Rothamsted Research and the Value of Excellence:

A synthesis of the available evidence

Report to Rothamsted Research

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Forward by the Director and Chief Executive of Rothamsted Research
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Assessing the impact of agricultural research is difficult because science is a complex and lengthy process, with pathways to impact that vary widely. It is common that research and development stages towards new technologies and know-how last 15 or even more years, followed by many more years for reaching peak adoption by farmers and other users of new technology. Adoption is often slow and diffuse, also because unlike in manufacturing many agricultural innovations need to be tailored to specific biophysical and even socioeconomic environments. Some of the many impact pathways may be known well, whereas others are not or are very difficult to quantify. Attribution presents another problem, i.e., it is often very difficult to quantify how much of the observed technological progress or other impact can be attributed to a specific innovation or an institution. Progress in productivity and efficiency is the result of many factors, including technology, knowledge and policy. Even more difficult is to assess the impact of agricultural technology on a wider range of ecosystem services and consumer benefits.

Nevertheless, in science we need to be willing to rigorously assess the relevance of our research. In his report, Sean Rickard has attempted to quantify the cumulative impact Rothamsted Research has had through key impact pathways that are most directly linked to its research. The economic approach used is in my view sound, providing a robust framework and a first overall estimate of the wider impact. Therein lies the main value of this study: it highlights the tremendous value of agricultural research. It has been demonstrated numerous times that rates of return on investment in agricultural R&D are high in both developed and developing countries, that spill over of innovations among countries is substantial, and that investments in R&D often have large, long-lasting cross-sectoral growth benefits[1-7].

Therefore, the results in their entirety are not surprising to me, although many assumptions had to be made and various potential impacts could not be included or assessed properly. We are aware that this can only be a starting point for improving the assessment of our impact in the future. This report will guide us in that, and it will also be of great value for developing our future science strategy. We will need to put better systems in place that will allow us to fill many of the data gaps and reduce uncertainties about key assumptions made. Hence, I invite everyone to contribute to a discussion on that or even come and work with us on it. We owe it to all our stakeholders to be held accountable for our research by being able to demonstrate impact in the real world. This report is meant to stimulate further discussion on how to achieve that.

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Executive Summary

Agricultural productivity and the role of science

1. In the post war period agricultural science has achieved a great deal. Since 1950, the world's population has almost tripled, from 2.5 billion to 7.4 billion. Over the same period, global production of cereals has outpaced population growth rising from 631 million tonnes in 1950 to over 2,550 million tonnes in 2014. This has had the effect that the amount of cereals available per person has grown from 249 kilograms in 1950 to 350 kilograms in 2014. This success story is largely the consequence of unprecedented increases in crop yields across the world rising from an average of 0.96 tonnes per hectare in 1950 to more than 3.5 tonnes in 2014. The fact that the Malthusian nightmare of a world unable to feed its population has not been realised is attributable to improvements in agricultural productivity and this has only been made possible by large and consistent investments in agricultural science research.

2. Rothamsted Research is the oldest agricultural research institute in the world. It dates from 1843 and is credited with laying the foundations of modern scientific agriculture and establishing the principles of crop nutrition. Over its 172 years of existence, Rothamsted's researchers have made many significant contributions to agricultural science including pioneering contributions in the fields of virology, nematology and soil science as well as the discovery and development of pyrethroid insecticides. The benefit of its many scientific contributions have impacted on the productivity and quality of the UK agricultural industry's output thereby greatly improving its cost efficiency and competitiveness. But to confine attention to the agricultural industry would be to grossly underestimate the true value of Rothamsted's research.

3. UK agriculture provides some three quarters of the UK's food and drink industry's raw materials. As a consequent, the more productive and competitive UK agriculture is as a supplier of raw materials the more it imparts not only a competitive advantage to food processors and manufacturers but also higher living standards to consumers via lower food prices, superior quality produce and greater choice. **The UK food chain culminates in £198 billion of expenditure by consumers. In the process it generates £107 billion of gross value added, involves some 410,000 enterprises and provides employment for some 4 million people; some 13 per cent of the UK's total employment.**

4. **Productivity, or more correctly the growth of productivity, is the ability to increase output from a given quantity of productive inputs and as such is an obvious index of social welfare and a key indicator of efficiency and competitiveness.** Rising productivity

lowers the unit costs of production, it reduces waste and contributes to sustainability if it involves lower demands on natural resources per unit of output. Since the 1950s many studies have amassed convincing evidence demonstrating that individual nations and the world as a whole have benefited enormously from productivity growth in agriculture. But productivity growth depends on investment. Investment in farmer education, extension programmes and rural infrastructures all contribute to higher agricultural productivity but the studies are unanimous, it is investment in agricultural science that delivers the greatest contribution. The evidence shows that the benefits of agricultural research have generated value worth many times more than the investment costs.

Estimating the contribution of Rothamsted Research to the UK economy: the approach

5. We can separate Rothamsted Research's own or collaborative scientific contributions to agricultural productivity into three areas: plant science to increase potential yields; agronomy science to raise actual yields towards their potential; and crop protection science to minimise yield losses from pests and disease. Agricultural production is geo-climate sensitive, responding to local climate, soils and eco-systems thus productivity can only be maximised when scientific advances are aligned with the local geo-climate. Accordingly, Rothamsted Research can fairly claim that UK's agriculture's current level of productivity owes a considerable debt to its erudition and intellectual property. Of course Rothamsted Research is not the only organisation engaged in agricultural research in the UK but its long, proven record of many successful contributions justifies its ranking not only as a leader in the UK but also one of the world's leading centers of agricultural research.

6. In this report we seek to provide an estimate of the cumulative value of Rothamsted Research's total contribution to the UK economy, or more correctly to the living standards of its population. It is not however possible to provide a precise figure: in part because many scientific advances are the outcome of an incremental process where the work of more than one institution has contributed; and also data constraints have restricted the level of detail available necessarily limiting the analysis to aggregated data. In attempting to value Rothamsted Research's contribution we have eschewed the more traditional approaches that either focus on the institution itself to provide estimates of its employment or expenditure multipliers and/or attempt to estimate the Gross Value Added (GVA) for the agricultural industry of specific advances. While both are respected approaches – indeed the GVA methodology has recently been used by other research organisations in the UK – and both provide key information they greatly undervalue the total contribution of agricultural research.

7. The continued growth in the productivity and quality of agricultural production is not an end in itself; rather it is the basis for an efficient and competitive food chain which in

turn delivers to consumers' food security at affordable prices, as well as safety, quality and choice in their food purchases. This is the real value of a science based agricultural industry and as such it dwarfs the value estimated at the level of the research institution or even the agricultural industry. **It is this value at the level of households that this report seeks to quantify.** As noted above by adopting this approach it is not possible to provide a precise value; rather it involves making estimates based in part on studies and in part on experience and judgement. By making the methodology clear and transparent the reader can form an opinion as to whether the estimated annual value of the cumulative impact of Rothamsted Research to the living standards of UK households is reasonable. Moreover, it provides a framework for future work as more detailed data becomes available.

8. **The approach adopted in this report is to use an established economic methodology to assess whether in the absence of Rothamsted's contribution to agricultural productivity total output by UK agriculture would be significantly lower than it is today.** Lower productivity implies not only reductions in crop yields but also higher production costs. Combined these two factors would raise selling prices across all sectors of agriculture. This follows, despite Rothamsted's focus on crops and grasses, because the reduction in cereals' yields would divert land from growing other arable/horticultural crops while raising livestock feed prices and thereby the prices of meat and dairy products. In addition, grazing livestock production costs would also be higher in the absence of Rothamsted's work on grasses and silage. Imports would not make-up the shortfall – certainly not without a corresponding rise in prices – because the loss of the spillovers from Rothamsted's research for other agricultural industries would also adversely influence levels of production in Europe and further afield.

Estimating the contribution of Rothamsted Research to the UK economy: the findings

9. In this report we provide an assessment of how much lower UK agriculture's productivity would be in the absence of Rothamsted Research's cumulative research output and consequently how much higher the prices of agricultural products would be. After allowing for the proportion of food products' prices accounted for by the prices of agricultural products we estimate that consumer food prices would be almost 5 per cent higher than they actually. In 2014, UK households spend some £95 billion on food and soft drinks; that is, food and drinks purchased for consumption within the home. The effective of this would be an annual increase of more than £2 billion pounds in household's expenditure on food. In addition £55 billion was spent on food eaten outside the home e.g. in restaurants and a further £49 billion on alcoholic drinks. Although the agricultural content amounts to a smaller proportion of the total value when it comes to

food eaten outside the home and in alcoholic drinks the rise in agricultural prices would, we estimate increase expenditure on these items by more than a billion pounds per year. **Thus, we value the annual contribution of Rothamsted Research's erudition to feeding the nation in excess of £3 billion pounds a year.**

10. The contribution to the cost of adequately feeding the population is the main benefit of Rothamsted Research but other benefits flow from an agricultural industry that is productive and competitive. The first is the many jobs in the food chain that depend on agriculture. In the UK there are 115,951 food service enterprises e.g., restaurants, employing some 1.64 million people and 1.18 million people employed in 53,112 retail food outlets. Employment in food processing, manufacture, wholesaling and distribution amounts to some 663,000 jobs spread across 28,309 enterprises. If the price of food was higher, the food industry would be smaller with implications for the number of enterprises as well as employment. Another potential cost to society of more expensive food – particularly fruit and vegetables – would be some loss of nutritional and health benefits as household's reduced consumption. And a less productive agricultural industry would be accompanied by a reduction in the area of countryside available for leisure and recreation as farmers sought to bring into production less productive land.

11. Turning to the future, a number of recent, high profile studies have pointed out that in the coming decades the global food system is facing a serious challenge in supplying the increasing demand for food. One of these studies commissioned by the Royal Society introduced the concept of *sustainable intensification* as a solution to the severe restraints imposed by the limited scope to increase the agricultural land area and the increasing scarcity of natural resources including freshwater. The concept involves intensifying production i.e. increasing the output from the current area of cultivated land but in a manner that reduces both the use, per unit of output, of non-renewable resources and damage to essential ecosystem services. The Royal Society concluded that in order to deliver sustainable intensification there is a clear need for publicly funded science. Moreover the authors argued that in achieving this outcome genetic improvements via plant science must be augmented by advances in agronomy. In addition to those recommendations, it is now accepted that delivery of sustainable intensification will also require the collective contribution of bioinformatics, big data acquisition technologies and big data analyses tools and systems approaches to agriculture. The delivery of practical solutions for farmers underpinned by this multidisciplinary research will require the relevant and appropriate policy and regulatory frameworks, nationally and internationally.

Rothamsted Research and future work: the need and value of long term investment in agricultural science

12. Rothamsted Research has a long and successful record of delivering excellent science with relevance to farmers. Its broad based research encompasses the whole plant system including not only biotechnology, but also agronomy and agroecology to guide agricultural practice. Rothamsted Research set out its research strategy for 2012-2017 in response to these challenges. The 2012-2017 science strategy involves developing innovative approaches to crop genetics, nutrients, water utilisation, plant protection, nutrition and soil productivity. Rothamsted Research's strategy, in collaboration with partner research facilities in the UK and beyond, is designed to deliver the scientific knowledge, innovation and agronomic practices that will increase crop yields, livestock production and quality while minimising the use of non-renewable resources within sustainable production systems. The strategy which relies on a mixture of mathematical modeling, laboratory experiments and field trials, is focused on four outcomes: to more than double potential wheat yields by 2020; to improve the nutritional value of wheat and oilseeds; to provide renewable and low carbon crop alternatives to fossil fuel-based energy; and to design practical, sustainable agricultural systems. Rothamsted Research now is working on developing its future strategy (2017-2022) and its longer term vision. Rothamsted Research will continue on its strengths but also expand and further develop a multidisciplinary approach to provide high quality science with a strong focus on delivering relevant solutions for agriculture in the context of sustainable intensification.

13. Academic studies demonstrate that the returns to investment in agricultural science continue to be enormous. Perhaps 25 years ago it was understandable that many governments and food industry participants believed that the first green revolution had worked its magic and provided the science and technology to affordably feed the world. Consequently since the early 1990s there has been a significant scaling back in public expenditure on agricultural R&D across developed nations. And public funding has declined more in the UK than elsewhere. Now we are less sanguine. Once again we are reliant on science to provide solutions to one of the greatest challenges facing the world. But achieving the necessary advances is compromised by current levels of public investment. The science underpinning food crop production – as in all areas of biology – is being revolutionised by several new technological developments including genome sequencing and genetic modification. These technologies offer the prospect of greatly speeding-up the breeding of desirable traits in plants and Rothamsted Research is in the vanguard of these technologies. **The future affordability of food, and indeed the quality of life, depend on successful scientific advances in these new areas of research.**

14. Although the focus of this report is an economic valuation of the benefits of Rothamsted's research to the production of a sufficient, affordable and high quality food supply for the UK's population, it is important to acknowledge – particularly as the food challenge is global – Rothamsted's involvement in overseas research projects and its worldwide reputation. Rothamsted Research is a world leader in plant and agricultural sciences and it works with more than 50 countries to promote and share excellence in agricultural and environmental sciences as well as addressing concerns relating to sustainability. It fosters international co-operation in research for the benefit of international development and provides training opportunities and other capacity building measures to strengthen national research. Rothamsted Research is an important training destination for post graduate and postdoctoral participants from overseas. As such Rothamsted Research has become a very important linkage in the development of lasting relationships and collaborations with scientists throughout the world; an impact that is difficult to quantify but is likely to be large.

Chapter I: Introduction

I.1. Agriculture is one of the oldest human endeavors, but it must be constantly renewed through research and development. Science has profoundly affected the growth and development of agriculture. Agricultural scientific advances beget new technological opportunities that deliver to society on a continuing basis a wide range of benefits including enhanced choice, higher quality and more affordable food. The delivery of new technology is critical to a food chain that seeks to be efficient and competitive and thereby a basis for improved living standards and food security. Put simply, agricultural research and innovation are the foundations of a better quality of life.

I.2. Since 1960, the world's population has more than doubled, from 3.1 billion to 7.3 billion, and real per capita incomes have almost tripled. The fact that the world has avoided a Malthusian nightmare is attributable in large part to improvements in agricultural productivity achieved through technological change enabled by investments in agricultural R&D. In the post war period agricultural science has achieved a great deal. It has delivered unprecedented levels of productivity and efficiency at the farm level which in turn has lowered the unit cost of agricultural production and increased quality. Cereals lie at the heart of agricultural production; in addition to providing the basis for all cereal based food products they are also a major ingredient for the production of meat and livestock products. Since 1960, global production of cereals has more than tripled from some 750 million tonnes to 2,553 million tonnes in 2014. Less than 10 per cent of this increase can be explained by a rise in the arable area; overwhelmingly the increase is due to remarkable improvements in yields.

I.3. The need for agricultural science is as great today as it has ever been and in addition to the traditional challenges of delivering affordable food scientists must now do so in ways that enables farming to rise to the challenge of sustainability and climate change. Agricultural scientific research is a process that begins with scientists understanding the operational needs and developing strategic challenges facing the food industry. The process is primarily driven by the demand for affordable and safe food but it is facilitated by government policy and regulatory guidance. Scientific research is technologically complex and reliant on earlier work. Also, its benefits typically occur with long lags; that is, the subsequent improvements – many of which are broadly distributed – are manifested as products or processes some years after the primary scientific effort commenced and the link is not easily observed or understood by consumers. Owing to the long lags involved the value of investment in agricultural scientific research is seldom fully appreciated. Indeed, over the past twenty years or so governments in developed nations have taken a sanguine view of food security and consequently public expenditure on agricultural research is now less of a priority.

I.4. The recent shift to a new era of much higher, more volatile global agricultural prices – over the past 10 years global agricultural prices have averaged 82 per cent above their level in the previous twenty five years – should draw renewed attention to agricultural productivity as a counter to the growing scarcity of key resources used by farming industries across the world. Higher agricultural prices – associated with increased fertilizer and energy prices – reflect a widening gap between demand and supply as the global population increases in size and affluence. The challenge of increasing supply in the face of a growing scarcity of productive resources can only be addressed with the aid of agricultural science and in particular the contribution of public sector research institutions. Over the past twenty years early signs of a slowdown in the growth of agricultural productivity have emerged. If such a slowdown were to be sustained and widespread the longer term consequences for the affordability of food would be seriously adverse. Higher prices in rich countries but malnutrition and hunger in the world's poorer nations.

Objective

I.5. This report has been commissioned by Rothamsted Research to provide an estimate of the value of its scientific outputs to the UK economy. A research institution with the global reputation and longevity of Rothamsted Research will have contributed many thousands of individual advances to agricultural science. **However, it is not the purpose of this report to list individual achievements. The purpose of this report is to identify the broad areas of its research and the contribution this body of work has made to not only an efficient and productive farming industry but also to a competitive food industry and social wellbeing**. Although agricultural research might generally be primarily focused on the activities of farmers and their suppliers the ultimate impact will be cheaper, higher quality and safer food products. A full assessment of the benefits of agricultural research must therefore include the implications for downstream food businesses and final consumers.

I.6. Rothamsted Research's mission statement is … *to perform world-class research to deliver knowledge, innovation and new practices to increase crop productivity and quality and to develop environmentally sustainable solutions for food and energy production*. The most obvious of these benefits is the security associated with a plentiful, stable and affordable supply of food. Less obvious are the nutritional and health benefits from disease and blemish free produce. And frequently overlooked are the wider benefits arising from the appearance of a well-managed countryside that provide visual amenities and an enhanced quality of life. Also deserving of consideration is the likely future contribution of agricultural research to the development of plant based industrial materials that will play an important part in countering the effects of global warming and achieving sustainable industrial activities.

I.7. In this report we will attempt to estimate and express the cumulative value of the contribution of Rothamsted Research to the affordability of food and hence living standards for the UK's population. The methodology is summarised in the next chapter and for reasons that will be explained it will never be possible to provide a precise estimate but as an order of magnitude it will serve to show just how much value the work of the scientists at Rothamsted Research deliver's to households in the UK. The purpose is to provide a readable, independent and objective assessment that can be understood and referred to by a population of non-scientists including politicians, lobby groups and the general public. We will also take this opportunity to explain why Rothamsted Research continues to have great importance and value in contributing to solving some of the major challenges now facing agricultural producers and in particular helping to deliver sustainable production systems, affordable and nutritious food.

