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Department for Environment Food and Rural Affairs

Evidence Project Final Report

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Project identification

1. Defra Project code: IF01116
2. Project title: Desk study to evaluate contributory causes of the current ‘yield plateau’ in wheat and oilseed rape
3. Contractor organisation(s): NIAB TAG, SRUC, Cambridge University
4. Total Defra project costs (agreed fixed price): £ 27,553.00
5. Project: start date 01/09/2011

   end date 31/03/2012

6. It is Defra's intention to publish this form.

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(a) When preparing Evidence Project Final Reports contractors should bear in mind that Defra intends that they be made public. They should be written in a clear and concise manner and represent a full account of the research project which someone not closely associated with the project can follow.

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(b) If you have answered NO, please explain why the Final report should not be released into public domain

Executive Summary

7. The executive summary must not exceed 2 sides in total of A4 and should be understandable to the intelligent non-scientist. It should cover the main objectives, methods and findings of the research, together with any other significant events and options for new work.

To address the lack of progression in UK average farm yields for wheat and oilseed rape, national yield trends were analysed in relation to cropped area, genetic improvement, weather patterns, economic influences, crop nutrition and protection, plus other aspects of agronomy. Farm-specific data were evaluated to investigate the effects of changes or differences in agronomic practice, and research evidence examined to quantify their likely yield impact. Opportunities for overcoming yield constraints were considered, in the context of legislative, environmental and technical barriers, along with potential impacts on grain quality or end use.

From 1980 to 1996 wheat yields improved rapidly, by an average of 0.10 t/ha per year, aided by a fall in the proportion of second wheats. Since then yields have stagnated, despite the potential of new varieties increasing by 0.05 t/ha per year. A number of weather variables have influenced annual yield variation. Increased crop protection measures have minimised yield loss from weeds, pests and diseases while a move to earlier sowing has contributed positively to yield. The transition to reduced tillage may have had a negative yield effect in the short term, with a longer-term impact possible from deep soil compaction. Crop nutrition has also been a factor in yield limitation, as a result of sub-optimal applications of nitrogen (N) fertiliser in at least some situations, and the area of crop receiving sulphur (S) fertiliser initially rising more slowly than the area at risk of deficiency.

From 1984 to 1994 oilseed rape yields declined but, after varying wildly, they have improved since 2004. Yield potential has increased at nearly 0.05 t/ha per year through genetic improvement but prior to 2004 poor uptake of higher-yielding varieties meant that over half of this was not being deployed. Increased cropping frequency has undermined yield improvement over the whole period. From 1984 to 1994 the net impact of agronomy was negative, with decreasing N fertiliser doses and increasing S deficiency. An increase in spring oilseed rape and unfavourable weather patterns also reduced yield improvement. From 1994 to 2004 yields benefitted from rising S fertiliser use but a shift to shallow cultivation was detrimental. From 2004 to 2011 better uptake of new varieties, strengthening crop protection and favourable weather combined to give a rising yield trend.

No single factor has had a dominant influence on yield trends. Changes to agronomy have had a number of mainly small effects, with growers aiming to maximise profit not yield. To restore rising yields in the face of warmer conditions, economic or environmental pressures and evolving weed, pest or disease threats, a more holistic approach to agronomy is needed. Recommendations include improving selection and

management information for varieties, sowing wheat earlier on light land to mitigate drought and a focus on improving N use efficiency. Benchmarking of yields, resources to ‘health check’ cropping systems and increased utilisation of survey data are vital to guide and measure change. Further studies should include the yield effects of changing weather, the incidence and severity of deep soil compaction and pollination and seed set in oilseed rape.

Project Report to Defra

8. As a guide this report should be no longer than 20 sides of A4. This report is to provide Defra with details of the outputs of the research project for internal purposes; to meet the terms of the contract; and to allow Defra to publish details of the outputs to meet Environmental Information Regulation or Freedom of Information obligations. This short report to Defra does not preclude contractors from also seeking to publish a full, formal scientific report/paper in an appropriate scientific or other journal/publication. Indeed, Defra actively encourages such publications as part of the contract terms. The report to Defra should include:
   - the objectives as set out in the contract;
   - the extent to which the objectives set out in the contract have been met;
   - details of methods used and the results obtained, including statistical analysis (if appropriate);
   - a discussion of the results and their reliability;
   - the main implications of the findings;
   - possible future work; and

   any action resulting from the research (e.g. IP, Knowledge Exchange).

1. Introduction and Aims

The period from the 1940s to the 1990s saw exceptional growth in wheat yields. Improvements to farming methods, plant breeding and agronomy led to national average yields rising from 2.7 t/ha to 7.6 t/ha, 1 t/ha per decade, as the crop area doubled to 2.0 M hectares. Since then farm wheat yields have stalled, varying between 7.0 and 8.0 t/ha but with no rising trend. Oilseed rape yield trends have been complicated by the change from lower yielding spring varieties to higher yielding winter varieties and the introduction of low erucic acid (single-low) and then low glucosinolate (double-low) variety types. Since the double-lows became standard in the 1980s, farm yields have fluctuated wildly, with those for the mid 2000s little different to the 1980s. There has since been a hint of a rising yield trend, with the highest ever national oilseed rape yield in 2011 (3.9 t/ha).

With its favourable environment for achieving high yields and an efficient farming industry, the UK is well placed to respond to the challenges of rising global food demand. Genetic gain delivered by plant breeders has progressed at more than 0.5% per year for wheat yield and 2% for oilseed rape but farm yield trends suggest that either plant breeding benefits are not being realised on farm, or they are being negated by losses due to weather related effects or agronomic limitations.

The aims of this study were to identify agronomic factors that may be constraining wheat or oilseed rape yield improvement, assess the scope and opportunities for raising national yields through agronomy and highlight knowledge gaps or barriers to be addressed. Specific objectives included:

1. A review of existing evidence for agronomy as a contributory cause of yield plateau in wheat and oilseed rape, in the context of genetic improvement and changing weather patterns.
2. The examination of farm yield trends alongside national data sets for crop price, fertiliser or pesticide usage and other agronomic factors.
3. The use of farm specific data to investigate differences in, or changes to, agronomic practice that may be related to yield trends.
4. The examination of existing research evidence to quantify the likely yield impact of differences in, or changes to, agronomic practice.
5. An assessment of opportunities for, and barriers to, overcoming agronomic limitations to yield.

2. Materials and Methods

Published reports were reviewed that have examined yield trends in countries around the world, and the contributions of genetic, climatic, economic and agronomic factors to these trends. Specific attention was given to recent studies from France and Denmark. The review findings were used to guide subsequent investigations of UK data. National and regional yield trends for oilseed rape and wheat were defined using data from Defra statistics, derived from cropped areas and production tonnages collected by the Cereal and Oilseed Rape Production Surveys. For wheat, investigations focused on the period from 1980 to 2011, either side of the apparent onset in 1996 of yield plateau. For oilseed rape, the double-low variety era from 1984 was considered most relevant.

Published analyses have used historical datasets for wheat and oilseed rape from UK National List (NL) and Recommended List (RL) trials to assess the potential contribution of genetic improvement to national yield trends. These analyses were reviewed and supplemented to enable the net impact of the growing environment to be determined. The effects of seasonal weather on year-to-year variation in national yields were analysed as single correlations and as multivariate analyses. The extent to which changing weather patterns may have influenced yield trends was also considered. Analyses focused on air temperatures, total rainfall, soil moisture deficit and sunshine hours.

NL and RL trials are conducted under defined conditions that often differ from typical farm practice. Improvements in the yield potential of new varieties evident within trials may not be fully expressed in farm situations, due to limitations in site conditions and management practices on farm. Recent yield trends for RL wheat trials were analysed to pinpoint similarities or differences that could help to explain farm yield trends. Crop selection and management practices may be influenced by fluctuations in crop prices and developments in agricultural policies. Prices were charted alongside yield trends, and price and policy effects analysed by regression, to identify possible associations.

