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Research Review 99

Impact of fungicide programmes on the performance of cereals and oilseeds varieties (scoping review)

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1. Abstract

This project reviewed evidence on how reduced fungicide inputs impact the relative performance of cereal and oilseed varieties. It also identified potential options for testing varieties under reduced fungicide inputs. Several approaches were taken to review the evidence:

1. Consideration of current variety trial inputs, in relation to AHDB guidance on fungicide inputs, highlighting the potential areas for reducing fungicide use.
2. Reviewing evidence from the academic literature, AHDB reports and company trials data on the impact of reduced fungicide inputs on variety performance.
3. Meeting with stakeholders to gather views on reduced-input variety testing.
4. Consideration of mathematical modelling as a potentially cost-effective means of predicting how varieties are likely to perform under reduced inputs.

The knowledge gaps, findings and recommendations from exploring these approaches were summarised and suggestions for variety testing under reduced variety inputs provided.

Key knowledge gaps include:

- A lack of information relating to crops other than wheat
- A lack of understanding of potential interactions with other factors, such as nitrogen inputs
- A lack of knowledge on varietal tolerance to disease

Key findings include:

- Current Recommended Lists (RL) variety-testing approaches are suitable for testing under reduced fungicide inputs, with a fungicide protocol reflecting best practise on farm
- An ADAS variety x fungicide model (based on the multiplicative survival model) is suitable for predicting how varieties are likely to perform under different fungicide inputs

Key recommendations include:

- Three suggestions for variety testing under reduced fungicide inputs:
    1. Test all varieties under a reduced fungicide input programme.
    2. Test a subset of resistant and susceptible varieties and predict the performance of the rest using mathematical modelling.
    3. Demonstrate the potential for reduced inputs on a subset of resistant varieties.
- The recommendations also considered how RL tests could link with Variety Lists (VL) tests.

Recommended Lists review (2022–2023)

Typically, the main RL project runs in five-year phases, with a large-scale public review conducted during each project phase. The need for information on evidence of varietal responses under lower-input scenarios was identified as part of the RL 2022–2023 review, with this scoping review commissioned as part of follow-up activities.

2. Aim, objectives and scope

2.1. Aim

To review the evidence on how reduced fungicide inputs impact the relative performance of cereal and oilseed varieties.

2.2. Objectives

1. Collate relevant reports that incorporate research on cereal and oilseed varietal responses to different fungicide inputs.
2. Review the reports to determine whether different fungicide inputs impact variety yield ranking and quality characteristics.
3. Prepare a final report including a summary of key findings and any knowledge gaps identified.

2.3. Scope

The crops that are covered in the review are:

1. Winter and spring wheat
2. Winter and spring barley
3. Winter and spring oats
4. Winter rye
5. Winter triticale
6. Winter and spring oilseed rape
7. Spring linseed

3. Approach and methodology

A number of approaches were taken to review the evidence on how reduced fungicide inputs impact the relative performance of cereal and oilseed varieties, and to identify potential options for testing varieties under reduced fungicide inputs in the future. These different approaches are set out in individual sections of the report, with the methodology for each approach detailed in the relevant section. The approaches were as follows:

- The current variety trial inputs were considered in relation to AHDB advice on fungicide inputs, highlighting the potential areas for reducing fungicide use.

- Evidence from the academic literature on the impact of reduced fungicide inputs on variety performance was compiled and considered.

- Evidence from AHDB reports on the impact of reduced fungicide inputs on variety performance was considered.

- Evidence from company trials data on the impact of reduced fungicide inputs on variety performance was considered.

The knowledge gaps, key findings and recommendations from exploring these approaches are summarised and suggestions for variety testing under reduced variety inputs provided.

4. RL fungicide treated inputs and reduced input testing

4.1. Background

The current variety trial design and approaches to fungicide inputs are summarised below, together with AHDB recommendations for fungicide use on farm. Knowledge gaps, key findings and recommendations are outlined below. The potential to reduce the current RL fungicide treated programme to allow for reduced input testing is considered.

The current AHDB Recommended List (RL) project undertakes trials and tests for the 2021/22 to 2025/26 cropping years and provides independent data, through the production of the RLs for cereal and oilseeds. Lists are published each December for the following crops:

- Winter wheat
- Spring wheat
- Winter barley
- Spring barley
- Winter oats
- Spring oats
- Winter oilseed rape

In addition, trials are undertaken to provide independent data for Descriptive Lists (DLs) for the following crops:

- Spring oilseed rape
- Spring linseed
- Winter rye
- Winter triticale

All of results can be accessed via a dedicated web page: **ahdb.org.uk/rl**

Protocols for RL trialling are available online: **ahdb.org.uk/ahdb-recommended-lists-for-cereals-and-oilseeds-2021-2026**

4.2. RL treated and untreated yield trial set up

4.2.1. Cereals

Yield trials normally have three replicates in a block design. Fungicide treatments are applied to specified trials as described under each crop specification and/or in Protocol 201 (Fungicides). The protocol is updated annually (usually December/January) and issued separately. It is designed to meet the aim of keeping disease levels in treated plots as low as is possible in all varieties and in all trials and are not intended to follow commercial practice. Plots should have a minimum drilled width of 1.1 m (row width * number of rows) and an inter-plot gap of a maximum 0.55 m to give a total width of not less than 1.65 m. Plot length should be not less than 9.0 m after trimming back for harvest but may have to be longer depending on the harvesting equipment available.

4.2.2. Winter oilseed rape

Yield trials will normally have three replicates in a block design. The fungicide treatments are updated annually (usually December/January) and issued separately. The current treatment lists are shown in Protocol 204. Yield plots must be unbordered paired plots or bordered single plots (see 1.3.2). Unbordered paired plots must have a minimum harvested plot area of 36m^2 per replicate and have a minimum combined width of 3m (including inter-plot gap). Bordered plots must have a minimum harvested plot area of 18m^2. Yield plots should be drilled to a greater length than required and trimmed to their final length before the mid-stem extension stage. The plot width for calculating harvested area is measured centre gap to centre gap, with an inter-plot gap in the range 0.5m to 0.8m. If a swather is used the sown plot width should reflect the blade width used.

4.3. Current RL fungicide treatment lists

The fungicide protocol for each crop sets out the fungicide products and rates to be used to control disease at each of the key spray application timings (e.g. T0, T1). In some cases, a range of doses is indicated along with options for further additions where the situation requires, at the discretion of the trial operator. The following sections demonstrate the fungicide programmes set for trials run in 2024 (December 2023 Protocol).

4.3.1. Winter wheat

T0 GS30 = Cyflamid 0.25 – 0.35 l/ha + Tebucur 250 0.6-0.75 l/ha + Comet 200 0.4 – 0.6 l/ha
Note: Arizona is compulsory at T1 and T2 but can only then be used at one timing either at T0, T1.5 or T3; Arizona 1.0 l/ha.

T1 GS32 = Revystar XE 1.0-1.5 l/ha + Arizona 1.0 l/ha + Talius/Justice 0.15 l/ha.
Optional for an eyespot situation Entargo 0.5 l/ha.

Optional for a rust situation Elatus Era 0.6 l/ha.

T1.5 GS33 = Optional in a rust situation Sunorg Pro (Metconazole 250) 0.5 l/ha.
Optional in a septoria situation Prothioconazole 0.6 l/ha.
Note: Arizona is compulsory at T1 and T2 but can only then be used at one timing either at T0, T1.5 or T3 Arizona 1.0 l/ha.

T2 GS39–45 = Univoq 1.0 – 1.5 l/ha + Arizona 1.0 l/ha.
Optional nationally but compulsory for the East and Southern regions Tebuconazole 250 0.75 – 1.0 l/ha.
Optional - If mildew established Cyflamid 0.25 – 0.35 l/ha.

T3 GS55–61 = Prosaro 0.8 – 1.0 l/ha + Comet 200 0.4 – 0.6 l/ha.
Note: Arizona is compulsory at T1 and T2 but can only then be used at one timing either at T0, T1.5 or T3. If used at T3 it can only be used up to GS59. Arizona 1.0 l/ha.

Post T3 For extreme septoria or brown rust situations please contact the relevant trials co-ordinator. Tebucur 250 has a maximum total dose limit of 2l/ha and can be applied up to GS71. In extreme yellow rust situations, there may be flexibility for a third application of Tebucur 250 at 0.5 l/ha, but please contact the relevant trials co-ordinator before doing so.

4.3.2. Spring wheat

T1 GS29–31 = Ascra Xpro 0.8 - 1.0 l/ha + Comet 200 0.4 – 0.6 l/ha + Arizona 1.0 l/ha + Talius/Justice 0.15 l/ha

T2 GS37 = Univoq 1.0-1.5 l/ha + Arizona 1.0 l/ha + Optional if mildew established Cyflamid 0.25 – 0.5 l/ha

T3 GS51–61 = Prosaro 0.8 l/ha + Comet 200 0.4 – 0.6 l/ha + If including Arizona must not exceed GS59 Arizona 1.0 l/ha

Note: In a yellow rust situation, an application of tebuconazole 250 (0.75- 1.0 l/ha) can be made at an appropriate timing.

4.3.3. Winter barley

T0 GS26–30 = Proline 275 0.3 – 0.5 l/ha + Comet 200 0.3 – 0.5 l/ha.

T1 GS30–31 = Ascra Xpro 0.7 – 1.25 l/ha + Arizona 1.5 l/ha + Cyflamid 0.25 – 0.35 l/ha.

T2 GS39–45 = Revystar XE 1.0 – 1.25 l/ha + Arizona 1.5 l/ha + Optional: If net blotch or rhynchosporium is developing. Not to be applied after the start of flowering. Proline 275 0.3 – 0.5 l/ha.

T3 GS59–61 = Optional (to be considered compulsory if brown rust is a risk) Proline 275 0.3 – 0.5 l/ha + Comet 200 0.35 – 0.5 l/ha.

4.3.4. Spring barley

T0 GS13–15 = Optional: If disease is present Proline 275 0.2 – 0.4 l/ha.

T1 GS25–31 = Ascra Xpro 0.6 – 1.0 l/ha + Arizona 1.0 l/ha + Optional: if mildew is present Cyflamid 0.25 – 0.35 l/ha.

T2 GS45–59 Revystar XE 0.75 –1.0 l/ha + Arizona 1.5 l/ha.

T3 GS59–69 = Optional: If net blotch, rhynchosporium or fusarium developing Proline 275 0.3 – 0.5 l/ha.

4.3.5. Winter oats

T0 GS Mid to late tillering = Cyflamid 0.25 – 0.35 l/ha + Prothioconazole 0.35 l/ha.

T1 GS31 = Ascra Xpro 0.7 - 1.2 l/ha + Talius/Justice 0.15 l/ha.
Optional - if crown rust is a problem. Tebuconazole 250 0.5 l/ha.

T2 GS39–45 = Elatus Era 0.6 – 0.8 l/ha + Cyflamid 0.25 – 0.35 l/ha.

T3 GS45–59 = Optional: If crown rust pressure has remained high before GS59–61. Tebuconazole 250 0.5 l/ha + Comet 200 0.5 l/ha.

4.3.6. Spring oats

T0 GS13–15 = Prothioconazole 0.35 l/ha.
Optional: If mildew present. Cyflamid 0.25 – 0.35 l/ha.

T1 GS Mid to late tillering = Ascra Xpro 0. 7– 1.2 l/ha + Talius/Justice 0.2 l/ha.
Optional: If crown rust is a problem. Tebuconazole 250 0.5 l/ha.

T2 GS39–45 = Elatus Era 0.6 – 0.8 l/ha + Cyflamid 0.25 – 0.35 l/ha.
Optional: If crown rust pressure is a problem. Comet 200 0.5 l/ha + Tebuconazole 250 0.5 l/ha.

4.3.7. Winter rye and triticale

T0 GS30 = Tebuconazole 250 0.75 – 1.0 l/ha.
Optional: If mildew present, trial operators' discretion whether to use either at T0 or T1. Cyflamid 0.25 – 0.35 l/ha.

T1 GS31–32 = Increase rate for high rust. Elatus Era 1.0 l/ha.
Optional: If mildew present, trial operators' discretion whether to use either at T0 or T1. Cyflamid 0.25 – 0.35 l/ha.

T2 GS39–45 = Revystar XE 0.5-1.0 /l/ha.

T3 GS59–61 = Optional: Rye only if rust remains a problem before GS61. Prosaro 0.8 l/ha.

4.3.8. Winter oilseed rape – autumn application

Northern Region:
Optional on appearance of first symptoms of Light leaf spot and or Phoma, or apply by end of November = Proline 275 0.63 l/ha or Aviator Xpro 1.0 l/ha.

East / West Region:
Apply Shepherd 0.4 l/ha on appearance of first symptoms or, if no symptoms present by end of October (the 4-leaf stage). If a second autumn fungicide application after Shepherd is unlikely, then use Proline 275 in place of Shepherd.
If a second fungicide application is required for Phoma or light leaf spot control 4 – 6 weeks after previous application, or by end of December apply Proline 275** or Aviator Xpro 0.63 l/ha 1.0 l/ha. Fungicide applied at this timing will also provide protection for light leaf spot, even if symptoms are not visible in the crop.
* Consult the relevant trials co-ordinator if this product is unavailable.
**Proline 275 can be used twice in the programme across autumn and spring, but the max total dose must not exceed 1.26 l/ha.

4.3.9. Winter oilseed rape – spring application

Fungicide Protocol for the North and East/West regions:
Onset of spring growth prior to stem extension for foliar disease control = Proline 275 0.63 l/ha.

GS 4.0–4.3 First flowers opened, target Alternaria, Botrytis and Sclerotinia = Pictor 0.375 – 0.5 l/ha
Note: If there is a strong likelihood that soil or weather conditions will prohibit the application of the second Pictor spray, then apply full rate Pictor at this timing (maximum of 0.5 l/ha permitted).

GS 4.5–5.0 (up to 3 weeks later or just prior to 50% of pods at final size (GS 75 BBCH), target sclerotinia = Pictor 0.375 – 0.5 l/ha Please note that a fungicide application for Sclerotinia control should be applied to untreated trials especially where these trials are taken to yield.

4.4. AHDB fungicide use recommendations

AHDB fungicide use recommendations are built upon decades of expert knowledge on disease management best practise aimed at protecting crop yields. The recommendations are summarised below to allow comparison with the current RL treated yield fungicide protocols shown above, and therefore highlight potential areas for reducing inputs. However, due to the potential need for changing recommendations over time, it is important to regularly consult with independent experts over fungicide use recommendations. The AHDB fungicide use recommendations can be found here:
ahdb.org.uk/knowledge-library/fungicide-programmes-for-wheat-and-barley
ahdb.org.uk/knowledge-library/oilseed-rape-disease-management-guidance

4.4.1. Winter wheat

T0: 2–4 weeks earlier than T1 (leaf 3 emerged)
A T0 fungicide is only economic when mildew, yellow rust or brown rust risk is high on susceptible varieties and where these diseases are active. Some sprays targeted at foliar diseases at T0 may also help control eyespot. However, if eyespot is the main target, a T0 may not be economic. *Septoria tritici* control at this timing is rarely associated with yield benefits, even in high disease pressure situations. However, it can insure against a delayed T1 in susceptible varieties. Late-sown disease resistant varieties do not require a T0 for the control of *septoria tritici*.

T1: fully emerged leaf 3 (GS31–33)
Sprays at this timing can help protect the fully emerged leaf 3 – mainly from *septoria tritici* – and provide additional protection from other foliar diseases (including rusts and mildew) on leaves 2 and 4. It is also a key timing for eyespot control, but optimise the timing of the spray for the control of foliar diseases.

