Science and Public Policy Advance Access published March 11, 2014

Science and Public Policy (2014) pp. 1–15 doi:10.1093/scipol/scu004

Twenty five years of private wheat breeding in the UK: Lessons for other countries

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Crop research sectors in many countries are facing reduced public support with public breeding programs being gradually replaced by private ones. This paper explores the UK experience with the privatization of wheat breeding that began in 1987. The analysis presented in this paper is based on interviews with sixteen experts currently involved in wheat research breeding in the UK. Taking a snapshot of UK wheat research today, it would be easy to conclude that the UK sector made a smooth transition from public to private breeding. However, this is not the case. The UK faced many challenges in establishing an integrated wheat innovation system and has only recently developed policies and funding processes that have enabled upstream public scientists to work with private wheat breeding industry. As policy makers around the world contemplate the privatization of crop breeding, important lessons can be drawn from the UK crop research funding model.

Keywords: crop research and breeding; privatization; wheat innovation.

1. Introduction

The food crisis of 2007 and the higher grain prices that have since prevailed have renewed both private and public interest in agricultural research. Despite persistently high estimates of rates of return to agricultural R&D and the compelling evidence of the significant contribution of R&D to increases in farm productivity (Alston et al. 2000, 2011), most developed countries have reduced the intensity of crop research and breeding since 1990 (Alston et al. 2010). While some crops with strong property rights, such as maize and canola, have witnessed increased private investment to replace public funds, most crops have not. Given the budgetary pressures that most countries currently face it is unlikely that government support of agricultural R&D will be as generous as it was a half a century ago. Given this prognosis, there is a need to design an innovation system with sufficient research investment to sustain a more optimal pace of innovation.

The privatization of wheat breeding is increasingly viewed as a means to increase breeding activity. In the USA several land grant universities[1] have announced wheat-breeding partnerships with private multinational firms. In Canada, Bayer Crop Science has recently initiated a wheat-breeding programme in Western Canada. Agriculture and Agri-Food Canada, which currently operates Canada's largest wheat-breeding programme, has indicated its intention to privatize its commercial breeding activities (Jones 2012). Australia has privatized its wheat-breeding industry over the past decade and has attracted investment from many global crop research firms.

While the privatization of public crop breeding is a means to increase total research investment, it can also induce significant changes in knowledge sharing, research linkages, research networks, research practices, and research outcomes. It is therefore important to fully understand these broader implications of the privatization of crop breeding. Some of this understanding can come from examining the experience of other countries where privatization of breeding has already taken place.

The UK is an example of a country that has restructured its crop research funding by privatizing commercial wheat breeding. It has been 25 years since the UK government sold the Plant Breeding Institute (PBI) to Unilever in 1987. About a decade after privatization there were a number of studies that examined the UK agricultural research system reaching somewhat different conclusions. Pray (1996) suggested that, 'while it was still too early to tell', the privatization appeared to be successful in attracting additional research funds in the sector. McGuire (1997) expressed more concern suggesting that:

> ...in the UK, the declining public support for basic research and germplasm enhancement has proven to be a major constraint in the pursuit of new lines of work.

Thirtle et al. (1998) showed that the declining research output was predictably linked to declining investment in basic and applied research. Now that 25 years have elapsed, it is time to update these studies by observing the longer-term consequences of privatization such as industry structure, investment patterns, pricing behaviour, and see how public policies have been modified and adapted to support the private breeding sector. Given this path of development the UK provides an excellent case study for other countries contemplating a similar move.

The objective of this study is to examine the development of the wheat innovation system in the UK subsequent to the privatization of wheat breeding. The lessons that we draw from UK experience can guide future policy initiatives for countries where privatization of crop research is being contemplated. To the extent that properties of knowledge as either public or private good have similarities across sectors, this paper identifies some of the new incentives and challenges that can more generally emanate from the privatization of a public applied research programme.

The analysis presented in this paper is based on public information and personal interviews conducted in July of 2012 with 16 experts involved in wheat research/breeding in the UK. The interviews employed an open-ended question structure allowing the participants to describe the system as well as discuss in detail the perceived advantages and disadvantages of the UK crop research funding model. The interviews reflected viewpoints of both public researchers and private breeders including wheat scientists from the University of Bristol, John Innes Centre (JIC), Rothamsted Research, and National Institute of Agricultural Botany (NIAB); wheat breeders from Limagrain UK, KWS UK, DSV, Saaten Union UK, and Syngenta; and experts from the British Society of Plant Breeders (BSPB).

Section 2 provides a brief overview of the changes that have occurred in the UK crop breeding sector in the last 25 years. Section 3 reviews the theoretical literature on the microeconomic and macroeconomic effects of privatization. Section 4 discusses the research method employed in this study. The validity of theoretical predictions about the impact of privatization is empirically tested in Section 5. Finally, Section 6 draws some conclusions that identify potential challenges for other countries embarking on a journey of privatization.

2. Transition to privately funded crop breeding in the UK: Historical perspectives

The late 1980s marked a new era in the development of the UK crop breeding industry. In this section we provide some historical context and a brief overview of the changes that took place within the UK wheat-breeding sector. We also discuss the key changes in market and policy environments that contributed to the development of the private wheat-breeding sector in the UK.

2.1 Privatization of wheat breeding in the UK

The PBI held a dominant position in the history of the UK wheat research/breeding industry for 75 years. PBI was established at Cambridge in 1912 as part of the Department of Agriculture. In the early years, PBI's work mainly involved the development of improved wheat varieties with an emphasis on grain quality. Prior to the Second World War, PBI held about 25% of the winter wheat market (Thirtle et al. 1998). During and following the war PBI's market share had fallen to zero as foreign-bred wheat varieties dominated UK winter wheat. After the Second World War it became a national priority to increase food production and research was considered an essential means to this end. As a result, in the post-war years funding to agricultural research centres in the UK was increased substantially and the breeding work at PBI was expanded to include barley, peas, maize, oilseed rape, and others. The increased investment paid off. The PBI made a significant contribution to the UK wheat research and breeding industry and helped the UK become a global wheat research leader.

The returns on PBI research were very high. Thirtle et al. (1998) estimated a 50% annual social rate of return to wheat breeding at PBI. Pray (1996) estimated that by 1986 the royalties generated from the commercialization of PBI varieties were sufficient to pay for all PBI breeding and pre-breeding research and still generate a surplus of 23%. So not only were the breeding activities creating a social benefit, they were being paid for by the downstream users at no direct cost to the taxpayer. The fact that the PBI was self-financing is an important fact indicating that it did not have a soft budget constraint, which is assumed to give rise to inefficiencies in public enterprises.

Despite the PBI's apparent success, the Thatcher government felt that it was not the government's role to be closely involved in variety development. In 1985 the

Agricultural and Food Research Council proposed a policy that would re-organise British research institutes. The privatization of the PBI crop breeding programmes was one of the pillars of the proposed policy. In 1987, the PBI's breeding programmes and farm sites were sold to Unilever, a private food company. The units undertaking basic research were excluded from the sale and were later transferred to the JIC in Norwich. The commercial portion of PBI acquired by Unilever became known as Plant Breeding International Cambridge (PBIC), a 'private' breeding organisation. This sale effectively ended public commercial wheat breeding in the UK.