Report Structure

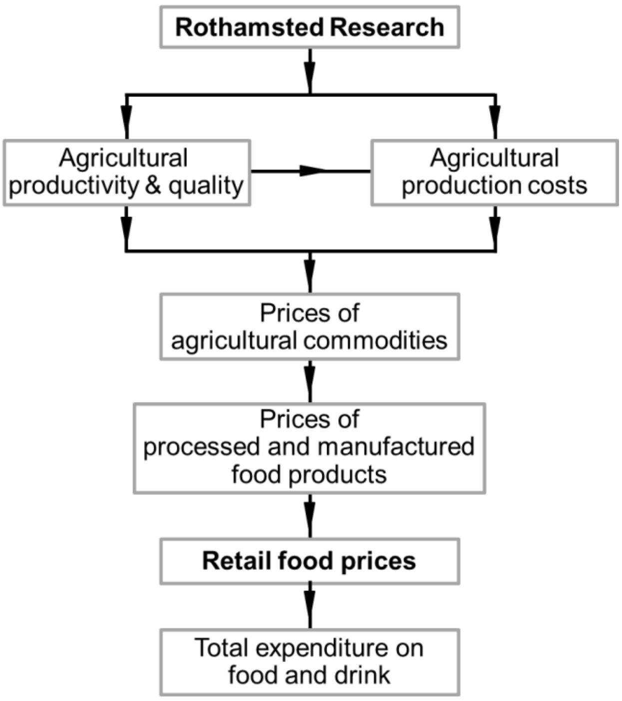
I.8. What follows is separated into four chapters. Chapter II, as indicated above outlines the methodology employed to translate lower agricultural productivity into higher retail food prices and levels of expenditure on food. It also summaries the strengths and weaknesses of the approach. Chapter III deals with the importance of productivity growth and its dependence on continuing scientific research. It also summarises traditional approaches to measuring the benefits of agricultural research. Chapter IV outlines the ways in which Rothamsted Research has contributed to food affordability, choice, quality and security for UK households. It then goes on to set out in some detail a quantitative estimate of the impact of Rothamsted Research on lowering the level of UK food prices and the savings for household expenditure arising from lower food prices. Chapter V summarises the current focus of scientific research at Rothamsted and its standing as a global centre of excellent research. It places the work of Rothamsted Research's scientists against the background of the growing challenges the world now faces in continuing to affordably feed its growing population by outlining its contribution to sustainable agricultural production. The chapter closes with an acknowledgement of the intangible benefits to the UK and beyond of Rothamsted Research's reputation for world class scientific research. Key references are set out at the end of this report.

Chapter II: Methodology

II.1. The primary purpose of this report is to provide a quantitative estimate of the annual welfare gain for UK households of Rothamsted Research's contribution to the cost of food. It is founded on the conviction that as a result of the scientific breakthroughs and advances emanating from its research food prices are significantly lower than they otherwise would be thereby generating social benefits in the form of higher living standards and improved nutrition. These benefits arising from Rothamsted's erudition are primarily delivered through the longer term, productivity growth of UK agricultural production involving higher volumes, lower costs and improved quality.

II.2. The first step in the analysis is to estimate the impact of Rothamsted's research activities on UK agricultural productivity and the implications for the industry's volume of output and unit production costs. All other factors remaining equal, we can calculate how much lower UK agriculture's total output would be and how much higher its production costs in the absence of the cumulative contribution of Rothamsted Research. Armed with this calculation we can then quantify by how much the prices of agricultural commodities would be above current levels. This flow from the fruits of research to the prices of agricultural commodities is summarised in the top half of Figure II.1

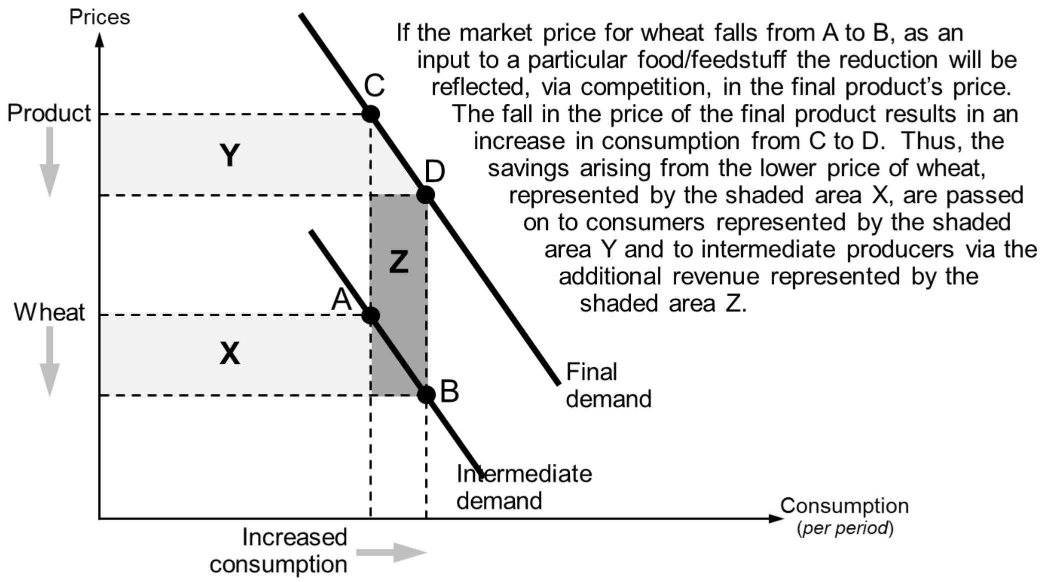
Figure II.1: The Approach



II.3. Agricultural commodities are the primary input into food processing and manufacturing and therefore the prices, volumes and quality of agricultural products will directly influence the prices all food products and hence total expenditure by households on food – as summarised in the lower half of Figure II.1. Our concern is not the annual fluctuations in the prices of agricultural commodities arising from the vicissitudes of the weather or disease. Rather we focus on longer term underlying trends that are driven by the fruits of new knowledge. These include both more productive plants and animals as well as more efficient farming practices. To the extent that new knowledge reduces the real prices of agricultural commodities i.e. lowers them in relation to other prices, we might reasonably expect in a competitive market that at the retail level real food prices will also be lower.

II.4. The first stage in the price chain is the effect of higher productivity on agricultural prices. Rothamsted's research is primarily directed at crops and grasses. In the case of crops e.g. cereals, they are a direct input to many consumer foods such as bread and biscuits and both crops and grasses are an indirect input to meat and dairy based consumer foods. A rise in the productivity of cereals and grass production will, all other factors remaining equal, result in lower unit production costs for intermediate producers and in turn these lower costs will result – as shown schematically in Figure II.2 – in a proportionally smaller reduction in the prices of final consumer products. For example, a rise in average wheat yields i.e. land productivity will, all other things being equal, be reflected in a lower wheat price.

Figure II.2: Relationship between Intermediate and Final Prices



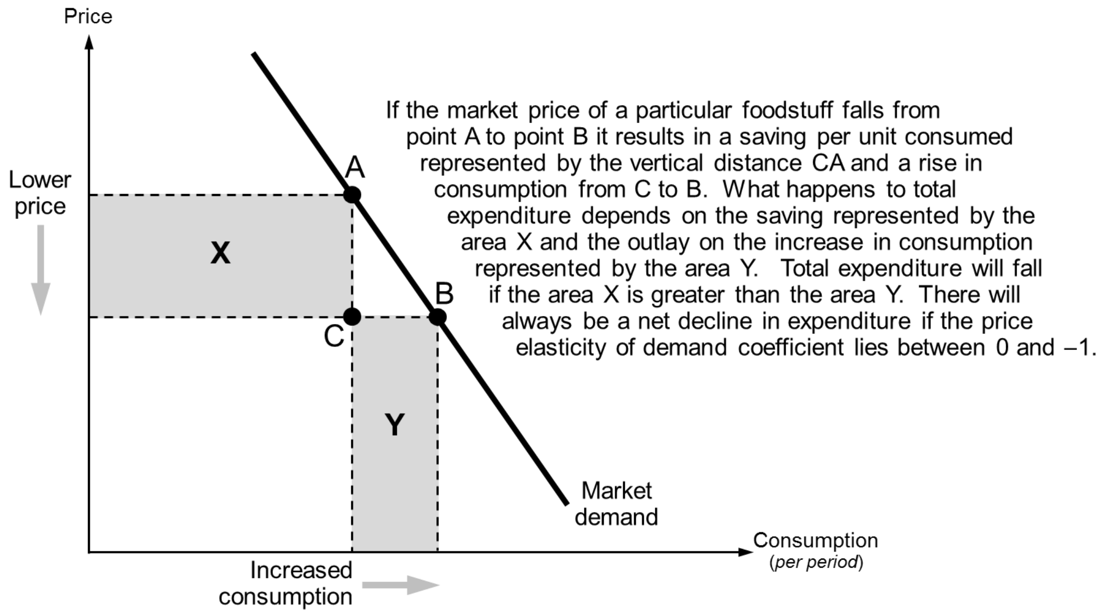
II.5. If demand by consumers, represented by the final demand curve in Figure II.2, remains unchanged a fall in the price of wheat as an input to an intermediate food or feed processor will reduce unit production costs by *AB* delivering a cost saving equivalent to the shaded area *X*. As all intermediate producers utilising wheat will benefit from the cost reduction, competition will result in the lower price being passed on to consumers via the price of the final product. This will cause consumption to rise from *C* to *D* delivering a welfare gain to consumers equivalent to the shaded area *Y* and additional revenue for intermediate producers represented by the shaded area *Z*. Thus, the welfare gain for final consumers of a fall in the relative price of an agriculture product depends on the proportion of the intermediate production costs represented by the agricultural commodity.

II.6. In the case of fresh fruits, vegetables and meats, the agricultural content accounts for the bulk of the price of the intermediate product. For products involving a large amount of processing and manufacture e.g. bread, the proportion of the value of the intermediate product will be smaller. In the case of animal feeds some crops are fed directly to animals and others undergo processing, but in both cases the agricultural content accounts for a large proportion of the intermediate product. As feeds represent a significant proportion of livestock costs – the proportion varying with the system but can exceed 70 per cent of dairying and intensive livestock variable costs – the price of feed crops, particularly cereals, has a significant influence on the prices of meat and dairy products. On average almost 50 per cent of the UK's output of cereals is sold directly for animal feed but after allowance for indirect sales eg, brewers' grains, the proportion rises to about 65 per cent. Grasses are either fed directly to cattle and sheep under a grazing system or indirectly as silage, haylage or hay. Thus, a productivity induced reduction in the costs of meat and crops to intermediate producers has the potential to significantly lower the price of consumer food products that are animal or cereal based.

II.7. The second stage in the price chain involves the addition of distribution and retail costs to intermediate food products. Thus, at the final consumer level – e.g. retail, restaurant or hotel – the proportion of the price paid by consumers that reflects the agricultural content – the so called farmer's share – can be quite small. Each year Defra publishes farm-gate shares for selected items [1]. The overall, weighted agricultural share of the final value of the products sold for home consumption is 40 per cent; ranging from 9 per cent for bread to 50 per cent for beef. The agricultural share of meals purchased in restaurant will be considerably lower than 40 per cent; the final proportion being determined by the service costs. Most importantly a major study [2] found that in the UK the evidence supports symmetric price transmission for the majority of commodities; that is, both increases and declines in farm-gate prices are reflected in retail food prices.

II.8. The final stage is to calculate the impact of lower retail food prices on household expenditure. This calculation makes use of official estimates of the response of households to changes in food prices [3] – see Appendix I. This relationship is known as the price elasticity of demand. In essence a price elasticity, for a particular food category, measures the percentage change in the volume consumed in response to a percentage change in price, all other prices remaining unchanged. Price elasticities of demand are generally negative; that is, for most food products a fall in its retail price leads to a rise in consumption. Figure II.3 illustrates the relationship between a consumer product's own price elasticity of demand, the volume consumed and total expenditure.

Figure II.3: Price Elasticity of Demand



II.9. In Figure II.3 point *A* shows the quantity consumed at the current price and lies on the demand curve which represents the household's demand for a specific product. Demand will be determined by the number and composition of the household, its total income and preferences and also the prices of substitute products. If now the price falls to point *B* consumption will rise from *C* to *B* generating a saving per unit consumed equivalent to the vertical distance *AC*. represented by area *X*. However, as the market price has fallen relative to other prices the household will generally increase its consumption involving additional expenditure equivalent to the area *Y*. The household will enjoy a net fall in total expenditure if the area *X* is larger than *Y*. This introduces

the importance of the price elasticity of demand. If the demand elasticity coefficient lies between 0 and 1 a fall in price will result in a decline in expenditure. For example if the price elasticity of demand is 0.3 a 10 per cent fall in price implies that total expenditure will decline by 6.9 per cent.

II.10. The value of the price elasticity of demand coefficient is determined by the desire and scope for substitution. A household may consider that its consumption of a necessity such as bread is sufficient and following a fall in the price of a loaf will choose to divert the savings to the consumption of another food item: in this situation the price elasticity of demand will be very close to zero. Alternatively, in the case of a 'luxury' product e.g. an expensive cut of meat, following a fall in its price a household might significantly increase its consumption. In this situation the price elasticity demand coefficient may exceed unity causing the household's expenditure on the 'luxury' product to increase but in the process raising its standard of living. Poorer households, who necessarily devote a large percentage of their income to food, benefit proportionally more than a rich household from a fall in the price of food. If they are already consuming lower quality food then they can use the saving to purchase some higher quality foods. The important point is that however a household responds to a fall in the relative price of food the net-effect amounts to an unambiguous welfare gain and price elasticities of demand enable the benefit to be quantified

Strengths and Weaknesses of this Approach

II.11. The approach adopted in this report has the advantage that it is systematic and founded on widely accepted economic concepts. It draws on official data based on long running household surveys [3]. That said, given the complexity of the issues involved it has been necessary to make a number of judgements in order to limit the workload and/or to substitute for a lack of data. In particular, we had to aggregate foods into fairly broad groups and then apply an elasticity coefficient to the group even though studies show that elasticities vary within food groups eg, in the meat group elasticities for beef, pork and poultry will vary, albeit that the difference is not large. Official estimates of the price elasticities of demand for food are necessarily based on short term fluctuations in price. However, this report is concerned with the long term: the consumer response to the declining trend in food prices – relative to non-food prices – driven by productivity growth. Over the longer term consumers have more time to adjust and other factors are likely to influence price responsiveness e.g. health concerns. Indeed, there is some evidence that the price elasticities of demand for foodstuffs have become smaller over time thereby increasing the welfare loss if the downward trend in food prices had been lessened, but for most foods the change is relatively small [4].

II.12. Another limitation is the difficulty of assessing the cumulative impact of scientific advances on agricultural productivity and hence agricultural prices. There is considerable evidence and quantification of the inverse relationship between changes in the supply of an agricultural product and its price. However, these generally relate to short-term fluctuations whereas we are concerned with a situation where agricultural output grows at a slower rate than it has over the post-war period. Arguably a greater difficulty is to assess the contribution of Rothamsted Research to the longer term growth of productivity and thereby to estimate the value of its erudition. We have been forced to resort to peer opinion and judgement but we have taken care to explain and justify our conclusions; indeed, we have tended to err on the side of caution. By being transparent readers are in a position to make their own judgements as to the estimates of Rothamsted's contribution to UK agricultural output contained in this report.

II.13. The main strength of the approach used in this report is that it provides a more realistic appreciation of the total contribution of agricultural science to living standards than is the case with traditional approaches. The traditional approach is to identify a particular invention or innovation and assess the impact for a farm's production cost or increase in revenue. While this approach has the advantage of coherence and relative simplicity it seriously undervalues the true value of an advance for households and living standards. It is only at the level of the economy that the importance and potential size of the cumulative national benefits arising from agricultural scientific research can be appreciated. In particular, when it comes to publically funded research it is imperative that a realistic value is attached to the output of a domestic agricultural scientific research institution with a track record of many years of success.

Chapter III: The Importance of Productivity and the Role of Science

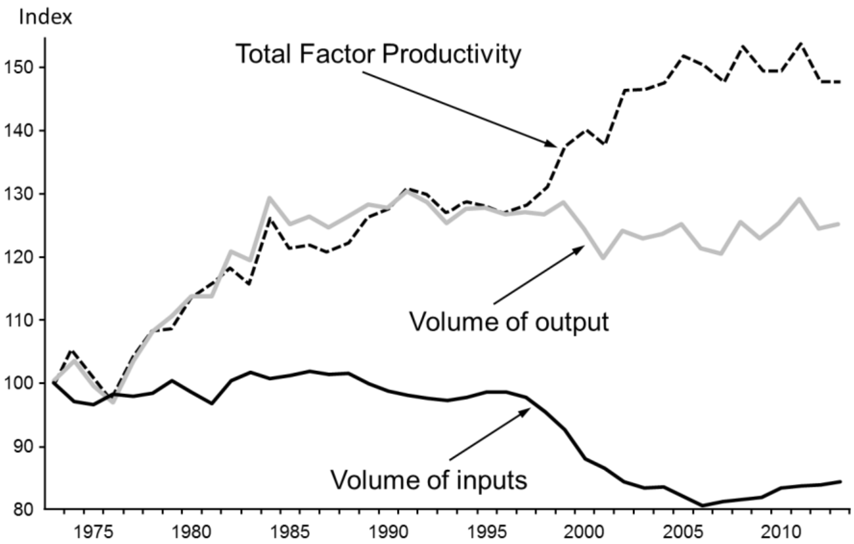
III.1. At the heart of a nation's living standards is the concept of productivity which may simply be defined as the volume of goods and services produced each year relative to the resources utilised. Although it is a recurring activity for a government to compare its country's level of productivity with that of competitor countries it is a concept that is more appropriately measured at an industry or enterprise level. Productivity is a snap-shot and it is the growth of productivity that really matters if living standards are to grow faster than populations. Productivity growth determines the extent to which a society can meet its growing demand for goods and services without having to increase in the same proportion the volume of resources used in their production.

