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The potential to increase productivity of wheat and oilseed rape in the UK

John Spink, ADAS Rosemaund, Hereford HR1 3PG
Peter Street, LINK Facilitator, Defra, London
Roger Sylvester-Bradley, ADAS Boxworth, Cambridge CB23 4NN
and Pete Berry, ADAS High Mowthorpe, North Yorkshire YO17 8BP

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Contents

Abstract

Agriculture and its technologies face unprecedented expectations for the 21st century. This briefing document considers the flexibility of land use in the UK (Part A), and prospects for crop production in the UK both in the short-term (Part B), as affected by expansion and intensification of cropping and improved crop management, and in the longer term (Part C), as affected by publicly funded research and innovation.

It is concluded that UK production of wheat and oilseed rape could be increased by 41% and 55% respectively over the next five or so years, but that this would depend on sustained high prices for crop products and it would cause some adverse environmental effects, particularly increasing greenhouse gas emissions and decreasing biodiversity through conversion of land to cropping.

However, the longer term holds a far more attractive prospect. The potential productivities of wheat and oilseed rape in the UK's exceptionally conducive environment for primary production are at least double what is currently achieved. Analysis of ideotypes designed to deliver such high levels of productivity indicates that they are compatible with reduced green house gas emissions and increased biodiversity. This is not only because high crop productivity could free land for other uses, but because productive crops are inherently efficient in their use of resources. However, the scientific and technological challenges in achieving potential productivities exceed those facing the UK 50 years ago, when the UK resolved to achieve self sufficiency in food. A second such success-story will depend on concerted programmes of public investment and support of at least equivalent extents to those of the 20th century.

Executive summary

The current diverse expectations of agriculture and its technologies are unprecedented. But agriculture's principal purpose remains the conversion of carbon dioxide, water and nutrients to foods, fibres and fuels through managed photosynthesis – primary production by cropped species. This briefing document, prepared to inform UK policy-makers, summarises the dynamics of the UK's cropped land (Part A) and explores the prospects for advancing production of its two most extensively grown crops, wheat and oilseed rape, both in the short term (Part B) and the longer term (Part C). Part B examines the scope for farms to extend cropped areas and to apply existing technology more widely. Part C examines the theoretical maxima for productivity of these two species in the UK environment, and uses current knowledge and ideas from the crop science community to detail the research needed to enable crop productivity to approach its potential. Environmental impacts are considered throughout, particularly on green-house gas emissions, because these are the main concern associated with increasing productivity.

Cropping in the UK has always been dynamic in response to market conditions. From 3M ha in the 1890's, the cereal area has fluctuated between 2M ha in the 1930's depression to 4M ha under price support policies in the 1980s. Current cereal area is again at 3M ha but increasing. Market conditions and technology also determine the balance between particular cereal and oilseed crops. Oats were replaced by barley as the main cereal in the 1950s when the internal combustion engine took over from horse power and wheat assumed predominance in the 1970s as its relative yield was increased by the 1st Green Revolution, and as plant breeding and the Chorleywood baking process enabled bread-makers to use more UK wheat. Wheat area has remained at about 2M ha for the last 20 years, whilst the area of barley has declined, being replaced in part by more profitable oilseed rape crops.

Prospects for crop improvement in the short term (Part B)

It is concluded that in 5-7 years there is a potential to increase annual production of wheat by about 5.8Mt to 20.1Mt (41% increase), of total cereals (inc. wheat) by 5.4Mt to 25.7Mt (27% increase) and of oilseed rape by 1.1Mt to 3.1Mt (55% increase). Most of these increases come from bringing uncropped land and grassland into production. Gains also arise from increased cropping intensity in arable rotations and better crop management. In the short term, expected gains through genetics are small but in the longer term the potential for genetic gains is large (Part C).

Whilst having the largest effect on production and being relatively easy to achieve the expansion of cropping has less satisfactory environmental repercussions than intensification or improved crop management. Yields on newly cropped land would be low and inputs of fertiliser and pesticides would be high so the expanded production would marginally increase resource use and green house gas emissions per tonne. Each hectare converted to cropping will release CO_2 previously sequestered, according to the duration of the uncultivated period. The most recently cultivated land should be favoured for conversion, but conversion of some temporary grassland (<5 years uncultivated) is likely, and would bring significant net CO_{2e} emissions – 3.7 t/ha/yr or more. Expansion of arable production onto set-aside and grasslands is also likely to bring public opposition due to a perceived negative impact on biodiversity.

Intensification of wheat and oilseed rape production is easily achieved; indeed crop areas are already reverting towards those seen when prices were higher. Intensification will be more benign for green house gas emissions than expansion of cropping, particularly if production to replace the crops displaced can be partly achieved by increases in productivity. However, intensification may have some negative impact on biodiversity through reduced crop diversity, especially less spring cropping. The main risk to intensification is from regulation and restricted availability of the plant protection products necessary to combat the associated increases in pest, weed and disease pressures.

Improved crop management will be the most environmentally benign route to greater production with little effect on green house gas emissions or biodiversity. However it will be the most difficult and protracted means of increasing production, depending on confidence in sustained profitable prices – we estimate that at today’s input prices more than £170/t for wheat and £410/t for oilseed rape – and on filling significant skills shortages.

Overall, short term improvements in crop production will depend on significant private investment to increase capacity of machinery, storage and transport, and significant public investment to educate skilled staff at all levels of the industry. Given global shortages of the major fertilisers (nitrogen, phosphate and potash) there will also need to be international investment in fertiliser production capacity or technological innovations to decrease nutrient requirements of cropped species.

The current European review of pesticide approval (EC/91/414) threatens losses of active ingredients for pesticides and is of major concern. The net impact could be to cut as much as 50% of current production on some farms. Further loss of ingredients through reduced discovery or approval, combined with continued development of weed, pest and disease resistance, could decrease production in the longer term, perhaps by as much as 70%. Research investment to develop innovative but practicable solutions to reduce the negative impact of pests and diseases on crop yields is urgently needed.

Longer term prospects for crop improvement (Part C)

With the adverse side-effects of short term increases in crop production, prospects for production in the longer term are of crucial concern. This will depend solely on progress in crop productivity, particularly as driven by publicly funded research and innovation. The conclusions here are far more promising – large gains in productivity could be accompanied by significant environmental gains – albeit that these innovations cannot be predicted with complete confidence and that they will take time, and sustained investment.

Crop improvement through breeding, husbandry and protection has largely used empirical approaches hitherto, but the longer term potentials of wheat and oilseed rape are considered here from a functional perspective. This is partly because physiological and genetical knowledge of yield determination in these species is now sufficient to allow some confidence in the estimation of yield expectations, and partly because the future challenges for crop improvement are more diverse than in the past. Thus the crucial interactions and trade-offs, particularly between productivity and efficient resource use, can be anticipated and considered. The report therefore adopts a design approach whereby feasible physiological targets are set and appropriate genetic or husbandry-based innovations are suggested for research. These are accompanied by an analysis of mechanisms to reduce the impacts of the biotic factors (pests, disease and weeds) that threaten to erode yield potentials; again genetic or husbandry innovations are proposed and specific research is outlined here.

Theoretical yield potentials in the UK environment, assuming that future research enables all physiological targets to be met, have been estimated to be 19.2 t/ha for wheat (Sylvester-Bradley *et al.*, 2005) and 9.2 t/ha for oilseed rape (Berry & Spink 2007). On current crop areas these yields would increase annual UK production to 35.3M t and 5.0M t for wheat and oilseed rape respectively, or 250% in both cases. These compare to current yields used in section B of 7.74 and 3.2 t/ha respectively for wheat and oilseed rape. Applying the management and genetic improvements from existing knowledge in section B was predicted to increase yields to 8.71 t/ha for wheat and 3.88 t/ha for oilseed rape. Clearly the realistic yield potential will be lower than the theoretical yield potentials outlined above. A recent review of yield potential (Defra, 2005b) estimated yields for 2025 and 2050 for wheat of 11.4 and 13.0 t/ha and for oilseed rape of 4.1 and 5.7 t/ha. These yields seem readily achievable given significant investment in production research, which would lead to production on the current area of 23.9 mt of wheat and 3.1 mt of oilseed rape, both above that predicted using current technology on significantly increased cropped land area.

For wheat to achieve its potential the targets requiring research and development are considered to be:

- Early canopy closure,
- Early stem extension,
- Delayed canopy senescence,
- Better nutrient capture and conversion,
- Improved light conversion,
- Increased partitioning of dry matter to grains,
- Better water capture and conversion, and
- Sustainable protection against pests, diseases and weeds.

It is considered that the appropriate research would require a wide range of timescales to application, and it would have a wide range of impacts. Generally, short-term research targets would have smaller impacts and longer-term research targets would have larger impacts. Also, in almost every case, improvements in productivity are predicted to reduce green house gas emissions per tonne of grain production. Given that the potential yield improvements are large, it is likely that current production could be maintained with significantly reduced land use, and that this would cause significant additional decreases in green house gas costs of crop production.

For oilseed rape to achieve its potential the key targets for research and development are considered to be:

- Improving rooting to exploit soil resources (nutrients and water),
- Better nitrogen conversion,
- Improved pre-flowering assimilate production and storage,
- Increased seed sink capacity,
- Improved light conversion, especially post flowering,
- Reducing harvest losses, and
- Sustainable protection against pests, diseases and weeds.

Again the timescales are various and there is an overall association between increasing productivity and decreasing greenhouse gas emissions.

Cross-rotational issues will be crucial in enabling species-specific innovations, particularly the control of weeds and the optimisation of farming systems. Necessary research targets include:

- Improved prediction of weed fecundity, population dynamics and competitive ability,
- New herbicide development to reduce risks of resistance and water contamination,
- Improve spatial targeting of herbicide applications., and
- More effective non-chemical methods of weed control

Whilst it is clearly difficult to estimate the exact time to delivery of any of the targets in most cases some progress can be made in the short term (<5 years) primarily through husbandry developments. Most of the targets will also require some genetic improvement which is likely to take 10-15 years and other targets will require the introduction of novel traits from wild relatives or unrelated species which could take up to 25 years, the likely timescales are outlined in the table below.

The achievement of any of the targets will have a varying impact on productivity and on the GHG costs of production. Generally speaking the reduction in GHG cost is proportional to the yield improvement assuming no increase in inputs. In some cases the improvements would result in both a production increase and a reduction in N fertiliser requirement in which case the reduction in the GHG costs per tonne of production is disproportionately large. The relative impacts of the targets on productivity per unit area and the GHG cost per tonne of production and per unit cropped area is summarised below. It should be noted that the potentially large GHG benefits of improved productivity on existing productive land in terms of avoiding indirect land use change to meet growing global demand or releasing land from production have not been taken into account. A more extensive life cycle analysis of the proposed changes should take this into account as well as the impact via changes in livestock production.

Lastly, it is clear that the significant research programmes envisaged to achieve improvements in crop productivity will depend upon a wide range of under-pinning investments, particularly in developing design strategies for crops, in germplasm enhancement and characterisation, in plant breeding, in crop nutrition and protection, in informatics and in development of the essential human resources for all these initiatives.

Intervention	*Time to impact (years)*	*Yield impact*	*GHG impact per t*	*GHG impact per ha*
WHEAT				
Early canopy closure C.1.2.1	**5-10**	⇑	⇓	=
Earlier stem extension C.1.2.2	***10-15***	⇑	⇓	=
Delayed canopy senescence C.1.2.3	***5-15***	⇑ ⇑	⇓ ⇓	⇓ ⇓
Nutrient capture and conversion C.1.2.4	***5-20***	⇑	⇓ ⇓ ⇓	⇓ ⇓
Improving light conversion C.1.2.5	***5-25***	⇑ ⇑	⇓ ⇓	⇓
Increased partitioning of dry matter to grains C.1.2.6	***5-20***	⇑	⇓	⇓
Water capture and conversion C.1.2.7	***5-20***	⇑ ⇑	⇓ ⇓	⇓
Protection against diseases C.1.3.2	***5-25***	⇑	⇓	⇓
Protection against pests C.1.3.3	***5-25***	⇑	⇓	⇓
Protection against weeds C.1.3.4	***5-25***	⇑	⇑	⇑
OILSEED RAPE				
Improving rooting to exploit soil resources (nutrients and water) C.2.2.1	***5-15***	⇑	⇓ ⇓	⇓
Nitrogen Use Efficiency C.2.2.2	***10-15***	⇑ ⇑	⇓ ⇓ ⇓	⇓ ⇓
Maximising sink capacity C.2.2.3	***10-15***	⇑ ⇑ ⇑	⇓ ⇓ ⇓	⇓
Improving post flowering radiation use efficiency C.2.2.4	***5-15***	⇑ ⇑	⇓ ⇓	=
Improving pre-flowering assimilate production and use for seed filling C.2.2.5	**10**	⇑ ⇑	⇓ ⇓	=
Reducing harvest losses C.2.2.6	***10-20***	⇑ ⇑	⇓ ⇓	=
Protecting against diseases C.2.3.2	***5-15***	⇑ ⇑	⇓ ⇓	⇓
Protecting against pests C.2.2.3	***5-15***	⇑	⇓	⇓
Protection against weeds C.2.2.4	***5-15***	⇑ ⇑	⇑	⇑
CROSS ROTATIONAL ISSUES AND WEEDS				
Weed management C.3.1	***5-15***	⇑	⇓	=
Rotation planning and optimising farming systems C.3.2	***5-15***	⇑	⇓	⇓
UNDERPINNING CROP SCIENCE AND RESOURCES				
Knowledge, techniques and materials	***On-going***	No direct effect	No direct effect	No direct effect

Introduction

Until now global supply for all the major arable grain commodity crops (corn wheat rice) has kept up with "real" demand through increased crop yield per unit area (through improved varieties, knowledge and application of new technology), rather than increased area. The UK has been no exception to this. Because of the success of the agricultural sector in the UK and globally in meeting demand over recent decades, and because of the relative wealth of the UK and its ability to source food on the world market the public has become complacent about food production.

However, currently global demand for grain is rising rapidly driven by growing population and incomes and rising meat production and consumption in developing countries and by demand for bio-fuels worldwide. At the same time yield increases for the major crops have been stagnating (USDA agriculture statistics), there have been crop failures and water shortages, so a serious supply/demand imbalance has developed which, along with export bans and speculation has led to price increases and price instability. Climate change is expected to lead to further instability.

Any supply response is in the context of significant increases in the cost of inputs, particularly for fertiliser and fuel as well as against an historic background of an endemic under-investment in R&D for commercial agriculture across the world driven by historic oversupply and low prices.

Over recent years the international trade in grains has fluctuated around 250-260 million tonnes or about 12 % of production. Of this, wheat accounts for about 110 m t or 5.5% of global production and for just over 43% of gain exports.

Putting UK arable production into the global context, the UK contributes to just over one percent of global grain production and less than 1% of oilseed production.

Production (1000 t - source USDA & Defra Statistics 2007/8)

		World	**EU**	**UK**
All Grains:	Production	1,796,257	210,598	19,048 *
	Index	100	11.7	1.1
Oilseeds:	Production	280,572	19,157	2,108
	Index	100	6.8	0.8

* NB later analysis uses a figure for total grain production of 20,279 mt which is the average of 2005-7.

As seen below, the UK is currently more or less self sufficient in grains (if the average 2005-7 production is considered) with import/export trade relating mainly to quality adjustment. For oilseed rape, the only significant oilseed currently grown, supply exceeds consumption requirements by a little over 10%. Clearly any increase in domestic demand for human food and industrial use (e.g. bio-fuel) will have an adverse effect on self-sufficiency unless addressed by agronomic interventions.

UK Self Sufficiency (1000 t 2007/8)

	All Grains	**Oilseed Rape**
Production	19,048	2,108
Imports	2,563	67
Exports	2,489	280
Consumption	20,512	1,896
Prodn. as % new supply	100	111

Grains and oilseeds are traded in a global commodity market on the basis of specification and the UK is part of this system, not protected from it. So, in periods of supply shortage the UK users experience rising prices and when the UK increases production or reduces demand this impacts in a small way on reducing world prices. Within the global commodity market, each nation has a mutual responsibility to increase production by the most efficient use of resources and in a sustainable way.

Since globally, the potential to increase productive land area is severely limited without significant environmental implications, the route to solving the problem is through a re-invigoration of yield improvement by:

- Genetic improvement
- Improved crop protection
- Optimised farming systems
- Improved access to supply and marketing services and credit.

The global supply/demand balance is being addressed elsewhere by Colin Thirtle. Since feed grains and oilseeds are part of a global commodity market there is an international responsibility for all producers to respond to the market challenges by increasing production in a commercially viable and environmentally sustainable way. The UK and Europe has a responsibility in this context, in order to do this the first three bullet points above must be addressed.

The purpose of this report is therefore to assess the potential to increase productivity in the UK, to provide evidence to support the estimates and to suggest approaches to achieve the potential, but not to attempt to quantify the cost of these approaches. The potential to increase productivity will depend on the industries capacity and willingness to respond to changing demands, the degree to which current knowledge and technology is being exploited and the potential to develop new knowledge and technologies. The report therefore reviews historic changes in production in the UK (section A) as a means of assessing the industries capacity and willingness to change and defines the potential to increase crop production using current knowledge (section B) and using research based development of new technology (section C). Whilst the report seeks to identify resource gaps, such as training it does not seek to advice on how these gaps should be filled. Likewise a number of research approaches are presented which demonstrate the potential to overcome existing productivity limitations, it is not intended that the ideas presented is an exhaustive list, nor is any prioritisation suggested. It is beyond the scope of this report to define a research strategy although clearly there is a need for a well researched and defined research strategy to maximise the return on both public and private investment.

A. Historic changes in land use, crop production and drivers for change

A.1 Total Agricultural Land use

The total land area of the UK is 24.4 mha of which some 18.4 mha is farmed (crops and grass) the remainder is made up of roughly 3 mha of urban land waterways etc and 2.8 mha of forest. Non agricultural land use has been increasing. Therefore the potential to increase the farmed area is severely limited.

A.1.1 Land use for cropping

Since the mid-1980's the total arable land in the UK has declined by over 1m ha (Figure 1). There are 2 prime explanations for this:

- Total farmed area has declined from 19 m ha in 1987 to 18.4 in 2004, largely due to an increase in forest area. Figures for 2007 show this to be down to 17.4 m ha but this is likely to be due to a change in the way the statistics are collated rather than a further real decline.
- There has been a significant decline in temporary grass land (grass less than 5 years old), from 1.8m ha to 1.2m ha. This loss has been partly due to the replacement of temporary grass with forage maize (included in 'other crops' in Figure 1), and grass not being reseeded and being classed as permanent pasture (grass over 5 years old) and therefore not classed as 'arable' land.

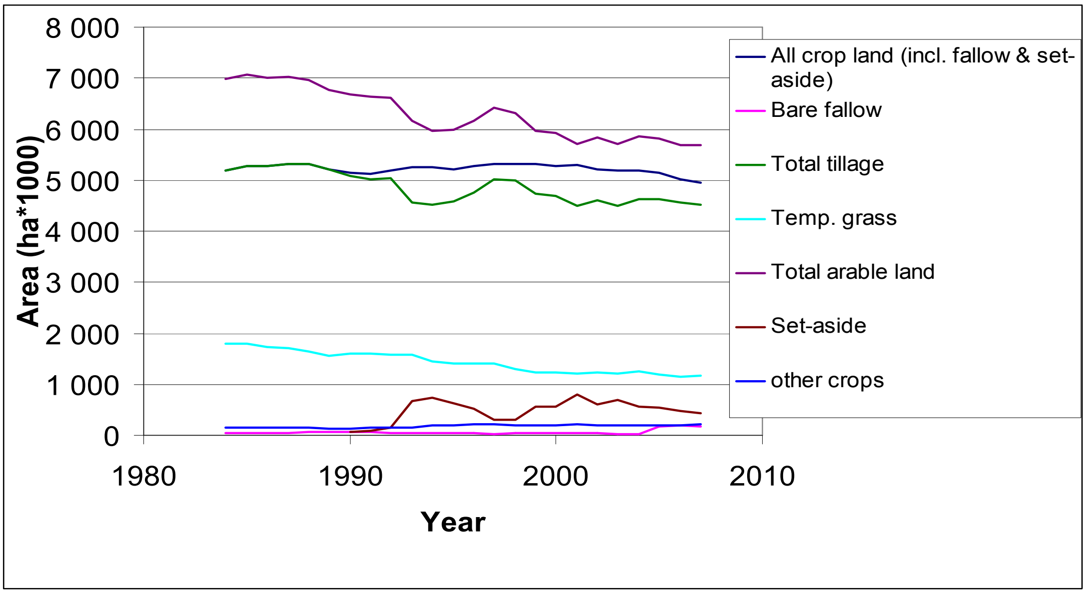


Figure 1 UK land use (ha),1984-2007 source: Defra June census data

Therefore to increase crop production in the UK requires either a switch from production of grass (with consequent effect on the livestock sector) into arable crops or increasing the yield from the currently cropped area.

A.1.1.1 Cereals

Land use

Changing land use and production of commodity crops in the UK is nothing new, Figure 2 shows the areas of the major cereal crops since the late 19th Century. The cereal crop area has continuously changed in response to market conditions. There were 3 mha in the 1890's, which rose briefly during the first world war to 3.4 mha and fell to an all time low of 2 mha in the depression of the 1930's. The area peaked again during the Second World War at 3.4 mha and stimulated by price support policies rose to an all time high of 4 mha in the mid-1980s. Since then, due to cost/price sqeezes the area fell to 3 mha in the early 21st Century but is now beginning to increase again due to improved commodity prices. Therefore, it is clear that farmers have the propensity to respond to market stimuli and to plant extra cereals at the expense of other crops. Improved market conditions will therefore stimulate a bounce back.

Market conditions and technology will determine which cereals are grown and the balance between cereals and oilseeds. Oats were the major cereal crop until the middle of the 20th century when the area went into rapid decline as the internal combustion engine replaced the horse as the source of motive power, the age of renewable transport fuels ended and was replaced by liquid fossil fuels! Oats were replaced by barley as the main crop until the 1980's.

In the 1970's a number of factors including; the development of the Chorleywood baking process (which allowed UK wheat to be included in bread grists at higher proportions), the advent of semi-dwarf wheat and increased yield potential compared to barley, resulted in the wheat area increasing at the expense of barley.

Wheat has remained the dominant cereal crop for over 20 years, with an area of about 2m ha p.a. whilst the area of barley has continued to decline due to low prices making its production uneconomic in many circumstances.

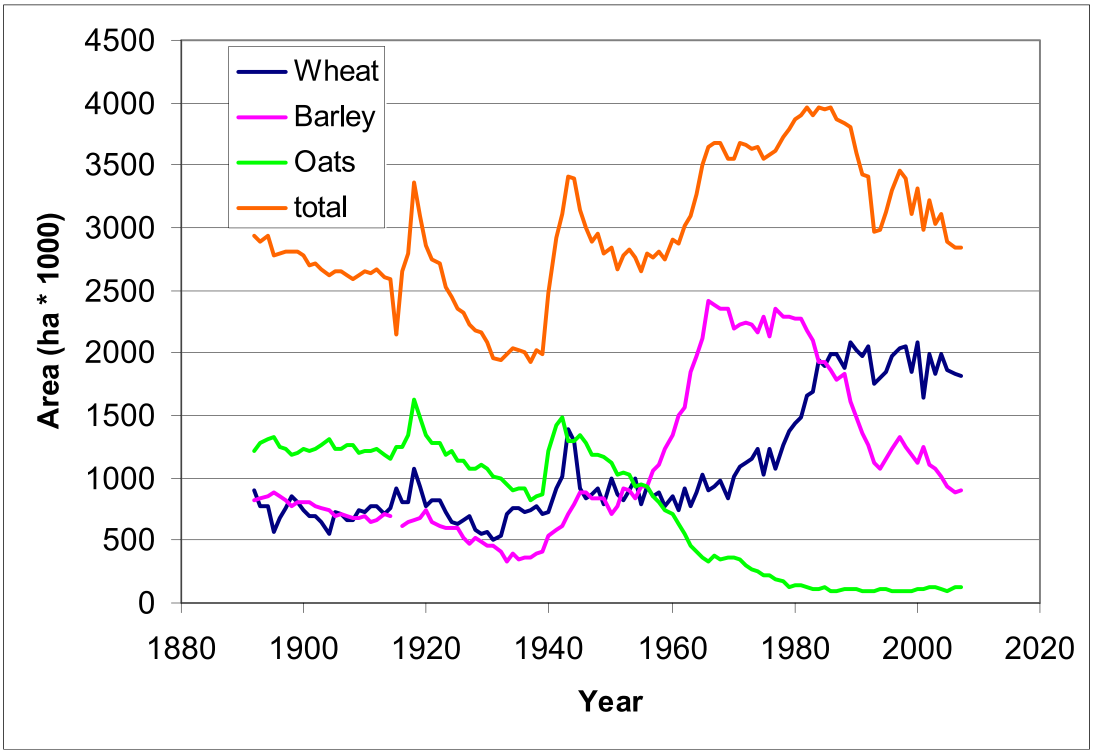


Figure 2 UK Cereal areas (ha), HGCA and Defra June census data1892-2007

Yield

From the end of the Second World War in the quest for food security yields were progressively increased for all crops through plant breeding and crop protection advances, this trend ended in the 1990's when improvement increases declined (Figure 3). All cereal crops yielded about 2 t/ha in the 1890's and by the 1990's had reached about 6 t/ha for barley and oats and just under 8 t/ha for wheat. The reason for the greater yield improvement in wheat was market driven, due to the greater demand and the relatively higher price of wheat, for bread making, as outlined above.

The reasons for the decline in yield improvements is the subject of debate. However a number of contributory factors can be identified:

- Cost/price squeeze resulting in reduced on-farm investment and management attention
- Declining market size and profitability for agricultural input supplies
    - Supplier consolidation and reduced investment
    - Reduced innovation
- Declining genetic gains due to;
    - Insufficient public investment in basic research underpinning commercial plant breeding
    - Poor profitability of commercial plant breeding, and conflicts for resource use between improving traits for yield, pest/disease resistance and environmental targets, associated with public pressure to select for the latter two.
    - Diminishing response to exploitation of existing knowledge/technology
    - Constraints on applying new technologies (e.g. biotechnology)
- Agricultural policies discouraging production

- Restrictions to availability of chemicals, loss of existing active ingredients, limitations to the use of remaining chemicals and lack of incentive and increased regulation limiting innovation of new chemistry.
- Restriction to the adoption of biotechnology
- Decoupling and the need for farmers to invest resource in environmental schemes.

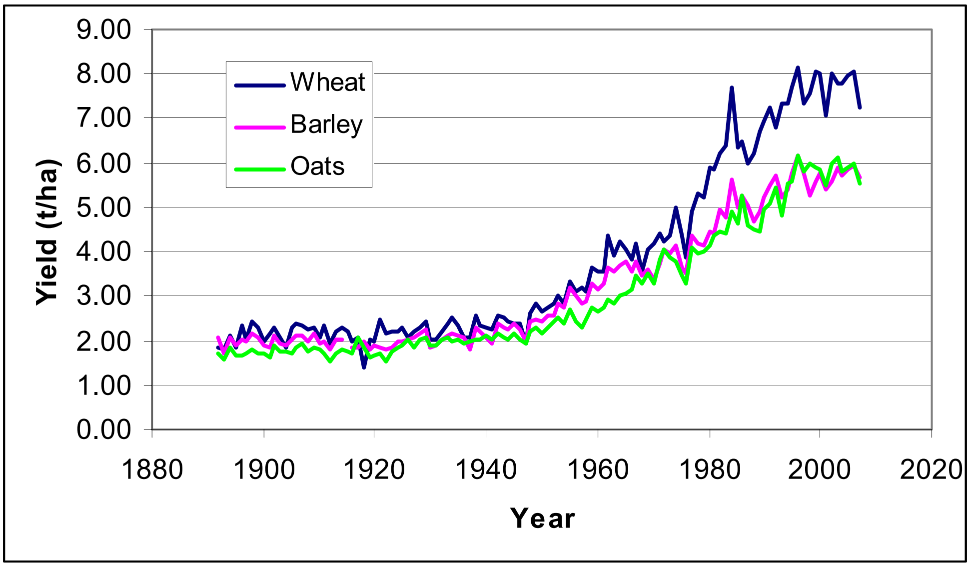


Figure 3 UK cereal yields (t/ha @ 85% dm), source HGCA cereal stats and Defra production statistics

Production

The area and yield changes discussed above resulted in a total UK cereal production of around 5m t p.a. from the end of the 19thC until the 1930's, when it decreased to around 4m t p.a., before progressively rising to a peak of 26 mt in 1984, and declining again to the current level of about 20 mt.

Until the 1930's, oats were the largest single commodity in production (Figure 4). From the 1960's barley production increased rapidly for animal feeding until wheat became the single largest commodity in the 1980's. Since when wheat production has remaining reasonably stable at an average of 14m t. The maximum wheat production occurred in 2000 at 16.7 mt.

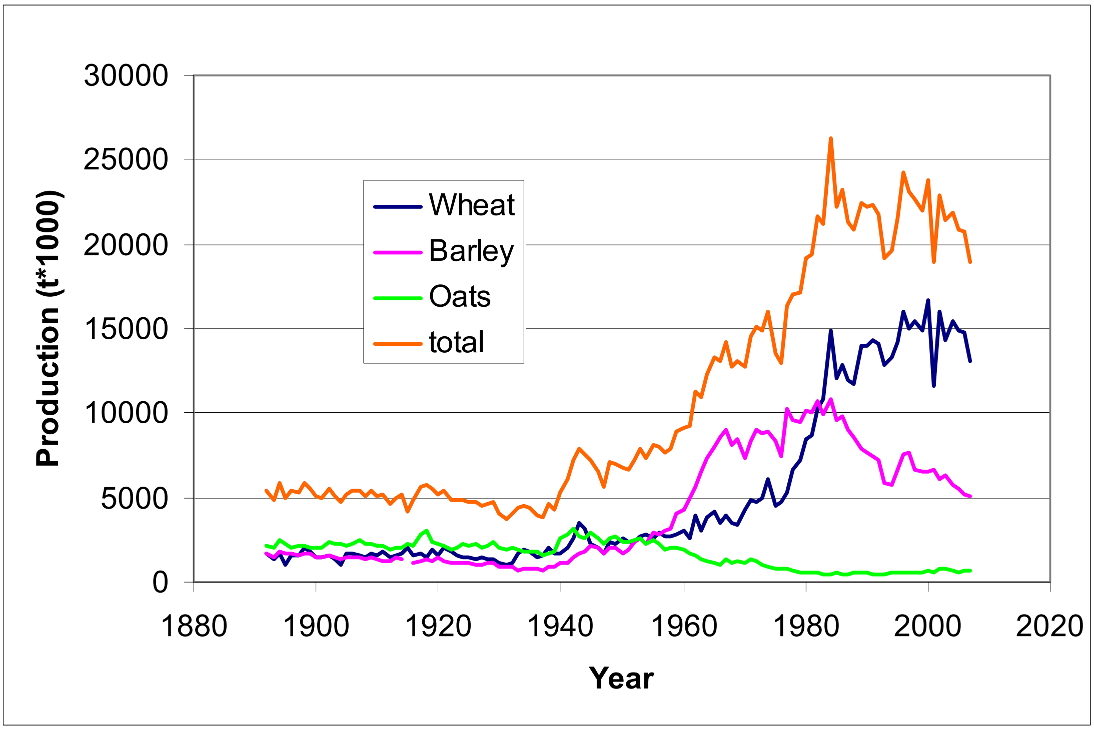


Figure 4. UK annual cereal production (t), 1982-2007 Source: Defra production statistics

A.1.1.2 Oilseed rape

Land use

Oilseed rape grown for oil is a relatively new crop to the UK; in 1970 there were less than 4,000 ha grown. The crop started to be grown more intensively in the mid-1970's and by 1980 there were 91,594 ha. Since the introduction of set-aside in the early 1990's, oilseed rape has been allowed to be grown for non-food uses on set-aside land, to meet the growing demand for rapeseed oil for biodiesel and other industrial feed stocks. The area has continued to increase, Figure 5 shows that it increased from less than 300,000 ha in 1983 to the maximum area in 2007 of 682,000 ha, of which 80,000 ha was grown for non-food use on set-aside land. This increased production is mainly competing with cereals for land.

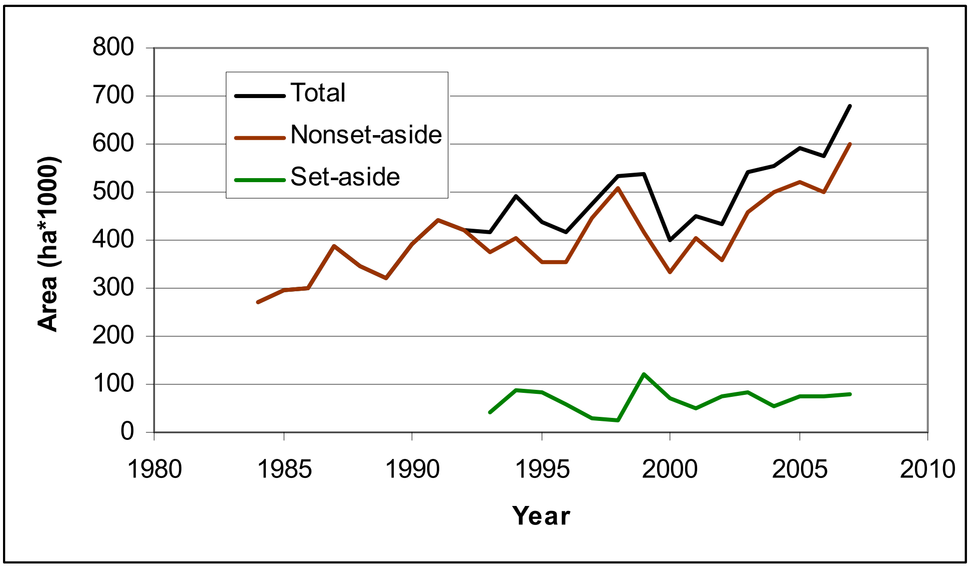


Figure 5. UK Oilseed rape area (ha), 1984-2007 source: Defra June census data

Yield

The average yield of oilseed rape has remained stubbornly static for the last 20 years. We have used the weighted average yield because the apparent yields differences between set-aside and non set-aside are technically inexplicable and may be due to the allocation of on-farm production into food and non-food end uses. Before 1985 there was a rapid increase in the yield of oilseed rape and the fastest rate of yield improvement was in the UK (see figure later). In the late 1980's and early 1990's yield of oilseed rape declined (Figure 6); this was due to the change to low glucosinolate varieties, which meant that the breeding industry had to introduce a novel trait which brought with it a yield penalty. This has yield drag has subsequently been overcome, with associated increased genetic potential. In line with all other oilseed rape producing countries in the world, no significant yield increases can be detected after 1985 (Berrry and Spink, 2006). This may be because;

- Environmental yield potential has been reached (unlikely).
- Yield potential not being realised due to lack of genetic progress, (likely).
- Agronomic practice and climate are preventing genetic potential from being realised (highly likely).