Prior to the privatization, a private wheat sector had existed in the UK for many decades. From the 1920s to 1950s, UK private firms had the largest share in UK winter wheat variety sales, only to be dominated by foreign variety sales during the 1950s and 1960s and by PBI varieties during the 1970s, 1980s and 1990s (Thirtle et al. 1998). A small wheat-breeding industry had co-existed with PBI after the introduction of Plant Breeders' Rights (PBRs) in 1964. Because the PBI was large, well-funded, and very effective, private companies found it very difficult to compete with it. During the latter years of the PBI, each firm only had 3–4% market share while the PBI held about 80% of the market.

McGuire (1997) notes that in 1994 PBIC still had a 59% market share of the winter wheat seed market. In 1998, the PBIC was sold to Monsanto, which was interested in wheat as a crop with a high potential for the application of genetic engineering techniques and development of hybrids. Strong consumer resistance towards genetically modified (GM) wheat and failed attempts to produce commercially viable hybrid wheat contributed to the loss of interest in wheat. Monsanto gradually withdrew its resources from wheat research/breeding and sold the breeding unit to RAGT Seeds Ltd in 2004.

Currently, wheat-breeding programmes in the UK reside with Limagrain UK Ltd., KWS UK Ltd., RAGT UK Ltd., and Syngenta UK Ltd. with the largest breeding programmes being in the range of £1.5 million per annum. There are also a few smaller private companies involved in wheat breeding and these include DSV (Deutsche Saatveredelung AG) UK Ltd. and Saaten Union UK Ltd. As shown in Fig. 1, in the period 2000–11 KWS UK Ltd has released the most varieties in the UK, while, based on the Home Grown Cereal Association (HGCA) recommended varieties lists, RAGT was the breeder for less than 12% of recommended winter wheat varieties over the past three years. Thus, the remnants of PBI have only retained a minor market share of UK wheat varieties.

The establishment and subsequent development of the private breeding industry in the UK was affected by a number of factors, including: global changes in crop variety development, strengthening of plant intellectual property rights (IPR) globally and in the UK in particular, and changes in the policy environment.

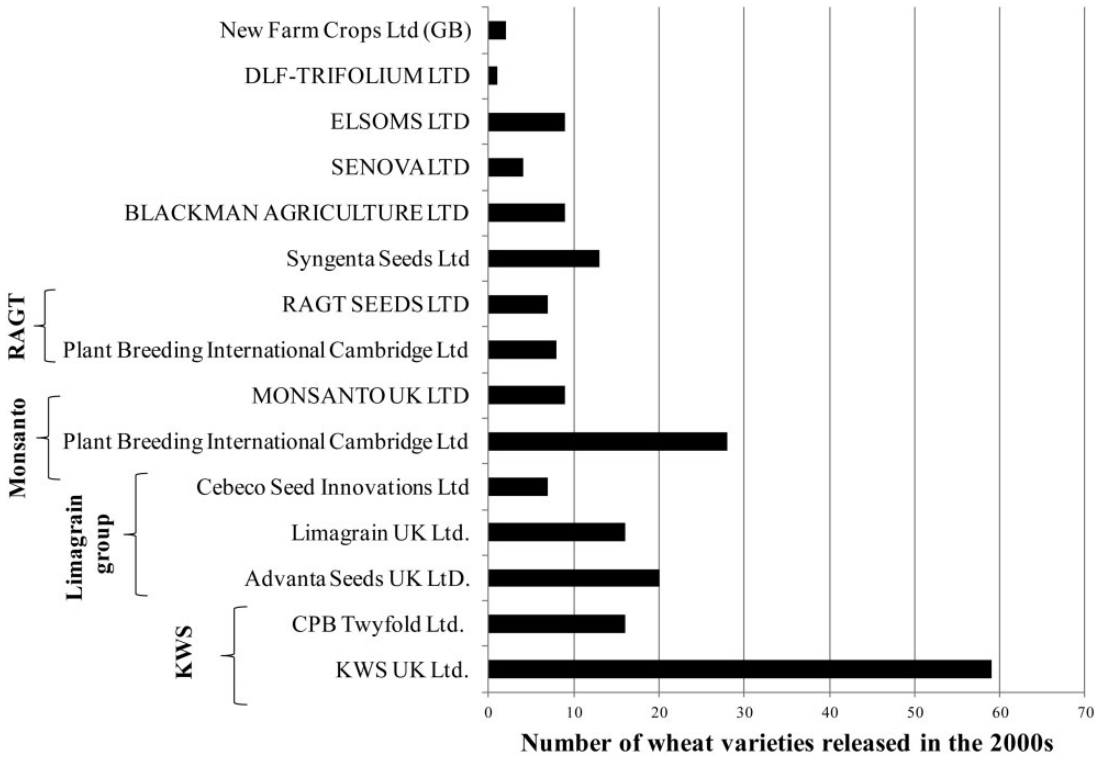

Figure 1. Number of varieties released in UK by breeding companies 2000–11.
Source: Compiled by the authors from the UPOV Variety Database.

2.2. Factors that affected transition to privately funded wheat breeding

2.2.1. Global changes in crop variety development. For most of the twentieth century, crop research and crop breeding were public activities with very little private investment. The exception to this general tendency existed in horticultural crops where seed production and/or vegetative reproduction was somewhat difficult and became a specialized business activity. The first major crop to experience privatization internationally was hybrid maize, which developed a private industry in the USA during the 1950s. A more significant privatization occurred during the 1980s when transgenic GM technologies were developed, which created an influx of private investment from large multinational firms from the pesticide industry. This investment was sustained and increased in those crops that received regulatory approval for GM production.[2] For wheat, following the initial influx of private investment, private investment from large multinational companies waned, and programmes were shut down as GM wheat failed to receive approval in any major market.

In Western Europe, private investment in wheat was sustained due to the presence of many small- and medium-sized family owned, national, and international breeding firms. Limited investment in wheat by large multinational companies provided excellent opportunities for the development of smaller European breeding companies that expanded their activities on the UK market following the privatization. The international nature of the private breeding firms in the UK facilitated the establishment of the private breeding industry as the firms could amalgamate their research and breeding efforts across Europe, thus lowering the costs of breeding new varieties for the UK market.

In the 2000s, due to advances in genetic marker systems and genetic mapping approaches, wheat once again experienced an influx of private investment. The use of genetic marker systems in commercial plant breeding has been revolutionized by the availability of single nucleotide polymorphism (SNP) based marker systems. SNP markers are effectively used to identify the presence of the specific gene, thus greatly speeding up the process of genetic selection. The costs of marker assisted selection (MAS) have decreased rapidly: a single informative marker analysis now costs less than US$1, while a genome-wide analysis (DNA chip) costs approximately the same as a yield trial plot. Routine screening of thousands of lines in a breeding programme with informative markers has therefore become affordable and cost effective. This exciting technical development has renewed the interest in wheat breeding by medium and large life science companies who can now combine their international collection of germplasm with the growing libraries of gene markers, to accelerate breeding and effectively compete with established breeding programmes. Given their capital requirements MAS technologies also tend to extend the economies of size in breeding.