III.2. It follows that productivity growth is an obvious index of welfare and is regarded as a key indicator of competitiveness. Rising productivity is not only the counterpart to productive efficiency but also it underpins increasing quality and wider choice in the goods and services on offer while controlling the cost of supplying these outputs. From the perspective of sustainability and reduced waste, rising productivity necessarily involves decreasing the volume of resources necessary to produce a given level of output.

III.3. Productivity is the ratio of the volume of output (Y) achieved in a given period, say a year – the numerator – to an index of the volume of inputs (X) used in its production – the denominator. Hence, the measure of productivity is given by Y/X and its determinants are then discussable in terms of the variables included in X. For convenience productivity is frequently measured with respect to a particular input; the most popular being labour productivity which is obtained by dividing the volume of output by the units of labour used in its production. In agriculture a widely used measure of productivity is the volume of output obtained from a hectare of land, generally described as yield. Measures that relate productivity to one, albeit key, input are known as partial measures and are both easy to calculate and interpret. However, they are deficient in that they do not allow for the possibility that the input in question is being substituted by another. A comprehensive measure of productivity would divide the volume of output achieved in a given period by all the inputs used in its production. Such a measure is known as multi-factor or total factor productivity (TFP). If TFP is measured at regular intervals and set out in a time series a rising trend reflects the volume of output increasing faster than the volumes of inputs used in its production and this is the primary indicator of rising welfare.

III.4. In the case of agriculture it is particularly important to assess TFP as a time series as year to year fluctuations reflect stochastic external events such as the vicissitudes of the weather or outbreaks of disease. Figure III.1 shows how the UK's agricultural industry's TFP has grown since 1973 and also how the volumes of outputs and inputs have separately contributed to its rise. Over the period TFP has increased by 49 per cent equivalent to an average of a little over one per cent per year. The total volume of output has grown 25 per cent over the period while the volume of inputs used has actually fallen by 16 per cent.

Figure III.1: TFP, Output and Input Indices for UK Agriculture



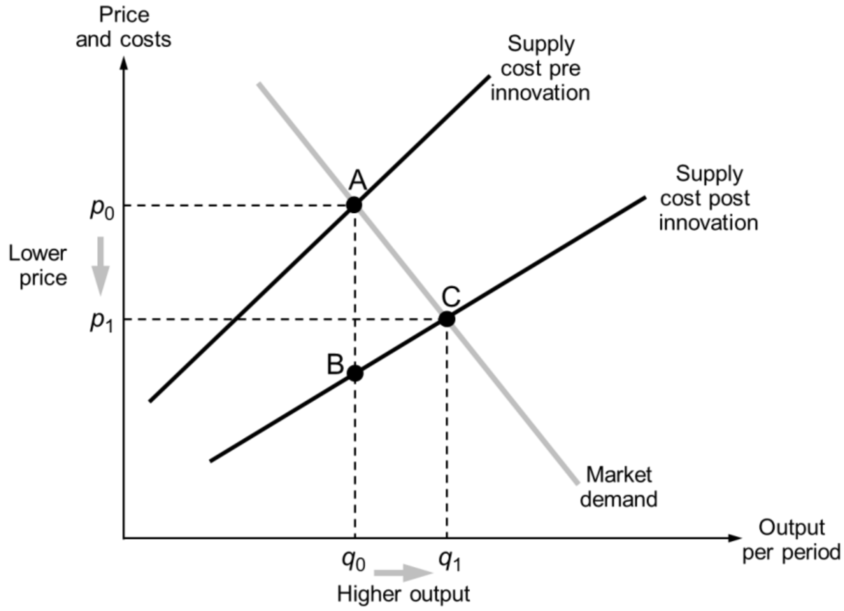
Source: Defra

III.5. Careful inspection of Figure III.1 shows that the trends in the drivers of UK agricultural TFP underwent fundamental change in the mid-1990s. The figure only shows data for the period starting in 1973; however, since the early 1950s output grew at an annual rate of 1.8 per cent per year until the mid-1990s since when its underlying trend has flattened. Throughout the period shown output displays considerable variability from year to year – particularly over the past seven years – due to the vicissitudes of crop production rather than livestock. In 2011 drought conditions were declared in East Anglia with near drought conditions in the South East, South West and the Midlands and in 2012 the very wet conditions further constrained crop output.

III.6. After remaining more-or-less flat until the mid-1990s the combined volume of inputs declined for ten years since when it has increased slightly; largely reflecting significant increases in plant protection products in response to adverse weather conditions. In comparison most other inputs including fuel, fertilizers, feeds and labour have decreased over the same period. What Figure III.1 confirms is that productivity growth is not solely dependent on output growth but in its absence the volume of inputs must continue to decline in order to generate rising TFP.

III.7. The importance of agricultural productivity for a population's welfare is captured in the prices and quality of agricultural products. As noted above many external factors influence agricultural prices ranging from the short term impacts of adverse weather and seasonal demand to the longer term influence of global market trends driven for example by the rising demand for food in emerging economies. However, in the absence of TFP growth we can say with confidence that agricultural prices would be considerably higher, resulting in more expensive food in shops and restaurants and consequently lower living standards for the population. Figure III.2 illustrates how productivity lowers food prices.

Figure III.2: Productivity and Food Prices



III.8. We can think of Figure III.2 as representing a particular agricultural product, say wheat. The market demand curve is defined for a point in time and represents the quantity that users of wheat wish to purchase at successively lower prices. This demand is a derived demand based on the final demands by consumers. For example, the demand by bakers will depend on the demand for bread, the demand by poultry farmers will depend on the demand for meat. The position of the supply curve is determined by the prices of inputs e.g. labour and TFP. Consider first the supply curve rising through point *A*. The curve's upward slope represents the fact that beyond some level of output unit production costs start to rise as more variable inputs e.g. fertilizers are combined with fixed inputs e.g. the area of land. If wheat farmers expect the market price to rise they

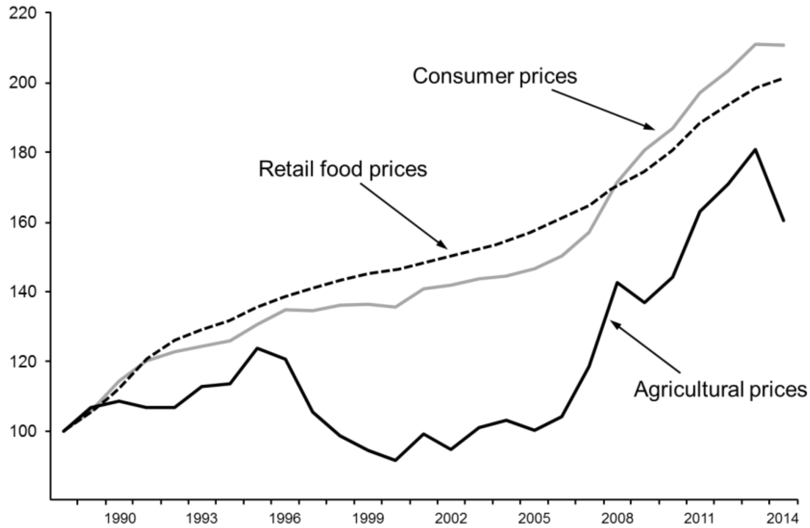
will plan to supply a greater quantity i.e. they will be prepared to incur the higher unit production costs involved in moving up the supply curve. As illustrated, if farmers expect a market price of p_0 they will plan to produce output q_0 and in the absence of a stochastic event e.g. inclement weather, the market will come to rest at point *A*.

III.9. Now consider the impact of a scientific advance that increases TFP. For example, an improved take-up of nutrients by the crop allowing wheat farmers to produce the same quantity using less fertilizer. The effect is to lower the unit cost of production – represented by a downward shift in the supply curve – and afford farmers a choice. Farmers can continue to supply the same quantity at a lower cost – point *B* – or alternatively continue to use the same volume of fertilizer which will result in an increase in total output to q_1, point *C*. The latter option will be chosen if, as is generally the case, it is the more profitable response. Thus the effect of the scientific advance is to increase the total supply of wheat causing the market price for wheat to fall and, all other factors remaining equal, users of wheat will purchase more because its lower price affords them the scope to increased sales and profits. For households the outcome is lower prices for food products where wheat is either a direct input e.g. bread or an indirect input e.g. meat and dairy products. It is also noteworthy that a productivity advance that involves the lower usage per unit of output of a non-renewable resource say, fertilizer, also makes a positive contribution to more sustainable production.

III.10. Figure III.2 shows the one-off effect of a scientific boost to productivity. But the scientific process is potentially unending and this delivers dynamic benefits to farmers in the UK and across the world. The greater the cumulative impact of such productivity advances the cheaper the cost of producing food, all other factors remaining equal, and hence the lower retail food prices. Figure III.3 shows how the prices of UK agricultural products have moved relative to retail food prices and consumer prices in general. The data show that until 2006 the rate of increase in agricultural prices was markedly slower than the increases in food and consumer prices but between 2007 and 2013 agricultural prices increased sharply. The effect on food prices and to a lesser extent consumer prices in general is clear to see which reinforces the importance of minimising the rate of increase in farm-gate prices.

III.11. The reason for the marked change in the performance of agricultural prices after 2006 reflects the coincidence of asymmetric trends in demand and supply. UK agricultural product prices are sensitive to global trends and in 2007 world prices reacted sharply to a) rising demand from developing nations, particularly China and b) falling stocks of agricultural products. The effect on prices of this rising demand was exacerbated by a leveling off in the growth of agricultural output, not only in the UK – see Figure III.1 – but across most of the world's agricultural producing nations. The patterns shown in Figure III.3 demonstrate the importance of agricultural productivity growth; this is even more so in the face of the twin challenges of rising global demand and a slowdown in the growth of agricultural output. We will explore these challenges in more detail in Chapter V when considering the wider contribution of agricultural science.

Figure III.3: Agricultural, Food and General Prices



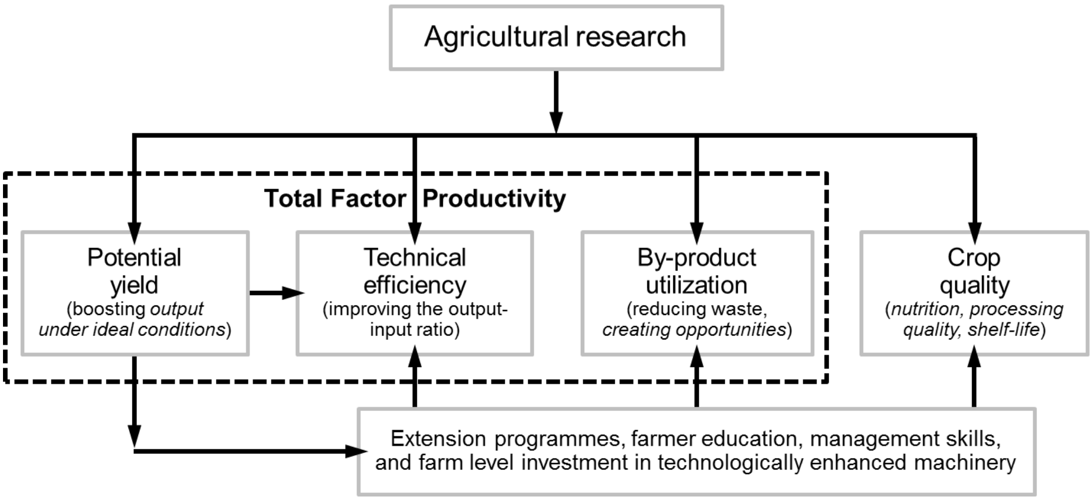
Source: Office for National Statistics and Defra

Productivity is Driven by Scientific Research

III.12. The growth of TFP derives from a number of sources including rural infrastructure, agricultural extension, engineering and information technology as well as soil fertility and the efficient take-up of nutrients by crops and animals. All of these contributing factors, particularly advances in crop and animal productivity, are dependent upon scientific research. We will focus on crops and grasses, mostly cereals, in part because this is an area of research closely associated with Rothamsted Research and in part because of the importance of cereals to farming and the food chain. Cereals account for two-thirds of the UK's arable area and almost everyone eats cereals in one form or another. In addition to providing the raw material for bakery food items, cereals also make-up the bulk of animal feeds and increasingly food ingredients and biofuels. Almost 50 per cent of the UK's output of cereals is sold directly for animal feed but after allowance for indirect sales eg, brewers' grains, the proportion rises to around two-thirds. Cereals also provide important ingredients for the food industry eg, starches and as key feed-stock for biofuels they have a new role in reducing the reliance on fossil fuels.

III.13. Measured in tonnes the output of cereals, the numerator in the TFP calculation, is delivered via three channels: a) incremental increases in the biological potential yield e.g. increasing the weight of a harvested product as a percentage of the total plant weight; b) improving technical efficiency i.e. narrowing of the gap between the average and potential yields by reducing the incidence of pests and disease and/or enhancing agronomy and management skills; and c) the development of economic uses for waste byproducts e.g. biomass – see Figure III.4.

Figure III.4: Science and Total Factor Productivity



III.14. Although rising yields are to be welcomed, indeed, necessary to feed a growing population it is only if they are achieved by the growth of TFP that they are likely to be accompanied by a downward trend in the prices of crops. As explained above, yields will rise in response to greater use of agricultural inputs, such as increased volumes of fertilizers and plant protection products. However, if usage exceeds the economic optimum the rise in yields will be accompanied by rising per unit production costs; a situation that in wastefully using scarce resources is neither efficient in economic terms nor ecologically sustainability. Conversely, if the growth of cereal yields is accompanied by TFP growth this reflects the fact that the total volume of inputs used in the production process is rising at a slower rate than cereals output. Indeed as implied in Figure III.1, in the UK over the post war period the total volume of inputs used in agricultural production has tended to decline. This unambiguously represents improving economic efficiency. Moreover, to the extent that producing a tonne of cereals now makes lower demands on non-renewable resources or scare natural resources so it also represents improving ecological sustainability.

III.15. A significant element in the growth of agricultural TFP has been crop science. Genetic changes have led not only to increased yield potential but also to improved disease resistance, more uniform ripening, shorter growing seasons, better adaptation to local climates and soil, improved tolerance to drought or waterlogging and greater suitability for mechanical harvesting. In addition to genetic improvement there have been equally dramatic improvements in the performance of inputs such as chemical fertilizers and crop protection products. For example, for many pesticides, potency, as indicated by reductions in the volume of chemical applied per treated hectare has increased. And machinery, particularly with the fusion of information technology has become much more efficient. Lastly but not least, the human capital has become better educated and more skilled.

III.16. Although difficult to measure, indeed frequently ignored when the numerator and denominator of the TFP calculation are measured in terms of volumes, is the contribution of higher quality output to productivity and economic value. For example, increases in the amount of protein per tonne of cereals have both productive and cost benefits for bakers, maltsters, feed producers and non-food manufacturers. Producing a competitive domestic alternative to imports of protein concentrated, soya bean meal for animal feed would not only reduce costs but also be desirable on environmental grounds. Similar productive, cost and environmental benefits arise from engineering plants to make omega-3 long chain polyunsaturated fatty acids into oilseeds – see Box III.1.

Box IV.1:
Rothamsted Research develops plants with high levels of omega-3 fish oils

Omega-3 long chain polyunsaturated fatty acids (LC-PUFA) have been shown to be beneficial for human health and the primary dietary sources of these fatty acids are fish. Increasing demand for fish oils is putting pressure on marine resources which can only be relieved by the identification of alternative sustainable sources of omega-3 LC-PUFA. There are no known oilseed plants that produce omega-3 LC-PUFA. Oilseed plants produce omega-3 short and medium chain fatty acids such as a-linolenic acid (ALA).

Scientists at Rothamsted Research have successfully engineered the metabolic processes in the seed of camelina (commonly known as false flax) traditionally cultivated as an oilseed crop to produce vegetable oil and animal feed, to produce long-chain omega-3 fatty acids. The engineered plants produce 12 per cent EPA (eicosapentaenoic acid) and 14 per cent DHA (docosahexaenoic acid). These amounts are very similar to those found in fish oil.

EPA and DHA omega-3 fatty acids benefit health by modulating both metabolic and immune processes as well as conferring health benefits in areas of coronary heart diseases. Professor Johnathan Napier, lead scientist of this project at Rothamsted said … *we have managed to generate a plant that can provide terrestrial sustainable sources of fish oils and this achievement can have potentially benefits for our health and the environment*.

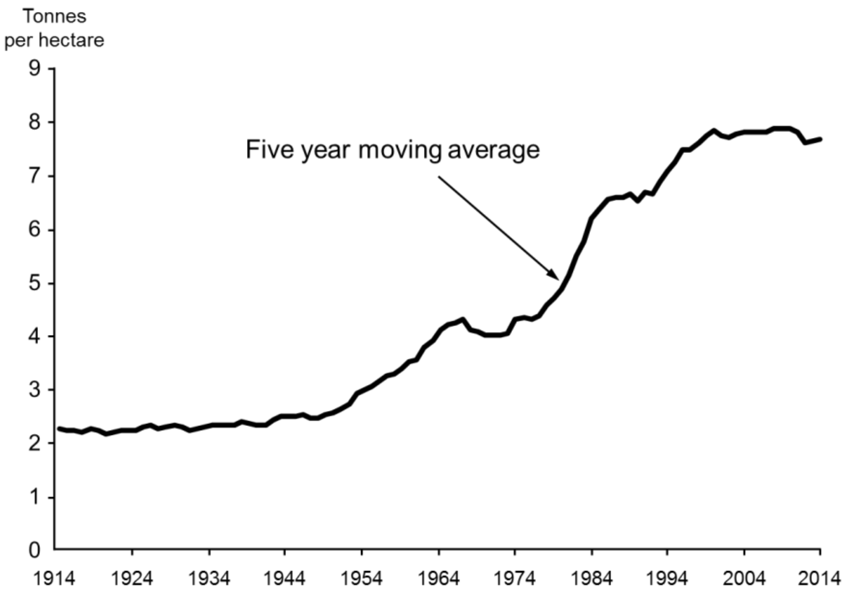
The Importance of Yields

III.17. Wheat is the dominant cereal in Europe and is second only to corn as the most produced cereal in the world. It covers more of the earth than any other crop, it is resilient, growing in the dry and cold climates where rice and corn cannot, and it is the leading source of vegetable protein for humans worldwide. Since 1950 global wheat production has more than doubled and in excess of 90 per cent of this increase was due to rising yields. The rise in wheat yields and crop yields in general that has occurred since 1950 has been powered by changes in the genetic potential of crops emanating from physiological, morphological and also lodging resistance improvements in crop varieties. All these improvements have in common that they are the direct result of investment in crop science.