National survey data were accessed to evaluate changes in fertiliser and pesticide use. Sources included the annual British Survey of Fertiliser Practice and biennial Pesticide Usage Survey. As part of CropMonitor in

England, annual disease surveys have been conducted in about 300 treated farm crops of winter wheat since 1975 and 100 crops of winter oilseed rape since 1987. Agronomic information has also been collected. Factors showing evidence of change over time were charted and compared to trends in national yields, with an estimate made of the potential qualitative or quantitative impact that could result from the extent of the changes observed.

Data from the Farm Business Survey in England were analysed for about 200 farms per year for wheat and 90 farms for oilseed rape from 2004 to 2009. They were used to identify differences in crop husbandry (as indicated by expenditure on inputs, labour and machinery) between farms in the top and bottom yield quartiles, and associations between cropped area, yield and margin. To enable yields to be examined alongside agronomic data from the same farm, several case study farms were identified. Growers were asked about their cropping strategies and changes to their farming systems since the 1990s, and information collected on soil types, cropped area, variety choice, rotation, fertiliser inputs and establishment practices between 1996 and 2011.
A review of research results from controlled field experiments was undertaken to help quantify the potential contributions of key agronomic factors to yield change. These were scaled up to provide an estimate of the potential impact that the factor may have had on national average yield trends. Data sources included published research reports and reviews from HGCA, plus published or unpublished experiments by SAC or NIAB TAG that have investigated responses to various agronomic factors under commercially-realistic conditions in the main arable areas of the UK.

Opportunities for overcoming agronomic limitations, and barriers to their adoption, were assessed. Potential environmental impacts and implications for grain quality or end use were also considered. Recommendations have been made for knowledge transfer or research where information gaps need to be addressed. Consultation with practitioners was a key part of the project, including a stakeholder meeting that provided an opportunity to capture knowledge and experience, focus the study and interpret data. Further discussions helped to refine conclusions and recommendations.

3. Limitations

This initial study has examined the possible contribution of a wide range of agronomic factors to recent national yield trends, in the context of other potentially important influences. It has focused on farm yields and practices, rather than research trials. Yield potential using substantially-modified agronomic practices and technology-related yield gaps that might exist have not been considered.
The study was dependent on published and unpublished surveys, the accuracy of which is limited by the scale and sophistication of their sampling methodologies. Surveys have been limited by the level of detail requested, including lack of differentiation between winter and spring cropping. While wheat is known to have been dominated by winter cropping, proportions of winter and spring rape have been more variable. The impact of the lower yielding spring rape crop on the combined winter and spring national yield trend has been estimated in this report, but it was too speculative to try to relate changes in agronomic practice to just the estimated winter oilseed rape yield trend.

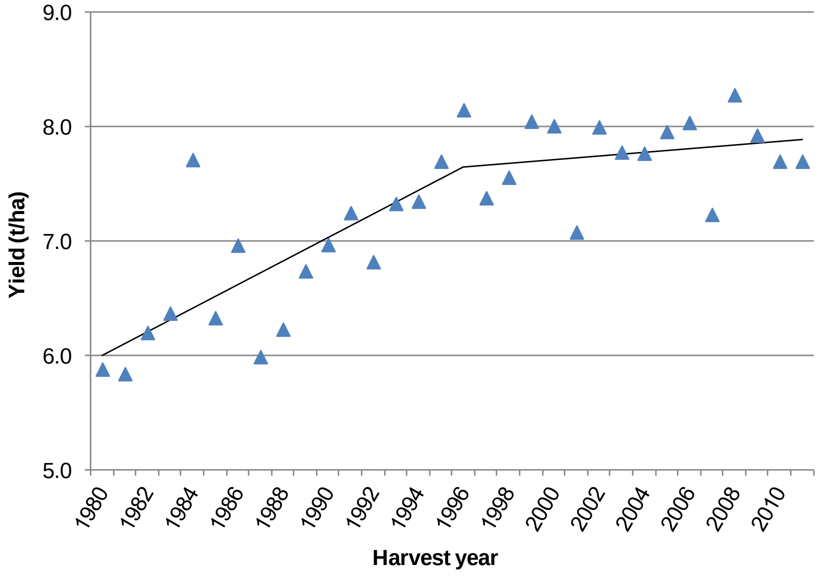
Weather data for the UK and England were available for the period studied. However, there has been no systematic collection of solar radiation and the use of sunshine hours as a surrogate has limitations. Examination of soil moisture deficit (SMD) data was also limited to specific locations. Testing of weather effects was limited to single and multiple correlations of yield with weather variables, and an examination of trends over time. This does not provide a proper assessment of the potential impact of climate trends on national yields, which could be explored through the use of a suitable crop model. However, this was considered to be outside of the scope of this study. There were a number of potentially important agronomic factors for which little or no data were available. These are highlighted in the report, and recommendations have been made to as to additional data that should be collected in future. Together, they could account for a significant proportion of the unexplained yield effects over part or all of the time periods studied.

4. Results

4.1. Wheat

Yield Trend

From 1980 to 1996 national average wheat yields increased by an average of 0.105 t/ha per year, but since 1996 the UK trend shows only a 0.016 t/ha per year rise (Summary Figure 1). Regional data since 1999 show that the trend for England (94% of the crop) is similar to the UK, whereas in Scotland yields continued to rise until the 2000s. Farm Business Survey data reveal a divergence in fortune for farms in different yield quartiles, with the gap between the top and bottom 25% rising from 3.0 t/ha in 1987 to 4.5 t/ha in 2009. Farms in the top yield quartile are growing twice the wheat area grown by farms in the bottom quartile, and are achieving the highest wheat gross margins.



Summary Figure 1. UK national average wheat yields from 1980 to 2011.

Genetics and Yield Potential

Previous estimates of the improvement in wheat yield potential due to genetics have ranged from 0.06 to 0.07 t/ha per year. A new analysis suggests that yields of the best NABIM Group 4 varieties have increased by nearly 0.10 t/ha per year, whereas for Group 1,2 & 3 yields have risen by about 0.04-0.06 t/ha per year, with an overall mean of 0.063 t/ha per year. Using certified seed weights for the top varieties and lifetime average yields in trials, it is estimated that since 1990, apart from a slight dip from about 1996 to 2002, the potential for a yield increase of 0.05 t/ha per year has been maintained on farm through the effective uptake of new, higher-yielding varieties.

Climate and Weather

Relationships between national wheat yields and monthly weather data for the UK or for England were examined for the 1980 to 2011 harvest years. Single variate analysis showed that a number of weather variables have contributed to yield variation. Multivariate analysis failed to contribute further to this picture. Rainfall for April showed a rising trend until 1996 but then a decreasing trend until 2011, with an increase since 1996 in April SMD. Sunshine hours for June show a rising trend, indicating the potential for increasing radiation during grain fill. High sunshine hours coincided with yield spikes in 1984 and 1996 and low hours with dips in 1987 and 2007. With rising temperatures, the trend in grain fill duration shows a decrease of about 3 days from 1980 to 2011. Heat stress during grain fill has been linked to yield stagnation in France, but since 1980 the incidence of June days above 25^{O}C in England has been variable, with a weak rising trend for the last 10 days in June. While not explaining past yield stagnation, this may have implications for the future. An increase in atmospheric CO_2 concentration could equate to a yield increase of up to about 6% or 0.36 t/ha between 1980 and 2011, a contribution to yield improvement of about 0.011 t/ha per year.

Economics and Policies

Wheat grain prices increased between 1980 and 1984, fell sharply from 1996 to 1998 and then remained flat before rising steeply but erratically from 2006 up to 2011. Regression analysis failed to show a significant short or medium term effect of changes in actual or inflation-adjusted prices on yield over the period as a whole. Nevertheless, the fall in prices between 1996 and 1998 that coincided with the start of yield stagnation was a likely driver for some of the changes seen in crop management since the late 1990s. The MacSharry proposals and set-aside seem to have had a positive impact on wheat yields, possibly due to removal of unproductive land from production.