2.2.2. Strengthening of plant intellectual property regime. To protect plant intellectual property (IP), almost all countries in the world have now adopted the system of PBRs based on the principles of the International Union for the Protection of New Varieties of Plants (UPOV). To adjust to market conditions and strengthen IPR in plant breeding, UPOV was revised a number of times, with the most recent revision in 1991. This latest revision no longer grants farmers automatic rights to save seed.

In 1994, the EU passed legislation to become compliant with UPOV-91, thus entitling breeders to charge a royalty on farm saved seed (FSS) as long as it is sensibly lower than the royalty on certified seed. Following the implementation of the EU legislation, a significant change in plant IP rights in the UK was brought about by the 1997 Plant Variety Act. The Act provided for an agreement between a breeders' association and a farmers' association to set a royalty rate for FSS. Using this provision, the BSPB negotiated a contractual arrangement with the National Farmers' Union (NFU) setting a uniform royalty rate on FSS equal to 52.5% of the weighted average royalty rate on certified seed grown one year before. Although it has taken many years for the system to become fully functional, the royalty collection system has a high compliance rate with very low costs. Overall, the system gives the UK breeders the ability to collect royalties on virtually all certified seed and about 90% of FSS.

2.2.3. Public provision of upstream research. The public provision of upstream research to support the private wheat-breeding sector has varied considerably since the sale of PBI and subsequent relocation of the public scientists to other institutions. Soon after privatization, as discussed below, the linkage between upstream and applied research was broken, which significantly undermined the ability of the private sector to develop successfully. This situation, where public scientists did very little research that applied to wheat, persisted for nearly 15 years, when Department for Environment and Rural Affairs (DEFRA) introduced a number of funding initiatives deliberately designed to encourage public researchers to do research relevant to the private wheat breeders.

Over the past decade, the public sector has made progress in developing funding mechanisms that provide incentive for public scientists to undertake a portfolio of research that has long-term commercial value for the industry. The LINK programme funded by DEFRA was one of the first initiatives to bridge the gap between public scientists and private breeders. In 2003 DEFRA launched

an initiative called the Wheat Genetic Improvement Network (WGIN). Meetings are organised every four months and are attended by researchers, breeders, and sponsors of wheat research including representatives of the Biotechnology and Biological Sciences Research Council (BBSRC), the HGCA, and wheat-breeding firms. By including a good cross-section of the wheat sector the WGIN can incorporate feedback right through the genetics to farming. The WGIN has been a rapid catalyst for getting breeders and academic people in the same room to talk about their common problems. After the review of a five-year WGIN initiative it was decided that the government support to WGIN had to be continued and funding was extended until 2013 to the amount of almost £1.7 million over a five-year period. The UK government is now looking into WGIN-3.

Although, somewhat late to join the game, the BBSRC is now sponsoring programmes designed to have public scientists work in consortia of wheat-breeding firms. The *Crop Improvement Research Clubs* (CIRC) is a £7 million five-year programme established in 2010. For every hundred thousand pounds raised by industry the BBSRC contributes nine hundred thousand to the 'Club' made up of the Scottish Government, and a consortium of 14 leading biotechnology, grain, and oilseed companies.

In February 2011 BBSRC also announced funding for a another consortium of researchers to increase the diversity of traits available in wheat via a comprehensive pre-breeding programme in an initiative known as Long and Large (LOLA)/Wheat Improvement Strategic Programme (WISP). With a second tranche announced in 2012, the six-year project has total funding of £16 million. LOLA/WISP pre-breeding consortium includes public scientists, NIAB, JIC, Rothamsted Research, University of Bristol, University of Nottingham, and the private breeders who sit on the advisory board. The goal of the pre-breeding programme is to have public researchers involved in the development of novel germplasm that can then be introduced by the private breeders into their elite lines. Germplasm developed in the pre-breeding programme is publicly available and is free of IP.

The LOLA/WISP pre-breeding programme has three core germplasm development activities. The first core activity of the pre-breeding programme involves the use of landraces from the Watkins collection held at the JIC. The main goal of this activity is to increase diversity. The second core activity is an alien introgression programme established at the University of Nottingham. The target traits in the programme are: yield, nitrogen utilization, phosphorus utilization, blowfly resistance, and aphid resistance. The third core activity is a synthetics wheat programme, where wheat is recreated from its progenetive species and then genotyped and sequenced to mine out novel genes. This work on synthetic wheat should provide a lot of information to the commercial sector about the adaptation of material and its usefulness. The UK Limagrain, KWS, and RAGT firms have formed a consortium to fund follow-on pre-breeding activities where the NIAB incorporates the results of the preliminary breeding work into the companies' breeding programmes by back-crossing synthetic wheats into elite germplasm. The germplasm developed in this follow-on pre-breeding programme is proprietary and is kept within the boundaries of the consortium of the three companies. This germplasm has to be released into the public domain eventually because the work is built upon a publicly funded synthetic wheat programme. However, the companies are given a number of years to capitalize on that novel germplasm before it is made publicly available.

In addition to funding for collaborative research it is important to note that the public funds are provided for centres of wheat research including two universities (the University of Bristol and the University of Nottingham), and two research institutes (Rothamsted Research Limited (at Harpenden)) and JIC (at Norwich)). The research institutions are funded primarily by the government (BBSRC and DEFRA) with a very small proportion of research funding coming from the private sector either in cash or in-kind, farmer organisation HGCA, and the EU. BBSRC funds about £14 (US$23) million worth of wheat projects annually. It supplies about half of the institutes' funding through five-year programmes called Institute Strategic Programme (ISP) grants and these grants form the core funding for the institutes. The institutes also compete with the universities for BBSRC's Responsive Mode grants that comprise about 20% of the institutes' funding. Responsive Mode grants are very competitive but they provide an opportunity for researchers to work on some aspects of research that are of particular interest to them. DEFRA used to be an important player in funding wheat research but has moved away from it in recent years. For example, the share of DEFRA funding in the Rothamsted Research's total funding decreased from 50% in the mid-1970s to about 10% currently. Overall, DEFRA funding currently amounts to about £2.4 million annually.

3. Public versus private ownership: Theoretical considerations

The literature on the effects of private ownership on the allocative and internal efficiency of enterprises is relatively rich and diverse. The theoretical literature discussing the microeconomic impact of privatization attempts to explain differences in performance between public and private enterprises from various perspectives including: the property rights perspective (de Alessi 1980; French 1985; Vickers and Yarrow 1988; Boardman and Vining 1989), the managerial perspective (Laffont and Tirole 1991; Stiglitz 1991; Sheshinski and Lopez-Calva 2003), the innovation

incentives perspective (Sappington and Stiglitz 1987; Schleifer 1998), and the political perspective (Schmidt 1990; Willig 1994; Boycko et al. 1996; Shleifer 1998).