III.18. In contrast to the last half of the twentieth century, the first decade of the new millennium saw a slowdown in the growth of yields for the world's major crops. Figure III.5 shows the five year moving average for wheat yields in the UK. Between 1950 and 1995 wheat yields displayed a positive rate of growth – an average of almost 3 per cent a year – compared with little in any growth between 1914 and 1950. However, since 1995 the rate of growth has stalled. The leveling of the trend since 1995 should not be unexpected; but attempting to quantify the precise impact of specific factors is beyond the scope of this report. A contributing factor has been the unprecedented increases in the prices of fertilizers and energy. Despite recent falls in the prices of oil, fertilizers and energy remain some 160 per cent above their levels at the start of 1995 – at its peak in 2008 fertilizer prices were more than 300 per cent above their level in January 1995

III.19. Another influence has been the introduction of policies to encourage environmentally friendly production methods [5]. In the EU the basis of farm support was switched from farm-gate prices to direct payments in 1992 and since then there has been greater encouragement to reduce the intensity of cereal farming. Another factor, which we will return to below, has been the reduction in expenditure on public sector agricultural research. By far the greatest influence on yield growth between 1950 and the mid-1990s has been the fruits of public sector, scientific research. These not only raised the yield potential but also narrowed the gap between the average and potential yields by reducing the incidence of pests and disease and/or enhancing agronomy and management skills.

Figure III.5: UK Wheat Yields

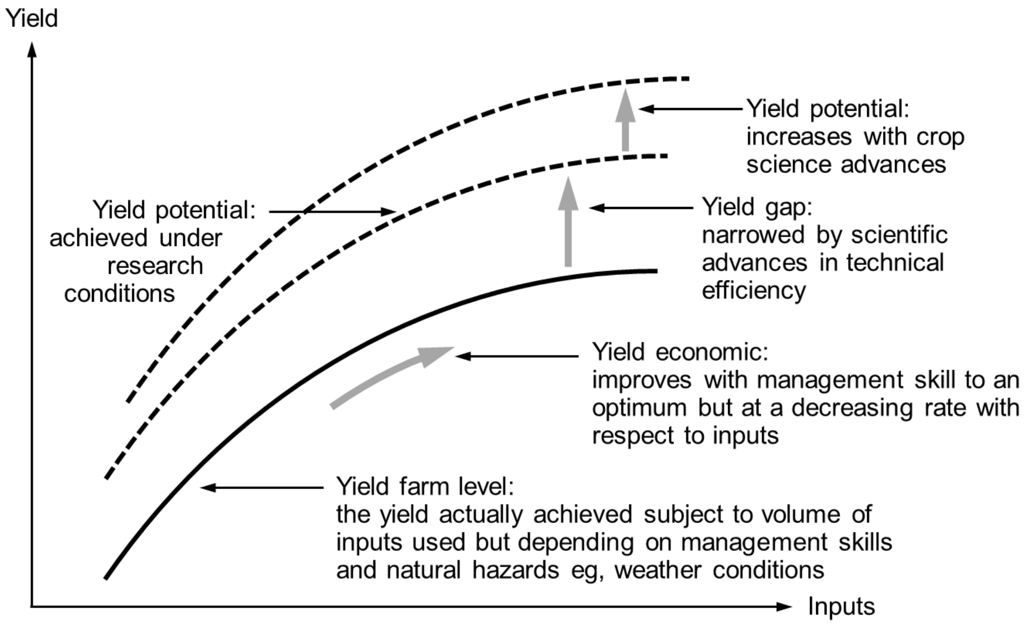


Source: Defra

III.20. Individual varieties of crops and plants have theoretical, potential yield ceilings – this means the maximum yield that can be reached under ideal conditions. Scientific discovery brings forward an advance in genetic potential so the yield ceiling for the crop in question will rise serving to create scope for increases in farm-level yields. As indicated by Figure III.5 following a scientific advance, exponential increases in yields can occur over periods of three or four decades but such growth will eventually level-off in the absence of further advances to raise the biophysical ceiling. The levelling-off implied in Figure III.5 might correctly be viewed as a temporary phenomenon. The wide range of new developments in fields such as genomics, molecular biology, physiology, double haploids and bioinformatics provide support for the view that crop science offers considerable potential to further raise yield ceilings in the future.

III.21. Figure III.6 illustrates the impact of a scientific advance on potential yields and the relationship ie, the yield gap between the potential and farm level yields. The yield gap is normally expressed as a percentage of the farm yield because it is increases in the farm yield that are directly linked to crop production. At any point in time only one point on the farm yield curve will deliver maximum economic efficiency. This point depends on the level of expected prices but it would rarely be economic to operate at the top of the farm yield curve.

Figure III.6: Potential Yields and the Yield Gap



III.22. Focusing on the potential yield curve, most advances would correctly be described as incremental eg, transgenic plants but from time-to time a revolutionary or drastic advance arrives rendering existing varieties uneconomic and giving rise to a new genre of crops e.g. dwarf wheat that is credited with initiating the 1960s green revolution. A drastic advance, even when diffused throughout the farming industry, rarely achieves its maximum potential in its first form. The normal pattern is that in the ensuing years science will continue to deliver incremental additions through a

confluence of developments including plant breeding, crop protection and agronomy.

Box III.2
Applied Bioinformatics at Rothamsted Research
Plant disease epidemics are a considerable problem both in natural environments and in commercial agriculture and consequently when there is an emerging epidemic, control measures are imposed to prevent further spread. Such controls complicate the characterising of the disease and limits the availability of data that could allow an assessment of the effectiveness of the control measures imposed.

Scientists at Rothamsted Research in collaboration with Cambridge University have developed a model allowing characterisation of the disease transmission process, even when epidemiological data are limited due to the presence of control measures. Using citrus greening – one of the world's most destructive plant diseases – as a case study, Rothamsted researchers developed a method that is able to characterize the disease transmission process and the temporal and spatial patterns of the pathogen's invasion when the epidemiological parameters had to be estimated.

Dr Stephen Parnell, until recently at Rothamsted Research, pointed out that citrus greening … *is an extremely damaging disease and continues to spread throughout the citrus regions of the world. This study not only provides insights into the epidemiology of the disease but also it could also help estimate the costs and benefits of surveillance and control strategies.*

III.23. The role of crop science in raising potential yield ceilings is necessary but not sufficient to maximise yields at the farm level. At the farm level advances in potential yield ceilings must be augmented by the application of science to plant physiology, ecophysiology, agroecology and soils in order to protect and narrow the yield gap. Examples of advances arising from such research include improved fertilizer productivity, greater crop tolerance to extreme weather conditions and better informed planting dates. These areas of agronomical science have been supplemented by scientific advances in engineering and farm management. Such developments are necessary to ensure that the yield gap does not widen and even narrows as crop ceilings rise. Narrowing the yield gap not only delivers an unambiguous gain in TFP but also it facilitates research to bring forward new varieties with higher potential ceilings. Moreover, in periods when the rate of increase in yield potential slows the focus on the exploitable gap between average farm yields and genetic yield potential becomes more important. What is perhaps not generally appreciated is that scientific research is required just to maintain current yields and prevent them from falling. For example, yield improvements in crops tend to be lost over time because pests and diseases evolve making individual crops susceptible to attack and with climate change soil borne pathogens are likely to be an increasing problem with warmer weather.

Publicly Funded Agricultural Research

III.24. Publicly funded agricultural research has been a major contributor to the advances outlined in the previous paragraphs. Indeed, it would not be an exaggeration to say that the supply of abundant and affordable food and fiber in the UK is the product of a period of sustained growth in publicly funded investment in agricultural R&D that began in the 1930s. It is a feature of agriculture across the world that the bulk of organised research is undertaken by public agencies though in developed nations the proportions are now more evenly balanced with private organisations. The dependence on public research is a direct consequence of the fact that the overwhelming majority of farms are small, family businesses and even the largest corporate farms are small when compared to their counterparts in other industries. Thus, individual or even groups of farms are in no position to fund the large fixed costs, the salaries of specialised scientists and long gestation periods involved in agricultural research. Indeed, a particular feature of crop science is the considerable lag between the initial research and the impact on production as well as the need for long term monitoring of advances in order to assess their durability – see Box III.3.

III.25. Since the early 1990s there has been a significant scaling back in public expenditure on agricultural R&D across developed nations. Unfortunately there are no robust published data relating to UK expenditure on agricultural science research, either by sector of performance or by field of science [6]. In constant price terms the Biotechnology and Biological Sciences Research Council's (BBSRC) annual research spending has increased on average by 2.8 per cent over the 10-year period to 2013/14 while agricultural research funded by Defra has declined substantially, at an average, annual rate of 7.9 per cent. In 2013/14 Defra spent £43.5 million, whereas the BBSRC spent more than twice that amount – £94.9 million. The main offsetting factor in total expenditure has been growth in DfID spending on agricultural science, which alongside health spending has been protected from central government budget reductions. Coincidentally, in 2013/14 DfID also spent £94.9 million on agricultural research.

Box III.3

Rothamsted Research

In 1843 the world's first 'agricultural experiment stations' was established 25 miles north of London in Harpenden when John Bennet Lawes, the owner of the Rothamsted Estate, appointed Joseph Henry Gilbert, a chemist, as his scientific collaborator. The scientific partnership between Lawes and Gilbert lasted 57 years, and together they laid the foundations of modern scientific agriculture and established the principles of crop nutrition. The station started several long-term field experiments and several of them are still running. These are the oldest, continuous agronomic experiments in the world now known as the 'Classical Experiments' in recognition of their uniqueness and value.

With remarkable prescience, Lawes and Gilbert retained samples of crops, soils, fertilisers and manures applied to the experiments and successive generations of scientists at Rothamsted have continued to add to the collection which now comprises more than 300,000 samples. The collection now known as the Long-term Experiments National Capability has had a very wide range of uses for agricultural science and its use by both national and inter-national research collaborations is actively encouraged. An electronic open access database allows users to easily retrieve many years of experimental data ideal for the development and calibration of mathematical models and also specialist background information on the effects of agricultural practices on soils, crops and associated ecosystems including long term measures of crop responses to nitrogen and other nutrients.

III.26. Since the 1970s it is now more common for agricultural research to be shared between public and privately funded research institutions in developed nations and the evidence favours a complementary relationship. Public and private funders tend to invest in different 'portfolios' of agricultural research topics: private firms specialize in fewer topic areas and focus their R&D in areas with established product markets; whereas public institutions invest in a broader portfolio of topics. For example, public R&D investment addresses not only food production and productivity but also areas such as nutrition, food safety, the environment and natural resources. Publicly funded research is more focused on basic or 'blue-sky' research that advances knowledge and potentially contributes in the long term to the delivery of specific products. In contrast, most private R&D emphasizes applied research and product development. For example, decades of publicly funded research in molecular genetics and biotechnology in the latter half of the 20th century enabled private firms to develop new techniques with commercial potential in agriculture.

III.27. Alongside the scaling back in public expenditure on agricultural R&D across developed nations there has been an increase in crop breeding by private sector firms. The UK is an example of a country that has restructured its crop research funding by privatizing commercial wheat breeding. Breeding depends heavily on the public provision of upstream research and initially privatisation dissolved the linkage which significantly undermined the ability of the private sector to develop successfully [7]. It is only in recent years that the government has sought to address this with the introduction of a number of funding initiatives designed to encourage closer collaboration between public researchers and private wheat breeders. One outcome, involving Rothamsted Research is the formation of the Crop Improvement Research Clubs (CIRC). These create opportunities for public sector scientists to work in consortia with private sector wheat-breeding firms. In addition to funding for collaborative research public funds are provided for centers of wheat research including Rothamsted.

III.28. We have observed above the levelling-off in the growth of cereal yields and it is a fact that this has occurred post the UK privatization of plant breeding. That said, it is difficult to determine the extent to which reduced public sector funding and the privatization of cereals breeding have caused the yield slowdown but privatisation and the associated changes in pre-breeding research brought many changes that collectively could have contributed to a slowdown in genetic improvement [7]. 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 in the future to a faster rate of increase in yields. In the medium term the many changes to research funding initiatives have at the very least challenged the research system's continuity and integrity i.e. ensuring that scientific research proceeds free of outside influence or coercion, and that scientific findings are transparent. In the UK Rothamsted Research is involved in basic research that may ultimately lead to the development of new wheat lines that could potentially increase wheat yields by 30 per cent.

III.29. One response to the forgoing might be to argue that as advances in agricultural science are diffused it matters little whether the research is undertaken in the UK or elsewhere. But this overlooks the fact that most new, agricultural technologies are geo-climate sensitive, responding to local climate, soils and the eco-systems. Unlike most innovations in manufacturing or transportation, agricultural technology has a degree of site specificity because of the biological nature of agricultural production, in which appropriate technologies vary with changes in climate, soil types, topography, latitude, altitude, and distance from markets. The site-specific aspect circumscribes the potential for knowledge spillovers and the associated market failures that are exacerbated by the small-scale, atomistic industrial structure of agriculture. It is plausible to imagine that some new technologies increase productivity in a particular geo-climate region, so farmers adopting the new crop or technique will benefit from lower production costs and thereby gain a competitive advantage.

Traditional Approaches to Measuring the Benefits of Research

III.30. Almost 60 years ago, Zvi Griliches was one of the first economists to statistically demonstrate that public investment in agricultural research was … *both significant and important as a source of aggregate output growth* [8]. Others have followed in his footsteps and have improved upon and refined the data, measures and models of productivity. Indeed, in the ensuing years there have been many economic assessments of the payoffs from public investment in agricultural research mostly using sophisticated modeling techniques to provide estimates of the social rate of return to this investment i.e. the per cent return on in the expenditure. The return is 'social' because it includes all of the economy wide benefits from higher productivity and we will attempt to quantify this social return to Rothamsted's research in the next section. Such studies have usually found very high annual rates of return, in excess of 40 per cent for research [9].

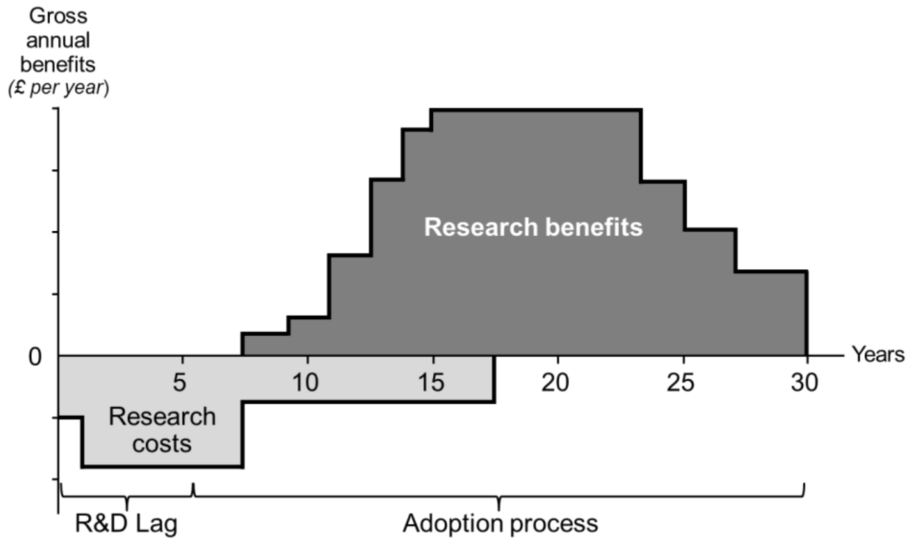
III.31. The many studies that have been undertaken since Griliches' seminal work in the 1950s have amassed convincing evidence demonstrating that individual nations and the world as a whole have benefited enormously from productivity growth in agriculture. The evidence suggests that the benefits have been worth many times more than the costs. Indeed, such are the benefits that it would have been profitable to have invested more in agricultural research. The implication of all the many studies that have analysed the relationship between research and agricultural productivity has been succinctly summed up by a group of leading academics working in this area as …*substantial government intervention notwithstanding, the world has systematically underinvested in agricultural R&D, and is probably continuing to do so*. [10].

III.32. Agricultural science, indeed all science, is a cumulative, dynamic process in which today's new knowledge is derived from the accumulated stock of knowledge. This dynamic feature of research results in long lead times between the research stage and the point at which the new knowledge is adopted at the farm level and begins to affect productivity. It is not until the advance is adopted at the farm level that the benefits will be revealed in agricultural production. Hence, the wider societal accumulation of these benefits will in part depend on the extent and speed of diffusion. Widespread adoption is not the end of the matter. Given the nature of the scientific process at some point in the future the advance is likely to be augmented or superseded by new science. Thus, an estimate of the social return necessitates reasonably accurate measurement of the length of the time lags involved and this has attracted considerable academic endeavour.

III.33. The long time lags associated with agricultural research mean that time-series statistical studies require many years of data including the annual, investment expenditure on the research as well as the annual value of the gain in productivity. Where long time series of suitable data are lacking economists have resorted to estimation devices that are likely to have distorted the findings – such as imposing restrictions on the lag distribution length and its shape. As more data have become available so more recent studies of publically funded research have revealed that the lags involved are much longer than previously estimated. Empirical work indicates that the productivity consequences of public funded agricultural R&D are distributed over many decades, with a lag of 15–25 years before peak impacts are reached and with continuing effects for decades afterwards [11].

III.34. It is not our intention to engage in yet another complex statistical exercise but rather to present the benefits of agricultural research in a more readily appreciated form. Nevertheless, the time lags involved are important and these can be separated into four stages: a) the research and development stage that delivers either a new product or more generally an improvement to an existing product or process; b) an adoption stage in which the advance is introduced to a group of farmers who are prepared to experiment; c) a diffusion stage – as captured in the S-shaped diffusion curve – over which farmers adopt the new product or process; and finally d) the augmenting or supplanting of the existing technology by a new advance. Figure III.7 shows a stylised lag structure of the pattern of costs and benefits over time arising from an investment in agricultural research that leads to a successful outcome, say a new crop variety with increased disease resistance, that is progressively adopted by a proportion of farmers. The process starts when a public institution or private organisation invests in the research, a stage that is likely to take several years of effort before a commercial opportunity is realised and this is represented as the research costs in the figure.

