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Development of UK wide risk forecast scheme for Ramularia Leaf Spot in barley

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CONTENTS

1. Abstract

Ramularia leaf spot, caused by *Ramularia collo-cygni,* is one of the major fungal diseases of barley in the UK. It reduces both yield and quality of harvested grain. Control of the disease relies on the appropriate use of fungicides but visual symptoms only appear late in the growing season, after the last stage at which fungicides can be applied legally. Therefore, farmers have to decide whether to protect their crop in the absence of visible disease symptoms. A robust risk forecast would help inform their decision and allow them to use an appropriate treatment or alternatively decide not to treat the crop.

This project had three aims; i) to refine the Scottish model by comparing leaf wetness after stem extension with disease levels in the crop over years and sites, rather than a calendar based forecast, ii) to extend the forecast used in Scotland to the rest of the UK by using information from the meteorological network funded by AHDB and disease scores from RL and other trials, and iii) to gather information on disease levels across the UK and quantify levels of fungal DNA in grain and plant samples using a real time PCR. In addition data on RLS levels in winter and spring barley RL varieties was generated to assist in the calculation of resistance scores.

Through the course of the project it became apparent that the existing Scottish model was not refined enough to be utilised further and more factors which could influence disease levels had to be considered. A wide range of influences on disease levels including weather conditions during crop growth, crop factors e.g. sowing date and variety, and also the presence of other diseases, were examined. The only factors which appeared to have any influence on disease levels were rainfall, temperature and leaf wetness in the crop over the course of the growing season. More research is needed to establish the influences of these factors on disease development at different sites and over a number of years in order to construct a risk forecast.

Current guidelines to growers on the risk of ramularia leaf spot disease in their crop are based on geographical location i.e. higher risk in the north and west of the UK. Our findings show that within these regions disease levels can be varied but that the highest levels are generally seen in the high risk areas. The variation of disease levels within a region is still considerable and it may be that risk could be associated with more distinct climate regions in future.

The link between environmental conditions and movement of the fungus within the crop was difficult to establish from the plants grown in the field and more detailed work in controlled conditions may be required to establish the relationships between the environment and fungal colonisation of barley.

Ramularia leaf spot is a problem which is on the increase in the UK and control is increasingly problematic. This project has given some potential avenues of research which could be explored in order to help farmers protect their crops. However more work is still required in order to produce a robust forecast scheme.

2. Introduction

Barley was the second most important cereal crop grown in the UK in 2013: 7.1 million tonnes of barley were grown with a market value of £1.31 billion. Ramularia leaf spot (RLS) caused by *Ramularia collo-cygni* (*Rcc*) is now a major disease of barley crops in the UK and has also been observed in a number of countries across the temperate regions of the world. Estimates of damage range from 20% to 70% of total yield (Walters *et al*, 2008). The losses are not only in total grain yield but also in quality, as the number of thin grains increases with severe infections. Disease symptoms generally appear in the crop post flowering at growth stages when fungicide applications are no longer permitted. There are no fully resistant varieties to RLS but some levels of resistance have been indicated in AHDB trials and resistance ratings have been calculated for spring barley since 2012 and winter barley since 2017. Data for winter barley varieties were included in the AHDB Recommended Lists barley and oats pocketbook.

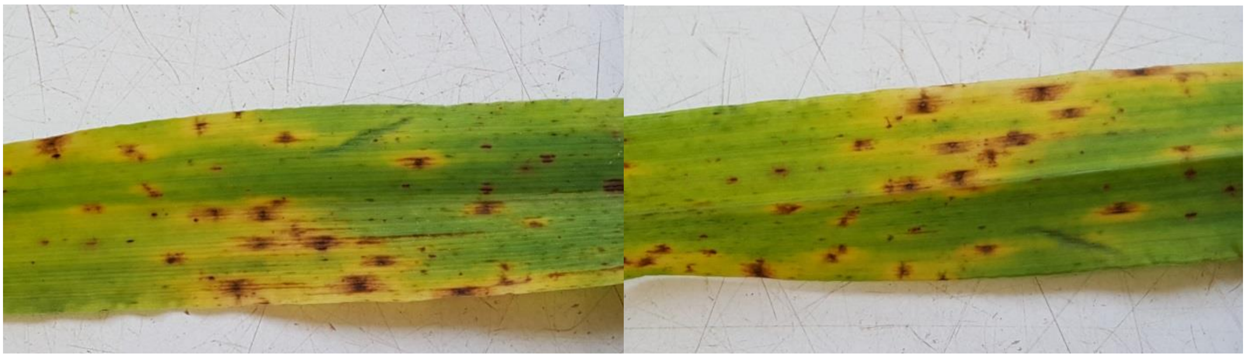

Figure 1. Ramularia leaf spot (RLS) symptoms on a barley leaf. Adaxial and abaxial surfaces are shown above. Note the 5 R's which aid symptom recognition: rectangular, restricted by veins, reddish brown, ring of chlorosis and right through the leaf.

The highest disease rating in spring barley on the current 2018/2019 spring barley AHDB Recommended List (RL) is 6.6 (cv. RGT Asteroid) and the lowest is 5.8 (cv. Propino). For winter barley crops, the highest rating is a 6.0 (cv. California) and the lowest is a 4.0 (cv. KWS Tower). *R. collo-cygni* is known to be seed borne and to move asymptomatically in plants prior to flowering (Havis *et al*, 2014). Risk forecasts to major economic crop pathogens in the UK have been produced over the last 20 years e.g. eyespot, fusarium head blight, light leaf spot. These risk forecasts take into account factors such as; previous cropping, cultivations systems, varietal susceptibility, spore movement and climatic conditions at important crop growth stages. The effect of these factors on RLS epidemics is only slowly being elucidated but some information is now available which indicates that some factors (e.g. spore movement) may not be the major factor affecting disease levels (Havis *et al*, 2013). Limited information on the effect of the environment on Ramularia epidemics has been published (Walters *et al*, 2008; Havis *et al,* 2015). A number of factors were implicated to be influencing RLS epidemics e.g. rainfall and high light intensity post flowering (Havis et al., 2015)

Research from Norway indicated a strong relationship between high levels of relative humidity in spring barley in early June when the crop was at growth stage 30 and final disease severity (Salamati and Reitan, 2006). The greater the levels of relative humidity on the crop in early June the higher the levels of RLS observed later in the season. This observation was used to formulate a risk forecast for winter and spring barley crops in Scotland based on leaf wetness in barley crops at stem extension (early April and June respectively) (Havis *et al*, 2013). Information for the forecast was derived from SRUC operated meteorological stations and validated by observation of disease levels in untreated plots at trial sites across Scotland. The risk forecast was published from 2011 onwards at a point in the growing season when late season fungicide options were still to be decided i.e. early May for winter barley and late June for spring barley. The initial version of the RLS forecast was further developed using the evidence base of a recent DEFRA-LINK project entitled CORACLE project (Brown *et al,* 2014).