T2: flag leaf fully emerged (GS39)
This is the most important spray timing in wheat. It controls disease on the top two leaves, which contribute about 65% to yield. Yield responses to this spray timing are most likely to be profitable. The main target disease is *septoria tritici*, although rusts are also targets. Prompt timing is most important on varieties susceptible to *septoria tritici* (e.g. disease ratings 5 or less).

T3: GS59 or GS63–65
At GS59, use a T3 spray to top up foliar disease control on the top two leaves or, at GS63–65, to control fusarium/microdochium ear blight. A spray at GS63–65 also gives additional top-up control of foliar diseases, although it is not as effective as a spray at GS59. Consider the relative importance of foliar disease and ear blight to decide which timing to use. If no T3 spray is planned, it is important not to delay the T2 spray. Sprays applied around GS59 can help maintain canopy size and prolong its duration by protecting leaf and ear green area against foliar diseases. It is only usually required for brown rust, where it is seen. At this timing, *septoria tritici* control is usually only needed in the north and west of the UK, where it is often wetter, with an extended growing season.

4.4.2. Spring wheat

The main diseases to consider in spring wheat are *septoria tritici* and – particularly at earlier spray timings – mildew and rusts. Compared with winter wheat, the gaps between fungicide timings are shorter. As less persistence is required, lower doses are an option.

T1: GS29–31
Use a multisite plus azole, possibly with the addition of a mildewicide for mildew and/or a strobilurin for rusts.

T2: GS37
Use a multisite plus azole, possibly with the addition of a mildewicide for mildew and/or a strobilurin for rusts.

T3: GS51–61
As per winter wheat, a T3 may be required for fusarium control, if it is wet during flowering. An azole is an appropriate choice, possibly with the addition of a strobilurin in high brown rust situations.

4.4.3. Winter barley

Yield potential in barley is determined early in the season. Consequently, early disease control is relatively important, but season-long protection maximises grain storage capacity. There are four key spray timings, but T1 and T2 sprays adequately protect most crops.

T0: GS23–29 late tillering, early spring
Yield responses to fungicides are highly variable at this timing. Only spray if overwintering disease levels are high in susceptible varieties.
Mildew, brown rust, rhynchosporium and net blotch are the main diseases to consider at this timing. Use a specific mildewicide for mildew control.

T1: GS30–32, stem extension
This is the main timing in winter barley. Treatment helps maximise survival of formed tillers and spikelets, increasing final grain numbers. Six-row barley responds similarly to two-row barley. Rhynchosporium, net blotch, mildew, eyespot and brown rust are the main diseases to consider at this timing.

T2: GS39–59, flag leaf and ear emergence
About 40% of the fungicide yield response can come from this timing. Greater yield responses often occur in years with a later harvest. It is the key timing for ramularia control, with GS45–49 (awns peeping) being the optimum timing for this disease. Brown rust and net blotch are also targets, along with rhynchosporium in wetter western regions and in wet summers.

T3: after GS59
Avoid sprays after GS59, as they seldom give an economic yield benefit and few products are approved. Where fusarium head blight is a concern, use non-chemical control measures. In very high-risk situations, consider a spray during early flowering (GS63–65), subject to the latest timings on the label.

4.4.4. Spring barley

Fungicides can provide early protection of developing tillers and spikelets and protect grain development and filling. One or two sprays, applied at T2 and/or T1, protect most crops. Sowing date, variety and disease risk influence the optimum spray timing. As usual, use mixtures of modes of action in which components have activity and similar efficacy on the target disease.

T0: GS12–22 (before mid-tillering)

This spray is only required if mildew is present on a susceptible variety. If disease pressure warrants it, use a specific mildewicide.

T1: GS25–31 (late tillering)
This is the main timing for rhynchosporium control, although brown rust, net blotch and mildew are also targets. About 40% of yield response to fungicides comes from this timing.

T2: GS39–59 (flag leaf fully emerged to ear emerged)
This is the main timing for net blotch, brown rust and ramularia control. It also provides some rhynchosporium control. About 60% of yield response to fungicides comes from this timing. Where the T1 spray has been omitted from the fungicide programme, an earlier T2 timing (GS37–39) may be appropriate. GS45–49 (awns peeping) is the optimum time for control of ramularia.

4.4.5. Winter oats

T0: GS25–29
This timing is required for mildew control, where this disease is a risk.

T1: GS30–31
This is the most important time for disease control in oats. T1 usually consists of an azole for mildew control and a strobilurin for crown rust. If mildew is highly active at T1, it will not be controlled by azoles alone.

T2: GS39–55
A T2 is usually required for late-season foliar disease control. Later applications can also give control of fusarium head blight. If crown rust infection is seen, then consider an azole or, in high-pressure situations, an azole with strobilurin. For resistance management, do not use strobilurins alone for mildew control.

4.4.6. Spring oats

The spray programme for spring oats is the same as for winter oats, except a T0 is only required for mildew control in susceptible varieties in high-pressure situations.

4.4.7. Triticale

Yellow rust is the main disease of triticale, but septoria tritici, mildew, rhynchosporium, brown rust and fusarium are also important. To protect against yellow rust, a three-spray programme is usually required: T0, T1 (GS32) and T2 (GS39). Use rust active azoles, with or without strobilurins, at T1/T2. Even in severe yellow rust situations, a spray before GS30 is unlikely to be economic. Septoria tritici levels are not usually as high as in wheat and SDHIs are not usually needed for disease control.

Consider mildew and include protectants for mildew, as necessary. Although there are differences in disease resistance between triticale varieties, these are not published in the Recommended List.

4.4.8. Rye

The main diseases of rye are brown rust, mildew and ergot. However, rhynchosporium, fusarium, eyespot, take-all, and *septoria nodorum* are also important. The strains of brown rust and mildew that infect rye are not the same ones that cross-infect with wheat or barley. Mildew can cause high yield losses (up to 25%), but is relatively easy to control. Rye undergoes rapid stem elongation and is tall, meaning it can grow away from rhynchosporium infection on the lower leaves, so this is less likely to spread up the canopy than in barley. Ergot tolerance is much higher in hybrid rye than in conventional rye. Rye does not suffer badly from *septoria tritici*.

To protect against brown rust and mildew, a three-spray programme may be required: T1 (GS29–30), T2 (GS39–47) and T3 (GS51–59). Use a combination of azoles, strobilurins and SDHIs. The T2 timing is the most important: protecting against brown rust late in the season ensures yield and quality is maximised. On biomass crops, the T3 timing is too close to forage harvesting to be economic.

4.4.9. Oilseed rape – phoma and light leaf spot control

Treat varieties with lower resistance ratings for stem canker (7 and below) and backward crops first, when 10–20% of plants have phoma leaf spot. Only treat varieties with high resistance ratings for stem canker (8 to 9) if more than 20% of plants have phoma leaf spot. When reinfection occurs (based on the presence of new lesions), consider a second spray – typically, four to ten weeks after the first spray. Adjust spray programmes to account for any late-autumn fungicide (November) required for light leaf spot control (consider efficacy against both phoma and light leaf spot).

The stem canker resistance ratings in the AHDB Recommended List use a standard 1 (susceptible) to 9 (resistant) scale. Updated annually and based on final assessments of stem canker severity in early summer, varieties with strong levels of resistance are far less likely to require multiple fungicide applications. It is important to note that although some resistant varieties may exhibit high levels of spotting, they will only develop low levels of canker. Two sprays at half the recommended label rate are sufficient to achieve good control of phoma leaf spot and stem canker, according to AHDB fungicide performance data. Although complete control is possible with three sprays, it is not economical to use such an intensive fungicide programme.

Across the growing season, one or two light leaf spot fungicide sprays are usually applied.

In a high-risk situation (e.g. early sown susceptible variety), apply the first spray in November. This may coincide with the first or second fungicide application for phoma leaf spot, which will require the selection of a product with efficacy against both diseases. Continue to inspect crops throughout winter. If light leaf spot is present, apply a fungicide as soon as possible. Sclerotinia fungicides can also have activity on light leaf spot, if the disease is present during flowering.

Appropriate fungicide dose depends on the site and the year. Generally, half doses give good control in England and Wales. However, high-risk crops may require higher doses.

4.4.10. Oilseed rape – Sclerotinia control

Fungicide timing is important for good control, as products available to control sclerotinia stem rot are protectants and have little or no curative activity. The optimum timing for a single spray is, usually, just before mid-flowering on the main raceme and prior to significant petal fall. Treatments provide good control for about three weeks. Two sprays may therefore be required to protect crops at high-risk sites throughout the flowering period (especially when the flowering period is extended). Biological control of sclerotinia with *Coniothyrium minitans* is also an option. The naturally occurring fungus colonises and deactivates soil-borne sclerotia, which limits potential for infection.

4.5. Knowledge gaps

- Information is available for cereals and winter oilseed rape to guide reduced input fungicide programmes; with less information available for spring oilseed rape and spring linseed. A reasonable approach would be to follow the principles identified for the major crops, to guide inputs into the minor crops e.g. by focusing on key fungicide timings to protect yield formation.

4.6. Key findings

- The Recommended Lists (RL) yield trial protocols provide comprehensive methodology for variety testing. The methods are broadly typical of accepted methodology for field experiments, and therefore acceptable in principle for testing varieties under reduced fungicide input programmes. The protocols are updated regularly and this approach would allow for new, effective fungicide products to be incorporated into testing protocols as they appear on the market.

- RL trial protocols are designed to meet the aim of keeping disease levels in treated plots as low as is possible in all varieties and in all trials and are not intended to follow commercial practice. Testing varieties under reduced fungicide inputs could in principle be conducted using existing RL methodology but with a fungicide protocol specific to the reduced input trials. The consideration is then about the extent to which fungicide inputs can be reduced, and the extent to which the fungicide protocol allows for flexibility of spray decisions for the trial operator.

- RL fungicide protocols for treated trials incorporate a range of fungicide modes of action that are agreed upon in advance and are suitable for control of the key target diseases. The same approach would be suitable for testing under reduced fungicide inputs, but with focus on reducing the number of sprays and total doses applied.

- Fungicide protocols for cereals treated trials include 3 or 4 mandatory spray timings, with the option of incorporating additional products into these applications or in additional applications, depending on the disease pressure within the trial.

- Fungicide protocols for oilseed rape treated trials include a mandatory autumn spray timing for trials in the East or West, or an optional autumn spray for trials in the north. For all regions, there are three mandatory spray timings in the spring.

- AHDB fungicide use recommendations have been built on decades of AHDB research and knowledge transfer, with input from experts from a range of research centres and through consultations with industry. Analysis of these recommendations represents a suitable approach for deriving fungicide protocols for variety testing under reduced inputs. This approach would promote best practise for commercial fungicide use.

- AHDB fungicide use recommendations for cereals typically focus on the key T1 and T2 spray timings that protect yield formation, with additional spray timings generally only recommended according to varietal resistance, local disease pressure and the need to protect the crops against ear diseases. Testing varieties at reduced inputs could therefore also focus on these spray timings, with limited use of fungicides outside of these timings.

- AHDB fungicide use recommendations for oilseed rape offer considerable flexibility in terms of adjusting fungicide spray timing and dose according to crop development, varietal resistance and local disease pressure. These recommendations can be used to guide a fungicide protocol for reduced input variety testing, with limitations on both the number of spray timings and the dose.

4.7. Recommendations

- The Recommended Lists (RL) yield trial protocols provide comprehensive and broadly accepted methodology for variety testing in field experiments. Should it be considered appropriate, these field trial methods could also be used for reduced fungicide input variety testing, with a fungicide protocol specific to the reduced input trials.

- AHDB fungicide use recommendations have been built on decades of AHDB research and knowledge transfer. These recommendations should form the basis for deriving fungicide protocols for variety testing under reduced inputs, together with ongoing, regular expert input. This approach would promote best practise for commercial fungicide use.

- Testing cereals varieties under reduced inputs should focus on the key T1 and T2 spray timings, with limited use of fungicides outside of these timings.

- Testing winter oilseed rape varieties under reduced inputs should focus on limiting both the number of spray timings and the dose.

- For crops where limited information may be available to guide reduced fungicide input protocols (e.g. spring oilseed rape, spring linseed) then a suggested approach is to follow the principles identified from fungicide use recommendations for cereals and winter oilseed rape.

- The current focus of RL trials on treated yields under more intensive fungicide inputs than current commercial practise creates competition between breeders for the highest treated yield under intensive inputs. Analysis of the disease tolerance levels in UK wheat varieties (van den Bosch et al. 2022) suggests that creating competition for the highest achievable yield under commercial fungicide inputs would be more productive. A recommendation therefore is to explore the potential for maximising achievable yield through breeding for disease tolerance, in addition to considering appropriate fungicide programmes for reduced input variety testing.

5. Evidence from academic literature

5.1. Methods

This section details the Rapid Evidence Assessment (REA) which was undertaken with the aim of reviewing the scientific literature to provide an understanding of cultivar/variety behaviour under different fungicide applications. The REA was carried out following standard methodology aimed at unbiased searches of information. A more detailed explanation can be found in section 5.3

5.2. Research questions

The primary research question for this REA was:
Do lower fungicide input treatments impact performance of cereal and oilseed varieties? To structure the REA, seven crop species commonly grown for commercial purposes in the UK were studied.

5.3. REA process

The REA process followed the following key steps:

1. Protocol design (search term generation, Inclusion/exclusion criteria)
2. Conducting the REA

    a. Systematic searches

Search terms were applied using the key words outlined below in Web of Science. The project team documented the date of each search, noting the number of articles returned.

    b. Evidence Screening: RAG Screening titles and Abstracts

RAG (Red-Amber-Green) rankings were used to screen the evidence based on title and abstract content, ranking it as ‘clearly relevant’ (Green), ‘clearly not relevant’ (Red) or ‘uncertain’ (Yellow). Evidence that was ‘clearly not relevant’ was discarded and evidence that was ‘clearly relevant’ or ‘uncertain’ was recorded and carried through to the full reading. To avoid the duplication of work, searches were combined at this stage and duplicate titles removed.

    c. Full reading (in priority order)

Working in an ascending fashion through the ‘Green’ abstracts, the content was read. Where the content was clearly relevant (‘Green’) the researcher moved directly into data extraction. Where the content was initially evaluated as ‘Amber’ at evidence screening, a full reading was conducted and if there was relevant evidence found, the data was extracted. If relevant evidence was not found it was discarded and not taken further with a short justification recorded.

d. Complete Data Extraction

Where the content was clearly relevant ('Green'), data was extracted. Due to time constraints a time suitable REA protocol was developed. This meant the number of relevant titles taken forward to full data extraction was limited to 50 per research question crop group combination.

Search criteria

The systematic searches outlined below were conducted using Web of Science. These were initially based on the crop species outlined by AHDB in Table 1.

Table 1. Scope of crops to be included in Rapid Evidence Assessment (REA).

Crop	Alternative name	Latin name
Wheat		*Triticum aestivum* subsp. *aestivum, Triticum aestivum* subsp. *spelta*
Barley		*Hordeum vulgare*
Rye		*Secale cereale*
Triticale		*Triticosecale*
Oats		*Avena sativa, Avena strigosa*
Oilseed rape	Rapeseed, canola	*Brassica napus*
Linseed	Flax	*Linum usitatissimum*

5.4. Search terms

Searches were conducted using Boolean search terms. The operator 'AND' was used to combine key words together, producing relevant search results.

In total 2 search strings were produced for each key crop group (Table 1). The operator 'AND' was used to link crop group, variety/cultivar and fungicide. The outputs of the search are summarized in Table 2. Splitting the searches into crop groups and research questions ensured that a range of relevant material was sourced.

