced support mechanisms for wheat doctoral training based on strategic need, and should consider creative enabling solutions to train and retain excellent PhD students in wheat research.

    There is a specific issue with the funding of PhD students in high overhead cost research areas such as wheat research, where growing the necessary experimental crops adds significantly to the cost of research. The lack of a studentship component to cover overheads means that institutions have to effectively subsidise these students, and may consequently limit PhD student intake in such areas. This is particularly prohibitive to the development of doctoral cohorts, with the benefits that this brings, and particularly so in a university setting. Another solution would be to associate wheat research studentships with grant awards; the student should not be integral to the implementation of the associated grant, but their association would serve as a capacity-building device: the key output being the trained student.

KEC

11. **Funding for applied research:** BBSRC should seek to make the message heard, at a high policy level, that an absence of funding for applied research, previously funded by Defra LINK, is a serious constraint to the UK's ability to meet the sustainability agenda and derive public good from public investments in strategic agricultural research.

12. **Research translation:** BBSRC should develop metrics to better follow translation routes for wheat research and identify possible failures, and target mechanisms to address. AHDB, and specifically HGCA, is ideally placed to have more of a knowledge brokering remit in drawing together primary research and promoting it to industry, to facilitate feedback of industry needs to inform academic research programmes, and to maximise

opportunities for research to underpin the development of innovative products and practices. This could be achieved by nominating a specific HGCA scientist to liaise with academic wheat researchers so that research findings are promulgated to the industry and applied on a field scale level as soon as possible. BBSRC could encourage this by identifying a senior wheat researcher to undertake formal, senior-level liaison with the corresponding HGCA leader, to develop shared understanding of research outcomes and opportunities.

13. **BIS strategic context:** The developing BIS agri-tech strategy is welcomed as a helpful development which should inform RC strategy around IP protection in the wheat genomics area and the execution of applied wheat research. Hopefully it will make recommendations that address some of the generic issues raised in this strategy. If it does not, BBSRC should consider further actions.

Communication

14. **Community engagement/development:** BBSRC should engage with the wheat community following publication of the strategy, and at regular intervals thereafter, to facilitate community self-analysis in response.

    This could possibly occur via a regular wheat workshop with appropriate BBSRC engagement, perhaps as an additional output of a pre-existing network mechanism such as the WISP meeting which already takes in much of the academic community. However, these interactions should also draw in industry and policy makers (and others, potentially) to facilitate the translation of research and inform future research programmes. A regular strategic workshop event would serve, in particular, as an effective mechanism to draw in and inform researchers moving into the area. The wheat Portal will also serve as an effective mechanism for information exchange, and acknowledge BBSRC's current leadership in this project.

15. **Research impact showcasing:** BBSRC should seek to develop appropriate communication routes for demonstrating the importance of the long-term investments required to underpin strategic impacts.

    There is a need to better showcase the impact of past and present wheat research to users, policy makers and the wider public. This should include developing and promoting flagship case studies and associated impact metrics.