The aim of this project was to use data available from previous years' crops to study the effects of climatic and other risk factors on levels of RLS, and to investigate a variety of approaches to incorporate disease risk into a forecast using methodology developed previously (Hughes *et al*, 2014). Data from the new network of meteorological stations set up by the AHDB throughout the UK were used to extend the geographical coverage of the forecast, the objective being UK-wide risk forecasts. Risk forecasts were evaluated against disease observations from adjacent untreated crops or AHDB RL plots.

The biological process which underlies the forecast has not been evaluated but recent work has shown that leaf wetness and high humidity during artificial inoculation can promote growth of *R. collo-cygni* and increase leaf colonisation (Brown *et al*, 2014). In addition, sampling of crops and quantification of *R. collo-cygni* DNA levels delivers valuable information on the effect of environment on pathogen movement within the plant at different locations. The movement of the fungus has been tracked at Scottish sites prior to this project (Havis *et al,* 2014) but sampling during this study gave information on the rate of fungal movement at sites across the UK, where environmental conditions may be very different.

The use of varieties with known resistance ratings generated information on the effect, if any, of varietal resistance on fungal movement (Tables 7&8). Crops were sampled prior to stem extension (Zadocks growth stage (GS) 30), at full ear emergence (GS59) and at harvest (GS 90) (Zadocks *et al,* 1974). No effect of variety on *Rcc* movement was observed in the data.

Losses due to RLS have been estimated at very high levels in South America but in the UK, losses average around 0.5 t/ha (Havis *et al.,* 2015). The reduction in grain quality due to RLS also leads to a further economic cost to growers. This is due to an increase in the number of thin grains at harvest. Currently, there are no fully resistant varieties available and control depends on the use of effective fungicides. In the last 3 years there has been an increase in the detection of mutations within the fungus, which reduce the efficacy of fungicides in the ergosterol biosynthesis inhibitors (EBI) and succinate dehydrogenase inhibitors (SDHI) groups (FRAG 2016). Control in the UK now relies on the use of chlorothalonil (Havis *et al.,* 2018). The vast majority of symptoms appear in the crop post flowering. However, at this point in crop development, no fungicide applications are permitted. Therefore, the use of normal disease symptom thresholds to predict economic damage and to trigger crop protection sprays is not possible. A relationship between severity of RLS in the crop, expressed as Area Under Disease Progress Curves values, and leaf wetness in the crop at a date approximating to stem extension had been demonstrated in Scottish barley crops. Increased leaf wetness during stem extension produced higher RLS values post flowering. This risk forecast had been used for both winter and spring barley crops in Scotland. The aims of this AHDB funded project were threefold; i) to refine the Scottish model by comparing leaf wetness after stem extension with disease levels in the crop over years and sites, rather than a calendar based forecast, ii) to extend the forecast used in Scotland to the rest of the UK by using information from the meteorological network funded by AHDB and disease scores from RL and other trials, and iii) to gather information on disease levels across the UK and quantify levels of fungal DNA in grain and plant samples using a real time PCR.

3. Materials and methods

3.1. Assessment of Ramularia Leaf Spot symptoms in RL trials in the UK

3.1.1. Winter barley 2015

In 2015 10 (F-1) leaves were sampled from each variety in the untreated plots of 15 winter barley RL trial sites across the UK (Figure 2). Varieties were run in the trials in 2015. Leaves were taken between GS 75 and 85 when RLS symptoms were visible. Disease symptoms were assessed on a percentage leaf area basis using a scoring scheme developed from previous work (AHDB, 2018).

Figure 2. Winter barley RL trials in 2015 from which untreated samples were taken.

3.1.2. Spring barley 2015

In 2015 10 F-1 leaves were sampled from untreated plots in 10 spring barley RL sites across the UK (Figure 3). A total of 25 varieties were run in the trials. Leaves were taken between GS 75 and 85 when RLS symptoms were visible. Disease symptoms were assessed on a percentage leaf area basis using a scoring scheme developed from previous work (AHDB, 2018).

Figure 3. Spring barley RL trials sampled and assessed in 2015.

3.1.3. Winter barley 2016

In 2016 10 F-1 leaves were sampled from both untreated and treated winter barley plots in 15 winter barley RL sites across the UK (Figure 4). A total of 19 varieties were run in the trials. Leaves were taken between GS 75 and 85 when RLS symptoms were visible. Disease symptoms were assessed on a percentage leaf area basis using a scoring scheme developed from previous work (AHDB, 2018)

Figure 4. Winter barley RL and disease observation plot (DOP) sites sampled and assessed in 2016.

3.1.4. Spring barley 2016

In 2016 10 F-1 leaves were sampled from untreated and treated spring barley plots in 16 RL sites across the UK (Figure 5). A total of 22 varieties were run in the trials. Leaves were taken between GS 75 and 85 when RLS symptoms were visible. Disease symptoms were assessed on a percentage leaf area basis using a scoring scheme developed from previous work (AHDB, 2018).

Figure 5. Spring barley RL and DOP sites sampled and assessed in 2016.

3.1.5. Winter barley 2017

In 2017 10 F-1 leaves were sampled from both treated and untreated winter barley plots in 22 RL sites across the UK (Figure 6). A total of 25 varieties were run in the trials. Leaves were taken between GS 75 and 85 when RLS symptoms were visible. Disease symptoms were assessed on a percentage leaf area basis using a scoring scheme developed from previous work (AHDB, 2018).

Figure 6. Winter barley and spring barley RL sites sampled and assessed in 2017. Winter barley sites are in green. RLS data were recovered from 22 sites in 2017, spring barley sites are in blue. RLS data were recovered from 16 sites in 2017.

