REPORT ON ECONOMIC, FINANCIAL AND MARKET STUDIES TO DEMONSTRATE THE ECONOMIC VALUE OF RESEARCH CARRIED OUT BY ROTHAMSTED RESEARCH.

Topic No 1 – Agrochemical Resistance

Fungicides in combinable crops in the UK

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1. EXECUTIVE SUMMARY

1.1. Main conclusions

(i) Rothamsted Research (RRes) is a not-for-profit organisation sponsored by the Biotechnology and Biological Research Council (BBSRC) . The BBSRC are part of Research Councils UK (RCUK) who manage R&D investment for the UK Government. RRes has been asked by RCUK to demonstrate the value of its research and its economic impact. In turn RRes commissioned Innovation Management (an independent consultancy) to evaluate the economic benefits arising from the Institute's research work. A series of projects were agreed as suitable areas for evaluation with the first topic being resistance to agrochemical treatments of fungicides, herbicides and insecticides.

(ii) The development of resistance to agrochemicals is an international problem that affects all classes of active ingredients and all major crops. The regular use of crop protection chemicals can lead to the target organisms (fungi, weeds and insect pests) becoming resistant. This can result in significant yield losses and even crop failures. In the UK the principal crop is cereals with 2.1 million hectares of winter wheat and 1.0 million hectares of barley grown for a variety of end-uses.

(iii) Fungicide resistance is an important factor in the successful cultivation of cereals in the UK (and in other countries of Northern Europe ie: France and Germany). It is estimated that the UK market for fungicides in cereals is around £200 million with winter wheat the main component (£150 million).

(iv) Fungicides are used against several diseases with the major disease of winter wheat being *Septoria tritici*. It is estimated that virtually 100% of UK wheat is treated with fungicides against this disease. Other wheat diseases include Powdery Mildew, Rusts and Tan Spot. In barley the key diseases include *Rhyncosporium,* Powdery Mildew, Net Blotch and Rusts.

(v) Several different chemical classes of fungicides are used in UK cereals. The main product categories are sterol biosynthesis inhibitors (SBIs which include the triazoles) and the Quinone outside Inhibitors (aka strobilurins or QoIs). Other commonly used groups include the chloronitriles (chlorothalonil), anilinopyrimidines and the recently introduced carboxamides (SDHIs), along with several classes of mildew fungicides.

(vi) In winter wheat complete control of *Septoria* is not possible. This is not because of fungicide resistance but reflects the difficulties in crop management. Inclement weather conditions can result in the inappropriate timing of treatment, which together with inappropriate product choice for the disease complex and inappropriate dose results in a residual effect of *Septoria* on crop yield. It can be calculated that this results in an underlying annual loss to UK cereal growers of around £43 to 53 million (the calculation reflects the crop yields and cereal prices in any given year).

(vii) The average response of crop varieties to fungicide use is around 20 per cent yield improvement. Thus without fungicide use UK cereal growers would suffer an economic loss of between £380 to £465 million each year (with the range again reflecting cereal prices and yields).

(viii) The Oil Seed Rape (OSR) fungicide market is valued at £30 million in the UK, with the main area of disease problems being Northern England and Scotland. Light Leaf Spot is resistant to some classes of fungicides. Other key diseases are Downy Mildew, *Alternaria* and *Phoma.* The most important group of fungicides used in OSR are the triazoles and their continued use is threatened by the forthcoming European legislation (EC/91/414). If the triazoles were removed from the OSR market then it is predicted that this would result in the loss of winter OSR in Scotland with a consequent significant effect on the farming practices in the country.

(ix) RRes has played a key role in the successful management of fungicide resistance. This is acknowledged by the crop protection industry who have a co-ordinated response to the problem based upon the work undertaken by RRes. The agrochemical manufacturers have stated that 'RRes are influential in setting a strategy for the successful management of fungicide resistance'. This strategy is followed by crop advisers, distributors and crop consultants and leads to 'reduced risk recommendations' which help to sustain the commercial life of the current products.

(x) At present it costs around £200 million and takes more than ten years to develop and introduce new crop protection products so it is essential that current products are used wisely. This enables UK farmers to have sustainable crop management tools in order to produce high quality cereal grains for UK consumers.

1.2. Economic comparisons

RRes activities	**Market place impact**	
14 Research projects over 9 years Total investment of £2.4 million Up to 40% of EU independent research effort Key provider for policy reports and pivotal in steering resistance strategy	On national economics	Protecting UK cereal market value – up to £ 2 billion per year Minimising losses from *Septoria* in wheat – already at around £50 million per year, potentially over £400 million Protecting losses in barley and OSR diseases Supporting UK fungicide market – cereals at £190 million and OSR: £30 million
	On policy	Guidelines for mandatory strobilurin strategy Recommendations on mixtures
	To rest of EU	Important contributor to same parameters in northern EU countries - Fivefold or more total market size

1.3. Pointers for the future

Drivers for change	Potential responses from RRes
Greater emphasis on UK and EU food security Potential withdrawal of triazoles New fungicide chemistry imminent Emergence of new disease threats and evolution of existing pathogens	Greater understanding of genetics and molecular biology of resistance mechanisms Molecular diagnostics for early warning of resistance development Improved risk assessment translating into guidance on doses, timings, mixtures etc. Improved KT pathway through partnerships with industry, independent advisors and farmers

2. BACKGROUND AND PROJECT OBJECTIVES

2.1. Background and overall objectives

This is the first of several studies to be carried out with the objective of establishing a methodology and reporting format which can be applied to a range of different topics. Rothamsted Research, RRes, have earned an international reputation for work carried out on agrochemical resistance monitoring procedures and mechanisms. This first report covers fungicide resistance. Herbicide resistance and insecticide resistance will be addressed subsequently.