Factors Influencing Recent Yield Trends in RL Trials

The overall yield trend from 2002 to 2011 for varieties in their first year on the HGCA RL is shown in Summary Table 1. Different yield trends are apparent across RL climatic regions, with the wetter West and cooler North increasing more rapidly than for the same varieties in the dry East. Yield improvement is evident on heavier textured soils but there was almost no change on light soils. There was a consistent yield improvement in early sown RL crops, whilst late sown crops had high seasonal variation and no increase. These differences suggest a possible weather impact (notably spring or summer droughts) on the performance of wheat in at least some areas of the UK.

RL data set	Annual yield change (t/ha)	R^2 of fitted line	se of regression coefficient	Significance *F*
Fungicide treated	0.040	0.382	0.0179	0.057
Dry East region	0.005	0.012	0.0174	0.764
Wet West region	0.025	0.124	0.0233	0.319
Cool North region	0.082	0.586	0.0243	0.010
Heavy textured soils	0.067	0.320	0.0347	0.088
Light textured soils	0.003	<0.001	0.0377	0.945
Early sowing	0.071	0.604	0.0217	0.014
First wheat	0.017	0.072	0.0210	0.452

Summary Table 1. Yield trends in RL trials from 2002 - 2011, for varieties in their first year on the RL.

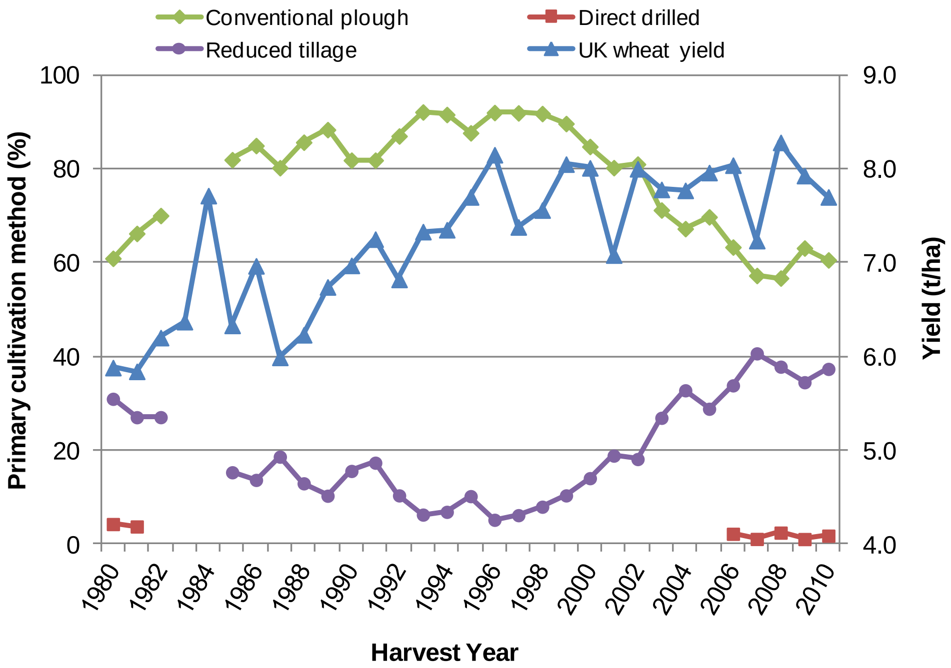
Agronomy

Average amounts of N fertiliser applied to wheat have been static since 1983. The optimum dose for modern varieties has risen by about 20 kg N/ha per tonne of yield improvement over varieties grown in the 1980s. However, the rise in break-even N to grain price ratio has negated this, which could be limiting yield by 0.12 t/ha, causing a yield decline of 0.006 t/ha per year. Grain %N values based on Cereal Quality Survey data also indicate that N use on wheat crops may be sub-optimal. Applications of phosphate (P) and potash (K) fertilisers have fallen by half since 1996. P and K budgets have been in deficit since the 1990s, but the proportion of fields tested with soil indices below critical is not rising. The crop area receiving S fertiliser rose in the 1990s but was insufficient to treat all crops at high risk of deficiency, lowering yields by up to 0.4 t/ha. The deficit was reduced from 1996 to 2002, with a likely contribution to yield improvement of up to 0.025 t/ha per year. This may be an over-estimate as not all crops treated would have been those at highest deficiency risk. There is little evidence to implicate trace element deficiencies as a cause of yield stagnation.

The severity of septoria leaf blotch infection in farm crops was generally higher between the late 1990s and early 2000s, coinciding with the pathogen developing resistance to strobilurin fungicides and a fall in fungicide doses applied. Yield loss is estimated to have increased by an average of 0.01 t/ha per year during that period. From 2002 to 2011 increasing fungicide doses and lower septoria pressure reversed this. Between the 1980s and 1990s the incidence of take-all fell from 15% to 5%, linked to a declining area of second wheat, with an estimated reduction in the national yield loss from 6% to 2%. Take-all incidence has since varied, with little indication of a rising trend.

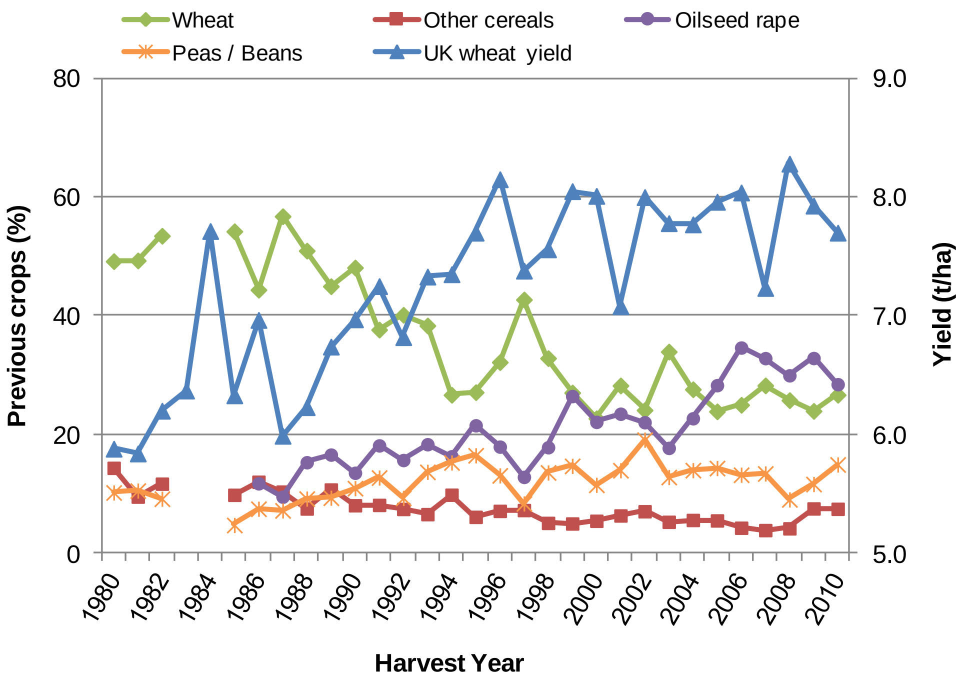
There is little indication of rising pest incidence since 1996. Severity of attacks by orange blossom midge may have contributed to annual variation during the 1990s and early 2000s. The incidence of some nematode species may be increasing, but the implications of this for yield are uncertain. There is no evidence of an increase in rabbit damage that could be linked to yield stagnation. While there is little data to quantify changes in weed populations, it is widely known that control of grass weeds, in particular black-grass, is a concern in many key wheat producing areas. While the direct impact on yield may have been minimal due to a rise in the number of herbicides applied to maintain efficacy, there is an increasing number of farms where overall crop management strategies are influenced by the need to maximise black-grass control as well as optimising yield.