3.1.6. Spring barley 2017

In 2017 10 F-1 leaves were sampled from untreated spring barley plots at 16 RL sites across the UK (Figure 6). A total of 20 varieties were run in the trials. Leaves were taken between GS 75 and 85 when RLS symptoms were visible. Disease symptoms were assessed on a percentage leaf area basis using a scoring scheme developed from previous work (AHDB, 2018).

3.2. Assessment of risk forecast based on maximum leaf wetness for 14 days at stem extension (Scottish forecast – based on Norwegian observations)

This section addresses objective ii) by assessing how effective the Scottish model is in predicting RLS severity and whether it could be extrapolated to the rest of the UK. Initial analysis looked at the reliability of the forecast when compared across seasons using Scottish data before analysing data from across the UK over the cropping seasons 2015-17.

Disease and weather data from spring and winter barley field trials at two Scottish sites (Bush Estate, Midlothian and Drumalbin farm, Lanarkshire) were collated. Weather data were collected from Delta-T automatic weather stations at the two trial sites. Sensors were used to detect air temperature, soil temperature, leaf wetness, humidity, wind direction, solar radiation and rainfall. Leaf wetness figures of over 95% were taken as equivalent of full leaf wetness.

Disease data were collected by visual assessments of symptoms in untreated plots of the RL varieties in each year between GS 75 and 85. Data were gathered for 10 years at Bush Estate (2005-2014) and 7 years at Drumalbin (2007-2014). Disease data was gathered for each year of the analysis. Leaf wetness data, gathered from SRUC meteorological stations, over the 14 day period after stem extension in the crops, and final RLS severity in the crop, were graphed. The data were analysed to see if there was any correlation between leaf wetness for 14 days at stem extension and disease levels across years. Crop development stages varied between years with GS 30/31 being reached anywhere between May 20th to June 4th for spring barley at the Bush Site. Leaf wetness figures were based on the environmental conditions in the crop for 14 days from these dates onwards.

3.2.1. 2015 UK data

Meteorological data from AHDB RL trial sites were supplied by Tara Ross and Dr Bastiaan Brak. Site operators were contacted to establish trial sowing dates and dates at which crop growth stage reached GS 30 (stem extension). Minutes of leaf wetness for 14 days from the start of stem extension were calculated and compared to final disease levels in the crop collected as in section 3.1. Fifteen RL sites were used for the winter barley analysis plus one SRUC trial site (Lanark), 10 from the Northern area (2 from Northern Ireland, 3 from Humberside and Yorkshire and 5 from Scotland). Six sites were from the south (Cornwall, Hampshire, Oxfordshire, Suffolk, Norfolk, and Cheshire). Ten sites were used for the spring barley analysis (Hampshire, Oxfordshire, Norfolk, Lincolnshire, North Yorkshire, Central Scotland, Eastern Scotland and North-east Scotland).

3.2.2. 2016 spring barley data

In 2016 additional data were collected from the spring barley RL trials, based on published work which identified environmental conditions which increased RLS levels in crops. These included solar radiation 3 weeks post heading (Formayer *et al*., 2004), rainfall 3 weeks post heading and average temperature 3 weeks post heading in the crop (Marik *et a*l, 2011). An analysis of the data from the RL trials was carried out to see if these conditions had any effect on RLS development. However, these parameters all examine the effect of the environment post-flowering on RLS development. This growth stage is too late for any management interventions.

Therefore, additional crop data and environmental variable data were gathered and analysed for the spring barley trials in order to identify any factors pre-flowering in the crop which could be influencing final RLS severity. RLS was assessed as described previously (3.1.2). Details of environmental variables are given in Table 1.

Table 1. Environmental and crop data collected from 2016 RL spring barley trials.

Geographical factors	**Field factors**	**Crop Factors**	**Environmental factors**
Site location	Previous crop	AHDB RL RLS resistance rating	Cumulative temperature from sowing to GS 59 (°C)
AHDB RLS risk region	Cultivation system	Varietal maturity date (from RL data)	Cumulative rainfall from sowing to GS 59 (mm)
Met Office climate region	Sowing date	% Ramularia (GS 75-85)	Cumulative leaf wetness from sowing to GS 59 (min)
		% Rhynchosporium (GS 75-85)	Rainfall at GS 30/31 (mm)
		% Mildew (GS 75-85)	Full leaf wetness at GS 30/31 (min) (GS as reported by site manager)
		% Brown rust (GS 75-85)	Radiation 3 weeks post heading (watts/m^2)
		% Net blotch (GS 75-85)	Rainfall 3 weeks post heading (mm)
		% Tanspot (GS 75-85)	Average temperature for 3 weeks post heading in crop (°C)
		Fungicide treatment	

3.2.3. 2017 spring barley

In 2017 similar data to that collected in 2016 were collected from the RL trial sites and analysed to assess the potential influence of factors on RLS severity.

3.3. Effect of environmental parameters on *Ramularia collo-cygni* DNA levels in spring barley crops

3.3.1. 2015

Spring barley leaf samples were collected from 10 RL and SRUC trial sites across the UK at a number of growth stages. Prior to stem extension at GS 21-30, whole plants were sampled at random from untreated plots drilled with different varieties (Propino, NFC Tipple, Concerto, Sanette and Scholar). The aim was to establish *Rcc* DNA levels in the plots pre stem extension. The same plots were sampled at GS 59 where 10 F-1 leaves were sampled from each plot. Just before harvest at GS 80, 10 flag leaves and 10 ears were sampled at random from each plot. DNA was extracted from the leaves and grains and *Rcc* DNA levels quantified using the method of Taylor *et al.,* 2010. Changes in *Rcc* DNA levels were correlated with leaf wetness in the crop at GS 30/31 for the 14 days after stem extension. RLS severity at GS 75-85 was assessed as described previously.

3.3.2. 2016

Spring barley leaf samples were collected from 3 SRUC trial sites across the UK at a number of growth stages. At GS 21, 10 second-emerged leaves were sampled at random from untreated plots from 5 varieties (Propino, NFC Tipple, Concerto, Sanette and Scholar). The same plots were sampled at GS 59 where 10 F-1 leaves were sampled from each plot. Just before harvest 10 flag leaves and 10 ears were sampled at random from each plot. DNA were quantified as described previously. Changes in *Rcc* DNA levels were correlated with leaf wetness in the crop at GS 30/31 for the 14 days after stem extension. RLS severity at GS 75-85 was assessed as described previously.