Figure III.7: Stylised Representation of Research Benefits and Costs



Source: Based on Alston, Pardey and Ruttan, [11]

III.35. The next stage is to interest a group of farmers in this new technology who are generally referred to as early adopters. The research institution continues to incur costs in the early stages of adoption but as more farmers appreciate the benefits of the new technology – e.g. the achievement of higher yields and/or lower production costs – so the returns to society accumulate. The figure suggests that typically it takes about eight years (from year seven until year fifteen) for the product, material or process to be fully adopted. After a period of years something better starts to replace the advance or it loses its effectiveness due, for example, to buildup of resistance in the pathogen.

III.36. In principle an economic evaluation of the research endeavour weighs the size of the research and extension costs against the economic benefits from adoption – the two shaded areas in Figure III.7. But this tends to be focused on the benefits to agriculture and takes no account of the value of any spillovers, not only for other agricultural products but also food processors and consumers. The costs of previous research i.e. the many influences on existing knowledge that will have contributed to the discovery and development of the new knowledge are sunk costs and therefore need not be considered. However, care should be taken to allow for external contributions e.g. extension services and farmer education as failure to do so may over-attribute observed gains to a particular source.

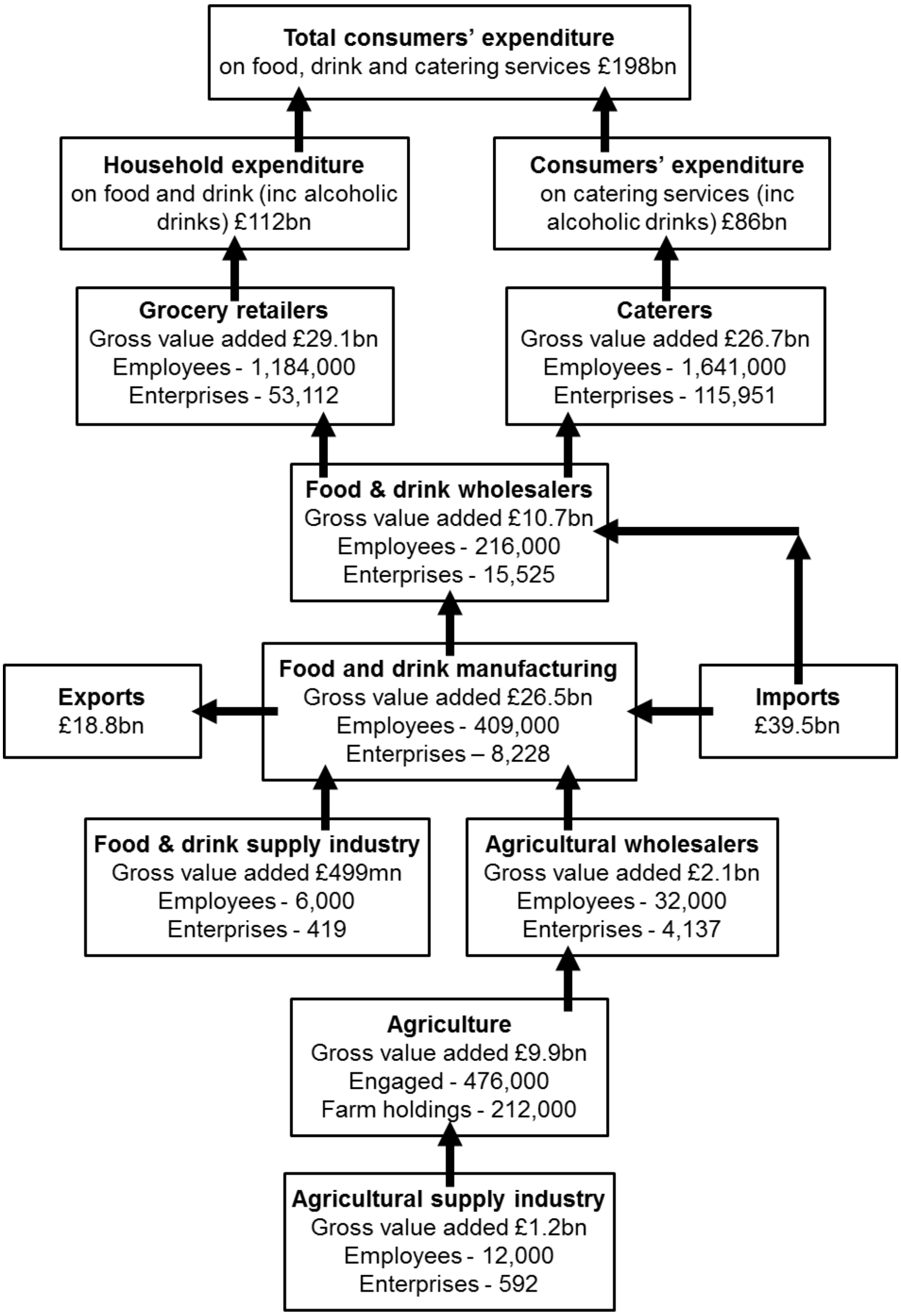
Chapter IV: Assessing Rothamsted Research's Contribution

IV.1. We have demonstrated in the previous section how scientific research has contributed to the growth of TFP and in particular crop yields with knock-on beneficial effects for society via the affordability and quality of food. In this section we will attempt a broad quantification of the benefits of Rothamsted Research's output. In reality it is impossible to isolate and value the many thousands of developments that have flowed from the work at Rothamsted over its 172 years of existence to the advantage of UK farming and beyond. Thus, in this chapter we have focused on the benefits arising from Rothamsted's crops and grass research activities over the post war period with the aim of assessing their value, not at the farm level but for the final consumer and thereby the economy.

IV.2. By attempting to put a realistic and understandable monetary value on the cumulative impact of Rothamsted's scientific contributions i.e. increasing the productivity of crops and grass production in the UK, we hope to demonstrate how such enterprise translates to a significant improvement to the quality of life for the population of Britain. We are aware that concentrating on productivity gains and in particular yields will result in an under-valuation of Rothamsted's contribution as productivity is only part, albeit a key part, of the value of agricultural scientific advances but other quality benefits e.g. disease resistance, nutritional attributes and food safety are notoriously difficult to isolate. For example, the disease resistance of new varieties is difficult to measure if farmers are not exposed to disease outbreaks and fortunately the UK has not faced a severe disease outbreak for many years. That such attributes have considerable value is beyond doubt and analytical methods, involving the collection of suitable data, exist to assess the value attached by consumers but they are beyond the scope of this report. Suffice to say, from society's perspective the health benefits of a sufficient, nutritious and affordable supply of food are immense.

IV.3. Our estimate of Rothamsted's contribution starts with the food chain. Farming sits at the heart of the food chain combining the land, nutrients and knowhow to produce crops and livestock. These agricultural products are then sold to food processors and manufacturers, downstream of agriculture, who convert them into final products for sale to consumers and food service outlets e.g. restaurants. UK agriculture provides some three quarters of the UK's food and drink industry's raw material needs. Combined, food processing and manufacture contributes approximately 15 per cent of the UK manufacturing sector's gross value added and 15 per cent of its employment. Figure IV.1 is based on an official estimate of the economic contribution of the sectors of the UK food chain that are supported by the agricultural industry and for the fourth quarter 2014 [1].

Figure IV.1: The UK Food Chain



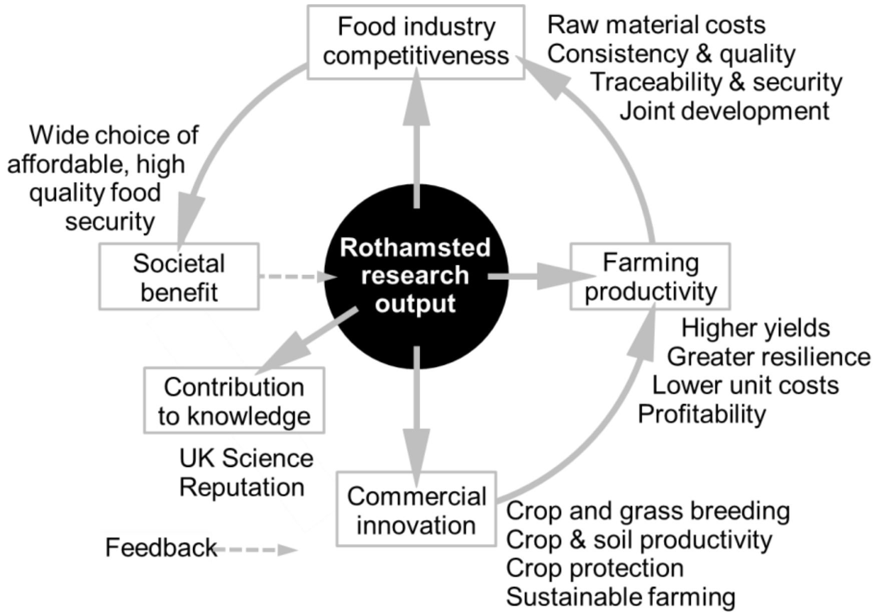
Source: Defra

IV.4. Figure IV.1 shows that the UK food chain culminates in £198 billion of expenditure by consumers. In the process it generates £107 billion of gross value added, involves some 410,000 enterprises and provides employment for 3.98 million people, 12 per cent of the UK's total employment. Although the UK imports some £40 billion of food products less than £8 billion are in the form of unprocessed agricultural products compared to UK agriculture's market output of almost £26 billion i.e.UK agriculture accounts for almost three-quarters of unprocessed agricultural products flowing into the UK food chain [1]. This suggests that there may be scope to expand the contribution of UK agriculture but nevertheless it remains the case that the food chain overwhelmingly depends on an efficient and productive domestic agricultural industry.

IV.5. Food chain productivity starts with the efficacy of the inputs farmers purchase e.g. fertilizers and continues with agricultural production. The domestic presence of not only internationally competitive suppliers but also internationally renowned research centers such as Rothamsted Research create a number of advantages for farming which in turn benefits other industries further down the food chain. The manufacture and supply of competitively priced inputs that are suited to local conditions imparts a competitive advantage but arguable greater advantage arises from invention and innovation by upstream suppliers and research centers. Localism shortens the lines of communication and encourages close working relationships between researchers, suppliers and farmers speeding the flow of information and ideas. Returning to a focus on productivity the full value of a scientific advance can only be captured if suppliers have the capabilities to convert the new knowledge into a cost-effective product and farmers have to capabilities to adapt their operations to maximise the heightened efficiency embedded in an advance.

IV.6. Thus all supply chains start with knowledge and the chain's competitiveness depends on the ability of its participants to constantly bring forth and utilise new knowledge that is manifested in new products and higher productivity. This brings us back to the contribution of publically funded research and in particular the contribution of Rothamsted Research. Figure IV.2 summarises Rothamsted's contribution to the food chain which can be thought of as delivering drastic or incremental scientific advances to agricultural suppliers and farming. As these advances are taken-up and diffused across businesses so the value of the economic impact rises, not only for adopting businesses but also for downstream processors and manufacturers and ultimately final consumers. The extended value of a scientific advance can be thought of as having three dimensions; a) financial value; b) strategic value, and c) social value. Financial value helps to secure the future of a business or industry; strategic value provides opportunities for competitive advantage; and social value arises from an enhanced supply of affordable food.

Figure IV.2: Rothamsted's Contribution to the Food Chain and Society



An Overview of Rothamsted Research's Contribution

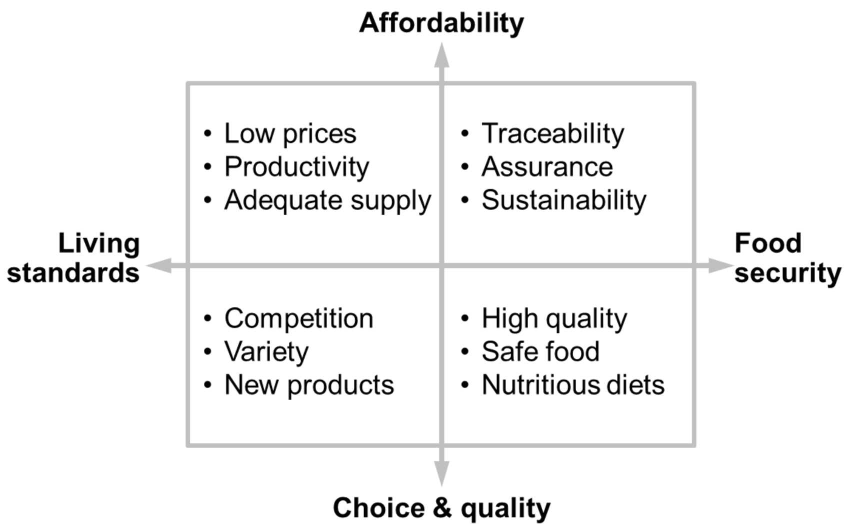
IV.7. Figure V.2 starts with Rothamsted's output. As noted in the introduction Rothamsted's mission statement is to perform world-class research to deliver knowledge, innovation and new practices to increase crop productivity and quality and to develop environmentally sustainable solutions for food and energy production. As with a publically funded university part of the purpose of a publically funded scientific institution such as Rothamsted Research is to make a contribution to knowledge that will form an input, not only into its own activities but also to the work of other public and private institutions. Through published articles and collaborations, innovative research results are diffused widely aiding further research and unanticipated commercial opportunities. Not easily valued in financial terms – any attempt would almost certainly be a gross underestimate – is the contribution to academic knowledge by Rothamsted's erudition which should rightly be viewed as enhancing the UK's scientific reputation and an addition to the country's accumulated research capital.

IV.8. The bulk of Rothamsted Research's output is in the form of cutting edge scientific advances that underpin technologies that have a direct commercial value. As we have observed, increasingly this work is undertaken in collaboration with private sector companies where its contribution remains focused on supporting efficient and competitive agricultural production. Its research has a direct impact on TFP growth by raising potential crop ceilings, reducing the yield gap, boosting the effectiveness of fertilizers, enhancing soil nutrients, providing crops with better resistance and protection from disease. In addition its research contributes to improving the quality of agricultural produce e.g. nutritional value and farm systems e.g. reduced waste. Year to year volatility in a feature of farming. The vicissitudes of the climate as well as the effects of global price instability on agricultural commodity markets can have a substantial impact on farm sector earnings. Technological advances that raise productivity and lessen the risks associated with disease and weather not only lower unit costs and mitigate volatility but also they raise the sector's competitiveness and sustainability.

IV.9. A small proportion of the UK agricultural industry's output is exported as unprocessed products – about 8 per cent in value terms – the rest is sold as an input to the food industry for processing and manufacture. Most fresh fruit and vegetables undergo a degree of processing eg, sizing and packaging. It follows that the cost of agricultural products, their consistency and quality as well as the traceability and security associated with domestic producers are major influences on the food industry' competitiveness. The consistency and quality of agricultural produce are ultimately dependent upon the care and skills of farmers but to a large extent these attributes have been enhanced and capable of being delivered at lower cost by scientific advances. Put simply without technological advance at the agricultural supply and production levels – based on the output of research institutions such as Rothamsted Research – UK food processors and manufacturers would have to cope with greater variability in supply and quality of their raw materials. This would result in waste with inevitable adverse knock-on effects for costs and competitiveness.

IV.10. We noted in the previous chapter that many agronomic technologies have a biological component that is sensitive to local climate, soils and eco-systems. This augments the direct benefits to the UK food industry summarised above from the existence of domestic agricultural research facilities. If a drastic or incremental scientific advance is aligned to a particular geo-climate region, so the food companies buying from farmers in the region will benefit in the form of lower prices and/or other attributes flowing from the localisation of research facilities. This is not the only benefit of localism. The greater the proportion of its raw materials that the food industry can source from domestic producers the shorter the supply chain and the greater the scope for jointly working to solve challenges. This affords an institution such as Rothamsted Research greater opportunity to work jointly with the two or more stages in the food chain providing yet another potential source of competitive advantage. Finally, an efficient and competitive food industry provides consumers with a wide choice of affordable high quality food; that is the basis of higher living stands. All these benefits accruing to the key stages of the food chain and the outcome for households are to a significant extent dependent on good science and the technologies it begets. Figure IV.3 summarises the benefits for households.

Figure IV.3: A Summary of the Benefits for Households



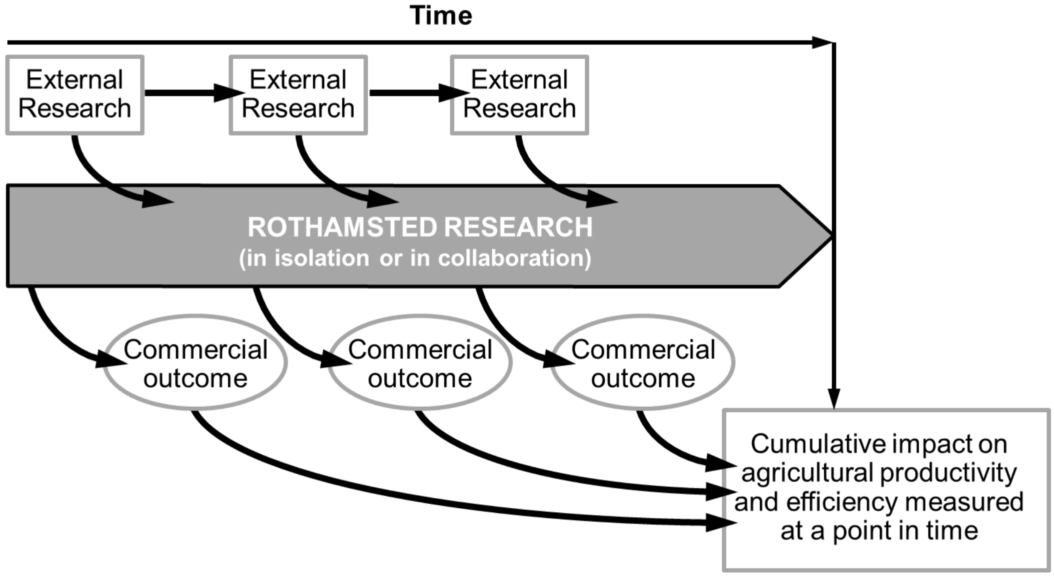
Measuring Rothamsted Research's Contribution

IV.11. Rothamsted Research – on its own or in collaboration with other public and private research organisations – has been responsible for many scientific contributions to UK agriculture's TFP growth and international competitiveness. These scientific contributions can be separated into three discrete areas: a) soil and fertilizer science to increase TFP by narrowing the yield gap at the farm level; b) crop science to raise potential yield ceilings; and c) crop protection science to protect yields by reducing losses from disease and adverse weather. In the next chapter we will broaden the contribution of Rothamsted Research to protecting the environment, reinforcing sustainability as well as helping agriculture to rise to the challenge of feeding a growing world population in the face of climate change and excessive demands for the world's non-renewable resources.