5.5. Evidence screening

To ensure that the review focused on the most relevant material to UK fungicide practices used for variety trial under AHDB, exclusion criteria were developed. Articles were excluded which were:

- Studied based on crops not listed in Table 1.
- Studies containing seed treatments.
- Studies containing less than one fungicide treatment.
- Studies containing less than two varieties.

In total 1439 papers were sourced of which 272 were taken to the title and abstract reading stage and 68 were taken to the full reading stage from which data was extracted.

Table 2. Break down of literature identified and reviewed.

Search Criteria	Crop group	Articles sourced	Articles Screened	Articles Fully Read
'Crop group' and Cultivar and Fungicide	Wheat	658	50	16
	Barley	206	50	13
	Oats	33	14	6
	Oilseed rape	50	27	5
	Rye	16	9	1
	Triticale	14	9	2
	Linseed	3	1	0
'Crop group' and Variety and Fungicide	Wheat	317	50	11
	Barley	84	38	7
	Oats	16	6	2
	Oilseed rape	20	8	5
	Rye	12	6	0
	Triticale	8	3	0
	Linseed	2	1	0

5.6. Data extraction

All evidence identified as suitable for full data extraction was collated in an evidence extraction Excel database. For each relevant publication the following information was captured:

- Author Title
- Journal Volume
- Number
- Pages
- ISSN
- DOI
- url
- Year
- Type of Article

Relevant evidence in relation to the research questions, including but not limited to:

- Crop
- Country
- Number of Varieties/Cultivars Type Of Fungicide
- Rates of Application
- Timing of Treatments
- Site Seasons (Total trial number)
- Plot replication
- Years
- Experimental Design

- Statistic Package used
- Statistical method
- Yield data
- Quality of Grain
- Parameters of Grain Quality
- Disease
- Abstract
- Conclusion of Study
- Quality of Paper

5.7. Quality assessment of evidence

A database of relevant publications was created in a systematic way, to ensure that data extraction was consistent. To assess the quality of evidence, information was collected on:

- Type of evidence (e.g. research paper, review paper)
- Research design (e.g. field, laboratory or glasshouse)
- Crop(s) studied
- Geographical context

The researchers made a professional judgement, based on the below principles of credible research enquiry in Table 3, to ensure that only high-quality evidence was included in the REA. A score of 1-5 (1 being not at all, 5 being completely) was assigned for each paper based on the quality categories (transparency, appropriateness, cultural sensitivity, validity, reliability, and cogency) and criteria summarised in Table 3. Papers which were given a score of <2 on the overall quality were excluded from the review write-up.

Table 3. Principles of credible research enquiry.

Principles of quality	Associated questions
Transparency	Does the study present or link to the raw data it analyses?
	What is the geography/context in which the study was conducted?
	Does the study declare sources of support/funding?
Appropriateness	Does the study identify a research design?
	Does the study identify a research method?
	Does the study demonstrate why the chosen design and method are well suited to the research question?
Cultural sensitivity	Does the study explicitly consider any context-specific cultural factors that may bias the analysis/findings?
Validity	To what extent does the study demonstrate measurement validity?
	To what extent is the study internally valid (within the sample)?
	To what extent is the study externally valid (within the wider population)?
	To what extent is the study ecologically valid (within the environment)?
Reliability	To what extent are the measures used in the study stable?
	To what extent are the measures used in the study internally reliable?
	To what extent are the findings likely to be sensitive/changeable depending on the analytical technique used?
Cogency	Does the author 'signpost' the reader throughout?
	To what extent does the author consider the study's limitations and/or alternative interpretations of the analysis?
	Are the conclusions clearly based on the study's results?

5.8. Results

The results of the academic literature search are set out in a separate Excel file and summarised below, by crop species.

5.8.1. Wheat

A total of 27 relevant articles were identified for wheat; all studying winter wheat and one also covering spring wheat. Three of the articles were from each of the USA, Canada and Ethiopia, two articles were from each of Italy, Denmark, Austria and Germany, and one article was from each of Hungary, UK, Luxembourg, Portugal, Ireland, Poland, Czechia, Croatia, Argentina and China. The studies explored between two and 15 varieties and between one and two fungicide modes of action. Between one and seven trials were conducted, with the number of plot replicates ranging from two to four. Experimental designs included split-plot and randomised block. Statistical methods used were analysis of variance (ANOVA), Tukey test, linear regression, least significant difference (LSD), Fisher tests, Pearson correlations and chi square. A total of 25 of the studies generated yield data and grain quality data included thousand grain weight, hectolitre weight, specific weight, Hagberg falling number, protein content, gluten content and DON content. Diseases present in the trial included fusarium head blight, septoria tritici blotch, brown rust, powdery mildew, Alternaria black point, tan spot and yellow rust. A theme across the studies was that both varietal resistance and fungicide use were important for controlling disease and therefore for maintaining yield and quality in wheat. Differences between fungicide treated and untreated were reported more commonly than differences between fungicide treatments. One study reported that variety yield rankings depended on the year and whether plots were fungicide treated or untreated, with fungicide use more important in years with high disease pressure. Another study reported that the combination of resistant varieties with fungicide use provided the best economic benefits.

5.8.2. Barley

A total of 18 relevant articles were identified for barley; covering both winter and spring crops. Three of the articles were from the USA, two articles were from each of the UK, Canada, Italy and Ireland, and one article was from each of Ethiopia, Uruguay, Sweden, Ecuador, Estonia and Germany. The studies explored between two and 26 varieties and between one and five fungicide products. Between one and three trials were conducted, with the number of plot replicates ranging from two to four. Experimental designs included split-plot and randomised block. Statistical methods used were analysis of variance (ANOVA), Tukey test, linear regression, least significant difference (LSD), Shapiro-Wilk test, Student-Newman-Keuls test, mixed effect models and Duncan’s new multiple range test. A total of 16 of the studies generated yield data, and grain quality data included thousand grain weight, specific weight, protein content and malting parameters. Diseases present in the trial included rhynchosporium, fusarium head blight, rust, powdery mildew and net blotch. Five studies reported that fungicides controlled disease across the varieties, with one study reporting no significant effect of fungicide input and one study reporting interactions between site, year, variety and fungicide on disease and yield. Disease was reported to negatively impact yield, thousand grain weight and carbohydrate content, with two studies reporting smaller yield losses in resistant/intermediate varieties compared with susceptible varieties. One study reported that reduced fungicide doses resulted in lower yields across varieties.

5.8.3. Oats

A total of seven relevant articles were identified for oats; six of which related to winter oats and one of which related to winter and spring oats. Four of the articles were from Brazil, one from Argentina, one from Canada and one from Estonia. The studies explored between two and 15 varieties and between one and two fungicide modes of action. Between one and four trials were conducted, with the number of plot replicates ranging from three to five. Experimental designs included split-plot and randomised block. Statistical methods used were analysis of variance (ANOVA), Tukey test, linear regression, least significant difference (LSD), Liliefors' normality test, mixed model analysis and critical point models. All of the studies generated yield data and grain quality data included thousand grain weight and hectolitre weight. Diseases present in the trials included crown rust and leaf spot. Two studies reported no differences between fungicide treated and untreated, and four studies reported that performance was in line with varietal resistance levels and fungicide inputs. In one study it was commented that more resistant varieties did not need fungicide inputs.

5.8.4. Triticale

A total of two relevant articles were identified for triticale; both studies were from Germany and explored winter triticale together with other winter cereals. The studies explored 30+ varieties and an unknown number of fungicide modes of action. Between three and 40+ trials were conducted, with three plot replicates in one study and an unknown number in the other study. Experimental designs were randomised block. Statistical methods used were regression analysis and modelling. Both studies generated yield data and grain quality data included ear density and single ear weight. Diseases present in the trials included powdery mildew, brown rust, septoria leaf blotch and yellow rust. Significant improvement of yield was reported with fungicide treatments, with variable levels of efficacy depending on the disease.

5.8.5. Rye

One relevant article from Germany was identified for winter rye. The study explored five varieties and one fungicide product. Two trials were conducted, with three plot replicates in randomised complete block design. Statistical methods used were analysis of variance (ANOVA) and t-test. The study generated yield data and included analysis of protein and asparagine. The study found a significant impact of the management system, with higher asparagine content in the conventional management system compared with the organic system. With an appropriate choice of the cultivar, a 12.5% reduction in asparagine was possible.

5.8.6. Oilseed rape

A total of eight relevant articles were identified for winter oilseed rape. Two of the articles were from the UK, one from Germany, one from Poland, one from Latvia, one from Lithuania, one from Turkey and one from Canada. The studies explored between two and 15 varieties and between one and five fungicide products. Between one and five trials were conducted, with the number of plot replicates ranging from three to four. Experimental designs included split-plot and randomised block. Statistical methods used were analysis of variance (ANOVA), Fisher test, mixed models, restricted maximum likelihood (REML), general linear models, t-tests, least significant difference (LSD) and Levene's test. Seven of the studies generated yield data and quality data included thousand seed weight, moisture content, seed oil content, free fatty acid, oil content, protein content, oleic aid content and linolenic acid content. Diseases present in the trial included alternaria, phoma, light leaf spot, powdery mildew and sclerotinia. Five studies reported that fungicides reduced disease levels, but across studies the impact of fungicides on yield and quality was more variable. One study reported significant fungicide x variety interactions; another study reported no such interactions.

5.8.7. Linseed

No relevant articles were identified for linseed.

5.8.8. Knowledge gaps

- Whilst seven or more relevant articles were found for wheat, barley, oats and oilseed rape, very few articles were found for triticale, rye and linseed.
- The evidence primarily related to winter crop types, with fewer studies exploring spring types.
- Whilst most studies included a measurement of grain or seed yield, there was very little consistency in quality parameters measured.
- Studies didn't tend to cover a wide variety of diseases that can impact the crops.
- Different timings of the fungicide sprays were only present in wheat and barley studies and showed variable effect on disease.

5.8.9. Key findings

- Studies generally – but not always – reported significant impacts of fungicide treatments in reducing disease levels. In some cases fungicide use had a significant benefit in terms of yield or quality, though these effects were more variable.
- Varietal performance was generally reported as being in line with varietal resistance to disease. In some cases interactions between variety and fungicide were reported, with resistant varieties responding less to fungicide inputs.

- Disease pressure, year and location played a significant role on the interaction between fungicides and variety.

5.8.10. Recommendations

- Given the paucity of published studies for crops such as rye, triticale and linseed, particularly under relevant UK or European conditions, publication of variety x fungicide field work for these crops (particularly spring types) should be a priority.
- The evidence relating to grain or seed quality is scant, due to inconsistencies in parameters measured. A focus should be on consistent measurement of key grain or seed parameters.
- Due to the variable effects of varieties and fungicides reported across studies, a recommendation is for reduced fungicide input studies to incorporate as many site seasons as is feasible, to allow more meaningful interpretation of the results.

6. Evidence from AHDB reports

6.1. Methods

AHDB reports represent an excellent source of evidence for this review project as they typically summarise testing of UK varieties and fungicide inputs, under UK conditions with associated local disease pressures and crop yields. The findings are therefore highly relevant for considerations of future UK variety testing under reduced fungicide inputs. The abstracts of online AHDB reports relating to varieties and fungicide use were scanned for relevance to this review project on the impact of reduced fungicide treatments on variety performance. The initial search was on recent AHDB reports as these were considered likely to best reflect current variety performance and fungicide spray programmes. Relevant reports are summarised below, with a particular focus on how trials were set up and any information relating to yield and quality under reduced inputs. The report summaries were then considered in relation to the current project and any relevant knowledge gaps, key findings and recommendations were outlined. Further AHDB reports were not included if it was considered that the relevant findings essentially duplicated those from reports that were already included. The AHDB report summaries are set out below in project title alphabetical order. The identified knowledge gaps, key findings and recommendations are included in the relevant sections with those titles, at the end of the report.

6.2. Combining agronomy, variety and chemistry to maintain control of septoria tritici in wheat. AHDB Project Report No. 634. June 2021.

This project explored integrated pest management strategy (IPM) methods for the control of Septoria leaf blotch (*Zymoseptoria tritici*) in winter wheat. It investigated the impact of four factors on the severity of septoria and final yields: sowing date, seed rate, variety and fungicide. The work involved

25 field trials in the UK and Ireland, conducted across five harvest years (2016–20). The plot size in each trial was a minimum of 20m^2, and in 2019 and 2020 the site at ADAS Rosemaund was irrigated to increase disease pressure. All sites relied on natural disease infection. A randomised, split plot design incorporating standard randomisation of treatments within each replication was used. The different sowing dates were sown in split plots, and seed rate, variety and fungicide randomised within. Sites 1 – 18 incorporated 48 treatments with three replications. Sites 19 – 25 incorporated 24 treatments with three replications.

Three varieties were sown at each site with differing susceptibilities to septoria. These are referred to as ‘susceptible’, ‘moderately susceptible’ and ‘moderately resistant’. Varieties were chosen and their resistance scores recorded based on the AHDB Recommended List that would have been available to growers at the time of sowing. Varieties were also chosen for their good resistance to other, non-target diseases. The varieties used were changed during the project to reflect choices relevant to growers and the changing recommendations. Four levels of fungicide input were tested. These were referred to as ‘low’, ‘medium’ and ‘high’ input programmes, with an untreated that received no fungicides for the control of septoria. Products were carefully selected so that higher input programmes involved additions to the lower input strategies. This minimised the risk of changes in product or mode of action activity from invalidating the results. Products used were substituted, when necessary, to reflect changes in product efficacy and regulation.

In all trials, disease, yield, and grain quality were summarised by analysis of variance. Each season, results from all sites were combined to provide an across site mean for disease, yield and specific weight and analysed using analysis of variance. An analysis across all sites and seasons was also completed, and sites were additionally analysed in groups by disease pressure. When analysing sites across years the data from the high seed rates was used for sites 1 to 18 to create a balanced design.

It was found that earlier sowings consistently resulted in higher disease severity during the main yield-forming period than later sowings. This is most likely due to crops being exposed to spores earlier in the season. Variety and fungicide also had a significant effect on septoria severity, with a clear interaction between the two. The yield response to fungicides was much smaller in more resistant varieties, compared to susceptible varieties. Higher seed rates, and, therefore, thicker crops, can lead to greater disease severity. However, the effect was small and inconsistent across trials. Factors were tested for a significant impact on specific weight in each trial year. In 2016-2019 inclusive, variety and fungicide were found to have significant effects alone and through interaction with each other. In 2020 there was no significant differences in specific weight by variety or fungicide as differences between treatments were small, possibly due to the very dry conditions.

It was concluded that growers should tailor their fungicide strategy to variety and sowing date to better optimise the use of fungicides. By sowing varieties with stronger disease resistance later in the autumn, there may be considerable scope to reduce the risk of a damaging septoria epidemic – enabling the use of lower fungicide inputs. The report includes a measure of the extent to which varietal susceptibility to septoria may be increased or decreased with earlier or later sowing, respectively.

Knowledge gaps: this research focussed on septoria, so provided little or no information on the control of other diseases and how that might vary by variety or disease pressure.

Key findings: Varieties and fungicides have significant direct and interacting effects on wheat grain yield and specific weight in septoria field trials. The yield response to fungicides was much smaller in more resistant varieties, compared to susceptible varieties. Growers should tailor their fungicide strategy to variety and sowing date to better optimise the use of fungicides.

Recommendations: Any programme of variety testing at reduced fungicide inputs should consider the potential impact of sowing date on the data.

6.3. Consequences of intensive fungicide use or integrated disease management for fungicide resistance and sustainable control. AHDB Project Report No. 588. February 2018.