The overall objectives from the accumulation of these studies is to assist Rothamsted Research to be able to:

- Report on the **economic, societal and environmental** impact of current research
- **Define a methodology** for assessing the impact of these factors on future research
- Provide the basis for helping BBSRC and Government to **develop UK agricultural research policy,** including the risks associated with neglecting strategic areas

The potential measurable benefits are numerous and will vary in importance from topic to topic. They will include:

- Patentable discoveries
- Applied Knowledge – transferable to UK agriculture
- Applied Knowledge – transferable to world and developing countries' agriculture
- Responses to potential future developments and risks in agriculture and food supply
- Support for agricultural and land use policy development at national and EU level
- Providing a vehicle for training and research expertise
- Specific outputs from Rothamsted Research: International reputation, multidisciplinary activities

Specific requirements set by RRes Management were that the studies should:

- Be based on methodologies demonstrating benefits from specific research as well as contributing to potential over-arching market place impact
- Be of value for external use eg. BBSRC, as well as the basis of a useful tool for internal use in helping to prioritise future research
- Be based on robust conclusions with documented data sources
- Cover historical (up to 30 years), immediate past and current research
- Measure the relative value of RRes research in the particular field using a scoring system based on citations of publications

- Establish a methodology which in outline will work for all project areas while retaining a degree of flexibility

2.2. Objectives specific to fungicide resistance

The evolution of strains of fungal diseases, that are resistant to commercially used fungicides, has been rapid and potentially of critical economic importance to farmers, the grain supply and export trade and to the agrochemical industry. Rothamsted Research has been at the forefront of fundamental and applied research aiming to understand and therefore influence resistance strategies in the UK. In addition the work has provided support to similar activities in Northern Europe.

The objective of this study is to report on the risks associated with fungicide resistance, measured in terms of economics, at farm level and industry level. Against this an assessment will be made on the relative contribution that Rothamsted Research has made in the past, is continuing to make and will need to consider for the future.

The specific areas to be covered are diseases of wheat: Mildew and *Septoria*; diseases of barley: Net blotch and *Rhynchosporium* and light leaf spot in Oilseed rape

3. METHODOLOGY

Collection of information was executed under two broad headings: External and Internal.

Statistical and technical information was acquired through literature and internet searches. The sources are quoted throughout the report but important published data was obtained from:

Defra
FAO
J Nix handbook
CSL arable crop surveys
HGCA Crop Monitor
FRAC reports
FRAG UK reports
Pesticide Guide
ECPA/Croplife
CPA
Phillips McDougall

A number of important references were supplied by Bill Clark, Brooms Barn, who also kindly supplied access to previous economic studies.

Face to face interviews were carried out with managers responsible for fungicide resistance strategies in Syngenta, BASF and Bayer CropScience. The managers were all very supportive and open with the nature of the information supplied.

Internal data on the costs of Rothamsted projects and an analysis of the press coverage attributed to Rothamsted Research was provided by Susannah Bolton.

4. EXTERNALLY SOURCED INFORMATION

4.1. Crop statistics

(i) Areas and yields

Wheat remains the most important crop in the UK. .

Table 4.1. Production of combinable crops in the UK - 2008

Crop	Area	Yield	Total production
Source: Defra crop survey 2008	Million hectares	Tonnes/ha	Million Tonnes
Wheat	2.08	8.3	17.23
Winter barley	0.42	6.7	2.80
Spring barley	0.62	5.4	3.48
Oats	0.14	5.8	0.78
Oilseed Rape	0.60	3.3	1.97

Average yields are high compared with the EU as a whole (Table 4.2). Yields of cereals exceeded those in France and Germany in 2007 (Table 4.3). Yields of oil seed rape were marginally lower than those in Germany but exceeded those in France

Table 4.2. Production of combinable crops in the European Union - 2007

Crop	Area	Yield	Total production
Source: FAOstat 2007	Million hectares	Tonnes/ha	Million Tonnes
Wheat	24.81	4.88	121.0
Barley	13.72	4.27	58.5
Oilseed rape	6.53	2.80	18.3

Table 4.3. UK Yields compared with France and Germany - 2007

Crop	Yields: Tonnes/ha		
Source: FAOstat 2007	UK	France	Germany
Wheat	7.34	6.25	7.11
Barley	5.82	5.60	5.71
Oilseed rape	3.10	2.89	3.44

(ii) Crop economics

The value of cereals to the UK economy is considerable. In 2007 cereals ex-farm value was estimated at £1.91 billion. This represented around 12% of the country's total agricultural output at £15.72 billion. The equivalent figures in 2006 were £1.51 billion,10% of the total of £14.50 billion. A recent characteristic of the cereal grain, and oil seed, market is the volatility of prices. Thus in 2008 there will have been a substantial increase in the total value based largely on escalated prices. In 2009 a decline in total value can be predicted as global wheat prices have declined and planted areas were reduced due to weather factors. Source: Defra quick stats 2007

The average gross margin achieved from the main cereal crops and oil seed rape are similar. Milling wheat is generally the most profitable. It can also be seen from Table 4.4 that agrochemicals represent a significant part of the cost of growing the crops.