IV.12. One feature of Rothamsted's research is its longitudinal 'classical experiments' which have monitored the growth of crops and grasses on the same plots of land for about 172 years generating a great wealth of knowledge as to their performance according to the levels and proportions of soil nutrients. Through the knowledge gained from its management and documentation of its classical experiments, Rothamsted has been, and continues to be at the forefront of the scientific revolution that has greatly increased the productivity of UK crops and in particular cereals, in the post war era. Its work remains highly relevant to the challenges now facing agricultural production. In order to provide an indication of the benefits arising from Rothamsted's scientific output it is neither feasible nor necessary to attempt to list all the advances in raising and protecting the productivity of crops and grasses that can be attributed to a greater or lesser extent to Rothamsted programmes. Rather we can attempt to take a snap-shot of the cumulative impact on this research on the current productivity of UK agriculture. In essence, we can seek to estimate how much less would be produced by British farmers and how much higher would be their costs of production and food prices if Rothamsted's contribution was discounted.

IV.13. As noted above all research is a continuous process building on existing knowledge and increasingly it involves collaborations. It is therefore important to recognise that it is only rarely that one institution can claim 100 per cent of the knowledge embedded in a particular advance. That said, Rothamsted scientists have or currently hold patents in 26 patent families. Consequently, the proposed method of assessing its contribution is similar to capturing at a point in time the cumulative impact on agricultural production of all relevant advances (patented or otherwise) that have been discovered or significantly developed at Rothamsted in isolation or as part of a collaboration. Providing the intellectual property can be identified with Rothamsted we can credit the advance to Rothamsted Research and this cumulative approach is summarised in Figure IV.4.

Figure IV.4: An Approach Measuring Rothamsted's Contribution



IV.14. In Figure IV.4 the time period is not defined but given the evidence that the time lags involved are as long as 35 years or more we can reasonably think of the current cumulative impact as the product of specific advances extending back to the 1970s; advances which are built *inter alia* on the learning derived from its longitudinal

classical experiments. The boxes labeled 'external research' reflect the input from other organisations, either in the form of a direct collaboration or as published knowledge. This external knowledge is then augmented, as appropriate, by Rothamsted's scientists and applied to their areas of research. The fruits of this research are recorded in the figure as 'commercial outcomes;' that is, outcomes that have been adopted by British farmers and the cumulative effect is aggregated for the national farm.

IV.15. Turning first to fertilizers and soil enhancers, Rothamsted Research has since its inception carried out research into the agronomical management of nutrients to sustain and improve upon attainable yields. Its' longitudinal 'classical experiments' have enabled the identification and measurement of optimal management for yields, providing many high impact results for the agricultural industry regarding the use of fertilizers and break crops. Significant contributions by Rothamsted's scientists to the understanding of plant nutrition, soil chemistry, crop physiology and molecular biology have had a cumulative effect on the efficiency of nutrient management practices on British farms. Although average cereal crop yields in the UK remain about 70 per cent of the potential yield, the knowledge gained from Rothamsted's longitudinal experiments has helped narrow the gap between attainable and potential yields. Put simply Rothamsted's research to address resource-use efficiency and reverse soil degradation is a continuing, major contribution to the UK's agricultural industry's productivity growth. As a result of this research average yields (and therefore revenue) on British farms are higher than they otherwise would be and inputs are used more efficiently (i.e. unit costs are lower than they otherwise would be).

IV.16. For the reasons set out previously relating to the development and sharing of knowledge it is very difficult to provide a precise estimate of the extent to which Rothamsted's research in the area of agronomical management has contributed to sustaining/boosting attainable farm level yields while lowering unit production costs. That said, Rothamsted is the lead partner in the consortium that is arguably the most respected source of advice on fertilizer usage and this advice is estimated by experts as contributing significantly to cereal yields. To take but one, recent example, Rothamsted's identification of a growing sulphur deficiency – the result of reduced air pollution – has encouraged corrective responses that have prevented significant declines in both the yields and the quality of cereals. Corrective action in the form of applying sulphur fertilizer at an early stage has now become common benefiting yields – depending on soil type and location – by between 5 and 25 per cent.

Box IV.1

Fertilizer Recommendations

Rothamsted has made a major contribution to improving national fertilizer recommendations. Farmers are provided with continually updated information on soil characteristics and crop nutrient requirements in order to more precisely match nutrients to maximise crop production whilst minimising losses to the environment. One consequence of Rothamsted's research is that farmers no longer apply N in the autumn or winter thereby reducing the risk of leaching. It is reckoned that surplus N applied to wheat crops is now less than a third of what it was 20 years ago (75 kg/ha). It is also estimated that nitrate leaching in nitrate sensitive areas (NSAs) and nitrate vulnerable zones (NVZs) has been reduced by 20 per cent. Rothamsted has made a unique contribution to sulphur recommendations through a combination of deficiency risk assessment and plant diagnostics. The prevention of yield losses due to sulphur deficiency is estimated to be worth £30 million per year to the farming industry but considerably more in terms of higher yields to the food chain.

Rothamsted's recommendations are incorporated into the national 'Fertilizer Recommendations' book (RB 209) published by Defra. Results are also disseminated in guides published by sponsors, e.g. HGCA, PDA, British Sugar, the farming press, at farming events, and by ARIA. It is difficult to isolate and calculate a precise financial value for Rothamsted's contribution to 'fertilizer recommendations' but in terms of a reducing farmers costs and the cost of removing nitrate from drinking water the sums exceed £200 million per year. However, as will be explained in the text the prevention of yield losses amount to a much greater benefit for the food industry and households.

IV.17. On the basis of the cumulative impact of Rothamsted's published research in the area of agronomical management, and in particular achieving an optimal balance of nutrients in soil, it would not be unreasonable to argue that the underlying average levels of crop yields in the UK – that is, after allowing for the annual fluctuations arising from the vicissitudes of the weather – are around 5 to 10 per cent higher than they otherwise would be. Further, the knowledge contained in Rothamsted's published research on the management of soil nutrients and crop responses to nutrients, based on interactions among the essential nutrient requirements under varying environmental conditions, has spread beyond farmers and agronomists in the UK to researches and producers across the world to the benefit of production and the UK's scientific reputation.

IV.18. The second discrete area of research that culminates in a significant contribution by Rothamsted to TFP is crop science to raise potential yield ceilings. Research leading to increases in potential yields for a wide range of crops and grasses, has a long and successful history at Rothamsted Research (including research by previously separate institutes that are now part of Rothamsted Research). The normal process for raising the yield potential for cereals is one of small, incremental increases spread over decades and these modest improvements require considerable and sustained investment in research and collaboration. The quantum leap in cereal yields arising from the introduction of dwarfing genes developed the 1960s is the exception that proves the rule. If UK agriculture is to rise to the challenge identified in the introduction of greatly increasing output while reducing the volume of non-renewable inputs per unit of output there is a pressing need to augment the narrowing of the gap between attainable and potential cereal yields with the raising of potential yields as evidenced by Rothamsted's 20-20 wheat research programme.

Box IV.2
20:20 Wheat

In 2012 Rothamsted Research, as part of its 5-year research strategy, embarked on a strategic theme to provide the knowledge base to increase the UK's wheat yield from its current farm gate yield of around 8 tonnes per hectare to a potential of 20 tonnes within the next 20 years. In order to achieve this objective Rothamsted's scientists are researching novel approaches to increasing yields. . Some idea of the complexity and erudition involved can be gained by understanding that the work will have a particular focus on genotype advances to improve total crop biomass and grain yield through improved photosynthetic efficiency, altered canopy and root architecture, modified seed development and enhanced nutrient utilisation efficiency as well as protection against specific pathogens. The research will embrace breeding, exploiting novel germplasm, transgenesis and other forms of genome remodeling. Success will result, for a given volume of water, higher yields resulting from a 50 per cent increase in photosynthetic efficiencies. One consequence of this research is a multi-million pound research partnership with Syngenta on wheat improvement.

IV.19. Plant breeding in the 20th Century was greatly changed by the discovery of Mendelian genetics and its associated statistical analysis which now has evolved to methodologies that allow better and more efficient selection procedures. Significant advances in the area of experimental statistics were also achieved at Rothamsted Research where Ronald Fisher, Frank Yates and others utilised the institution's longitudinal data in their work. This highly successful methodology has evolved into what has become known as bioinformatics bringing greatly enhanced efficiency and precision to conventional plant breeding; for example, the mapping of marker-traits in crop species. Research into potential yields is an ongoing process that responds not only to advances in biological science but also to changes in agricultural practices and the growing environment.

IV.20. In the post war period researchers at Rothamsted contributed to increasing the yield potential of field crops by their work, *inter alia*, in areas such as prolonging the crop's yield-forming period, increasing its capacity to capture water and nutrients and improving photosynthetic efficiency. Rothamsted has for many years been in the vanguard of researching primary photosynthetic carbon metabolism in order to achieve higher productivity and better quality products. Again it is very difficult to put a precise estimate as to the cumulative impact of Rothamsted's crop science that has contributed to the breeding of high yielding, more resilient crops. To attempt to put it in some perspective, UK wheat yields increased by some 5.7 tonnes per hectare (200 per cent) between 1950 and 2014, an average increase of 90kg per year and about half of this increase, around 3 tonnes, can be attributed to advances in plant breeding [12].

IV.21. We know that crops are sensitive to local climates, soil, and other biophysical attributes. This sensitivity to local agroecology increases the importance of a domestic research base and allows us to attach additional weight to the proportion of the growth of UK agriculture's crop yields that can be attributed to plant breeding and the contribution of Rothamsted Research science to these programmes. Commercial plant breeders are increasingly multinationals but they all rely to a greater or lesser extent on the work of university and research institute crop scientists. This is either directly through published research and partnerships, or indirectly by the recruitment of scientists who have been trained at centers of excellence such as Rothamsted. Despite the difficulties of isolating Rothamsted's contribution over many years to the long term process of raising potential yield ceilings, the work by its crop scientists is estimated by experts to have contributed in the range between 10 and 20 per cent – say 15 per cent – of the increase in cereal yields.

IV.22. The third discrete area of Rothamsted's research that contributes significantly to TFP is crop protection science to protect yields by reducing losses from disease and adverse weather. In addition to agronomical management and plant breeding the growth of UK agricultural productivity also owes much to scientific advances for the control of pests and disease. This is another area where Rothamsted has a global reputation and high profile success in the area of crop protection. Arguably its greatest achievement in this area was the development of synthetic pyrethroids.

Box IV.3
Synthetic Pyrethroids

Pyrethroid insecticides were developed in the 1960s by a team of scientists led by Michael Elliott at Rothamsted. The team identified the most active components of pyrethrum – a natural though relatively weak insecticide mixture extracted from the East African chrysanthemum flowers – and modified the molecular structures to improve their activity against insects. Pyrethrum rapidly knocks down flying insects but has negligible persistence hence the importance of pyrethroids; essentially chemically stabilized forms of natural pyrethrum. It was not until the 1970s that the Rothamsted team had sufficient knowledge to be in a position to license compounds suitable for commercial exploitation and during the 1970s the team went on to discover a range of other pyrethroids, including permethrin, deltamethrin and cypermethrin. Pyrethroids have proved to be a remarkably successful group of insecticides being both highly effective and environmentally friendly; indeed, because of their natural origin some pyrethrum-based insecticides are used by organic farmers.

Today pyrethroids account for around one sixth of global insecticide sales, and global annual sales of one product, deltamethrin, exceed £130 million. They are also used to impregnate bed nets, which help to reduce the spread of malaria as part of initiatives such as the World Health Organisation's Global Malaria Programme and the US government’s President’s Malaria Initiative. The toxicity of pyrethroids to humans is very low – hence it’s use in bed nets. While Rothamsted Research makes no direct income from the sale of pyrethroids, in a global pesticide market worth more than $7 billion each year, pyrethroids make a significant contribution to the UK economy.

IV.23. Rothamsted Research’s development of synthetic pyrethroids set new standards for contact insecticides. Today, some forty years since their introduction, synthetic pyrethroids, or more correctly their derivatives – there are some 30 variants nowadays – account for 17 per cent of global insecticide sales. Since the 1980s advances have substantially increase the spectrum of activity to include the control of mites, soil pests and even sea-lice. Rothamsted’s crop protection research is not confined to insecticides, it also embraces herbicides and fungicides research. It is widely accepted that crop protection plays a key role in safeguarding crops against competition from weeds, animal pests, pathogens and viruses this research directly impacts TFP. The potential crop yield losses from these pest groups could be considerable; in the extreme, in excess of 60 per cent [13]. In the absence of herbicides, the farming industry's effectiveness in controlling weeds would be diminished and productivity would suffer with the need to increase ploughing. Indeed, it is the science of pesticides that supports highly productive, modern farming techniques.

IV.24. In order to estimate the combined impact of the many contributions of Rothamsted Research to the increase in UK cereal yields i.e. wheat and barley – these two crops account for 96 per cent of UK cereals production – we need to weight together the estimates set out above. We have estimated that Rothamsted's work on agronomical management has contributed between 5 and 10 per cent of the growth of cereal yields and its work on potential yield ceilings has contributed between 10 and 20 per cent. Its work on crop protection has protected these yield gains rather than added to them. It would not, however, be correct to sum the gains from agronomical management and yield ceilings as these advances, together and with crop protection, combine to deliver an overall increase in yields. On the basis of the foregoing it would be reasonably to conclude that UK cereals production would be some 15 per cent lower than it currently is – around 3.3 million tonnes – in the absence of the cumulative contribution of Rothamsted Research. The estimate is reasonable in the sense that there has been a conscious effort to take a conservative view of Rothamsted's cumulative contribution.

IV.25. While cereals remain at the heart of agricultural production Rothamsted's work has contributed to TFP across the spectrum of all arable crops, vegetables, fruit and grasses. For example, the control of the main aphid vectors for potato, sugar beet and soft fruit. Research by Rothamsted into pesticides has evolved to include their sustainability by the investigation of new pest and pathogen species as well as the emergence of new genotypes of indigenous organisms. Pioneering work at Rothamsted has revealed the primary mechanisms of resistance, arising from modifications or over-expression of proteins targeted by pesticides, or by enhanced detoxification or excretion of pesticides before they reach their target. This scientific research, in conjunction with agrochemical companies, underpins the more productive use of pesticides including the design of more effective and/or selective compounds. As noted above the losses due to insects, weeds and fungi can be considerable but as ever isolating Rothamsted's contribution over many years cannot be done precisely. In discussions with experts it was their judgement that a reasonable estimate of the contribution of Rothamsted's scientists to crop protection would be equivalent to protecting between 5 and 10 per cent of yields across all non-cereal crops grown in the UK. Put simply, in the absence of the cumulative contribution of Rothamsted Research yields across the range of arable crops and vegetables would be between 5 and 10 per cent lower.

IV.26. So far we have focused on crops but Rothamsted through its absorption in 2008 of the former Institute of Grassland and Environmental Research (IGER), North Wyke facility in Devon now extends its erudition to the production of grasses enhancing research into the interactions of grassland areas and animal production systems. Between the end of the war and its merger with Rothamsted, the IGER was responsible for many advances in the productivity of grazing livestock systems based on improvements in grassland management and forage production. Of note is its early influence in developing and diffusing silage systems in the UK and its continued contribution to improving the productivity of silage through grass varieties, supplements and nutrient management.

IV.27. Rothamsted is now responsible for the research programmes at North Wyke and we can fairly include the many advances in ruminate productivity arising from the work at the North Wyke site to the value of the output of Rothamsted Research. In particular, the work at North Wyke, sometimes in collaboration with other research institutes, has contributed to the six-fold increase in the production of grass silage in the UK since the 1960s and further advances in the range of crops and pastures that can be utilised for silage. In the case of dairying it is widely accepted that high quality silage – in particular its digestibility – raises productivity by boosting the level and quality of milk production and reducing dependence on purchased feed. The positive relationship between good quality silage and stocking rates, pasture utilisation and weed control also applies to beef and sheep production; in essence, research into ruminate feeding has contributed to a significant increase in 'whole farm' for grazing livestock. In particular, the investment in a Farm Platform at North Wyke provides access to a system for studying and also improving the productivity of grassland livestock systems.

IV.28. We observed above that it is not possible to precisely isolate Rothamsted's, née North Wyke's contribution over many years to the current level of productivity on UK grazing livestock farms but we do know that it is likely to be significant. In the case of milk yields there exists a linear relationship between output per cow and the percentage of silage digestibility with increases of between 50 and 70 per cent [14]. Since the 1960s milk yields in the UK have been steadily increasing by 1.5 per cent per year and of this more than doubling in the output per cow a large proportion can be credited to research relating to feeding practices and grassland management. In addition, Rothamsted's contribution to cereals productivity has made available a plentiful supply of cereal based feeds and thereby an additional source of dairy sector productivity growth. Overall it is not unreasonable to link between 10 and 20 per cent – say 15 per cent – of the increase in UK milk production to Rothamsted. In addition, other contributions to productivity such as higher stocking rates – which also apply to beef and sheep production – can be attributed to research at North Wyke. Again the precise impact of these advances on the output and cost of milk and meat production, let alone the proportion that can fairly be ascribed to Rothamsted, is difficult to estimate given the variety of production systems employed but very approximately a 20 per cent increase in stocking rates can lower beef production by costs by 5-7 per cent and considerably more for dairying. Moreover, the inverse relationship between yields and dairy cow numbers has released grassland for other gainful activities.