The aim of this project was to produce evidence on the consequences – for fungicide resistance evolution and for gross margin - of intensive fungicide use compared to an integrated disease management approach, combining variety disease resistance and fungicides. Field experiments with winter wheat varieties rated as resistant, intermediate or susceptible to septoria (*Zymoseptoria tritici*) infection, compared the effect on selection for fungicide insensitive strains of *Z. tritici* from the combined effect of host resistance and a reduction in foliar azole fungicides enabled by host resistance and/or using disease forecasting. Whilst no data were presented in the report on the impact of treatments on yield or quality, it was explained by the authors that it is well known that impact on yield is closely correlated with the septoria disease severity at GS75. Hence, the project findings are referred to below.

Results showed a clear increase in selection for less sensitive isolates of septoria with increased total fungicide dose, increased number of sprays and a more susceptible variety. The effect of integrated disease control on gross margins (GM) was analysed for trials contributed by industry partners (at least 4 trials/year for 3 years) all using the same fungicide products to provide low, moderate and high intensity programmes applied to varieties rated as resistant, intermediate or susceptible to *Z. tritici*. In 2014, septoria pressure was high and all programmes gave an increase in

GM over untreated. With no treatment, the resistant variety gave the highest GM. Across all treatments in 2014, on average the susceptible variety had the highest GM. In contrast, 2015 was a low-septoria year, and the untreated resistant variety had the highest GM. Of the three treatment programmes, for all varieties, the highest GM was with the lowest fungicide inputs. Responses to disease control were moderate in 2016, and GM was similar between fungicide programmes.

Modelling work showed that the effective life of a fungicide active ingredient can be prolonged by using resistant varieties and disease forecasting. A forecasting model, developed previously, was coupled to an economic model accounting for risk aversion in spray decisions and extended to account for selection for insensitive pathogen strains due to fungicide applications. Simulations using this model showed that the use of a septoria resistant variety or combining a septoria resistant variety with using disease forecasting to guide treatments, could substantially slow the development of fungicide resistance. The key messages from the project are [a] development of resistance to fungicides is driven by the number of sprays and the dose rate, [b] uncertainty about future disease encourages risk-averse intensive fungicide programmes, [c] current UK fungicide programmes are appropriate when disease is high, on susceptible varieties, [d] variety resistance makes the intensity of spray programmes less critical, and forecasting economically viable, and [e] use of strategies which integrate variety resistance will slow selection for fungicide resistance.

Knowledge gaps: This report highlights the potential for different seasons to have different impact on the gross margins of disease control strategies that rely more on varietal resistance or on fungicide inputs. However, more information is needed to guide growers on the impacts of different fungicide inputs on gross margins.

Key findings: Different disease control strategies can impact the gross margin of disease control. Greater fungicide use can drive the pathogen population more quickly towards resistance. Varietal resistance makes the intensity of spray programmes less critical and forecasting economically viable.

Recommendations: Any programme of variety testing at reduced fungicide inputs should consider whether to focus on the potential impact of different fungicide inputs on gross margin. Messaging around reduced fungicide inputs should also refer to beneficial impacts of varietal resistance on fungicide resistance selection and on the viability of disease forecasting.

6.4. Exploiting new fungicides and varieties to reduce fixed costs. AHDB Project Report No. 281. June 2002.

This project set out to examine how the introduction of the new strobilurin fungicides, coupled with the introduction of winter wheat varieties with superior disease resistance could be exploited to reduce the fixed costs of wheat production by reducing the number of fungicide applications from three to two whilst maintaining disease protection throughout the season. The project was conducted in Norfolk in the 1999 to 2001 seasons on crops of Riband and Claire, representing disease susceptible and disease tolerant varieties respectively. The drilled plots were 12 m long and 1.6 m wide from outside row to outside row (14 rows at 12.0 cm spacing). Plots were separated by a buffer of the same size with a 54 cm gap between successive plots and buffers. This gave an effective plot width of 2.1 m, which was used for harvest yield calculations. Treatments were applied to the plot and to half of the buffer at each side. For harvest purposes, plot length was reduced to 9.0 m.

The disease pressure in the three seasons varied considerably, with 1999 being typified by early intense pressure from *Septoria tritici*, which was sustained throughout the season and later from brown rust. In 2000, disease pressure built during the season and was mainly from septoria. The 2001 season was typified by low disease pressure. The difference in untreated yield between the two varieties underlined the benefit in selecting a variety with disease resistance. In Riband, a three-spray programme was necessary in the first two years, when there was high disease pressure, to achieve maximum margins. With Claire, a two-spray programme gave the highest yield and thus proved the most cost-effective treatment. The project demonstrated that the combination of improved disease resistance and more effective fungicides calls in to question the need for the traditional three-spray approach to control diseases in disease resistant winter wheat varieties. Savings in time and application costs are important for growers. Any additional cost in fungicide when employing a two-spray strategy over that used in a conventional three spray programme is offset by the convenience of a reduction in passes through the crop and the simplicity the two-spray strategy provides in terms of crop management.

Knowledge gaps: None identified.

Key findings: The project highlighted that the combination of resistant varieties and effective fungicides allowed for a reduction in the number of spray timings needed for disease control. This allows potential savings in time and application costs.

Recommendations: Any programme of variety testing at reduced fungicide inputs should consider the potential savings to growers of reducing the number of spray applications, in addition to potential savings from reduced total dose applied.

6.5. Fungicide performance in wheat, barley and oilseed rape (2015–18). AHDB Project Report No. 628. March 2019.

This project tested the efficacy of fungicides against the main pathogens of wheat, barley and oilseed rape across four harvest seasons (2015–18). The diseases targeted were those with the highest incidence and/or greatest potential economic impact for growers. The fungicides included new active substances, new mixtures of existing chemistry and treatments established as current commercial standards. A wide range of modes of action were trialled, including azoles, SDHIs, strobilurins and multi-site inhibitors. Fungicides were tested at a range of application rates against each pathogen to enable creation of dose response curves. These curves allow comparisons to be drawn between treatments for disease control and yield, and for shifts in efficacy to be monitored over several years.

Wheat experiments were conducted against three foliar diseases: *septoria tritici*, yellow rust and brown rust. These diseases were assessed in nine or ten trials across seven sites each year, selected for high disease risk and using susceptible cultivars to create high disease pressure for each of the target diseases. The plot size in each trial was in the range of 20 – 60 m^2 for all sites. Brown rust trials were inoculated to ensure products were effectively tested against a disease which can otherwise be spasmodic. A randomised block design incorporating standard randomisation of treatments within each replication was used. Each trial incorporated between 18 and 67 treatments with three replicates.

Winter barley experiments were conducted against three foliar diseases: net blotch, powdery mildew and rhynchosporium, and ramularia in spring barley. There were seven sites each year. Sites were selected to represent a high-risk scenario for the target diseases, based on prevailing environmental conditions and history. Trials were drilled with susceptible cultivars at the correct seed rate for the locality and soil type. The size of the plots in each trial ranged from 20 to 60 m^2, typically 12 m x 2 m. All trials relied on natural infection. A randomised block design incorporating standard randomisation of treatments within each replication was used. Each trial incorporated 36 to 40 treatments, including an untreated control and each treatment was replicated three times.

Oilseed rape experiments were conducted against three diseases: sclerotinia stem rot, phoma leaf spot/stem canker and light leaf spot. There were seven sites each year (two sites for phoma leaf spot/stem canker, three sites for light leaf spot and two sites for sclerotinia stem rot), all selected for high risk of naturally occurring infection. Varieties susceptible to the target diseases, but resistant to non-target diseases, were selected where possible. Disease risk in relation to geographical risk was also considered when selecting varieties. The size of the plots in each trial was a minimum of 40 m^2. Fungicides were applied, where appropriate, to control non-target diseases to minimise their impact on yield. A randomised block design incorporating standard randomisation of treatments within each replication was used, with 30 treatments including two untreated controls, replicated three times. The untreated control plots were randomised within the trial, with one in each half of the block.

In wheat, fungicide treatments were tested by applying single applications at rates, ranging from quarter to double dose on septoria tritici, yellow rust, brown rust and head blight. Single applications were also used to test the effect of fungicides against rhynchosporium, net blotch, ramularia and powdery mildew in barley. For oilseed rape, phoma leaf spot/stem canker and light leaf spot were tested using a two-spray programme. Efficacy against sclerotinia stem rot was evaluated using a single fungicide application at early to mid-flowering.

In all crops, disease and yield was summarised for all sites/seasons by analysis of variance and the validity of the analysis was checked by examination of the residuals. Exponential dose-response curves were plotted for each fungicide/activity using the equation y = a + bekx (y = % disease or yield and x = proportion of the full label application rate). All curves were constrained to pass through the mean of the untreated plots. Each season, results from all sites were combined to provide an across site mean for disease and yield. Analysis from previous fungicide performance projects has shown that, whilst no transformation is needed for yield, a logit transformation of % disease provides a more valid analysis and can be back-transformed for ease of evaluation. This process provided a more equal weighting between sites. Exponential curves were fitted to REML adjusted means to provide over-site means and season summaries. In all crops and diseases, dose response curves varied considerably between fungicides, with apparent variation in both the curvature and the asymptote. This emphasises that both product choice and dose can have marked differences on disease control. It was stated that these data can be used by growers and agronomists to generate robust fungicide programmes targeting specific disease threats and to evaluate shifts in treatment efficacy over time.

It was stated that yield responses to single spray applications, which do not fully control disease, will not reflect yield responses that will be seen in practice where a more comprehensive strategy of repeat applications is usually employed. These results however are of use to compare the relative activity of different active substances and any shifts in efficacy over time. In general, the crop yields tended to reflect the extent of disease control, however some disparities were noted for diseases of wheat and oilseed rape. In practice, commercial disease control strategies involve a number of fungicide application timings, with products often being applied in mixtures for efficacy and resistance management.

Knowledge gaps: This report highlights a potential knowledge gap in terms of whether crop yields tend to follow disease control from fungicides. It was reported in this project that they did in general, though with some disparities. However, given that commercial spray programmes are likely to include a number of spray applications and different fungicide modes of action in mixture and/or alternation, the potential for such disparities to be apparent seems less likely than in the fungicide performance project trials.

Key findings: In all crops and diseases, dose response curves varied considerably between fungicides, with apparent variation in both the curvature and the asymptote. This emphasises that both product choice and dose can have marked differences on disease control in susceptible varieties. It also shows that the appropriate product may differ depending on the disease in question.

Recommendations: Any programme of variety testing at reduced fungicide inputs should consider product choice and dose carefully, to maximise disease control. The AHDB fungicide performance data provide a very useful resource to guide choice of both product and dose. Consideration should also be given to good resistance management; ensuring a diversity of fungicide modes of action in a spray programme is key.

6.6. Managing roots, nitrogen and fungicides to improve yield and quality of wheat. AHDB Project Report No. 359. February 2005.

The aim of this project was to determine whether root growth, distribution and activity late in the growing season (particularly after flowering) influence grain yield and quality of cultivars in response to fungicide and late-season nitrogen applications. Four experiments were carried out over three seasons on a free-draining sandy loam overlying sand at the Crops Research Unit of the University of Reading. These investigated the effects of cultivar, irrigation/drought, fungicide applications, and late-season nitrogen applications to soil or foliage on root growth and distribution, canopy green area duration, grain yield, grain quality, and root activity in nitrogen uptake from the soil.

Experiment F1 was conducted in the first two years and involved two winter wheat cultivars and eight fungicide treatments arranged in a split-plot design with three randomised blocks divided into cultivar main plots (20m x 8m) partitioned into fungicide treatment sub-plots (10m x 2m). Experiment F2 was conducted in all three years and was also a split-plot design, but with six winter wheat cultivars as main plots, randomised in three blocks. In 2000/01 and 2001/02 cultivar main plots (12 x 10 m) were divided into six subplots (2 x 10m) to receive one of each of the factorial combinations of three fungicide treatments; further divisions were made to include different nitrogen treatments. In 2002/03 there were no late-season nitrogen treatments, so the experiment comprised three blocks, divided into six cultivar main plots (6 x 10 m), divided into three sub-plots (2 x 10m) each receiving fungicide Treatment 1, 2 or 8. Experiment F3 was only conducted in the 2002/03 growing season. A split-split-plot factorial design was used where two irrigation treatment main plots (12m x 20m) were replicated in three randomised blocks. Main plots were divided into four sub-plots (6m x 10m). These received one of the four factorial combinations of two fungicide treatments (1 and 8) and two late season nitrogen fertilizer treatments. The sub-plots were further split into three cultivar sub-subplots (2m x 10m).

It was found that when fungicides were applied, the size of root system was maintained during early grain-filling, and root length typically increased. There were significant differences between cultivars in the quantity of roots below 30 cm depth. Fungicide applications had small, but seasonally variable, effects on root growth but consistently increased green leaf area duration. Application at flag leaf emergence generally gave good control of all diseases with little benefit from a further application at ear emergence. There were significant differences between cultivars with Consort being most responsive. Fungicide applications significantly increased grain yields (through increased thousand grain weight and specific weight) and grain N content by delaying leaf senescence via disease control. Grain yield and N content were related to green leaf area duration after anthesis. It was suggested that fungicide application may delay both senescence of leaves and of the root system, leading to increased N in the grain, either through continued uptake of N into the crop, or through retention of N in the plant that would otherwise leach from the plant.

Knowledge gaps: This report highlights the potential for interactions between fungicide use and nitrogen inputs in terms of grain yield and quality. However, more information is needed to guide growers on the impacts of reducing both fungicide and nitrogen inputs independently or together.

Key findings: Different disease control strategies can impact the rooting of different varieties, which may in turn impact increased nitrogen in the grain, grain yield and grain quality.

Recommendations: Any programme of variety testing at reduced fungicide inputs should consider whether there is sufficient information available to guide growers on likely impacts of reducing nitrogen inputs as well. If evidence is limited, then this should be made explicit, and it may be better to focus on fungicide inputs and nitrogen inputs separately.

6.7. Understanding effects of new wheat fungicides on disease development, crop growth and yield. AHDB Project Report No. 261. September 2001.

This project used three years of field experiments at two sites to investigate whether strobilurin fungicides have physiological effects on winter wheat that could be detected and exploited in the field, and to test the effects of mixing strobilurins with azole fungicides. Field experiments were completed in the 1998-2000 harvest years at ADAS sites in Herefordshire and Cambridgeshire. The design for each experiment was a randomised block with three replicates. Experiments which included destructive sampling for growth analysis had duplicate plots of each treatment, one of which was used for growth analysis and the other for disease assessment and yield determination. Fungicides were applied in two-spray programmes, at GS 31-32 and GS 39.

It was found that on a resistant cultivar at a low disease site, there were consistent yield increases resulting from strobilurin application, although yield responses were smaller than at the site with severe disease. Dose-response curves for strobilurins were generally similar to those for azole fungicides. Experiments on the interaction between fungicides and nitrogen assimilation indicated that strobilurin fungicides did not affect nitrogen uptake, but there was an indication (not statistically significant) that the optimum nitrogen rate was slightly higher for strobilurins, compared with epoxiconazole or an untreated control. There were no differences between strobilurins and epoxiconazole in maximum green area index, and no evidence of any effect of strobilurins on radiation use efficiency either pre-anthesis or post-anthesis. Canopy size showed a close inverse relationship with disease, and yield was closely correlated with canopy size. There were no clear indications that yield increases resulted from physiological effects on the crop. Under conditions of severe disease, yield was strongly correlated with increase in canopy duration, and there was no evidence of any physiological effects of strobilurins. Overall, these results show that the value of physiological effects to growers under normal conditions of moderate or high disease risk would be small in relation to the large fungicidal effects that occur consistently. If there are additional physiological effects of strobilurins on wheat, they should be regarded as a bonus from use of these fungicides, rather than a core feature of their activity.