Property rights have been claimed to be important in explaining differences in performance of public versus private enterprises and the use of resources in terms of both allocative and productive efficiency of firms (Vickers and Yarrow 1988). In public enterprises managers are removed from ownership and do not have rights to the wealth of the firm. Therefore, the property rights theory of the firm suggests that public enterprises should perform less efficiently and less profitably than private ones. De Alessi (1980) postulates that non-transferable ownership in a case of a public enterprise:

> ... rules out specialization in their ownership, inhibiting the capitalization of future value consequences into current transfer prices and reducing the incentive of those who bear such consequences to monitor managerial behaviour.

As a result, managers of firms with attenuated property rights (public firms) generally display more discretionary behaviour and choose to increase their consumption of non-pecuniary goods at the expense of firm wealth, thus lowering the productive efficiency of the firm (De Alessi 1980; French 1985). Empirical studies on the linkages between ownership and efficiency yield mixed results. Boardman and Vining (1989) survey the empirical studies highlighting the fact that they do not unanimously support the theoretical prediction of inefficiency of public enterprises. Using a set of the 500 largest manufacturing and mining corporations in the world outside the USA and taking profitability as a measure of X-efficiency, Boardman and Vining (1989) find robust evidence that state and mixed enterprises are less profitable and less efficient than private corporations.

Theory suggests that changes in ownership structure influence firms' behaviour by altering managerial incentives. Managers in public organisations are not under pressures from the shareholders to perform efficiently. Incorrect investment decisions and consequent losses in public enterprises are not penalized as harshly as in private ones, where economic losses can lead to bankruptcy. Governments are unable to make certain commitments, in particular, the commitment to competition and the commitment not to subsidize (Stiglitz 1991). As a result, the bankruptcy of a public enterprise is not credible because governments will always choose to provide a subsidy thus spreading the cost resulting from inefficient management across a dispersed group of taxpayers rather than close the firm and face strong political opposition by well-organised, publicly visible groups like unions (Sheshinski and Lopez-Calva 2003). Soft budget constraints translate into the softening of managerial incentives, thus giving rise to the moral hazard problem: increased incentives to undertake undue risk, to maximize returns in the non-bankruptcy states at the expense of returns in the bankruptcy state (Stiglitz 1991). Privatization can be viewed as a way to enhance the commitment of the government to harden the budget constraint.

The political perspective literature acknowledges that government enterprises are managed to achieve a variety of political objectives, while private enterprises are largely managed to earn profits, and therefore the latter are more cost-efficient and responsive to market changes. Schmidt (1990) argues that privatization reduces the amount of information available to a politician to intervene and make decisions, thus leading to the reduction in subsidies. When theoretically comparing the incentives of managers at public enterprises and regulated private enterprises, Willig (1994) asserts that it is information rents that drive the differences between the two. He shows that privatization insulates an enterprise from political influences that lead to inefficiency and the efficiency gains from privatization stem from the fact that state-owned enterprises are subject to politicized directives while private enterprises enjoy a degree of insulation (Willig 1994).

The political argument for privatization presented by Boycko et al. (1996) assumes that the amount of information available to the politician is unchanged with privatization. The key element that distinguishes public versus private ownership in their paper is spending on labour, given that one of the key objectives of politicians is employment. The authors show theoretically that privatization increases the transaction costs associated with a desire of the politician to resist restructuring and maintain excess labour in a private firm. Foregone profits in a public enterprise due to excess labour are less costly to the politician than subsidies to be paid to the privatized firm to convince the profit-maximizing firm to use its profits for excess labour spending (Boycko et al. 1996; Sappington and Stiglitz 1987). As a result, privatization is likely to induce restructuring and, therefore, yield efficiency gains.

When privatization is discussed in the context of a world of incomplete contracting and asymmetric information, the theoretical literature suggests that, due to unforeseen contingencies that cannot be specified *ex-ante* and asymmetric information, one cannot predict with certainty the effect of privatization on efficiency (Laffont and Tirole 1991; Schmidt 1996). On the one hand, privatization induces the manager to place greater weight on profit goals, thus enhancing productive efficiency of the enterprise. On the other hand, asymmetric information causes a distortion in the allocative efficiency of the privatized firm (Schmidt 1996).

While the existing theoretical literature generally favours privatization, it has been recognized in the literature that public ownership may have advantages over free markets in internalizing externalities, coordination in the presence of the failure of pricing mechanisms and in dealing with market failures in general (Sappington and Stiglitz 1987; Stiglitz 1991). The R&D industry in general, and crop research and breeding in particular, are prone to market

failures. When unprotected by IPR, the knowledge embodied in a seed for a new variety shares the non-excludable and non-rival characteristics of public good (Gray 2012). When farmers are free to replant the harvested material, the knowledge is non-price excludable, making it difficult for private firms to capture a return from breeding investment. The knowledge is also non-rival, because once created a variety can be reproduced and used over and over again without exhaustion. These characteristics are the source of market failure and are at the root of public involvement in crop research.

The implications of non-excludability are well understood. When a good is not price excludable, benefits can spillover to users without payment leaving private firms without incentive to produce the goods (Alston 2002). A system of well-defined IPR is required to create incentives for private investment.

The implications of the non-rival characteristic are also important but arguably less understood. Once knowledge is created, it is non-rival in use because it can be used again and again without exhaustion (Gray 2012). Years of breeding and testing efforts go into the development of a new variety. Once the new variety is created, these large costs are sunk and become a fixed cost. The marginal cost of applying this new embodied knowledge on more acres is very low and approximates zero once the variety reaches commercial production. Given the large fixed costs and low marginal cost, the breeding firm has significant economies of size in the production of a variety. These size economies are further enhanced by firm-specific knowledge, complementary assets and capital, which are employed in the creation of subsequent or multiple varieties.

These toll good related size economies create conditions for a natural monopoly where one firm has a significant cost advantage over multiple firms, creating strong incentives for the creation of a concentrated breeding industry (Fulton 1997; Lesser 1998). A possibility of exploitation of monopoly power in 'natural monopoly' sectors is at the core of the argument in favour of public ownership (Shleifer 1998).

Public ownership can also have advantages when markets are not well defined. This currently applies to the development of varieties with improved N-use efficiency, P-use efficiency, and water-use efficiency to adapt to or mitigate the impacts of climate change. In the absence of defined markets, private companies lack incentives to deliver sustainable varieties, which necessitates the involvement of the government. In France, for example, the absence of defined markets is at the core of the activities of the Institut National de la Recherche Agronomique (INRA) in developing crop varieties for organic agriculture. The formal analysis of agency problems and incomplete contracts, however, suggests that inefficiency costs associated with public ownership can in many cases outweigh the gains from solving a market failure problem (Sheshinski and Lopez-Calva 2003).

The literature on the macroeconomic effects of privatization is not as rich as that on microeconomics ones. Mansoor (1987) suggests that the budgetary impact of privatization will be positive if it entails efficiency gains. Efficiency gains, and as a result, higher profits for firms will lead to higher revenue for the budget. In addition, reduction in government transfers (subsidies) following privatization should improve the financial health of the public sector (Davis et al. 2000). The macroeconomic impact of privatization is, however, not straightforward. The private sector is generally more risk averse than the public sector, meaning that it will be willing to pay less than their net worth for the assets, thus leading to a tightening of the government's intertemporal budget constraint (Mackenzie 1997).

