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Abstract and Summary

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Fungicide doses in sequences and mixtures for winter wheat

by

Stuart Knight[1], Jonathan Blake[2], Simon Oxley[3] and David Parsons[4]

[1]The Arable Group, The Old Rectory, Morley, Wymondham, Norfolk, NR18 9DB

[2]ADAS Rosemaund, Preston Wynne, Hereford, HR1 3PG

[3]SAC, West Mains Road, Edinburgh, EH9 3JG

[4]Cranfield University, Cranfield, Bedford, MK43 0AL

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Abstract

The performance of individual fungicides applied as single sprays to control foliar diseases in winter wheat has been evaluated in HGCA-funded research since 1994. A new project was commissioned to add information on the effects of using a sequence of two sprays or a mixture of two or more products, with the aim of establishing principles by which farmers could develop effective programmes from HGCA fungicide performance data. The project focused on control of *Septoria tritici* [(1)], and the impact of mixtures on the dose-response of the triazole fungicide Opus (epoxiconazole). Field experiments were conducted on three varieties representing a range of susceptibilities to septoria, and at four locations over a three year period, to give a range of disease pressures. The main treatments compared single sprays (at GS39) against 2-spray programmes (at GS32 and GS39), and Opus applied alone against mixtures with Bravo (chlorothalonil) or Bravo plus the strobilurin Vivid (pyraclostrobin).

In 2005 and 2006 septoria was the main disease present and the major influence on green leaf area and grain yield. Adding Bravo to a 2-spray Opus programme reduced the dose of triazole needed to obtain equal control of septoria, often by 50% or more, allowing optimum yields to be obtained at 15-30% lower doses of Opus and improving margins. Even when mixed with Bravo, optimum triazole (Opus) doses were 45-65% higher for the most compared to the least septoria-susceptible variety, and 40-60% higher under medium-high than under low septoria pressure. In 2007 yellow or brown rust were present as well as septoria at all locations, and in some cases these had an equal or greater influence on yield. The strobilurin Vivid was of more benefit than Bravo as a partner to control rusts. Adding Vivid, as well as Bravo, resulted in up to 70% lower optimum Opus doses whilst maintaining or improving margins.

Raising the grain price from £80 to £160/t increased the optimum dose of Opus by 25-30%. However, a range of doses would have given margins close to the optimum, and applying a dose slightly above the expected optimum would allow for application delays or higher than expected disease pressure. Early septoria progress, as indicated by within-season disease monitoring experiments, did not correlate well with end of season septoria levels or fungicide responsiveness. The Wheat Disease Manager computer programme, designed to predict yield response to fungicides from information available at the time of treatment, and a mixture calculator that was created to combine dose-response curves for disease for two individual fungicide active ingredients and produce a value for the mixture, both gave promising results.

[(1)] Most recent scientific name is *Mycosphaerella graminicola*

Summary

Introduction

The performance of individual fungicides in winter wheat, applied as single sprays, has been evaluated in HGCA-funded research since 1994. The experiments have allowed comparative dose-response curves to be produced for a range of fungicides, and for the control of the major foliar diseases. Using epoxiconazole (Opus) as an example, the research indicated a downward shift in the performance of triazole fungicides against *Septoria tritici* [(1)] between 1995 and 2005, and this has provided a compelling argument for the use of robust doses on farm to maintain disease control.

In practice the majority of wheat crops receive more than one fungicide spray, with each application consisting of a mixture of at least two products. A new project was commissioned to add information on the effects of using a sequence of two sprays, or a mixture of two or more products, on dose response curves for disease, green leaf area and yield, with the aim of establishing principles by which farmers could develop fungicide programmes in winter wheat from HGCA fungicide performance information. Due to its importance as the most widespread and damaging foliar disease of wheat in the UK, and the decline in performance of the major fungicide group (triazoles) used against it, control of septoria was the main focus of the project.