The proportion of wheat crops sown after ploughing rose from 60% to 90% from the 1980s to 1996 but had fallen back to 60% by the late 2000s (Summary Figure 2). Evidence for yield effects of minimum tillage over a long period is sparse, but estimates of wheat yield reduction have ranged from 0 to 4%. Two scenarios were considered for the period since 1996. Assuming a continuing 3% penalty from reduced tillage, a decline in yield about 0.007 t/ha per year is indicated. In an ongoing study, a larger short-tem yield penalty was observed during the transition from ploughing to non-inversion. This may be a year effect, but assuming a 12% penalty in the year of transition only, a yield decline of 0.004 t/ha per year is indicated. Machinery wheel loads have progressively increased, inducing high stresses in deep soil horizons irrespective of the tyres or tracks used. Soil compaction below sub-soiling depth may remain for a long time. UK research has indicated that soil compaction from trafficking can reduce cereal yields by an average of 16%, but there are no data to quantify the incidence and severity of compaction. In addition, up to 15% of under-drained land on cereal farms is potentially being mole drained less often than it should be. The mean organic matter content of arable soils declined from 3.3% in 1980 to 2.8% in 1995, but there is no evidence that this has been a direct cause of wheat yield stagnation.



Summary Figure 2. Establishment methods for winter wheat crops in England from 1980 to 2010.

The proportion of second or subsequent wheat crops declined from 50% in the 1980s to 30% in the 1990s (Summary Figure 3), due to an increase in wheat following peas / beans or oilseed rape. In a recent wheat and oilseed rape rotation study, the average yield penalties were 1.0 t/ha (10%) for second wheats and 1.4 t/ha (14%) for subsequent wheats. The decline in successive wheat crops could account for 0.015 t/ha per year of the rise in national wheat yields from 1980 to 1996. Since the 1990s, the proportion of wheat crops following oilseed rape has risen to 30%. The proportion of wheat after peas / beans has changed little, but there has been substitution of beans for peas. A five-year crop sequence study in England showed that wheat yields after peas were higher than after beans, which may have had a minor impact on yield trends. Wheat yields following oilseed rape were higher than following peas. In France yields were found to be lower after oilseed rape than after peas, which could be explained by a lower amount of N being applied to oilseed rape.



Summary Figure 3. Proportion of crop types preceding winter wheat in England from 1980 to 2010.

The proportion of wheat crops sown before 1st October has increased from less than 20% in the 1980s to nearly 40% since the late 1990s. An analysis of NIAB TAG trials data over several sites and seasons compared yields of wheat varieties when sown in early-mid September, or from late October onwards, against the traditional late September / early October window. An average 1.4% yield advantage to 'early' sowing and 3.7% yield penalty to 'late' sowing were found. Advantages to September sowing have been variable in other studies. It is estimated that the trend towards earlier sowing could account for a national yield improvement of 0.003 t/ha per year since 1980. With conflicting results from field experiments and no data available to examine trends, the impact of farm seed rates on the national wheat yield trend is uncertain. However, target plant populations and seed rates advised in the early 2000s may have been sub-optimal for yield in some situations.

4.2. Key Factors Influencing Wheat Yield Trend

Key factors that have contributed to the trend in UK average wheat yields from 1980 to 1996 and from 1996 to 2011 are shown in Summary Table 2. Some appear to have changed after 2002, so the latter period has been subdivided. Factors for which it has been possible to reliably estimate their effects do not account for all of the yield trend in either phase, with a proportion unexplained. In addition to weather patterns, a number of variables are highlighted as potentially having had an influence, especially during the 1996 to 2011 period, most notably deep soil compaction, but also of relevance are UV-B levels, soil pH, under-drainage, seed rates and timeliness and targeting of inputs and operations. Many of these are thought to have had a small negative impact on yields.

Period	**1980-1996**	**1996-2002**	**2002-2011**
	Yield gain + or loss - with estimate of t/ha per year. 0 neutral, ( ) uncertain		
Farm Yield	+0.105	+0.016	
Genetic potential	+0.05	+0.05	
Variety choice	0	-0.01	0
Agronomic effects			
Nutrition N Nutrition S	-0.006 (-)	-0.006 +0.025	-0.006 0
Disease control	(+)	-0.01	+0.01
Rotation	+0.015	0	
Cultivation	+0.001 to +0.002	-0.004 to -0.007	
Sowing date	+0.003	+0.003	
Rising CO_2 levels	+0.011	+0.011	
Weather and/or other factors	+0.030 to +0.031	-0.040 to -0.043	-0.045 to -0.048

Summary Table 2. Factors contributing to the national wheat yield trend from 1980 to 2011.

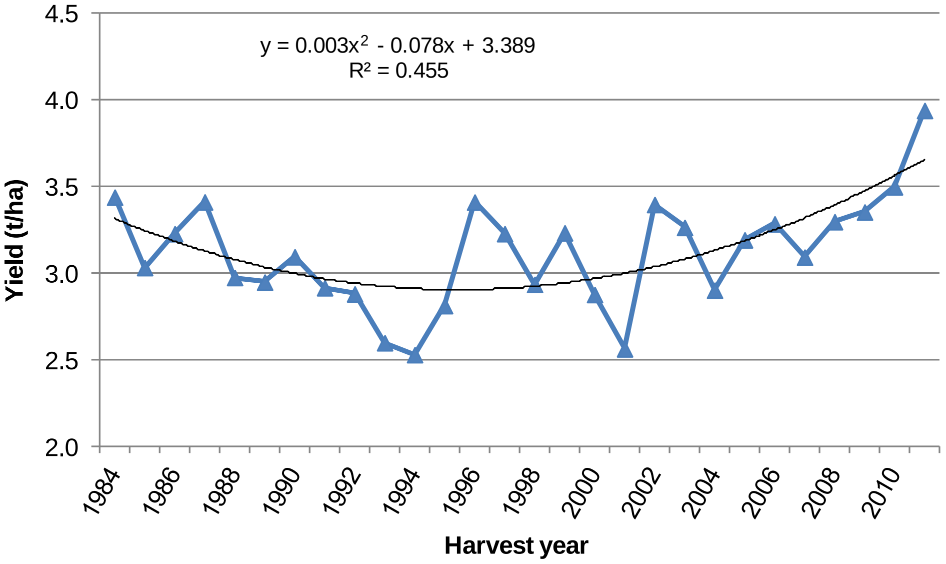
4.3. Oilseed Rape

Yield Trend

From 1984 to 1994 national oilseed rape yields fell by an average of 0.040 t/ha per year. Over the next ten years yields were highly variable, with an overall increase of 0.022 t/ha per year, but since 2004 yields have risen by an average of 0.075 t/ha per year (Summary Figure 4). Regional data from 1999 show that the trend for England reflects that for the UK, whereas yields in Scotland have maintained steadier improvement. A higher proportion of spring rape in the 1990s led to increased annual variation and reduced yield improvement. Farm Business Survey data from 1987 to 1999 show similar trends for the top and bottom yield quartiles, with a slight increase in the gap between them in the 1990s. No consistent relationship is evident between yield quartile and crop area.