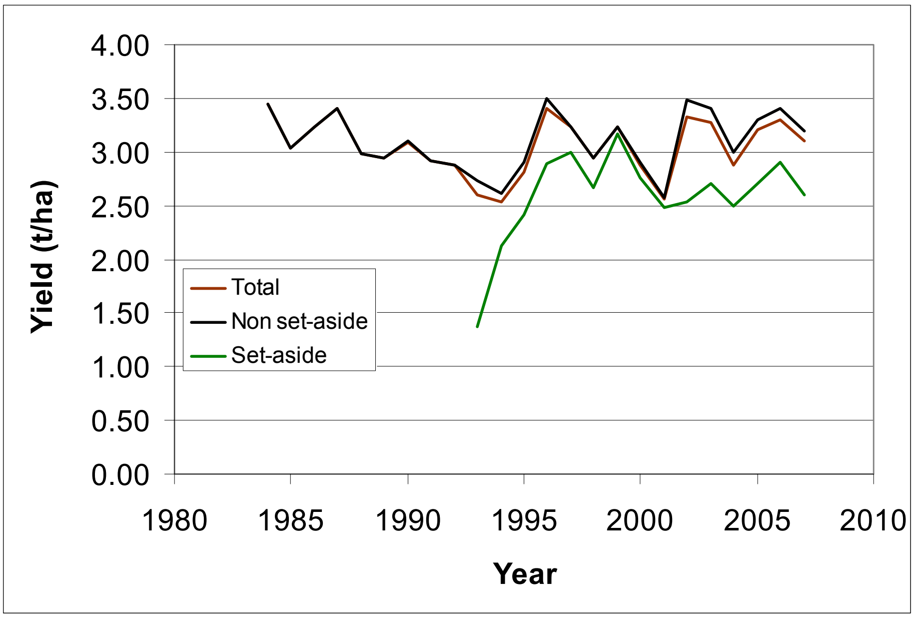


Figure 6 Oilseed rape yields (t/ha @ 91%dm) Source: Defra production statistics

Production

Oilseed rape production (Figure 7) has closely mirrored the area, due to the average yield remaining static at just over 3 t/ha over the whole period. There have, however, been significant season-to-season variations of about 0.5 t/ha, with average yields close to 2.5 t/ha in 1993, 1994 and 2001, and 3.5 t/ha in 1996 and 2002.

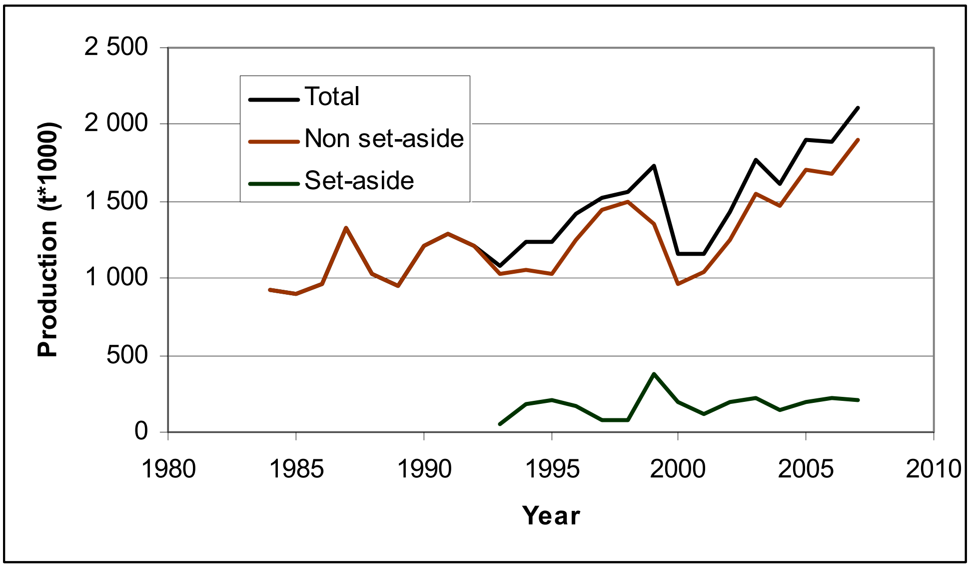


Figure 7 UK annual oilseed rape production (t), 1983- 2007 Source: Defra production statistics

A.1.2 Current drivers for change

The previous analysis shows that land use and production will change in response to market conditions and political priorities.

The above production trends also demonstrate that for the last 20 years there has been a general decline in the intensity of production driven by politics and low commodity prices.

A number of factors have recently driven a decline in world stocks and an increase in world commodity prices, including:

- Population growth
- Increased prosperity in the Far East and Asia driving a change in diet demanding more vegetable oil and grain meat production.
- Poor yields and harvest failures in major grain producing nations such as Australia due to drought and climate change.
- World wide demand for agricultural commodities to produce biofuels.

Sustained high commodity prices which more than offset the increase in input costs (primarily fuel and fertiliser) will therefore reverse these trends and drive an increase in the level of production.

The real driver for change will be the increased profitability of wheat and oilseed rape production and stability of costs and prices.

In terms of profitability the following table models gross and net margins for an average arable farm (ADAS data). The table compares potential profitability in 2005 with 2005 input and output prices with predictions for the 2008 crop based on the same yield assumption but at 2007-8 input and June 2008 output prices. This shows potentially significantly increased profits, from a loss which impeded investment to profitability sufficient to stimulate increased investment and management inputs. Given recent volatility in input and output prices, the question is - what will the long term level of profitability be? And what is the breakeven price or the price level needed to sustain increased investment?

Table 1. Gross and net margin estimates for wheat and oilseed rape.

	Wheat		OSR	
	2005	**2008**	**2005**	**2008**
YIELD/HECTARE	7.74	7.74	3.20	3.20
PRICE/TONNE *	67.00	155.00	145.00	369.00
PRODUCE SALES/HECTARE	518.58	1199.70	464.00	1180.80
DIRECT COSTS	£/Ha	£/Ha	£/Ha	£/Ha
SEED	33.00	40.28	32.60	22.26
FERTILISER	103.00	230.00	104.00	240.00
HERBICIDES	51.00	50.88	63.00	78.44
FUNGICIDES	59.00	66.78	17.80	34.98
GR REGLATORS	11.00	7.42	0.00	0.21
INSECTICIDES	9.00	8.90	6.30	9.12
OTHER SPRAYS	7.00	7.28	7.99	10.28
MISCELLANEOUS	0.00	0.00	0.33	0.00
TOTAL	273.00	411.55	232.02	395.29
Gross Margin	245.58	788.15	231.98	785.51
FIXED COSTS	540.00	610.00	540.00	610.00
Net margin	-294.42	178.15	-308.02	175.51

* 2008 harvest sold forward in May for August delivery

Based on the above model the farm gate prices giving breakeven net margins and the breakeven price plus 20% to allow an adequate level of profitability to stimulate continued investment and improvement are:

	June price (£/t) (27/6/08 for harvest delivery)	Breakeven (£/t)	Breakeven + 20% (£/t)
Wheat	155	132	158
OSR	369	314	377

However during this cropping year both fertiliser and wheat have been highly volatile. For instance wheat prices peaked at over £200/t in the spring and have fallen back to a spot price at harvest of less than £120/t with a current futures price of Nov 2009 of £136/t. At the same time fertiliser prices have been progressively increasing such that whereas it would have cost £230 to fertilise the 2008 crop with fertiliser bought in advance the same application would now cost £311/ha and prices are still rising. The increased fertiliser price has increased the wheat break even price to £142/t which compared to the futures price for wheat for next harvest of £136/t ie production at a loss. Comparable data for oilseed rape show that at current prices fertiliser costs have increased to £333/ha increasing the breakeven price to £344 against a futures price for harvest ’09 of £288/t.

	August price (£/t) (21/8/08 for harvest ‘09 delivery)	Breakeven (£/t)	Breakeven + 20% (£/t)
Wheat	136	142	170
OSR	288	344	413

Using Fertiliser prices of £370/ t for Ammonium nitrate and £590/t for 0:24:24 - Farmbrief 14th August 2008. And fertiliser input rates as per Maff reference book RB209.
Futures prices from FWi.co.uk and United oilseeds.

This ignores the difficulties of financing fertiliser purchase in a short market where the fertiliser has to be bought before the crop is planted, with farmers needing to finance the fertiliser for the current crop yet to be harvested and also the fertiliser for the following year. For a 400ha arable farm on a wheat, oilseed rape rotation at August 2008 prices they would have £128,800 invested in fertiliser for the current crop plus the same amount again for fertiliser for the coming year at total investment of £257,600. Formerly fertiliser for the coming year would have been paid for after the sale of the previous crop and much of the financing would have been in the form of merchant credit. Financing this will limit investment elsewhere in the business.

Against this cost:price squeeze farmers are considering reducing their plantings, so the potential for increasing production described in this part is unlikely to be delivered unless stability and profitability can be restored. Stability is unlikely unless world grain stocks are rebuilt as they are the only counteracting pressure to speculate in the market.

Accepting that output prices will oscillate around a trend, the analysis indicates that an average price higher than those existing today (August 2008, already significantly below the maximum reached earlier in the year) will be required and that if they decrease below the break-even price it is unlikely that the potential to increase production in the UK will be realised. The enthusiasm for expansion in arable agriculture in spring 2008 when commodity prices peaked is already dissipating.

B: Prospects for increasing production using current knowledge

This section of the report sets out to predict the likely scale of increases in production through increased land area being dedicated to the major commodity crops and increased production per unit area brought about by further extension of modern cropping technologies. Estimates are made for the two main UK crops for which there is the greatest pressure to increase supplies (wheat and oilseed rape). Implications for other arable crops are also considered.

The markets for different end uses determine varieties and types of each species planted. The productivities of different types are reasonably similar for both wheat and oilseed rape so this analysis just determines the total potential to increase crop output, without distinguishing end uses. Note that the removal of compulsory set-aside (and the requirement that it could only be used to produce non-food crops) allows free choice of variety on any land.

The analysis uses average areas and yields for the period 2005-7 as its baseline.

Baseline for predictions (detail in Appendix B1**)**	
Average yields 2005-2007 (Defra statistics)	**t/ha**
Wheat	7.74
OSR (mean of food and non-food crop)	3.20
Average areas 2005-2007 (Defra statistics)	**hectares**
Total area on agricultural holdings	17,379,000
Total croppable area	**6,212,000**
Total crops	**4,388,000**
Wheat	1,839,000
OSR (including 77,000 ha for industrial use on setaside land)	617,000
Other arable crops (mainly cereals, sugar beet, pulses & potatoes)	1,764,000
Horticultural crops	168,000
Other croppable land	**1,824,000**
Bare fallow / land withdrawn from production	175,000
Set-aside (excluding 77,000 ha industrial OSR ???)	480,000
Temporary grass (sown in the last 5 years)	1,169,000

The opportunities for increasing production from this baseline using current knowledge include:

- **Increasing the crop area by**
  - Using land previously taken out of production
  - Using land that has been growing grass
- **Increasing the proportion of wheat and oilseed rape in the rotation**
- **Increasing yield per unit area on cropped land by**
  - Improved crop management
  - Genetic improvement
  - Irrigation
  - Fertilising above the current economic optimum/recommended level

Each of these changes will now be considered individually. Of course their impacts would tend to be cumulative, so aggregate effects are calculated at the end of this section, together with some discussion of whether changes might interact.

B.1 Increasing the arable crop area

B.1.1 Using land previously taken out of production

Defra statistics for 2005-2007 show 480,000 ha of set-aside land (of which 77,000 ha were producing non-food OSR) and 175,000 ha of bare fallow (voluntary set-aside) giving a total of 582,000 ha of non-productive cultivable land. We assume that 80% of this can be easily brought back into production, the rest remaining as permanent set-aside because it is not easily cropped (difficult corners, wet land etc). Therefore an additional 465,600 ha of land is available for cropping. It is reasonable to assume that crops on this land would provide average yields.

It is assumed that the maximum intensity for OSR production would be one year in three, but that if yields of second wheats are poor, land may be used in a Wheat-Break-Wheat-OSR rotation ('break' here meaning non-take-all-susceptible crops other than OSR, such as pulses, oats, sugar beet or potatoes). The overall ratio between wheat and OSR will depend on relative gross margins of all crops. These currently favour wheat. However, the gross margins of 2nd wheat crops relative to OSR vary by region and soil type (mainly through pest and disease severities affecting yields). Overall, it seems likely that OSR could occupy 25-33% of the land, wheat 50-66%, and that some of the released land (about 13%, or 60,528 ha) would be used for other break crops. This would partly offset loss of production of 'other break crops' due to increasing intensity of wheat and OSR on land already cropped (see below). In estimating extra production of pulses, oats, sugar beet and potatoes we have assumed the same distribution in the extra area to that in the current area. In reality distribution will depend on relative crop prices and agronomic constraints (see below).

The potential effect:
Current production (2005-7)

Wheat	14,233,860 t/annum (7.74 t/ha)
OSR (from non set-aside land only)	1,728,000 t/annum (3.20 t/ha)

Crop	**Increased area**			**Increased production**		
	Min	Average*	max	Min	Average	Max
Wheat	232,800	270,048 (58%)	307,296	1,801,872 (13%)	2,090,171 (15%)	2,378,471 (17%)
OSR	116,400	135,024 (29%)	153,648	372,480 (22%)	432,077 (25%)	491,674 (28%)
Other		60,528 (13%)				

* percentages are of the 80% of set-aside brought into cropping

Contributions of other crops on former uncropped land

	New area (ha)	**Yield (t/ha)**	**Production gained (t)**
Barley	31,001	5.8	179,803
Oats	3,894	5.8	22,586
Rye, triticale and mixed corn	871	4.9	4,266
Potatoes	7,198		
Sugar beet	0		
Peas & field beans	0		
Linseed	4,603		
Hops	0		
Other crops	68		
Total			206,655

Total increase in supplies

	Wheat	Oilseed rape	Other cereals	All cereals
Extra production (t)	2,090,171	432,077	206,655	2,296,826

The release of unproductive land has the potential to provide for a very significant increase in production, particularly when compared to UK wheat exports which averaged 2.5 mt per annum between 2003 and 2007. Implications for GHG emissions of cropping previously unproductive land will be relatively small; they are detailed in Section B5.2.2.

B.1.2 Increasing the arable area through reduction of grass land

Defra statistics show that there are 1,176,000 ha of temporary grassland (<5 years old) and therefore suitable for cultivation; this has decreased by 35% from 1,800,000 in 1984 due to the downturn in livestock production. Some of this land (c. 140,000 ha) has been converted to the production of forage maize and the remainder left in longer leys and therefore classified as permanent pasture.

Given the decline in the temporary grass area over the last 20 years, it seems unlikely that there will be a further major decline. However, with economics of livestock production still poor compared to arable cropping, most commentators consider that at least a further 10-20% of temporary grass is likely to be converted to arable production, i.e. between 117,600 and 235,200 ha. This land is likely to be utilised in similar proportions to converted set-aside land (i.e. 25-33% oilseed rape and 50-66% wheat) and to give similar yields, as is outlined below.

Conversion		Wheat		OSR	
		Area (ha)	Production (t)	Area (ha)	Production (t)
10%	50% ww:25% OSR	58,800	455,112	29,400	94,080
	66% ww:33% OSR	78,792	609,850	38,808	124,186
20%	50% ww:25% OSR	117,600	910,224	58,800	188,160
	66% ww:33% OSR	157,584	1,219,700	77,616	248,371

The average conversion (15%) and use (58% wheat and 29% OSR) gives an additional 103,194 ha of wheat producing 798,721 t/annum and 51,156 ha of oilseed rape producing 163,699 t/annum. Converted grassland would also provide land for other non-take-all break crops (pulses, oats, sugar beet and potatoes). As with the use of land previously taken out of production this would help to offset loss of their existing areas as a result of increasing the intensity of wheat and oilseed rape in the rotation (see below). Areas and production estimates below are based again on the distribution and yields of other crop species on existing cropped land.

Crop	Increased area (ha)	Increased production (tonne / annum)
Wheat	103,194	798,721 (6%)
OSR	51,156	163,699 (9%)
Other crops	22,932	

Contributions from other crops from former grassland

	New area (ha)	Yield (t/ha)	Production gained (t)
Barley	11,745	5.8	68,121
Oats	1,475	5.8	8,557
Rye, triticale and mixed corn	330	4.9	1,616
Sugar beet	0		
Hops	0		
Peas & field beans	0		
Linseed	1,744		
Other crops	26		
Potatoes	2,727		
Total			78,295

Total increases in production

	Wheat	Oilseed rape	Other cereals	All cereals
Extra (tonnes)	798,721	163,699	78,295	877,016

These contributions to increased food supplies from former grassland are modest compared to the contributions from former uncropped land, and should be regarded as conservative estimates. Much of the extra cereal production is likely to be used on farm and not enter the marketing chain, but it would reduce the demand for grain purchased for livestock feeds.

Even with these moderate estimates of grassland conversion, there would be substantial impacts on livestock production. Based on a recent report for Defra (by Dr Elwyn Rees), for every 100,000 ha of grass converted to arable production livestock numbers would reduce by 56,000 dairy cows, 21,600 beef cows, 120,000 other cattle and 180,000 ewes.

Implications for GHG emissions of converting temporary grassland to cropping will be significant; they are detailed in Section B5.2.2.

B.2 Increasing the area of wheat and oilseed rape in arable rotations

Previously in the UK when arable commodity prices have been high farmers have increased the proportion of cereals and oilseeds in the rotation and increased the area of production. With current high commodity prices this reaction is expected to recur. Indeed there is already evidence that it is taking place.

Wheat currently occupies 44% of cropped land; about 60% of this is first wheat. First wheats on average yield 8.14 t/ha and non-first wheat yields 1 t/ha less. Growing non-first wheat requires higher inputs of pesticides and fertiliser (~10%). The sustainable maximum intensity that wheat could reach is taken to be 2/3 of arable land, constrained by risks of pests, weeds and diseases. Increasing the intensity of OSR production also increases weed, pest and disease pressures. The sustainable maximum that OSR could occupy is taken to be 33%. Little or no impact on yield per unit area would be expected at these levels.

Although there is modest scope for some crop substitution (e.g. wheat and OSR for sugar beet and pulses) production of other arable crops is unlikely to decline significantly, as relatively small reductions tend to significantly increase their prices until they compete economically with wheat and oilseed rape again. It seems most reasonable, therefore, to assume that the wheat and OSR could only be sustainably produced at the maximum areas on which they have been produced in the last 25 years: 2,086,000 ha and 682,000 ha (including non-food OSR grown on set-aside land) respectively. This leaves approximately 1.5 mha for production of other crops. In estimating the production foregone we have assumed a pro-rata reduction in areas of other crops. This is a reasonable estimate but will vary depending on relative prices and agronomic constraints.

	Existing area (ha)	**Area lost (ha)**	**New area (ha)**	**Yield (t/ha)**	**Production lost (t)**
Barley	906,000	158,260	747,407	5.8	917,907
Oats	114,000	19,880	93,887	5.8	115,304
Rye, triticale and mixed corn	25,000	4,444	20,989	4.9	21,777
Sugar beet	134,000	23,497	110,969		
Hops	2,000	349	1,651		
Peas & field beans	210,000	36,749	173,551		
Linseed	30,000	5,172	24,428		
Other crops	208,000	36,283	171,351		
Potatoes	139,000	24,313	114,821		
Total		308,948	1,459,052		

GHG emissions associated with production of each of the major UK crops, as they are normally grown, have been assessed here in line with the assumptions described by Berry *et al.* (2008). Detailed data for wheat and OSR are given in Appendix B2. Data for other crops use the same emission factors. The table below shows the GHG emissions saved due to reduced crop areas and the extra GHG emitted due to expansion of wheat and OSR areas. This shows a net change in area of 309,000 ha causing a net increase in emissions of 303,963 t CO_{2e}/annum, or 0.98 t CO_{2e}/annum/ha. The increase arises because all of the crops being replaced have lower N fertiliser use than wheat or OSR. The only crop being replaced with higher emissions per ha than wheat or oilseed rape is potatoes which has significantly greater fuel requirements.

	Area lost (ha)	Area gained (ha)	GHG kg/ha	GHG saved (t)	GHG gained (t)
Wheat		247,000	3,242		800,767
Oilseed rape		62,000	3,285		203,682
Barley	158,260		2,723	430,938	
Oats	19,880		1,911	37,984	
Rye and mixed corn	4,444				
Sugar Beet	23,497		2,103	49,421	
Hops	349		-	-	
Peas and Field Beans	36,749		685	25,164	
Linseed	5,172		1,395	7,215	
Other crops	36,283		1,474	53,466	
Potatoes	24,313		3,961	96,299	
Total	**-308,948**	**+309,000**		**700,487**	**1,004,450**
				2.27 t/ha	3.25 t/ha

Total increase in crop production

	Wheat	Oilseed rape	Other cereals	All cereals
Extra (tonnes)	1,763,580	198,400	-1,054,989	708,591 (3.7%)*

* as a percentage of all grain production in 2007/08 of 19,045,000 t

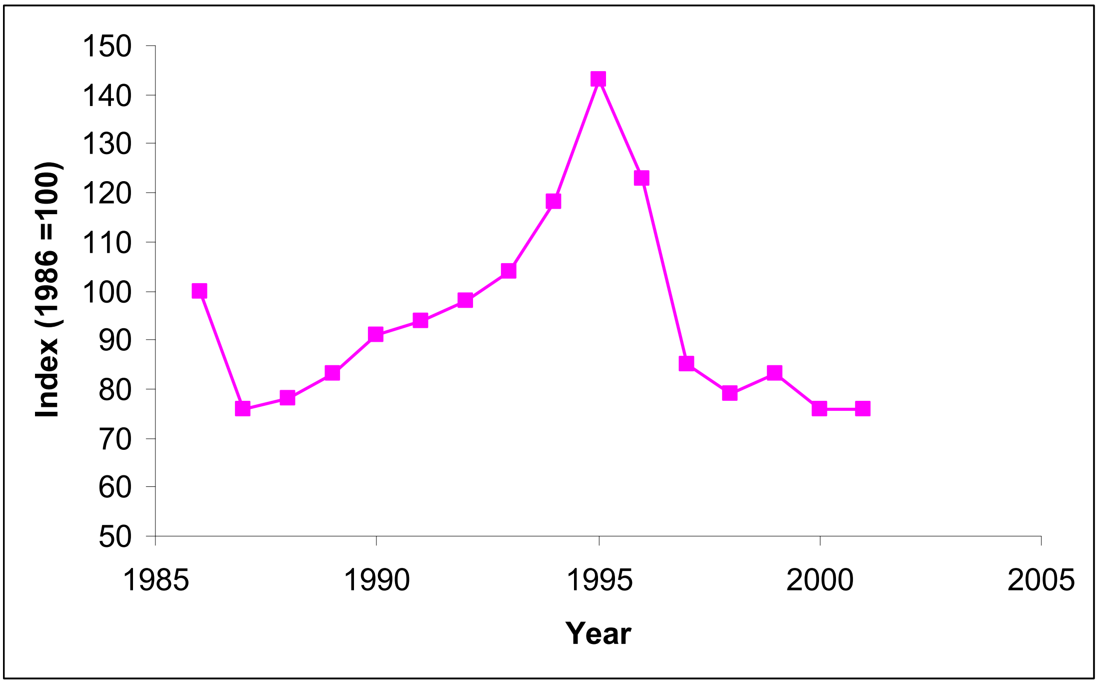
Whilst there is a significant increase in wheat and OSR production of 12 and 11% respectively this is off-set by a loss in production of crops. The net increase in cereal production is less than 4% and there is also a significant reduction in the output of other crops. Increasing intensity of cropping in the rotation would do little to increase total food supplies and would have significant environmental dis-benefits.

It should be noted that the approach to quantifying GHG emissions adopted here is relatively simplistic and does not equate to a full Life Cycle Analysis. It will be important in subsequent work to consider the indirect effects of changes in UK cropping, for instance on GHG emissions by livestock or due to consequent changes in cropping elsewhere.

B.3 Increasing yield per unit area on cropped land

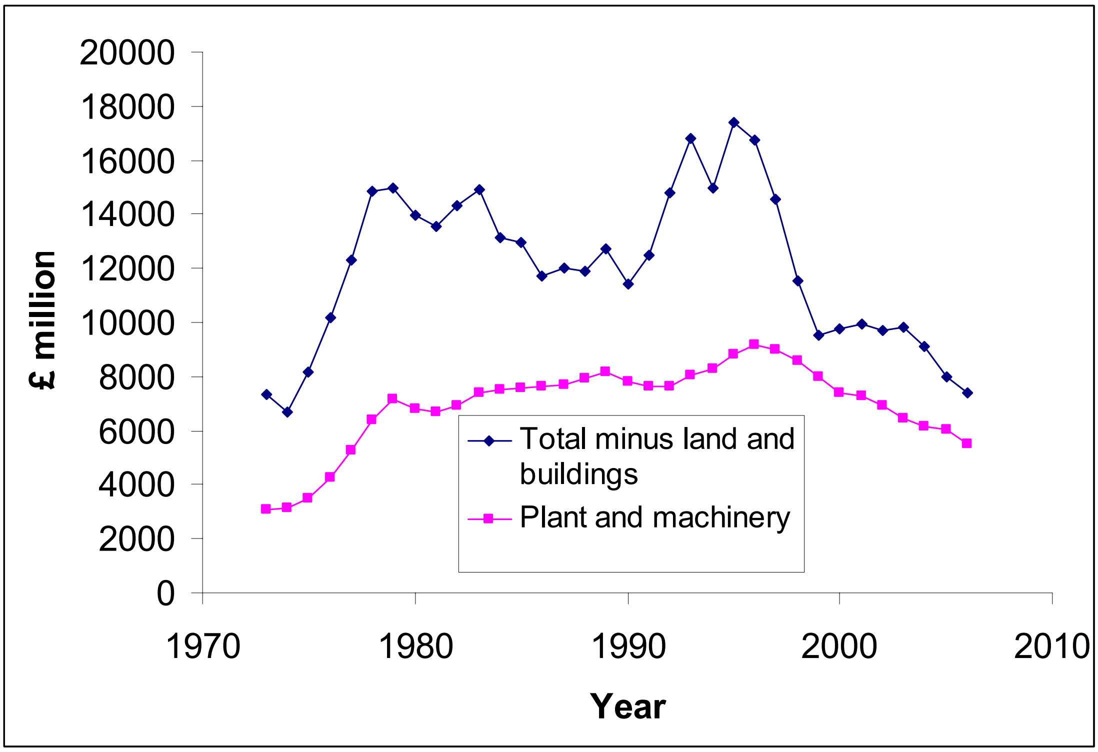
B.3.1 Improved crop management

Following a decline in the mid 1980s wheat gross margins increased progressively until 1995, fell rapidly until 1997 and then declined steadily.



Real (RPI adjusted) gross margins for wheat indexed to 1986 – derived from Defra Farm incomes in the UK
Actual gross margins; 1986 - £566/ha, 2001 - £590/ha
Real gross margin; 1986 - £764/ha, 2001 – £584/ha (in 2000 prices)

These economic pressures have caused reductions in fixed costs in arable farming achieved largely through economies of scale; farms have merged into fewer units with fewer staff, larger machinery, less intensive cultivation and slower replacement of equipment. Thus the real net worth of agriculture (excluding land and building values) rose to a peak in the mid-1990's and has declined steadily since. Equally, the investment in plant and machinery has declined in real terms over recent years (see figure below for agriculture as a whole, and note that investment in plant and machinery is biased towards the arable sector). Since arable equipment has increased in size, complexity and unit cost in recent years so the number of re-investment units has declined.



Net worth of agriculture adjusted by the RPI – derived from Defra Agriculture in the UK reports

Changes in size of arable farms are difficult to demonstrate as Defra statistics give holding numbers by farm size, the largest class being >100ha, which is small for an arable unit in the UK. The statistics actually show an increase in the number of tillage and grass holdings from 230,400 in 1989 to 251,200 in 2005. However, this is due to an increase in small farms (<20 ha) from 97,500 in 1989 to 133,000 in 2005.

Additionally the total agricultural workforce, which includes farm owners and spouses, declined from 695,000 in 1989 to 541,000 in 2005, a reduction of 22% (Defra report ‘Agriculture in the United Kingdom’). The decline in paid labour is even more stark, falling from 328,000 in 1989 to 182,000 in 2005, a reduction of 44%. The workforce is also aging; in 1990 22% of farm owners were over 65 and this rose to 30% in 2005. The number of farm owners under 35 years of age also declined from 8% in 1990 to 2% in 2005.

The reduced investment in plant and machinery and reduced staffing has caused a decline in management intensity per unit area leading to less accurate matching of crop inputs to requirement, reduced cultivations, less accurate timing of inputs, and a stagnation in crop yields.

In order to estimate the scope for yield improvement by restoration of management and investment to former levels it is instructive to examine the widening gap between on-farm yields and yields achieved in experiments used to support the Recommended List (RL) of varieties (Figure 8 and Figure 9).Part of this gap arises through shortfalls in management and resource deployment and part is due to poorer soils on some farms, but the best farms match or exceed yields in the variety testing system. Nevertheless, it is clear that in recent years RL and on-farm yields have diverged and it is hard to ascribe this to anything other management factors. Defra statistics show that the top and bottom deciles for wheat yield are 121% and 65% of the average yield. Comparable figures are 124% and 75% of the average for oilseed rape. This demonstrates a significant variation in farm performance and indicates that significant opportunities are likely to exist to raise the averages.

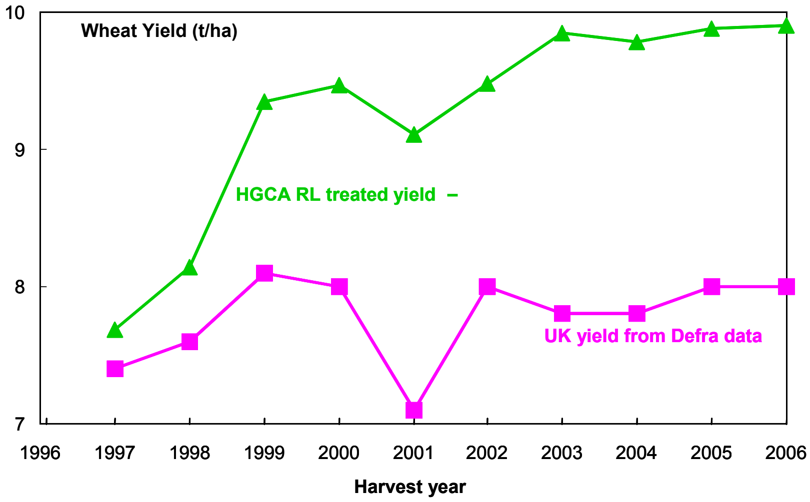


Figure 8. Average UK wheat yields from 1997-2006 based on HGCA RL trials, and on-farm yields from Defra statistics

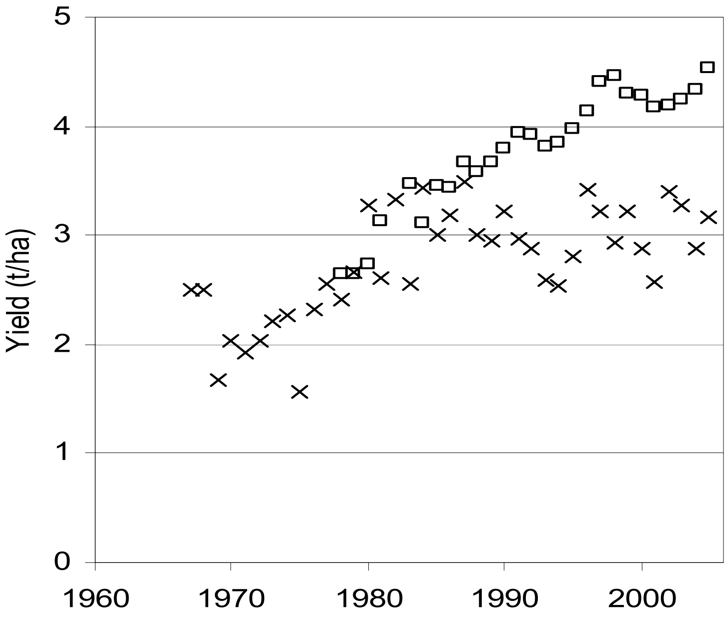


Figure 9. Average yield of varieties evaluated in the national variety testing system (□) (Anon. 2006) and average farm yield (X) (FAOSTAT Data, 2006).