An additional limitation of the existing HGCA research was that fungicide performance was being evaluated on very susceptible varieties and in high disease risk locations. This ensures a stringent test, and enables potentially small differences in fungicide performance to be detected. In practice a range of varieties are present on farm, and not all of these are highly disease susceptible or grown in high risk areas. The ubiquitous nature of septoria and relative stability of varietal resistance mean that this disease most lends itself to adjusting fungicide dose (rather than fungicide choice). However there was a need for information to support decisions on the appropriate size of the adjustment in dose to account for varietal susceptibility and disease pressure.

The number of potential combinations is such that it would clearly not be possible to determine experimentally the dose response implications of all possible fungicide sequence and mixtures and for every disease. Therefore, the project also provided an opportunity to look at how closely the relative disease control and yield performance of mixtures and sequences could be predicted using computer programmes.

[(1)] Most recent scientific name is *Mycosphaerella graminicola*

Field Experimentation: Materials and Methods

Field experiments were conducted at three locations in England (in Herefordshire, Hampshire and Norfolk) and one in Scotland (Borders) in three successive seasons from 2004/05 to 2006/07. The experiments examined the impact of using sequences and mixtures of fungicides (compared to single sprays) on the dose response of Opus (125 g/l epoxiconazole, BASF) for foliar disease control, preservation of green leaf area, grain yield and margin. The treatment groups and Opus doses used are outlined in Table 1. The mixture partners used were Bravo 500 (500 g/l chlorothalonil, Syngenta Crop Protection), which has primarily protectant activity against septoria, and Vivid (250 g/l pyraclostrobin, BASF), which has good activity against rusts but like all strobilurins now has very limited septoria activity due to resistance. The mixture partners were included at fixed doses of 1.0 l/ha for Bravo and 0.5 l/ha for Vivid at both T1 and T2 (equivalent to a half dose at each timing). Treatments were applied in 200-220 l/ha water as a medium-fine spray, using conventional flat fan nozzles.

Table 1. Treatment groups, application timings and doses

Treatment Group	T1 Spray (GS32, leaf 3)	Opus doses (l/ha)	T2 Spray (GS39, flag lf)	Opus doses (l/ha)
untreated	none	-	none	-
single-spray Opus	none	-	Opus alone	0.25, 0.5, 1.0, 2.0
two-spray Opus	Opus alone	0.15, 0.3, 0.6, 1.2	Opus alone	0.25, 0.5, 1.0, 2.0
two-spray Opus + Bravo	Opus + Bravo 500	0.15, 0.3, 0.6, 1.2	Opus + Bravo 500	0.25, 0.5, 1.0, 2.0
two-spray Opus + Bravo + Vivid	Opus + Bravo 500 + Vivid	0.15, 0.3, 0.6, 1.2	Opus + Bravo 500 + Vivid	0.25, 0.5, 1.0, 2.0

At each location experiments were conducted on three varieties representing a range of susceptibilities to *S. tritici*, indicated by their resistance ratings to septoria on the HGCA Recommended List for Winter Wheat. These were Consort, most susceptible and rated 4, Einstein, intermediate and rated 5, and Robigus, least susceptible and rated 7. At all sites, treatments were evaluated using a randomised block design, in separate but adjacent trials for each variety. The main assessments and measurements were:

- foliar disease (% leaf area affected) and green leaf area by leaf layer on up to four occasions, with the main assessment at between GS69 and GS80.
- grain yield and specific weight

Results from individual experiments were analysed statistically by ANOVA, and used to fit exponential dose response curves. Margins, defined here as output value (yield x grain price) less the fungicide chemical costs (not including application costs), were calculated from the fitted yield curves using the following prices: grain £120/t (except where stated otherwise), Opus £26/litre, Bravo 500 £4.50/litre and Vivid £26/litre.

Field Experimentation: Results

In 2005 and 2006 the major pathogen present at all sites was *S. tritici*, and control of septoria was therefore the main foliar disease influence on green leaf area and grain yield. In 2007, yellow rust or brown rust were present at all locations, in addition to septoria. In a number of cases, control of rusts was an equal or greater influence on green leaf area and grain yield, and this was taken into account when selecting which yield and green leaf area results to combine when summarising performance.