Genetics and Yield Potential

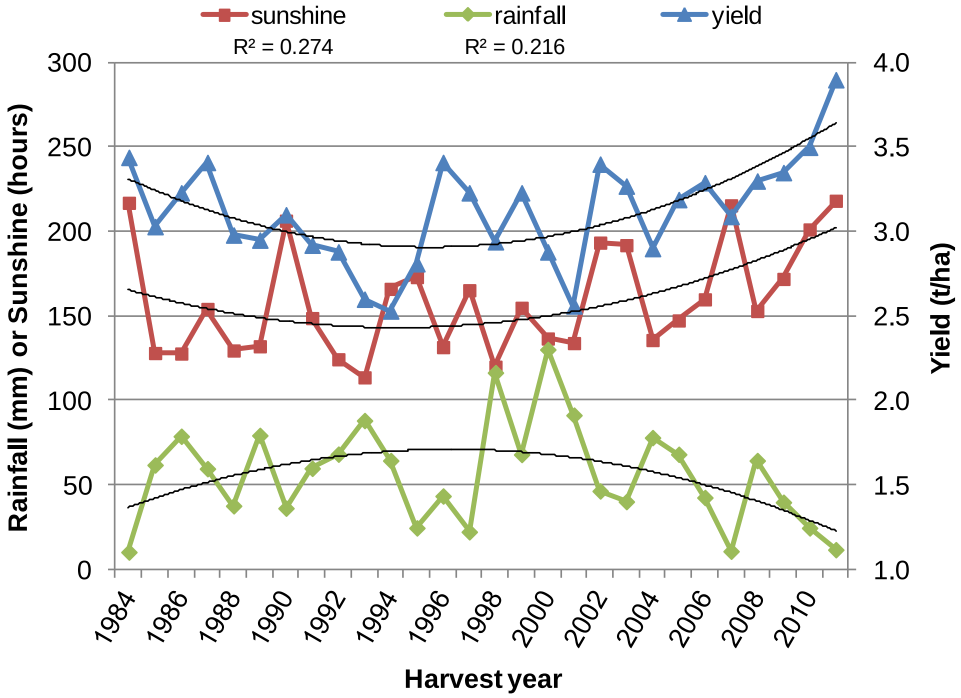
An updated analysis of NL and RL data shows that annual improvements in yield offered by the best new oilseed rape varieties are equivalent to 0.06 t/ha for conventional varieties and 0.05 t/ha for hybrids. These are similar to previous estimates, and equate to a potential yield gain on farm of about 0.048 t/ha per year. Although only one measure of variety selection on farm (as farm saved and imported seed account for part of the area), certified seed data indicate that prior to 2004 uptake of new high yielding varieties was poor due to growers selecting varieties that were easier to manage and harvest. This led to a widening gap in theoretical yield potential between that of the best varieties available and that of the variety set being grown. This is estimated to have reduced yield gain on farm from genetic improvement by more than half. Since 2004 better uptake of new varieties has started to close this gap, with a small positive contribution to yield improvement.



Summary Figure 4. UK national average oilseed rape yield trend in the double-low era (1984 to 2011).

Climate and Weather

Relationships between UK oilseed rape yields and monthly weather data for England and for the UK as a whole were analysed from 1984 to 2011. Single variate analysis indicated that several weather variables have contributed to yield variation. Multivariate analysis did not add to this. Yield responded positively to increasing sunshine hours and negatively to increasing rainfall in April, with trends over time in yield and sunshine remarkably similar (Summary Figure 5). The most likely explanation for this is improved seed-set, resulting from enhanced pollination or increased crop photosynthesis. Higher yields have also been associated with cold, dry, sunny December weather, probably due to a suppressing effect on some pests and diseases (phoma, but not light leaf spot).

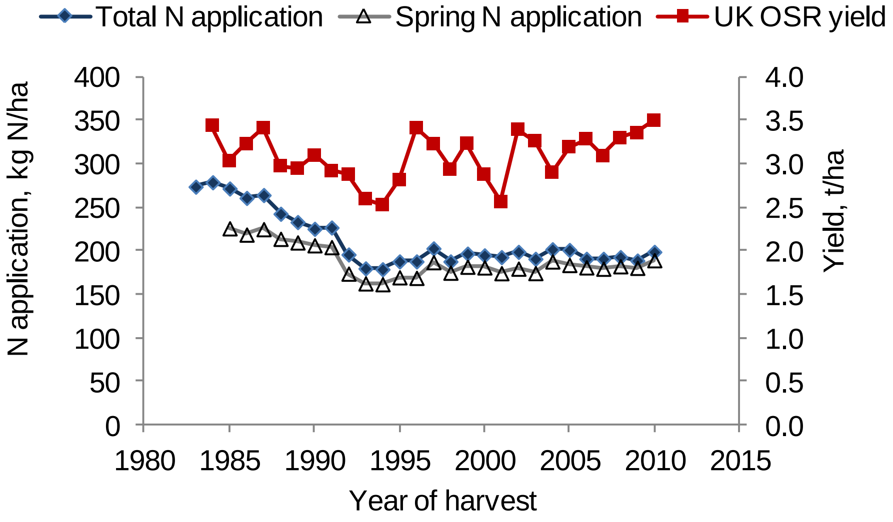


Summary Figure 5. Trends for UK oilseed rape yield and April rainfall and sunshine for England.

Economics and Policies
Oilseed rape prices fell sharply after 1991 and between 1996 and 1999, before rising rapidly from 2006 to 2011. Regression analysis failed to indicate a significant short or medium-term impact of crop price change on oilseed rape yields. A subsequent analysis showed that for the period from 1984 to 1994, characterised by falling prices and declining yield, crop price and yield were highly correlated ($r = 0.767$, $p < 0.01$). After 2000 rising prices again saw a relationship between crop price and yield ($r = 0.661$, $p < 0.05$). The spike in the area of spring oilseed rape grown in the mid 1990s partly resulted from the introduction of area payments, which made the lower inputs of spring rape more attractive, despite a lower yield potential, once this was offset by the crop subsidy.

Agronomy

The average amount of fertiliser N applied to oilseed rape fell from about 270 kg N/ha in 1983 to 179 kg/ha in 1994 (Summary Figure 6). A reduction in autumn N use explains 30% of this, but the decline in spring N dose accounts for an estimated yield drop of 0.20 t/ha. It is uncertain if the N requirement of modern varieties has risen with yield potential, but a NIAB TAG survey has hinted that current amounts of spring N (180-190 kg N/ha) are sub-optimal. P and K applications have fallen since the 1980s but net budgets have only been in deficit since the 2000s. The proportion of crops treated with S fertiliser increased from 5% in 1993 to 60-70% by 2003. S deficiency may have limited national yields by up to 0.4 t/ha in the early 1990s. By the early 2000s the estimated yield penalty had fallen to about 0.1 t/ha, a contribution to yield improvement of about 0.027 t/ha per year, assuming that the fields being treated were those at highest risk of deficiency. There is no evidence to link changes in trace element status of oilseed rape crops to observed yield trends.



Summary Figure 6. Trends in the amount of N applied in total and in spring to oilseed rape in Britain.

The proportion of crops treated with a fungicide in autumn increased from the mid 1990s to 2000s. During this period, crop survey data indicate a higher incidence of phoma leaf spot in the autumn but a fall in light leaf spot incidence in the spring. Since then autumn fungicide use has remained high, and average levels of phoma leaf spot and stem canker have fallen, but the incidence of light leaf spot has risen. By 2002 use of fungicides at flowering had fallen to half of its 1994 level. This trend was reversed from 2004 due to sclerotinia concerns, improving prices and availability of new fungicides. With substantial variation, opposing disease trends and gaps in survey data it is not possible to reliably estimate the overall impact of disease on the national yield trend, but it is thought to have accounted for a small net yield decline from 1984 to 1994 and a small net yield improvement from 2004. Yield impacts over time of verticillium wilt and clubroot are also unknown.