Knowledge gaps: None identified.

Key findings: Overall, these results show that the value of physiological effects to growers under normal conditions of moderate or high disease risk would be small in relation to the large fungicidal effects that occur consistently.

Recommendations: Any programme of variety testing at reduced fungicide inputs should consider whether the choice of fungicide mode of action may alter the findings due to the potential for physiological effects. However, the findings from this study suggest that, in the absence of substantial evidence to the contrary, such physiological effects from fungicides are likely to be small relative to their impact through effective disease control.

6.8. Wheat fungicide margin challenge 2021 (ADAS/AHDB). AHDB Project No. 638. November 2021.

The ADAS/AHDB wheat fungicide margin challenge was set up to connect farmers across a network of regional sites to develop crop management strategies that focus on margin maximisation, rather than headline yields. The challenge was designed to provide a fair comparison between farmers' regional fungicide strategies in winter wheat plots (with a locally popular variety) on a single site. All of the plots were taken through to harvest, with the aim to achieve the highest net margin. In 2019, the approach was tested at a single site (Herefordshire). In 2020, the challenge covered three regions (West, East and South). In 2021, the challenge was widened to include six regions. The rules were as follows:

- Each region features around 10 AHDB entrants*
- Entrants design a bespoke fungicide programme, with application overseen by ADAS staff

- ADAS includes three additional fungicide strategies for comparison: ‘untreated’ (no fungicides), ‘blockbuster’ (very high fungicide inputs to establish yield potential) and an ‘expert’ entry
- Standard spray timings are used: T0 GS30, T1 GS32, T2 at GS39 and T3 at GS61–65
- All other inputs (excluding fungicides) follow standard farm practice and are applied by the host grower
- Each programme is replicated on four randomly allocated plots (minimum plot size of 20m2)
- Entrants receive in-season updates on crop/disease progress
- ADAS records fungicide spend, disease levels and grain yield
- Although strategies and results are shared among participants, entrants are not revealed (without permission)
- Margins are calculated for each treatment, based on average grain prices and average fungicide and application-cost data

*AHDB entries consist mainly of Monitor Farmers, Steering Group members or Arable Business Group members. This approach provides wider benefit, as the approaches taken are used as a basis for discussion at on-farm meetings. The AHDB Farmbench tool is also used to allow growers to directly compare their own fungicide strategies against those entered in the challenged.

Across the six regions, untreated yields were generally substantially lower than fungicide treated yields, with the untreated control generally ranked last in terms of margin (£/ha). In the three regions where specific weight was also recorded, the untreated control also had substantially lower values compared with fungicide treated plots. The ‘blockbuster’ fungicide treatment generally performed very highly in terms of yield but ranked moderately or poorly in terms of margin. For the remaining treatments there was no significant relationship between total fungicide spend and margin for any of the regions (R2 = -0.04 to 0.07), suggesting that high margins were determined by the fungicide programme being well suited to the variety and the disease pressure in the trial, rather than the fungicide spend *per se*. The following key points were reported:

- In 2020, a relatively low septoria pressure year, the lowest cost programmes delivered the highest margins
- In 2021, higher disease pressure resulted in moderate–to–high spend programmes achieving the highest margin over fungicide cost
- Multi–site fungicides were a valuable addition – 5 out of 6 winning programmes featured a multi-site
- It is important to know what yield response you can achieve to help budget for fungicide spend

Knowledge gaps: The ADAS/AHDB fungicide margin explores a range of different fungicide input levels in a way that enables strong interaction and knowledge exchange with the industry. However, more varieties would need to be included in each trial to explore the interaction between varietal resistance and fungicide input levels.

Key findings: Higher disease pressure results in higher fungicide inputs providing better margins, with multi-site fungicides often proving a valuable addition to fungicide programmes. Careful consideration of local disease pressure, varietal resistance ratings and potential yield responses on-farm are important for determining fungicide programmes that maximise the margin over fungicide cost.

Recommendations: Any programme of variety testing at reduced fungicide inputs should consider the potential for seasonal differences in disease pressure to impact the results. Flexibility in spray decisions may help to limit fungicide inputs when disease pressure is lower, therefore taking an approach designed to maximise margin over input costs.

7. Evidence from Saaten Union Trials Data

7.1. Background

During consultations with stakeholders regarding this review project, data from company field trials were requested to provide evidence for testing varieties under reduced fungicide inputs. Saaten Union provided data from two years of field trials conducted in 2021 and 2022, exploring the performance of wheat varieties under three different fungicide treatments: untreated (no fungicide), T2 spray application only (reduced input) and T1, T2 and T3 spray applications (farm input).

7.2. Results

7.2.1. 2021

The yield results are shown in Figure 1. The yield responses of the farm input programme relative to the untreated ranged from ~1.3 to ~5.9 tonnes per hectare (t/ha), suggesting significant levels of disease in this trial and large differences in varietal resistance. The reduced input treatment generally resulted in lower yields than the farm input treatment. However, for varieties that appeared to have better disease resistance levels based on yield responses (Merit, Astound and Mayflower), the reduced input and farm input treatments had similar yields. The margin (£/ha) after fungicide costs are shown in Figure 2. The values largely reflect the grain yields and show the economic importance of a full fungicide programme on more susceptible varieties under apparent) high disease pressure.

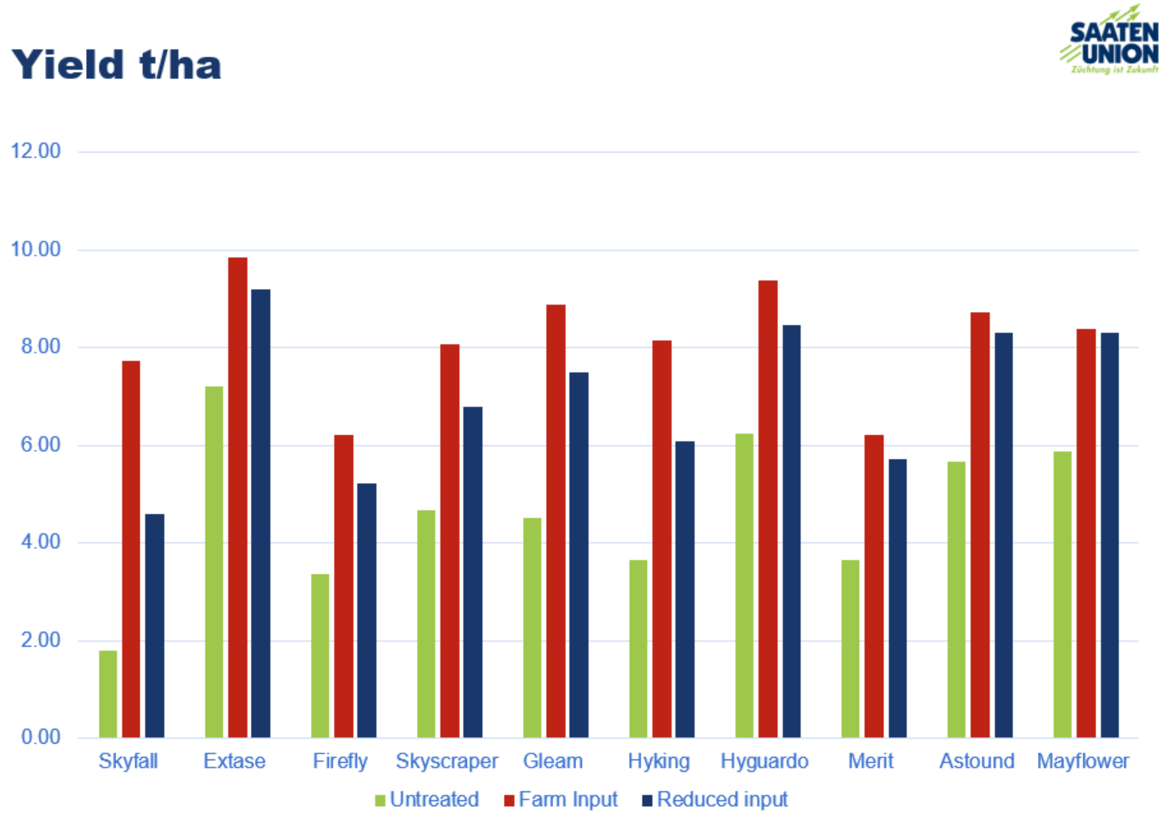

Figure 1. Saaten Union 2021 Yield results.

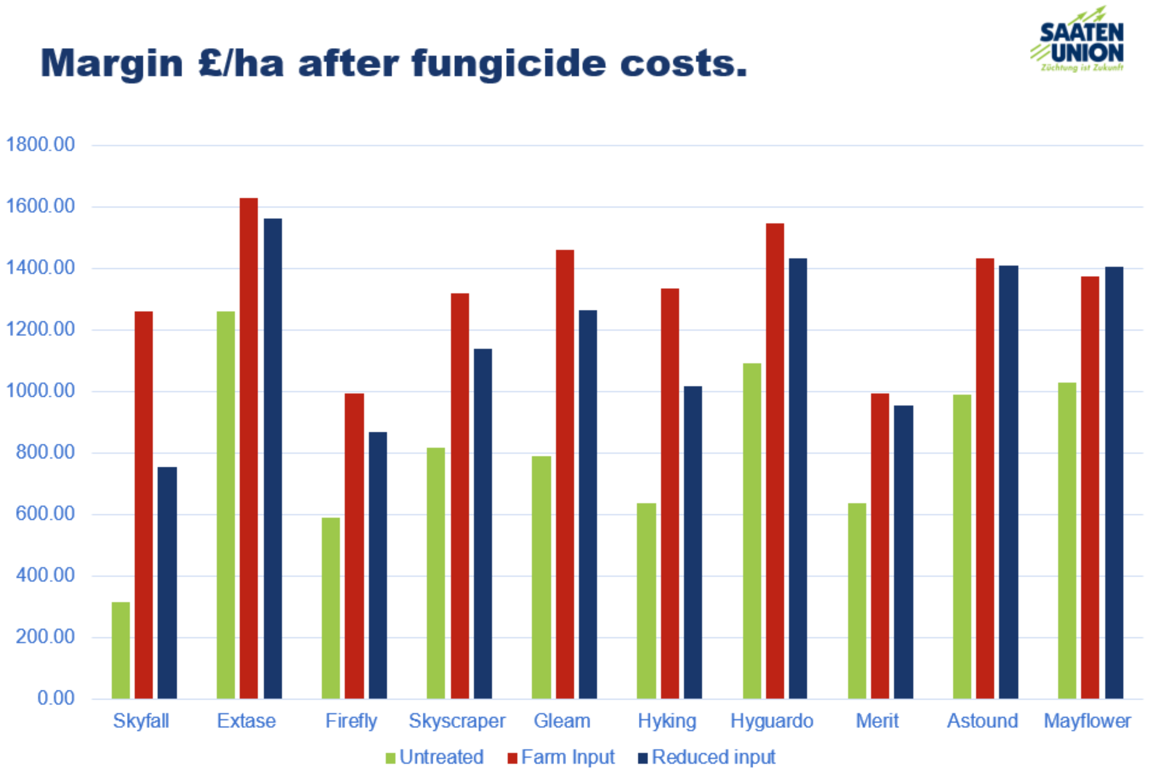

Figure 2. Saaten Union 2021 Margin results.

7.2.2. 2022

The levels of yellow rust in the trial, scored on a 1-9 scale with a greater number indicating higher disease levels, are shown in Figure 3. Yellow rust disease levels were described as low, which is reflected in the lack of obvious fungicide response for most varieties except for Gleam, which appeared more susceptible than the other varieties. The most resistant varieties in this trial appeared to be Blackstone, Bolinder and Mayflower. The yield responses of the farm input programme relative to the untreated more susceptible variety Gleam and less than 1.5 t/ha for the other varieties, as shown in Figure 4. The reduced input treatment generally resulted in lower yields than the farm input treatment. However, for varieties that appeared to have better disease resistance levels (Blackstone, Bolinder and Mayflower), the reduced input and farm input treatments had similar yields.

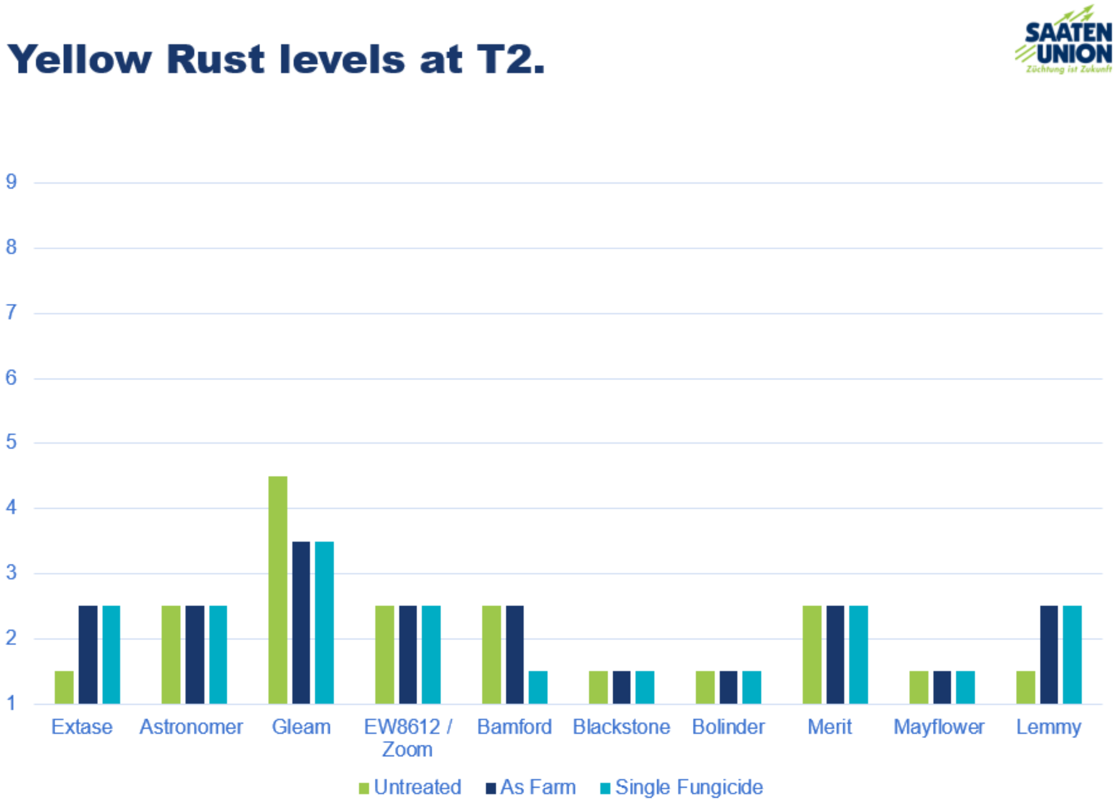

Figure 3. Saaten Union 2022 yellow rust levels.