Disease Control: *Septoria tritici*

Septoria levels varied between sites and seasons, from less than 10% to more than 75% on leaf 2 of the untreated for Consort, and from less than 5% to more than 25% on leaf 2 for Robigus. In some experiments a two-spray Opus programme resulted in better overall control of septoria on the top two or three final leaf layers than for the same total dose of Opus applied as a single spray. However in a number of cases there was no benefit to splitting the same dose between two sprays rather than one, especially where the total Opus dose applied was 0.5 l/ha or less. In seven out of eight experiments, adding Bravo substantially reduced the amount of Opus needed to get equal control of septoria on the final two or three leaf layers, compared to a two-spray Opus programme alone (Table 2).

Table 2. Reduction in the total dose of Opus needed to achieve the same level of septoria control, as a result of adding Bravo to a two-spray Opus programme. (Based on a comparison of the doses required to give an average 75% control compared to the untreated on the top 2-4 leaf layers at the final assessment timing).

Experiment(s)	% reduction in Opus dose required as a result of adding Bravo			
	Consort		Robigus	
	Mean	Range	Mean	Range
7 Site Mean excl. Herefordshire 2006	56%	12-70%	78%	69-90%
Herefordshire 2006	no reduction	-	no reduction	-

Adding Vivid as well as Bravo had little additional effect on septoria control. The exception was Herefordshire in 2006, where the addition of Bravo (only) to a two-spray Opus programme did not improve septoria control. There was however a small benefit where both Bravo and Vivid were added. The most likely explanation for this is wet weather that caused high infection pressure prior to application of the T2 sprays, resulting in high eradicant (triazole) requirement.

Disease Control: Brown Rust and Yellow Rust

In 2007, following a mild winter and unusually warm spring, brown rust was present in wheat crops across much of England, from an early stage. In these experiments, the disease was a particular problem on Consort and Robigus in Norfolk and on Einstein in Hampshire, but it did not appear until late in the season in Herefordshire. Conversely, yellow rust was the major problem on Robigus in the Borders. The addition of Bravo to a two-spray Opus sequence rarely improved brown rust control compared to the same dose of Opus applied alone. However, adding Vivid as well as Bravo to Opus generally resulted in an increase in brown rust control for the same dose of the triazole (Table 3).

Table 3. Reduction in the dose of Opus needed to achieve the same level of brown rust control, as a result of adding Bravo or Bravo + Vivid to a two-spray Opus programme. (Based on a comparison of the doses required to give 90% control compared to the untreated on the flag leaf and leaf 2 at the final assessment timing, mean of 4 trials).

% reduction in total dose of Opus required as a result of adding partner(s)			
Bravo		Bravo + Vivid	
Mean	Range	Mean	Range
2%	0-55	45%	0-87

In one trial, the addition of Bravo to a two-spray programme with Opus did not benefit the control of yellow rust compared to Opus alone. The addition of Vivid + Bravo did improve control compared to Opus + Bravo, but was no better than Opus alone.

Disease Control: Green Leaf Area

In 2005 and 2006, when septoria was the dominant disease, the amount of green leaf area remaining on the top three leaves at the final assessment timing mirrored the control of septoria achieved for each fungicide treatment. The addition of Bravo to a two-spray Opus programme therefore substantially increased the amount of green leaf compared to Opus alone, except Herefordshire in 2006 when the main improvement to leaf area was obtained where Bravo and Vivid, rather than Bravo only, were added. In 2007, in situations where brown rust and septoria were of equal significance, both Bravo and Vivid contributed to an increase in green leaf area compared to Opus alone. However, where brown rust or yellow rust were dominant, only where Vivid was added as well as Bravo was there an increase in green leaf area.

Grain Yield and Quality

The effects of Opus dose and fungicide treatment were mostly similar between sites and seasons in the first two years. At total Opus doses of 0.5-1.0 l/ha or less, there was often little yield difference between single and two-spray programmes that had received the same amount of triazole. In a two-spray programme, addition of Bravo substantially increased yield compared to the same total dose of Opus alone on all varieties. The yield difference decreased with increasing Opus dose. The addition of Vivid as well as Bravo gave a further small yield benefit, which often decreased only marginally at higher Opus doses. Herefordshire in 2006 was different, with a more obvious yield advantage from a two-spray Opus programme compared to a single spray, a smaller yield benefit from adding Bravo and a larger improvement from the addition of Vivid as well as Bravo, which decreased rapidly with increasing Opus dose.