4. Results

4.1. Disease levels in varieties in RL trials

4.1.1. Winter barley 2015

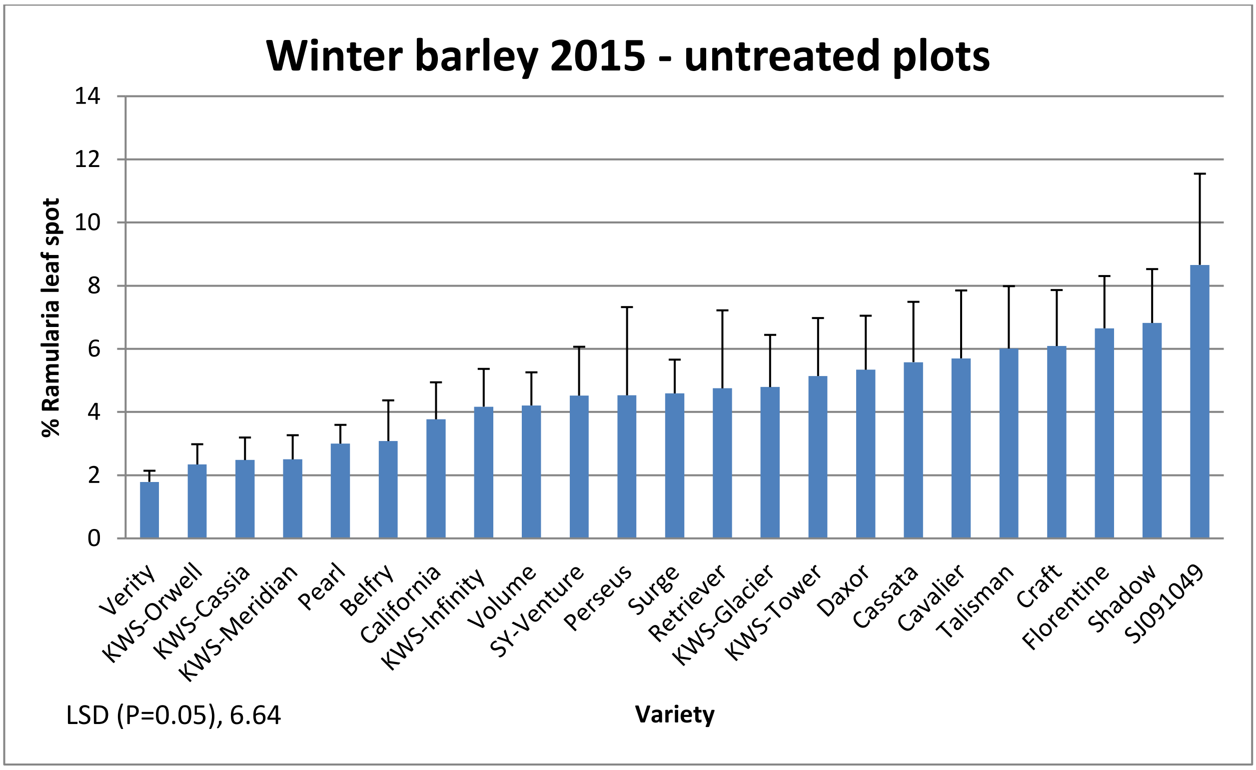

Figure 7. Mean Ramularia Leaf Spot levels on F-1 leaf layer in untreated winter barley varieties in the 2015 season in trials across the UK. Trials were scored once between GS 75-85. Error bars above bars in graph show variation in scores across all of the trials assessed

Figure 7 shows in the winter barley trials in 2015 the highest RLS levels were observed in cvs Shadow and SJ091049 (6.8 and 8.6% respectively). Lowest levels were recorded in cvs Verity and KWS Orwell (1.8 and 2.3% respectively). Verity and SJ091049 were significantly different to each other in 2015. The new varieties on the list this year, Cavalier and Tower were intermediate in their susceptibility to RLS. Full data are shown in Supplementary Table 1