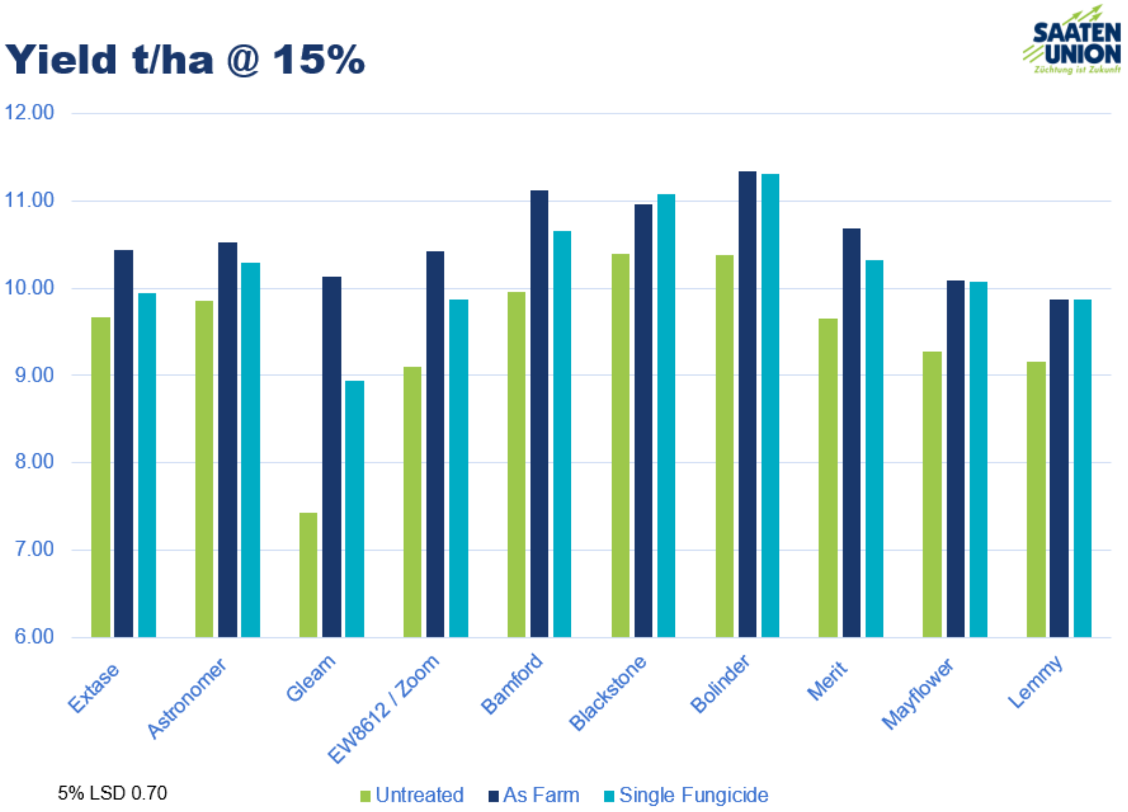

Figure 4. Saaten Union 2022 yield results.

7.3. Knowledge gaps

- The Saaten Union trials data provide important insights into testing wheat varieties under reduced fungicide inputs; however a comprehensive trials programme across crops is needed to draw more general conclusions about variety testing under reduced inputs.
- The 2021 results include margin after fungicide costs data. For AHDB testing of varieties under reduced inputs it would be useful to understand the full cost savings of reducing the number of spray applications, including time and fuel costs.

7.4. Key findings

- The reduced input treatment generally resulted in lower yields than the farm input treatment in both trials. However, for varieties that appeared to have better disease resistance levels, the reduced input and farm input treatments had similar yields.
- The margin (£/ha) after fungicide costs largely reflect the grain yields in the 2021 trial and show the economic importance of a full fungicide programme on more susceptible varieties under (apparent) high disease pressure.

7.5. Recommendations

- Reduced fungicide input trials such as these conducted by Saaten Union are highly valuable for understanding the potential to reduce fungicide use intensity on farm. Further testing using a similar approach, exploring different crops across sites and seasons is recommended. Consideration should be made as to the value of including more susceptible crops in high disease risk situations, if preliminary data suggests that such approaches may lead to damaging yield losses in certain seasons.
- Including economic analysis of different fungicide input levels would be highly valuable to growers and the industry in general. Such analysis should consider all of the on-farm costs associated with crop sprays.

8. Stakeholder Engagement

8.1. Background

An online meeting with stakeholders was conducted on 27th February 2024 to inform them of the AHDB Review and to ask for their views and for any relevant data that could be shared. This was a joint meeting, covering both the fungicide and nitrogen projects. The background to the fungicide project was presented. It was stated that current Recommended List (RL) trials are treated using a full fungicide programme designed to minimise disease, together with some untreated trials. We indicated that there is a demand from levy payers for information on variety performance at lower inputs and that AHDB have commissioned high-level reviews on evidence for any significant changes to cereals and oilseed varietal performance when trialled with different fungicide programmes. The aims, objectives and scope of the project were described and the breeders present were then asked to provide feedback on: (i) their previous experience with variety testing at lower fungicide inputs, and (ii) their views on knowledge gaps and further areas of research that were needed. Notes from the meeting relevant to the fungicide project are set out below.

8.2. Breeders previous experience relevant for review

Elsoms:

- LINK projects
- AHDB workbooks to compare sites with different N/fungicide input rates on the same soil type

Saaten Union:

- NoatS project
- Ran internal trials for ~10 years comparing 10-12 varieties with 2-3 different N rates, and lower (than RL) fungicide rates

Syngenta:

- Hybrid barley work with ADAS (Sarah Kendall)
- Internal commercial level fungicide trials
- Mentions problem of disease bias based on input timing, localized disease pressure, varietal resistance/ranking, fungicide used

IBERS:

- Spring oat trials at different N rates
- No recent work on fungicides

8.3. Views on key knowledge gaps

- Is old data relevant to current growers? E.g. regen growers using direct drilling
- Interactions between biologicals/other novel inputs impacting fungicides and N input rates
- Interactions between low N and low fungicide inputs and impact on yield + agronomic features
- BASF:
    - soil science, particularly soil microbiology
    - Considering disease tolerance as well as resistance to inform application rates
    - Systems scale approaches: interacting and confounding effects of changes in agronomy, need to consider what future systems may look like
- Limagrain;
    - PGR application timings in RL are broad, huge variability in application date
    - Need for tramline variety trials with different input rates (N+fungicide) which consider commercial rates, not RL/NL rates
    - Need to consider varieties in their own merits and in the context of localized environment
    - Growers want data considering gross margins, not just yield

8.4. General comments for the review

- Consider effects of different input rates for protein content
- Consider differences in cultivation approaches
- Consider seeding rate / plant number
- Consider effects on other agronomics features e.g. crop height for fungicide and N
- Consider differences in split rates (as well as total input level) and application timings

8.5. General comments and recommendations

Growers want commercial rate trials from AHDB comparing varieties:

- AHDB did this in the past – comparing varieties under multiple fungicide input levels

Problem with NL trial protocol

- Aim to eradicate disease within trials which is subsequently what breeders work towards
- NL trials not set up to determine response under lower input so breeders don't aim for this

Problem with RL trial protocol

- Untreated fungicide trials aren't informative if considerations about local disease pressure aren't taken into account
- RL trials need to record what fungicides go on which trials for wheat
- Breeders need time to adapt, changes have to be phased in by AHDB
- Disease resistance takes several breeding cycles to achieve
- Protocol needs to be changed to reflect targeted fungicides to certain crops

9. Prediction of Variety and Fungicide Interaction

9.1. Background

Having the ability to make a reasonable prediction of variety and fungicide interactions could provide a highly cost-effective means of understanding how varieties are likely to perform under reduced inputs. This could be achieved by deriving a model to describe these interactions and parameterising the model using real variety performance data. The model could then be used to provide generic information to growers on how varieties tend to behave under reduced fungicide inputs, or it could be used to generate specific predictions on how each variety is likely to perform under reduced inputs, with limited field trial testing each season on a small panel of varieties to ensure that the model parameterisation is optimised.

The multiplicative survival model (MSM) has been used by ADAS for more than 20 years (Paveley et al. 2003) to predict the level of disease control that would be expected from two or more fungicide sprays, based on the level of disease control observed from single sprays. Grimmer et al. 2015 showed that the same model can be used to predict the action of two or more resistance genes in wheat. ADAS has also shown that MSM can be used to predict the level of disease control from combinations of varietal resistance and fungicide inputs for potato late blight (Ritchie et al. 2018). A recent study also used multiplicative survival to model the combined effect of host resistance and fungicides on *Zymoseptoria tritici*, septoria leaf blotch disease of wheat (Taylor & Cunniffe, 2023). We have recently tested MSM in wheat variety x fungicide trials with BASF, who are willing to share the data from these trials as an in-kind contribution to this project. The MSM-based model that we have derived, together with the findings from testing the model with data from the BASF project, are set out below.

9.2. ADAS Variety x Fungicide model

ADAS developed a model that can be used to predict average proportional yield loss due to disease, accounting for the effects of fungicide application, varietal disease resistance and varietal tolerance. The model equations are generic for a foliar fungal pathogen, presented here for the example of *Zymoseptoria tritici*, septoria leaf blotch of wheat. We show how the model can be parameterised using data on varietal resistance ratings and untreated grain yield from the AHDB Recommended Lists. The model could in theory be parameterised using the type of data collected in AHDB Fungicide Performance Trials, but currently these experiments mostly use varieties that are susceptible to disease. In the example shown here, we use fungicide dose response data from BASF-funded field trials, measured on five different varieties with septoria resistance ratings ranging from 4.3 to 8.1. The model could be used to predict the proportional yield response of any Recommended List variety to a fungicide for which adequate dose response data are available.

Model equations

Pathogen growth rate and effect of host resistance and fungicide

The growth rate, r, of of the pathogen population is reduced by the effect of cultivar host resistance:

$$r = hr_0\left[1 - q\left(1 - \mathrm{e}^{-kD}\right)\right] \tag{1}$$

where r_0 is the growth rate of the wildtype strain on a completely susceptible strain (with AHDB resistance rating = 3) with no fungicide; h is a (fractional) multiplier on growth rate r_0 due to cultivar host resistance; q is the asymptote parameter for the effect of the fungicide on the pathogen growth rate; k is the curvature parameter for the effect of the fungicide on the pathogen growth rate; D is the fungicide dose applied. The value of h is parameterised for each variety. The model uses a time step approach and fungicide dose concentration follows first-order decay:

$$D(t+1) = D(t) - \upsilon D(t) \tag{2}$$

Where $D(t)$ is the fungicide concentration remaining at time t, and υ is the decay rate of the fungicide, which can be estimated from information in literature about the average foliar concentration half-life of the fungicide:

$$\upsilon = \frac{-\ln(0.5)}{halflife} \tag{3}$$

Disease severity

The model tracks disease severity over time (Figure 1). Disease severity (%) at time *t*, $S(t)$, depends on r and the initial severity at $t = 0$, S_0. Pathogen growth is density-dependent and the maximum severity is 100%:

$$S(t+1) = S(t) + r(t)\left(\frac{[100 - S(t)]}{100}\right)S(t) \tag{4}$$

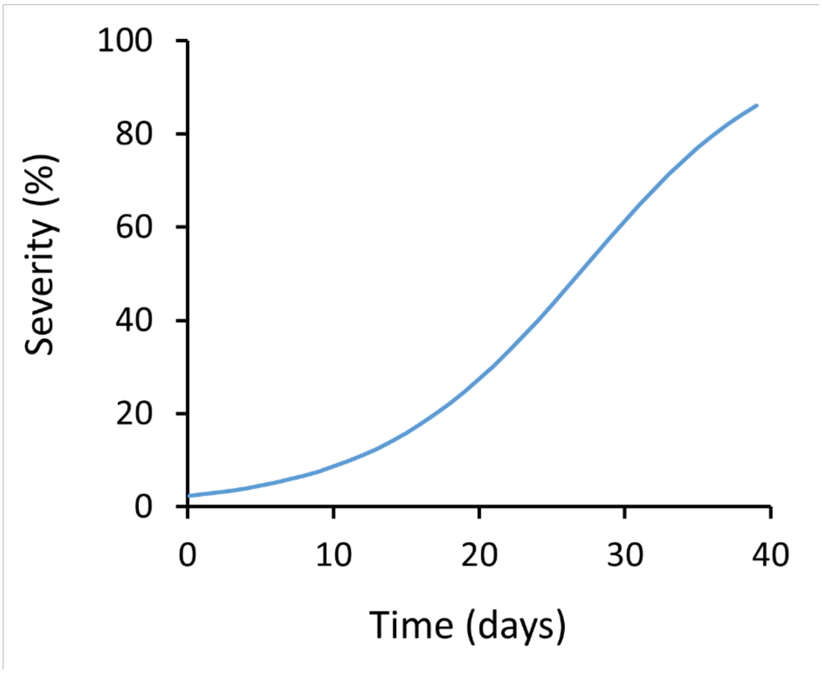

Figure 1. *An example of the modelled disease severity of a septoria epidemic over time.*

The area under the disease progress curve (AUDPC) is calculated as $\sum_0^T S(t)$, where $t = T$ is the end of grain filling or the end of the period of monitoring.

Proportional yield loss due to disease

Yield loss due to disease depends not only on disease severity, but also on cultivar tolerance (van den Bosch et al. 2022). The average percentage yield loss due to disease, L, is estimated as:

$$L = 100 \times \alpha\beta \ \times relAUDPC \tag{5}$$

where α is a measure of the disease tolerance/intolerance of the cultivar, β is the average rate of yield loss due to disease (across all varieties) and the relative AUDPC (‘*relAUDPC*’) is calculated as the ratio of the AUDPC for a variety x fungicide combination and the AUDPC for the most susceptible cultivar grown with no fungicide applied.

Model parameterisation

Host resistance, h

The effect of host resistance on the growth rate, *h*, can be estimated from the AHDB varietal resistance rating, denoted here as C_{Rat}. $C_{Rat} = 3$ for a completely susceptible cultivar. Resistance ratings are calculated based on multi-year average levels of disease severity on each variety (ahdb.org.uk/recommended-lists-disease-ratings). For septoria resistance ratings in wheat cultivars, we calculate an average level of severity on an untreated crop, S_C, for each cultivar based on its resistance rating, using the conversion shown in ADAS report to AHDB, PR634:

$$S_C = e^{-\frac{12.567 - C_{Rat}}{2.8632}} - 1 \tag{6}$$

It should be noted that the equations used to convert average levels of disease severity to resistance rating differ for each disease, and are also updated by AHDB between years to adjust for average levels of disease in the years included in the rolling multi-year average. Therefore resistance ratings are comparable within the same year's Recommended List, but comparison between different years should be approached with caution.

The value of *h* is fitted assuming an average epidemic (but could be fitted directly from actual disease progress data if collected as part of Recommended List trials). The pathogen population is modelled as a single strain with no fungicide applied. We assume that r_0=0.1173 for $C_{Rat} = 3$, based on the average growth rate on susceptible strains (Hobbelen et al. 2011; te Beest et al. 2013), and that the epidemic reaches S_C at $t = T =$ 30 days after the start of the simulation (it should be noted that using a different value for T will alter the results slightly – if site-level data on disease progress curves is available, this may improve the accuracy of the parameterisation).

Since $S_C = \sum_0^T S(t)$, $S(t+1) = S(t) + r\left(\frac{[100 - S(t)]}{100}\right)S(t)$, $r = hr_0$ and $S(0) = S_0$, a value of S_0 can be fitted for $C_{Rat} = 3$ using least squares optimisation so that the epidemic reaches S_C at $t = T$. Then, using the fitted value of S_0, h can fitted for each cultivar in turn using least squares optimization so that the epidemic reaches S_C at $t = T$. If cultivar affects the infection efficiency, then the initial severity will be lower on more resistant cultivars. For simplicity, it is therefore assumed that $S_{C0} = hS_0$. The accuracy of this assumption may vary between cultivars depending on the mechanism of host resistance. An example of fitted values of h is given in Table 1.

Dose response to fungicide

Given fitted values of h for each variety, it is possible to fit q and k based on fungicide dose response data, including data on the disease severity progress in untreated plots. Data from at least 3 or 4 non-zero dose rates are required, and information on application timing. As a minimum, data on all of the dose rates on at least one relatively susceptible variety are required, but ideally data should additionally be available from several varieties with a range of resistance ratings.