The effects of fungicide treatment on the response of grain yield to Opus dose varied between experiments in 2007. There were some similarities between sites on Consort. When compared with the same total dose of Opus alone in two-spray programmes, the addition of Vivid as well as Bravo gave a larger yield benefit than just adding Bravo. In all cases the yield advantage over Opus alone decreased with increasing Opus dose, although in Hampshire, Herefordshire and Norfolk there was a yield benefit to the inclusion of Vivid (plus Bravo) up to the highest Opus dose evaluated.

Grain specific weight data were collected for most of the experiments. In a number of cases differences between treatments were fairly small and not statistically significant, especially for Einstein and Robigus. Where there were treatment effects, these showed very strong similarities to the effects of fungicide treatment on grain yield.

Margin

Optimum Opus doses for each of the two-spray fungicide treatments, and the margins achieved at those doses, are summarised below in Table 4 for Consort and Robigus in

2005 and 2006 (when septoria was the dominant disease). Only six of the eight experiment are included, as yield data for the Borders site were vary variable due to flooding in 2005 and responses to fungicide dose were erratic in 2006. The addition of Bravo to a two-spray Opus programme gave a higher margin and at a lower optimum dose of Opus. The addition of Vivid as well as Bravo further reduced the optimum Opus dose, but the highest margin achieved was similar to Opus + Bravo. On Consort the optimum Opus dose for the Opus-only two-spray treatment was above the maximum permitted total dose in two sprays (2.0 l/ha). The optimum Opus dose for the Opus + Bravo treatments was only just within this limit. On Robigus all treatments had an optimum Opus dose well within the maximum permitted in two sprays.

Of the six experiments, three had relatively low septoria pressure and three had medium-high disease pressure. For Consort, optimum Opus doses were about 40% higher in the medium-high than in the low disease pressure experiments, for each treatment group. For Robigus, optimum Opus doses were about 60% higher in the medium-high than in the low disease pressure experiments. As a consequence, optimum Opus doses (in mixtures) were about 65% higher on Consort than on Robigus in the low disease pressure experiments, but only about 45% higher on Consort than on Robigus in the medium-high disease pressure experiments.

Table 4. Effect of fungicide treatment, variety and disease pressure on optimum dose of Opus in two-spray programmes (mean of 6 experiments from 2005 and 2006: 3 with medium-high and 3 with relatively low septoria pressure).

Fungicide Treatment Group	Optimum Opus dose l/ha in two-spray programmes (and margin £/ha achieved at optimum dose)					
	Consort			Robigus		
	6 Site mean	3 Site (med-high)	3 Site (low)	6 Site mean	3 Site (med-high)	3 Site (low)
Opus two-spray	2.8 (1139)	3.2+	2.3	1.4 (1213)	1.8	1.1
Opus + Bravo	1.9 (1166)	2.2	1.6	1.2 (1237)	1.5	0.9
Opus + Bravo + Vivid	1.4 (1167)	1.6	1.1	0.9 (1240)	1.1	0.7

For the Opus + Bravo treatment, an analysis was done to identify the range of Opus doses that would have given a margin within £2/ha of that achieved at the optimum, for Consort and Robigus and under medium-high and low disease pressures (Table 5).

Table 5. Range of Opus doses in a two-spray programme including Bravo that would have given margins within £2/ha of that achieved at the optimum Opus dose (mean of 3 experiments with med-high and 3 with low disease pressure from 2005 and 2006).

Septoria Pressure	Optimum Opus dose, and highest and lowest doses (l/ha) that would have given a margin within £2/ha of the optimum					
	Consort			Robigus		
	Highest	Optimum	Lowest	Highest	Optimum	Lowest
Med-high	2.6	2.2	1.9	1.8	1.5	1.2
Low	1.9	1.6	1.3	1.2	0.9	0.7

Typically, Opus doses within 15-20% above or below the optimum would have resulted in a margin within £2/ha of that achieved at the optimum dose. For both Consort and Robigus, the highest dose that could have been applied to achieve a margin within £2/ha of the optimum in the low disease pressure experiments was approximately the same as the lowest dose that could have been applied to achieve a margin within £2/ha in the medium-high disease pressure experiments.