The insights from theoretical literature on the microeconomic and macroeconomic effects of ownership structure leads to a number of hypotheses that can be empirically explored in the privatization of UK plant breeding. Economic theory suggests that privatization creates a well-defined impetus towards profit maximization and thereby increases the incentives for management and employees to employ limited resources efficiently. The literature also suggests that public ownership has some advantages over private ownership in markets characterized by spillovers, natural monopolies and other market failures. The following hypotheses can be formulated:

H1: Privatization creates more competitive environment and, therefore, the industry's output will increase.
H2: Privatization improves allocative efficiency.
H3: The privatized industry will generate more profits and increase investment.
H4: A Private industry will be less able to exploit economies of size and will lead to duplication of effort.
H5: Privatization will lead to a reduction in subsidies in an industry.

Using publicly available quantitative data and a qualitative research method discussed in Section 4 we will attempt to assess the empirical validity of these hypotheses for the UK crop breeding industry in Section 5.

4. Research methodology

For our analysis, we consider publicly observable outcomes such as: yield improvement, industry structure, royalty income, industry investment, and public policy interventions. The analysis also heavily relies on qualitative data gathered through personal interviews. The advantage of using a qualitative research method is that it gives us flexibility and freedom to explore a phenomenon in-depth (Strauss and Corbin 1990). This approach is especially relevant to our research as the impacts of privatization go well beyond observable changes such as

increased profitability. Privatization of crop research also changes the way different players interact, which has short- and long-term impacts on industry performance and output. Therefore, the full impact of privatization is too broad, complex and unstructured for quantitative study alone.[3] Soliciting the perception of experts intimately involved in the industry provides informed insight into the consequences of privatization.

The experts interviewed for this study were identified through a process that began with the web of science, which was followed by a snowball sampling: email requests for additional contacts and advice from interviewees. This process enabled us to interview 16 experts who represented wheat scientists from the University of Bristol, JIC, Rothamsted Research, and NIAB; wheat breeders from Limagrain UK, KWS UK, DSV, Saaten Union UK, and Syngenta; and experts from the BSPB. This approach not only encompassed almost all of the experts engaged in wheat research/breeding in the UK, but all of the participants had worked in the industry prior to the privatization and were therefore well positioned to comment on the changes that the privatization brought.

The interviews were all conducted during July 2012. The interview process was in full compliance with the requirements of the Ethics Boards of the University of Saskatchewan and the University of Regina. The interviews were semi-structured and generally required 60–120 minutes to complete. The questionnaire (provided in the Appendix) was sent to participants in advance so that the interviewees could respond rather than react to the questions. Whenever a response to an interview question introduced a phenomenon, concept, or aspect of the UK system that required further elaboration, additional unstructured questions were used to elicit additional explanation in an effort to obtain a more complete understanding.

The interview data were analysed using Attride-Stirling's thematic network analysis (Attride-Stirling 2001) that starts with the identification of key themes arising from qualitative data followed by the exploration of the text within each theme.

5. The economic outcomes of privatization: Empirical evidence

Taking a snapshot of the UK wheat research/breeding industry today, it would be easy to conclude that the UK sector made a smooth transition from public to private breeding, and operates a small, integrated, more efficient wheat innovation system. However, some of the expected outcomes of privatization, as hypothesized above, have never been realized while some took years to be realized. Understanding the consequences of privatization can provide many important lessons and enrich the existing empirical literature on the impact of privatization.

5.1. Output of the privatized wheat-breeding industry

The first hypothesis derived from the theoretical literature is that privatization will generally increase the industry's output. In the context of a breeding industry, output would be best measured by the amount of downstream benefit created. From the social point of view, new varieties that increase yield, increase quality, and/or reduce input use create value for farmers, and these characteristics should therefore be used to reflect the output of the breeding industry.

There is no indication that new varieties have reduced input use or significantly increased wheat quality. The disease resistance of new varieties is difficult to measure if farmers are not exposed to disease outbreaks. As the interviewees indicated, the UK has not faced severe disease outbreaks in the last decade. Thus, there has not been enough opportunity to observe if the presence of the private sector has improved the quality of cultivars with respect to their ability to resist diseases. As for the quality of new wheat cultivars, most of the participants echoed the concerns that, with the privatization, breeding for quality ceased to be the goal of the breeding industry: the breeders' main target is yield. The following quote supports this:

> Big gap in research is quality. . . . There is a danger that we are going to make big piles of grain that no one wants to eat; also we are going to miss big opportunities because the first grade molecular marker for wheat was a quality marker so you could screen early on in the generations before you could ever do quality tests and make some great predictions. So again I feel it is a missed opportunity. . . . I think the quality is ignored as a trait because it is very intangible.

Lack of research on quality can be analysed from the incomplete contracting perspective. Schleifer (1998) states that privatization is good because it creates stronger incentives to introduce innovations—both to reduce costs and to improve quality. He also mentions that in some cases, however:

> . . . cost reductions for which private suppliers have stronger incentives have potentially deleterious effects on the non-contractible quality.[4]

So, in some cases the incentives for private firms to reduce costs may lead to inefficient outcome. In situations like this, a public enterprise sometimes becomes an efficient producer precisely because its employees are not motivated to find ways to hold costs down (Schleifer 1998). Research on, and breeding for, quality seems to fall under this situation. Breeding for quality is more costly than breeding for yield because quality is not such an obvious characteristic as yield. Therefore, the importance of quality is usually underestimated by farmers, thus reducing demand for

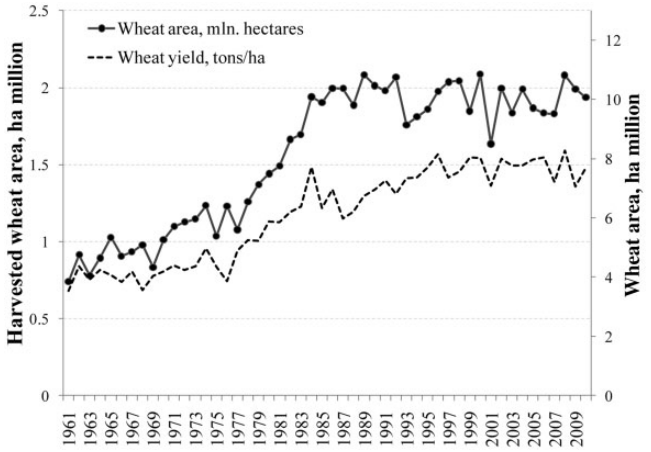

Figure 2. UK wheat yields and area 1961–2009.
Source: FAO agricultural statistics.

seeds of higher quality but lower yields. Therefore, in search of ways to reduce breeding costs, firms fail to make efficient investment into quality-related research and breeding, while public breeding could potentially correct for this failure.