As an example of scope for better crop management we can take the increased use of large high throughput ‘single pass’ cultivation methods rather than plough based inversion/multi-pass systems. These systems have been used over the last decade to reduce costs and have been shown to reduce oilseed rape yields by 13% as follows:

Cultivation method	Plough	‘Topdown’	‘Biodrill’
Yield (t/ha)	4.64	4.39 (-5%)	4.02 (-13%)

Average of 2006 and 2007 trials at 2 seed rates (source Masstock Arable, CPM magazine May 2008)

Potential magnitude of the production increase

It is assumed that management intensity could revert to the levels achieved in the late 1970’s and early 1980’s if ‘real’ cereal prices were high for a significant period. However, it might take 10 years to fully achieve such management improvements because the industry needs to be convinced that long-term profitability of production will remain before it will invest. It will also be necessary redress the shortfall in trained staff (agronomists, farm workers etc) that has developed in the industry over the last 20 years, and this may require investment in agricultural colleges and the like.

Comparing RL practice with commercial practice:

- On average 1.8 fungicides are applied to oilseed rape commercially compared to between 3 and 6 carefully timed sprays in the RL testing system.
- All RL trials are under inversion tillage compared to no-tillage or minimum tillage for the majority of commercial crops
- RL trials have sulphur fertilisers compared to only half of commercial crops.

It seems reasonable that improved attention to management and timing of inputs could recover half of the apparently ‘lost’ yield so we have assumed that it would be possible to increase wheat yields by 10% and oilseed rape yields by 15%, We assume that these increases would be achieved over 10 years i.e. half after 5 years. For other cereal crops we assume that production could increase by 5% in 5 years and 10% in 10 years. Based on their current areas and base yields the increased production is set out below.

Crop	Area affected	Potential long-term yield improvement	Increased production, tonnes	
		t/ha	5 years	10 years
Wheat	1,839,000	0.774	711,693 (5%)	1,423,386 (10%)
OSR	540,000	0.480	129,600 (7.5%)	259,200 (15%)

Total increase in production

(tonnes)	Wheat	Oilseed rape	Other cereals	All cereals
5 years	711,693 (5%)	129,600 (7.5%)	301,867	1,013,560
10 years	1,423,386 (10%)	259,200 (15%)	603,734	2,027,120

These levels of production improvement are significant but modest in terms of moving towards the theoretical biological potentials of the two species: 19.2 t/ha for wheat and 9.2 t/ha for OSR, as discussed more fully in Section C. The yields with existing varieties and improved management represent only 46% and 58% of these potentials respectively.

It is worth noting that within the normal range of inputs there is little correlation between crop inputs and outputs and accurate timing of inputs has a greater impact on efficacy than the level of inputs. It seems reasonable therefore that these yield improvements would be achieved with little net increase in crop inputs or GHG cost per ha, resulting on balance in a net reduction in the GHG cost per tonne of production.

B.3.2 Genetic improvement

Yields of new varieties of wheat and oilseed rape introduced in the UK have increased by 0.7 and 0.5 t/ha/decade respectively in recent years. Figure 8 and 9 show this upward trend for RL data. However for wheat since about 2002 and oilseed rape since the late 90's these genetic gains appear to have ceased.

There are several factors which may be influencing the rate of genetic gain in both species (for a comprehensive review see Caligari *et al.,* 2002). The Plant Breeding Institute and other government sponsored breeding programmes no longer exist and innovations associated with these public investments may all now have been exploited. New breeding technologies (e.g. marker assisted breeding, gene mapping etc) may not yet have delivered their potential benefits. The number of target traits for breeders has increased: more emphasis is being placed on pest as well as disease resistance; there has been significant progress in introgression of pest and disease resistances (e.g. to wheat blossom midge). Also physiological and genetical research has been initiated and intensive work will be needed to understand and improve resource use efficiency, particularly of nitrogen.

In addressing this wider range of targets there is an increasing need to identify and introduce novel traits from distant crop relatives, particularly as breeders have not traditionally addressed issues such as resource use efficiency, having concentrated on yield, quality and disease resistance hitherto. The new research required is long term and high risk and cannot be funded out of the royalties currently available from marketing new wheat and OSR varieties. Investment in private sector plant breeding has been low because of the declining profitability of agriculture over the last 2 decades, because rewards derived from the royalty system are low, and because IP is hard to protect with these true-breeding species (allowing use of home-saved seed, and rapid transfer of new germplasm between competing breeders).

Without investment in plant breeding we therefore believe that the current nil or slow rates of yield gain will continue over the next five years, and we take it that they are unlikely to exceed 0.1 t/ha over that period for either crop.

Variable rates of yield improvement have existed for the minor cereal crops. There has been on-going public investment in barley and oat breeding and the annual percentage yield gains are exceeding those in wheat, albeit from a lower base. Those for other cereals have been less where many of the genetic gains have been in disease resistance and quality. Overall we assume genetic yield gains for other cereals will be similar to wheat and OSR at 0.1 t over the next 5 years. (Scope for faster improvements in wheat and OSR is outlined in Section C.)

Crop	Area affected	Yield improvement after 5 years	Increased production
	(ha)	(t/ha)	(tonnes)
Wheat	1,839,000	0.1	183,900 (1.3%)
OSR	540,000	0.1	54,000 (3.0%)

Total increase in production after 5 years

Extra (tonnes)	Wheat	Oilseed rape	Other cereals	All cereals
5 years	183,900	54,000	104,500	288,400

Note that in recent years the industry has failed to capitalise on improved varieties, so these gains will only be realised if they are combined with improved management.

B.3.3 Irrigation

The economic and environmental costs of irrigation are significant, and irrigation equipment requires significant investment so, where irrigation is installed, it tends to be prioritised on crops that respond most profitably: potatoes, sugar beet and horticultural crops. Due to their relatively low value, less than 1% of the cereal area is irrigated (13,440 ha; Defra statistics for 1995, a dry year). Currently 12% of the UK wheat crop is grown on drought prone land and will experience yield limiting droughts 2 years in 3. For the UK wheat crop as a whole, yield losses of 10-20% occur due to drought (Foulkes *et al*. 2001). The research necessary to quantify the potential yield loss due to drought has not been done on oilseed rape.

In theory for wheat average yields could be increased by 15% through irrigation but in practice expansion of the irrigated area is likely to be slow and irrigation is likely to be focussed on higher value crops. Therefore a maximum 5% yield improvement could be expected on say 1% of the wheat and OSR area, and very high grain prices would be needed to justify it use.

Crop	Area affected	Yield improvement	Increased production
	(ha)	(t/ha)	(tonnes)
Wheat	18,390	0.39	7,117 (0.5%)
OSR	540	unknown	NA (NA%)

These effects are very small compared to those for other measures so are ignored subsequently. A much better approach to reducing yield loss due to drought stress will be to improve crop capture and conversion of water by plant breeding. These are both targets for future research, as described in Section C.

B.3.4 Fertilising above the current economic optimum/recommended level

Rates of nitrogen fertiliser currently used are intended to match the economic optimum. Yields achieved are less than the maximum achievable yield but (by definition) the available yield increases would not cover the costs of additional fertiliser. Small yield gains could be achieved but would require subsidy or reduced fertiliser prices to make them economically viable.

Data from recent N response experiments show that wheat yields could be increased by 1.9% (0.15 t/ha worth £22/ha @ £150/t) but this would require an additional 77 kg/ha N costing £66/ha (D Kindred, unpublished data). This would increase GHG costs per tonne from 396 kg CO_2e/t to 515 kg CO_2e/t (30% increase) and emissions per ha from 3,067 to 4,064 kg CO_2e/ha, which over the 1,839,000ha of wheat would increase total emissions by 1.8 mt CO_2e.

Comparable data for oilseed rape show that yield could be increased by 0.11 t/ha requiring an additional 100 kg/ha N (P Berry, unpublished data). This would increase GHG costs per tonne from 1,012 kg CO_2e/t to 1,360 kg CO_2e/t (30% increase) and emissions per ha from 3,285 to 4,613 kg CO_2e/ha, which over the 540,000ha of OSR would increase total emissions by 0.7mt CO_2e.

Fertiliser prices have risen rapidly of late, driven by a dramatic increase in global demand as well as by increases in cost of the natural gas from which nitrogen fertiliser is manufactured.

Crop	Area affected	Yield improvement	Increased production
	(ha)	(t/ha)	(tonnes)
Wheat	1,839,000	0.15	275850 (2%)
OSR	540,000	0.11	59400 (3.5%)

These yield improvements are small, they are economically non-viable and environmentally costly.

B.4 Aggregate effects

The potential productivity improvements are discussed below in the context of individual effects and aggregate effects.

- Individual effects – The productivity improvements quantified above are based on 2005-2007 production and each improvement is considered in isolation.

- Aggregate effects – The reality is that effects on crops yields will apply to all land, whether originally cropped, or only recently brought into production. Aggregation assumes application of improved management and genetics on all cropped land.

B.4.1 Individual effects on production gain

The potential effect on production is very significant with increases of about 6.3 mt for wheat, 5.4 mt for total cereals (inc. wheat) and 1.2 mt for oilseed rape. The increase for total cereals is less than for wheat because increasing the intensity of wheat in the rotation partly occurs at the expense of other cereals.

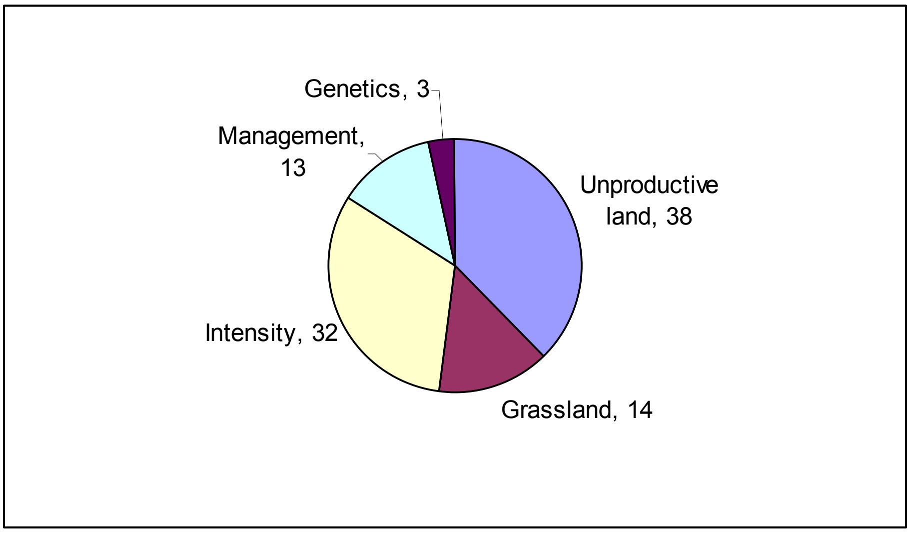
The biggest effect is achieved by bringing uncropped land and grassland into production (Figure 10): 52% for wheat, 62% for total cereals and 61% for oilseed rape. The next largest gain for wheat (32%) and oilseed rape (20%) is from increasing their intensity in current arable rotations. This already has significant momentum but the effect on total cereal production is much smaller (14%) because the wheat increases at the expense of other cereals. Although not assumed here, yields on the newly cropped areas may be less and the inputs (fertiliser and pesticide) will be greater, with resultant increases in resource use per extra tonne causing increases in GHG emissions.

The gains through improved management are significant and environmentally benign but are very dependant on confidence of the industry in sustainable profitability. The predicted gains for management are greater than for genetics, but in the longer term the potential for genetic gains will be much greater (see Section C).

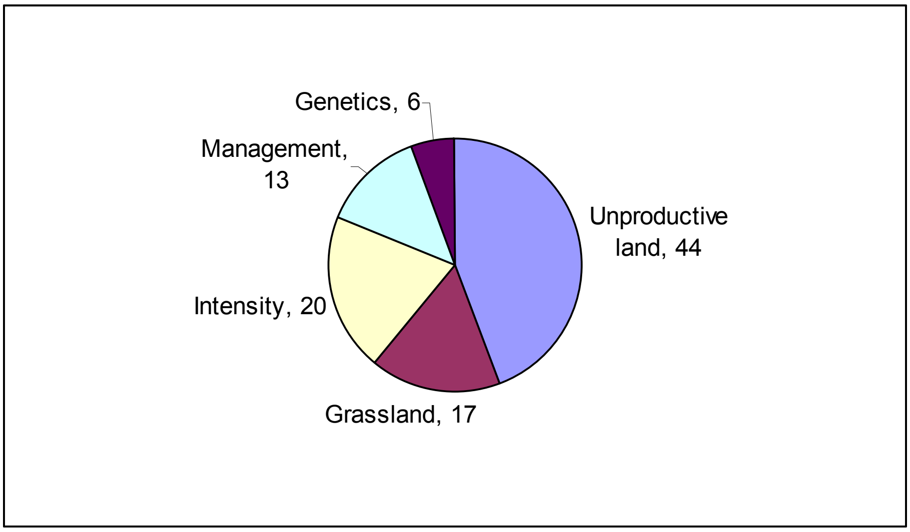
Table 2 Individual effects on crop production over 5 years

Effect	Wheat	OSR	Total cereals
Current production	14,233,860	1,974,400	20,279,527
Unproductive land	2,090,171	432,077	2,296,826
Grassland	798,721	163,699	877,016
Intensity	1,763,580	198,400	708,591
Management	711,693	129,600	1,013,560
Genetics	183,900	54,000	104,500
Total gain	5,548,065	977,776	5,000,493
% Increase	**39%**	**50%**	**25%**
Total production	19,781,925	2,952,176	25,280,020

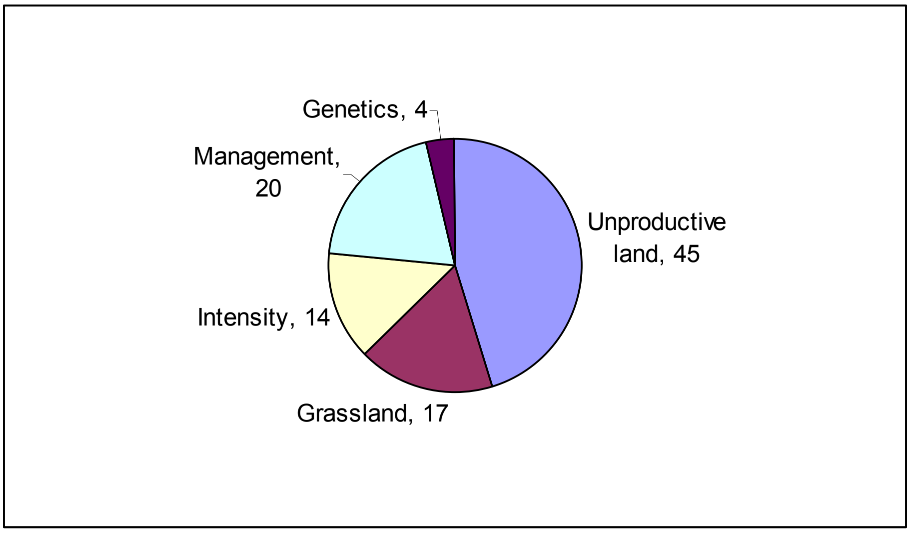
The sum of the independent effects on total production increases wheat production by 39% to 19.8 mt p.a., and oilseed rape by 50% to 3.0 mt p.a. and of total cereal production by 25% to 25.4 mt p.a., which is comparable with the total cereal production in the 1980’s (Figure 4).



Wheat



Oilseed rape



Total cereals

Figure 10 Individual effects on production gain (%) for wheat, oilseed rape and total cereals

B.4.2 Aggregate effects on production gain

The analysis of individual effects shows what could be achieved by each individual change in reality the gains through management and genetics of wheat and OSR would be realised over the whole cropped area including former uncropped land, converted grassland and the extra area on currently cropped land. The following table shows the aggregate effects on crop production in the UK, if current land and knowledge were more fully exploited:

Effect	Wheat	OSR	Other cereals	Total cereals
Current production	14,233,860	1,974,400	6,045,667	20,279,527
Unproductive land	2,090,171	432,077	206,655	2,296,826
Grassland	798,721	163,699	78,295	877,016
Intensity	1,763,580	198,400	-1,054,989	708,591
Management	944,317	207,643	263,781	1,208,098
Genetics	245,522	83,057	91,160	336,682
Total gain	5,842,311	1,084,876	-415,098	5,427,213
% Increase	**41%**	**55%**	**-7%**	**27%**
Total production	20,076,171	3,059,276	5,630,569	25,706,740

These effects are very significant: annual wheat production could increase from 14.2 to 20.1 mt , and OSR from 2.0 (2.2 mt including non-food OSR) to 3.1 mt, increases of 41% and 55% respectively. The associated decrease in production of other cereals would be 0.4 mt (7%), resulting in total cereal production of 25.7 mt, an increase of 27%. However, it is important to recognise that adoption in the medium term of all the changes considered here is highly unlikely; some changes would precede others depending on economic conditions and government policies. Hence the next section considers factors likely to influence each of the changes.

B.5 Ease and risk of delivery and environmental implications

B.5.1 Increasing yield per unit area on cropped land – *Genetic improvement*

The modest gains envisaged through genetic improvement are pessimistic hence virtually assured. However, they are significantly less than what could be achieved in the longer term with greater investment in appropriate research and development (see Section C).

There would be little or no increase in resource use per tonne of output through the progressive adoption of higher yielding varieties, hence effects on GHG emissions are taken to be neutral.

B.5.2 Increasing the wheat and oilseed rape area

B.5.2.1 Using land previously taken out of production

For both crops the single biggest gain in production is through conversion of currently non-productive land. This is also the easiest and least risky contributor to increasing UK production.

B.5.2.2 Conversion of grassland into arable production

The conversion of existing temporary grassland to arable production is predicted to have a relatively small impact on total production. This is because a relatively small reduction in the grass area is predicted, to minimise the impact on meat and milk production. Larger effects could be achieved, but only at the expense of large negative impacts on livestock production.

In the case of conversion of set-aside land or grassland to arable production there is likely to be public opposition due to the perceived negative impact on biodiversity. In terms of GHG emissions each ha converted will release GHG (CO_2 and N_2O) from organic matter previously sequestered in uncultivated ground. The amount released will depend of the duration of the uncultivated period. For land converted from rotational set-aside the release of GHGs will be negligible as the land will have been fallow for too short a period for there to have been any appreciable build up of soil organic matter. In the case of grassland there will have been a build up of soil organic carbon which will be released over a period of years following conversion. In a recent review carried out for the RFA net CO_{2e} losses were estimated at between 3.7 and 6.2 t CO_{2e}/ha/yr (Guo & Gifford, 2002, Murty *et al*. 2002, & Smith *et al.* 1996). In this study we are assuming that temporary (<5 year old) grass is cultivated so it is likely that the loss of CO_2 will be at the lower end of these estimates. In addition there will be CO_2 and N_2O emissions from the new cropping activity, mainly relating to fertiliser and fuel use. These are expected to be similar to those for production of these crops on current productive land (see Appendix 2). Note that indirect effects on GHG emissions, particularly those associated with livestock, have not been included in estimates of emissions made here. These will undoubtedly be significant and should be considered in future work.

B.5.3 Increasing the area of wheat and oilseed rape in the rotation

Probably the next most easily achievable gain is through improved intensity of wheat and oilseed rape production – this is already taking place and represents a reversion to previous levels when ‘real’ prices were higher. The main risk associated with this change relates to the availability of and regulatory environment for plant protection products, which would be required to cope with increased pest, weed and disease problems. The current chemical armoury is significantly smaller than 10 years ago and is under on-going threats from increased resistance and regulatory pressures (see below).

The change in GHG emissions due to changes in cropping will depend on the crop being substituted, but the net effect is expected to be close to neutral when substituting for other cereal and root crops; substituting for legumes is likely to increase emissions.

There is a potential negative impact on biodiversity through reduction of crop diversity as well as a reduction in spring cropping.

It should be noted that increasing production of wheat and OSR through this mechanism will reduce the production of other food, feed or fuel crops. There is undoubtedly scope to increase the productivity of these substituted crops with appropriate research, enabling their production to be maintained on a smaller land area, releasing land for crops where demand is increasing.

B.5.4 Increasing yield per unit area on cropped land – *Improved crop management*

It is important to note that potential gains through crop management have the most environmentally benign footprint of the three interventions predicted to have large effects. This intervention is mostly concerned with maximising the response to resources used rather than increasing resource use. Since the farming system is not changing, the implications for bio-diversity and diffuse water pollution would be minimal.

It is predicted that the GHG cost per tonne of production would be decreased by 10% compared to the baseline, with no overall effect on total UK emissions. This is because the changes required are associated with more efficient use of existing inputs and resources resulting in a productivity improvement, and hence a reduced GHG cost per unit of production. This estimate excludes any impact on GHG emissions for either direct or indirect land use change. If increased supply were to be achieved through bringing into production semi-natural grasslands or forest areas there would be much larger increases in GHG emissions (see table below).

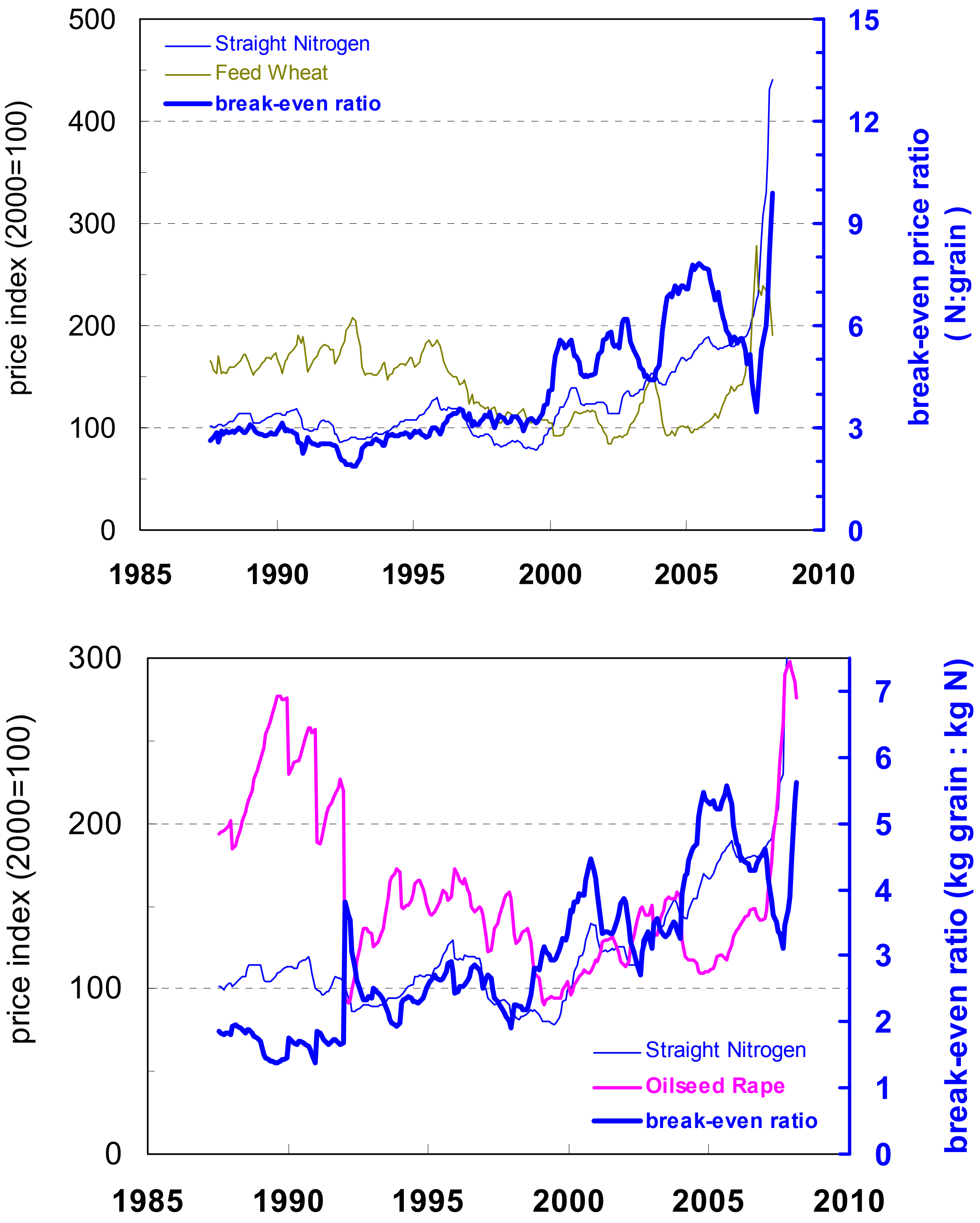
Estimated CO_2 release (t/ha) over a 30 year period from bringing into cultivation various ecosystem types, from IPCC and Searchinger *et al*. (2008)

	CO_2 release (t/ha over 30 year period)	
Ecosystem type	IPCC	Searchinger *et al.*
Tropical Forest	553-824	604-824
Temperate forest	297-627	688-770
Tropical grassland and savannah	189-214	75-305
Temperate grasslands	139-242	111-200
Wetlands	748	1146

These effects would be avoided by providing the additional production through increased productivity of existing cropped land. However, this management improvement is probably the most difficult intervention to achieve because it depends on land managers having confidence in the sustained commercial viability of cropping, as indicated in Section A.1.2. It is worth repeating here that improved price stability is unlikely unless international grain stocks are re-built to curtail speculative trading.

If global supplies do not fully meet rising demands then real, market-led increases in grain and oilseed prices are probable. These should offset the rising prices of inputs for crop production and should also maintain a viable level of profitability over a run of years. However, it is likely that instability in prices of crop products will increase due to environmentally driven seasonal supply difficulties and resulting in short markets and increased speculation. Cyclical production activity may further exacerbate such price instability. It is the instability in prices as much as the price level itself which appears to be the major constraint to re-investment in the infrastructure, skills and personnel required to release the potential gains in production through better crop management. Section B.3.1 outlined how the low prices through the last decade limited investment and how the net worth of agriculture and employment of staff declined. The net worth of plant and machinery fell from a peak of about £8,000m in the mid 90s to about £5,000m today (Section B.3.1). Whilst agriculture in the UK has not been prospering, investment decisions have been delayed and responses to higher prices have been damped so that area planted and productivity growth have been small.

As shown in the figures below, lower (in real terms) and steadily declining prices for wheat existed from mid 80s to 90s and reasonably stable but low prices were then a feature of the market up until the price spike of 2007/08. However fertiliser prices whilst relatively stable through to about 2000 have since increased year on year, with very rapid rises during 2007/08 and increased price instability. The net result has been an increasing and much less stable break-even (N:grain) price ratio with resultant reduced profitability. A similar situation exists for oilseed rape, although the effects are more dramatic due to of the removal of price support in the early 1990's.



Nitrogen fertiliser price and wheat and oilseed rape values and their effect on the breakeven ratio. Derived from Defra statistics https://statistics.defra.gov.uk/esg/datasets/apimonth.xls

Confidence at farm level in sustained profitability will allow the wealth accumulation necessary for the investment in both the equipment and the staff required to enable more intensive management input and timeliness of operations. However, this would depend on replacement of staff and skills lost at all levels in the industry over recent decades (as described in Section B.3.1; employed staff in agriculture fell by 44% since 1989 with an ageing workforce). To encourage new entrants into the industry, agriculture needs to be seen as a profitable and dynamic industry at the national level, fulfilling the increasingly important societal need of feeding people in an increasingly hungry world in an environmentally sustainable way.

There is a strong feeling within the agricultural industry that the recruitment of staff, particularly graduates with training in production agriculture has been becoming increasingly difficult due to a declining number of young people entering the industry. Statistics on student numbers are only readily available at a fairly crude level, students being classified in ‘agriculture and related’ disciplines. A comparison of the available data from 1979/80 and 2006/07 shows that agriculture and related full time undergraduate student numbers have actually increased from 5,124 to 9,785 over that period. This does not appear to support the industry view. It is however important to note that the increase was concurrent with dramatic increases in total full time undergraduate students; the percentage of students choosing to study agriculture and related disciplines fell from 2.04% to 0.8% during the period.

The data and evidence provided below provides support for the notion that the availability of key courses in agricultural production and training of new entrants into the industry has declined. (Note that it has not been possible within the resources available for this report to obtain comparable data over a 20-30 year period with a sufficiently detailed breakdown of courses to identify student numbers studying subjects related to production agriculture.)

- The table below which shows that in the 2004-05 academic year there was a total of 12,092 FTE students studying land-based courses in further and higher education. However, of these only 40 were studying agricultural crops compared to, for example, 1,151 studying courses related to environmental conservation and 357 taking equine studies. There were a further 3,968 studying courses ‘related to agriculture’. A detailed breakdown of courses included in each of the broad classifications below is provided in Appendix B.6.

Student numbers (FTEs 2004-05). Extracted from ‘Review of provision for land-based studies’ May 2007. Final report to HEFCE by JM Consulting and SQW Ltd.

Subject group	**Student numbers**
Agricultural crops	40
Agricultural livestock	695
Animal care	2,078
Aquaculture/Fisheries management	18
Equine studies	357
Land management	740
Land-based engineering	0
Landscaping	1,655
Production horticulture	39
Related to agriculture	3,968
Related to environmental conservation[1]	1,151
Trees and timber	415
Other	938
Total	12,092

Source: HESA, ILR

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[1] Environmental science subjects have been excluded.

- The number of Universities that offer straight agricultural science degrees (ie. those relating to agronomy and productivity) have reduced in recent years. Seal Hayne (formerly Plymouth polytechnic) has closed down and no longer offers agriculture degrees and Edinburgh, Aberdeen, Leeds and London (Wye College) Universities have also stopped their agriculture courses. At Nottingham (Sutton Bonington) the staff of the Agriculture department have been merged with plant and environmental sciences.

- A Defra project reporting on prospects for plant breeding and genetics in 2002: (Defra ST0158) stated:- 'In reality, there are now very few courses available in the UK. These are basically more founded in botany or genetics, not agriculture. The most relevant courses still being offered are at East Anglia and Birmingham. The Masters courses at Reading, Aberystwyth and Cambridge have now stopped. Most of the students on these courses are from overseas and normally return to their own countries after completing their course.'

- A similar decline in weed science teaching was recently reported at an AAB conference by Bob Froud-Williams (The Status of University Education in Weed Science.R.J.Froud-Williams, 2008).

- In terms of crop production education A H Cobb (Dean, Harper Adams, pers. comm.) points out that no HE courses entitled 'Crop Protection' exist but that a number of courses offer crop protection components. There is only one MSc in Crop Protection (Harper Adams) and the same institution is the last to offer a degree in Agricultural Engineering.

This decline in agricultural training has also been mirrored by the decline in funding for agricultural research as outlined in Colin Thirtle's report (Section 6.9). Expenditure on R&D in the UK has not increased since 1982 and total factor productivity ceased growing from 1984 having previously grown at 2% p.a. since 1953. At the same time, yield growth fell from 2% to 0.2% p.a. but labour productivity continued to increase with the strive for economies of scale. There was no compensating investment in private R&D. Instead, patent counts declined. Similarly, public R&D spend stagnated generally for the major high income countries (constant 2000 international dollars 10,534 m 1991 to 10,191 m in 2000) with R&D being concurrently re-targeted towards public interest issues other than agricultural productivity and food supply.

Filling the skills gap will take time if, as is outlined above, the provision of agricultural training at all levels from agricultural colleges to universities has declined in the past 2 decades or more. There will be a significant lag period between people wanting to enter the industry, the provision of training being established and trained staff becoming available in the labour market. A delay in the availability of trained staff will have the knock on effect of delaying investment in additional staff resource at the farm level, resulting in a delay in the realisation of the potential.

Arguably as a precursor of this happening there will need to be a change in the public perception of the agricultural industry from a 'low tech' polluting and environmentally damaging industry to one that fulfils a key societal need and is attractive to young people. This may require a change in the way agriculture is presented in primary and secondary education.

For the reasons outlined above in relation to the investment environment and trained manpower, it would be reasonable to assume that no more than 50% of the potential for increasing yield through improved crop management will be achieved in the short term (5 years).

B.6 Constraining factors

Whilst this analysis has shown considerable potential to increase production the volatility in costs and prices even over the period in which the report has been produced has undermined farmers' confidence to invest and modify their farming systems to increase productivity. The main requirement for releasing current potential is therefore a sustained period of profitable cropping and cost:price stability. Without this, the significant private investment required to overcome logistical problems such as machinery, storage and transport capacity will not be forthcoming. In addition public investment will be required in the education of skilled staff at all levels within the industry.

Restoration of confidence would probably require a net margin 20% above the breakeven at today's costs and prices, indicating a minimum wheat price of £170/t and £413/t for OSR, given current average input levels and yields (see section A.1.2).

With the current shortage of supply and resulting high prices for all the major macro nutrients (N, P & K) and pressures to increased cropped areas in other producing countries there will need to be international investment in increased fertiliser production capacity or technological crop improvements to decrease nutrient requirements.

Of major concern is the current review of pesticide approval (EC/91/414) which proposes that these should be based on hazard rather than risk assessment. If implemented this could result in loss of 80% of pesticides, causing reduced pest and disease control, hence significantly lower yield per unit area (and increased GHG costs per tonne of production) and reduced cropping intensity. The net effect will depend on which of the proposals is adopted. The predicted loss of production from the current level varies from 26% to 62%. Loss of existing active ingredients and reduced discovery or approval of new active ingredients combined with continued emergence of pest and disease resistances to existing pesticides would decrease production further, perhaps by as much as 70%. The ADAS report to ECPA (www.bcpc.org/events/FoodChainForum/index.asp) assesses the effect of reduced availability of pesticides on yield and crop gross margins and indicates the necessary crop price increases required to maintain the same gross margins. As an example for wheat:

	Commission	**Parliament**	**Parliament + CF**
% Yield Impact	-26	-44	-62
% price inc. required*	30	70	120

* price increase required to maintain gross margin
Commission – Commission proposals. Parliament – EU Parliament. CFS – EU Parliament plus substitution recommendations.