Over the duration of this project, the wheat grain price ranged from less than £80/t to more than £160/t. Further analysis showed that optimum Opus doses would have been 25-30% higher on Consort with wheat at £160/t than with wheat at £80/t. On Robigus, optimum doses would have been 30-50% higher with wheat at £160/t than at £80/t. The adjustments to Opus dose that would have been justified were smaller when Bravo and Vivid were included in mixture with Opus, then where Opus was applied alone. Fungicide prices were kept constant for this analysis, although in practice these may also change with changing wheat price.

Table 6. Effect of fungicide treatment and variety on optimum dose of Opus (and margin achieved) in two-spray programmes (4 site summary for 2007)

Variety	Fungicide Treatment	Optimum Opus dose l/ha in two-spray programmes (and margin £/ha achieved at optimum dose)			
		Borders	Hampshire	Herefordshire	Norfolk
Consort	Opus two-spray	2.0 (985)	3.2+ (921)	3.2+ (939)	3.2+ (910)
	Opus + Bravo + Vivid	1.20 (961)	1.68 (929)	1.6 (942)	1.52 (917)
Robigus	Opus two-spray	1.04 (1030)	1.76 (951)	1.76 (961)	2.64 (942)
	Opus + Bravo + Vivid	0.32 (1026)	0.24 (977)	0.4 (1079)	1.2 (1007)

The effects of fungicide treatment on optimum Opus dose (and margin) varied in 2007 (Table 6). At all sites optimum Opus doses on Consort were lower for Opus + Bravo + Vivid than for Opus alone in a two-spray programme (for which the optimum was above the highest dose evaluated at three sites). The addition of Bravo plus Vivid substantially reduced the optimum Opus dose on Robigus at all sites, while maintaining or increasing margins. On Consort the addition of just Bravo also resulted in consistently lower optimum Opus doses, but this was not true for Robigus.

Seasonal Disease Risk

'Live monitoring' experiments conducted on winter wheat as part of CropMonitor were a useful source of information on disease progress during the project. These involved detailed weekly assessments of foliar disease on each emerging leaf layer from GS31 through to GS75, on four wheat varieties that did not receive any fungicides. Three of the sites (Hampshire, Herefordshire and Norfolk) at which sequences and mixtures experiments were located also hosted live monitoring experiments that were sown at about the same time and in the same or nearby fields. In 2005 and 2006 two of the varieties in the live monitoring were the same as in sequences and mixtures (Consort and Robigus). In 2007 Ambrosia was substituted for Consort in live monitoring, but this has a similar rating (4) for resistance to septoria on the HGCA Recommended List. On the whole, early septoria progress as indicated by the live monitoring experiments was not a good guide to septoria levels at the end of the growing season (even on the final three leaf layers) or optimum Opus dose. The data suggest that the rate at which septoria levels increased towards the end of the growing season may have been more important. In 2007 the development of rusts would also have had a significant impact.

Predicting the Performance of Fungicide Mixtures

Data from the 2005 and 2006 field experiments were used to test the extent to which it was possible to predict yield responses to fungicide programmes. Predicted yield response values were obtained using the computer programme 'Wheat Disease Manager' (WDM), which accounted for local weather (from the Met office network), varietal disease resistance (from the HGCA Recommended List for Winter Wheat) and observations of disease severity prior to spray decisions, entered into the observations dialog of WDM. Details of the products, doses and spray timings for each fungicide treatment were entered, and the yield responses predicted for each spray programme were noted. The yields obtained in the double dose treatments in the experiments were taken as representing the 'potential yield' for each variety at each site and were entered into WDM. This allowed the predicted yield responses for each programme to be plotted as predicted yield against the actual yields obtained from the experiments.