Table 4.4. UK Production economics of cereals and oil seed rape crops – 2008

Source: J Nix Handbook 2009	Variable costs £/ha		Outputs £/ha	
	Agrochemicals	Total	Return	Gross margin
Milling Wheat – Winter	143	551	1110	559
Malting Barley - Winter - Spring	109 79	370 314	834 788	463 474
Oilseed Rape – Winter	118	465	975	510

Based on the figures in tables 4.1 and 4.4 the total ex farm value of oil seed rape is around £ 5-600 million.

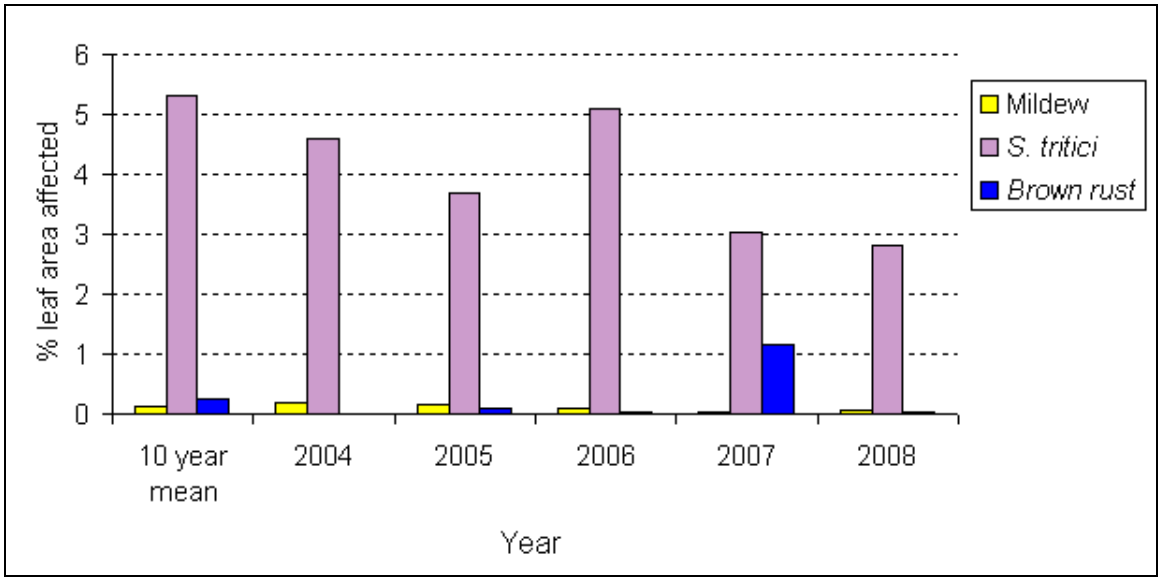
4.2. Disease Incidence

Crops grown in the United Kingdom, due to its maritime climate, are particularly vulnerable to fungal diseases. Only Ireland has greater disease pressure.

HGCA support an annual Crop Monitor based on the sampling of disease incidence in crops. This is executed by Central Science Laboratory (now re named FERA). The following charts are based on the 2008 survey.

Septoria tritici is the most common foliar disease of winter wheat, affecting 84% of samples in 2008. This is despite the fact that extensive fungicide programmes are adopted.

Figure 4. 1 Disease incidence in Winter Wheat



Survey data on barley is less frequently available. However in 2005 incidence of *Rhynchosporium* was the lowest recorded since 1995, continuing the gradual decline in severity evident since 2000. Net blotch *(Pyrenophora teres)* levels were higher than in any year since 2000 but still well below the 10-year average. In the case of barley the combination of disease resistant varieties and universal application of fungicides has resulted in relatively low incidence of disease.

Table 4.5 Disease incidence in Winter Barley

National foliar and stem base disease levels (GS 71-73)

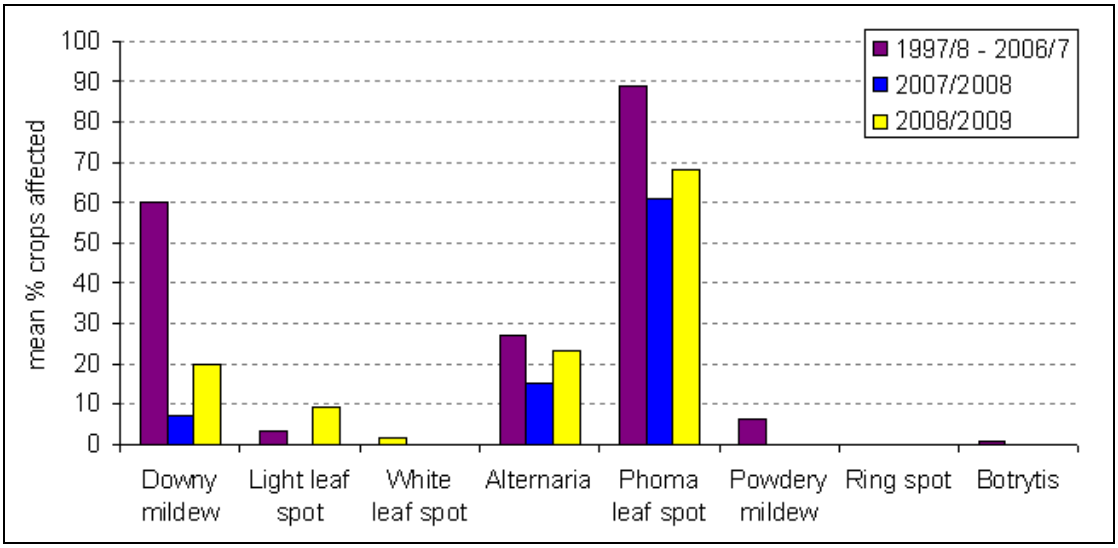
Disease	10-year mean (1995-2004)	2003	2004	2005 *
Powdery mildew	0.7	0.4	0.7	0.4
Brown rust	1.0	0.3	0.2	0.2
Rhynchosporium	2.8	2.7	1.6	0.7
Net blotch	1.6	0.2	0.8	0.8
Eyespot	7.1	2.8	3.2	5.5

Foliar diseases - percentage area of leaf 2 affected
Stem base diseases - percentage stems with moderate or severe lesions

According to Crop Monitor data, *Phoma,* Downy Mildew and *Alternaria* are the most important foliar diseases of oil seed rape.