Clearly, implementation of the review findings would severely limit if not remove the potential to release the production increases described above and would create problems that would require very serious investment in ameliorating innovation. This is perhaps the biggest threat to the potential market recovery described in this paper.

C: The potential for R&D to contribute to productivity increases in the UK

Part B reviewed how yield and production can be increased using current knowledge (available genetic material and agronomy), and showed these yields to be significantly less than the theoretical potential. This section reviews the potential to increase the productivity of wheat and oilseed rape through research and technical development given the constraints of the UK agro-environment.

The brief for the review was confined to these two major crops; and particularly to looking at implications of increasing their productivity and resource use for green house gas (GHG) emissions. The evaluation has not considered research targeted specifically at the important issues of environmental improvement and agricultural sustainability. However, priority has been given to maximising output per unit of nitrogen (N), currently the most costly and environmentally damaging input (in terms of climate change).

This review builds on two earlier coordinated studies: “Yields of UK crops and livestock: physiological and technological constraints, and expectations of progress to 2050” (Defra 2005) and “Agricultural Futures and Implications for the Environment” (Morris *et al.*, 2005). The former report (Defra 2005) is supported by a 650 page volume entitled “Yields of Farmed Species” (Sylvester-Bradley & Wiseman 2005) which details much of the background information and arguments underpinning this review, and considers in a similar way the prospects for productivity of further crop and livestock species. This Defra report (2005) provides estimates of changes in productivity of UK crops and livestock through to 2050 according to different socio-economic scenarios. The complementary tasks of the present review have been to document more fully the research ideas that hold promise for improved productivity with reduced environmental impacts into the future, and to consider more fully the likely environmental repercussions of improvements in crop productivity, especially effects on green house gas emissions.

Historically crop improvement through breeding, husbandry and pest and disease control has employed predominantly empirical approaches. This was necessary because the understanding of yield formation and the ability to link genetics to crop performance were limited . In addition when environmental concerns were less and agricultural inputs were cheap the tendency was to target yield with less concern for efficient resource use. Today we cannot progress the challenge of increasing productivity without addressing the use of resources and other environmental consequences.

We now have a better understanding of the physiological processes which drive yield and are starting to understand their genetic control sufficient to enable a more objective approach to identifying crop potentials and the constraints to crop improvement.

Hence in reviewing the potential to increase productivity we have used a design framework based on the physiological determinants of yield, so that crucial interactions and trade-offs between innovations can be anticipated and considered. Clearly many innovations are possible, and these will not all be additive. Note that, whilst crop physiological understanding remains imperfect it will limit the identification of targets; as understanding improves so research requirements will develop further.

At its simplest, progress in crop productivity is considered to depend on enhancing (i) photosynthesis and (ii) partitioning of photosynthate to harvestable organs. Photosynthesis can be improved in rate, duration or both, through supply, capture and conversion (to harvestable crop dry matter) of the resources on which it depends: light, carbon-dioxide, water and nutrients. These resources are very different in their determination and impacts:

- Carbon-dioxide supplies and light energy levels are fixed by location – only in extreme circumstances (in glasshouses) is it worth altering these. Near complete light capture is achieved by evergreen perennials (grassland & forests), but not by annual crop species. Better capture and high conversion are desirable and have no environmental disadvantages. Better conversion has hither-to proved a relatively intractable research objective.

- Water supply is usually fixed by rainfall and soil type at a location. Supplies in the UK are not currently a major constraint given current levels of productivity, but is predicted to become a constraint as climate change impacts and the utilisation of radiation improves. Irrigation to enhance supply has large capital costs normally incompatible with grain or oilseed production in temperate climates. However, if facilities are justified elsewhere variable costs are small. Increased supply and capture of water both have deleterious environmental impacts. Increased conversion is therefore the most desirable means to improve productivity. However, this has again to-date proved an intractable research objective.

- Soil fertility sets basal nutrient supplies. These are commonly augmented by fertilisers which have minor capital cost and increasingly significant variable costs. Supplies are set locally according to economic marginal returns (and guided by national regulations); they therefore depend on efficiencies of capture and conversion. These are currently far from the theoretical maxima for most crops. Better capture and conversion would be highly beneficial both economically and environmentally; they would reduce fertiliser use.

Conversion efficiency for nitrogen is adversely affected particularly by foliar pathogens, which destroy green tissue, reducing productivity and increasing GHG emissions per unit of production (Berry *et al*., 2008). Hence, efficiency depends on maintaining healthy crops – a task which will be challenging, as many of the changes required to increase production will also increase the severity or impact of particular pests and diseases.

Given assumptions about genetic and management limits to the supply, capture and conversion of resources by each species, potential productivities of wheat and OSR can be estimated for any location; recent values for the UK are 19 and 9 t/ha respectively (Sylvester-Bradley *et al.,* 2005; Berry and Spink, 2006). Taking these estimates, the approach used here is to review the impacts and progress in productivity of wheat and oilseed rape that are likely to arise from ideas currently in play in the crop science community.

The approach adopted for each crop is to:

- Estimate the potential yield under UK conditions.
- Identify and prioritise the *constraints* to the realisation of this potential, the possible researchable *interventions* in crop function to alleviate these constraints and from this the *research* required.
- Identify the scope for protecting these yield gains against pests, weeds and diseases, and the associated research required.

Having dealt with species-specific and physiological driven issues there are separate sections on cross cutting issues:

- Rotational issues of self sufficiency in nutrients, and weed control.
- Underpinning physiological, crop design, genetic knowledge and materials and shared genetic techniques.

Some of the innovations identified here depend on public sector (P) investment, others joint collaborative (pre-competitive, involving industry and government) (P+I) and some will be addressed by industry (I). This section concentrates mainly on activities requiring public sector support (P & P+I). Whilst there is some scope for international collaboration particularly in some of the development of basic genetic resources and techniques and in underpinning physiological understanding, a great deal of the work required will need to be conducted under UK agro-ecological conditions if the outcomes are to result in effective uptake and impact in this environment.

C.1. Wheat

C.1.1 Theoretical yield potential

Wheat yield in the UK is usually limited by light rather than water. Duration of light capture by annual crops such as wheat is constrained by the time needed for ripening, harvest, re-planting and re-establishment of sufficient canopy to fully intercept the incident light. These processes must occur when light levels are relatively high so it is estimated that wheat could only ever intercept 60% of incident light in the UK. This figure, with improved conversion coefficients for light energy to dry matter, gives a final crop biomass of 27 t/ha in the north east and 31 t/ha in the south and west. At least 2.6 t/ha of this is needed for leaf production and a further 6 t/ha is required for the stems, leaving 18.4 t/ha for the ears; on average 14% of the ear is non-grain material giving a potential biomass yield of 16.4 t /ha, equivalent to 19.2 t/ha at 85% dry matter (Sylvester- Bradley *et al.*, 2005).

To achieve this potential will require both genetic and cultural interventions to overcome the main constraints to maximum resource capture and conversion including:

- Early canopy closure - maximising light interception during the period of maximum growth rate
- Earlier stem extension – to provide a sink for assimilate early in the season.
- Delayed canopy senescence - maximising light interception during yield formation
- Nutrient capture and conversion – to support canopy interventions whilst minimising increases in fertiliser requirements
- Improving light conversion – to increase dry matter per unit of photosynthetically active radiation intercepted.
- Increased partitioning of dry matter to grains – probably through earlier flowering or increased stem carbohydrate storage
- Water capture and conversion – to avoid premature canopy senescence
- Control of biotic stresses – to protecting the potential gains.

Each of these constraints will now be described, with appropriate interventions and the necessary research.

C.1.2 Improving resource capture and efficiency of use

C.1.2.1 Early canopy closure

Constraint

In order to intercept 60% of annual incident solar radiation wheat’s canopy must expand more rapidly in spring, the targets being a Green Area Index (GAI) of 2.5 in mid April and 4.0 in early May with the maximum reaching GAI 7.

Interventions

Husbandry

The targets for canopy expansion and growth are well within those experienced with existing germplasm. It seems eminently feasible therefore that this target can be met using husbandry approaches alone, and would require the development of agronomic packages including manipulation of sowing date, seed rate and the use of fertiliser N.

Genetic

The etiolation response of basal internodes must be counteracted genetically if earlier canopy expansion and hence changes in light quality (R:FR ratio) are not to result in increased lodging. As an interim measure this problem may be addressed by use of low seed rates and growth regulators.

Research needed

- Development of agronomic packages to advance canopy closure whilst minimising adverse effects on lodging risk. (P+I)

- Development of varieties with higher lodging resistance, especially due to etiolation of the stem base. (P+I)

C.1.2.2 Earlier stem extension

Constraint

To maintain high rates of crop growth it is necessary to maintain a high sink capacity for photosynthates (Evans and Wardlaw 1996). If grain yield is to be doubled, sink capacity is bound to be enhanced at the end of the grand growth phase, however, sink capacity will also need to be enhanced in April and May, when full interception is first achieved.

Intervention

Husbandry

It seems unlikely that husbandry approaches can significantly increase early season sink capacity.

Genetic

In the absence of husbandry solutions it will therefore be necessary to seek a genetic solution, most probably by developing an earlier start to stem growth, as proposed by Slafer *et al.* (2001).

Research needed

- This will require a more detailed physiological understanding of the influence of vernalisation, photoperiod and earliness *per se* genes (already identified) on internode and crown root initiation. (P)
- Examination of existing variation in these traits (P+I)
- Identification or introduction of novel developmental genes. (P+I)
- The combination within a single genotype of a number of developmental genes to give the desired developmental pattern. (P+I)

C.1.2.3 Delayed canopy senescence

Constraint

Canopy senescence is currently complete in East Anglia by the end of July. This must be delayed by about 8 days so that, overall, the period of full light interception is extended from 75 to 90 days.

Canopy longevity is governed strongly by water capture, crop nutrition, disease control and their interactions. True delays in senescence must be proven in conditions of ample water supply and with no disease. There is a strong dependence of senescence on the plant's internal N dynamics, particularly the redistribution of N from canopy to developing grain. Senescence can be delayed by reducing or delaying this N transfer.

Root and stem diseases tend to affect nutrient and water transfer to the canopy, hence the maintenance of canopy function, whilst foliar diseases tend to reduce green leaf area. The primary effect of all three forms of disease is through reducing light capture.

Intervention

Husbandry

Significant delays of 5-8 days in canopy senescence have been achieved by use of strobilurin fungicides and urea (Ruske, Gooding and Jones 2003) in wheat.

An optimum canopy of GAI 7 will contain approximately 210 kg/ha N (Sylvester-Bradley *et al.* 1997). N supplies may be augmented to encourage further late uptake, both to ensure grain is useful for bread-making, where this is intended, and to prevent premature redistribution of canopy protein to the grain. About 160 kg/ha extra N uptake would be required for 19 t/ha grain if the protein concentration is to meet the current UK threshold for bread-making (2.2% N, DM basis). Thus a lower protein requirement for bread-making (through innovation in protein composition or in bread-making technology) might indirectly enhance crop productivity.

Genetic

This may be achieved by extending the longevity of individual stem-borne leaves, or increasing their number. Although there is less variation in canopy senescence than in canopy closure, significant genetic variation has been shown (Miralles, Dominguez and Slafer 1996; Verma, Foulkes, Caligari, Sylvester-Bradley and Snape, 2004) and the John Innes Centre has recently identified a non-glaucous phenotype with delayed senescence, associated with a gene (Vir) inherited from *Triticum dicoccoides*.

Sources of variation are likely to arise through:

- Delayed grain protein synthesis – or reduced protein, where end-uses allow (e.g. feed and alcohol production),
- Increased N capture,
- Decreased N requirement by the canopy (less N per unit green area).
- Deviation from the usual inverse relationship between yield and N content

Research needed

- Genetic control of stem-borne leaf number and aging. (P)
- Genetic control of crop N dynamics (see below). (P)
- Further research on controls of senescence in wheat. Putative 'stay green' mutants have been identified in wheat and these require further analysis, particular to confirm functionality rather than simply a block in chlorophyll breakdown. These traits need to be characterised and, if compatible with productivity, need incorporating into UK germplasm. (P+I)
- Development of strategies for delayed N application to provide for late N uptake which maintain or increase the efficiency of N recovery. These might include delayed release fertiliser formulations or form (solid vs liquid) of fertiliser application. (P+I)
- Changes to bread-making technologies that would allow use of lower grain protein concentrations. (P+I)

C.1.2.4 Nutrient capture and conversion

Constraint

UK wheat crops currently take up N amounts equivalent to about half of their N supplies, and they use about 75% of uptake to form grain proteins. Particular grain proteins are valuable for bread-making (~35% domestic grain use) but have low value for livestock feeding, biscuit making or alcohol production (~55% domestic use); N from low grade proteins is excreted and subject to the inefficiencies of recycling through livestock manures and sewage treatment.

With present uptake and redistribution efficiencies it is predicted that crops yielding 19.2 t/ha would have fertiliser requirements exceeding 400 kg/ha N, as well as high requirements for phosphate. The net increase in phosphate input to the environment might not be huge, depending on the reduction in cropped area which might result from such high yielding crops, and on whether minimum soil phosphate levels would have to be increased to provide for the increased crop demand. However, high yielding systems using large N applications would have considerably increased carry-over of residual N from one crop to the next. Extrapolating from long-term experiments where carry-over effects have been assessed (e.g. Bhogal, Rochford and Sylvester-Bradley 2000) we predict that over-winter mineral N levels in soil would increase by about 50%; depending on soil type and overwinter rainfall, a portion this would leach and a portion would be available to the succeeding crop.

Intervention

Husbandry

To avoid excessive nutrient loading of wheat soils, greater use could be made of:

- Application and formulation practices to minimise competition for soil available N between crop and soil flora. For instance, foliar fertilisers might avoid acquisition of available N by soil flora. However, efficiencies of foliar N fertilisers are currently poor.
- Gluten enhancement of flours for bread-making (e.g. Robertson and Cao 2001).

Genetic

Breeding for increased yields of wheat in recent years has increased N requirement but also inadvertently increased wheat's capacity to recover fertiliser N (Foulkes, Sylvester-Bradley and Scott 1998). However, this increased recovery has been insufficient to keep up with increased demand. As breeders seek ever-higher wheat yields, they will therefore have to be more conscious of improving the efficiency with which the crop acquires and uses N. Approaches might include:

- Joint breeding for high yield and low grain protein could break the association between wheat productivity and fertiliser use, as has occurred in UK barley (Sylvester-Bradley et al., 2008). Greater separation of breeding programmes for bread-making and 'energy' wheats may be required.
- If wheat breeding and variety testing took place with two N regimes (constrained as well as ample N supplies) improvements in N capture and conversion could be detected.
- It is apparent that cereal species differ significantly in their capture and conversion of nutrients. Apparently, wheat performs less well than oats, barley or triticale.
- Substantial variation in both uptake and utilization of N in modern wheat varieties has been identified (WGIN report, 2009).
- Manipulation (utilising genetic transformation) of enzymes involved in N assimilation (alanine amino transferase and glutamine synthetase; Lea & Azevedo, 2007) have been shown to increase N capture in other crop species (Good et al., 2007). Such transformations hold significant promise to improve N capture by wheat by up to ~50% (Aldhous, 2008; Arcadia Biosciences, 2007), at least under low input conditions.
- A more vertical root distribution may discourage competition for nutrients between crop roots and soil flora. However, optimum distributions may differ for water, N and phosphate capture.

- Our understanding of genetic and environmental factors influencing growth and development of below-ground organs has lagged far behind that of above ground organs. Fundamental research is required to understand and elucidate the nature of root development in crop plants. This is necessarily a difficult undertaking, since there are many components that need to be taken into account, including the crop genotype, together with soil quality and structure, climate, the soil microbial community and any symbioses or pathogenic interactions.
- Model plants such as Arabidopsis have been studied over the past years to understand more about how cells in the root divide and acquire their identities; it is important to extend this research to crop plants and to elucidate the contribution of free living and symbiotic interactions in the soil such as arbuscular mycorrhizal associations. There is work underway at Duke University USA, for example, using Arabidopsis mutants; alterations in cell division and cell identity have been found leading to dramatic changes in the radial pattern of the root. They have isolated the genes mutated in these lines and found that several of them encode transcriptional regulators. One aspect of Brassica root development is fundamentally different to cereal roots in that it is non-mycorrhizal. In addition, mycorrhizal associations in cereal can be very different in terms of both symbiont species and the intensity and productivity of the association, depending upon the site, nutrient availability and previous cropping regime.
- Root growth may be further influenced due to agronomy and agrochemical inputs; whose influence may persist for more than one cropping season. Furthermore, negative or even positive impacts due to the presence of the roots of other species needs to be quantified in this context. Environmental considerations are of increasing importance, particularly the impact of diffuse pollution and loss of major plant nutrients out of the soil system into the ground water. Roots are, of course the main route whereby mineral nutrients are sequestered; their uptake efficiency, importance to soil structure and subsequent cycling in the soil system are therefore of relevance to this concern. Root structure and development will also be influenced by the physico-chemistry of the rhizosphere as well as the soil microbial community and the plant microbial interactions.

- Wheat stores N in its true stems, and it accumulates N in its leaves. If these stores can be shown to be unnecessary, genetic reduction of N storage which is likely to require the introduction of traits from wild relatives or exotic material as extant variation in adapted material has not been found is likely to reduce fertiliser use.
- As a more long term objective there is the potential to introduce root nodulation and atmospheric nitrogen fixation into wheat and other non-leguminous species. If this can be achieved and sufficient N can be fixed this would have very significant environmental (GHG) and commercial benefits. This would require GM approaches to introduce genes from unrelated species and whilst conventional wisdom is that the nodulation itself would be relatively easy to achieve, the achievement of functionality of the nodule bacteria interaction in N fixation is far more problematic and long term. However the potential rewards are so great that it is almost certainly an objective worth pursuing.

Research needed

- Comparisons of cereal species (oats, barley, triticale, wheat) to identify the physiological and metabolic basis for their significant differences in N capture and conversion. (P+I)
- Identification and characterisation of N stores in wheat canopies, leading to genotypes with reduced storage. (P)
- Identification of wheat germplasm with variation in traits determining N capture, storage and conversion. (P+I)
- Development of formulation of soil- or foliar-applied N fertilisers that improve the efficiency of uptake and strategies for their use. (P+I)
- Improved recovery of soil N including assessment of impact of the the upregulation of alanine aminotransferase in UK wheat germplasm. (P+I)
- Increased demand for mineral inputs requires an integrated approach that includes studies of roots and root-rhizosphere interactions. The contribution from mycorhizza also needs to be considered. Synthetics (hexaploids which have been newly created using ancestral D genomes) have been shown to contribute useful root characters in drought tests e.g. Reynolds et al. 2007, J. Ex. Bot. 58, 177 (P)
- Nitrogen fixation through nodulation. (P)

C.1.2.5 Improving light conversion

Constraint

The benchmark for conversion of light energy in UK wheat is 2.2 g biomass per MJ photosynthetically active radiation. In order to achieve yields of 19 t/ha this needs to increase to 2.8 g/MJ, similar to levels achieved pre-flowering (Shearman *et al.* 2005), but there will be a greater challenge in achieving such levels after flowering, particularly during the latter stages of grain filling. Recent cases where conversion has been estimated at this level have been associated with varieties having the 1BL.1RS wheat–rye translocation (Shearman *et al.* 2005) or the 7DL.7Ag wheat-*Agropyron elongatum* translocation (spring wheat in Mexico: Reynolds *et al.* 2001). In general, it appears that high conversion in light-limited conditions is associated with high specific leaf N at the top of the canopy (Evans 1989), and high sink capacity (Evans and Wardlaw 1996).

Intervention

Husbandry

There are a number of husbandry approaches that can be employed to increase specific leaf N and sink capacity. For instance high light conversion has been reported with low plant populations (Whaley *et al.* 2000), and high N nutrition (Dines 1998).

Genetic

A number of mechanisms have been suggested for genetic improvement of light conversion (Reynolds *et al.*, 2000). These include genetic transformation of Rubisco, manipulation of leaf angle (which is under relatively simple genetic control), and manipulation of leaf-N distribution within the canopy. Greater sink strength may arise synergistically through greater light conversion before flowering, and a relatively larger partitioning of assimilates to the developing spike (Reynolds, Pellegrineschi and Skovmand 2005). However, balancing source- and sink-strength is a complex genetical challenge.

A number of these traits will inevitable require the introgression of traits form exotic material, this has been shown to be a successful strategy with many examples. The introduction of the 7Ag.7DL introgression from *Triticum agropyrum* provided an increased level of Radiation Use Efficiency (RUE) during grain filling – thus increasing yield potential per se. This introgression is attractive to wheat breeders as it can be recognised using genetic markers and ’tracked’ through the breeding programme by selection.

The use of a transgenic approach may be required. Though contentious further development work on the environmental benefits/ disadvantages of this strategy needs to be implemented. Wheat breeders are likely to be ambivalent to such an approach – if the consequential improvements in grain yield was synergistic to environmental benefits- making this approach very attractive. One advantage of such an approach is that any transgenes involved could be clearly identified and tracked through a breeding programme using laboratory based marker assisted selection (MAS) strategies.

Research needed

- Identification of husbandry strategies that could be combined with particular genotypes.(P+I)
- Further analysis of the physiological basis of genotype by environment interactions will be needed to indicate the best avenues for genetic improvement. (P)
- Genetic improvement of Rubisco, possibly using introgressions from alien cereal species. (P)
- Manipulation of leaf angle (which is under relatively simple genetic control) and leaf-N distribution within the canopy to optimise light distribution in the canopy. (P+I)
- Increase partitioning of assimilates to the developing spike at anthesis to reduce sink limitation and maximise sink size during grain filling. (P)
- Incorporate partial or full C4 capability into UK wheat. This is a long term option and an extremely challenging scientific objective. Rice feasibility assessed by Hibberd *et al.*2008. (P)

C.1.2.6 Increased partitioning of dry matter to grains

Constraint

There are two routes to enhancement of grain weight: (i) increasing the part of the growing season that is taken up by grain filling, by bringing flowering earlier in the life of the crop, or (ii) increasing the amount of pre-flowering assimilation that is redistributed to the grain, by enhanced deposition of fructans pre-flowering. Essentially these two routes are of equal utility in terms of grain biomass accumulation, but advanced flowering has the disadvantages of attracting greater risk of frost damage in spring (Spink et al. 2000), and of dictating that leaves must live longer through grain filling and that grain filling must be prolonged beyond current experience. Possibly these are the reasons that there has been no detectable advance in flowering dates of UK varieties over the past 30 years, whilst there has been a significant trend for greater Water soluble carbohydrate (WSC), primarily fructans in stems (Shearman *et al.* 2005). Disadvantages in enhancing fructans deposition further may be that this will reduce availability of assimilates for concurrent formation of fertile florets (Blum 1998).

A limit to the proportion of the growing season that can be committed to production of grain is set by the requirement for assimilates to form support structures (leaf, stem and chaff). Leaf assimilate requirement depends largely on the leaf area required for full interception, which is relatively stable at GAI 6-7, requiring ~4 t/ha of leaf & sheath biomass. Chaff biomass does not vary much in proportion to grain biomass (~14%). The requirement for stem biomass has proved more difficult to estimate until recently when estimation of biomass requirements to resist lodging have become possible (Berry *et al.* 2007). Ideotype design work has shown that, unless stronger constituents of stems can be introduced, acceptance of some lodging risk may be necessary to further improve grain yields.

Intervention

Husbandry

Whilst there is potential to advance flowering date through earlier drilling as outlined above, the potential utility of this approach is limited by the risk of frost damage to the developing ear. Husbandry approaches are therefore likely to have limited application with out genetic improvements for example to reduce frost susceptibility.

Genetic

Current UK varieties have a 6-day range of flowering around the 12th June, with the exception of the French-bred variety Soissons, which possesses the *Ppd-D1* gene for photoperiod insensitivity, and flowers at the end of May. The success of Soissons in the UK encourages the belief that there is scope for advancing flowering to early June without incurring undue frost risk (Whaley *et al* 2004). The pattern of total biomass accumulation to achieve a 19.2 t/ha crop indicates that about 14.5 t/ha biomass would need to be accumulated by 4th June. This is sufficient for 3.5 t/ha WSC formation, in addition to the biomass requirements for leaf, structural stem and ear already discussed, and is similar to the larger quantities of WSC in current varieties (Foulkes *et al.* 2002). Thus, we suggest that the potential yield could be achieved, either by advancing flowering to early June, or by holding flowering in mid-June whilst seeking further enhancement of stem WSC to 5.5 t/ha by breeding.

Enhancing stem WSC is probably preferable to advancing flowering because it imposes less on leaf longevity. The flag leaf generally emerges (benchmark date: 24th May) about two phyllochrons before flowering. Its senescence is a little delayed but largely concurrent with that of the second leaf and the third leaf (counting back from the ear), so the benchmark pattern of canopy senescence (with GAI 3 on 13th July and GAI 1 on 25th July) indicates that current green duration for these leaves is 55 to 75 days. If the date of flowering remains on 12th June the need to prolong canopy life by 8 days appears realistic. Further extension of leaf life may be more difficult because photosynthetic efficiency tends to diminish with leaf age (Dreccer *et al.* 2000) and because, in other environments, redistribution of stem biomass has been associated with earlier senescence (Blum 1998). However, recent work at the John Innes Centre identified the value of a non glaucous phenotype as determined by the presence of a gene (Vir) inherited from *Triticum dicoccoides*. This phenotype delayed senescence thus allowing plants to continue to photosynthesise and increase yield potential. This again illustrate the potential of accessing exotic genepools and utilising wide crosses.

Research Needed

- A more detailed physiological understanding of the influence of vernalisation, photoperiod and earliness *per se* genes that have already been identified. (P)
- Identification or introduction of novel developmental genes -new sources of diversity will need to be accessed and there are a range of sources that should be considered including historic germplasm collections and novel germplasm from synthetic wheat created from ancestral parents of bread wheat. (P)
- The combination within a single genotype of a number of developmental genes to give the desired developmental pattern. (P+I)
- Better characterisation of the relationship between height and grain yield, so that height and the requirement for stem biomass can be reduced further without reducing grain yield. (P+I)
- Identification and characterisation of tissues and their constituents (e.g. lignins) that confer structural strength on wheat stems, and introduction of compositional changes that reduce the biomass required to resist stem lodging. (P)
- Introduction of changes in anchorage roots that increase resistance to root lodging. (P)
- Genetic enhancement of the storage of fructans in the stem. (P)

C.1.2.7 Water capture and conversion

Constraints

The possible impacts of maximising wheat yield on water in the environment are, if anything, more serious than the predicted effects of nutrients. There is little evidence that efficiencies of water use by crops have increased as yields have been increased over recent decades (Foulkes *et al*. 2001; 2002; Sylvester-Bradley and Foulkes 2003). This did not matter whilst yield increases arose through better harvest index, but with further increases likely to arise more through greater light capture and total crop growth there is cause for concern. Assuming fixed water conversion (ratio of above-ground biomass production to concurrent evapo-transpiration), for average conditions in eastern England, water draining from cropped land could be reduced drastically, to about one fifth of current amounts (271mm to 56mm) as a result of future yield enhancement. Of course this is an extreme case where it is assumed that artificial water storage and irrigation are widely available. However, it illustrates that, depending on uncropped land and other changes in land use, there is a clear risk that breeding for improved crop yields without regard to improving water conversion will increasingly reduce both the flows of surface waters and the recharge of aquifers.

Currently for the 12% of UK wheat fields located on drought-prone sandy or shallow soils, yield-limiting droughts occur about two years in three (Foulkes *et al*. 2001), and for all UK wheat fields it has been estimated that the loss in yield potential due to drought over a run of years is in the region of 10-20% (Foulkes *et al.*, 2002). Taking into account environmental constraints on extension of irrigation (Department for Environment, Food and Rural Affairs 2004), we have to conclude that it is likely there will be much land where rainfall becomes the main determinant of yield, and that there will be many seasons when water supplies are inadequate everywhere. Although root biomass may increase in proportion to aerial biomass at anthesis in the crop, this can only improve recovery of soil-stored winter rainfall, not annual water supply. Therefore it is important that we breed for better water conversion.

Intervention

Husbandry

The economics of irrigation for broad-acre crops will become more viable as their yield potentials increase, and as climates change. Whilst irrigation is likely to remain uneconomic on farms with moisture-retentive soils, it will become more worthwhile on light and medium textured soils and, particularly where other more valuable crops in the rotation will justify installation of irrigation systems, cereal crops may well attract irrigation, particularly early in the summer when capacity exceeds the demands of other crops. Thus greater demand for and use of irrigation are to be expected, and efficiencies of irrigation systems will be of increasing concern.

Of husbandry options available for cereals, crop establishment as affected by cultivations and sowing techniques has the most significant effect on root depth and distribution. There will be an increasing need for establishment techniques to be optimised for subsequent soil water capture.

Genetic

It is possible that genetic increases in water conversion could ameliorate the potential influence of UK droughts. However, success depends upon approach: under drought in Australia Rebetzke *et al*. (2002) found that increases in transpiration efficiency (ratio of above-ground biomass production to crop transpiration), after selection for reduced carbon isotope discrimination, gave greater crop biomass and greater grain yield. On the other hand, using the same selection approach, Araus *et al*. (2002)

found reduced stomatal conductance gave lower intercellular levels of CO_2 and decreased photosynthesis and biomass. It appears that the better result comes from seeking increased WUE through increasing photosynthesis (perhaps through an increasing sink), rather than through directly reducing stomatal conductance. Seeking improvement of light conversion from 2.2 to 2.8 g/MJ might translate into improvements in water conversion. However, in practice, better light and CO_2 conversion would probably increase stomatal conductance, and moderate or negate potential improvements in water conversion. Furthermore, a greater proportion of seasonal growth will occur in June and July with high yielding crops; this is when vapour pressure deficit is greatest, and will tend to decrease season-long water conversion. In summary, although small improvements in water conversion may be feasible, it is unlikely that they will be sufficient to alleviate the anticipated limitation to growth and grain yield of water availability. Thus, irrespective of any effects of climate change, we anticipate that wheat improvement in the UK will increasingly be influenced by drought, and the rate of yield progress is likely to slow. We estimate, assuming no breeding improvement in water conversion, that a potential yield, unrestricted by water, of 19.2 t/ha reduces to 14 t/ha if irrigation remains unavailable in wheat-growing regions.

Being pessimistic about improvement of water conversion, yield improvement will become more dependent on improved soil exploration by root systems, particularly in temperate regions where soils are recharged with water over-winter. Root studies are rare and measurements are uncertain, so it is encouraging that some genetic variation was found in root exploration of recent UK wheat varieties (Ford *et al.* 2006).

Research needed

- Genetic improvement of rooting at depth and partitioning to improve exploitation of stored soil water. (P)
- Improvement of water capture by improved establishment techniques. (P+I)
- Genetic improvement of WUE. This will be an integral part of research to improve light conversion (see above). (P)
- Improvement of the efficiencies of irrigation techniques. (P+I)

C.1.3 Protecting the potential gains

The current dynamic equilibrium is that diseases are reasonably well controlled in most arable crops in most seasons, but still cause loss of yield – estimated at between 2% and 6% (300,000 tonnes to 900,000 tonnes) per annum in wheat, depending on seasonal disease pressure (Hardwick *et al.*, 2001). Annual losses in barley vary between approximately 4% and 12% (Cereal Disease Survey – England and Wales).

Severe yield losses due to pests are uncommon, and only on rare occasions when a previously unimportant pest becomes significant because of suitable climatic conditions such as orange wheat blossom midge in the late 1990's, are losses reported. It must be concluded therefore that currently pests are reasonably well controlled although it should be noted that this is often through the use of prophylactic inputs which increase the risk of pesticide resistance developing.

The potential yield loss from weed infestations is greater than for pests and diseases. Weeds are generally well controlled in most arable crops but this is heavily dependent on the use of effective herbicides. In organic farming systems, weeds are a major constraint primarily because non-chemical methods are less effective than herbicides. The continued availability of effective herbicides, integrated with improved non-chemical methods of weed control, is critical to increasing production.

C.1.3.1 Implications of increased intensity of production

The changes predicted in Section B (exploitation of current knowledge) and in Section C above, will result in more severe weed pest and disease pressure which if not addressed will limit the potential to increase the productivity. For example:

- An increase in specific leaf nitrogen would increase the absolute rate of epidemic progress of biotrophic pathogens (rusts and powdery mildews) (Neumann *et al.,* 2004).
- An increase in leaf life of 8 days to increase partitioning to grains would be disproportionately challenging to protect against diseases, as epidemics increase exponentially through time.
- An increase in radiation use efficiency will decrease the tolerance of crops to disease (Paveley *et al*., 2001; Bingham *et al*., in press)

The following section describes the new pest and disease pressures that will have to be addressed using new technology.

C.1.3.1.1 Increasing land for cropping

Pests

Converting grassland, or long-term set aside with grass weeds, back to arable production will increase the infestation/damage by leatherjackets (*Tipula* spp.), wireworms (*Agriotes* spp.) and frit fly (*Ocinella frit*). These species are locally damaging and insecticidal seed treatments are available, but the treatments for these species are different from treatments used for the main pest target, autumn invading aphids carrying BYDV. There is evidence that cereal cyst nematode could be more prevalent and damaging in continuous wheat. The potential threat at present is limited by natural suppression in soil. This could change with spread of new pathotypes or species associated with environmental change. There would also be potential problems with weeds, especially perennials such as docks, thistles and couch grass, which tend to be favoured by non-disturbance.

C.1.3.1.2 Increasing intensity in the rotation

Diseases

There will be increased incidence of soil-borne and trash-borne diseases that survive on crop debris. Root and stem base diseases, such as take-all and eyespot, would increase in severity. Take-all losses could make second or third wheat crops uneconomic. Trash-borne diseases, such as fusarium, will probably be more severe, with serious consequences should the ear blight phase of the disease contaminate more grain with mycotoxins.