Quantifying the Value of Rothamsted Research's Contribution

IV.29. In this section we will follow the methodology set out in Chapter II in order to attach a value to the cumulative contribution of Rothamsted Research's to the volume of UK agricultural output as set out above. The first step in quantifying the cumulative value of Rothamsted's contribution to TFP growth is to deduct from the UK's current levels of crop and livestock production the estimated contribution of Rothamsted Research. Table IV.1 is the first step in this assessment and shows, for broad-based UK agricultural sectors, the loss of domestic output if production – converted for all sectors into thousands of tonnes – was 5, 10 or 15 per cent lower than it actually is.

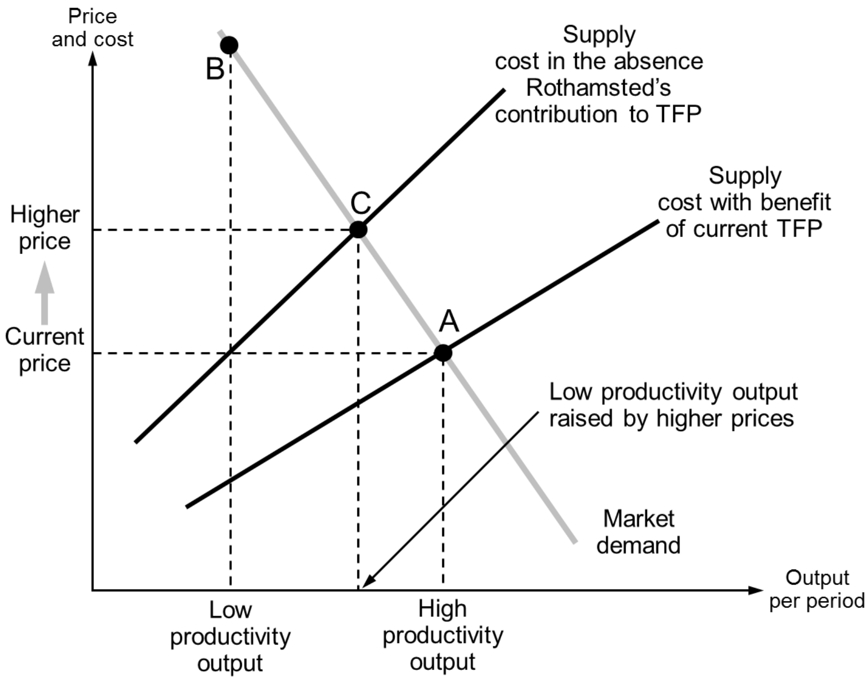
Table IV.1: Estimated Percentage Reductions in UK Agricultural Output

	Thousand tonnes*	5% reduction	10% reduction	15% reduction
Cereals	21,259	20,196	19,133	18,070
Other arable	8,675	8241.25		
Vegetables	2,570	2,442		
Milk	14,161	13,452	12,745	
Beef/sheep	1,197	1,137	1,077	
Pigmeat	770	732	693	
Poultry	1,609	1,529	1,448	
Eggs	664	631	625	

* *Defra: average for five years 2010-2014:*

IV.30. Looking first at cereals. We have explained above that because of the biological nature of agricultural production, production technologies must be geo-climate sensitive and therefore the productivity gains inherent in a scientific advance are to a greater-or-lesser extent influenced by their alignment to climate, soil types, topography, latitude and altitude. Thus, despite the many contributions to a knowledge advance we are justified in directly attributing some of the gain in UK agricultural productivity to the existence of domestic research facilities. Against this background we have estimated in the previous section that in the absence of the cumulative output of Rothamsted Research (which includes the benefits of keeping pests and disease under control) the total production of cereals would be some 15 per cent below current levels. All other factors remaining equal, a fall in cereals production would result in an increase in cereal prices and consequently higher prices for all cereal based products ranging from consumer goods such as bread and breakfast cereals to animal feeds. It would also result in higher prices for a wide range of arable and horticultural crops. Figure IV.5 summaries the situation for cereals.

Figure IV.5: The Supply Response to Lower TFP



IV.31. The current underlying position – ignoring annual weather induced fluctuations – is represented by point *A*. In the absence of the cumulative contribution of Rothamsted Research to TFP the available supply of cereals using the same volume of inputs as at present would be some 15 per cent lower than is currently the case and in this theoretical situation cereal prices would be markedly higher as indicated by point

B. However, the upward pressure on cereal prices would, given the demand for cereals, attract more resources into cereals production e.g. land and fertilizers causing production to rise. The final outcome would ultimately be determined by the response of consumers to higher prices but what is clear is that the market price for cereals would settle at a level significantly higher than is currently the case e.g. point *C*. An increase in the cereals area would involve an overall rise in production costs i.e. more resources would be employed in cereals production, but in reality the scope to increase the cereals area is limited. Over the past 30 years the UK cereals area has declined by 860,000 hectares (21 per cent) with about half of this reduction being taken up by an increase in the area of oilseeds – an additional benefit arising from higher cereal yields. Much of the rest of the decline reflects land that has been lost to development. Thus, in the absence of Rothamsted's contribution the UK cereals area would be larger than it is today and therefore less land would be available for other arable and horticultural crops or grasses. Put simply, even if slower productivity growth had been confined to cereals the constraints this would have imposed on the diversion of land into other uses would have amounted to a significant loss of agricultural output and cost to the nation.

IV.32. There have been many studies designed to isolate the relationship between changes in cereal yields and cereal prices and a reasonable summary suggests that a one per cent fall in production, all other factors remaining unchanged, results in at least a 2 per cent rise in cereal prices and some estimates are much higher [15]. This implies that point *C* in Figure IV.5 would represent a 30 per cent increase in cereal prices. This raises another question; namely, would this price increase be moderated by an increase in imports? This is unlikely, given the spillover of research either directly or indirectly to other grain growing regions of the world. For example, Rothamsted's contribution to improving agronomical management will have influenced farming practices and costs in Europe and beyond. On this reasoning, the EU would be suffering a similar fall in the output of cereals and across the world grain production would be lower. It follows that the prices of imports would be higher and again the UK would have to bear the cost of a higher import bill. At a global level some of the loss of yields would be offset by bringing more land into agricultural production but much of it at great cost to biodiversity and natural resources e.g. deforestation.

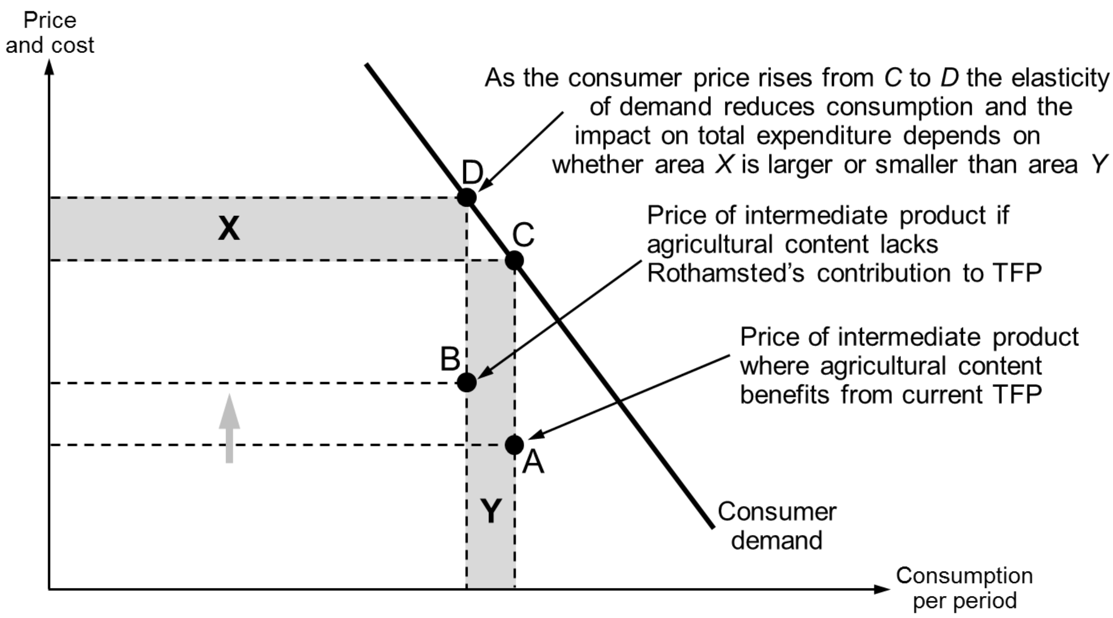
IV.33. We have discussed the justification for lower volumes of output in the cereals and dairy sectors and provided estimates in Table IV.1. In the case of dairying a significant cause of the fall in output would be due to higher feeding costs. As noted above, dairy farming productivity and production costs not only benefit from lower cereal prices but also Rothamsted research into silage and more general grass based feeding systems. The relationship between increases in cereal prices and dairy production costs also depends on the particular feeding system – purchased feed costs are considerably higher for autumn calving systems compared to spring calving. Thus, the impact of a 30 per cent rise in cereal prices would encourage more spring calving but overall production costs would be approximately 10 per cent higher. Again the final outcome would depend on the response of consumers' to higher prices.

IV.34. Beyond cereals and dairying the cumulative contribution of Rothamsted Research has benefited output and productivity across a wide range of arable and horticultural crops; for example, through its work on fertilizer practices and soil nutrients. Moreover, in terms of the output of these crops and their prices, as explained above total output would be lower and prices generally higher if the nation had been forced to devote more land to lower yielding cereals and larger numbers of dairy cows. It would be very difficult to attempt to repeat the cereals analysis above for other arable and horticultural crops but on the basis of the foregoing we feel justified in arguing that in the absence of Rothamsted's contribution the total supply of these crops would be lower. We suggested in Table IV.1 that in this situation the overall production of a wide range of crops including oilseeds, potatoes and sugar beet would be (at least) 5 per cent lower than current levels. Price responses to lower production levels across the various arable crops are as high or higher than cereals. For example, a five per cent fall in the production of potatoes results in a 15 per cent rise in price.

IV.35. Turning to the production of meat, the reductions shown in Table IV.1 arise from two sources: in the case of beef and sheep a decrease in the productivity of grasses; and in all cases, but particularly for pigs, poultry and eggs, higher priced feed costs emanating from higher cereal prices. Rearing and finishing grazing animals is done under a number of differing feeding systems ranging from extensive grassland systems through to intensive (beef) systems where stock are largely fed cereals and bulk feed e.g. silage. In the case of pig and poultry meat, cereals are the major cost – approximately 80 per cent of variable costs. The complex mix of potential rearing and finishing systems makes it very difficult to provide an overall estimate of the impact on meat production but if attention is confined to cereals then for intensively produced beef, pigs, poultry and eggs a 30 per cent rise in cereal feed prices would raise total production costs by between 10 and 15 per cent. Reverting to Figure IV.5 the effect of higher feed costs would be to push the supply curve upwards reducing output and raising price as captured by the movement from *A* to *C* and once again the final outcome would be determined by the consumer response to higher prices.

IV.36. In order to estimate the impact of these higher agricultural prices on consumers' welfare we need to calculate – as explained in Chapter II – the proportion of the retail price accounted for by the agricultural content; the so called farmers share. This provides an estimate of the rise in the consumer price after the addition of processing, distribution and retail costs. The higher price will cause consumers to purchase a lower volume but as explained in Chapter II this reduction will be determined by the consumer's price elasticity of demand. And as the elasticity coefficient for food products generally lies between 0 and −1 the outcome is both a fall in consumption and a rise in total expenditure. This outcome is summarised in Figure IV.6 where given an elasticity lying between 0 and −1 the price induced increase in expenditure – area *X* – exceeds the savings from consuming less – area *Y*. In short consumers have suffered a reduction in their welfare i.e. living standards.

Figure IV.6: Calculating the Loss of Welfare



IV.37. Currently UK households spend some £95 billion on food and soft drinks that are purchased for consumption within the home. Table IV.2 shows how this expenditure is distributed between the broad food groups using official weightings. The estimated price increases explained above are then applied at the retail level and the increase in expenditure calculated using the published demand elasticities for each category. **On this basis, in the absence of Rothamsted Research's cumulative scientific contribution to the productivity of UK agriculture, the country's population would be spending approximately £2 billion more than they currently do on food eaten within the home while consuming a smaller volume.** This however is

not the total welfare loss associated with food. Households also spend £54 .8 billion and £49.1 billion respectively on food eaten outside the home and on alcoholic drinks. Although in both cases the agricultural content amounts to a relatively smaller share of the consumer price than for food consumed in the home in both cases a rise in agricultural prices will result in an overall increase in expenditure. In the case of alcohol the price elasticities of demand for beer, wine and spirits all fall between 0 and 1 [16] and this appears to also be the case for food eaten outside the home though studies show estimates ranging from 0.23 to 1.76 [17]. The calculated average increase in the retail prices for the food groups shown in rows 1 to 5 in Table IV.2 was 4.8 per cent. **If we assume just a 1.5 per cent rise in the prices of alcohol and food eaten outside the home this would increase the welfare cost by £1.04 billion bringing the total to just over £3 billion per year**.

Table IV.2: Implied Increases in Expenditure on Food and Drink

		Weighting per cent[1]	Expenditure[2] £bn	Estimated increase £bn
1	Cereal based	*16*	14.67	0.459
2	Vegetables	*10*	9.17	0.322
3	Meat	*23*	21.09	0.706
4	Dairy products[3]	*13*	11.92	0.439
5	Eggs	*2*	1.83	0.065
6	Ready meals	*5*	4.58	0.092
7	Other[4]	*31*	31.18	0.025
8	Total home consumption		**94.45**	**2.109**
9	Alcohol		49.12	0.491
10	Restaurants etc		54.77	0.548
11	**Total (£bn)**		**198.35**	**3.148**

[1] ONS weightings for food consumed in the home, [2] Defra estimate 2014, [3] Including butter,
[4] Fish, Fruit, Oils& fats, Soft drinks, Confectionary

IV.38. This chapter has attempted to measure the cumulative benefit of Rothamsted Research's scientific contribution to the affordability of food and the value to households of this welfare gain. However, we should not overlook other economic benefits that flow from an agricultural industry that is efficient and competitive. The first is the many jobs in the food chain that depend on agriculture – 3.98 million – as identified in Figure IV.1 above. If the price of food was higher, the food industry would be smaller and this would mean fewer jobs not only in the sectors that supply inputs to farming and food businesses but also in distribution and the food service sector. Some of the shortfall would be made up by increased imports of agricultural commodities but to the extent that retailers directly imported finished food products, jobs would be lost in the intermediary stages. Put simply, employment in food processing and manufacture – the UK's largest manufacturing sector – in food distribution and food services, which together account for some 2.2 million jobs, would be lower with implications for the number of enterprises as well knock-on effects for other sectors of the economy. A number of enterprises, particularly smaller, medium sized enterprises would find the shortfall and additional cost of raw materials too great a burden and cease trading. By applying the employment multiplier, for every two jobs lost in the food processing and manufacturing industry another one would be lost elsewhere in the economy and given the location of many food companies there would be a disproportionate loss of jobs in rural areas.

IV.39. To the extent that the UK was forced to rely to a greater degree on food imports so there would be a deterioration in self-sufficiency, the country's import bill would be bigger and the supply of foodstuffs would be subject to greater volatility and insecurity. No attempt has been made to assess these costs, but any deterioration in the UK's food trade deficit and loss of employment amount to significant costs to society. Another potential cost to society of more expensive food – particularly fruit and vegetables – would be some loss of nutritional and health benefits. Finally, a very real but difficult cost to estimate would be the impact on consumer satisfaction of the loss of Rothamsted's work on improving the quality of food.

IV.40. So far we have focused on the impact of lower productivity on food prices and domestic producers. But the absence of Rothamsted's advances to aid productivity would have wider effects on living standards. One would be some loss of some countryside for leisure and recreation as farmers sought to bring into production additional land areas. Some £10 billion is spent by the UK population on rural leisure trips each year and according to Natural England once people reach their destination their main activity is walking. If agricultural productivity was significantly lower than it currently is there would be some loss of open access land that is used particularly for walking IV.40with knock-on adverse consequences for the leisure and recreation of many people.

Chapter V: Rothamsted's Contribution Beyond Productivity

V.1. So far we have concentrated on assessing the cumulative impact of Rothamsted Research on food affordability stemming from its contribution to increasing UK agricultural productivity. However, as indicated above this is only part of the total value of its scientific research. An area of increasing importance is sustainability i.e. the protection of natural resources including measures to mitigate climate change. A scientific consensus has developed that three of the most important issues of the 21st century are food security, the depletion of the world's natural capital and climate change [18]. Agricultural production makes great demands on natural resources; not only land but also freshwater and none renewable resources such as fertilizers. Agriculture is responsible for around 10 per cent of global greenhouse gas (GHG) emissions, though the impact increases markedly if deforestation is included. The challenge of conserving natural resources and reducing agriculture's GHG emissions must be set alongside concerns regarding the world's ability to adequately feed its population in the future.

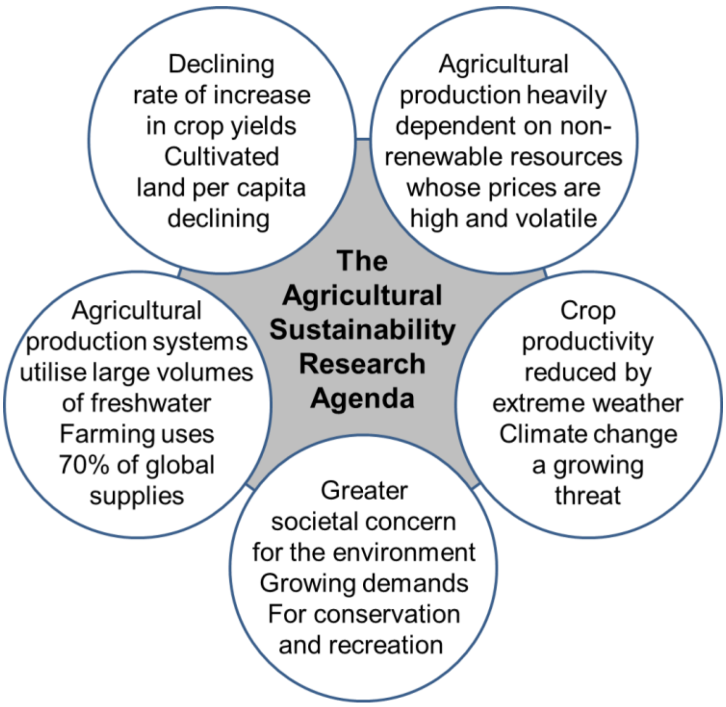
V.2. By 2050, global demand for food is projected to grow by some 60 per cent and meeting this demand from existing agricultural resources will necessitate a comparable increase in global agricultural TFP. Maintaining – let alone increasing – the UK's contribution to global food production will therefore require a similar rise in domestic agricultural TFP. But in rising to this challenge science will need to find solutions to an unprecedented confluence of five fundamental problems: a steady decline in the area of good agricultural land per capita; the slowing in the growth of crop yields; increasing pressures on the availability of freshwater; high and volatile prices for key resources eg, energy and fertilizers; and the adverse effects of extreme weather caused by climate change.