4.1.2. Spring barley 2015

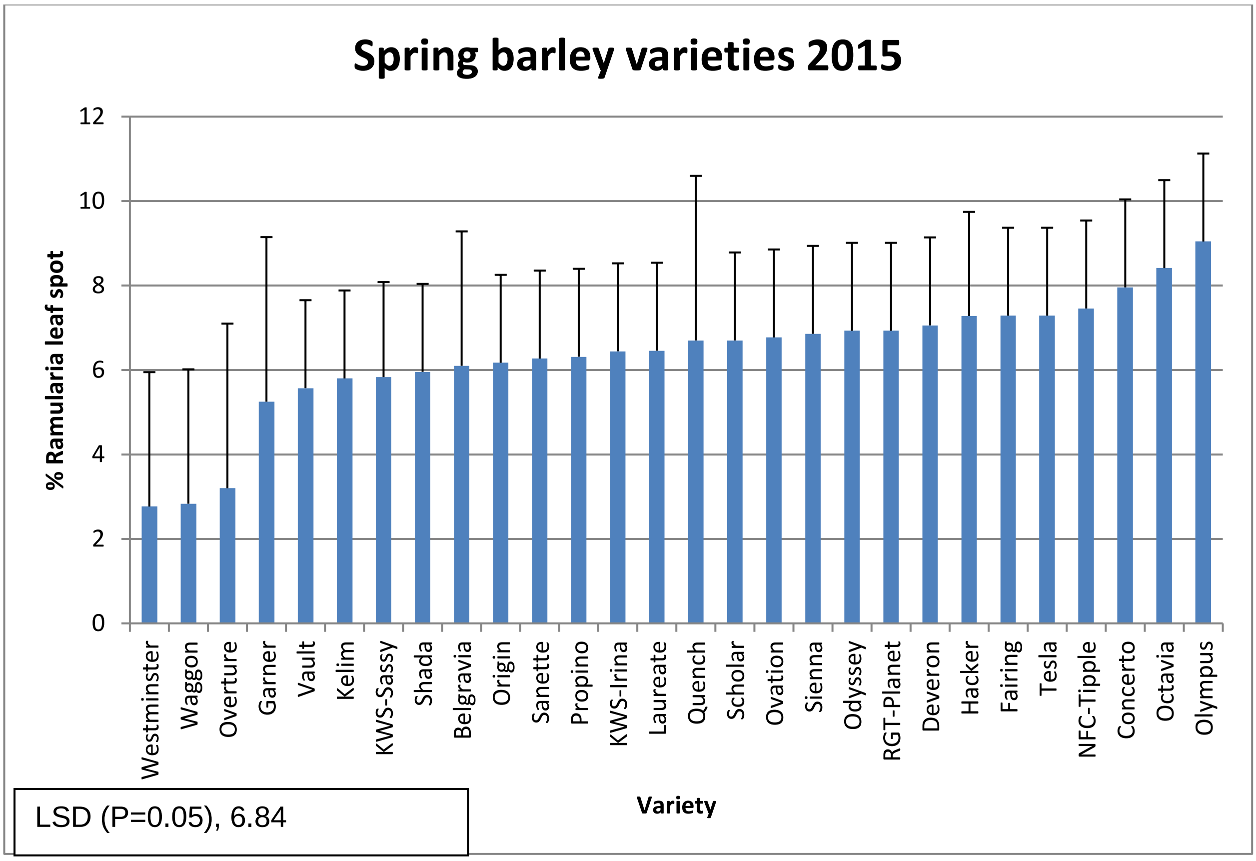

Figure 8. Mean RLS levels on F-1 leaf layer on untreated spring barley varieties in 2015 across the UK. Error bars above bars in graph show variation in scores across all of the trials assessed.

Figure 8 shows in the spring barley trials in 2015 the highest RLS levels were observed in cvs Olympus and Octavia (9 and 8.4% respectively). Lowest levels were observed in cvs Westminster and Waggon (2.7 and 2.8% respectively). The lowest scores were seen in three feed varieties (Westminster, Waggon and Garner). Trials were scored once between GS 75-85. There were no significant differences between varieties in these trials. Full data are shown in Supplementary Table 2.

4.1.3. Winter barley 2016

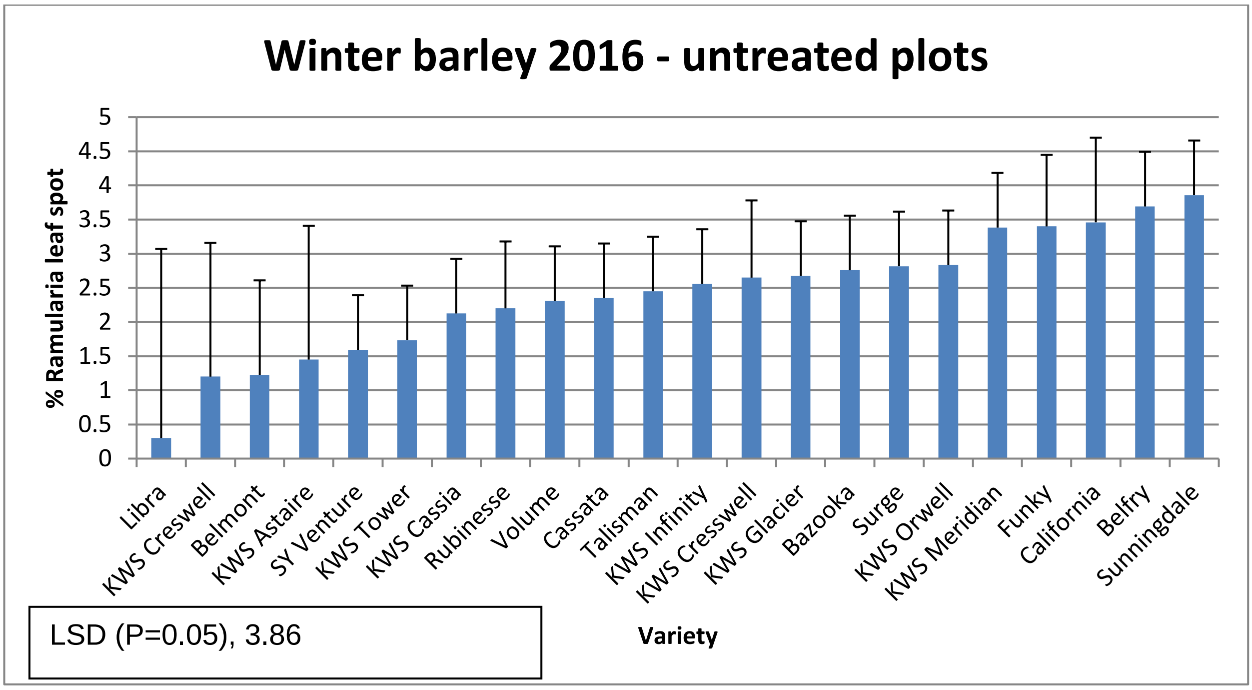

Figure 9. Mean RLS levels on F-1 leaf layer in untreated winter barley in 2016 across the UK. Error bars above bars in graph show variation in scores across all of the trials assessed

Figure 9 shows in the 2016 winter barley trials the highest RLS levels were observed in cvs Belfry and Sunningdale (3.7 and 3.8% respectively). Lowest levels were recorded in cvs Libra and KWS Cresswell (0.3 and 1.2% respectively). KWS Infinity was added to the list this year but was no more than intermediate for RLS susceptibility. Trials were scored once between GS 75-85. There were no significant differences in these trials. Full data are shown in Supplementary Table 3.