From the farmers' perspective, the genetic yield gain of new varieties is probably the most important measure of output of the breeding industry.[5] Fig. 2 shows UK wheat yields in the period 1961–2009. After two decades of rapid growth wheat yields levelled off beginning in the late 1990s and have been very flat since. While this levelling-off occurred post UK privatization, the same phenomena also occurred in France and Germany. A study by Knight et al. (2012) suggests that several factors including climate changes, compressed crop rotations, shallower cultivation, decreased inputs due to environmental regulations, and a slowdown in genetic improvement as well as unknown factors, have contributed to this yield plateau. In an effort to control for possible adverse effects of environmental change, a notable study by Clark et al. (2012) grew 64 varieties in side-by-side tests to control for environmental effects. They found that there was no evidence of a decrease in the rate of yield gain, but they did not find any evidence of an increase in the rate of yield gain. Despite the range of theories, governments in each of these countries are now investing heavily in genomic pre-breeding projects designed to introduce germplasm with novel traits into wheat germplasm. This longer-term development activity had been part of PBI's success prior to the privatization. While it is difficult to determine the extent that changes to wheat breeding caused the yield slowdown, it is clear that the privatization of breeding and the associated changes in pre-breeding research brought many changes that collectively could have contributed to a slowdown in genetic improvement,

Given the long lags involved in variety development it is too early to determine whether the more recent reconfiguration of the wheat sector will lead to future increases in output. One of the most recent developments in the UK wheat industry is the discovery of new wheat lines that could potentially increase wheat yields by 30%. The work on these lines started in 2006 and has been conducted at NIAB in collaboration with Limagrain, KWS, and RAGT. It should be noted that this discovery is very unlikely to have happened had there not been research and pre-breeding support from the public sector (BBSRC funding).[6] BBSRC is supporting the follow-on research, which specifically targets promising leads and provides the cash to take the discovered lines closer to commercial exploitation. The three breeding companies mentioned above are embedded in this follow-on project with public support playing a crucial role in this potentially groundbreaking endeavour.

5.2. Changes in allocative efficiency

Theory suggests privatization should increase allocative efficiency within a firm. There is some evidence to support this hypothesis. Many of the interviewees commented on how lean and efficient the private breeding programmes were. This observation is consistent with the limited resources available to each breeding firm. The total UK royalty revenue of £17 million with the reinvestment rate of 30% as indicated by the interviewees leaves around £1 million per wheat-breeding programme, which is very small by industry standards. So, the evidence would support the hypothesis that privatization increased allocative efficiency.

Private firms, however, are often focused on short-term profit-making and invest a suboptimal amount in activities that may generate long-term rewards for shareholders. In the case of PBI they recognized that variety development required a balance of investment between long-term research and shorter-term breeding activities. In the case of UK private wheat-breeding firms, most firms indicated that with their limited budgets they focused nearly all of their efforts on breeding activities and were not in a position to invest in long-term research. In the absence of public support there is no evidence that the private firms would invest in pre-breeding research despite the potential for very high returns. More recently, it was only as the public sector heavily subsidized the cost of these activities that firms were able to make modest investments in the research as part of the consortia.

5.3. Profitability of the privatized breeding sector

Privatization is often seen a vehicle that will generate sales revenue that will allow the private firms to make the investments required by the sector, which a budget constrained public sector is unable to make. Despite the well-defined PBRs and the effectiveness of the UK royalty collection system, total royalty revenue remains very modest in the UK. The 2010/11 total royalty

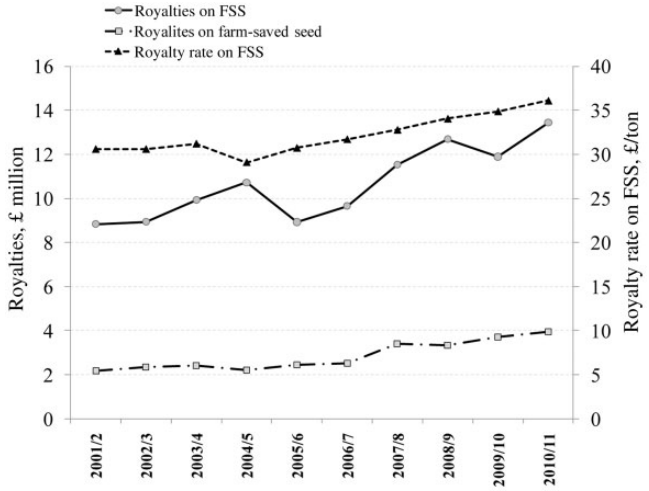

Figure 3. Wheat royalties in the UK 2001–11.
Source: British Society of Plant Breeders.

income of £17 million is about £1 per ton produced or 0.5% of gross sales. As a point of comparison, Gray (2012) estimates the Canadian hybrid canola seed sales generate CAN $578 million or £371 million in rents for breeders in a similar sized industry. As shown in Fig. 3, as new better varieties have been adopted over time, UK royalty rates have slowly increased. FSS royalty rate was £36.1 per ton of seed in 2011, which is equivalent to £0.56 per ton of harvested grain. Because these FSS royalty rates are 52.5% of the weighted average certified seed royalty in the previous year, this implies a 2010 weighted average royalty was £68 per ton. While these royalty rates have increased over time one has to also keep in mind that wheat prices have approximately doubled since 2006: a further indication of a royalty system that does not generate significant revenue relative to the gross sales of wheat.

From an economic perspective any wedge between what a farmer is willing to pay for varieties and the benefits they receive from those varieties will limit the ability to generate revenue for private breeding. The ability of farmers to plant last year's varieties as a FSS, while paying only 52.5% of the average royalty rate, severely constrains what any firm can charge for seed royalty on a new variety. As a result, new seed royalties must be conservatively priced in order to capture some market share. In turn, next year 52.5% of these conservative seed royalty rates are reflected in the FSS rate, thus perpetuating the underpricing. The private sector also views a 52.5% royalty rate on FSS as an element creating some underinvestment in the system and this is supported by a quote from one private wheat breeder:

> The one factor I think which actually interferes with the function of the free market is the situation with farm saved seed. I think the European regulation where farmers can go with farm saved seed and pay half the royalties, saying it is inequity is probably the wrong emphasis but I think it's an artificial subsidy in the system.

5.4. Knowledge fragmentation and duplication of effort

Theory suggests that the entry of multiple firms into a toll good industry, will reduce size economies, will tend to duplicate effort, and will fragment the use of knowledge. After the sale of the PBI the breeding industry fractured and is now made up of four small and two very small breeding firms. This resulted in several small firms duplicating research effort in order to compete in the small UK market. Given the small size of these breeding firms they have learned to cooperate in activities such as testing competitor lines and developed mechanisms to share knowledge and resources. This knowledge sharing has increased significantly in the subsidized public–private research consortia, allowing the industry to recapture some of the economies of scale.

5.5. Post-privatization public expenditure to support wheat innovation

One of the rationales often used for privatization is to improve public finance by reducing the demands on the public treasuries. It is not clear this has occurred in the case of UK wheat-breeding sector. With PBI wheat royalties were sufficient to pay for all PBI wheat-breeding activities with an additional 23% left over to pay for pre-breeding and other research. When PBI was sold the revenue stream was lost to the public sector in return for a £100 million cash payment. In the first 15 years following privatization, very few public resources were spent on wheat research but this could not be sustained for the reason discussed below.