Pests

In the short-term, this could increase pests that diapause in the soil beneath the crop. These include orange and yellow wheat blossom midges (wbm), *S. mosellana* and *Contarinia tritici*, respectively, (although feed wheat cultivars resistant against orange wbm have been produced and resistance will be introduced into higher quality bread wheats (Oakley et. al., 2005).

The increase in mild winters, as a result of climate change, has already increased the range of originally localised pests (e.g. gout fly) and greater crop intensity will lead to larger populations and requirement for control.

Second wheat may be direct drilled and unless well managed (e.g. by insecticidal sprays or seed treatments, further selecting for the development of resistance) this can provide a “green bridge” for aphids to transfer from one wheat crop to the next, taking BYDV with them. There may also be an increase in slugs in crop debris.

Weeds

Increased intensity of autumn sown wheat and oil-seed rape will exacerbate the current difficulties with managing annual grass weeds. The consequent reductions in spring cropping and broad-leaved crops will reduce opportunities for the effective management of these weeds. Indeed, our perception is that if farmers were encouraged to increase winter wheat cropping there is an increased risk that this strategy would fail because of the farmers’ inability to control weeds. Such a scenario is made more possible if the anticipated changes to pesticide regulations (successor to EU Agrochemical Registration Directive 91/414 – see Section B6) actually are implemented.

C.1.3.2 Future developments diseases

Constraints

Foliar diseases in wheat primarily restrict the achievement of yield potential by reducing canopy survival directly by eroding green area during seed filling and therefore restricting assimilate availability. Likewise stem base disease reduce canopy survival but indirectly by destroying the vascular system restricting water uptake and inducing canopy senescence through drought. In contrast root diseases can affect yield potential by reducing shoot number and therefore grain number through severe early season disease or by reducing canopy survival in the same way as stem base diseases with later developing disease. The magnitude of the yield loss due any given level of disease will therefore depend on the relative importance of assimilate supply and storage capacity. As the yield potential of the crop approaches the theoretical potential the magnitude of yield loss for any given level of disease is likely to increase.

Pathogen populations respond to selective pressures created by disease management, resulting in accumulation of new virulences against host resistance and insensitivity against fungicides. Hence, improvement and protection of yield through disease control is a treadmill, rather than a staircase. Discovery of new modes of action and introgression of new resistance genes, is partly negated over time by pathogen adaptation, and any diminution in the rate of scientific, technological and agronomic progress would result in substantial increases in yield losses.

To realise the full yield potential of wheat, several diseases caused by fungal pathogens need to be controlled. While modern wheat cultivars have a background level of resistance to most of the major pathogens, this is often inadequate to prevent losses in seasons of high disease pressure. Crop protection is therefore heavily dependent on the programmed application of fungicides. Irrespective of concerns about the costs and environmental impacts of chemical inputs to the crop, the durability of these approaches is threatened by the development of pathogen resistance to such chemicals. At present the solution for this problem is chemical diversification (within and between mode of action groups) and maintenance of an efficient discovery pipeline for new active ingredients. Whether this is sustainable in the long term is debatable.

For soil-borne virus mosaic diseases, the only control options are based on cultivar resistance through conventional plant breeding; GM approaches may widen the options available.

Intervention.

Breeding for host resistance is often associated with ‘yield drag’, caused either directly by the physiological effects of the resistance response on the plant, or indirectly by reducing the effective size of the breeding population from which yield traits can be selected.

Disease resistance responses (particularly those based on hypersensitive response) and disease symptom expression can have negative or positive effects on stomatal conductance, and hence potentially impact on radiation use-efficiency and water use efficiency (Prats *et al*., 2006; Paveley, data unpublished). These mechanisms may be partly responsible for yield drag. Characterisation of new resistance genes should therefore include quantification of any associated deleterious effects. This is exemplified by the case of the introduction of resistance to eyespot (*Pseudocercosporell herpotrichoides*) using the introgression from the D genome of *Aegilops ventricosa*). This resistance has high value for the control of eyespot but as – a consequence of ‘yield drag’ very high yield potential material has still to be developed.

Durable resistance tends to be partially effective. Similarly, fungicide treatment is partially effective. Hence, some disease remains, which the crop needs to be able to tolerate. Tolerance (the ability to maintain yield in the presence of disease) has deteriorated in UK wheat varieties over recent decades (Parker *et al*., 2004, Foulkes *et al*., 2006) and future selection for yield traits is likely to increase yield loss per unit disease severity (Paveley *et al*., 2001). There is therefore a need to identify tolerance traits which can be incorporated with durable resistance traits to reduce yield loss.

The GHG costs associated with fungicide use and host resistance breeding are both small in comparison with the resulting yield gain, so disease management reduces GHG emissions per tonne of produce (Berry *et al*., 2008).

The genetic base for resistance to several pathogens is narrow (e.g. fusarium ear blight, eyespot), or non-existent (e.g. take-all). A high priority is to use the full range of gene discovery routes to widen the genetic base of resistance available. There is a need to find novel mechanisms of resistance that will require more critical bioassays/ screens to identify them. An example is recent work on take-all at RRes, where wheat genotypes vary in the extent to which the disease multiplies on the crop, and hence the amounts of inoculum available to infect a subsequent crop. Ideally novel sources of resistance in wheat itself, its progenitors and wild relatives, and allelic diversity of known sources, should be sought. Research is also required to provide a detailed analysis of different resistance mechanisms to ensure functional as well as genetic diversity.

In parallel with the search for new resistance sources, there must be more fundamental work on the regulatory mechanisms controlling inducible plant defence in crops such as wheat. This will lead to better integration between crop improvement through breeding and targeted use of alternative chemicals such as plant defence activators. More work is required on effective integration of cultivar resistance (conventional and GM) and use of “smart” chemicals.

Diversification of bioactive compounds for disease control is also required. The first priority is to counter regulatory moves to further reduce the currently available portfolio of pesticides. This is essential to ensure effective control options and safeguard the best, environmentally benign chemicals from the risk of resistance. A strong discovery pipeline must also be maintained.

Research on the mechanistic basis of pesticide resistance, and especially the genetic changes involved, would help to ensure robust risk assessments and sensitive diagnostic tools to monitor the emergence and spread of resistance. Development of whole genome approaches to identify new resistance mechanisms is also a priority to develop pro-active rather than reactive approaches to resistance management.

It is unlikely, in the short term, that biological approaches to control of the major fungal pathogens of wheat will replace pesticides. Nonetheless there is a need for better understanding of interactions between pathogens and the microbial community in the rhizosphere and phylloplane, both to clarify the basis of suppression and to identify new antimicrobial bioactives.

Effective surveillance, monitoring and diagnosis of pathogens will be essential to counter new threats and especially the incidence of emerging diseases responding to environmental change. New technologies are available for this task but research is required to evaluate their utility in the field and especially how to optimise sampling and modelling of disease outbreaks.

Research needed

- Identify novel sources of resistance in wheat itself, its progenitors and wild relatives, as well as allelic diversity from known sources. (P)
- Characterise new sources of diseases resistance genes taking account of resistance mechanisms and pleotropic and yield drag effects. (P)
- Identify disease tolerance traits which can be incorporated with durable resistance traits to reduce yield loss. (P)
- Provide a detailed analysis of different resistance mechanisms to ensure functionality as well as genetic diversity. (P)
- Improved understanding of induced plant defence mechanisms. (P)
- Development of bioactive and environmentally benign chemicals for disease control to increase availability of pesticides, (P+I)
- Improve the understanding of the mechanistic basis of pesticide resistance and the genetic drivers to develop strategies to protect current and future compounds. (P)
- Identify the potential to suppress disease using antimicrobial bioactives developed from an improved understanding of the interaction between the pathogens and the microbial communities in the rhizosphere and phyloplane. (P)
- Develop better surveillance monitoring and diagnosis to better target disease control strategies to improve the effectiveness of pesticide use, reduce the need for pesticides and provide a corner stone for the development of Integrated disease management. (P+I)

C.1.3.3 Future developments pests

Constraints

In common with diseases, pests limit the crops achievement of its yield potential through either restricting photoassimilate production or the potential storage of photoassimilate. In wheat, pests impact on yield formation through both mechanisms and in a number of cases through restricting both, it should be noted however that the impact of a number of pests is primarily through affecting grain quality rather than yield formation.

The main target for pyrethroid insecticide application is the autumn migration of BYDV carrying cereal aphids (*Rhopalosiphum padi* and *Sitobion avenae*) (Garthwaite *et al.*, 2006). The impact on disease is not through direct feeding damage but the transmission of virus disease that restricts canopy size and function.

The main spring/summer target for chlorpyrifos and pyrethroids (and now thiachloprid) is currently orange wheat blossom midge (*Sitodiplosis mosellana*) (Garthwaite *et al*., 2006), although the use of resistant cultivars is becoming more common these are not available for quality bread-making wheats. Chlorpyrifos use in wheat in 2006 was 10 times higher than in 2002 (Pesticide Usage Survey, 2006), and orange wheat blossom midge has been the main factor causing this. In an outbreak in 2004, crop losses were estimated to be 6% (1 million tonnes) nationally, which was compounded by reductions in grain quality, despite insecticide application to around 500,000 ha (Bruce & Smart, 2008). Damage caused affects crop yield, quality and acceptance for milling. Typically one larva feeding on a grain site will reduce yield by about 30%. If two or three larvae feed per grain site yield loss can be as much as 75% or even higher if ear emergence is late. In addition to direct feeding damage, larval feeding can induce premature sprouting in the ear and a reduction in Hagberg Falling Number. Secondary fungal attack can follow under damp conditions. Grain aphids (*S. avenae*) are an occasional problem however their numbers are suppressed by insecticide inputs targeted at OWBM control. Warmer summers as a result of climate change may increase the incidence of this pest which limits yield formation by acting as an alternative (to the grain) sink for photoassimilates.

Other pests (ADAS Pest Incidence Report, 2007) – Gout fly (*Chlorops pumilionis*), which is spreading up country due to milder conditions and wheat bulb fly (*Delia coarctata*), which is locally important in the East and North, cause yield damage by reducing shoot survival and therefore canopy size and assimilate production as well as the number of grain sites.

There are many other minor pests, which may become important with climate change or if minor yield loss due to damage becomes less acceptable. Possible invaders due to climate change are greenbug, *Schizaphis graminum*, *Diabrotica spp*. and Russian wheat aphid, *Diuraphis noxia*.

Intervention.

The context of increased demand for agricultural production coupled with increasingly stringent pesticide legislation means that there is now an even stronger case for agricultural research into new ways in which losses due to pests can be reduced. There are alternatives to broad-spectrum eradicant pesticides such as the use of host plant resistance and biological control with natural enemies. Currently the use of host plant resistance is limited due to constraints in obtaining resistance to multiple pest and disease targets in combination with the other required agronomic characteristics whilst biological control is limited in an open field environment where it is hard to maintain sufficient numbers of natural enemies in the right place at the right time. Research into insect-plant interactions has given us insights into novel interventions that could be deployed to reduce pest pressures but it is unlikely that these will offer a complete replacement for targeted use of insecticides.

Small lipophilic signalling molecules can be used to induce or prime plant defence responses so that treated plants are more resistant to subsequent attack by pest insects and more attractive to the natural enemies of these pests (Pickett *et al*., 2006; Bruce *et al*., 2008). Some of these are confidential but research findings with the compound *cis*-jasmone are in the public domain (Pickett *et al*., 2007a&b; Bruce *et al*., 2008; Blassioli Moraes *et al*., 2008). There is scope to extend this work in the future to develop more effective treatments. By finding the optimal dose and timing of inducing and priming agents as well as developing new more effective treatments. Synergists can be used to formulate higher molecular weight compounds so that they can be delivered through the plant cuticle. Development of new plant activators from compounds in aphid saliva is possible. There are some parallels with abiotic stress resistance in which plants become "hardened". A long-term goal is to discover the underlying mechanisms of this process so that plants can be bred which are more resistant both to biotic stress such as insect attack and abiotic stress such as drought.

Plant breeding for resistance to insects is the ideal way of controlling pest species – no toxic insecticides are necessary, but insect resistance traits have to reside in a genetic background with appropriate overall agronomical qualities. Internationally, there are wheat cultivars with resistance to aphids (e.g. greenbug, and Russian wheat aphid) and to midges of the family Cecidomyiidae (orange wbm and Hessian fly, *Mayetiola destructor*). However, these traits may be suitable for a particular geographic or climatic area. The resistance is often attributable to a single gene resulting in the selection of resistant biotypes of the pest (e.g. greenbug, and Russian wheat aphid Hessian fly and more recently, a resistant biotype of orange wbm has been identified in Canada by Smith *et al*., 2007). Breakdown of resistance requires ongoing development of new resistant varieties and in the future it would be better to develop resistance from more than one gene as this would be more robust. Very high levels of resistance may not be necessary to prevent most of the potential losses. Indeed, high levels of constitutive resistance will give increased selection pressure for counter-resistance in the insect. In addition, where species overlap, selection for resistance against one pest will not protect the crop against the others and may lead to an increase in their populations e.g. we are now seeing more yellow wbm since the introduction of orange wbm resistant cultivars. Apart from orange wbm resistant cultivars, which were discovered by chance through a breeding link with Canada (Oakley *et al*., 2005), there are no other pest resistant wheat cultivars in the UK. If GM approaches could be made more acceptable to public perception, wheat transformation could facilitate the rapid introduction of resistance traits, including those from related plant species, into elite breeding lines and, with care to avoid the transfer of undesirable traits, allow for the development of multi-pest resistant cultivars. This could include not only lethal and sub-lethal plant resistance traits, but also non-toxic resistance mechanisms such as the introduction of genes for the production of insect behaviour-modifying chemicals or of inducible promoters, which can be "switched on" by semiochemical signals and enhance the plants natural defence mechanisms (Pickett *et al*., 2006).

Screening trials of new wheat varieties conducted under insecticide treated conditions have meant that insect resistance has in many cases been precluded from consideration as a trait for breeding and opportunities to develop resistant varieties may have been lost. Crop domestication has increased susceptibility to insects by making crops nutritionally more suitable for them. Furthermore plants have natural defence mechanisms that have inadvertently been bred out during the domestication of crops, for example, hydroxamic acids are used against insects in wheat. Domestication has also reduced crop genetic variability making plants more vulnerable to adapted pests and has reduced defences that carry an energetic cost by selection for yield (Migui & Lamb 2003). Screening of wheat varieties for insect resistance is a promising area for further development and improvement of established varieties that have good agronomic characteristics but are susceptible to insect attack.

Plant molecular biology studies will facilitate identification of natural plant defence mechanisms by seeing which genes are upregulated in infested plants. This approach could be extended to micro-array studies of wild relatives of crop plants after exposure to insect attack to identify insect resistance genes. These genes could be bred into elite lines of wheat crops either by conventional breeding or by transgenic methods. Selection for resistance traits will be easier when there is a wide range in response and thus it is important to conserve genetic diversity. Many different wheat varieties are grown around the world, in the USA alone at least 1000 different varieties are grown each year, each adapted to a particular locality and/ or suited to a particular end use and management (Cook 2006). In fact, the tens of thousands of wheat accessions available for testing make searching for resistant line a “daunting task” (Migui & Lamb 2003). In addition to the wheat varieties being commercially grown, wheat germplasm is collected and stored in gene banks such as the one at ICARDA (Ceccarelli et al 1992). Close relatives of crop species are potentially rich reservoirs of genes for resistance to pathogens and insect pests and these genes can be transferred to crop cultivars through hybridization (Jauhar 2006), although the time taken to transfer resistance increases and chances of success decrease moving from local germplasm to more distant material or material from related species (McIntosh 1998). In the future, wheat transformation (Patnaik & Khurana 2001, Jones 2005) could facilitate rapid introduction of resistance traits into elite breeding lines and allow development of multi-pest resistant varieties. It may even be possible to develop non-toxic pest resistance mechanisms, for example, a terpene synthase gene for production of the aphid alarm pheromone has been cloned into thale cress *Arabidopsis thaliana* (Brassicaceae) (Beale et al 2006) and preliminary studies at Rothamsted demonstrated that this compound is released by transformed wheat. This approach could facilitate the manipulation of volatile semiochemicals, which are difficult to formulate for field release. With the advent of genomic technologies it may be possible to develop resistant plants by transforming wheat plants with known resistance genes, particularly those in species that are related to wheat. It is desirable that the alien segments should be very small to avoid any problems of undesirable traits associated with alien transfers (McIntosh 1998). The wheat genome is a challenge because it is hexaploid and very large: it is approximately 16,000 Mb which is 5 times bigger than the human genome and 35 times bigger than that of rice (Jones & Kanyuka, 2004). It is also necessary to understand and control factors causing transgene silencing, instability and rearrangement, which are often seen in transgenic plants, and are highly undesirable in lines to be used for crop development (Repellin et al 2001). The lack of sufficient target genes identified for transfer has also been mentioned as a limitation (Stoner 1996). However, genomic information should help to overcome these issues and there is the advantage of wheat having considerable syntergy with rice (Salse et al 2008). Thus, genomic insights obtained from rice studies may provide relevant information for investigating traits in wheat and facilitate study of the wheat genome. Some progress has been made towards mapping the wheat genome itself (Qi et al 2004).

Development of new insecticides is still required. By understanding how ligands bind to proteins for olfactory recognition in insects it might be possible to find insect-specific inhibitors that can be used to disrupt this process – a novel target for chemical intervention against insects.

Semiochemical baited traps (e.g. Bruce *et al*, 2007) and suction traps (Harrington and Woiwod, 2007) can be used to monitor insect populations and it would seem sensible to use and develop these to monitor pests which are increasing their Northern ranges as a result of climate change. In wheat the species to consider would be greenbug, *Schizaphis graminum*, *Diabrotica* spp. and Russian wheat aphid, *Diuraphis noxia*. Forewarned is forearmed and by detecting these pests in the UK early on would open the possibility to have more time to develop interventions to reduce yield losses that they would cause in the long-term.

Research needed.

- Priming / inducing plants with activators (P)
- Heterologous expression of semiochemical synthase genes (P)
- Breeding plants with altered secondary metabolism (P)
- Interfering with insect olfaction (P)
- Development of monitoring systems (P+I)
- Improve crop husbandry to decrease severity of attacks. (P+I)
- Improve insecticide timing to provide better control. (P+I)
- New more effective insecticides including biopesticides such as entomopathogenic fungi and natural endocrine disruptors (P+I)
- Breeding for resistance to pests (P+I)

C.1.3.4 Future developments weeds

Constraints

Weeds also pose a major constraint to crop production. However, as they are not directly linked to the crop grown and are more associated with the field in which the crop is grown, detailed consideration of weeds is included in this report in a single section (C.3.2 below). However, it should be pointed out that weed management is different in all crops and the constraints, interventions and research needs are similarly different. As far as winter wheat is concerned the major problem is the increasing prevalence of herbicide resistant annual grass weeds. If these weeds are not controlled effectively there is a risk that many of the anticipated yield increases highlighted in the previous sections will be lost.

C.2 Oilseed rape

C.2.1 Theoretical yield potential

Oilseed rape is currently sink limited with 85% of the variation in yield being due to seed number (rather than the crops ability to fill the seeds). Encouragingly it has been shown that there is considerable scope to increase sink capacity (Spink and Berry, 2005). However if sink capacity is increased to its potential then a significant increase in source capacity will be required thus increasing the demand for nutrients, water and sunlight which in turn will require an increase in the capacity to capture these resources or an increase in the efficiency with which these resources are used. All of these constraints can potentially be addressed by improved husbandry and genetic knowledge.

The current UK average yields are 3.1t/ha, RL yields are 4.5t/ha and the assumption was made in section B that the average farm yield using current knowledge could be increased to 3.6 t/ha. The theoretical yield potential for oilseed rape in average UK conditions using existing germplasm has been estimated at 6.5 t/ha (Berry and Spink, 2006). Several researchable constraints must be addressed to achieve this including improved genetic understanding to combine all of the best traits that have been observed into one variety, and improved agronomic understanding to allow the germplasm to achieve its high yield potential. With further genetic improvements, described below, the potential is estimated to increase to 9.2 t/ha (Berry and Spink, 2006). However this potential could not be achieved without further improvement in nutrition and crop protection.

Generally under UK conditions the most limiting resource that constrains crop growth and yield is availability of light. However, in order for the crop to utilise the available light as efficiently as possible the acquisition of other resources such as nutrients and water also need to be optimised as does the partitioning of biomass to maximise harvestable yield. The crop traits required to optimise resource use efficiency to achieve this higher yield potential are detailed below. They include:

- Improving rooting – oilseed rape has been shown to have a limited root system at depth and therefore prone to premature senescence during seed filling.
- Improving nitrogen use efficiency – oilseed rape is relatively inefficient in its use of N (low offtake cf. input), although this would not increase yield it would improve GHG efficiency.
- Maximising the sink capacity of the crop – increasing its ability to store photosynthate produced during seed filling.
- Improving post flowering radiation use efficiency – increasing the efficiency of light conversion post flowering to maximise photosynthate availability for seed filling.

- Improving pre-flower assimilate use – making more of the photoassimilate produced before flowering available for seed filling by increasing the production and remobilisation of soluble sugars stored in the stem.
- Reducing harvest losses – reducing seed losses due to pod shatter immediately prior to or during harvest

C.2.2 Improving Resource Capture and Use efficiency

C.2.2.1 Improving rooting to exploit soil resources (nutrients and water)

Constraints

The root system of oilseed rape has been shown to be sub-optimal resulting in low yields in dry years (Blake and Spink, 2005 and Farre *et al*, 2003) and a high requirement for nitrogen (N) fertiliser (Dreccer *et al*). This results in high green house gas (GHG) emissions associated with the production of oilseed rape and contributes to the high risk of nitrate leaching – higher than most other arable crops. The GHG cost of growing oilseed rape is affected most by variation in nitrogen fertiliser use and crop yield (Mortimer *et al*, 2003), both of which are affected by rooting. The increased area of nitrate vulnerable zones (NVZs) has increased the importance of minimising nitrate leaching.

Water extraction is principally determined by the volume of soil explored by roots which is usually measured in terms of root length density (RLD). In wheat, a minimum RLD of 1 cm/cm^3 of soil is required to extract all of the available water from the soil (Barraclough and Leigh, 1984), the critical RLD in oilseed rape has not been established but circumstantial evidence suggests it is similar to that of wheat. Oilseed rape has been shown to have a lower RLD than wheat particularly at depth (Barraclough, 1989 and Kjellstrom, 1991), it has been shown that the RLD of oilseed rape crops is frequently less than $1cm/cm^3$ below a soil depth of 40 cm (Dreccer *et al,* 2000 and Barraclough and Leigh, 1984). Oilseed rape roots descend to 120 to 180 cm (Kjellstrom, 1991), so this represents a significant volume of soil which is not fully explored by the roots. Recent work (Blake and Spink, 2005) showed that after a moderately dry June, with 50% of the long term average rainfall, an increase in RLD below 40 cm of only 20% increased yield by 0.5 t/ha. In this study, differences in RLD were caused by different crop management (primarily a plant growth regulator).

Relatively small improvements in rooting and root function will therefore result in significant yield improvement in drought conditions, reductions in nitrate leaching as a result of better recovery from the soil and a greater amount harvested in the seed, and reduced GHG emissions . However it is not well understood how plant breeding and crop management can be used to maximise rooting. The time–consuming nature of direct root measurement also makes it very difficult for agronomists and physiologists to study effects of rooting, or for plant breeders to improve rooting, without rapid screens or QTL being identified.

The required improvement in RLD can be achieved through both husbandry and genetic means as described below. With the potential to increase yield by 1.0t/ha on 25% of the crop which experiences dry conditions an average response of **0.25 t/ha** can be expected in addition fertiliser N requirement could be reduced by a modest **10kg/ha**, a relatively low figure due to low residues of N in the lower soil layers which improved rooting could exploit.

Intervention

Husbandry

There is anecdotal or laboratory evidence as well as limited field trials evidence that several agronomic practices may influence rooting, and hence recovery of nitrogen, water and other nutrients.

Oilseed rape is considered to be sensitive to compaction. Some progressive growers have sought to establish oilseed rape by drilling immediately behind subsoil cultivation equipment, to improve the rooting environment. However, there is little evidence to support the use of this technique, a better understanding of subsoil cultivations and min till establishment on the extent and depth of rooting would provide an informed basis for decision making at crop establishment.

Root growth may be enhanced by earlier sowing, however, this can cause yield loss (Carver *et al*, 1999) due to an excessive canopy being produced which utilises light inefficiently, produces too many pods, and is prone to lodging (Spink *et al*. 2002). High plant populations may lead to increased concentration of the roots in the upper soil profile, as has been shown in some other species (Kirby and Rackham, 1971), possibly at the expense of rooting at depth (Hoad *et al*., 2001). Low plant populations may therefore improve rooting, but increase the crops susceptibility to slug and pigeon attack and reduce the crops competitive ability with weeds. Therefore in addition to considering cultivation practice at establishment sowing date and seed rate combinations need to be developed which allow better rooting whilst avoiding other adverse agronomic effects.

In addition to agronomic factors at establishment there are agronomic techniques which can be utilised post establishment to manipulate rooting. Spring applications of the growth regulator metconazole has been shown to increase rooting at depth (Blake and Spink, 2005). In contrast the effects of autumn applications of these PGRs have received little or no detailed study in the UK. Based on laboratory experiments in Germany, autumn metconazole applications have been promoted to improve both winter hardiness, and the root/shoot balance. Developing the use of growth regulators to improve rooting in the UK may, therefore, provide a means to overcome the problems posed by the other agronomic techniques.

In addition to the use of PGRs to improve root exploration there is evidence from work on other species which suggests that early spring N applications encourage shallow rooting (Hoad *et al*., 2001), and by delaying spring N in oilseed rape, it may be possible to encourage deeper rooting. This delay may also benefit yield by preventing excessive canopy growth (Lunn *et al*. 2001). Other nutrients have also been shown to affect rooting, sulphur (S) deficiency has been linked to restricted root growth in glasshouse experiments (Helal and Schnug, 1995), demonstrating that adequate S nutrition is essential to maintain root integrity, prevent root mortality, and improve root efficiency. The effect of S levels on root growth has not, however, been studied in the field where deficiency is becoming increasingly widespread, due to reduced atmospheric deposition.

Genetic

Genetic differences in the RLD of oilseed rape have been observed between cultivars, Apex and Capitol (Kamh *et al*. 2005). Cultivar differences in root biomass have been observed in pot experiments (Lou *et al*. 2003), further illustrating that differences exist for rooting traits between oilseed rape cultivars.

Uptake of nitrate and ammonium ions is determined by the RLD and the level of active transportation across plasma membranes of plant cells. Membrane transporter systems are highly efficient but several factors are likely to affect the absorption per unit length of root, including; transporter density, transporter activity and the composition of transporter types. Recent Defra Project Report AR0714 published in 2005 'A study of the scope for the application of crop genomics and breeding to increase nitrogen economy within cereal and rapeseed based food chains' concluded that although many transporter genes have been cloned in Arabidopsis extensive analysis of the transporters in crop species has not been carried out. In the field, cultivar differences in the duration and rate of N uptake have been observed (Horst *et al*. 2003 and Barraclough 1989). These may be caused by genetic differences in either the activity or number of ion transporters.

The rate of N uptake slows dramatically after flowering, despite N being available in the soil for uptake. It is possible that this is triggered by hormones produced during flowering which affect ion transporter functioning (Rossato *et al*., 2002). Breaking this possible link may allow the uptake of N to be prolonged, thereby increasing the efficiency with which applied N is recovered. Research is required to develop new germplasm with takes up N after flowering.

Root architecture has been extensively characterised in Arabidopsis at both the molecular and cellular levels (Dolan *et al*, 1993; Casimiro *et al*, 2001). Many of the key genes that regulate Arabidopsis root development have been isolated and characterised (Casimiro *et al*, 2003). These include regulatory sequences that control rates of root growth, branching and root hair development, these represent potentially important target traits in crop species. The UK has great strengths in Arabidopsis root biology, and the many resources and tools generated by this community are now available for exploitation by the crop community.

Whilst there is evidence that there are differences in some rooting traits between elite lines, there are other specific traits have not been identified and hence their genetic control is unknown, and others that have only been identified in wild relatives. It is also not clear whether there is sufficient variation in those traits for which variation has already been found within elite lines, if not then wider genetic variation will need to be sought in related species or more exotic material.

Research requirements

- Field studies are required to assess the effects on root growth of growth regulators other than metconazole such as tebuconazole and paclobutrazole.

It must also be investigated whether metconazole is able to affect rooting from applications in the autumn which would allow a greater window of application. (P+I)

- Identify genes from existing and novel sources controlling root growth and transporter activity per unit root length eg. upregulation of alanine aminotransferase. (P+I)
- Understand the physiological mechanism which causes the reduced N uptake after flowering and identify breeding lines with prolonged N uptake. (P)
- Develop rapid screens or QTL to help plant breeders to incorporate rooting traits into breeding programmes. (P+I)
- Develop and establishment agronomic approaches (especially N and S nutrition) which maximise root exploration at depth and which are compatible with high yields. (P+I)

C.2.2.2 Nitrogen Use Efficiency

Constraint

Nitrogen use efficiency (NUE) is defined here as kg of seed yield per kg of available N. Improving the NUE of the crop can be achieved by either 1) reducing the N requirement of the canopy whilst maintaining yield or 2) increasing yield without increasing N requirement. Whilst the former would have significant environmental benefits in terms of GHG emissions and reduced risk of nitrate leaching in this report the scope for increasing productivity is of great importance. Both routes can be achieved through either improving the efficiency with which available N is taken up by the plant (e.g. through improved rooting) or by reducing the amount of N required by the canopy to support its growth.

As indicated previously oilseed rape receives a greater rate of N fertiliser (average 207 kg/ha) than almost any other arable crop, but has a N offtake of only 96 kg N/ha. As a result the winter after an oilseed rape crop is often the most leaching prone phase of a rotation (Johnson *et al*. 2002 and Lord *et al* 1999). This can be a significant problem since the majority of oilseed rape is grown in nitrate vulnerable zones. Significant GHG emissions, equivalent to 166,937 t CO_2 p.a., are associated with UK oilseed rape production (Mortimer *et al*. 2003). Of these emissions, 83% are associated with the manufacture and application of N fertiliser. In addition to creating an obvious pollution problem contributing to climate change these emissions are likely to restrict the marketing opportunities for the crop. Fertiliser costs have also risen steeply over recent years and N fertiliser now accounts for 45% of variable costs (Nix, 2008), resulting in a significant financial incentive to improve NUE for the grower.

Several constraints cause oilseed rape to have a low NUE. Oilseed rape has a relatively low N uptake efficiency due to its poor rooting at depth and also because the rate of N uptake slows dramatically after flowering, despite N being available in the soil at this time. The requirement that the crop canopy has for N is also high with only 50% of the N in the canopy being harvested in the seed. Previous research has also shown that higher yield potential crops require more N fertiliser to achieve the potential yield. If the yield potential of 9.2 t/ha identified above were to be reached in the absence of improvements in NUE then the N fertiliser input to the crop would have to increase to about 400 kg/ha, to support crop growth and N offtake in the seed.

Improving NUE could be achieved through agronomic improvements and genetic manipulation. Agronomic practices also indirectly affect NUE by affecting yield, e.g. if sub-optimal practices are employed which cause low yields then this will result in low NUE.

Intervention

Husbandry

Timing of N has a large impact on the efficiency with which it is used to produce yield. It was been shown that crops with large canopies in the spring produce more yield when the N fertiliser is delayed because this prevents the crop from producing an over-large canopy which constrains seed set and causes lodging. Research is required to understand how N should be managed for different genotypes in different environments to maximise NUE.

N inputs to the crop are generally applied relatively early in its lifecycle. The majority of diseases have their impact on crop growth and yield formation relatively late in the lifecycle of the crop. This is the case not just for disease controlled late in the season such as sclerotinia but also for diseases for which control needs to be applied early such as phoma which impacts on crop yield by destroying the stems vascular system during seed filling. N inputs have therefore been applied prior to the adverse effects of disease. As a result yield loss due to disease will reduce output per unit of N applied. Research required to reduce these indirect effects of disease on NUE are considered in the section ‘Protecting potential gains’.

Genetic

Large genetic differences in yield performance at high and low N levels have been shown (Nyikako, 2003; Kessel and Becker 1999). Breeding lines with similarly high yields at commercially used rates of N can have a 50% variation in yield when grown at low rates of N. The relationship between N supply and yield is best described by a linear plus exponential function (Sylvester-Bradley *et al*. 1984). When this relationship was fitted to 3 varieties it was shown that the economic optimum varied by 60 kg N/ha between the most efficient and least efficient varieties.

There is clearly significant scope for improving N uptake efficiency and reducing the N requirement of oilseed rape without reducing yield potential. The main problem is how to identify the breeding lines and varieties that have a low N requirement. The previous work has shown that yield at high N is not a good indicator of the yield at low N.

The most likely route for success will be to identify heritable plant characteristics that are associated with low N requirement and develop rapid methods of assessing these traits in plant breeding programmes. Rapid assessment methods could include traits that can be assessed; by eye, with an instrument, or using DNA markers (QTL). Initial work indicates there is significant variation within current breeding germplasm. Even greater advances may be achieved through the introgression of traits from wild relatives or novel sources of genes.

A number of target traits have been identified which could be exploited to significantly increase NUE:

Improved rooting at depth: This has been described in the rooting section.

Prolonged N uptake: This has been described in the rooting section.