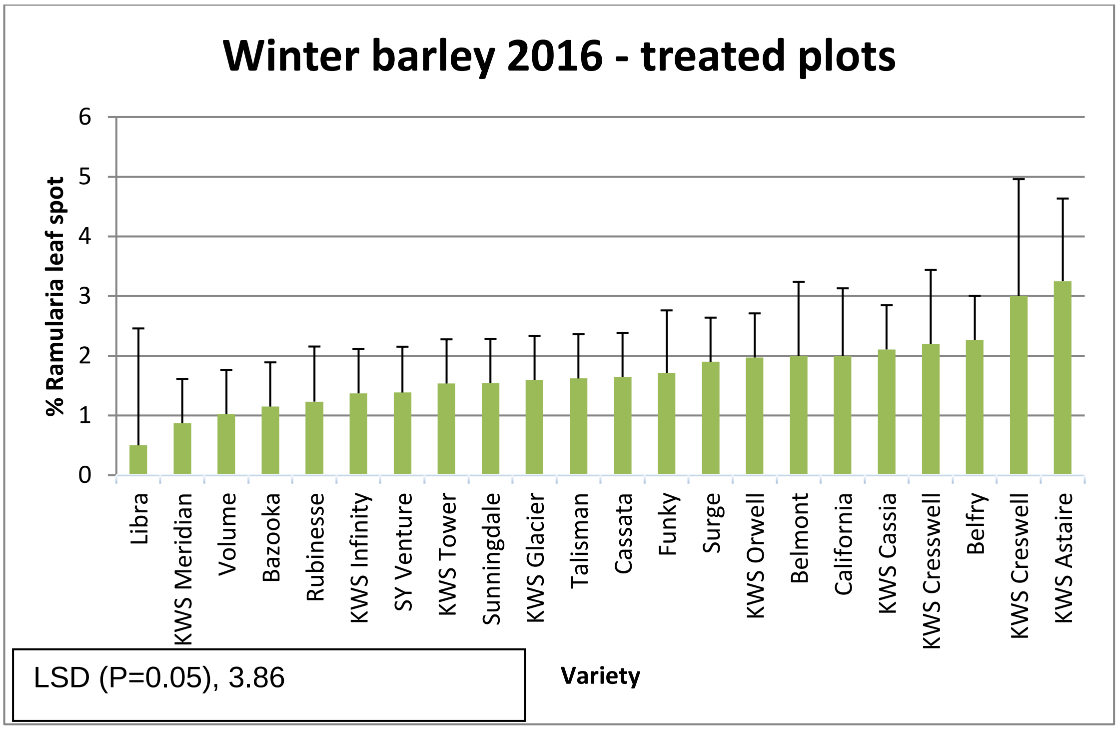

Figure 10. Mean RLS levels on leaf F-1 layer in treated winter barley in 2016 across the UK. Error bars above bars in graph show variation in scores across all of the trials assessed

Figure 10 shows the highest levels of RLS in the treated trials were observed in cvs KWS Cresswell and KWS Astaire (3.5 and 3% respectively). Lowest levels were observed in cvs Libra and KWS Meridian (0.5 and 0.8% respectively). Trials were scored once between GS 75-85. There were no significant differences between varieties in these trials.

4.1.4. Spring barley 2016

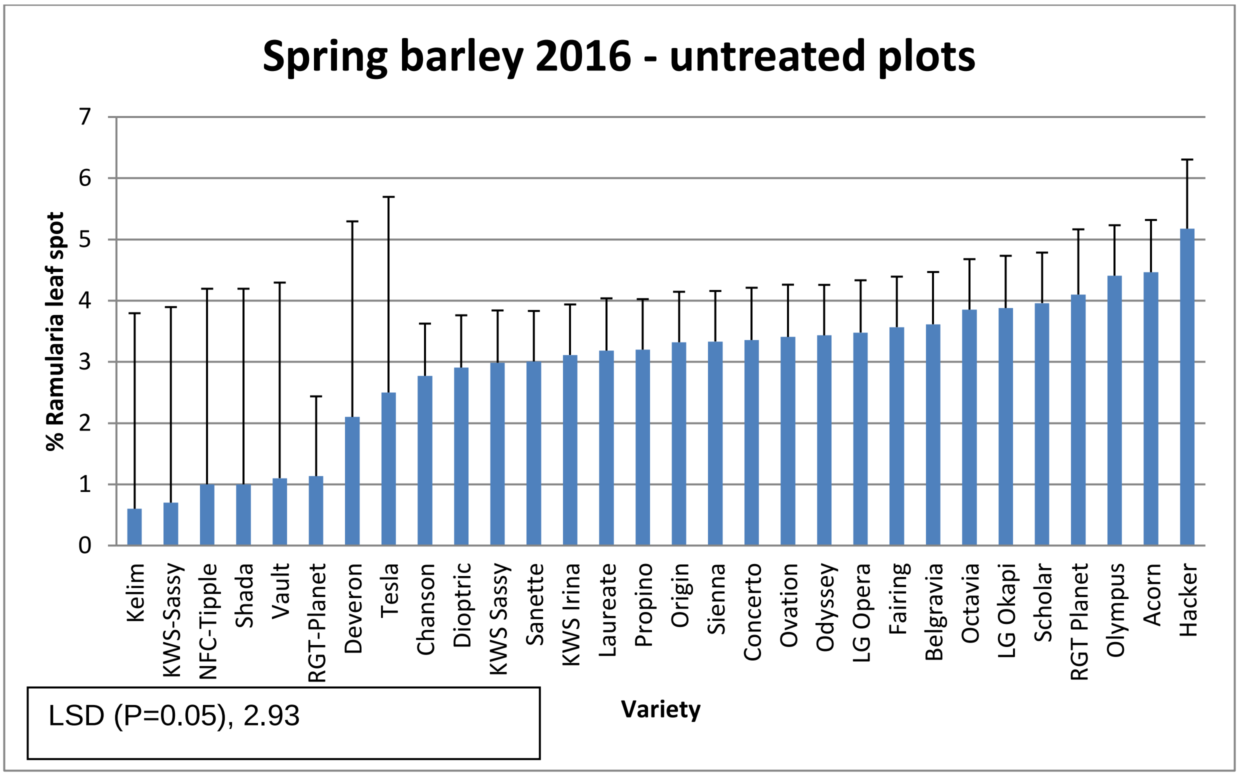

Figure 11. Mean RLS levels on leaf F-1 leaf layer in untreated spring barley in 2016 across the UK. Error bars above bars in graph show variation in scores across all of the trials assessed

Figure 11 shows that in the spring barley trials in 2016 the highest RLS levels were observed in cvs Hacker and Acorn (5.1 and 4.6% respectively). Hacker was significantly different from Kelim, KWS-Sassy, NFC –Tipple, Shada, Vault and RGT-Planet in these trials. Of the new varieties on the 2016 RL Kelim had the lowest levels, although there were limited data from one site. Vault and RGT-Planet were also new to the RL. Lowest levels were recorded in cvs Kelim and KWS Sassy (0.6 and 0.7% respectively). Trials were scored once between GS 75-85. Full data are shown in Supplementary Table 4A and 4B.