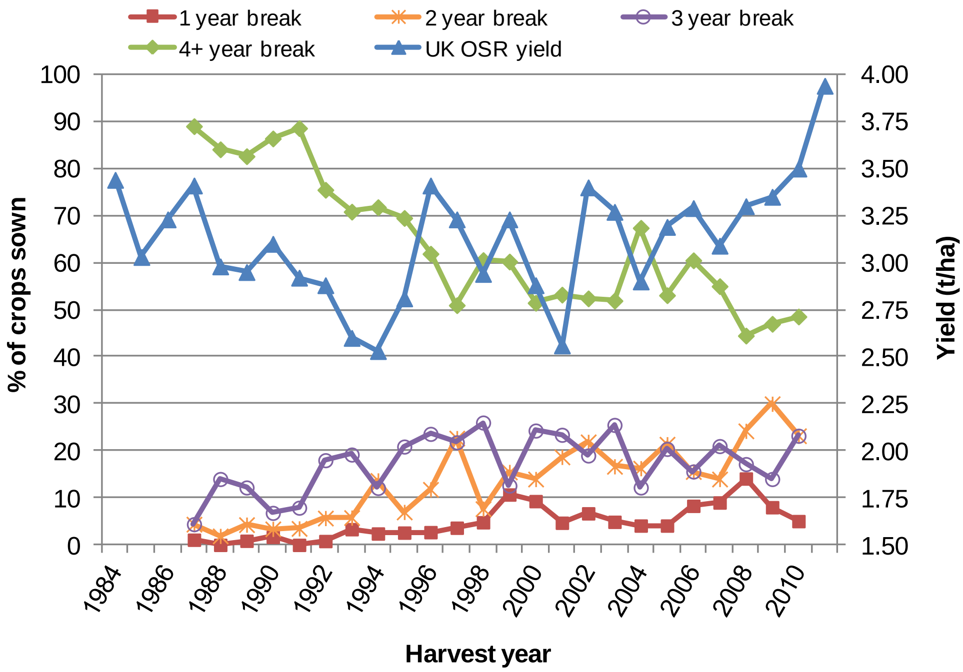
With potential to reduce yields by up to 26%, the effects of Turnip Yellows Virus (TuYV) may have had an impact on the national trend for oilseed rape. The annual occurrence of aphids causing TuYV is variable, but there is little evidence to suggest an increase. From 1987 to 1997 autumn insecticide use increased erratically from less than 10% of crops treated to around 70%. From the 1990s to mid 2000s there were similarities in the patterns of annual insecticide use and national yield. The increasing use of insecticidal seed treatments since 2002 may have diminished this.

Survey data indicate that from 1988 to 2006 the number of pollen beetles in farm crops averaged below 5 per plant in nearly all years. There is no indication of a rising trend in beetle numbers over that period, but despite this an increasing proportion of crops have received an insecticide spray at flowering since 2002. Although pollen beetle damage will account for some yield loss in some crops, if anything this is likely to have decreased. Wood pigeon numbers have nearly trebled since the mid 1970s, but the level of impact on national oilseed rape yields is not known.

Only two weed species, chickweed and black-grass, are estimated to cause annual yield losses of 0.5% or more with current herbicide treatments. Survey data show a rising number of herbicide applications, and a doubling of the number of active ingredients applied, from 1998 to 2008. Although black-grass has become more difficult to control, it is unlikely that this would have had a significant direct impact on national yields. Other management changes aimed at maintaining or improving grass weed control may have had an incidental effect. Farm Business Survey data show that farms in the top quartile for yield are spending more per hectare on pesticides than farms in the bottom quartile. The gap between top and bottom has increased from 15% in 2004/05 to 25% in 2008/09. Expenditure on pesticides was less for oilseed rape than for wheat in 2004/05, but is similar in 2008/09, suggesting that investment in oilseed rape has increased more than in wheat.

Although comparisons are limited by a lack of UK data, reduced tillage may have had more impact on oilseed rape than on wheat. Average yield reductions relative to ploughing of 9% and 5% have been recorded for shallow and deep non-inversion respectively in one experiment, but these have not been consistent. On farm there was an initial shift from ploughing to autocasting or shallow non-inversion. Although saving cost, conserving moisture and potentially improving black-grass control, it is likely that this had a detrimental effect on yields. More recently deep tine systems that give a greater degree of spoil loosening have become common, along with direct drilling. The net yield impact is unclear. Although it cannot be quantified with certainty, the shift to non-inversion is estimated to have reduced overall yield improvement by 0.006 t/ha per year from 1994 to 2010.

Survey data highlight a decrease in the proportion of oilseed rape crops sown after a break of 4 or more years, with a rise in crops sown after a break of 2 or 3 years (Summary Figure 7). Data from a recent 8-year field experiment in the UK, in which a range of crop sequences involving oilseed rape and wheat were evaluated, have led to yield loss estimates of 3%, 6%, and 12% for oilseed rape crops with a break of 3 years, 2 years or 1 year respectively, compared to a break of 4 or more years. These could underestimate the yield loss for short rotations maintained over a longer period. The resulting reduction in national yields is estimated to have risen by 0.004 t/ha per year.



Summary Figure 7. Proportion of oilseed rape crops in England sown after a 1, 2, 3 or 4+ year break.

4.4. Key Factors Influencing Oilseed Rape Yield Trend

Key factors that have contributed to the UK oilseed rape yield trend from 1984 to 2011 are shown in Summary Table 3. They are split into three phases, defined by falling yields until 1994, variable yields from 1994 to 2004 and rising yields since 2004. Yield potential has continued to benefit from genetic improvement, but from 1984 to 2004 poor uptake of high-yielding varieties that were less attractive to grow meant that on farm over half of this was not being deployed. Factors for which it has been possible to reliably estimate their effects account for most but not all of the trends in yield in each phase. In addition to weather patterns, a number of variables are highlighted as potentially having had an influence. From 1984 to 1994, increased varietal susceptibility to lodging, rising numbers of pigeons and relatively high levels of TuYV may have contributed to the remaining yield decline of 0.027 t/ha per year. From 2004 factors that may have contributed positively include increased use of insecticidal seed treatments and the effects of lower seed rates and fungicides with growth regulatory activity on management of the crop canopy and lodging control. The overall positive impact of these may be larger than the 0.015 t/ha per year indicated, as at the same time factors such as soil compaction and soil-borne diseases may have had a negative effect on yields.

Period	1984-1994	1994-2004	2004-2011
	Yield gain + or loss - with estimate of t/ha per year. 0 neutral, ( ) uncertain		
Farm Yield	-0.040	+0.022	+0.075
Genetic potential	+0.048	+0.048	+0.048
Variety choice	-0.031	-0.038	+0.014
Spring OSR area	-0.009	-0.003	+0.008
Agronomic effects			
Nutrition N Nutrition S	-0.02 (-)	0 +0.027	0 0
Crop Protection	(-)	0	(+)
Rotation	-0.004	-0.004	
Cultivation	+0.003	-0.006	
Weather and/or other factors	-0.027	-0.002	+0.015

Summary Table 3. Factors contributing to the national oilseed rape yield trend from 1984 to 2011.

4.5. Opportunities for Overcoming Agronomic Limitations to Yield

Variety Selection

The Recommended Lists provide robust, comparative information on the yield potential of varieties and their agronomic characteristics. But the challenge facing growers is to select varieties that are appropriate for their farm and to optimise their management. More information (site characteristics, local environment or farming system) is needed to help match varieties to specific farm situations, to demonstrate how varieties that offer a step forward in yield can be grown profitability on farm.

Nutrient Supply

To respond to higher yield potential and support rising yield trends, the extent to which N supply limits current yields of oilseed rape and wheat must be reduced. There is a likely to be a case for increasing the amounts of N fertiliser applied to some crops but, with economic and environmental constraints to consider, part of the answer must be to focus on N use efficiency. Plant breeding and fertiliser technology are important, but agronomy also has a role to play, by creating conditions that will maximise N uptake by the crop. For S nutrition, more could be done to ensure that all crops at risk of deficiency, or likely to give a yield response, are identified and receive S fertiliser.