Figure 4. 2 Foliar disease incidence in Oil seed rape

(Incidence of diseases on the leaf)



Sclerotinia stem rot (*Sclerotinia sclerotiorum*) is also a common and potentially damaging disease in oilseed rape. Defra surveys in England (HGCA, 2004) have shown an average incidence of stem rot of 2-4% in winter oilseed rape. This equates to a 1-2% yield loss. A few crops suffer severe attacks every year. More widespread epidemics can occur, given favourable weather.

4.3. Fungicide markets

(i) Value to industry

The market for fungicides is second only in importance to herbicides globally.
The UK market for fungicides is approximately 10% of the total EU market.

Table 4.6. Fungicide market values - ex industry level 2007

Region	Annual sales value	Currency conversion rates
World	£ 5.30 billion (US $ 8.0 billion)	£1.0 = $ 1.51
EU	£ 1.92 billion	£1.0 = € 1.11
UK	£ 180 million	£1.0 = € 1.11

Sources: ECPA 2007 data, Phillips McDougall 2007 data

(ii) Value at farm level

The annual expenditure at farm level on fungicides for the main combinable crops is reported in table 4.7. below.

Table 4.7. Annual fungicide expenditure at user level in the UK

Region	2008 harvest year
Wheat	£ 150 million
Barley	£ 40 million
Oil seed rape	£ 30 million

Source: Agrochemical Industry survey data 2008

2008 usage was higher than average due to the exceptionally high cereal prices for the season.

(iii) Extent of use of fungicides

Virtually all of the crop area receives fungicide treatments and the vast majority of crops receive multiple applications.

Table 4.8. Per cent of crops treated and number of applications - 2008

Crop	Per cent area treated	Average number of applications
Wheat	95.5	3.0
Winter barley	98	2.0
Spring barley	89	1.8
Oil seed rape	94	2.1

Source: Agrochemical Industry survey data 2008

The trend has been continually upwards. The HGCA Crop Monitor data for winter wheat is broadly in line with the industry data and shows a steady increase in the number of applications.

Number of applications	2008	3.2
	2007	3.0
	2006	2.7
	2005	2.8

Weather conditions and the incidence or not of brown rust may be the cause of annual variations in the frequency of treatments.

4.4. Fungicide products

A wide range of products are marketed in a highly competitive environment. For the purposes of this study it is not necessary to itemise each product or to present market shares. Nonetheless in studying the impact of resistance it is important to categorise the types of product available by chemical grouping or mode of action. The leading products relevant to each crop are also listed.

(i) Fungicide categories

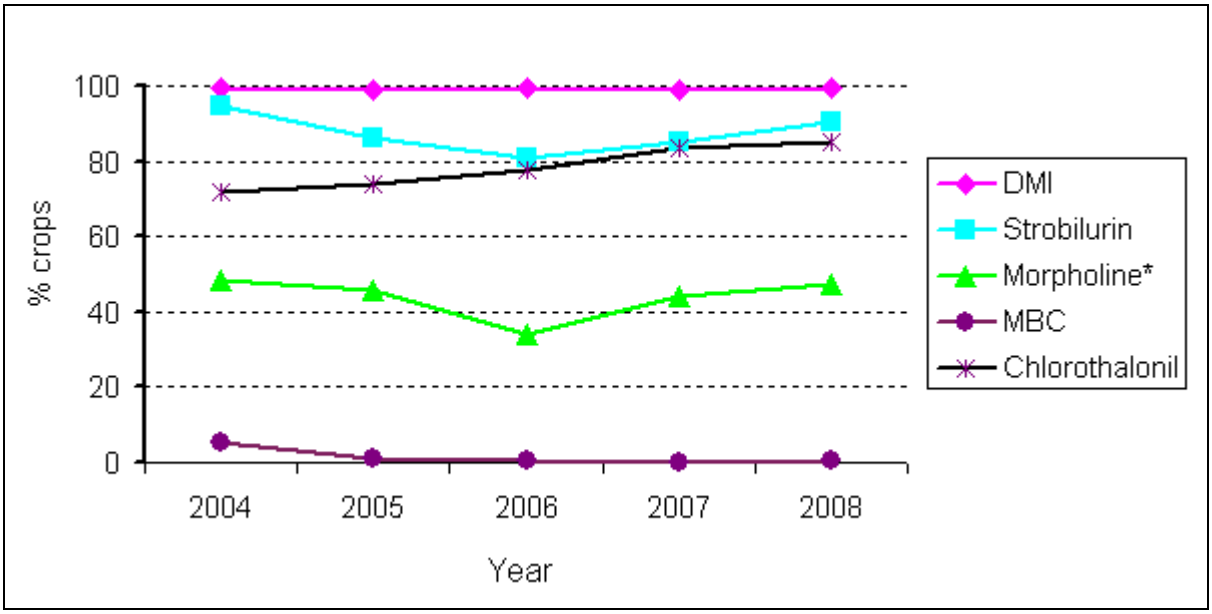
The main categories of foliar fungicide used on cereals in the UK are listed