Of the 15 site x season x variety combinations tested, significant relationships between predicted and actual yields were recorded in 13 cases. Predicted yield responses to fungicide treatments as a proportion of untreated yield loss were generally in agreement with actual responses, although predictions tended to underestimate losses where the crop was untreated. The model could be recalibrated to resolve this underestimation, and more accurately predict potential yields.

The ability to predict the disease control performance of a fungicide mixture was examined by developing a 'mixture calculator' capable of taking dose-response curves for two individual active ingredients, combining them to produce response curves for the mixture, and displaying the result graphically. The calculator uses two methods of combining response curves, the additive dose method (ADM) when the mode of action is the same and the multiplicative survival method (MSM) when it is different. The resulting % disease is presented against the individual dose response curves for the two components of the mixture either as a single (straight line) value representing the chosen dose of each component, or as a curve where the full dose represents the chosen dose of each. Predicted performances against *S. tritici* and *S. nodorum* for a mix of two triazole fungicides, two non-triazoles and a triazole with a non-triazole, were compared against formulated mixtures of the two active ingredients using HGCA fungicide performance data from 2005. Taking into account the variability found in the experiments, the fungicide mixture calculator gave acceptable results.

Conclusions and Implications for Levy Payers

In situations where the dominant foliar disease on winter wheat was *S. tritici*, the addition of Bravo to Opus in a two-spray (T1 + T2) fungicide programme has:

- reduced the dose of triazole (Opus) required to obtain equal disease control, often by 50% or more,
- allowed optimum yields to be obtained at 15-30% lower doses of triazole (Opus), whilst improving margins.

Even when mixed with Bravo, optimum triazole (Opus) doses were an average of:

- 45-65% higher for the most septoria susceptible variety compared to the least.
- 40-60% higher under medium-high than under low septoria pressure.

Where brown or yellow rust were an equal or greater threat on one or more varieties:

- Vivid was of more benefit than Bravo as a mix partner for Opus to control rusts.
- Adding Vivid as well as Bravo resulted in up to 70% lower optimum triazole (Opus) doses whilst in most cases maintaining or increasing margins.

However it is important to note that choice of triazole at T1 and T2 (to reflect the target diseases) is important as well as triazole dose, and choice of mixture partner(s)

All other things being equal, increasing the grain price from £80/t to £160/t increased the optimum dose of the triazole (Opus) typically by 25-30%. Changing triazole dose is though only one way of responding to grain price. Other ways include applying an additional spray (for example at T0 or T3), or applying an appropriate mixture partner where this was otherwise not planned. Results obtained here suggest that adding a suitable mixture partner will often be more cost-effective than increasing the triazole dose. A range of triazole doses can deliver margins that are close to that achieved at the optimum. Applying a dose that is slightly above the expected optimum, especially where relatively low doses are being considered, will provide insurance in the event of higher than expected disease pressure or unexpected delays in application. However, robust disease control is best achieved through using appropriate fungicide mixtures rather than routinely applying higher than necessary doses of triazole. This may also help to avoid a potential escalation in selection for less sensitive disease isolates.

Figure 1 can be used as a guide to the relative dose of triazole that is likely to be required to achieve optimum yield, based on the septoria resistance rating of the variety, seasonal/regional septoria pressure, the threat (or not) from rusts and choice of mixture partner(s). The figure is based on the relative optimum doses obtained in the experiments, and therefore assumes programmes with well-timed applications at T1 and T2, the use of a triazole with good activity against septoria and rusts, and (where applicable) the addition of chlorothalonil or a rust-active strobilurin at robust doses at both timings. The longer the horizontal bar, the higher the dose of triazole required. Where the bar extends beyond the vertical dotted line, this indicates that it is unlikely that optimum yield will be achieved with this particular treatment for this combination of varietal resistance and disease pressure, so an appropriate partner (or further partner) should be used. Where the bar is very close to, or touching, the dotted line, using an appropriate partner (or further partner) is preferable to avoid over-reliance on the triazole component.