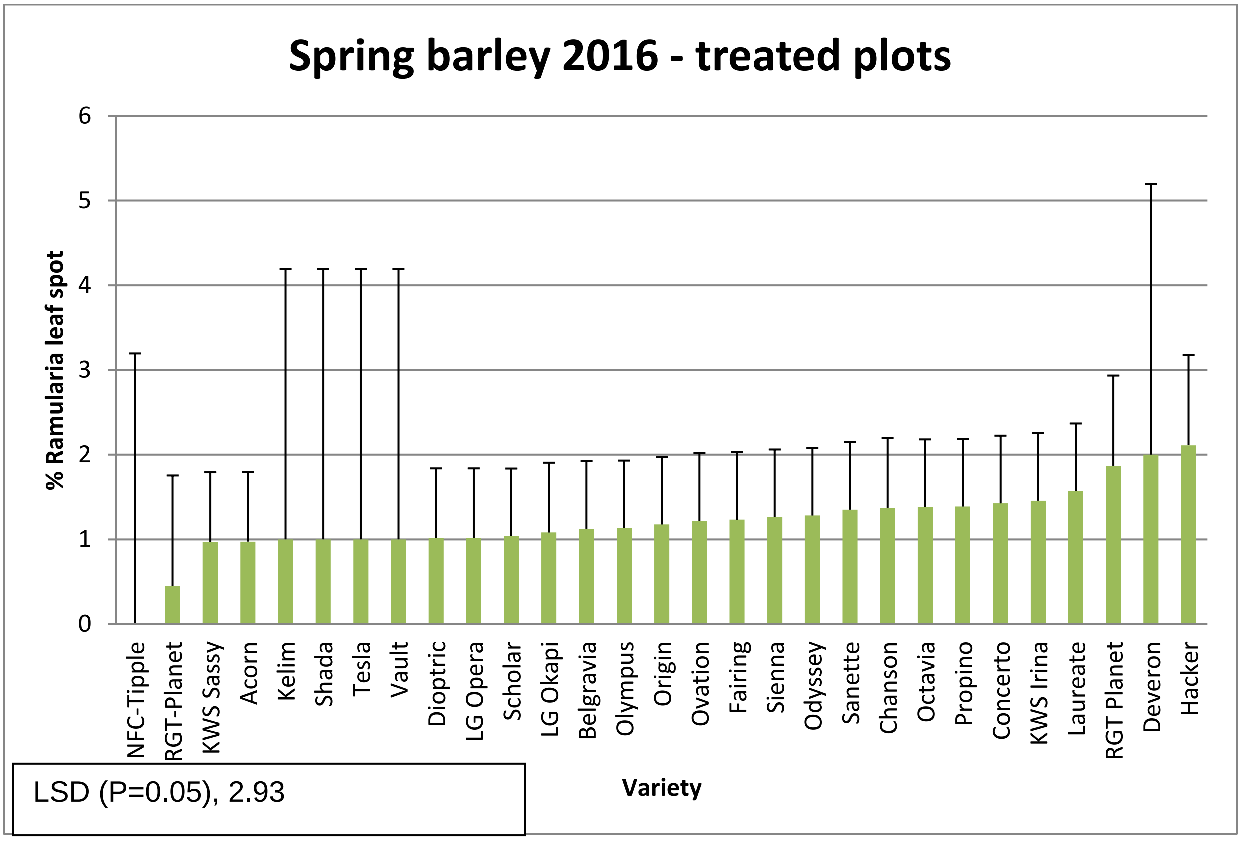

Figure 12. Mean RLS levels on F-1 leaf layer in treated spring barley in 2016 across the UK. Error bars above bars in graph show variation in scores across all of the trials assessed.

Figure 12 shows that highest levels were observed in cvs Deveron and Hacker (2 and 2.1% respectively) and lowest levels in cvs NFC Tipple and RGT-Planet (0 and 0.4% respectively). NFC Tipple was only grown at one site in 2016. Trials were scored once between GS 75-85. There were no significant differences between varieties in this year for the treated plots.