Optimised stem N storage: At harvest, oilseed rape stems contain about 62 kg N/ha, of which 17 kg N/ha is estimated to be in structural tissue and 45 kg N/ha is storage (McGrath and Zhao, 1996). This storage N does not appear to be utilised, as seed N is preferentially relocated from the pod walls in high and low N environments (Malagoli *et al*. 2005 and Hocking and Mason, 1993). The relocation of N from pod walls to seeds will reduce the post-flowering supply of assimilates for seed filling by hastening senescence. The potential for this approach has been demonstrated in other species, for example, maize lines that are able to remobilise stored nitrogen during seed filling have been shown to have a greater N use efficiency (Hirel *et al*. 2001). Therefore we predict that oilseed rape genotypes which relocate more N from their stems to the seed or/and accumulate less stem N (both characterised by low stem N at harvest) would be expected to perform better in low N environments. QTL have been identified for variation in shoot N content in Arabidopsis (Loudet *et al* 2003). The high level of synteny between Arabidopsis and Brassica species indicates that genetic variation for stem N content may also occur in oilseed rape or its close relatives.

Low seed protein content: Protein content has been negatively associated with high yields at low levels of N supply (Nyikako, 2003). It is possible that relocation of N from the pod walls is slower in low protein lines and this extends seed filling. Alternatively this relationship may be the result of other traits improving yield and diluting the protein. Protein content has been observed to vary by 40% amongst 64 Oilseed rape varieties (Malabat *et al*. 2003). This study showed that breeding to increase oil content has reduced protein content mainly by reducing the seed storage proteins napin and cruciferin.

Low leaf N loss: About, 46 kg N ha^{-1} is lost in dead plant material of which half is re-captured by the plant (Malagoli *et al*. 2005). Kessel and Becker concluded that varietal differences in the amount of N lost in shed leaves was important for yield performance in a low N environment. Horst et al. measured two-fold differences in the amount of N lost as dead leaves between varieties, but these differences were not correlated with yield at low N. Therefore the evidence is mixed as to whether this trait is important for low N requirement.

Research needed

- Identify germplasm within Brassica napus and other related species with prolonged N uptake, greater N uptake per unit of root length, more nitrate ion transporters per unit of root, less stem N storage, low seed N and low amounts of N in shed leaves. (P)

- Develop methods to help plant breeders rapidly select new varieties with the above traits. (P+I)
- Identify N fertiliser strategies for improving NUE and investigate whether specific strategies must be employed for maximise NUE in different types of germplasm. (P+I)
- Develop mutants with very low levels of the seed protein fractions napin and cruciferin and assess whether these have a lower NUE. (P)
- Homologues for NUE genes identified in arabadopsis should be sought in adapted oilseed rape. (P)

C.2.2.3 Maximising sink capacity

Constraint

The number of seeds per metre squared has frequently been demonstrated to be the most important yield component in oilseed rape accounting for 85% of yield variation (Mendham *et al*. 1981).

The number of seeds per metre squared is determined during a critical phase for pod and seed abortion lasting about 300 ^{o}Cd after mid-flowering (Mendham *et al*. 1981; Leterme 1988). In most field situations this equates to about 19-25 days. The crop produces significantly more flowers and potential pod sites than survive, in order to increase seed number per unit area it is the survival of pods and the seeds within them that needs to be addressed, rather than the initial production of potential pod and seed sites. Pod and seed survival have been shown to be related to the amount of radiation intercepted by photosynthetic tissue per flower and per pod during this critical period (Leterme 1988; Mendham *et al*. 1981). The radiation intercepted by green tissue at this time is severely reduced by the layer of flowers which absorb and reflect radiation, before it can reach photosynthetic tissues. Early lodging reduces RUE during flowering which also reduces seed set.

In order to significantly increase the yield potential of the crop, seed number per unit area is the most important target. The evidence presented above indicates that in order to achieve this, the target should be seed and pod survival, achieved through increased photoassimilate availability during flowering, rather than increasing the potential number of seeds per unit area.

Intervention

Husbandry

There are a number of husbandry approaches which could be employed to increase radiation use efficiency and therefore photoassimilate availability during pod and seed set.

Reducing the flower cover from 50%, which is typical of a farm crop, to 38% will increase the amount of radiation received by the green tissue by 25%. Excessive flower cover can be reduced by modifying husbandry, for example; by avoiding very early sowing, using lower seed rates and applying plant growth regulators (Lunn *et al*. 2003), however as outlined previously there are likely to be agronomic problems associated with some of these approaches.

During flowering, crops with an optimum number of pods have about 2.5 units of leaf area and 1.5 units of stem area (Lunn *et al.* 2001). The radiation use efficiency per unit area of leaf material is three times greater than stem tissue (Major 1975), therefore if leaf area can be increased to 3 units by increasing the size and duration of the leaves, and the stem area can be reduced to 1 unit through shortening, then the overall radiation use efficiency of the leaf and stem canopy would increase by about 12%, resulting in increased seed set.

If flower cover can be reduced by 25% and leaf area increased as described above then the increase in photoassimilate during the period of seed determination is estimated to increase by 37%. Applying this to crops with an optimum number of pods would increase the number of seeds from 93,000 to 130,000/m^2. Crops with 130,000 seeds/m^2 have been recorded in the UK (Fray *et al*. 1996) and in Australia (Rao *et al*. 1991) in order to achieve this each pod would have to contain 19 seeds, which is well below the maximum observed of 30 (Mendham & Salisbury 1995), this would therefore seem to be a reasonably feasible target. Assuming no increase in seed size this improvement would result in a very significant yield increase of **1.4 t/ha**, but would require an increase in photoassimilate availability post flowering in order to fill the seeds.

Plant growth regulators shorten the crop and reduce lodging. Plant growth regulators have also been shown to reduce the amount of light reflected by the flower layer and therefore offer the potential for improving seed set in the absence of lodging.

Genetic

In addition to the husbandry approaches outlined above there are potential genetic approaches for increasing seed number.

Flower cover at mid flowering has been shown to vary by 50% between varieties (Yates & Stevens 1987). This variation was due to a combination of a variation in petal size of more than 50% and variation in flower number, the varieties with moderate flower covers of 38 to 50% had a greater seed yield than varieties with a flower cover of greater than 50%. There therefore seems to be sufficient variation within elite lines to produce varieties with the optimum flower cover, however, as this is achieved by a combination of flower size and number both of which are likely to be under multi-gene control it is likely to be a complex trait to breed for. An understanding of the underlying traits, their genetic control and markers for the genes is likely to be needed before this trait could be reliably selected for in breeding programmes.

Bringing flowering forward into cooler days will increase the number of days required to achieve the 300°Cd period over which seed number is determined which will increase the radiation received during this period. Anecdotal evidence indicates that yield losses from frost damage are rare in the UK and there appears to be scope to bring flowering forward by a modest amount of about one week without increasing the risk of frost damage to levels that will reduce yield. This may be done by choosing early developing varieties and/or early sowing. Early sowing is likely to lead to excessive canopy growth increasing flower cover so it seems that genetic control is a more realistic option. Bringing flowering forward by 7 days will increase the radiation received by the crop during the seed determination period by a modest 2%. However, little is known about genetic control of development in oilseed rape, the design of ideotypes to achieve earlier flowering in the UK environment or indeed the future UK environment following climate change needs considerable work.

A more extreme method of increasing radiation capture during flowering would be the selection of apetalous varieties which should reduce the amount of light reflected by the flower canopy in turn increasing the number of seeds set to at least 150,000/m^2. Whilst sources of apetally have been discovered and there have been attempts to breed with them in the private sector it is a trait that has proved very difficult to breed with, public investment in pre-breeding may develop the trait to the point that it is viable for inclusion in private breeding programmes.

Improvements in husbandry and genetics could achieve a significant increase in seed number with potential yield increases of **2.27 t/ha**. It should be noted that in the absence of an increase in post flowering photo-assimilate it is unlikely that all of this increased yield potential would be realised due to source limitation resulting in reduced seed size.

Research needed

- Identify combinations of husbandry and germplasm to maximise the traits that increase sink size (earlier flowering, smaller flower size, lodging resistance traits and improved seed set). (P+I)
- Identify germplasm in Brassica napus and related species for the traits that increase sink size. (P)
- Break the links between apetally genes and deleterious traits to facilitate the introduction of apetally into UK genetic material. (P+I)
- The triazole products which are used as growth regulators in oilseed rape are registered as fungicides. The development of specific growth regulators for the crop would result in greater crop benefits (e.g. greater seed set) that is achieved from current products..(I)

C.2.2.4 Improving post flowering radiation use efficiency

Constraint

In order to fill the increased seed number achieved through maximising sink capacity there needs to be a concomitant increase in supply of photoassimilates available post flowering. The solar radiation use efficiency (RUE) during seed filling has been measured at between 0.4 g/MJ (Habekotte 1997) to 0.75 g/MJ (Dreccer et al. 2000). This compares with RUEs before flowering of 1.2 g/MJ (Mendham et al. 1981), 1.35 g/MJ (Habekotte 1997; Justes et al. 2000) and 1.7 MJ/g (Rao et al. 1991). The pre-flowering values are within the range of RUEs commonly observed for C3 crops within temperate environments (Sinclair et al. 1999). RUE is less during seed filling for two reasons: Firstly, 45% more assimilate is required to produce each gram of oil rich seed compared with pre-anthesis biomass (Sinclair & de Wit 1975). Accounting for this means that the post-anthesis RUEs are equivalent to pre-anthesis RUEs of 0.58 to 1.09 g/MJ. Secondly, pods have a photosynthetic capacity which is estimated at between 50% and 70% of leaves (Gammelvind et al. 1996; Major 1975). Therefore it is clear that the RUE during seed filling cannot be expected to match that attained before flowering. A realistic expectation of the RUE that could be achieved during seed filling is given below.

The photosynthetic capacity of stems and pods has been estimated at 37% and 67% respectively of the leaves (Major 1975). Therefore, maximising the proportion of leaves within the canopy will increase overall photosynthesis. At flowering, the optimum canopy structure has been estimated to have a green area index of about four (Lunn *et al*. 2003) of which three units are leaf and one unit is stem.

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The RUE of stems and pods has been estimated at 37% and 67% respectively of the leaves (Major 1975). Therefore, maximising the proportion of leaves within the canopy will increase overall RUE. As described above, at flowering, the optimum canopy structure has been estimated to have a green area index of about four (Lunn *et al*. 2003) of which three units are leaf and one unit is stem. During flowering and seed determination the leaf area decreases and the pod area increases resulting in little change in the overall GAI, but a change in the proportions of leaf, stem and pod. In dense canopies the leaf area at the end of flowering can be close to zero, whilst in less dense canopies, leaves can make up 30% of the total green area and can persist throughout most of the seed filling period (McWilliam *et al*. 1995; Stafford 1996). The green area of the stems and pods changes little during seed filling

(Norton *et al*. 1991). If we assume that through husbandry we can achieve the best of these figures then averaged over the whole seed filling period, leaves would represent 18% of the total green area, stems would represent 29% of the area and pods 53% of the area. If the relative RUE is as reported by Major (1975), then the RUE during seed filling is estimated to be 76% of RUE before flowering. Accounting for the extra energy costs of forming oil rich seed, reduces this to 53%. The maximum pre-flowering RUE has been measured at 1.7 g/MJ (Rao et al. 1991), so it seems reasonable to assume that the post flowering RUE measured by Dreccer et al. (2000) of 0.75 g/MJ is a realistic target. It is estimated that the RUE of current farm crops is 0.47 g/MJ. Increasing the RUE to 0.75 g/MJ is estimated to increase the yield by **1.0 t/ha** at current seed numbers or **1.8 t/ha** at the maximum seed number defined above. This difference in yield increase occurs because there is a limit for how much individual seeds can be filled for the crop with lower seed number. However, even this RUE would be insufficient to allow the crop with the high seed number to fill its seeds completely.

The above assumes no improvement in the RUE of the various canopy components, the exact reasons for the low RUE of stems and pods have not been identified, however, it has been suggested that there is a correlation with stomatal density (Major, 1975). If all canopy components had RUEs equal to that of leaves then the post flowering RUE could be increased further to 1 g/MJ, this is a very large step increase and it seems more reasonable to assume 0.88g/MJ could be achieved. If this could be achieved then yield would be increased by 2.6 t/ha for the high seed number crop.

An alternative or complimentary approach to increasing the rate of photoassimilate supply is to increase its duration, this could be achieved by advancing the start of flowering, as discussed in the increasing sink size section or delaying the end of seed filling which is likely to be linked to the removal of N from pod walls as discussed in the NUE section.

It is worth noting that the potential benefits of increased photoassimilate availability may also increase the oil concentration in the seed, however this may require genetic improvement of the crops ability to store oil in the seed.

Intervention

Husbandry

There has been a body of research primarily funded by the HGCA into manipulation of canopy structure in oilseed rape (eg Lunn *et al*. 2003). This work has investigated a range of husbandry factors including sowing date and seed rate. Delaying sowing and reducing seed rate can both improve canopy structure and post flowering RUE, however, the industry is reluctant to employ either technique because of potential problems with establishment resulting in bare patches in crops (in part due to slug damage), pigeon grazing in small crops over winter, and poor weed control due to limited crop competition. .

Manipulating N fertiliser timings and rates and the use of triazole fungicides that have growth regulatory effects in oilseed rape through effects on the gibberellic acid synthesis pathway have both been investigated as a means of restricting canopy expansion in spring and improving post flowering RUE. However relatively little is known about the dynamics of N uptake and factors effecting its efficiency and even less about the use of foliar N fertilisers which could be used to delay canopy senescence and prolong seed filling. More information about the potential impact of disease control on seed filling is given in the section ‘Protecting potential gains’.

Genetic

Attaining the RUE target set out above could be further facilitated by selecting lines with erectophile pods (Fray *et al*. 1996) and by selecting for resistance to lodging. Lodged crops have been shown to reduce yield by between 16 and 50% (Bayliss & Wright 1990; Armstrong & Nichol 1991).

Low radiation use efficiency of stems and pods has been linked with the low density of stomata of these tissues (Major 1975). There is no known variation within elite lines for stomatal density, variation will therefore have to be sought in related or novel sources. If the genes that control stomatal density can be identified in Brassica napus there is the possibility of up-regulating their activity.

Research needed

- Identify germplasm with variation in the key traits associated with RUE (stomatal density, pod erectness, lodging resistance and delayed senescence) and develop methods for rapidly selecting these traits. (P+I)
- Physiological analysis of the lodging process to identify the key traits that determine lodging resistance. (P)
- Agronomic research and the development of improved herbicides for use in the crop to facilitate the use of delayed drilling and reduced seed rates as a means of improving canopy structure. (P+I)
- Improve understanding of N use to allow widespread later application of fertilisers as a means of manipulating canopy structure and delaying senescence. (P+I)
- Development of improved formulation of foliar nitrogen to improve uptake efficiency and facilitate later application of N. (P+I)
- Better understand how growth regulators reduce lodging including which lodging traits they affect. Develop specific anti-lodging PGRs. (P+I)

C.2.2.5 Improving pre-flowering assimilate production and use for seed filling

Constraint

As discussed yield potential, particularly of crops with a large sink capacity is likely to be limited by the availability of assimilates for seed filling. An alternative and complimentary approach to increasing photoassimilate supply directly post flowering, is to remobilise and utilise some of the excess photoassimilate formed pre-flowering for pod filling.

In some species water soluble carbohydrate (principally fructans) accumulated before flowering and predominantly stored in the stem can contribute significantly (up to 30%) to yield formation. However, they are generally assumed in the UK to contribute a negligible amounts to 12% of yield in oilseed rape (Stafford 1996; Mendham 1995; Habekotte 1993). This results in a relatively short yield forming period the success of which is weather dependant and variable from year to year.

Intervention

Husbandry

No husbandry approaches are predicted to increase remobilisation of soluble carbohydrate reserves.

Genetic

If germplasm could be identified for which stem reserves contributed an extra 10%, to yield then yield would be increased by **0.3 t/ha** if applied to currently available varieties.

Research needed

- Identify germplasm and crop management which increases the contribution that carbohydrate stored in the stems makes to yield. (P+I)
- Identify the genetic control of stem carbohydrate storage and remobilisation and develop methods of rapidly selecting this trait. (P)

C.2.2.6. Reducing harvest losses

Constraint

If allowed to fully develop, oilseed rape pods have a tendency to dehisce (typically termed “shatter”) before and during harvest. Crop management for OSR usually involves application of a “desiccant”, usually glyphosate-based. This process has a significant carbon footprint and, because it kills the plant before maturity, reducing the potential yield. Without application, seed (yield) losses typically exceed 50%. Even with treatment, losses of 10% can occur.

Intervention

Husbandry

Treatment with desiccants is already routine, there are no other husbandry treatments likely to have a significant effect.

Genetics

There is extensive variation for pod shatter resistance available in Brassica species, there is therefore a need to identify useful sources of variation and introgress them using marker-assisted approaches. An alternative approach would be to exploit emerging knowledge of pod development from basic science to manipulate the expression of specific genes involved in the control of pod shatter using GM approaches.

Research needed:

- Survey genetic variation in Brassica species and identify markers for loci potentially controlling the trait. (P)
- Test usefulness of a range of allele that might reduce pod shattering by introduction into oilseed rape. (P+I)
- Develop understanding of the genetic control of dehiscence in Arabidopsis and manipulate expression of the corresponding genes in oilseed rape to test utility. (P)

C.2.3 Protecting the potential gains

Diseases greatly decrease yields of oilseed rape in the UK, despite efforts in breeding for disease resistance to major pathogens and use of fungicides (£20M p.a.). Disease-induced losses are currently estimated to amount to >£80M p.a., with phoma stem canker the most serious problem, especially in southern England (Fitt *et al.*, 2006a), followed by light leaf spot, which is most serious in Scotland (Boys *et al.*, 2007). Occurrence of serious epidemics of sclerotinia (Rogers *et al.*, 2008) or alternaria is more sporadic.

Estimating the yield losses caused by pests is more difficult than for disease due to the absence of pest monitoring and pest-yield loss relationships. Nonetheless it is clear that significant crop losses are caused by pests such as slugs and pigeons which can result in 100% crop failure.

C.2.3.1 Implications of increased intensity of production

The changes predicted in section B could result in more severe pest and disease pressure which if not addressed will limit the potential to increase the productivity as described. The following section describes the new pest and disease pressures that will have to be addressed using new technology.

C.2.3.1.1 Increasing land for cropping

Diseases

Increasing land area for cropping is likely to increase severity of some diseases, particularly those that are also present on weed hosts, such as phoma stem canker and light leaf spot. Land brought into cropping is predicted to be dedicated to the most profitable crops resulting in shorter rotations, which will increase severity of soil-borne and trash-borne diseases.

C.2.3.1.2 Increasing intensity in the rotation

Diseases

This is likely to lead to an increase in severity of soil-borne and trash-borne diseases in oilseed rape, with consequent decrease in yield unless steps are taken to protect crops.

Soil-borne diseases include clubroot (*Plasmodiophora brassicae*) (Wallenhammer et al., 2000) and verticillium (*Verticillium longisporum*) (Zhou *et al*., 2006). The main means of control is by breeding for resistance to the pathogen. Some resistance to *P. brassicae* has been incorporated into cultivars such as Mendel.

Trash-borne diseases include phoma stem canker (*Leptosphaeria maculans*), light leaf spot (*Pyrenopeziza brassicae*), sclerotinia (*Sclerotinia sclerotiorum*) and alternaria (*Alternaria brassicae*). Changes in crop husbandry are likely to increase the severity of trash-borne diseases (Aubertot *et al*., 2006). Under predicted climate change, some will increase in importance (e.g. phoma stem canker, Evans *et al*., 2008), especially since some genes for resistance are known to be temperature-sensitive (Huang *et al*., 2006). By contrast, other diseases may decrease in severity (e.g. light leaf spot, Evans *et al*., unpublished).

Pests

Resistance to pyrethroids in pollen beetles (*Meligethes aeneus*), a major pest of oilseed rape, is now widespread in Europe. In the UK, pollen beetles are almost exclusively controlled by pyrethroids, many applied prophylactically and sometimes repeatedly. The first evidence of pyrethroid resistant populations in the UK was discovered in 2007. Increasing the area of OSR grown will increase the risk of exerting selection pressure for the development of more widespread resistance and presents a significant threat to the sustainability of the UK oilseed rape crop and to farm incomes. Minimum tillage after oilseed rape increases numbers of pollen beetle parasitoids, but increases problems with slugs and some diseases.

Intensification of OSR crops will favour cabbage root fly, *Delia radicum*, which is currently an occasional pest in the UK, but has attained key pest status in Europe, particularly in Germany.

C.2.3.1.3 Increasing yield per unit area

Diseases

Unlike those of cereals, oilseed rape yields (nationally) have not increased in recent years. This is despite the introduction of new varieties with a higher yield potential. Diseases probably play an important part in preventing the higher yield potential from being realised. To achieve the potential for increased yield there is therefore a need for improved disease control, there is existing knowledge which can be applied to achieve this primarily through optimised fungicide treatment.

Currently treatments (e.g. against phoma stem canker) are often applied too late or too early (West *et al*., 2001; Gladders *et al*., 2006). Additionally different products on the market have different spectra in terms of their effectiveness for disease control at different times. Greater use should be made of web-based forecasts eg (http://www3.res.bbsrc.ac.uk/leafspot; http://www.rothamsted.ac.uk/ppi/phoma). Similarly the prediction and optimum spray timing of sclerotinia must be improved.

C.2.3.2 Future developments diseases

Constraints

Diseases erode the potential yield of a crop either by reducing the production of photoassimilate or the crops ability to store available photoassimilate. In oilseed rape the main yield losses due to diseases are causing a reduction in photoassimilate supply for example stem cankers such as phoma and sclerotinia which destroy the stem's vascular system usually during pod filling restricting water uptake and causing premature canopy senescence. However there are diseases which reduce the crop's ability to store photoassimilate, for example light leaf spot which is most damaging when it infects the developing flower buds reducing seed set. Disease control in winter oilseed rape through use of fungicides and resistance can make a greater contribution to climate change mitigation per tonne of crop than disease control in winter wheat.

In order to minimise the impact of disease on yield potential one must first understand the life cycle of the disease and its interaction with the crop.

Although modern oilseed rape cultivars have some background resistance to the main two pathogens, none are completely resistant, and growers often need to rely on fungicides to control the diseases. This may not be sustainable, due to the decrease in supply of new products and problems with fungicide resistance.

The importance of some diseases (e.g. phoma stem canker) is likely to increase with climate change (Evans *et al*., 2008). In addition as the climate changes new diseases may develop which previously could not complete their lifecycle.

Intervention

There are a number of husbandry approaches that can be developed to reduce the impact of disease on yield formation. Understanding the epidemiology of a disease can identify points in the life cycle of the disease where changing husbandry practice, such as delaying drilling or reducing the number of crops in the rotation, is able to decrease the severity of epidemics. Improving fungicide timing by predicting disease development and matching fungicide timing to points in its life cycle when it is amenable to control to provide more effective control (only applicable to some diseases). This is likely to be most effective in conjunction with the development of new more effective fungicides and understanding their mode of action.

Whilst husbandry can contribute to improved disease control the most effective control is likely to be achieved through a combination of husbandry and genetic approaches. In order to do this there is a need to improve genetic resistance to major pathogens present in commercial oilseed rape cultivars. There is already some resistance to pathogens in commercial oilseed rape cultivars (e.g. against *L. maculans*) (Fitt *et al*., 2006). But there is a need to breed for 'durable resistance'. It is not clear whether this can be achieved through major gene resistance or if it will require stacking of a number of minor genes, which will be likely to provide more durable resistance due reduced risk of the development of resistance but will be a much more difficult technical challenge.

Internationally there is already considerable information about resistance to *L. maculans* and genomic work on Brassica rapa and *L. maculans* will increase the amount of information available. Less is known about resistance to some of the other pathogens.

Breeding for disease resistance could use either the conventional route or the GM route.

Research needed

- Better understanding of how diseases interact with the crop to decrease yield (phoma stem canker, light leaf spot, sclerotinia, alternaria). (P)
- Better understanding of the cycle of the main pathogens (including effects of weather) to help with developing strategies to optimise disease control. (*Leptosphaeria maculans, Pyrenopeziza brassicae, Sclerotinia sclerotiorum, Alternaria brassicae, Verticillium longisporum*). (P)
- Predictions of future disease problems under climate change. (P)
- Improved forecasting schemes to more accurately predict the severity of epidemics (deliver via www.). (P)
- Breeding for resistance to major pathogens responsible for diseases of oilseed rape. (P+I)
    - *Leptosphaeria maculans.* Collaborate with others (e.g. France, Canada, Australia) involved in breeding programmes. Better understand the mechanisms of disease resistance including the temperature sensitivity of R genes.
    - *P. brassicae*. Collaborate with breeders (e.g. KWS). Need to define genetics of host-pathogen interaction more clearly.
    - *S. sclerotiorum*. Collaborate with others (e.g. Chinese).
    - *A. brassicae*. Little breeding work (collaborate with India).
    - *V. longisporum.* Collaborate with researchers in Germany/Sweden where the disease is more prevalent.

n.b. To achieve the best results, given constraints on funding, it is important to collaborate with scientists in other countries, but UK capacity in these research areas is needed in order to be able to collaborate effectively.

C.2.3.3 Future developments pests

Constraint.

Pests prevent the crop from realising its yield potential through either restricting photoassimilate production or the potential storage of photoassimilate.

The pollen beetle (*Meligethes aeneus*) is the most numerous of a suite of pests that attack oilseed rape (Alford et al., 2003). It is economically the most important spring pest and is the major target of spring-applied insecticides (Garthwaite *et al*., 2006). Oviposition and feeding damage by adults, and first instar larvae within the bud, results in bud abscission and loss of yield. Only plants at the green-yellow bud growth stages are susceptible to yield-limiting damage (Tatchell, 1983). Backward winter oilseed rape and spring oilseed rape crops are most at risk, as the damage-susceptible growth stage occurs after pollen beetles have emerged from overwintering and are actively seeking feeding and oviposition sites. Insecticide sprays were applied to 85% of crops in 2006, 13% receiving four or more sprays and >99% of applications being pyrethroids (Garthwaite *et al*., 2006). Half of sprays were applied in spring and pollen beetles are often exposed to at least two treatments: once at green-yellow bud stage and again during flowering (targeted at seed weevils, *Ceutorhynchus assimilis*). Although pollen beetle populations rarely exceed spray threshold levels (15 beetles/plant found at green-yellow bud for a normal winter crop, over 5 per plant for backward crops and over 3 per plant for spring oilseed rape crops (Oakley, 2003)) according to Defra data collected though the Central Science Laboratory's Crop Monitor project, 20% of insecticide treatments were targeted against them in 2005/6. Current HGCA advice on crop monitoring (scouting) is to walk a transect into the crop, but it is likely that, for ease, growers/advisors select plants mainly from the crop edge, where beetle density is naturally at its highest as these pests infest the crop from the edges (Cook *et al*., 2004). This practice has resulted in treatments being applied prophylactically increasing selection pressure for pyrethroid resistance.

Although monitoring programmes in 2007 found strongly resistant individuals at sites in Kent and East Anglia (Pollen beetle working group of the Insecticide Resistance Action Committee), resistance in the UK is not yet widespread and pyrethroids retain their effectiveness. Measures are urgently required to minimize further selection for resistance to preserve the activity pyrethroids and other insecticides in a limited armoury.

Of the other pest targets, the seed weevil, which causes direct damage to developing seed, is locally a problem in the South West, but is often targeted with pyrethroid insecticides unnecessarily along with the associated pest the pod midge (*Dasineura brassicae*), the distribution of which depends on seed weevil damage. The midge larvae feed inside the pod on the wall tissue resulting in "bladder pod" and premature

pod splitting. The cabbage stem flea beetle, (*Psylliodes chrysocephala*), is a sporadic though sometimes damaging pest of winter sown OSR. Larvae excavate stems and petioles prior to elongation and are normally controlled by seed treatments and occasional autumn application of pyrethroids. Cabbage aphid, (*Brevicoryne*) *brassicae* is also treated occasionally, while the peach-potato aphid, *Myzus persicae*, which transmits Beet Western Yellows Virus, is controlled by seed treatments, although there is considerable evidence of insecticide resistance in this aphid species (Williamson *et al*., 2004). Flea beetles, (*Phyllotreta* spp.) are the main constraint for the establishment of spring oilseed rape. Stem weevils, (*Ceutorhynchus pallidactylus*), and (*C. picitarsis*), Diamondback moth, (*Plutella xylostella*), and other Lepidoptera are usually only minor pests.
Other pests which may become important due to climate change include, the turnip sawfly, *Athalia rosae*, which is currently a problem in southern counties of the UK, the silver Y moth, *Autographa gamma*, and the Egyptian cotton leaf worm, *Spodoptera littoralis*.

Intervention.

The following points relate specifically to oilseed rape, please also see more generic points relating to interventions against crop pests in the wheat section:

There is a requirement to better target insecticide use against pests such as pollen beetles based on the crops inherent tolerance to pest attack. Small, or backward, crops are less tolerant to pollen beetle damage because they have a smaller number of flowers and pods and therefore can afford to lose less of these before the pod number falls below the optimum required for high yield. Crops with large canopies can tolerate more damage from pollen beetle before losing yield. Thresholds at which beetles are sprayed need to be linked mechanistically with the crop's tolerance against yield losses.

Pest control would be further improved by developing easy to use, accurate monitoring traps utilising semio-chemical signals (Smart and Blight, 1997, 2000) and developing decision support systems that identify the main period of risk by modelling the population dynamics of insect pests, in combination with local meteorological data, could focus monitoring efforts and further reduce unnecessary insecticide treatments.

Habitat manipulation, e.g. by trap cropping, can be used to reduce the area that needs to be treated with insecticides, and can potentially eliminate the need for insecticide use altogether (Cook et. al., 2007a). Trap crops are plant stands deployed to attract, intercept and retain insects thereby reducing damage to the main crop (Cook *et al*., 2007b). The trap crop, which comprises highly attractive host plants of a growth stage, cultivar or species preferred by the pest, is planted in proximity to the main crop to be protected. Turnip rape (*Brassica rapa*) has been identified as an effective trap crop for pollen beetles in spring oilseed rape since it has a yellow-green leaf colour, flowers 2-3 weeks earlier than the rape and thus attracts a large proportion of invading pollen beetles and seed weevils (Cook *et al*., 2007a). However, to be economically and commercially viable, further studies should test commercially available cultivars that are more attractive or more resistant to pollen beetles as trap crops and main crops, respectively. The identification of traits including different leaf glucosinolate profile, leaf colour, bud colour, flower colour (or apetallous) and time to flowering would all be useful to develop this approach (Cook *et al*., 2006a&b).

Enzyme-inhibiting synergists have been used to prevent insects using non-specific esterases and microsomal oxidases to detoxify insecticides. Thus insecticide potency and efficacy are increased and less insecticide is required to give equivalent control. In addition this approach has been used successfully to overcome insecticide resistance (Bingham *et al*., 2007a&b) and could be employed against the rise of resistance in pollen beetle populations.

There are no pest resistant oilseed rape cultivars, although GM/BT oilseed rape has been developed it is not available for use in the UK. Alteration of the glucosinolate (GS) profile of oilseed rape (e.g. the alkenyl GS) could provide cultivars with some resistance to specialist pests without affecting the deterrent effect of GS on non-specialist herbivores such as pigeons (Cook *et al.*, 2006a). There is great scope to extend the search for durable pest resistant traits and also to understand better the resistance mechanisms involved.

The GM approach is applicable for oilseed rape. This multi-control approach would reduce greatly the chances of development of resistant biotypes. The chemical ecology of the pest/crop complex needs to be fully understood to avoid negative effects, particularly against natural enemies.

Research needed

- Improve crop husbandry to decrease severity of attacks. (P+I)
- Link thresholds for pest control with the crop's tolerance against yield loss from pest attack. (P+I)
- Develop better monitoring and decision support systems and link with improved threshold estimates to improve timing of application to provide more efficient use of existing insecticides. (P+I)
- New more effective insecticides with different modes of action. (I)
- Investigate mechanisms of resistance and utilise synergists to enhance the efficacy of existing insecticides (P+I)
- Breeding for traits that give resistance to pests either directly or for use in habitat management systems and similar approaches. (P+I)
- Also see list for wheat pests above.

C.2.3.4 Future developments weeds

Weeds also pose a major constraint to crop production. However, as they are not directly linked to the crop grown and are more associated with the field in which the crop is grown, detailed consideration of weeds is included in this report in a single section (C.3.2 below). However, it should be pointed out that weed management is different in all crops and the constraints, interventions and research needs are similarly different. The major issues with oilseed rape are, as with winter wheat, the effective management of annual grass weeds and secondly the control of other Brassica weeds, which can compete with the crop and contaminate the harvested product.

C.3. Cross rotational issues and weeds

As well as the specific within crop constraints on production identified previously there are additional constraints linked to the sequence of crops. For example, weed management, certain pests (such as nematodes), soil-borne diseases (such as some viruses, or take-all) and nutrient status are all issues of crop rotations and farming system design. This is highlighted by the fact that effective weed management and ability to build fertility are the two major constraints on organic farming.

C.3.1 Rotation planning and optimising farming systems

Rotational planning and farming system design considers not only the sequence of crops but other issues including rotational cultural practices and other techniques such as controlled traffic farming.

The optimisation of rotations and farming systems will always be a compromise between a number of objectives, some of which will inevitably conflict. Whilst this report primarily considers productivity and resource use efficiency which are likely to coincide with practices to conserve soil resources and preserve soil function there may be a conflict with the desire to protect or enhance biodiversity with increased crop diversity.

Information on managing specific issues such as crop nutrition, pests, diseases and weeds provide essential building blocks. However, success is only achieved if they are both practical and relevant within a farming system. How those individual components are best optimised will depend on the farming system within which they are applied, and how that system is able to handle constraints such as labour and machinery and soil type. For instance, when the optimum timing of nutrients is known this may need to be varied because it is not physically possible to spread the whole farm with fertiliser at the optimum time. In such circumstances it would therefore also be important to know tolerances around an optimum as well as the optimum itself. It is also important that the context into which information generated will be placed is widely known by those doing the research.