Fungicide group	Chemical families	Examples
DMI - fungicides (Demethylation inhibitors) Sterol biosynthesis inhibitors, SBI – class I	Triazoles Imidazoles	Prothioconazole (Proline) Tebuconazole (Folicur) Epoxiconazole (Opus)
Amines “Morpholines”. SBI – class II	Morpholines	Fenpropimorph (Corbel)
QoI – fungicides (Quinone outside inhibitors)	Strobilurins	Azoxystrobin (Amistar) Pyraclostrobin (Vivid)
Chloronitriles	Phthalonitriles	Chlorothalonil (Bravo)

(ii) Fungicides used

Figure 4.3 shows how each category of these categories of fungicides are universally used. DMI fungicides being adopted 100%.

Figure 4.3 Per cent of treated wheat crops receiving applications from the major fungicide groups



Source: CSI Crop Monitor 2008

Another source from industry shows the development by product type. The relative decline of strobilurins since 2001/2002 was reversed in 2007/8 due to the high incidence of rusts.

Table 4.8. Annual fungicide expenditure on wheat by product type in the UK

Fungicide type	2007/2008		2005/2006		2001/2002	
	Value (£)	% of total	Value (£)	% of total	Value (£)	% of total
Strobilurins	73,975,099	30%	55,091,302	32%	85,248,600	51%
Triazoles	119,249,654	49%	93,129,571	54%	45,306,032	27%
Chlorothalonil	13,421,681	5%	10,606,519	6%	3,537,530	2%
Others	38,086,590	16%	13,898,338	8%	33,836,272	20%
Total	**244,733,024**		**172,725,730**		**167,928,434**	

Source: Agrochemical Industry survey data 2009

Table 4.9 Leading wheat fungicide product shares Source: CSL arable crop survey 2006

Active ingredient	Brands	Hectares treated - million
Chlorothalonil	eg Syngenta, Bravo	1.79
Epoxiconazole	eg BASF, Opus	1 .11
Prothioconazole/tebuconazole	Bayer, Prosaro	0.53
Prothioconazole	Bayer, Proline	0.45
Pyraclostrobin	eg BASF, Comet	0.41

Table 4.10 Leading winter barley fungicide product shares Source: CSL arable crop survey 2006

Active ingredient	Brands	Hectares treated - million
Fluoxastrobin/ Prothioconazole	Bayer, Fandango	1.79
Chlorothalonil	eg Syngenta, Bravo	0.15

93% of treated crops received at least one application of a DMI fungicide.

Table 4.11 Leading spring barley fungicide product shares Source: CSL arable crop survey 2006

Active ingredient	Brands	Hectares treated - million
Chlorothalonil	eg Syngenta, Bravo	0.19
Fluoxastrobin/ Prothioconazole	Bayer, Fandango	0.12

Table 4.12 Leading oil seed rape fungicide product shares Source: CSL arable crop survey 2006

Active ingredient	Brands	Hectares treated - million
Metconazole	BASF, Caramba	0.24
Carbendazim/ Flusilazole	Du Pont, Harvesan	0.13
Flusilazole	Du Pont, Capitan, Genie	0.13
Boscalid	BASF, Filan	0.12
Carbendazim	Various	0.10 m

4.5 Fungicide Resistance

Resistance occurs when a pathogen becomes so insensitive to a fungicide that the performance is impaired. Resistance can be rapid so that control is lost in a single step. More commonly resistance develops gradually with the pathogen becoming progressively less sensitive and generally there is no initial detectable loss of control (Clark, 2008)

(i) UK History of fungicide resistance

The pattern of the development of resistance to fungicides used for important cereal diseases in the UK was described by (Lucas, 2006)

Table 4.13 Cereal fungicide resistance chronology in the UK

Year recorded	Fungicide group	Disease
1982	DMI	Powdery mildew
1994	Morpholine	Powdery mildew
2000	QoI (Strobilurins)	Wheat powdery mildew
2002	QoI (Strobilurins)	Septoria

The most significant development has been the rapid spread of *Septoria* resistance to strobilurin, first observed in Ireland and UK in 2002 and spreading to other European countries thereafter.

There is also increasing evidence of DMI, triazole, resistance for the control of Septoria. Field performance has been good provided appropriate timings and doses were adopted.

Barley disease control with strobilurins has also deteriorated. The first to demonstrate resistance was powdery mildew with no control where resistance occurred, then net blotch with weaker control in some cases and then *Ramularia.* The first record of strobilurin resistance to *Rhynchosporium* has now been recorded in France. (Oxley, 2009)

Light leaf spot, which is a disease of oilseed rape occurring mainly in Northern Britain, has demonstrated resistance to benzimidazole fungicides.

A major outcome of the increased incidence of resistance has been the development of detailed resistance strategies co-ordinated by the Fungicide Resistance Action Group (FRAG) UK. FRAG is a technical working party that comprises both industry and

independent specialists. A number of guidelines are offered in terms of doses, mixture policy and how many applications of a particular chemical group should be made.