Data on the disease severity progress in the absence of fungicides is used to fit r_0 and S_0 for each site using least squares optimisation. The model is then run to predict each observed measurement of disease severity, fitting q and k to the fungicide dose response data using least squares optimisation.

This approach gives flexibility to extrapolate for different fungicide doses and application timings (although ideally there will be data available from multiple application timings available for parameterisation). It is also assumed that the values of q and k are independent of wheat variety, so predictions can be extrapolated for the effect of variety and fungicide combinations to additional varieties that were not included in the fungicide performance trials.

Yield loss due to disease

The value of α, a measure of the disease tolerance/intolerance of each cultivar, can be estimated based on AHDB Recommended List data:

$$\alpha = \frac{(1-\theta)}{\varphi} \tag{7}$$

where θ is the untreated grain yield as a proportion of the treated control (as published in the AHDB Recommended List), and φ is the ratio of the AUDPC for the variety and the AUDPC for a variety with $C_{Rat} = 3$, in the average epidemic described in 'Model parameterisation: Host resistance, *h*' and in the absence of fungicide. This calculation assumes that all yield loss in untreated crops compared to the treated control is caused by septoria. Modelling yield loss for multiple diseases on the same crop would require additional data.

***Table 1**: Values of h and α based on published data in AHDB Recommended Lists.*

Variety name	Septoria resistance rating, C_{Rat}	Severity on cultivar, S_C (%)	h	φ	θ	α
N/A	3	27.26	1	1	N/A	N/A
Barrel	4.3	16.94	0.861	0.662	0.71	0.438
Elicit	5.1	12.57	0.784	0.516	0.78	0.426
Gleam	6.3	7.92	0.674	0.355	0.81	0.536
Graham	6.8	6.49	0.630	0.302	0.87	0.430
Extase	8.1	3.75	0.516	0.196	0.93	0.357
N/A	9	2.48	0.437	0.141	N/A	N/A

The average rate of yield loss due to disease (across all varieties), β, can be parameterised for each individual site or as a cross-site average. A default value of $\beta = 1$ can be used, or ideally β can be parameterised to yield data, if available, using least squares optimisation.

As a variety with $C_{Rat} = 3$ may not be available or suitable for Recommended List trials, the value of *relAUDPC* used in equation 3 may be calculated as the ratio of the AUDPC for a variety x fungicide combination and the AUDPC for the most susceptible cultivar grown with no fungicide applied. The reference susceptible cultivar/s used to calculate *relAUDPC* should be the same across experiments/sites. Changing the reference cultivars may require recalculation of fitted values of β.

It should be noted that van den Bosch *et al.* (2022) measure yield loss due to disease intolerance using loss of green leaf area, 'Healthy Area Duration' (HAD) as the measure of the severity of the disease epidemic. Where HAD can be measured or accurately predicted using a model (for example combining a crop model of the effect of temperature and rainfall with a disease model of the effect of septoria), this will give stronger predictions of yield loss for a particular site than *relAUDPC*. However, the use of *relAUDPC* instead of HAD enables parameterisation of α directly from untreated grain yield data in the AHDB Recommended Lists and offers a level of standardisation between different experiments which may have been monitored for different lengths of time. This method is suitable for predictions of the average percentage yield loss due to disease for different variety and fungicide combinations.

Example application: BASF variety x fungicide trials

ADAS ran experimental wheat variety x fungicide field trials for BASF. BASF have agreed to share results from these trials as an in-kind contribution to this project. As part of these trials, ADAS collected data on five wheat cultivars (Barrel, Elicit, Gleam, Graham and Extase) at three sites in 2021, each site including untreated plots and plots with a fungicide applied at T2 at four dose rates (25%, 50%, 75% and 100% of full dose rate), with four replicates of each treatment at each site. For the same fungicide and cultivar, a field trial at a single site in 2023 collected data from untreated plots and plots with a fungicide applied at T2 at five dose rates (25%, 50%, 75%, 100% and 200% of full dose rate), each treatment with four replicates. The application of the model to the data from these field trials is demonstrated below.

The values of h and α were parameterised from AHDB Recommended List data, as shown in Table 1 for each cultivar. To fit the fungicide dose response parameters, q and k, first r_0 and S_0 were fitted using data from the untreated plots for all five cultivars for each site. Then q and k were fitted using the severity dose response data for Barrel, Gleam and Extase only, leaving data from fungicide-treated plots of Elicit and Graham to validate the approach. Observed yield loss was calculated relative to the maximum observed yield (at maximum fungicide dose) at each site. *relAUDPC* was calculated using Barrel ($C_{Rat} = 4.3$) as the reference variety, and a single value of β was fitted using observed *relAUDPC* and observed yield loss values for all three 2021 trial sites (the 2023 yield data was not used for the parameterisation as yield at this site was impacted by lodging for some varieties). The % yield loss was then predicted using the predicted values of *relAUDPC*.

Model fit to the observed data was evaluated using R^2 and root mean square error (RMSE) (Table 2). A very good fit was achieved to observed severity data (Figure 2a), observed AUDPC (Figure 2b), observed *relAUDPC* (Figure 2c) and observed average % yield loss (Figure 2d).

***Table 2**: Model fit (R^2 and root mean square error (RMSE)) to observed data from BASF experimental field trials. R^2 and RMSE values reported for all observed data (including fungicide-treated plots of Elicit and Graham), and separately in brackets for fungicide-treated plots of Elicit and Graham which were not used in fitting the model. Values for relAUDPC calculated excluding values for untreated Barrel plots, as this was used as the reference variety for calculating relAUDPC.*

Variable	R^2	RMSE
Disease severity (%)	85.7 (83.5)	9.2 (9.7)
AUDPC	78.7 (60.1)	2.8 (3.6)
relAUDPC	68.5 (42.7)	0.15 (0.18)
Average yield loss (%), 2021 data	85.3 (94.6)	3.9 (2.9)

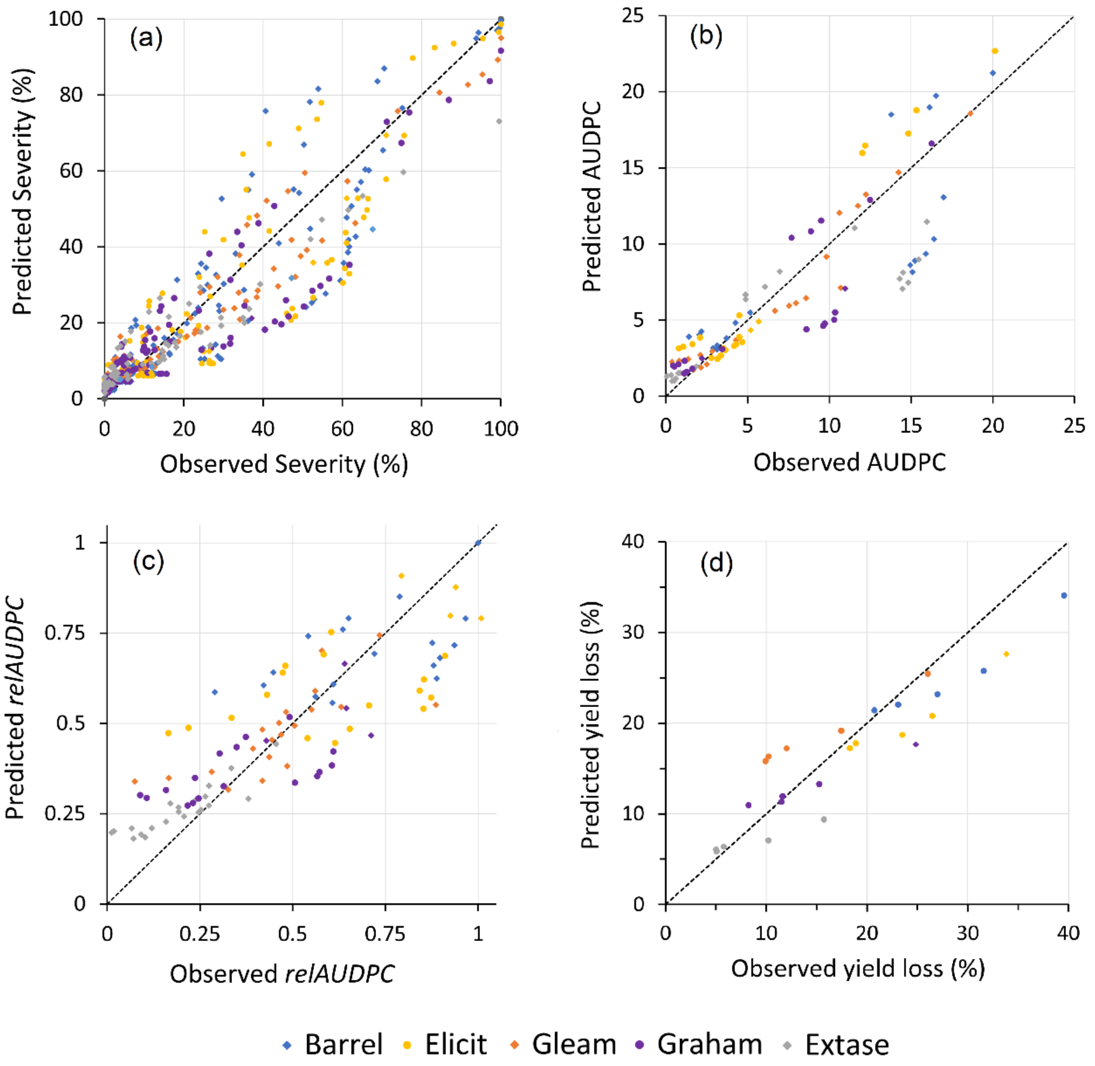

Figure 2. *Observed vs. predicted (a) disease severity (%); (b) area under the disease progress curve (AUDPC); (c) relAUDPC (ratio of AUDPC for a variety x fungicide dose combination and AUDPC on untreated plots of Barrel) and (d) cross-site average yield loss (%) due to disease. Varieties indicated by colour of points: Barrel (blue); Elicit (yellow); Gleam (orange); Graham (purple); Extase (grey). Diamond-shaped points indicate data used for model fitting; round points were not used for model fitting (fungicide-treated plots of Elicit and Graham). Black dashed line indicates 1:1 line: if the fit is good and unbiased, points will lie close to the 1:1 line and be evenly distributed above and below the line.*

The results can be visualised as a contour plot, for example showing how expected yield loss changes with fungicide dose and AHDB varietal resistance rating (Figure 3). This requires a defined scenario of fungicide application timing/s, disease risk (determined by r_0 and S_0) and varietal tolerance level.

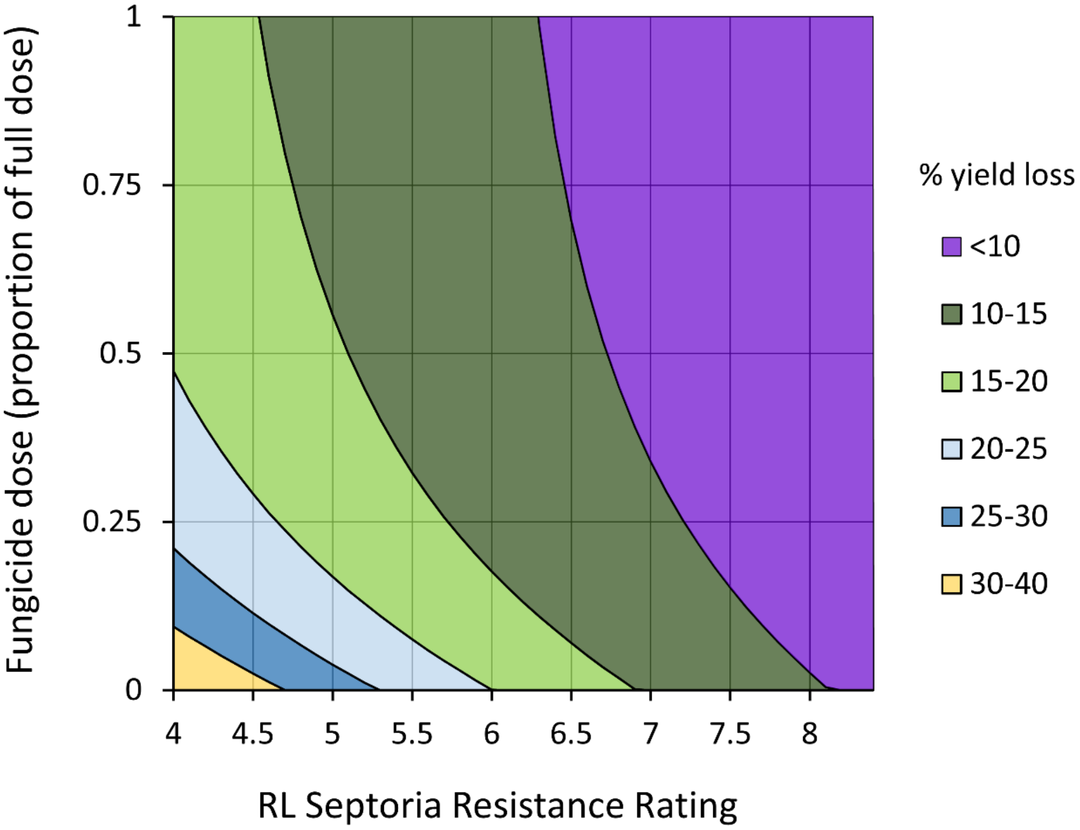

Figure 3: *Contour plots for cross-site average percentage yield loss due to septoria for varying fungicide dose (single application at T2) and AHDB Recommended List septoria rating, for an approximately average level of disease tolerance (α = 0.437). The predicted % yield loss would be lower for cultivars with a greater level of disease tolerance. Note that this is the predicted % yield loss in a year with a damaging septoria epidemic treated with a single fungicide application: lower levels of yield loss would be predicted for a year in which the growth rate of the pathogen is lower due to less conducive environmental conditions, or for more intensive fungicide programmes.*

To summarise, the ADAS Variety x Fungicide Model, based on MSM, offers potential to predict varietal yield performance under different combinations of varietal resistance, varietal tolerance and fungicide inputs, and can be parameterised from data collected as part of AHDB Recommended List and Fungicide Performance trials. Collection of additional data as part of the Recommended List and Fungicide Performance trials could strengthen the parameterisation of the model to improve its predictive ability. Whilst the model has so far been parameterised and tested using data for septoria tritici blotch in wheat, it could also be parameterised for other diseases and other crops. Such modelling approaches could be built into a user-friendly tool to provide a highly cost-effective means of understanding and visualising how varieties are likely to perform under reduced fungicide inputs.

10. Knowledge gaps

10.1. RL fungicide treated inputs and potential for reduced input testing

- Considerable information is available for cereals and winter oilseed rape to guide reduced input fungicide programmes; with less information available for spring oilseed rape and spring linseed. A reasonable approach would be to follow the principles identified for the major crops, to guide inputs into the minor crops.

10.2. Academic literature

- Whilst seven or more relevant articles were found for wheat, barley, oats and oilseed rape, very few articles were found for triticale, rye and linseed.
- The evidence primarily related to winter crop types, with fewer studies exploring spring types.
- Whilst most studies included a measurement of grain or seed yield, there was very little consistency in quality parameters measured.
- Studies didn’t tend to cover a wide variety of diseases that can impact the crops.
- Different timings of the fungicide sprays were only present in wheat and barley studies and showed variable effect on disease.