Of particular importance at this time is to design farming systems that mitigate the problems of the high cost of fertiliser and the GHG and other environmental consequences of its use by optimising artificial fertiliser inputs. Systems design would amongst other things consider the potential to use N fixation either through the use of pulses or the development of N fixing cereals and oilseeds, to select and sequence crops to minimise losses of N from the system, to maximise the use of agricultural and non-agricultural waste and co-products as nutrient sources, integrate livestock and arable enterprises etc.

Weed control has for a number of years been considered largely as a within crop issue. However, the rapid increase in weed resistance to a number of specific herbicides and loss of active ingredients, means that consideration of rotational and cultural techniques to reduce the weed burden are once again coming to the fore. Weeds need to be managed in time (over and between different crops) and the choice of cultivation will determine where weed seeds are in the seedbank profile and therefore the likelihood of them emerging. Ploughing for instance buries seeds to a depth from which they cannot emerge, but ploughing in a later year can then bring some surviving seeds to the surface, the time over which they remain viable depending on the species and environmental conditions. Similarly some soil borne pests and diseases can carry over on host plants through many seasons.

It is therefore important to be able to strategically integrate different sets of information, and to manage impacts through a rotation so that implications of practicality and logistics are included in any optimisation. This understanding of farming systems approaches is essential to enable and deliver most other research but it is also of great importance in managing farming systems to minimise greenhouse gas emissions.

Constraints

As outlined above there are a large number of interacting considerations when designing a farming system, which requires the input from a wide range of disciplines. The optimisation of the system will also be highly dependant on the prioritisation of the deliverables of the system, for example; productivity, profitability, resource use efficiency, biodiversity.

Optimisation of cropping systems id currently constrained by:

The availability of a sufficiently wide range of crops with high productivity potential and high value to diversify the rotation and reduce disease, pest and weed pressure.
Inability to accurately predict future political and economic influences on costs and returns from alternative crops – resulting in many operators concluding that optimising long-term decisions is too complex, and rotations being planned on a year-to–year basis.

The high cost and long term nature of farming systems research mean that it rarely supported by the industry alone and is only viable with public sector investment

Intervention and research needed

- There is a pressing need to develop a quantitative framework of the major commodity crops based on the biological potential outlined in this report and the supporting literature. This must consider both within and between crop optimisation. Ultimately this process should be extended to include the full range of available crop options, and could be used as the basis of developing and prioritising a research strategy (P)

- Successful systems research depends on successfully defining the purpose for which the model is built and in this context identifying the boundaries of the system to be modelled, the components of that system and the interactions between them. On the basis of this conceptual design the information and data required to operate the model can be identified and the researchable knowledge gaps exposed to enable model completion. (P+I)
- Farming system models need to be developed to design sustainable farming systems to inform policy and improve decision making within the agricultural sector. Particularly to optimise the efficiency with which nutrients are used within the farming system and minimise external inputs. (P+I)
- Datasets on typical farms and scenarios would provide a valuable resource to populate models and plan rotational implications. There are increasing opportunities to improve availability of data. With increasing uptake of computer based recording and on-line submission of data there is real potential to improve the quality of data available. It would be appropriate to consider over time how data collected for other reasons, such as from the Whole Farm Approach, could be used to improve the relevance of these models and provide a more accurate assessment of impacts in future. To maximise this opportunity requires a common vision of data requirements. (P+I)

C.3.2 Weed management

Weeds can be defined as plants that adversely affect crop production. They can be derived from seeds or from perennating organs such as roots or rhizomes. They do not normally occur singly, but in mixed populations of several species which require the combined use of a range of weed control options.

Weeds generally compete with crops for light, water and nutrients and also are hosts for pests and diseases and, if uncontrolled, reduce yields and resource use efficiency and hence increase GHG emissions per unit of output.

Farmers control weeds for six major reasons:

- to protect crop yield
- to protect crop quality
- to maintain ease of harvest
- to prevent problems in following crops
- to reduce spread of pests and diseases
- pride

Typical yield losses in experiments across a range of crop species from uncontrolled weeds can be as high as 60%. In winter wheat, for which most information exists, a yield loss of 5% is equivalent to approximately the cost of a single herbicide treatment. To put this in context, this loss can be caused by about 12 black-grass plants per square metre, a level which occurs commonly in agricultural fields.

Potential yield loss due to uncontrolled weeds and impact on quality of poor weed control.

Crop	***Yield loss (%)***	***Quality effects***	***Other effects***
Oilseed rape	Average 26% Range 3 to 62% (Lutman *et al.*, 1995)	Price reductions for weed admixture of cleavers, charlock, black-mustard	Delayed/longer harvest period Greater seed losses Higher drying costs
Winter wheat	Average 40% Range up to 80% (J. Clarke, Pers. Com.)	Quality reductions from admixture, such as from wild oats.	More weeds in following crops Delayed and longer harvest and increased drying. Grass-weeds provide a host for diseases such as ergot.

Although herbicides make up the major expenditure on crop protection in the UK, accounting for about half of the total pesticide sales, weed control is not totally reliant on herbicides. Other measures include crop rotation, mechanical weeding and encouraging competitive crops.

Rotational aspects

Agricultural systems aim to reduce weeds throughout a rotation and any measures that can be used to minimise the risk will be used. Weeds are triggered to emerge by a combination of factors and as a result emerge at different times of the year and compete with the crop at different times. Different species therefore cause different problems in different crops with spring sown crops having a different range of important weeds to autumn sown crops. Certain crops are therefore better able to compete with some weeds, and increased crop density is already used in the battle against weeds. Alternation of the sowing date of crops will also change weed species present. A range of crops in the crop rotation also allows a different range of herbicides to be used. The drawback of delayed sowing or spring cropping for many farmers is lower yields and profitability. On heavy clay soils, delayed sowing and spring cropping can be impracticable. On many lighter soils, such as sands, spring cropping and a spread of sowing dates is already widely practised. In the past, a fallow year was used to control weeds. With modern weed control options, this is no longer economically viable, especially since a full year's cropping is omitted. However, this has partially been replaced by set-aside in recent years, but this is no longer available as it was dependent on the area payment and relied on the ability to control weeds with a herbicide. On many farms crop rotation is now very restricted, often consisting solely of autumn-sown crops of cereals, oilseed rape and field beans. Such restricted rotations decrease the benefits to weed control arising in more diverse rotations. Increased growing of autumn sown wheat and oil-seed rape will increase the threat from annual grass-weeds in particular.

Cultivation

Ploughing provides a major control of some weeds, with reductions of up to 80% of some species being possible. However ploughing is more expensive than non-inversion tillage and can have adverse environmental implications, such as increasing nitrate leaching and soil erosion. The balance of cultivation method, sowing date and herbicide use ensure that weeds remain at manageable levels through the rotation. One major opportunity in the rotation to control weeds is prior to the establishment of the crop. The use of non-selective herbicide or cultivation can reduce weed problems by over 80%. Where possible, inter-row cultivation, especially in crops such as sugar beet, is used but this is expensive, not as effective as herbicides and in steeply sloping fields can increase soil erosion risk. It is worth pointing out that even organic farmers aim to achieve high levels of weed control in their farming systems and would adopt more effective systems if they were available. In certain circumstances weed control by hand pulling is practised but it is expensive and only small areas can be covered. Weed introductions by admixture with seed and movement within machines are minimised at all times.

Herbicides

Over the last 50 years herbicides have provided a reliable and economic addition to cultural control measures. Whilst their use can have beneficial GHG effects through protecting yield they are a source of diffuse pollution of groundwater and subject to increasing regulation.

Herbicides can be selective or non-selective and are either taken into the plant through the roots (residual) or green leaves or stem (contact). Using herbicides with different modes of action reduces the risk of weeds developing resistance. This is aided by the use of a rotation which mixes monocotyledonous and dicotyledonous crops in the cropping sequence so that monocot weeds can be controlled in the dicot crop and vice-versa. The rates of use and concentrations of active ingredient approved for each herbicide are those which provide a high level of safe control. Herbicide application allows a large area to be covered in a small time window. Herbicide resistance and the need to prevent herbicides contaminating water are two major constraints to continued use of herbicides. Resistance in grass weeds is a major issue and because many herbicides are applied at high rates of active substance, often to bare soil in high rainfall months it is very difficult to prevent them reaching water.

The presence of herbicides in ground and surface waters is making farmers reconsider their herbicide strategies. But risk averseness combined with results from research programmes such as TALISMAN, SCARAB, IFS which have shown that in arable rotations, reduced herbicide inputs can lead to increases in the weed seedbank in the soil (Squire, pers. comm.) makes them reluctant to reduce usage. Non-chemical methods of weed control tend to be less effective, more variable and are often more expensive than herbicides with the consequence that most farmers are still heavily dependent on herbicides for effective weed control.

Timing of weed control

Very often weed control options have to be selected in anticipation of a problem. This applies to cultural control as much as to herbicides. Currently herbicides are applied pre-crop or weed emergence or selectively post-emergence. Most herbicides are more active on young weeds hence bringing control earlier and ‘in anticipation’ of the weed problems. To cutback or refine weed control requires more information on the time of optimum weed removal, rates of herbicide required and improved herbicides which allow later use. The need for herbicide treatment could be based on individual weed thresholds, which can allow for ‘patch’ spraying within fields but that will not be practical or cost-effective for several years.

Weed distribution

Weeds are often very patchy in their distribution within fields and can be higher nearer the field edge (Marshall, 1989). Despite a number of research programmes, worldwide, this patchy distribution has not yet been commercially exploited by utilising GPS (Global Positioning Satellite Systems) techniques to restrict herbicide use to weed patches.

Weed species

In most crops, fairly high levels (95%) of weed control are achieved but all in all crops certain species are particularly aggressive and are hard to control. In autumn sown crops these are species such as black-grass, bromes and cleavers, whereas in spring sown crops they are species such as fat-hen, polygonums, thistles, volunteer potatoes and black nightshade.

In relation to autumn-sown wheat and oilseed rape the weeds of commercial concern and for the reasons above are increasingly difficult to control are:

Wheat – The grass-weeds black grass, couch grass, brome species, ryegrass and wild oats

Oilseed rape – The broad-leaved weeds cleavers, mayweed, cranes-bills and poppies

Constraints

Recent policy has been to enhance biodiversity in farmland. This has represented a significant challenge in agriculture to accept the major role that weeds and weed seeds play in enhancing biodiversity and hence the need to only remove weeds of commercial importance and where possible design rotations which are not only diverse but where possible leave quality stubbles as a food source.

The trend in the last 10 years to establish winter cereal and oilseeds using non-inversion cultivation techniques has increased weed problems, particularly favouring the annual grass weeds. This has put greater pressure on weed control and has increased farmers’ dependency on a decreasing range of herbicides. These pressures have been further increased by the trend to earlier drilling which also increases weed populations in autumn sown crops.

The declining availability of effective herbicides for grass-weed control is becoming a major constraint for both winter wheat and oilseed rape. Herbicides are being withdrawn from the market as a consequence of EU and UK regulatory action (e.g. atrazine, simazine, trifluralin, isoproturon) or for commercial reasons (imazamethabenz, flamprop-M-isopropyl). The development of resistance means that the efficacy of some of the remaining herbicides is severely compromised in some situations (e.g. fenoxaprop), Critically, these losses are not being matched by new introductions so there are fewer available options for grass-weed control each year and no new herbicide modes of action imminent from manufacturers. The loss of effective herbicides will increase reliance on rotational and cultural control options. This will decrease the frequency of the major commodity crops in rotations and may result in cultural practices to reduce weed burden but which are detrimental to the inherent yield potential of the crop. There is a real risk that farmers will cease growing oilseed rape if the predicted loss of herbicides comes to pass, as weed control will become almost impossible.

Crop genetic improvement is unlikely to deliver major benefits in relation to weed management, as it may with pests or diseases. Modest weed control benefits can be achieved form the exploitation of more competitive crop cultivars, such as wheat with more planophile leaves, greater height and greater tillering. Such attributes are particularly beneficial to organic growers. The other exception to this would be the use of that herbicide tolerance in crops, most of which is based on GM technology, the use of which have been deemed to be unacceptable in UK agriculture. Unless sound agronomic practices are adopted there is a risk that their use may be a short term solution as evidence from elsewhere in the world is that resistance to the herbicides used in GMHT crops (such as glyphosate) has increased and as a result many growers are resorting to ‘traditional’ herbicides as well. The focus on developing GMHT crops is considered by some to have contributed to the reduction in effort in finding new herbicides.

There are significant cost and efficacy implications in using many of the cultural control options available to control weeds. Ploughing and mechanical weed control require high fuel inputs and can have adverse environmental implications.

Intervention

Whereas in other areas, breeding and genetics can have a major impact, that is not the case for weeds, (with the exception of GMHT crops as described above). There are also many other rotational issues. The need is therefore for good underpinning biology and farming systems knowledge, as well as the development of new chemistry. This area has suffered from lack of investment in the past, perhaps because of the perceived ‘low tech’ nature of many of the needs. These needs include:

- Improved knowledge on weed biology (including competitive ability and fecundity) to underpin other requirements.
- Innovative herbicide development to reduce herbicide resistance risks and present a low risk to water contamination.

- Ability to accurately identify weed distribution in fields and target localised sprays (patch spraying).
- Improved non-chemical methods and information on their consistency at an individual field scale.
- Increased ability to predict future weed development, and hence problems, under different management regimes thus enabling land managers to be less risk averse (this would also be of benefit to those managing plant species to enhance biodiversity).
- An effective communication programme with agronomists and managers to ensure they have increased confidence in any predictive approaches.

Research needed

- **Underpinning information on weed biology** is an essential requirement and directly relevant to many aspects of weed management. Although much is known about some of the major weeds, there is a major gap in many other species. The information is currently focussed on winter wheat and further development into other crops is required. (P)
- **Development of new herbicides and novel methods of use of existing herbicides** is required to provide new tools. This would need to be in partnership with herbicide manufacturers. Novel solutions such as treating with residual herbicides within plant rows and mechanical weeding between them could reduce overall loading and risks to water. However, the real need is for new active substances which provide effective control of grass weeds. (P+I)
- **Improved weed detection,** in association with GPS location technologies would lead to the ability to more accurately target herbicides within a crop with post-emergence herbicides. This is at an early stage, but could provide the ability to reduce overall amounts of herbicide used. A range of sensing technologies will be required. (P+I)
- **Improved prediction methodologies** to provide a framework for better decisions on the use of herbicides to improve their efficacy and reduce pesticide burden. (P+I)
- **Develop strategies to reduce herbicide resistance** (P+I)
- **Developing strategies to minimise environmental contamination and diffuse pollution in surface run-off and ground water** Understand and reducing risks to the environment and society associated with herbicide use (P+I)
- **Developing spray technology to minimise the risk to operators and bystanders** (P+I)
- **Improved mechanical weeding** equipment would help increase accuracy and efficient of operation. Consideration would need to be given to minimising environmental impacts. (P+I)
- **Developing better methods of non-chemical weed control** in order to improve overall efficacy, reduce variability and reduce dependence on herbicides. (P+I)
- **Environmentally beneficial weeds:** identifying species of particular value to invertebrates and birds, and methods of maintaining their presence whilst minimising adverse effects on crop production. (P)

- **Development of methods for the use of GMHT** crops which maximise their value in rotations without the development of herbicide resistance seen overseas or the excessive use of the relevant herbicides such that they become commonly found in water at levels that result in the removal of their use. (P+I)
- **Improved methods of Knowledge Transfer** to ensure uptake of the outputs from research will be essential. (P+I).

C.4 Underpinning Crop Science and resources

The opportunities identified in section C require not only R&D on the researchable constraints but also investment in underpinning activities to provide:

- Sufficient knowledge of crop functions and appropriate design procedures to prioritise and coordinate protracted programmes of crop improvement.
- Materials such as mapping populations and novel germplasm as sources of the required traits.
- Appropriate science and genetic technology to understand the genetic control of these traits.
- Transfer of the target traits into adapted materials.

Targeting the most telling improvements in resource capture or conversion requires better knowledge of yield determination than is available at present. Most easily-observable traits are determined by the interaction of genotype and environment (GxE) and are therefore specific to field conditions. The chance of identifying traits or markers that are robust across environments is increased if physiological knowledge can be employed to identify the more heritable underlying traits. This requires the development of Quantitative frameworks for yield formation and resource use efficiency for each of the crops, which can be based on the analysis used in this report. Investment in field-based crop research declined rapidly in the 1980’s since which time there have been significant changes in genotypes and climates. Thus the plant breeding industry have improved crop performance, but do not know how improvement has been achieved, not even whether through increases in total biomass or through partitioning into harvestable yield! More detailed in-field crop analysis is key to the on-going development of these quantitative frameworks and prioritising routes for crop improvement.

Throughout this report we have identified the major role that genetic improvement could play in increasing productivity and the sustainability of wheat and oilseed rape production. In seeking to achieve efficient resource use, high yields, resistance to pests and diseases and sustainability there is a pressing need to understand genetic processes more fully in order to exploit the available polymorphism. It will be important to progress from exploitation of polymorphism in current adapted UK lines to precise selections of novel polymorphisms from unadapted germplasm, wild relatives and exotic materials. Such sources have already been used in developing the major crops by introgressing major traits such as disease resistance and they will increasingly provide sources of other sustainable traits. Beyond this we need to be able to identify the genetic control of useful traits (e.g. nodulation) in non-related species and have the appropriate technology (e.g. GM) to transfer them into the crop species of interest.

Much available germplasm in the primary genepool of crops, and certainly in the secondary and tertiary genepools, is not in a form that most breeders can currently access, and radical improvements are needed in the relevance and quality of the data available on these genetic resources if this material is to have the needed impact on agricultural productivity and sustainability. This is now possible through advances in technology and genetic resources but will require significant public investment to release the potential.

Crop genetic resources therefore need to be 're-visited'. The success of the CIMMYT synthetic programme illustrates the potential impact that broadening the genetic base may have (Trethowan and Mujeeb-Kazi, 2008). However there must be a well defined strategy based on traits identified from sound crop design to develop wide crosses. Crossing 'blindly' in the hope that 'something will turn up' is both inefficient and unlikely to deliver benefits. Key advantageous traits, primarily of a physiological basis must be identified. For too long breeders have looked at genetic resources in terms of relatively simple characters – such as disease resistance. However there is an as yet untapped genetic pool of physiological characters which need to be identified, characterised as to value and integrated selectively into breeding programmes.

Investment will therefore required to support programmes for all of the main arable crops to develop experimental populations which are polymorphic for the agriculturally important traits and which are more amenable to mapping and forward genetic approaches than conventional agronomic lines.

In addition to generic molecular techniques, there are crop specific molecular techniques required to underpin crop improvement. Most wheat and oilseed rape genetic improvements already discussed are complex traits which are strongly influenced by the environment. Furthermore, wheat has a hexaploid and oilseed rape has an allotetraploid genome (made up of the diploid B. rapa and B. oleracea nuclear genomes). This combination of diploid genomes in wheat and oilseed rape causes extensive genetic replication which reduces the sensitivity for QTL detection. Therefore carrying out QTL analyses in the diploid species as well as commercial lines is likely to aid QTL detection. The diploid genomes should also be a rich source of novel genes and variant alleles, which could be utilised for improvement through generation of synthetic polyploids. The high level of synteny between Brassica species and Arabidopsis and between wheat and other cereal species such as rice and barley could help to elucidate the gene functions underlying the QTL.

Whilst there has been significant progress in genotyping in recent years there has been significantly slower progress in phenotypic analysis. Identification of genes controlling specific traits requires the analysis of large numbers of lines, the lack of progress in developing rapid phenotypic screens is therefore a significant barrier to progress requiring underpinning research.

Many of the research targets identified require the identification of key crop traits, the identification of the gene or genes controlling these traits and their introgression into

UK breeding programmes. The speed with which these developments can be introduced into commercial use is therefore dependant on speed of the breeding techniques being used. From the identification of a specific trait in unadapted material to its introduction into commercial varieties will take anything from 10 years for simple traits to much longer with complex traits using conventional breeding techniques.

Hybrid wheat, which has been seen as the ‘Holy Grail’ of wheat breeding should not be written off because of past failures. Experience gleaned from past programmes whether based upon genetic or chemical strategies has highlighted the benefit of hybrid consistency and resilience under adverse environmental conditions. There is therefore a need for basic research to develop advanced breeding techniques from the tertiary gene pool through interspecific hybridization and novel chromosome manipulation methods. Hybridization techniques are well established, but there is a need for new and novel approaches for interspecific and intergeneric recombination through an understanding of chromosome pairing, recombination and syntenic relationships. Whilst there have previously been problems with seed production these could be overcome given these novel approaches to plant manipulation, either through conventional means or transgenesis. An example of the development of a novel ideotype would be the use of Rht3 in a heterozygous form (used as a female in a hybrid combination) resulting in a semi dwarf plant type.

Whilst this report has concentrated on individual traits it should be noted that there is a need for the integration of multiple sets of traits of interest; otherwise, narrow concentration on single traits can result in the loss of others not being considered coincidentally. These considerations require that not only the direct benefit of new targets to the crop need to be considered but also the net effect, which must take into account the alteration in rate of improvement in other traits arising through loss of selection pressure and from genetic correlations. This would require on-going iterative development of crop design models that would link specific genetic changes to phenotypic expression that would need to run over a longer time period than would be possible within the normal government funded research programme of 3-4 years and would need to encompass traits that would be of future public interest; potentially beyond the remit of individual plant breeders responding to today’s requirements.

Though the evolution of laboratory techniques has led to a revolution in genotyping material there is still a significant gap between the breeding community and the creators of the technology. Phenotyping work is behind that of genotyping and the characters being used so far in breeding programmes represent the ‘easier’ targets such as major disease resistance, alien introgressions or dwarfing genes. Whilst these are commendable they are generally still working within the genetic pool currently being utilised within the breeding community. The task is now to develop a strategy incorporating a wide range of disciplines in order to develop populations for phenotyping and consequential genotyping. Populations currently available should only be used if they express traits of high physiological significance techniques, now routine, such as double haploid production should be used to establish these target populations.

With increasing numbers of markers and traits breeders and researchers will be faced with a mass of information that under current systems would be too difficult to comprehend. It is imperative that computer software packages be developed in order to allow the breeder to refine the selection criteria and prioritise those traits of high value.

In order to achieve these underpinning requirements a wide range of techniques materials and skills need to be developed, these are outlined below, with the likely source of funding indicated.

Knowledge, techniques and materials needed

Crop Design - prioritising routes to improvement & specifying key traits

- Characterising agronomic environments (P)
- Determining species-specific limits e.g. life-cycles, photosynthetic & nutritional systems. (P)
- Characterising and inter-relating crop functions (P)
- Defining potential productivity (P)
- Optimising and validating Ideotypes (P)
- Integrating genetic & management synergies (P+I)
- Specifying and devising screening technologies for key traits ... smart screens (P+I)

Germplasm - Donors of key traits

- Alien introgression (P)
- Synthetics (including both wheat and oilseed rape) (P)
- Diversity (progenitor Species; landraces, international collections) (P)
- GM – transgenics (P+I)
- Model Species (P)
- Mutagenesis (chemical, transposons, irradiation, spontaneous) (P+I)
- Activation tagging (GM) (P)
- RNAi & synthetic miRNA (GM) (P)

Identification and Characterisation of key traits

- Mapping populations (multiple and bi-parental) (P+I)
- Fine mapping for QTL and gene isolation (P)
- TILLING (P)
- Association Genetics (P)
- Genomics, proteomics, metabolomics (P)

Phenotyping

- Multi-location and multiyear replicated trials (P+I)
- Whole plant characters (both above and below ground) (P)
- End use quality (P+I)
- Physiology, biochemistry, phenology (P+I)
- Mechanised data capture capability (P+I)
- Controlled environments; cabinets, field based (e.g. drought) (P+I)
- Plant microbe interactions (both pathogenic and mutualistic) (P)

Breeding

- Crossing / Selfing (P+I)
- Cell biology (synthetics / GM / Double haploid, interspecific crosses (P)
- Marker technology (e.g. SSR, SNP, AFLP, DArT, Illumina, SSAP IRAP etc) (P)
- Marker assisted selection; MARS, MAIC (P+I)
- Seed production (P+I)
- Trait based Selection (field and glass) (P+I)

Informatics

- Informatics for traits (P)
- Environment (agrochem, climate) (P)
- Germplasm (P)
- Bioinformatics (P)
- Statistics, quantitative genetics (P)

Infrastructure and Equipment

- Computing (P+I)
- Mechanisation (GPS led data collection) (P+I)
- GIS (P+I)
- 2nd Generation sequencing (P+I)
- MS, HPLC, GC (P+I)

Human resources including training of all below

- Plant Breeders
- Geneticists
- Phenotypers
- Quantitative geneticists
- Statisticians
- Physiologist
- Biochemist
- Plant Pathologists
- Entomologists
- Weed scientists
- Molecular biologists
- Cell biologists
- Trials experts
- Agronomists

Conclusions and further suggestions

The evidence, ideas and views of the UK's crop science community collected here clearly form a consensus that there is enormous potential for further improvement of the productivities of UK crops. The theoretical yield potentials in the UK environment, assuming that future research enables all physiological targets to be met, have been estimated to be 19.2 t/ha for wheat (Sylvester-Bradley *et al.*, 2005) and 9.2 t/ha for oilseed rape (Berry & Spink 2007). On current crop areas these yields would increase annual UK production to 35.3M t and 5.0M t for wheat and oilseed rape respectively, or 250% in both cases. These compare to current yields used in section B of 7.74 and 3.2 t/ha respectively for wheat and oilseed rape. Applying the management and genetic improvements from existing knowledge in section B was predicted to increase yields to 8.71t/ha for wheat and 3.88 t/ha for oilseed rape. Clearly the realistic yield potential will be lower than the theoretical yield potentials outlined above. A recent review of yield potential (Defra, 2005b) estimated yields for 2025 and 2050 for wheat of 11.4 and 13.0 t/ha and for oilseed rape of 4.1 and 5.7 t/ha. These yields seem readily achievable given significant investment in production research, which would lead to production on the current area of 23.9 mt of wheat and 3.1 mt of oilseed rape, both above that predicted using current technology on significantly increased cropped land area.

It was beyond the brief of this document to quantify the cost of, or prioritise, the research needs in anything other than the crudest terms. Clearly much further deliberation will be required before effective programmes for crop improvement can be set out. In this it will be important to consider how a push for productivity will change not only the extent of public investments but their character – clearly there will be an extent to which the focus of plant science will need to be on both the laboratory and the field, and there may be structural repercussions of such a re-emphasis. For example, an enthusiasm for education in the sciences of primary production may need to be rekindled, since skills shortages in agriculture are now clearly evident.

It is likely that many agronomic innovations, given suitable economic stimuli, could be applied more quickly than most genetic innovations. It is also likely that the more fundamental genetic innovations will take longer to application than genetic innovations relying on adapted germplasm and conventional plant breeding. However, on the basis of this quick review, we have attempted to identify the key research needs required for advances in crop productivity. In the tables below we have summarised the likely funding source for each of the interventions (Public (P), Public and Industry collaborative work (P+I) and Industry (I)) and estimated the timescale for delivery. We have also estimated the relative impact of each of the research approaches on crop productivity per unit area and the GHG cost of production per tonne of produce. It is important to note there is no essential link between the productivity and the environmental impacts of crops, almost all of the productivity increases would reduce the GHG cost per unit of production. However, it should be born in mind that if in the process of increasing potential production the requirement for inputs (primarily of fertiliser) is also increased then GHG emissions will increase per unit area of production. These effects have been estimated but it is important to note that the real effect is dependant on the combination of developments that could occur concomitantly and on what happens to overall production. For example if total production is not increased but production per unit area is increased, less land would be required for production then the overall GHG emissions from food production would fall. It is likely that if food production per unit area is increased at a faster rate than demand increases then there could be an increase in overall production whilst still allowing a reduction in the productive area, which may result in no overall increase in emissions but a significant increase in productivity. The overall impact of increased productivity on the GHG costs of food production has not therefore been estimated as it is dependant on assumptions about demand for food and therefore knock-on effect on land use change.

Whilst every effort has been made to identify the key research needs, it should be noted that the absence of a potential research avenue does not mean it does not have value for increasing crop productivity or resource use efficiency. Indeed, as is the nature with research, as knowledge increases then potential avenues for improvement will be discovered. It will therefore be necessary to continuously reconsider the most appropriate targets for crop improvement in the UK, the extent and timescales of the investments required, the likely returns, and the probable costs of inaction.

Recent reviews on some aspects of crop improvement may prove useful:

- ‘The role of future public investment in the genetic improvement of UK grown crops’ (Caligari *et al*., 2002).
- ‘Review of BBSRC-funded research relevant to crop science’ (BBSRC 2004), and
- ‘The rationale for Defra investment in R&D underpinning the genetic improvement of crops and animals’ (Moran *et al.*, 2007).

It is concluded that much of the research proposed here must occur in the UK, simply because the UK has a peculiar environment in global terms. However, it will also be important to consider scope for (i) international collaborations, since concerns over sustainable productivity are global and there will be many equivalent initiatives globally, and (ii) technological dissemination, particularly to developing regions where global imbalances in primary production will be felt first, and most acutely.

This briefing was largely confined to a consideration of two cropped species. Issues and solutions for other cropped species have been addressed through the recent Defra review (2005b) and they obviously have some essential differences, for example in the cases of legumes (Weightman, 2005), root crops (Allen *et al.*, 2005) and perennial crops and forages (Cottrill *et al.*, 2005; Defra 2005). However, it is evident that many of the innovations suggested here will have analogies for other species.