The first and most significant step was to limit the number of strobilurins to two per season. This was a policy set out by PSD. During 2003 there was considerable debate on whether the use of strobilurins should be discontinued completely. However their value in the control of Brown Rust and their contribution to yield enhancement due to the greening effect has resulted in their expanded use (Figure 4.3)

(ii) Benefits from managing fungicide resistance

Important factors related to successfully managing fungicide resistance can be defined as applied to different parts of the supply chain:.

(a) To the farmer

-increased yields
-improved quality of outputs
-phytosanitary effects especially good neighbours ?
-improved crop management
-improved cultivars and plant breeding targets

(b) To the agrochemical industry

-ROI improved
-product life extended
-opportunity for novel mixtures and co-formulations
-increased appetite for NPD investment
-cash flow
-PR and agrochemical image enhanced
-wealth creation

(c) To the grain processors

- less wastage
-improved factory operations (mills/bakery/brewers)
- better quality outputs

For the future

Promoting the benefits of better fungicide resistance strategies offers:

-better agronomy
-better awareness across cereal industry
-Government awareness of farming value to UK economy
-improved sprayers and application?

(iii) Measuring the economic importance of fungicide resistance

(a) To the farmer

Losses of yield were recorded in Ireland in 2003, however yield loss in the UK specifically due to strobilurin failure is not measurable – mainly because the policies and strategies adopted have sustained the yield levels.

Putting a value to successful fungicide resistance management is therefore best achieved by recording the consequences of yield loss, and other costs, that would be lost if widespread resistance occurred.

Septoria is by far the most economically significant cereal disease, consequently it is this disease that calculations are based on.

There are three factors to consider:

The following calculations are based on estimates and methods kindly supplied by Bill Clark together with data collected through interviews with agrochemical industry managers

- **Existing yield loss due to *Septoria tritici***

Despite the fact that diseases resistant varieties are grown, and that fungicide usage is universal, yield losses can be attributed to *Septoria.*

The annual Crop Monitor data records the per cent of *Septoria* recorded on leaf 2.
A proven formula converts this to estimated yield loss by multiplying by a factor of 0.42 (provided the incidence levels are within a range of 0-45%)

During the period 1998-2008 the average septoria incidence was 5.3%. Which equates to a yield loss of (5.3 x0.42) = 2.23%

National wheat crop yield in 2008 = 17.23 million tonnes production (Table on 4.1.)

If all the Septoria had been controlled then the average yield would have been 8.49 tonnes/ha and total and production would have been 17.62 million tonnes. A recovered loss of 393,000 Tonnes.

Based on a range of ex-farm prices of wheat £110 - 135/tonne this equates to:
£43 - 53 million

This loss is due to a number of factors:

- poor application timing due to adverse weather
- poor product choice or
- wrong dose (too low).

The effect of inferior fungicide performance due to resistance will also be a contributing factor.

- **Yield losses if no effective fungicides used**

In the national variety trials the average response of wheat varieties to fungicide use is around 20% (UK HGCA CEL trials).

On this basis, UK yields would be reduced by 20% from 8.3 t/ha to 6.65 t/ha, if no fungicides were used or fungicides were no longer effective.

From a total production of 17.23 million tonnes of wheat this represents a loss of **3.45 million** tonnes down to 13.78 million tonnes.

At a wheat prices of £110 – 135/tonne this equates to: **£380 - 465 million**

- **Fungicide costs**

Most wheat crops get on average, 3 fungicide sprays, containing 5.5 products (containing 7.5 active ingredients). This is equivalent to 2.5 full label doses of product. (2006 Pesticide usage survey).
On the basis of an 'average' full dose fungicide cost at £20/ha, 2.5 full label doses will equate to £50/ha. On 2 million hectares, that is equivalent to applying **£100 million/year** in fungicide applications.

This compares with agrochemical industry data (Table 4.7) for the value of the wheat fungicide market, at user level, of **£150 million** in 2008.

(b) To the agrochemical industry and the supply chain

In assessing the "cost" of fungicide resistance to the industry it is difficult to apportion resistance management as a finite activity. It is clear however that resistance management is now an integral part of the cost of new product development, product stewardship and the regulatory process. This applies at the national level, affecting development and marketing activities in the UK, and other EU countries. Considerable resistance monitoring and research studies are also carried out at the companies' central research laboratories.

A number of areas were considered in the discussions with agrochemical industry managers and in some cases a financial estimate has been possible.

Table 4.14 Impact of fungicide resistance on agrochemical industry activities

Activity	Impact
Monitoring for resistance	A major effort executed at European level – applied to both established and new compounds, as laboratory bioassay of field samples. An industry funded pan European survey is currently underway to assess resistance issues amongst growers
Field development	Continued modification of recommendations, timings, doses, mixtures – both initiated on own findings and reactive to policy. In some cases individual companies may benefit from enhanced sales of products in mixtures. A significant proportion fungicide development costs can now be attributed to resistance management
Registration processes	Now a mandatory to present resistance risk data and management strategy for any new product.
Product withdrawal	Potentially a major cost where resistance brings about a precipitate end to a product. A new global compound discovery and development cost is estimated to be £ 200-300 million. Commercial pay back may not be positive until 6-7 years from launch. Thus removal before then, because of resistance, is a major cost to the industry. An example was trifloxystrobin.
Communication	Although communication to dealers, advisors and to a lesser extent, farmers is carried out, this is generally part of a general marketing programme. Reference to resistance management may be beneficial and enhance the company's reputation.