V.3. In its widely praised report which discussed in some detail how the agricultural industry might effectively respond to the challenges outlined above the Royal Society introduced the phrase *sustainable intensification* [19]. Recognising the severe restraints on the scope to increase the agricultural land area and the availability of freshwater, the report's authors recognised the need to intensify production i.e. increase, the output from the world's current area of cultivated land. But this additional production would have to be delivered without excessive use of non-renewable resources and further damage to essential ecosystem services, hence the word 'sustainable.' Put simply, sustainable intensification reinforces the central importance of TFP where higher crop yields are delivered alongside the conservation of natural resources and the minimisation of GHG emissions. The role of science in rising to the 21st Century trilemma of producing more food while reducing the industry's demands on non-renewable natural resources and mitigating GHG emissions is undeniable. According to John Beddington the UK Government Chief Scientific Adviser from 2008 to 2013 the agricultural industry needs a scientific revolution with a particular focus on … *crop improvement; smarter use of water and fertilizers; new pesticides and their effective management to avoid resistance problems; the introduction of novel non-chemical approaches to crop protection; reduction of post-harvest losses; and more sustainable livestock and marine production. Techniques and technologies from many disciplines, ranging from biotechnology and engineering to newer fields such as nanotechnology, will be needed* [20, pp61].

Rothamsted's Contribution to Sustainable Intensification

V.4. The Royal Society's report in recognising the importance of science based solutions concluded that in order to deliver sustainable intensification there is a clear need for publicly funded science. Moreover the authors argued that in achieving this outcome genetic improvements via crop science must be augmented by advances in agronomy. These are the areas of research where Rothamsted has a long and successful record. Rothamsted's broad based research encompasses the whole plant system including not only biotechnology, but also agronomy and agro-ecology to guide agricultural practice. And in rising to the challenge of the trilemma a broad based approach will be necessary to alter the fundamental biology of crops and agronomy. Areas of research in which Rothamsted has an enviable track record such as the genetics and phenotypes of plants appear to offer substantial advantages, particularly in the areas of photosynthetic efficiency, nitrogen fixing, increasing biotic and abiotic stress tolerance and breeding for disease resistance. Figure V.1 provides a summary of the areas that Rothamsted, and other research institutions, must now concentrate on providing science based solutions.

Figure V.1: The Agricultural Sustainable Research Agenda



V.5. Rothamsted Research has set out its strategy for responding to these challenges involving developing innovative approaches to crop genetics, nutrients, water utilisation, plant protection, nutrition and soil productivity. Rothamsted's strategy, in collaboration with partner research facilities in the UK and beyond, is designed to deliver the scientific knowledge, innovation and agronomic practices that will increase both crop yields and quality while minimising the use of non-renewable resources within sustainable production systems. The strategy which relies on a mixture of mathematical modeling, laboratory experiments and field trials covers four discrete areas of research: to more than double potential wheat yields by 2020; to improve the nutritional value of wheat and brassica seeds; to provide renewable and low carbon crop alternatives to fossil fuel-based energy; and to design practical, sustainable agricultural systems. In essence, sustainability is a theme that runs through all of the work at Rothamsted Research.

Box V.1

Energy Crops

There is widespread agreement that the world needs to reduce its dependency on fossil fuels in order to alleviate global climate change and to provide sustainable sources of energy for the future. In rising to this challenge Rothamsted scientists are focusing on 'second generation' sustainable bioenergy crops such as willow, poplar, miscanthus and switchgrass. These crops have the advantage that unlike bio-crops eg, sugar beet and maize, they do not compete directly for arable land and their production does not involve high inputs of nitrogen fertilizer.

The production of these ‘second generation’ perennial bioenergy crops saves on nutrient and pesticide inputs and GHG emissions associated with arable bio-crops as they recycle the majority of their nutrients during growth. They are fast growing with the potential to produce large yields and provide a feedstock for heat, power and fuel processes that is close to being carbon neutral ie, the quantities of carbon dioxide released into the atmosphere when the crops are burned are equal to those absorbed by photosynthesis when the crop is grown.

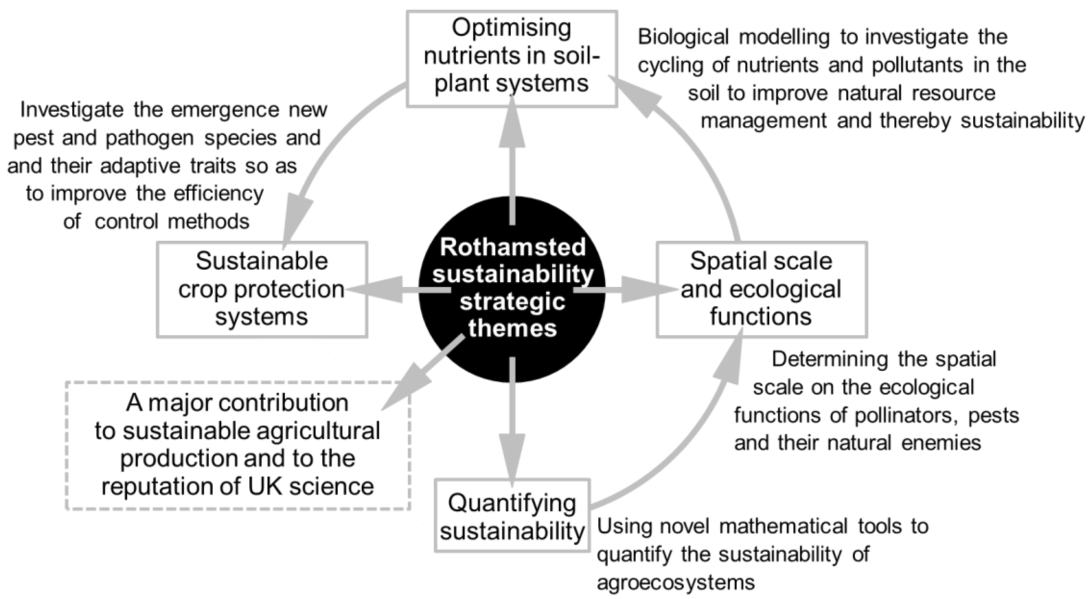
In its research Rothamsted Research has explored the possible use of a large number of different 'non-food' plant species as biomass crops. AS a result of this work two main types of ‘second generation’ energy crops were identified for UK farmland: coppiced trees and energy grasses. The most developed and widely grown biomass crops in the UK are Short Rotation Coppice (SRC), willow (Salix) and miscanthus grass. Bioenergy research at Rothamsted is now focusing on improving the productivity of these specific crops.

V.6. At the heart of Rothamsted’s programme to double potential wheat yields is the objective of using crop science to reduce the volume of natural resources employed and the environmental impact per hectare. The research is focusing on genotype improvements through improved photosynthetic efficiency, altered canopy and root architecture, modified seed development and enhanced nutrient utilisation efficiency. Very importantly in attempting to substantially increase in photosynthetic efficiencies the research is aimed at doing so without increasing the units of water and using advanced sustainable technologies to mitigate yield losses through pests and diseases. In addition Rothamsted’s researchers are building on their understanding of soil properties and root characteristics to help breeders produce new crops that are more efficient in their uptake of water and nutrients.

V.7. Rothamsted is exploiting the genetic knowledge it has uniquely developed from its long-term trials in perennial energy crops to increase the biomass and energy production from Willows and Miscanthus. This research is contributing to the UK's target of an 80 per cent reduction in greenhouse gas emissions by 2050 via the development of energy crops and the increased sequestration of carbon in agricultural soils. Lowering carbon emissions is part of a more general approach by Rothamsted to researching more sustainable agricultural systems involving improved ways of managing pest control, biodiversity, grazed grassland and soils. This research builds on Rothamsted's existing work on the primary mechanisms of resistance. It also involves researching and developing alternatives to traditional pest control by exploiting its long-established expertise in chemical ecology and the ecology of pests as well as developing new knowledge of the key soil parameters that are important to sustainability.

V.8. Building on its capability Rothamsted Research is currently developing its future strategy for its sustainability research. Currently four broad themes are being explored: sustainable crop protection; optimization of nutrients in soil-plant systems; movement and spatial ecology in agricultural landscapes; quantifying sustainability as summarised in Figure V.2. By it focus on sustainable intensification, Rothamsted Research is likely to continue making significant and valuable new contributions. Its new science strategy will also require new ways of working, staying focused on a an outcome-driven R&D approach, including working closely with public and private sector partners.

Figure V.2: Rothamsted's Sustainable Intensification Themes



Box V.2
Reducing Greenhouse Gas Emissions

Rothamsted scientists have demonstrated how improvements in nitrogen fertilizer manufacture and application could help reduce China's agricultural greenhouse gas emissions by around 60 per cent by 2030. This emissions reduction could contribute an overall decline in China's greenhouse gas emissions of 6 per cent and therefore amounts to a significant contribution in the global battle on climate change. Working in collaboration with China's Agricultural University, Beijing, Rothamsted scientists used their knowledge of fertilizers to examine several scenarios for reducing over-use and mis-use of nitrogen fertilizer on Chinese farms and calculating the decreases in greenhouse (GHG) emissions that could be achieved. The works revealed that a combination of technical innovations in manufacturing nitrogen fertlizers and changes in agricultural management could result in annual GHG emissions being reduced to of 204 teragrams of carbon dioxide equivalents (Tg CO2-eq) instead of the projected 542 Tg CO2-eq by 2030. China is the world's biggest manufacturer and user of nitrogen fertilizers – accounting for around 30 per cent of global manufacture – in order to feed its population of 1.3 billion people. In addition to identifying the scope for more sustainable use of nitrogen fertilizers the researchers also set out how China could change its policies and current use of subsidies to bring about more efficient agricultural and environmental practices on Chinese farms.

The Wider Benefits of Rothamsted Research

V.9. As observed above the benefits of agricultural research that do not have an agricultural productivity component are very difficult to measure but nevertheless of significant potential value. This applies to research that results in raising the nutritional quality of crops. To give but two examples, Rothamsted is researching the synthesis and feruloylation of wheat cell walls to develop wheats with enhanced health benefits eg, fibre and minerals. It is using metabolic engineering to develop oilseeds capable of producing high levels of polyunsaturated fatty acids, typical of those found in oily fish. That there is a value; indeed, a significant value in developing health enhancing crops is beyond doubt but again attempting such an exercise is beyond the scope of this report.

V.10. Although the focus of this report is the benefits of Rothamsted's research to a sufficient, affordable and high quality food supply for the UK's population, it is important to acknowledge – particularly in the knowledge that the 21st Century trilemma is a global one – Rothamsted's involvement in overseas research projects and its worldwide reputation as a global leader in plant and agricultural sciences. This is another area where Rothamsted adds value particularly where it is engaged in collaborations with other centers of research excellence to help countries to improve and increase their agricultural production. From a clinical economic perspective we might be tempted to view such activities as a contribution to the value of the UK's exports of services but such peer-to-peer collaborations not only enhance Rothamsted's scientific reputation but also that of the UK's. Rothamsted has many joint projects involving partners from across the world and the value of being able to engage with the best in strong international linkages is enhanced by the opportunities they offer to exploit synergies with partners working on themes to improve the productivity, quality and sustainable of crops and livestock to generate efficient solutions to global issues in these areas.

V.11. Rothamsted Research works with developing countries to promote and share excellence in agricultural and environmental sciences as well as addressing concerns relating to sustainability. It fosters international co-operation in research for the benefit of international development and provides training opportunities and other capacity building measures to strengthen national research. Rothamsted is an important training destination for post graduate and postdoctoral participants from overseas. As such it has become a very important linkage in the development of lasting relationships and collaborations with scientists throughout the world and a consequence is that it now has a large number of alumni who wield substantial influence in universities, research institutes and private companies around the world.

Box V.1
Educating the Future

Rothamsted has joined with the University of Hertfordshire, the Royal Veterinary College and Oaklands College to create a new undergraduate programme designed for students interested in gaining scientific knowledge in the area of agricultural production systems and food security. It has been developed in consultation with leading industry players in agriculture and food production, so that the students will benefit from understanding aspects of sustainable agriculture and food security both in the business environment, food production and the management of land.

The degree includes modules ranging from cell biology to global agricultural systems. Part of the degree will include taking work placements of up to a year and therefore the students will gain insight of the current and future needs for innovation throughout all parts of the food production system and in so doing they will enhance their employability prospects. Rothamsted Research Director and Chief Executive, Professor Achim Dobermann commented that 'the next generation of young people will be the one to lead transformative changes in the world, towards a more sustainable development path. Through this new programme Rothamsted will broaden its contributions to equipping young people with the knowledge and skills that will be required for a sustainable intensification of agriculture and food systems.'

V.12. Another dimension of the value generated by Rothamsted Research arises from a particular feature of agricultural research in that some of the benefits spillover to other areas that were not the original purpose of the research. These are indirect or incidental benefits but should be viewed as multiplying the directly assessed value of Rothamsted's erudition. An example of a tangible research spillover or 'positive externality' would be a situation where a solution arrived at to control insects on a particular crop is likely to be applicable (perhaps with modifications) to other crops. Many spillovers of agricultural research are intangible. Such benefits would include reduced stress for farmers as a result of lower production costs and/or the ability to better control disease. Again if higher productivity increases the scope to release land for recreational activities, wild-life habitats or carbon sequestration, this would be a difficult to quantify but nevertheless amounts to a very real and valuable addition to the quality of life. It follows that a full measure of the benefits of agricultural research should ideally take-in the spillover benefits but in practice quantification is practically impossible.

End Piece

V.13. We have estimated that in the absence of Rothamsted Research's cumulative research output UK consumer food prices would be almost 5 per cent higher than they actually are. The effective of this would be an annual increase of more than £2 billion pounds in household's expenditure on food and a further increase of £1 billion in expenditure on food eaten outside the home and in alcoholic drinks. Thus, we value the annual contribution of Rothamsted Research's erudition to feeding the nation in excess of £3 billion pounds a year. An additional benefit to society from the provision of affordable agricultural produce – particularly fruit and vegetables – are the nutritional and health benefits as household's increase consumption. While its contribution to lowering the cost of adequately feeding the population is the main benefit of Rothamsted Research other tangible benefits flow from an agricultural industry that is competitive and productive. For example, many jobs in the food chain depend on agriculture. Employment in food processing, manufacture, wholesaling and distribution amounts to some 663,000 jobs spread across 28,309 enterprises. If the price of food was higher, the food industry would be smaller with implications for the number of enterprises as well as employment. And a less productive agricultural industry would be accompanied by a reduction in the area of countryside available for leisure and recreation as farmers sought to bring into production less productive land.

V.14. The foregoing suggests that the value to the nation of the tangible benefits of agricultural scientific research are considerable. Although impossible to measure the intangible benefits are also likely to be very large. A major intangible benefit of the work of an institution such as Rothamsted Research is the contribution to expanding the general pool of knowledge. Research spillovers are a major justification for public funding of basic research: it expands the scientific information available to both other research institutes and commercial organisations to draw upon in their activities. Publicly funded basic agricultural research not only supports future agricultural research but studies have shown a positive impact on research elsewhere in the food chain. Put simply government funding for basic scientific research expands the technological opportunities available to society. Finally, the spillovers extend beyond national borders creating the scope for the world's poorer nations to raise agricultural productivity and thereby to reduce poverty.

V.15. What is clear is that the returns to investment in agricultural science continue to be enormous. Perhaps 25 years ago it was understandable that many governments and food industry participants believed that the first green revolution had worked its magic and provided the science and technology to feed the world. Consequently in the ensuing years, across the developed world governments reduced funding for agricultural R&D. Now we are less sanguine. Once again we are reliant on science to provide solutions to the trilemma of challenges now facing agricultural production. As noted above a notable feature since the early 1990s has been a significant scaling back in public expenditure on agricultural R&D across developed nations. And public funding has declined more in the UK than elsewhere. The science underpinning food crop production – as in all areas of biology – is being revolutionised by several new technological developments including genome sequencing and genetic modification. Both these technologies offer the prospect of greatly speeding-up the breeding of desirable traits in plants and are embraced in Rothamsted's research strategy.

Appendix I

Table AI.1 below shows the price elasticities for various food groups consumed by households in the UK used in this report. They are calculated using the Defra publication [21], Family Food 2011. Although the publication also includes its own set of price elasticities of demand for various food groups we have chosen to calculated our own using data shown how consumers respond to changes in food prices over the longer term – in this case 2007 to 2011. Economic theory suggests that consumers normally respond to an increase in the price of a food product by purchasing a smaller quantity. If the product is viewed as essential the percentage decline in the quantity consumed will be smaller than the percentage rise in price. In the jargon the product is price inelastic and the elasticity coefficient will fall between 0 and −1. In practice the situation is complicated as consumers may choose to trade down to lower quality substitutes.

In this study we hypothesize that prices are higher because overall supply is lower. This is a different situation to one where a household can respond to a supply shortfall by switch to a cheaper alternative and therefore to allow for switching would be to undervalue the full value of an overall increase in the volume and quality of food produced as a result of scientific advances. The elasticities set out in Table AI.1 are consistent with the general finding by Defra that for most food products demand is inelastic.

Table AI.1: Own price elasticities for UK food and drink products

	Own price elasticity		Own price elasticity
Bread & cereal products	-0.33	Potatoes	-0.31
Biscuits & cakes	-0.10	Vegetables	-0.21
Milk & dairy products	-0.19	Fruit	-0.39
Carcase meat	-0.12	Beverages	-0.16
Eggs	-0.30	Alcohol	-0.32

Source: Authors calculations based on Defra's Family Food 2011

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