WHEAT					
Intervention	*Funding source*	*Time to impact (years)*	*Yield impact*	*GHG impact per t*	*GHG impact per ha*
Early canopy closure C.1.2.1		**5-10**	⇓	⇓	=
Development of agronomic packages to advance canopy closure whilst minimising adverse effects on lodging risk.	P+I	<5	↑	↓	=
Development of varieties with higher lodging resistance, especially due to etiolation of the stem base.	P+I	10	↑	↓	=
Earlier stem extension C.1.2.2		***10-15***	⇓	⇓	=
A more detailed physiological understanding of the influence of vernalisation, photoperiod and earliness *per se* genes on internode and crown root initiation.	P	10	↑	↓	=
Identification or introduction of novel developmental genes.	P+I	15	↑	↓	=
The combination within a single genotype of a number of developmental genes to give the desired developmental pattern.	P+I	15	↑	↓	=
Delayed canopy senescence C.1.2.3		***5-15***	⇓ ⇓	⇓ ⇓	⇓
Genetic control of stem-borne leaf number and aging.	P	10	↑	↓	=
Genetic control of crop N dynamics (see below).	P	15	↑	↓↓	↓↓
'Stay green' genes have been identified in wheat. These need to be characterised and, if compatible with productivity, need incorporating into UK germplasm.	P+I	10	↑	↓	=
Development of strategies for delayed N application to provide for late N uptake which maintain or increase the efficiency of N recovery.	P+I	5	↑	↓↓	↓
Changes to bread-making technologies that would allow use of lower grain protein concentrations.	P+I	5	=	↓↓	↓↓

Nutrient capture and conversion C.1.2.4		***5-20***	⇑	⇓ ⇓ ⇓	⇓ ⇓
Comparisons of cereal species (oats, barley, triticale, wheat) to identify the physiological and metabolic basis for their significant differences in N capture and conversion.	P+I	5	=	↓	↓
Identification and characterisation of N stores in wheat canopies, leading to types with reduced storage.	P	5	↑	↓↓	↓
Identification of wheat germplasm with good variation in traits determining N capture, storage and conversion.	P+I	10	↑	↓↓	↓
Development of formulation of soil- or foliar-applied N fertilisers that improve the efficiency of uptake and strategies for their use.	P+I	5	↑	↓↓	↓
Improved recovery of soil N through the incorporation of genes for the upregulation of alanine aminotransferase into UK Wheat germplasm.	P+I	10	↑	↓↓↓	↓↓↓
Increased demand for mineral inputs requires an integrated approach that includes studies of roots and root-rhizosphere interactions. The contribution from mycorhizza also needs to be considered.	P	10	↑	↓↓	↓
Nitrogen fixation through nodulation.	P	20	=	↓↓↓	↓↓↓
Improving light conversion C.1.2.5		***5-25***	⇑ ⇑	⇓ ⇓	⇓
Identification of husbandry strategies that could be combined with particular genotypes.	P+I	5	↑	↓	↑
Further analysis of the physiological basis of genotype by environment interactions will be needed to indicate the best avenues for genetic improvement.	P	10	↑	↓	=
Genetic improvement of Rubisco, possibly using introgressions from alien cereal species.	P	15	↑↑	↓↓	↓
Manipulation of leaf angle (which is under relatively simple genetic control) and leaf-N distribution within the canopy to optimise light distribution in the canopy.	P+I	10	↑	↓	↓
Increase partitioning of assimilates to the developing spike at anthesis to reduce sink limitation and maximise sink size during grain filling.	P	15	↑↑	↓↓	=
Incorporate partial or full C4 capability into UK wheat. This is a long term option and an extremely challenging scientific objective.	P	25	↑↑↑	↓↓↓	↓↓

Increased partitioning of dry matter to grains C.1.2.6		***5-20***	⇑	⇓	⇓
A more detailed physiological understanding of the influence of vernalisation, photoperiod and earliness *per se* genes.	P	10	↑	↓	=
Identification or introduction of novel developmental genes - new sources of diversity will need to be accessed.	P	20	↑	↓	=
The combination within a single genotype of a number of developmental genes to give the desired developmental pattern.	P+I	20	↑	↓	=
Better characterisation of the relationship between height and grain yield.	P+I	5	↑	↓	=
Identification and characterisation of tissues and their constituents (e.g. lignins) that confer structural strength on wheat stems, and introduction of compositional changes that reduce the biomass required to resist stem lodging.	P	15	↑	↓	↓
Introduction of changes in anchorage roots that increase resistance to root lodging.	P	10	↑	↓	↓
Genetic enhancement of the storage of fructans in the stem.	P	10	↑↑	↓↓	=
Water capture and conversion C.1.2.7		***5-20***	⇑ ⇑	⇓ ⇓	⇓
Genetic improvement of rooting at depth and partitioning to improve exploitation of stored soil water.	P	20	↑↑	↓↓	↓
Improvement of water capture by improved establishment techniques.	P+I	5	↑	↓	↓
Genetic improvement of WUE. This will be an integral part of research to improve light conversion (see above).	P	20	↑↑	↓↓	↓↓
Improvement of the efficiencies of irrigation techniques.	P+I	5	↑	↓	↑

Protection against diseases C.1.3.2		***5-25***	⇑	⇓	⇓
Identify novel sources of resistance in wheat itself, its progenitors and wild relatives, as well as allelic diversity from known sources.	P	20	↑	↓	↓
Characterise new sources of diseases resistance genes taking account of resistance mechanisms and pleotropic and yield drag effects.	P	25	↑	↓	↓
Identify disease tolerance traits which can be incorporated with durable resistance traits to reduce yield loss	P	10	↑	↓	↓
Provide a detailed analysis of different resistance mechanisms to ensure functionality as well as genetic diversity.	P	10	↑	↓	↓
Improved understanding of induced plant defence mechanisms	P	15	↑	↓	↓
Development of bioactive and environmentally benign chemicals for disease control to increase availability of pesticides	P+I	15	↑	↓	↑
Improve the understanding of the mechanistic basis of pesticide resistance and the genetic drivers to develop strategies to protect current and future compounds.	P	15	=	=	=
Identify the potential to suppress disease using antimicrobial bioactives developed from an improved understanding of the interaction between the pathogens and the microbial communities in the rhizosphere and phyloplane.	P	15	↑	↓	↓
Develop better surveillance monitoring and diagnosis to better target disease control strategies to improve the effectiveness of pesticide use, reduce the need for pesticides and development of Integrated disease management.	P+I	5	↑	↓	↓
Protection against pests C.1.3.3		***5-25***	⇑	⇓	⇓
Priming / inducing plants with activators	P	15	↑	↓	↓
Heterologous expression of semiochemical synthase genes	P	20	↑	↓	↓
Breeding plants with altered secondary metabolism	P	25	↑	↓	↓
Interfering with insect olfaction	P	10	↑	↓	↓
Development of monitoring systems	P+I	5	↑	↓	↓
Improve crop husbandry to decrease severity of attacks.	P+I	5	↑	↓	↑
Improve insecticide timing to provide better control.	P+I	5	↑	↓	=
New more effective insecticides including biopesticides such as entomopathogenic fungi natural endocrine disruptors	P+I	10	↑	↓	↓
Breeding for resistance to pests	P+I	10	↑	↓	↓
Protection against weeds This is covered in Cross rotational issues and weeds. See section C.3.2					

OILSEED RAPE					
Intervention	*Funding source*	*Years to impact*	*Yield impact*	*GHG impact per t*	*GHG impact per ha*
Improving rooting to exploit soil resources (nutrients and water) C.2.2.1		***5-15***	⇑	⇓ ⇓	⇓
Field studies are required to assess the optimum timing for manipulating root growth using the growth regulator metconazole, and to test the effect of other growth regulators such as tebuconazole and paclobutrazole.	P+I	5	↑	↓	=
Identify genes from existing and novel sources controlling root growth and transporter activity per unit root length eg. upregulation of alanine aminotransferase.	P+I	15	↑↑	↓↓↓	↓
Develop rapid screens or QTL to incorporate rooting traits	P	10	↑	↓	↓

into breeding programmes.					
Understand the physiological mechanism which causes the reduced N uptake after flowering and identify breeding lines with prolonged N uptake.	P+I	10	↑	↓↓	↓
Develop establishment and agronomic approaches (especially N and S nutrition) which maximise root exploration at depth and which are compatible with high yields.	P+I	5	↑	↓↓	↑
Nitrogen Use Efficiency C.2.2.2		***10-15***	⇑ ⇑	⇓ ⇓ ⇓	⇓ ⇓
Identify germplasm within Brassica napus and other related species with prolonged N uptake, greater N uptake per unit of root length, more nitrate ion transporters per unit of root, less stem N storage, low seed N and low amounts of N in shed leaves.	P	15	↑↑	↓↓↓	↓↓
Develop methods to help plant breeders to rapidly select new varieties with the above traits.	P+I	10	↑↑	↓↓↓	↓↓
Identify N fertiliser strategies for improving NUE and investigate whether specific strategies must be employed to maximise NUE in different types of germplasm.	P+I	10	↑↑	↓↓	↓
Develop mutants with very low levels of the seed protein fractions napin and cruciferin and assess whether these have a lower NUE.	P	15	↑	↓↓	↓
Homologues for NUE genes identified in arabadopsis should be sought in adapted oilseed rape.	P	10	↑	↓↓	↓↓
Maximising sink capacity C.2.2.3		***10-15***	⇑ ⇑ ⇑	⇓ ⇓ ⇓	⇓
Identify combinations of husbandry and germplasm to maximise the traits that increase sink size (earlier flowering, smaller flower size, lodging resistance traits and improved seed set).	P+I	15	↑↑↑	↓↓↓	↓↓
Identify germplasm in Brassica napus and related species for the traits that increase sink size and incorporate into commercial varieties.	P	15	↑↑↑	↓↓↓	=
Break the links between apetally genes and deleterious traits to facilitate the introduction of apetally into UK genetic material.	P+I	10	↑	↓	↓
Specific development of growth regulators for the crop, with higher levels of activity than the currently available materials.	I	10	↑	↓	=
Improving post flowering radiation use efficiency C.2.2.4		***5-15***	⇑ ⇑	⇓ ⇓	=
Identify germplasm with variation in the key traits associated with RUE (stomatal density, pod erectness, lodging resistance and delayed senescence) and develop methods for rapidly selecting these traits.	P+I	15	↑↑	↓↓	↓
Physiological analysis of the lodging process to identify key traits for lodging resistance	P	10	↑↑	↓↓	↓
Agronomic research and the development of improved herbicides to facilitate the use of delayed drilling and reduced seed rates as a means of improving canopy structure.	P+I	15	↑	↓	↑
Improve understanding of N use to allow widespread later application of fertilisers as a means of manipulating canopy structure and delaying senescence.	P+I	5	↑	↓	↑
Development of improved formulation of foliar nitrogen to improve uptake efficiency and facilitate later application of N.	P+I	5	↑	↓	=
Better understand how growth regulators reduce lodging including which lodging traits they affect. Test specific anti-lodging PGRs.	P+I	5	↑	↓	=
Improving pre-flowering assimilate production and use for seed filling C.2.2.5		**10**	⇑ ⇑	⇓ ⇓	=
Identify germplasm and crop management which increases the contribution that carbohydrate stored in the stems makes to yield.	P+I	10	↑↑	↓↓	=
Identify the genetic control of stem carbohydrate storage and remobilisation and develop methods of rapidly selecting this trait.	P	10	↑↑	↓↓	=

Reducing harvest losses C.2.2.6		***10-20***	⇑ ⇑	⇓ ⇓	=
Survey genetic variation in Brassica species and identify markers for loci potentially controlling the trait.	P	10	↑	↓	=
Test usefulness of a range of alleles that might reduce pod shattering by introduction into oilseed rape.	P+I	15	↑	↓	=
Develop understanding of the genetic control of dehiscence in Arabidopsis and manipulate expression of the corresponding genes in oilseed rape to test utility.	P	20	↑	↓	=
Protecting against diseases C.2.3.2		***5-15***	⇑ ⇑	⇓ ⇓	⇓
Better understanding of how diseases interact with the crop to decrease yield (phoma stem canker, light leaf spot, sclerotinia, alternaria).	P	5	↑	↓	=
Better understanding of pathogen life cycles (including effects of weather) to help with developing strategies to optimise disease control.	P	5	↑	↓	=
Predictions of future disease problems under climate change.	P	10	↑	↓	=
Improved forecasting schemes to more accurately predict the severity of epidemics (deliver via www.).	P	5	↑↑	↓↓	↓
Breeding for resistance to major pathogens responsible for diseases of oilseed rape.	P+I	15	↑↑	↓↓	↓
Protecting against pests C.2.3.3		***5-15***	⇑	⇓	⇓
Improve crop husbandry to decrease severity of attacks.	P+I	5	↑	↓	=
Link thresholds for pest control with the crop's tolerance against yield loss from pest attack.	P+I	5	↑	↓	↓
Develop better monitoring and decision support systems and link with improved threshold estimates to improve targeting and timing of pesticides.	P+I	5	↑	↓	↓
Develop New more effective insecticides with different modes of action.	P	15	↑	↓	=
Investigate mechanisms of resistance and utilise synergists to enhance the efficacy of existing insecticides.	P+I	10	↑	↓	=
Breed for traits that give resistance to pests either directly or for use in habitat management systems and similar approaches.	P+I	15	↑	↓	↓
Protection against weeds This is covered in Cross rotational issues and weeds. **See section C.3.2**					

CROSS ROTATIONAL ISSUES AND WEEDS					
Intervention	*Funding source*	*Time to impact (years)*	*Yield impact*	*GHG impact per t*	*GHG impact per ha*
Rotation planning and optimising farming systems C.3.1		***1-15***	⇑	⇓	⇓
Development of a Quantitative framework for crop and system design.	P	1 (on-going)	↑	↓	↓
Supply information and data required to operate the model and identify the researchable knowledge gaps exposed to enable model completion.	P+I	10	=	=	=
Develop models to design sustainable farming systems to inform policy and improve to optimise the efficiency with which nutrients are used within the farming system and minimise external inputs.	P+I	10	↑	↓↓	↓↓
Increase uptake of computer based recording and on-line submission of data to improve the quality of data available to improve the relevance of models and provide a more accurate assessment of impacts.	P+I	15	=	=	=
Weed management C.3.2		***5-15***	⇑	⇓	**=**
Underpinning information on weed biology	P	5	↑	↓	=
Development of new and novel herbicides	P+I	15	↑	↓	=
Improved weed detection	P+I	10	↑	↓	=
Improved prediction methodologies	P+I	10	↑	↓	=
Develop strategies to reduce herbicide resistance	P+I	5	↑↑	↓	=
Developing strategies to minimise environmental contamination and diffuse pollution	P+I	10	↑	↓	↓
Developing spray technology to minimise the risk to operators and bystanders	P+I	<5	↑	=	=
Improved mechanical weeding	P+I	<5	↑	↓	↑
Developing better methods of non-chemical weed control	P+I	<5	↑	=	=
Identifying and maximising environmentally beneficial weeds	P	<5	↑	↓	=
Development of methods for the use of GMHT	P+I	<5	↑	↓	↓
Improved methods of Knowledge Transfer	P+I	<5	↑	↓	↓

UNDERPINNING CROP SCIENCE AND RESOURCES	
Knowledge, techniques and materials needed	
	Funding source
Crop Design - prioritising routes to improvement & specifying key	

traits	
Characterising agronomic environments	P
Determining species-specific limits e.g. life-cycles, photosynthetic & nutritional systems.	P
Characterising and inter-relating crop functions	P
Defining potential productivity	P
Optimising and validating Ideotypes	P
Integrating genetic & management synergies	P+I
Specifying and devising screening technologies for key traits ... smart screens	P+I
Germplasm - Donors of key traits	
Alien introgression	P
Synthetics (including both wheat and oilseed rape)	P
Diversity (progenitor Species; landraces, international collections)	P
GM – transgenics	P+I
Model Species	P
Mutagenesis (chemical, transposons, irradiation, spontaneous)	P+I
Activation tagging (GM)	P
RNAi & synthetic miRNA (GM)	P
Identification and Characterisation of key traits	
Mapping populations (multiple and bi-parental)	P+I
Fine mapping for QTL and gene isolation	P
TILLING	P
Association Genetics	P
Genomics, proteomics, metabolomics	P
Phenotyping	
Multi-location and multiyear replicated trials	P+I
Whole plant characters (both above and below ground)	P
End use quality	P+I
Physiology, biochemistry, phenology	P+I
Mechanised data capture capability	P+I
Controlled environments; cabinets, field based (e.g. drought)	P+I
Plant microbe interactions (both pathogenic and mutualistic)	P
Breeding	
Crossing / Selfing	P+I
Cell biology (synthetics / GM / Double haploid, interspecific crosses	P
Marker technology (e.g. SSR, SNP, AFLP, DArT, Illumina, SSAP IRAP etc)	P
Marker assisted selection; MARS, MAIC	P+I
Seed production	P+I
Trait based Selection (field and glass)	P+I
Informatics	
Informatics for traits	P
Environment (agrochem, climate)	P
Germplasm	P
Bioinformatics	P
Statistics, quantitative genetics	P
Infrastructure and Equipment	
Computing	P+I
Mechanisation (GPS led data collection)	P+I
GIS	P+I
2nd Generation sequencing	P+I
MS, HPLC, GC	P+I
Human resources including training of all below	
Plant Breeders	P
Geneticists	P
Phenotypers	P

Quantitative geneticists	P
Statisticians	P
Physiologist	P
Plant Pathologists	P
Entomologists	P
Weed scientists	P
Biochemist	P
Molecular biologists	P
Cell biologists	P
Trials experts	P
Agronomists	P

Glossary

GAI- Green area index – the ratio of planar green area to the ground area it occupies
^{o}Cd – Day degrees - accumulated thermal time above a base temperature (normally 0^{o}C unless stated)
Phyllochron – the thermal duration for the emergence of a leaf
QTL – Quantitative trait loci
Radiation use efficiency - grammes of biomass produced per unit of light intercepted

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Appendix B1

Table 1: Land use (a)

Thousand hectares

	June 2005	June 2006	June 2007	% change 2007/2006
Total area on agricultural holdings	**17 284**	**17 491**	**17 363**	**-0.7**
Total croppable area	**6 347**	**6 159**	**6 131**	**-0.5**

Total crops	**4 455**	**4 359**	**4 350**	**-0.2**
Cereal crops	2 919	2 861	2 871	0.3
Other arable crops	1 366	1 332	1 310	-1.6
Horticultural crops	170	166	169	1.6
Other croppable land	**1 892**	**1 800**	**1 781**	-1.1
Bare fallow / land withdrawn from production	164	197	165	-16.2
Set-aside (a)	535	466	440	-5.7
Temporary grass (sown in the last 5 years)	1 193	1 137	1 176	3.4
Total permanent grassland	**10 065**	**10 458**	**10 278**	**-1.7**
Grass over 5 years old	5 711	5 967	5 965	0.0
Sole right rough grazing	4 354	4 491	4 313	-4.0
Other land on agricultural holdings	**872**	**874**	**954**	**9.2**
Woodland	583	606	663	9.4
All other land	289	268	291	8.9

Appendix B2

Wheat GHG costs of production.

Inputs

	Rate used		***Ref***	**emission factor**		**Reference**	**Emissions per ha** *kg Co2e/ha*	
Seed	175	*kg/ha*	*Nix*	0.68	*kg CO2eq/kg*	Mortimer 2004	119	*kg CO2e/ha*
Fertiliser								
N fertiliser	172	*kg/ha*	*BSFP*	7.11	*kg CO2eq/kg N*	NNFCC 2007	1223	*kg CO2e/ha*
Soil N2O emissions	172	*kg/ha*	*BSFP*	6.163	*kg CO2eq/kg N*	IPCC 2006	1060	*kg CO2e/ha*
P fertiliser	40	*kg/ha*	*BSFP*	1.85	*kg CO2eq/kg*	NNFCC 2007	74	*kg CO2e/ha*
K fertiliser	45	*kg/ha*	*BSFP*	1.76	*kg CO2eq/kg*	NNFCC 2007	79	*kg CO2e/ha*
Lime - Energy cost only	0	*kg/ha*		0.06	*kg CO2eq/kg*	Williams 2006	0	*kg CO2e/ha*
Pesticide								
(Herbicide)	2.45	*kg ai/ha*	*Garthwaite*	6.30	*kg CO2eq/kg*	La 2004	15	*kg CO2e/ha*
(Insecticide)	0.07	*kg ai/ha*	*Garthwaite*	5.10	*kg CO2eq/kg*	La 2004	0	*kg CO2e/ha*
(Fungicide)	1.07	*kg ai/ha*	*Garthwaite*	3.90	*kg CO2eq/kg*	La 2004	4	*kg CO2e/ha*
(PGR)	1.23	*kg ai/ha*	*Garthwaite*	4.70	*kg CO2eq/kg*	Author estimate	6	*kg CO2e/ha*
Primary energy for operations	4808	*MJ/ha*	*Williams 2006*	0.0864	*kg CO2/MJ*	Edwards 2006	415	*kg CO2e/ha*
Baling (energy for chopping subtracted)	600	*MJ/ha*	*Williams 2006*	0.0864	*kg CO2/MJ*	Edwards 2006	52	*kg CO2e/ha*
Yields								
Grain Yield @ 15% MC	7.74	*t/ha*						
Grain protein @ 0% MC	11.5	*%*						
Harvested grain yield mc	17	*%*						
Straw Yield	5	*t/ha*	Nix (2006)					
Grain Drying	2	*%*	*author estimate*	10.4	*kg CO2 per t per % dried*	Mortimer 2004	20.8	*kg CO2 per t grain*

GHG Emissions		
per hectare		
Wheat production (including combining)	2996	*kg CO2e/ha*
Grain production & drying (straw incorp)	3067	*kg CO2e/ha*
Straw production (incorp)	90	*kg CO2e/ha*
Grain production & drying (straw baled)	2985	*kg CO2e/ha*
Straw production (baled)	690	*kg CO2e/ha*
Grain prod & conversion to ethanol (incorp)	3276	*kg CO2e/ha*
Grain prod & conversion to ethanol (baled)	3205	*kg CO2e/ha*
per tonne		
Grain production & drying (incorp)	396	*kg CO2e/t*
Grain production & drying (baled)	386	*kg CO2e/t*
Straw production (baled)	138	*kg CO2e/t straw*
Grain prod & conv to ethanol (incorp)	1444	*kg CO2e/t eth*
Grain prod & conv to ethanol (baled)	1412	*kg CO2e/t eth*

	per ha	per t grain	per t ethanol
Seed	119	14.9	44.4
Nitrogen	1223	153.2	455.9
Nitrous oxide	1060	132.8	395.2
P, K & lime	153	19.2	57.1
Pesticides	26	3.2	9.6
Diesel	415	52.1	154.9
Drying	0	20.8	61.9
Ethanol	0	0	264.7
Total	2996	396	1444

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Appendix B2 (cont)

OSR GHG cost of production

Inputs

	Rate used		Ref	emission factor		Reference	Emissions per ha	
							kg Co2e/ha	
Seed	5	*kg/ha*	*Nix*	0.68	*kg CO2eq/kg*	Mortimer 2004	3	*kg CO2e/ha*
Fertiliser								
N fertiliser	207	*kg/ha*	*BSFP*	7.11	*kg CO2eq/kg N*	NNFCC 2007	1472	*kg CO2e/ha*
Soil N2O emissions	207	*kg/ha*	*BSFP*	6.163	*kg CO2eq/kg N*	IPCC 2006	1276	*kg CO2e/ha*
S fertiliser (SO3)	70	*kg/ha*	*BSFP*		*kg CO2eq/kg*		0	*kg CO2e/ha*
P fertiliser (P2O5)	40	*kg/ha*	*BSFP*	1.85	*kg CO2eq/kg*	NNFCC 2007	74	*kg CO2e/ha*
K fertiliser (K2O)	45	*kg/ha*	*BSFP*	1.76	*kg CO2eq/kg*	NNFCC 2007	79	*kg CO2e/ha*
Lime - Energy cost only	300	*kg/ha*		0.06	*kg CO2eq/kg*	Williams 2006	18	*kg CO2e/ha*
Pesticide								
(Herbicide)	2.45	*kg ai/ha*	*Garthwaite*	6.30	*kg CO2eq/kg*	La 2004	15	*kg CO2e/ha*
(Insecticide)	0.07	*kg ai/ha*	*Garthwaite*	5.10	*kg CO2eq/kg*	La 2004	0	*kg CO2e/ha*
(Fungicide/PGR)	1.07	*kg ai/ha*	*Garthwaite*	3.90	*kg CO2eq/kg*	La 2004	4	*kg CO2e/ha*
(PGR)	0	*kg ai/ha*	*Garthwaite*	4.70	*kg CO2eq/kg*	Author estimate	0	*kg CO2e/ha*
Primary energy for operations (min till)	3971	*MJ/ha*	*Williams 2006*	0.0864	*kg CO2/MJ*	Edwards 2006	343	*kg CO2e/ha*
Baling (energy for chopping subtracted)	600	*MJ/ha*	*Williams 2006*	0.0864	*kg CO2/MJ*	Edwards 2006	52	*kg CO2e/ha*
Yields								
Grain Yield @ 15% MC	3.2	*t/ha*						
Oil @ 0% MC	43.0	*%*						
Harvested grain yield mc	11	*%*						
Straw Yield	5	*t/ha*	Nix (2006)					
Drying								
Grain Drying	2	*%*	*author estimate*	10.4	*kg CO2 per t per*	Mortimer 2004	20.8	*kg CO2 per t grain*

GHG Emissions		
per hectare		
OSR production (including combining)	3285	*kg CO2e/ha*
per tonne		
Seed production & drying (incorp)	1012	*kg CO2e/t*

0.5

Appendix B3

UK arable commodity production, consumption and trade, source: USDA

Commodity	Attribute	2003	2004	2005	2006	2007
Total Cereals	**Production**					
	Area Harvested (1000 HA)	3056	3130	2919	2860	2872
	Volume of harvested production	21494	22005	21012	20826	19048
	Value of production (£ million) (a)	2332	2391	1384	1709	1757
	Value of production at market prices (£ million) (b)	1486	1707	1450	1513	1910
	Supply and use					
	Production (1000 t)	21494	22005	21012	20826	19048
	Imports from: the EU	1953	1934	2056	1847	1854
	The rest of the world	645	463	579	558	709
	Total imports	2598	2397	2635	2405	2563
	Exports to: the EU	4240	2934	3095	2709	2408
	The rest of the world	827	80	208	60	81
	Total Exports	5067	3014	3303	2769	2489
	Total new supply	19026	21388	20344	20462	19122
	Change in farm and other stocks	-2068	469	-360	52	-1390
	Total Consumption (1000 t)	21094	20919	20703	20514	20512
	Production as % of total new supply for use in UK	113	103	103	102	100
Wheat	**Production**					
	Area Harvested (1000 HA)	1837	1990	1867	1833	1816
	Yield (t/HA)	7.8	7.8	8	8	7.2
	Production (1000 t)	14288	15473	14863	14735	13137
	Value of production (£ million) (a)	1434	1677	1030	1072	1307
	Of which: sales	1048	1038	956	1004	1355
	Subsidies (b)	440	447	.	.	.
	On farm use	70	103	87	76	94
	Change in stocks	-124	90	-13	-8	-142
	Value of production at market prices (£ million)	994	1231	1030	1072	1307
	Prices (average prices weighted by volumes of sales (£ per tonne))					
	Milling wheat	76.5	87.4	76.4	76.7	108.3
	Feed wheat	68.4	77.4	67.1	72.3	97.7
	Supply and use					
	Production	14288	15473	14863	14735	13137
	Imports from: the EU	633	432	688	569	640
	The rest of the world	352	352	487	459	617
	MY Imports (1000 t)	985	784	1175	1028	1257
	Exports to: the EU	3121	2250	2444	2123	1947
	The rest of the world	657	43	22	17	10
	MY Exports (1000 t)	3778	2293	2466	2140	1957
	Total new supply	11495	13964	13572	13623	12437
	Change in farm and other stocks	-1924	664	-139	25	-1165
	Total Consumption (1000 t)	13419	13300	13711	13598	13602
	Of which: flour milling	5611	5600	5642	5625	5702
	Animal feed	6708	6627	7002	6868	6742
	Seed	281	275	254	254	275
	Other uses and waste	819	798	813	850	882
	Production as % of total new supply for use in UK	124	111	110	108	106

% of home grown wheat in milling grist	85	86	82	82	82

Appendix 3 (cont)

Oilseed rape

Production					
Area Harvested (1000 HA)	542	554	594	575	681
Yield (tonnes per hectare)	3.3	2.9	3.2	3.3	3.1
Production (1000 t)	1771	1607	1898	1890	2108
Of which:					
Production not on set-aside land:					
Area (thousand hectares)	460	498	519	500	602
Yield (tonnes per hectare) (a)	3.4	3	3.3	3.4	3.2
Production (a)	1548	1471	1706	1674	1900
Production on set-aside land:					
Area (thousand hectares)	82	55	75	76	80
Yield (tonnes per hectare)	2.7	2.5	2.5	2.9	2.6
Production	223	136	192	216	208
Value of production (£ million) (b)	417	375	262	310	422
Of which sales	283	262	249	312	404
Subsidies (c)	113	118	.	.	.
Change in stocks	21	-5	13	-2	18
Value of production at market prices (£ million) (d)	304	257	262	310	422
Supply and use					
Production	1771	1607	1898	1890	2108
Imports from: the EU	136	198	47	132	67
The rest of the world 14	-	-	-	-	
MY Imports (1000 t)	136	198	47	132	67
Exports to: the EU	271	101	168	179	280
The rest of the world	1	3	4	15	-
MY Exports (1000 t)	272	104	172	194	280
Total new supply	1634	1701	1773	1829	1896
Production as % of total new supply for use in UK	108	94	107	103	111

Appendix B4

Cereals and Oilseed Rape production estimates: 2007 Harvest United Kingdom – Final Results

CEREALS IN THE UNITED KINGDOM: AREA, YIELD AND PRODUCTION – see note (a)

	CROP	2003	2004	2005	2006	2007	% change 2007/2006
AREA (thousand hectares)	Total cereals	3 056	3 130	2 920	2 861	2 871	0%
	Wheat	1 836	1 990	1 867	1 833	1 816	-1%
	Barley – total	1 076	1 007	938	881	898	2%
	- winter	455	420	384	388	383	-1%
	- spring	621	587	553	494	515	4%
	Oats	121	108	91	121	130	7%
	Mixed corn	4	4	4	4	3	-18%
	Rye	4	6	6	7	6	-9%
	Triticale	15	15	13	14	18	27%
YIELD (tonnes per hectare) - see note (a)	Total cereals	7.0	7.0	7.2	7.3	6.6	-9%
	Wheat	7.8	7.8	8.0	8.0	7.2	-10%
	Barley – total	5.9	5.8	5.9	5.9	5.7	-5%
	- winter	6.3	6.4	6.5	6.7	6.1	-9%
	- spring	5.7	5.3	5.4	5.3	5.3	0%
	Oats	6.2	5.8	5.8	6.0	5.5	-9%
	Mixed corn	4.3	4.3	4.4	4.5	3.9	-12%
	Rye	5.8	5.7	6.7	6.1	5.7	-7%
	Triticale	4.1	4.1	4.2	4.3	3.9	-10%
PRODUCTION (thousand tonnes) - see note (a)	Total cereals	21 494	22 005	21 005	20 822	19 045	-9%
	Wheat	14 282	15 468	14 863	14 735	13 137	-11%
	Barley – total	6 360	5 799	5 495	5 239	5 079	-3%
	- winter	2 848	2 694	2 505	2 608	2 338	-10%
	- spring	3 512	3 105	2 990	2 631	2 741	4%
	Oats	749	626	532	728	712	-2%
	Mixed corn	18	17	18	17	13	-28%
	Rye	25	32	41	43	36	-15%
	Triticale	61	62	56	61	69	15%

Notes

(a) For Great Britain, production figures (and therefore yields) have been adjusted to 14.5% moisture content. For Northern Ireland, figures are based on 15% moisture content.

Appendix B5

Cereals and Oilseed Rape production estimates: 2007 Harvest United Kingdom – Final Results

OILSEED RAPE IN THE UNITED KINGDOM: AREA, YIELD AND PRODUCTION – see notes (a) to (c)

OILSEED RAPE		2003	2004	2005	2006	2007	% change 2007/2006
AREA (thousand hectares)	UNITED KINGDOM	542	# 554	# 594	575	681	18%
	UK SET-ASIDE	82	# 55	# 75	76	80	6%
	UK NON SET-ASIDE	460	498	519	500	602	20%
	England	422	455	480	463	562	21%
	Winter Sown	367	387	455	447	550	23%
	Spring Sown	55	69	25	16	12	-23%
	Wales and Northern Ireland	3	4	3	3	3	4%
	Scotland	35	39	36	34	36	8%
YIELD (tonnes per hectare) - see note (b)	UNITED KINGDOM	3.3	# 2.9	# 3.2	3.3	3.1	-6%
	UK SET-ASIDE	2.7	# 2.5	# 2.7	2.9	2.6	-9%
	UK NON SET-ASIDE	3.4	3.0	3.3	3.4	3.2	-6%
	England	3.4	2.9	3.3	3.3	3.1	-6%
		(+/- 0.1)	(+/-0.1)	(+/-0.1)	(+/-0.1)	(+/-0.1)	
	Winter Sown	3.6	3.1	3.4	3.4	3.2	-7%
		(+/- 0.1)	(+/-0.1)	(+/-0.1)	(+/-0.1)	(+/-0.1)	
	Spring Sown	1.9	2.1	1.8	1.8	1.5	-18%
		(+/-0.1)	(+/-0.2)	(+/-0.5)	(+/-0.2)	(+/-0.5)	
	Wales and Northern Ireland	3.4	2.9	3.3	3.3	3.1	-6%
	Scotland	3.4	3.3	3.3	3.6	3.8	3%
PRODUCTION (thousand tonnes) - see note (b)	UNITED KINGDOM	1,771	# 1,608	# 1,901	1,890	2,108	12%
	UK SET-ASIDE	223	# 138	# 196	216	208	-4%
	UK NON SET-ASIDE	1,548	1,471	1,706	1,674	1,900	13%
	England	1,418	1,330	1,571	1,541	1,753	14%
		(+/-55)	(+/-109)	(+/-54)	(+/-64)	(+/-68)	
	Winter Sown	1,312	1,183	1,527	1,512	1,734	15%
		(+/-52)	(+/-96)	(+/-53)	(+/-64)	(+/-68)	
	Spring Sown	106	147	45	29	19	-36%
		(+/-14)	(+/-34)	(+/-13)	(+/-7)	(+/-7)	
	Wales and Northern Ireland	9	11	11	10	10	-2%
	Scotland	121	130	124	123	137	11%

Notes

(a) Yield and production estimates for the UK have been adjusted to 9% moisture content

(b) Figures in brackets are 95% confidence intervals. Information on confidence intervals and RSE indicators can be found on page 2.

(c) Figures marked '#' have been revised since the publication of the provisional figures on 11 October 2007 as a result of more accurate set-aside data being made available by the Rural Payments Agency.

Appendix B6

Breakdown of FE and HE land base studies subject classifications

Subject group	Subject description	JACS	Student numbers
Agricultural crops	Mycology	C220	40
	Arable and fruit farming	D410	
	Agricultural pests and diseases	D411	
	Crop physiology	D412	

	Crop nutrition	D413	
	Crop protection	D414	
	Crop production	D415	
	Organic arable and fruit farming	D461	
Agricultural livestock	Livestock general	D420	695
	Livestock husbandry	D421	
	Organic livestock	D462	
Animal care	Animal science general	D300	2,078
	Veterinary nursing	D310	
	Animal health	D320	
	Animal toxicology	D325	
	Animal nutrition	D327	
	Animal welfare	D328	
	Poultry keeping	D423	
Aquaculture/Fisheries management	Freshwater fish	D432	18
	Aquaculture	D435	
	Fish farming	D430	
	Fish husbandry	D431	
	Organic fish farming	D463	
Equine	Equine studies	D422	357
Land management	Game keeping	D424	740
	Rural estate management	D440	
	Farm management	D441	
	Gamekeeping management	D442	
	Water resource management	D443	
	Land management for recreation	D444	
	Heritage management	D445	
	Wilderness management	D446	
	Agricultural irrigation and drainage	D472	
	Agricultural economics	L112	
	Land management	N231	
Land-based engineering	Agricultural machinery	D471	0
Landscaping	Landscape design general	K300	1,655
	Landscape architecture	K310	
	Landscape studies	K320	
	Landscape design not elsewhere classified	K390	
Production horticulture	Glasshouse culture	D416	39
	Amenity plant production	D417	
Related to agriculture	Agriculture general	D400	3,968
	International agriculture	D450	
	Organic farming	D460	
	Agricultural technology	D470	
	Agriculture not elsewhere classified	D490	

	Agricultural sciences general	D700	
	Agricultural biology	D710	
	Agricultural microbiology	D711	
	Agricultural chemistry	D720	
	Agricultural biochemistry	D721	
	Agricultural botany	D730	
	Soil as an agricultural medium	D750	
	Agricultural sciences not elsewhere classified	D790	
	Soil science	F870	
		L727	
	Agricultural geography		
Related to environmental conservation	Environmental biology	C150	1,151
	Environmental conservation	D447	
Trees and timber	Forestry general	D500	415
	Trees and shrubs	D510	
	Forestry pests and diseases	D511	
	Tree production	D515	
	Timber production	D516	
	Community forestry	D517	
	Organic forestry	D530	
	Forestry technology	D540	
	Forestry irrigation and drainage	D541	
	Forestry not elsewhere classified	D590	
Other	Others in veterinary sciences, agriculture and related subjects	D900	938
Total			12,092