4.6. Agrochemical Industry perspectives on Rothamsted

In the discussions with the agrochemical managers opinions were sought on the relevance of Rothamsted Research to fungicide resistance management. Some of the statements made were as follows:

- We need a UK Institute like Rothamsted conducting excellent science in this area .
- Rothamsted has a pivotal role in drawing together all the different strands of work on fungicide resistance .
- Rothamsted is absolutely critical to the management of fungicide resistance and it would be very sad if such an organisation were not there .
- Rothamsted is influential in setting a strategy for the management of fungicide resistance, which the agrochemical companies are obliged to follow .

- The work of Rothamsted means crop advisers and consultants can achieve reduced risk recommendations which help to sustain the commercial life of the current fungicide products .

- Although a UK Institute, Rothamsted messages are taken-up and utilised across Europe .

- Rothamsted's work helps agrochemical companies to have a co-ordinated response to fungicide resistance and keeps the different companies in line with a consensus of advice to growers thus avoiding any polarised views .

- There is no immediate impact on the direction of the agrochemical manufacturers R&D, but Rothamsted is seen as strongly complementary to technical support allowing an integrated message to be put across to farmers and growers .

- The work undertaken by Rothamsted enables the agrochemical manufacturers to constantly re-focus their technical support, which is vital because of the dynamics of fungal strains .

- Because Rothamsted has had such a significant impact on the management of fungicide resistance, then other factors will drive the market in the future .

There were differences in emphasis between companies, depending to some extent on the level of internal resource applied to resistance monitoring and management. However there was a consistent message of support.

The value of Rothamsted as an independent organisation acting as a co-ordinator of resistance policy amongst companies who are otherwise competitors was cited as a benefit.

Looking to the future there was a call for more on-going work on mixture recommendations and timings. The pending arrival of a new group of carboximide fungicides from at least two companies will call for additional attention in resistance management.

More fundamentally, the need for clear communication to the agricultural industry as a whole was called for. This has however to be backed by thorough and well funded research.

5. INTERNALLY SOURCED INFORMATION

5.1. Projects and costs (Provided by Susannah Bolton)

Scientific research projects	**Completed**	**Cost £**
2001 - Evolution of *Rhynchosporium* resistance	On going	62,500
4333 – wheat mildew resistance to strobilurins	2002	159,000
4437 – identification of fungicide resistance markers in *Rhynchosporium*	2004	18,000
4550 – providing scientific basis for avoiding fungicide resistance	2005	381,000
4679 – understanding fungicide mixtures to minimise resistance shift in *Rhynchosporium*	2008	40,000
4750 – triazole sensitivity in *Septoria* populations	2008	18,000
4844 – understanding resistance of light leaf spot in OSR	On going	31,000
4849 – understanding evolution and selection of azole resistance mechanisms in UK populations of Mycosphaerella	On going	425.873
4906 – impact of mutations in the target encoding gene for triazole resistance to *Septoria*	On going	281,000
4907 – relationship between varietal and fungicide resistance to *Rhynchosporium*	On going	37,000
4924 – underpinning regulatory decisions on fungicide resistance risk assessment	On going	188,000
4925 – effects of azole based spray programmes for *Septoria* control	On going	20,000
4931 – determination of sensitivity of European fields isolates of *Septoria* to a DAS fungicide	On going	49,000
4965 - understanding evolution and dynamics of resistance in cereals	On going	1,158,373
Policy papers and committee work		
HGCA report FRAG reports	2006	
Total Expenditure		2,442,873

5.2. Publications from RRes research (Provided by Susannah Bolton**)**

Selected peer-reviewed publications since 2000

Bean, TP; Cools, HJ; Lucas, JA; Hawkins, ND; Ward, JL; Shaw, MW; Fraaije, BA, 2009. Sterol content analysis suggests altered eburicol 14α-demethylase (CYP51) activity in isolates of *Mycosphaerella graminicola* adapted to azole fungicides. *FEMS Microbial letter* (currently on-line)

Cools, HJ; Fraaije, BA; 2008. Are azole fungicides losing ground against Septoria wheat disease? Resistance mechanisms in *Mycosphaerella graminicola. Pest Management Science* **64**, 681-684

Cools, HJ; Fraaije; BA, Bean; TP, Antoniw; J, Lucas, JA; 2007. Transcriptome profiling of the response of *Mycosphaerella graminicola* isolates to an azole fungicide using cDNA microarrays. *Molecular Plant Pathology* **8** 639-651

Fraaije, BA; Cools, HJ, Kim, SH; Motteram, J; Clark, WS; Lucas, JA 2007. A novel substitution I381V in the sterol 14 alpha-demethylase (CYP51) of *Mycosphaerella graminicola* is differentially selected by azole fungicides. *Molecular Plant Pathology* **8** 245- 254

Bearchell, SJ; Fraaije, BA; Shaw, MW; Fitt, BDL 2005. Wheat archive links long-term fungal pathogen population dynamics to air pollution. *Proceedings of The National Academy of Sciences USA* **102** 5438-5442

Fraaije, BA; Cools, HJ; Fountaine, J; Lovell, DJ; Motteram, J; West, JS; Lucas, JA 2005. Role of ascospores in further spread of QoI-resistant cytochrome b alleles (G143A) in field populations of *Mycosphaerella graminicola. Phytopathology* **95** 933-941

McCartney, HA; Foster, SJ; Fraaije, BA; Ward,E 2003. Molecular diagnostics for fungal plant pathogens. *Pest Management Science* **59** 129-142

Fraaije, BA; Lucas, JA; Clark, WS; Burnett, FJ 2003. QoI resistance development in populations of cereal pathogens in the UK. *BCPC International Congress Crop Science & Technology, Congress Proceedings* **1 and 2** 689-644

Fraaije, BA; Butters, JA; Coelho, JM; Jones, DR; Hollomon, DW 2002. Following the dynamics of strobilurin resistance in *Blumeria graminis* f.sp *tritici* using quantitative allele-specific real-time PCR measurements with the fluorescent dye SYBR Green I. *Plant Pathology* **51** 45-54

Dyer, PS; Hansen, J; Delaney, A; Lucas, JA 2000. Genetic control of resistance to the sterol 14 alpha-demethylase inhibitor prochloraz in the cereal eyespot pathogen *Tapesia yallundae*. *Applied and Environmental Microbiology* **66** 4599-4604.