Rotations

The increase in break crops and decrease in successive wheats contributed significantly to wheat yield improvement prior to 1996. However, there is evidence that the rise in oilseed rape cropping frequency is limiting oilseed rape yields. About half of the English oilseed rape crop is grown with a break of four or more years. If this proportion declines further, and the incidence of soil borne threats increases, the yield effects could be significant, especially on large farms growing wheat and oilseed rape only. Efforts must continue to address these threats, and wider rotations may form part of the solution. It is recognised that most rotations will continue to be driven by overall profitability rather than the yield potential of individual crops.

Crop Protection

Crop protection metrics indicate no reduction in robustness over the last 30 years. Breeders have improved pest and disease resistance, uptake of new chemistry has been good, and numbers of active ingredients applied and application rounds have risen. There is little evidence that a general increase in pesticide use is needed to remove yield restrictions, although inadequate control of weeds, pests or diseases will still limit yields in challenging seasons and situations. Efforts should be focused on the threat posed by pathogen evolution, pesticide resistance and a likely decline in number of modes of action to our ability to sustain rising yields in future. Good agronomy relies on a combination of chemical and cultural control measures. Although well publicised for weeds and diseases, this may become more important for insect pests and nematodes. More should be done to evaluate and demonstrate the benefits of combining chemical and non-chemical control.

Sowing Date

Earlier sowing of wheat is potentially a key measure to reduce the impact of weather-related yield limitations, notably to lessen the effects of spring / summer droughts that have occurred in several recent seasons. Wheat sowing dates have been advancing over the last 3 decades. Trials indicate this has contributed positively to the national yield trend. Early sowing is not without problems, such as lodging, grass weeds and elevated pest and disease threats. Some could be overcome by adjusting crop protection strategies, but even so it will not be the right strategy for every grower to improve yield and won't be of benefit in every year. Lighter soils most at risk from drought are less affected by black-grass and are the main target for earlier sowing. Changes to rotations may be needed to avoid late sowing, following late-harvested root crops with a spring crop instead of winter wheat. This particularly applies where soil conditions are poor, as it risks compounding drought risk with compaction, although spring crops themselves can be compromised by drought.

Soil Management and Cultivations

Soil management may have suffered through change being driven by what is technically possible and economically attractive rather than agronomically appropriate. New cultivation equipment and drills have saved time and fuel, and delivered effective establishment. However, the industry has been on a learning curve, during which yields may have suffered in the short term. There has been little emphasis on soil management studies, undertaken and interpreted in the context of today's production systems. The trend towards heavier machinery is a particular concern. The extent and impact of soil compaction at or below sub-soiling depth needs to be quantified, along with the state of UK soils in terms of other measures such as under-drainage and organic matter content.

Management Intensity

As fields and farms have increased in size, and growers have sought to simplify their management through block cropping, there is a risk that the husbandry applied to individual fields may become less well matched to their specific needs. However, Farm Business Survey data indicate that yield improvement is not necessarily compromised on farms that are growing a larger area of a crop, and that this may in part be due to greater investment in labour and machinery. 'Attention to detail', 'getting everything right' and 'continuing improvement' were articulated by practitioners as vital to achieving positive yield trends on individual farms. Approaches to this have included:

- Involvement in grower groups that seek out and share knowledge;
- Engaging the whole farm team in understanding crop performance;
- Investment in training, more effective machinery or technology to capture / analyse information;
- Making more use of agronomists or specialist advisors to help improve the farming system.

A number of precision farming techniques also have the potential to help deliver better targeting of agronomy, facilitating attention to detail while improving the outputs from labour and machinery.

4.6. Barriers to Overcoming Agronomic Limitations to Yield

Environmental constraints and tensions

Although soil processes that influence greenhouse gas (GHG) emissions are recognised, less is known about the relative contribution of crop management factors. Emissions are most likely to be reduced by a combination of increased crop N use efficiency and the avoidance of husbandry practices associated with significant nitrous oxide (N_2O) losses. Emissions of N_2O and carbon dioxide (CO_2) from soils are highly variable. Both soil management and crop species influence N_2O emissions. The overall impact of min-till or no-till on emissions needs to be considered in relation to soil type and structure. Under min-till systems the emission of CO_2 from fuel usage is reduced. Fuel consumption under no-till is invariably less than under ploughing though the difference will depend on the soil type, the depth of cultivation and the requirement for secondary cultivations.
Earlier sown wheat crops should on average have a larger biomass going into the winter, and will have taken up slightly more residual N from the soil (though this effect is much greater with oilseed rape). As a

consequence there may be a small reduction in leaching risk, especially on lighter soils for which earlier drilling is of greater benefit. It is likely that earlier sowing and the potential for larger crop canopies or earlier closure would reduce growth of spring-germinating weed species, which may have a negative effect on the diversity of arable plants and associated invertebrates, and reduce feed and access for ground-foraging or ground-nesting birds. This probable tension requires further specific consideration. In addition, the likely increase in pest and disease risk may have implications for autumn pesticide usage (notably seed treatments).

Legislative constraints

Regulations for Nitrate Vulnerable Zones (NVZs) establish a limit on the amount of N that can be applied to crops. Current limits for wheat and oilseed rape allow for additional N to be applied where expected yields exceed the standards assumed (8.0 t/ha and 3.5 t/ha respectively). If it can be shown that yield potential is higher, current regulations should not be a barrier to increasing N supply to support higher yields. However, any reduction in limits could constrain yields in future. A number of important pesticides have been lost in recent years, or are under threat, as a result of changing European legislation. The Water Framework Directive, Drinking Water Directive, Sustainable Use Directive and the adoption of hazard-based criteria for approvals may have implications for pesticide use in significant areas of the UK. Withdrawal of pesticides not only reduces opportunities to control pests, weeds or diseases but places extra pressure on those that remain available. In some cases this may increase their chance or level of detection in water or the risk of resistance development through over-dependence on the same mode of action for control. An integrated approach to crop protection regulation is essential to maintain yield improvement, including timely approval of new active ingredients to replace the loss of existing ones.

Uptake of technologies

On the whole, the application of technological developments does not appear to have been much of a constraint. However, the ability to exploit genetic potential at a whole field or farm level, rather than simply at the small plot scale at which progress is currently assessed, appears to be a barrier. Trial yields may be achieved at a relatively high input level and cost, which if transferred to farms may incur additional or undesirable environmental or economic costs. The extent to which, in the future, new plant breeding technologies, including genetic modification, might aid the realisation of improved yield potential on farm through novel solutions to current limitations could be important.

4.7. Quality and End Use Considerations

For wheat and oilseed rape a case has been made for increasing the supply of N and potentially the area receiving S. Increasing N dose or S application should not reduce feed wheat grain quality, and for breadmaking may improve the chance of meeting the required specification. High starch and low protein grain is preferred for bioethanol, so avoiding overuse of N may become vital as it accounts for about 70% of the GHG emissions from wheat production. For oilseed rape the % oil content of the seed decreases with increasing N dose but oil yield and gross output are still improved. Increasing N may also have an adverse effect on oil quality through an increase in seed chlorophyll concentration in some circumstances. In contrast applying S on a deficient site can increase % oil content and lead to an overall decrease in seed chlorophyll concentration. A small increase in glucosinolate content may occur with higher N doses or S application but this is unlikely to be sufficiently large to affect suitability of the meal for inclusion in non-ruminant livestock rations.

5. Conclusions and Recommendations

No single agronomic factor has had a clear dominant influence on trends in UK wheat or oilseed rape yields over the last 30 years. A proportion of the lost yield improvement remains unexplained, with aspects of climate change being amongst the likely causes. Plant breeding has continued to deliver genetic improvement in both crops, but until recently uptake of higher-yielding oilseed rape varieties on farm was relatively poor. Weather patterns have had an impact, but appear to have acted in varying and opposite directions for wheat and oilseed rape. Apart from 1980 to 1996 in wheat, alterations to agronomic practices have had a number of mainly small effects. Some of these have been driven by prices or policies, with growers seeking to maximise profit rather than yield. To restore rising yields in the face of warmer conditions, potentially more extreme weather, economic or environmental pressures and evolving weed, pest or disease threats, there is a need for some changes to farming systems, with a longer-term and more holistic approach to agronomy.