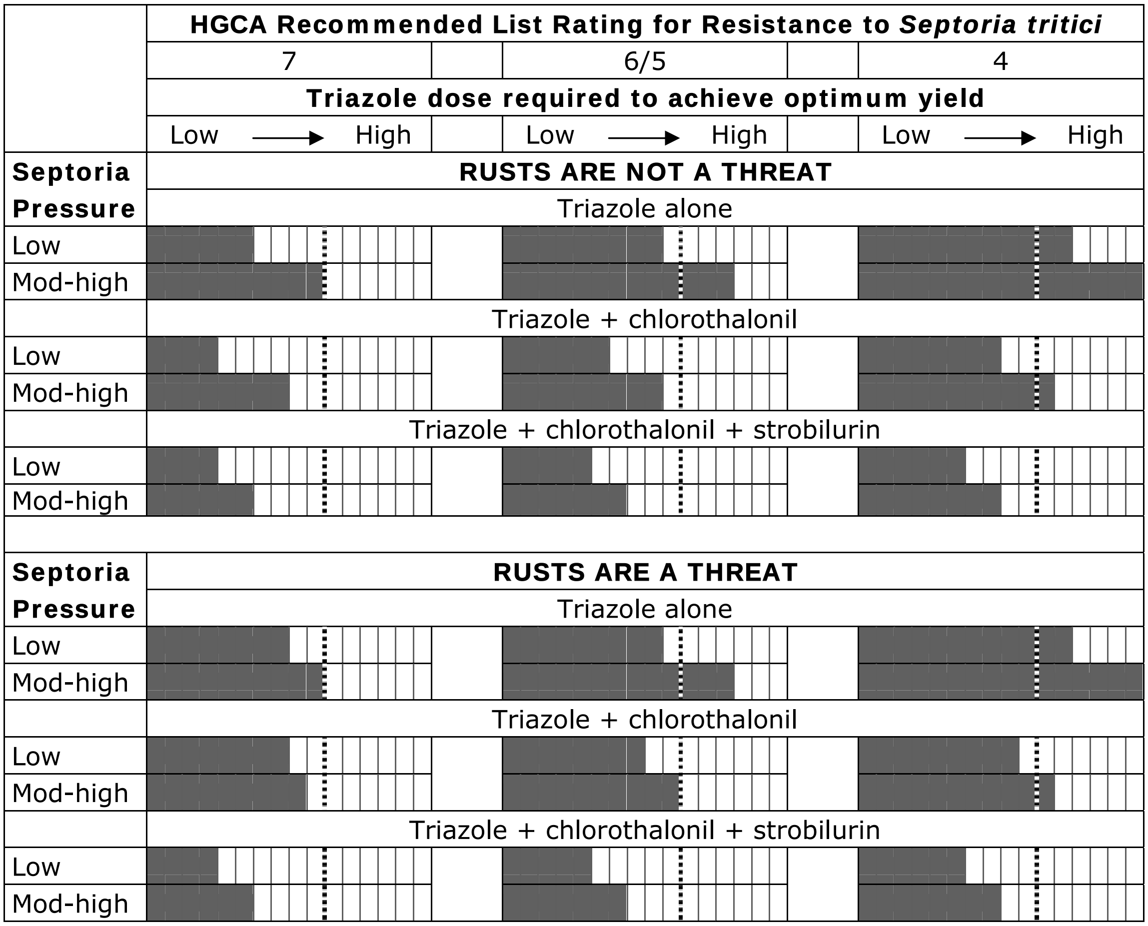

Figure 1. A guide to relative optimum triazole doses for different disease scenarios

Comparisons of the results obtained in the field experimentation within this project against indicators of disease pressure from within-season monitoring have highlighted the difficulties that exist in forecasting fungicide response based on septoria progress. Such information may have a role in monitoring rust development, which can affect the most appropriate mixture partner(s) for the triazole, and potentially the extent to which triazole doses can be reduced on varieties that are less susceptible to septoria.

Prediction of yield response (and economic return) from fungicides is a prerequisite for objective treatment decisions. To be of value the prediction needs to be made with information available at the time of the treatment decision. The degree of predictive value demonstrated here suggests that WDM could help support treatment decisions if the system could be delivered to users in an appropriate form. Although only limited testing was possible with the available data, a fungicide mixture calculator that was designed to take dose-response curves for individual fungicide active ingredients and combine them to produce dose-response curves for mixtures gave promising results.