The sale of PBI and subsequent relocation of some public scientists to other institutions were accompanied by a watershed in science funding and the combination had a devastating impact on public wheat research. As indicated by the interviewees, the BBSRC allocated funding to individuals and their institutions' programmes on the basis of the citation rates and the journal impact factors of their peer-reviewed publications. This diverted scientific effort away from applied wheat research towards more basic science on *Arabidopsis* and other model crops. The result was a disconnect between what the public researchers could obtain funding for and what the private wheat-breeding firms needed as input into their programmes . . . and the public researchers followed the money.

The physical separation of crop and plant scientists from the wheat breeders reduced the amount of pre-breeding research required to support the private breeding industry. Under the umbrella of PBI, wheat breeders and scientists all worked together to improve wheat varieties. The researchers understood the challenges faced by breeders and producers, while the breeders were exposed to new knowledge and theories that could improve their

practice. As outlined in more detail in Galushko and Gray (2012), several interviewees refer to the early period after privatization as 'lost years'. Both public and private researchers, although satisfied with the current system, felt that the UK system lost 15 years of progress, by fracturing an integrated research system.

> I think we probably lost 15 years of research to be honest. . . . With these various research integrations that are going on now, we pretty much got back to where we were 15 years ago I guess when those public breeding programs were privatized. And I don't think we've gained anything over that period of time. In fact as an industry generally, I think. I mean clearly some companies have probably gained but as an industry, in terms of genetic advance, genetic gain, I don't think we have.
>
> . . . from the heady days of PBI if you like, at that time Britain was leading, a world rank leader in research and development within crops and that has declined. I view Britain as very much just another country that would be involved; so when you go to the EU, when you're in a room with sixteen other institutes from across Europe, the context of Britain as the world leader is not there at all. So you might be thinking who in this room invests the most but I suppose it must be the Germans and French. Britain is very much outside; in some ways almost outside Europe in a sense, isolating itself. So I think Britain's standing as a research super power has diminished as a result of privatization and research capacity that we've lost.

To bridge the gap between basic and applied science and restore the research capacity of the wheat sector, the government had to substantially increase spending through the initiatives discussed in Section 2.

5.6. Other outcomes of privatization

Two other observed outcomes of privatization in the UK are a narrowing of genetic diversity and the reduced ability of the system to generate new scientists and breeders.

With the privatization of breeding and subsequent alienation of research institutes and universities from fieldwork, training of plant breeders has become an issue. The number of wheat scientists/breeders that the system has produced has decreased significantly. Currently, almost all of the wheat scientists and breeders are either approaching their retirement or will retire in 10 years or so. The system is not prepared to replace the retired scientists with a new generation scientists, which puts the whole wheat research industry in jeopardy.

Also, there is some evidence that the privatized UK wheat-breeding system initially narrowed the genetic diversity of UK wheat varieties. While PBI made its mark introducing and utilizing CIMMYT germplasm and introducing semi-dwarf wheat genetics into UK varieties, very little novel introgression happened since privatization. McGuire (1997) flagged this issue, arguing that most of the wheat varieties in the UK were coming from a very similar genetic base. It appears that the industry shares this view and is now willing to participate in the LOLA/WISP prebreeding activities with the objective of introducing novel germplasm into UK wheat varieties. Potentially significant advances will come through the synthetic derivatives developed by NIAB in collaboration with some of the UK plant breeding companies, some of which are derived from crosses with CIMMYT germplasm. Fulfilling this research need, however, requires substantial long-term public investment.

6. Conclusions: Challenges and future directions

At this point in time, the privatization of UK wheat breeding is, at best, a very qualified success. There is no evidence of an increase in industry output, total industry revenue and investment levels remain modest, and research and breeding activities are split between six small breeding programmes. After a 15-year gap in upstream research activities, heavily subsidized research consortia are sharing knowledge and undertaking long-term applied research with the potential to reinvigorate research output growth. This suggests that with enough public support and strong incentives for collaborative research, a modestly sized private research industry can operate effectively.

The UK experience highlights the challenges that can arise as a result of the privatization of crop breeding. The outcomes, policy changes, and responses that have occurred in the 25 years that have elapsed since the sale of PBI provide tangible examples of the outcomes from privatization of wheat research yielding lessons about measures that should be pursued and those actions that should not be repeated.

One challenge is to ensure that privatization does not lead to a fragmentation of research and breeding. One has to keep in mind that the open-pollinated nature of wheat can undermine the ability of the private sector to collect seed royalties due to extensive use of seed saving practices by farmers. The UK royalty collection system operates efficiently with coverage of more than 90% of the acreage. Despite this extensive coverage, the pricing effect of the discounted FSS royalty has kept royalty rates at low levels. The result is a very modest royalty stream generating £17 million in royalties, of which approximately £6 million is reinvested in breeding activities, or about £0.40 per ton of wheat produced. The UK experience clearly illustrates that breeding firms with limited budgets cannot afford to make significant investments in plant science or crop science, and therefore, require significant basic and applied research support from the public sector.

While the UK government may have anticipated long-term public research savings, the recent level of reinvestment suggests that private breeding activities continue to require significant long-term public support. The UK learned the hard way that without incentives to do otherwise, competitively based science funding will attract public researchers towards activities with academic impact and away from applied research. If there are no clear incentives to work together the links between producers, private breeders, and public scientists weaken. As these linkages become weaker the knowledge flow is impeded, thus further reducing the effectiveness of the upstream public science research. Fortunately the UK policy-makers have been able to design programmes that encourage collaborative research and are quite effective in bringing public scientists and breeders together. Although, it is also worth noting that some tension has continued to persist as the time frame and reference points for public scientists and breeders differ.

Another challenge is to ensure continuity of research efforts to preserve the integrity of the system. In the last 13 years, the UK government has introduced many new research funding initiatives (WGIN, LOLA, WISP, STB, and others), each designed to foster wheat innovation. While these programmes have brought much needed research resources to the sector, public researchers and the private breeders lamented the lack of a strategic plan and the inability to develop and fund long-term projects beyond the five-year commitment periods.

Training of new scientists and breeders when the public sector is alienated from breeding activities is also challenging. The UK experience clearly illustrates that breeding and crop science are not a dichotomy. Good crop scientists need to understand breeding and breeders need to understand crop science. Although there are now some training opportunities, the removal of commercial breeding activities from public institutions has made it more difficult to fund and train students in crop breeding science. This suggests a need for the public sector to be involved in at least pre-breeding so that scientists receive hands-on experience.

Despite past challenges and the lack of long-term strategic commitments, wheat scientists and breeders are very optimistic about the future. The current funding models have fostered real cooperation between engaged public scientists and private breeding firms. New sequencing technologies, and an upsurge in both public and private investment in wheat variety development holds the promise for significant discovery and progress. The future success of the private breeding industry depends on the ability of private wheat-breeding companies to exploit new developments in wheat molecular marker technology (for example, next generation sequencing) and cereals phenomics (high through automated phenotyping in both controlled environments and field conditions). With its experience in building public–private relationships, the UK wheat sector is well positioned to take advantage of knowledge generated in either the public or private sector to advance wheat breeding.