Short term: Getting the most from current technology

Short-term opportunities to raise farm yields involve additional knowledge transfer to address apparent shortcomings in agronomic practice. Not all growers will benefit, as many will already be employing best practice, but they may provide quick wins for others to improve crop performance.

1. Building on 'RL Plus', the outputs of the RL variety evaluation system should be supplemented by additional information, including potential interactions with soil conditions, fertility, rotation, crop environment and local climate, to guide variety selection for specific situations, recognising that limitations to performance may differ under challenging and varied farm conditions. This is both a knowledge transfer need and a gap in the current variety evaluation system.

2. Achievement of higher farm yields may require a less conservative approach to variety selection and management. Ease of harvesting and avoidance of lodging are understandable reasons why growers may reject higher-yielding varieties or hold back on seed rate and N use. Better tools and information to aid forecasting, monitoring and management of growth and lodging risk are needed, for example the use of canopy sensing technologies to target PGR treatments.

3. Various HGCA projects have studied aspects of crop husbandry that are relevant to early sown wheat crops. Key messages from these should be reviewed and brought together in a suitable format to inform best practice for the management of early sown wheat crops.

4. The proportion of wheat and oilseed rape crops currently treated with inorganic S fertilisers (40% and 60% respectively) equates to little more than that at high risk of deficiency. Although some will be receiving S in other forms *e.g.* organic manures, there is likely to be an area of crop, especially oilseed rape, at medium risk that isn't being treated. Updated advice on areas of the UK in which crops are at medium or high risk, and likely to respond to treatment, should be made available.

5. About 20% of soil samples tested are below the target P index for arable cropping, with 30% below the target K index. Although there is no evidence that this has contributed to yield stagnation or that the proportion of sites below target is increasing, with negative net budgets for P and K and off-take proportional to yield, there is a risk that this may change. Current soil testing technology should be checked for its effectiveness in modern arable conditions and further knowledge transfer is needed to reaffirm the benefits of regular soil testing, to ensure effective targeting of fertilisers to fields where yield is at risk, and to avoid low P or K indices becoming a yield limitation in future.

6. This study has highlighted the consequences of responding too late to pesticide resistance. In the case of septoria in the late 1990s, fungicide doses declined on the back of low crop prices and more expensive new fungicides, with little priority given to managing risk or robustness of control. With fungicide sensitivity a continuing issue for septoria and light leaf spot, the ongoing problem of resistant black-grass and emerging problems of resistant aphids and pollen beetles, it is essential to maximise awareness of risks and practical implications, especially how to manage resistance through changes to control strategy and the integration of chemical and cultural control measures.

7. While not always within a grower's control, timeliness is undoubtedly pivotal in the effectiveness of certain operations and inputs. Agronomy information tends to focus on comparison of products, doses or techniques, but the implications of mistiming for yield should be made equally accessible.

Short to medium term: Areas of uncertainty

1. A number of factors have been identified that may be having a negative impact on national yields, but for which information is lacking on their incidence or importance. Many are being investigated but more could be done to raise awareness or widen engagement in addressing the problem.

2. The extent to which changes in weather patterns / climate have contributed to yield trends in wheat and oilseed rape over the last 3 decades requires a dedicated investigation and analysis, including the use of suitable crop models, which was outside the scope of this study.

3. Reducing the extent to which N supply limits current yields of oilseed rape and wheat is vital to support a rising yield trend, but applying more N fertiliser is not sustainable because pollution risks and GHG emissions may increase even if efficiency of use could be maintained. Further studies are needed to show how fertiliser technology or agronomy can impact on or improve fertiliser efficiency,

including interactions with soil management and rooting.

4. It is unclear whether or not plant breeding has led to increased N use efficiency in modern oilseed rape varieties, or if they require more N. The extent to which current fertiliser N doses and timing are sufficient to realise the yield potential of varieties being grown needs to be clarified

5. There is a need to raise awareness and further evaluate the contribution of pollination to yield in oilseed rape. Operation Pollinator (http://www.operationpollinator.com/) is addressing this, but the extent to which this is a determinant of oilseed rape yields may be underrated. There is a potential 'win-win' by addressing the challenge of simultaneously raising productivity and environmental benefits, which could be achieved practically through greater use of pollen & nectar margins combined with crop management that takes more account of the value of insect pollination.

6. There is a critical knowledge gap with regard to the state and health of UK soils and implications for yield, including the incidence and severity of compaction at and below sub-soiling depth, the maintenance of under-drainage systems and variation or trends in soil organic matter levels.

7. Further evaluation of the incidence (location/season) of nematodes in wheat and oilseed rape is needed to understand their potential impact on crop performance, including the effects of weather, soil type, rotations and cultivations, and the implications for variety selection or plant breeding.

8. Further evaluation of short- and long-term yield implications for wheat and oilseed rape of the move from ploughing to non-inversion cultivation is needed. A recent study has indicated that penalties may be associated with the initial transition but it is unclear if this is just a first year affect, an unavoidable consequence or due to poor management of the transition phase. It could have particular importance for farms that use rotational ploughing as part of a cultural control strategy for grass weeds. New HGCA-funded projects on soil management may help to address this.
9. There appears to be little independent information on the extent of secondary (Mg) or trace element (Mn, B, Mo) deficiencies in oilseed rape, or on likely yield responses to their application. A full review of existing knowledge, and new data from field experiments to fill any gaps, are needed.

Medium term: Changing approach

Constraints to yield improvement have altered over time, often as a consequence of changes to cropping in response to prices or policies rather than for agronomic reasons. In some cases there may have been a price to pay in the long term for profitability in the short term. A new approach is needed to assessing and improving the longer-term performance, output and resilience of farming systems, while maintaining flexibility to respond quickly to emerging threats and new solutions.

1. Farm Business Survey data has highlighted the divergence in yield trends between farms in the top and bottom yield quartiles. Farm benchmarking is justifiably focused on financial performance, but more could be made of the data gathered in understanding differences between farms in their yield or yield trends. This could provide useful indicators of potential limiting or derestricting factors.

2. Information, tools and advice are needed to help growers 'health check' their farming system and to encourage a longer-term approach to cropping and crop management strategy. This goes beyond conventional benchmarking and includes the likely impacts of rotation, cultivation and soil management strategy on current and future yield potential, productivity and the vulnerabilities or robustness of the farming system.

3. Precision farming techniques and technologies have the potential to improve the timeliness and targeting of inputs or operations, and to help maintain attention to detail as farms get larger. However, they also need to be more practical and accessible for small or medium-sized farms.

Long term: Preparing for the future

This study has focused primarily on looking back in order to identify some of the factors that have contributed to the failure of farm wheat and oilseed rape yields to show consistent improvement. It is vital that there is also now a focus on future yield potential, from genetic, climatic and agronomic perspectives, so that the industry is better prepared.

1. Data on farm practice, from national statistics or surveys such as CropMonitor, are invaluable as

indicators of change. But there is information that is not being collected that would be useful, and other data lacks sufficient definition to fully characterise change. This would include variety choice and establishment method for oilseed rape, more precise information on cultivation type and depth for wheat, seed rates, weed incidence and a more universal survey of soil and crop nutrient status. This is vital for monitoring shifts in practice, to help anticipate effects or constraints on crop performance.

2. Although this study did not examine the specific impact of changing climate, there is evidence in both wheat and oilseed rape of positive and negative impacts from higher temperatures and drier springs. These have been linked to wheat yield stagnation in Europe, and are a potential threat to our ability to raise UK yields in future. Breeding and selection of varieties suited to changing and varying environmental conditions around the UK remain an important priority.

More information is available in the annexes, including a full technical report.

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9. This section should be used to record links (hypertext links where possible) or references to other published material generated by, or relating to this project.

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