10.3. AHDB Reports

- Many of the AHDB reports relevant to this review project are focussed on wheat, and septoria disease in particular, with less evidence available for other crops and diseases.
- There is potential for different seasons to have different impact on the gross margins of disease control strategies that rely more on varietal resistance or on fungicide inputs. However, more information is needed to guide growers on the impacts of different fungicide inputs on gross margins.
- There is a potential knowledge gap in terms of whether crop yields tend to follow disease control from fungicides. It has been reported that they do in general, though with some disparities. However, given that commercial spray programmes are likely to include a number of spray applications and different fungicide modes of action in mixture and/or alternation, the potential for such disparities to be apparent seems less likely than in the fungicide performance project trials.

- There is potential for interactions between fungicide use and nitrogen inputs in terms of grain yield and quality. However, more information is needed to guide growers on the impacts of reducing both fungicide and nitrogen inputs independently or together.

- The ADAS/AHDB fungicide margin explores a range of different fungicide input levels in a way that enables strong interaction and knowledge exchange with the industry. However, more varieties would need to be included in each trial to explore the interaction between varietal resistance and fungicide input levels.

10.4. Saaten Union trials data

- The Saaten Union trials data provide important insights into testing wheat varieties under reduced fungicide inputs; however a comprehensive trials programme across crops is needed to draw more general conclusions about variety testing under reduced inputs.

- The 2021 results include margin after fungicide costs data. For AHDB testing of varieties under reduced inputs it would be useful to understand the full cost savings of reducing the number of spray applications, including time and fuel costs.

10.5. Stakeholder engagement

- Whether old data is relevant to current growers? E.g. regen growers using direct drilling

- Interactions between biologicals/other novel inputs impacting fungicides and N input rates

- Interactions between low N and low fungicide inputs and impact on yield + agronomic features

- Soil science, particularly soil microbiology

- Considering disease tolerance as well as resistance to inform application rates

- Systems scale approaches: interacting and confounding effects of changes in agronomy, need to consider what future systems may look like

- PGR application timings in RL are broad, huge variability in application date

- Need for tramline variety trials with different input rates (N+fungicide) which consider commercial rates, not RL/NL rates

- Need to consider varieties in their own merits and in the context of localized environment

- Growers want data considering gross margins, not just yield

11. Key findings

11.1. RL fungicide treated inputs and potential for reduced input testing

- The Recommended Lists (RL) yield trial protocols provide comprehensive methodology for variety testing. The methods are broadly typical of accepted methodology for field experiments, and therefore acceptable in principle for testing varieties under reduced fungicide input programmes. The protocols are updated regularly and this approach would allow for new, effective fungicide products to be incorporated into testing protocols as they appear on the market.

- RL trial protocols are designed to meet the aim of keeping disease levels in treated plots as low as is possible in all varieties and in all trials and are not intended to follow commercial practice. Testing varieties under reduced fungicide inputs could in principle be conducted using existing RL methodology but with a fungicide protocol specific to the reduced input trials. The consideration is then about the extent to which fungicide inputs can be reduced, and the extent to which the fungicide protocol allows for flexibility of spray decisions for the trial operator.

- RL fungicide protocols for treated trials incorporate a range of fungicide modes of action that are agreed upon in advance and are suitable for control of the key target diseases. The same approach would be suitable for testing under reduced fungicide inputs, but with focus on reducing the number of sprays and total doses applied.

- Fungicide protocols for cereals treated trials include 3 or 4 mandatory spray timings, with the option of incorporating additional products into these applications or in additional applications, depending on the disease pressure within the trial.

- Fungicide protocols for oilseed rape treated trials include a mandatory autumn spray timing for trials in the East or West, or an optional autumn spray for trials in the north. For all regions, there are three mandatory spray timings in the spring.

- AHDB fungicide use recommendations have been built on decades of AHDB research and knowledge transfer, with input from experts from a range of research centres and through consultations with industry. Analysis of these recommendations represents a suitable approach for deriving fungicide protocols for variety testing under reduced inputs. This approach would promote best practise for commercial fungicide use.

- AHDB fungicide use recommendations for cereals typically focus on the key T1 and T2 spray timings that protect yield formation, with additional spray timings generally only recommended according to varietal resistance, local disease pressure and the need to protect the crops against ear diseases. Testing varieties at reduced inputs could therefore also focus on these spray timings, with limited use of fungicides outside of these timings.

- AHDB fungicide use recommendations for oilseed rape offer considerable flexibility in terms of adjusting fungicide spray timing and dose according to crop development, varietal resistance and local disease pressure. These recommendations can be used to guide a fungicide protocol for reduced input variety testing, with limitations on both the number of spray timings and the dose.

11.2. Academic literature

- Studies generally – but not always – reported significant impacts of fungicide treatments in reducing disease levels. In some cases fungicide use had a significant benefit in terms of yield or quality, though these effects were more variable.

- Varietal performance was generally reported as being in line with varietal resistance to disease. In some cases interactions between variety and fungicide were reported, with resistant varieties responding less to fungicide inputs.

- Disease pressure, year and location played a significant role on the interaction between fungicides and variety.

11.3. AHDB reports

- Varieties and fungicides have significant direct and interacting effects on wheat grain yield and specific weight in septoria field trials. The yield response to fungicides was much smaller in more resistant varieties, compared to susceptible varieties. Growers should tailor their fungicide strategy to variety and sowing date to better optimise the use of fungicides.

- Different disease control strategies can impact the gross margin of disease control. Greater fungicide use can drive the pathogen population more quickly towards resistance. Varietal resistance makes the intensity of spray programmes less critical and forecasting economically viable.

- The combination of resistant varieties and effective fungicides allows for a reduction in the number of spray timings needed for disease control. This allows potential savings in time and application costs.

- In different crops and diseases, dose response curves varied considerably between fungicides, with apparent variation in both the curvature and the asymptote. This emphasises that both product choice and dose can have marked differences on disease control in susceptible varieties.

- Different disease control strategies can impact the rooting of different varieties, which may in turn impact increased nitrogen in the grain, grain yield and grain quality.

- The value of physiological effects to growers under normal conditions of moderate or high disease risk would be small in relation to the large fungicidal effects that occur consistently.

- Higher disease pressure results in higher fungicide inputs providing better margins, with multi-site fungicides often proving a valuable addition to fungicide programmes. Careful consideration of local disease pressure, varietal resistance ratings and potential yield responses on-farm are important for determining fungicide programmes that maximise the margin over fungicide cost.

11.4. Saaten Union trials data

- The reduced input treatment generally resulted in lower yields than the farm input treatment in both trials. However, for varieties that appeared to have better disease resistance levels, the reduced input and farm input treatments had similar yields.

- The margin (£/ha) after fungicide costs largely reflect the grain yields in the 2021 trial and show the economic importance of a full fungicide programme on more susceptible varieties under (apparent) high disease pressure.

11.5. Prediction of variety and fungicide interaction

- Having the ability to make a reasonable prediction of variety and fungicide interactions could provide a highly cost-effective means of understanding how varieties are likely to perform under reduced inputs.

- This could be achieved by deriving a model to describe these interactions and parameterising the model using real variety performance data. The model could then be used to provide generic information to growers on how varieties tend to behave under reduced fungicide inputs, or it could be used to generate specific predictions on how each variety is likely to perform under reduced inputs, with limited field trial testing each season on a small panel of varieties to ensure that the model parameterisation is optimised.

- The ADAS Variety x Fungicide Model, based on the multiplicative survival model (MSM), offers potential to predict varietal performance under different combinations of varietal resistance and fungicide inputs. Whilst it has so far been parameterised and tested using data for septoria tritici blotch in wheat, it could be parameterised for other diseases and other crops.

- Such modelling approaches could provide a highly cost-effective means of understanding how varieties are likely to perform under reduced inputs.

12. Recommendations

12.1. RL fungicide treated inputs and potential for reduced input testing

- The Recommended List (RL) yield trial protocols provide comprehensive and broadly accepted methodology for variety testing in field experiments. We propose using these field trial methods for reduced fungicide input variety testing, with a fungicide protocol specific to the reduced input trials.

- AHDB fungicide use recommendations have been built on decades of AHDB research and knowledge transfer. These recommendations should form the basis for deriving fungicide protocols for variety testing under reduced inputs. This approach would promote best practise for commercial fungicide use.

- Testing cereals varieties under reduced inputs should focus on the key T1 and T2 spray timings, with limited use of fungicides outside of these timings.

- Testing winter oilseed rape varieties under reduced inputs should focus on limiting both the number of spray timings and the dose.

- For crops where limited information may be available to guide reduced fungicide input protocols (e.g. spring oilseed rape, spring linseed) then a suggested approach is to follow the principles identified from fungicide use recommendations for cereals and winter oilseed rape.

- The current focus of RL trials on treated yields under more intensive fungicide inputs than current commercial practise creates competition between breeders for the highest treated yield under intensive inputs. Analysis of the disease tolerance levels in UK wheat varieties (van den Bosch et al. 2022) suggests that creating competition for the highest achievable yield would be more productive. A recommendation therefore is to explore the potential for maximising achievable yield through breeding for disease tolerance, in addition to considering appropriate fungicide programmes for reduced input variety testing.

12.2. Academic literature

- Given the paucity of published studies for crops such as rye, triticale and linseed, particularly under relevant UK or European conditions, publication of variety x fungicide field work for these crops (particularly spring types) should be a priority.

- The evidence relating to grain or seed quality is scant, due to inconsistencies in parameters measured. A focus should be on consistent measurement of key grain or seed parameters.

- Due to the variable effects of varieties and fungicides reported across studies, a recommendation is for reduced fungicide input studies to incorporate as many site seasons as is feasible, to allow more meaningful interpretation of the results.

12.3. AHDB reports

Any programme of variety testing at reduced fungicide inputs should consider:

- The potential impact of sowing date on the data.

- Whether to focus on the potential impact of different fungicide inputs on gross margin. Messaging around reduced fungicide inputs should also refer to beneficial impacts of varietal resistance on fungicide resistance selection and on the viability of disease forecasting.

- The potential savings to growers of reducing the number of spray applications, in addition to potential savings from reduced total dose applied.

- Product choice and dose carefully, to maximise disease control. The AHDB fungicide performance data provide a very useful resource to guide choice of both product and dose. Consideration should also be given to good resistance management; ensuring a diversity of fungicide modes of action in a spray programme is key.

- Whether there is sufficient information available to guide growers on likely impacts of reducing nitrogen inputs as well. If evidence is limited, then this should be made explicit and it may be better to focus on fungicide inputs and nitrogen inputs separately.

- Whether the choice of fungicide mode of action may alter the findings due to the potential for physiological effects. However, in the absence of substantial evidence to the contrary, such physiological effects from fungicides are likely to be small relative to their impact through effective disease control.

- The potential for seasonal differences in disease pressure to impact the results. Flexibility in spray decisions may help to limit fungicide inputs when disease pressure is lower, therefore taking an approach designed to maximise margin over input costs.

12.4. Saaten Union trials data

- Reduced fungicide input trials such as these conducted by Saaten Union are highly valuable for understanding the potential to reduce fungicide use intensity on farm. Further testing using a similar approach, exploring different crops across sites and seasons is recommended. Consideration should be made as to the value of including more susceptible crops in high disease risk situations, if preliminary data suggests that such approaches may lead to damaging yield losses in certain seasons.

- Including economic analysis of different fungicide input levels would be highly valuable to growers and the industry in general. Such analysis should consider all of the on-farm costs associated with crop sprays.

12.5. Stakeholder engagement

- Problem with NL trial protocol
  - aim to eradicate disease within trials which is subsequently what breeders work towards
  - NL trials not set up to determine response under lower input so breeders don’t aim for this

- Problem with RL trial protocol
  - untreated fungicide trials aren’t informative if considerations about local disease pressure aren’t taken into account
  - RL trials need to record what fungicides go on which trials for wheat

- Breeders need time to adapt, changes have to be phased in by AHDB

- Disease resistance takes several breeding cycles to achieve

- Protocol needs to be changed to reflect targeted fungicides to certain crops

13. Suggestions for variety testing under reduced fungicide inputs

1. Test all varieties under a reduced fungicide input programme

During the stakeholder meeting, it was apparent that there was openness among the breeders present to the idea of varieties being tested at reduced fungicide inputs, albeit with several considerations raised as to how that might work in practise. Further recommendations for aspects to be considered if this approach is implemented were identified from analysis of AHDB project reports. Varieties could in principle be tested using current Recommended List methodology, but with a separate, reduced fungicide spray programme aimed to provide broad spectrum disease control, so that individual varieties are not overly penalised for susceptibility to a specific disease. The Recommended Lists could then provide treated yield, untreated yield and reduced fungicide input yield. This approach would be comprehensive in terms of testing varieties and putting field experiment data into the hands of growers but the additional variety testing would come at a considerable cost.

2. Test subset of resistant and susceptible varieties, predict performance of rest

A second potential approach could be to (i) test a subset of varieties that contrast in their resistance ratings to the major diseases under reduced fungicide inputs, (ii) use these field experiment data to parameterise a mathematical model that tracks variety performance depending on disease levels, and (iii) make predictions for the other varieties based on their resistance ratings. The advantage of the approach is that it would substantially reduce the burden of field experimentation required. However, with any modelling approach there is some degree of error to be expected in the predictions which are likely to be reasonably close but not perfect. A suitable mathematical model for making predictions is presented in this report. Whilst the model has so far been parameterised and tested using data for septoria tritici blotch in wheat, further work would be needed to parameterise for other diseases and other crops. Such modelling approaches could be built into a user-friendly tool to provide a means of understanding and visualising how varieties are likely to perform under reduced fungicide inputs.

3. Demonstrate the potential for reduced inputs on a subset of resistant varieties

A third potential approach could be to focus variety testing under reduced fungicide inputs on a subset of varieties with high levels of resistance to the key target diseases. The rationale for doing this is that growing susceptible varieties under reduced fungicide inputs is less likely to be adopted in practise as it would present a higher risk of yield loss. The aim of these trials would be to explore the potential for reduced fungicide inputs when growing more resistant varieties. They could for example have three levels of fungicide input: treated (as in current RL), untreated (as in current RL) and reduced input (new). Whilst such trials could be used for field demonstration purposes, the results could also be shared with growers through knowledge exchange events and/or as part of the Recommended List information. Advantages of this approach are that it would be substantially cheaper to deliver than the first approach and would allow different levels of fungicide input to be tested on different varieties, in the same trials. Although it would only provide information for a subset of varieties, they would be the ones most likely to be successfully adopted into reduced fungicide use programmes on farm.

14. References

Grimmer et al. (2015) Pyramiding of partial disease resistance genes has a predictable, but diminishing, benefit to efficacy. Plant Pathology 64, 748-753.

Hobbelen et al. (2011) Delaying Selection for Fungicide Insensitivity by Mixing Fungicides at a Low and High Risk of Resistance Development: A Modeling Analysis. Phytopathology 101, 1224-1233.

Paveley et al. (2000) Predicting effective fungicide doses through observation of leaf emergence. Plant Pathology 49, 748–766.

Paveley et al. (2003) Predicting effective doses for the joint action of two fungicide applications. Plant Pathology 52, 638-647.

Ritchie et al. (2018) Integrated control of potato late blight: predicting the combined efficacy of host resistance and fungicides. Plant Pathology 67, 1784-1791.

Taylor & Cunniffe (2023) Modelling quantitative fungicide resistance and breakdown of resistant cultivars: Designing integrated disease management strategies for Septoria of winter wheat. PLoS Computational Biology 19(3): e1010969.

te Beest et al. (2013) Accounting for the Economic Risk Caused by Variation in Disease Severity in Fungicide Dose Decisions, Exemplified for Mycosphaerella graminicola on Winter Wheat. Phytopathology 103, 666-672.

Van den Bosch et al. (2022) Maximizing realized yield by breeding for disease tolerance: A case study for Septoria tritici blotch. Plant Pathology 71, 535-543.