(i) Public press coverage on Rothamsted research into resistance

Search topic and author	Number of articles All Countries (%)	Number of articles UK (%)
Septoria	2812	
Septoria + Resistance	1094 (100)	407 (100)
Septoria + Resistance + *Clark*	76 (6.9)	52 (13)
Septoria + Resistance + *Lucas*	16 (1.5)	9 (2.2)
Septoria + Resistance + *Fraaije*	2 (0.2)	2 (0.5)
Septoria + Resistance + *Cools*	1 (0.1)	1 (0.25)
Strobilurin + Septoria + Resistance	407 (100)	113
Strobilurin + Septoria + Resistance + *Rothamsted*	16 (4)	5 (4.4)
Strobilurin + Septoria + Resistance + *Clark*	52 (13)	13 (11.5)
Strobilurin + Septoria + Resistance + *Lucas*	9 (2)	1 (0.9)
Strobilurin + Septoria + Resistance + *Fraaije*	2 (0.5)	1 (0.9)
Strobilurin + Septoria + Resistance + *Cools*	1 (0.25)	1 (0.9)

(ii) Media articles - searched through Google News

Search topic	Number of articles	(%)
Septoria	1970	-
Septoria + Resistance	776	100
Septoria + Resistance + *Clark*	77	9.9
Septoria + Resistance + *Lucas*	10	1.3
Septoria + Resistance + *Fraaije*	3	0.4
Septoria + Resistance + *Cools*	2	0.3
Strobilurin + Septoria + Resistance	388	100
Strobilurin + Septoria + Resistance + *Clark*	57	15
Strobilurin + Septoria + Resistance + *Lucas*	9	2.3
Strobilurin + Septoria + Resistance + *Fraaije*	2	0.5
Strobilurin + Septoria + Resistance+ *Cools*	1	0.25

(iii) Rothamsted activities as a proportion of independent research

Based on our discussions it is clear that as an independent Public Sector research Institute Rothamsted holds an eminent position in the field of research into fungicide resistance relevant to combinable crops in Europe. The other centre which features is INRA in France with smaller activities in Scandinavia and Germany.

Agrochemical company research scientists operating in European R & D central laboratories welcome the direct contact with Rothamsted scientists.

Amongst the Independent centres we would put Rothamsted's activities as at least 33-40% of the total effort.

This of course is outside of the in - company effort which is substantial.

6.0 SWOT ANALYSIS (Strengths, Weaknesses, Opportunities, Threats)

The key conclusions from the study are reported in the Executive summary

A SWOT analysis has been carried out looking at Rothamsted's position in the fungicide resistance sector:

Strengths

-expertise, facilities, science networks
-biological awareness/integrated approaches (viz genes to crops)
- UK based where disease incidence is high
-multifunctional Know How
-reputation
-trust
-independence

Weaknesses

-unpredictable nature of disease outbreaks
-reluctance of farmers to accept advice
-disagreement about 'best practice'
-abuse/misuse of advice
-attitude of organic farmers ?
- not seen as effective communicators to farmers and growers

Opportunities

-'sell' expertise via consultancy projects
-predict next resistance problem
-greater risk of resistance due to loss of triazoles through EC 91/414 legislation at EU level
-robust practical advice package
-continual updating of agronomy as circumstances change in a dynamic marketplace
-across industry linkage
-across Institutes links
-develop into EU wide approach

Threats

-new fungal pathogens/superbugs
-loss of synthetic chemicals through EC 91/414 legislation at EU level
-organic farming involvement
-withdrawal of agrochemical manufacturers from UK/EU markets

7. POINTERS FOR THE FUTURE

Several significant issues emerge from this review that can be seen as critical for the future. These include:

- The need to maintain an integrated approach involving RRes, the UK agrochemical industry and funding bodies such as Defra and HGCA. This will become increasingly important, even more so due to:
    - The potential removal of fungicide groups such as triazoles as a consequence of EC 91/414 legislation which will increase the risk of resistance problems developing more rapidly and widely
    - The pending arrival of fungicides based on new chemistry
- The economic benefit to the UK is extremely valuable (estimated at around £350 – 500 million per year)
- Other cereal and OSR growing countries benefit considerably from the work of RRes
- Consideration should be given to an increase in manpower in this area of R& D as RRes together with INRA, France, represent the only significant independent research centres supporting farmers and growers
- RRes has already considerably influenced policy regarding fungicide resistance management (notably the fact that PSD have limited the number of times that certain chemical classes can be used in a growing season) and the need to provide on-going support for policy decisions, for the benefit of UK agriculture and industry will continue.
- Efficient and reliable cereal, and OSR, production is essential to the UK and elsewhere in Europe and will become even more critical as food security issues gain importance. RRes effort on fungicide resistance management will be important in sustaining its contribution towards the value and quality of grain and the products derived from it in the retail trade.

8. REFERENCES

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