Acknowledgements

This work was supported by Genome Canada and Genome Prairie (grant number 2313). The authors would like to thank the participants in the study for their insightful comments and giving their time to meet with the authors and discuss the UK wheat research/breeding system in detail.

Notes

1. Bayer Crop Science works in partnership with South Dakota State University and the University of Nebraska; Monsanto works in partnership with Kansas State University, North Dakota State University, and Virginia Tech; Limagrain works in partnership with the University of Idaho and Colorado University.
2. Wilson and Dahl (2010) estimate the US annual private research investment at US$2 billion, which is concentrated in GM crops.
3. This is particularly true for concentrated industries, where publicly available data is often very limited.
4. Characteristics of the product with respect to which a contract is incomplete are referred to as non-contractible 'quality' (Hart et al. 1997).
5. The number of varieties is not an economically relevant measure of output unless greater variety choice contributes to an overall increase in farm yield, which is not apparent. While more choice and quicker turnover of new varieties can be an indication of increased competition, it can also be an indication of duplication of effort in the industry where different firms produce new wheat varieties that are very similar in their characteristics, in which case the 'effective' choice to farmers is not improved.
6. Informal conversation with one of the scientists at NIAB.

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Appendix Interview Questions

A. PERSONAL CHARACTERISTICS

In this section we would like to learn about your background and your research program.

(1) Can you, please, briefly describe your professional background? How many years have you been a wheat scientist/breeder?

(2) What types of wheat research does your organisation/unit do? What type of wheat are you working on [spring versus winter, milling v. feed]?

(3) What is your role/research program within your organisation?
(4) Are you involved in wheat genomics research?

B. RESEARCH FUNDING

In this section we would like to get an understanding of who funds research, how funds are allocated to different research projects, and how research priorities are set.

1. How is your research program currently funded? What's an approximate annual cost of your wheat research (for public scientists)/breeding (for private breeders) program? What proportion of funding is coming from the private/public sector? Has private funding of your research program increased over time?

Follow up question: Does the private sector fund different research than the public sector does? If yes, what is it that the private sector is interested in?

2. Is the current situation typical? Has funding changed much over time? If yes, please describe the nature of changes and how these changes have affected your research program.
3. Is there enough funding to remain internationally competitive? If you had twice the funds, where should these dollars be invested and why?
4. If you could change the structure of public research funding what changes would you make and why?
5. In terms of the whole country and in your opinion: Is the amount of wheat research/breeding investment adequate? Are there research needs that are not being met? Who (the public or private sector) should do this research?

C. **PUBLIC–PRIVATE PARTNERSHIPS**

(1) Do you have any formal partnership agreements with private firms (Local/National/International)? How would you describe your current linkages with the private sector?

Very strong	Strong	Weak	Very weak	No linkages
☐	☐	☐	☐	☐

(2) Has collaboration with the private sector increased in the last 10 years? If yes, what are the reasons? How has increased collaboration affected your research/breeding program?
(3) How important are the following factors in your decisions to form closer ties with the private/public sector?

	Very important	Important	Somewhat important	Not important	Uncertain
Gain access to markets where the private sector already has activities	☐	☐	☐	☐	☐
Tap into private/public sector's skills and expertise	☐	☐	☐	☐	☐
Gain access to private/public sector's technology	☐	☐	☐	☐	☐
Gain access to the public/private sector's connections with networks of different organizations	☐	☐	☐	☐	☐
Enhance funding	☐	☐	☐	☐	☐
Reduce R&D costs	☐	☐	☐	☐	☐
Influence private/public sector research direction	☐	☐	☐	☐	☐
Acquire more business credibility and authority	☐	☐	☐	☐	☐
Enhance the value of basic research; move research from proof of concept to product deployment	☐	☐	☐	☐	☐
Meet requirements of public funding agencies to collaborate with industry partners	☐	☐	☐	☐	☐
Other, please specify	☐	☐	☐	☐	☐
	☐	☐	☐	☐	☐

(4) Do private firms or farm organizations have any formal input into the content of your research program?
(5) How do you decide what research direction to take? How important are the following factors in guiding your research agenda?

	Very important	Important	Somewhat important	Not important
Scientific curiosity	☐	☐	☐	☐
Farmer needs	☐	☐	☐	☐
Food industry needs	☐	☐	☐	☐
End-users needs	☐	☐	☐	☐
Needs of the private industry-collaborator	☐	☐	☐	☐
Return-to-investment considerations	☐	☐	☐	☐
Others, please specify	☐	☐	☐	☐

(6) In what areas do you collaborate with the private/public sector (e.g. material exchange, personnel exchange, funding, etc.)? How is IP managed in public–private collaborative agreements?

(7) Can you give examples of how your research program has benefited from public–private collaboration (if at all) (e.g. increased funding, access to research materials you wouldn't have obtained otherwise, etc.)? Can you give us some examples of how public–private collaboration has impeded your research/breeding program (if at all)?
(8) Has collaboration with the private/public sector shifted your research priorities? Has it had an impact on your IP protection policies/strategies?
(9) In your opinion, what are the benefits and what are the costs of public–private partnerships?

D. **PUBLIC-PUBLIC PARTNERSHIPS**

(1) Are your involved in any formal public partnerships? (local/national/international)
(2) How would you describe your linkages with the public sector (other public institutions involved in wheat research/breeding)?

Very strong	Strong	Weak	Very weak	No linkages
☐	☐	☐	☐	☐

(3) Do these partnerships enable you to be internationally competitive?
(4) How easy is it to collaborate with public researchers elsewhere?
(5) Do the funding sources drive collaboration? Are you able to collaborate with who you should be collaborating with?
(6) Have these partnership become less or more effective over time.

E. **THE UK WHEAT INNOVATION SYSTEM**

(1) Can you describe the current wheat research/breeding system? How is it organized? Who are the major actors in the wheat research industry in the UK? What is the approximate share of the private/public sector in total wheat research/breeding?
(2) Can you describe major changes that have occurred in the wheat research industry in the last 10-20 years? [*How has funding changed? Has private support of public research increased in the last 10 years? How has the role of the public sector changed? How has the role of the private sector changed?*]
(3) Has there been any change in the composition of public and private R&D investment in the last decade? If yes, how?
(4) How has your research program been affected by all of the changes that you just described?
(5) Given the current system, do you think the UK will remain internationally competitive? If yes, in your opinion what are the strengths of the current system? If not, what challenges does the current system face?
(6) What do you think the system will look like ten years from now?
(7) If you see issues in how the system is functioning, do you think resources could address these issues?
(8) If you were going to reform the UK wheat research system what changes would you recommend and why?

F. **INNOVATION OUTCOMES & THE VALUE OF RESEARCH TO FARMERS**

(1) What are the yield potential levels you are aiming for?
(2) Has yield potential of varieties increased? Disease resistance? Milling/baking quality?
(3) What is the current rate of genetic gain for yield in your breeding program? Do you see a need for hybrid wheat?