4.1.5. Winter barley 2017

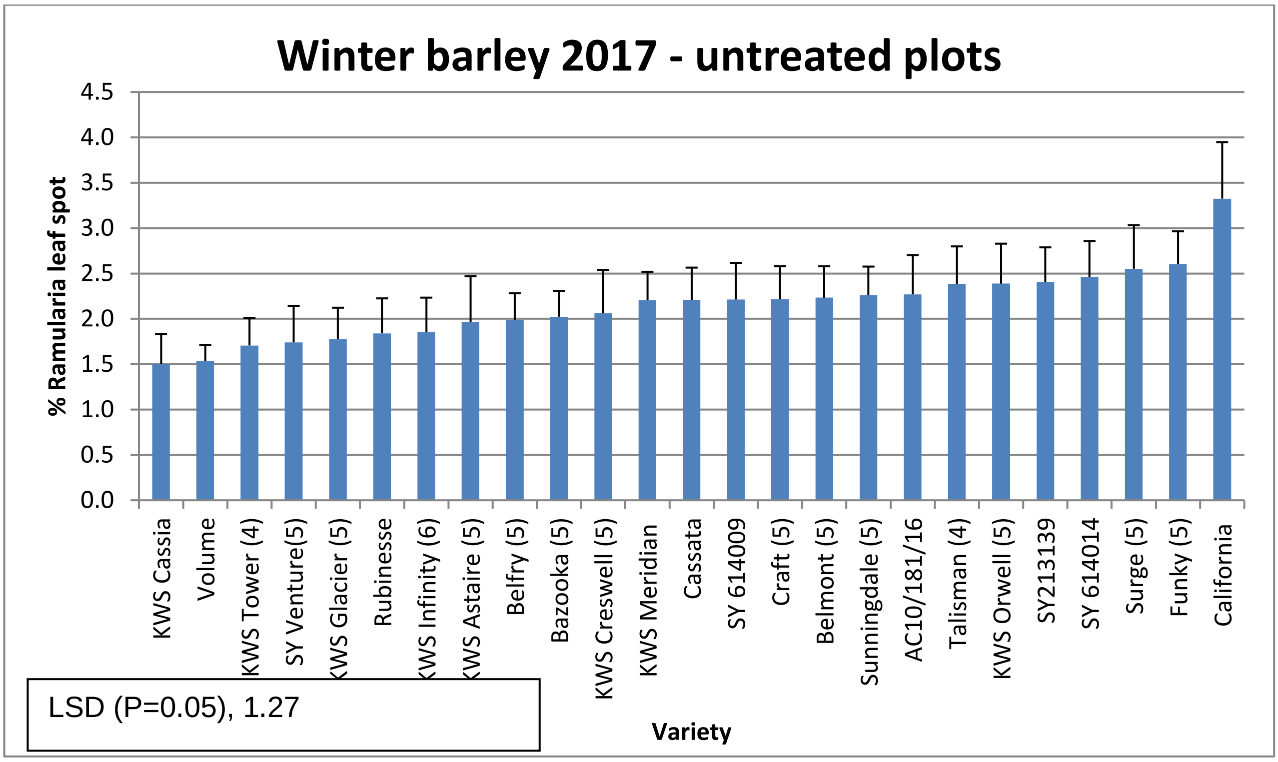

Figure 13. Mean RLS on F-1 leaf layer in winter barley in 2017 across the UK. Error bars above bars in graph show variation in scores across all of the trials assessed. Figures in brackets are official AHDB Recommended List resistance ratings from 2017 RL, where available.

Figure 13 shows in the untreated winter barley plots in 2017 the highest RLS levels were in cvs Funky and California (2.6 and 3.3% respectively). Lowest levels were observed in cvs KWS Cassia and Volume (1.5% for both). Disease levels were relatively low in this year in the RL trials. Trials were scored once between GS 75-85. Of the new varieties to the list, including Craft and Belfry, none give increased tolerance to the disease. Full data are shown in Supplementary Table 5A and 5B. California was the only variety significantly different from the other varieties in 2017.

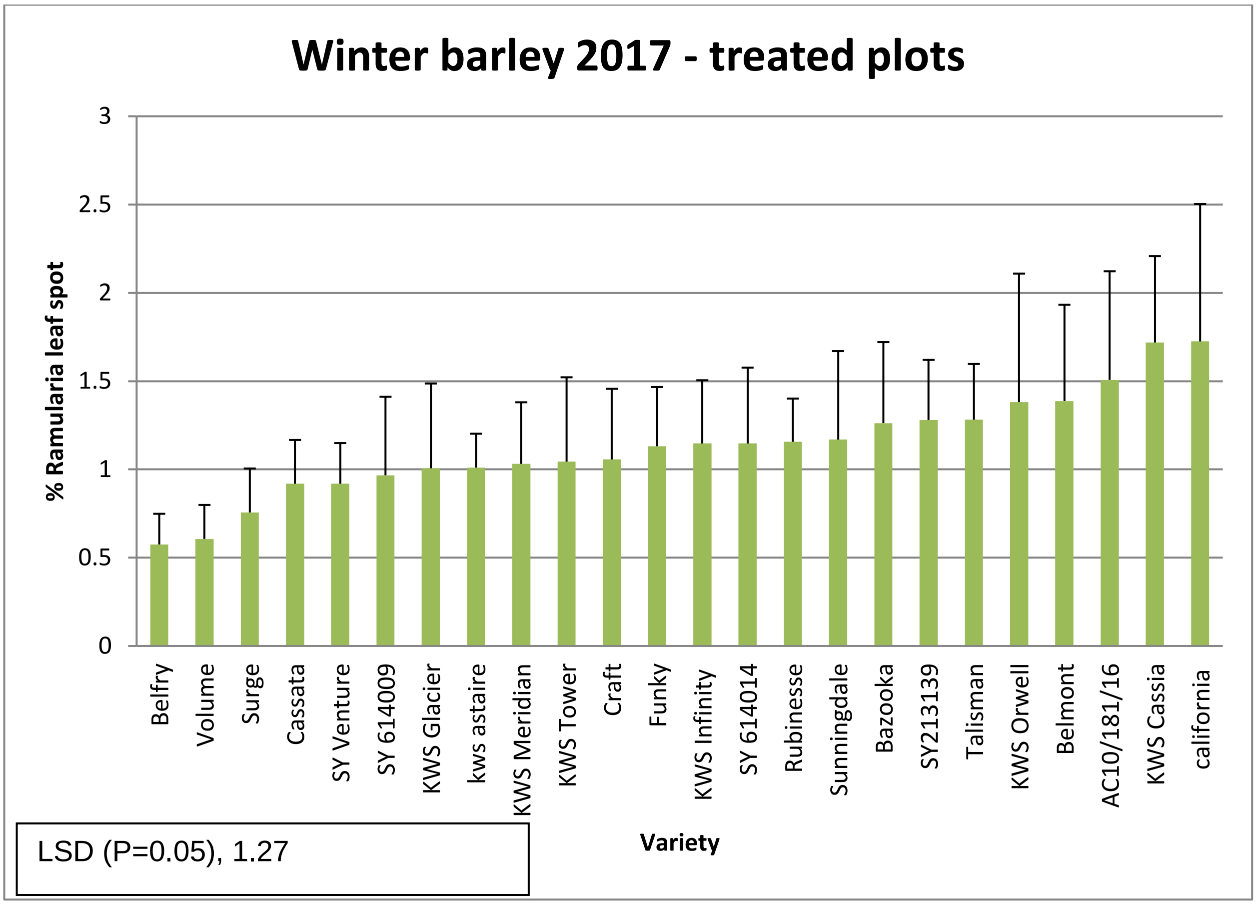

Figure 14. Mean RLS on F-1 leaf layer in treated winter barley in 2017 across the UK. Error bars above bars in graph show variation in scores across all of the trials assessed.

Figure 14 shows that in the 2017 treated winter barley trials the highest RLS levels were in cvs KWS Cassia and California (1.7% for both). Lowest levels were observed in cvs Belfry and Volume (0.6% for both). Trials were scored once between GS 75-85. There were no significant differences between varieties

4.1.6. Spring barley 2017

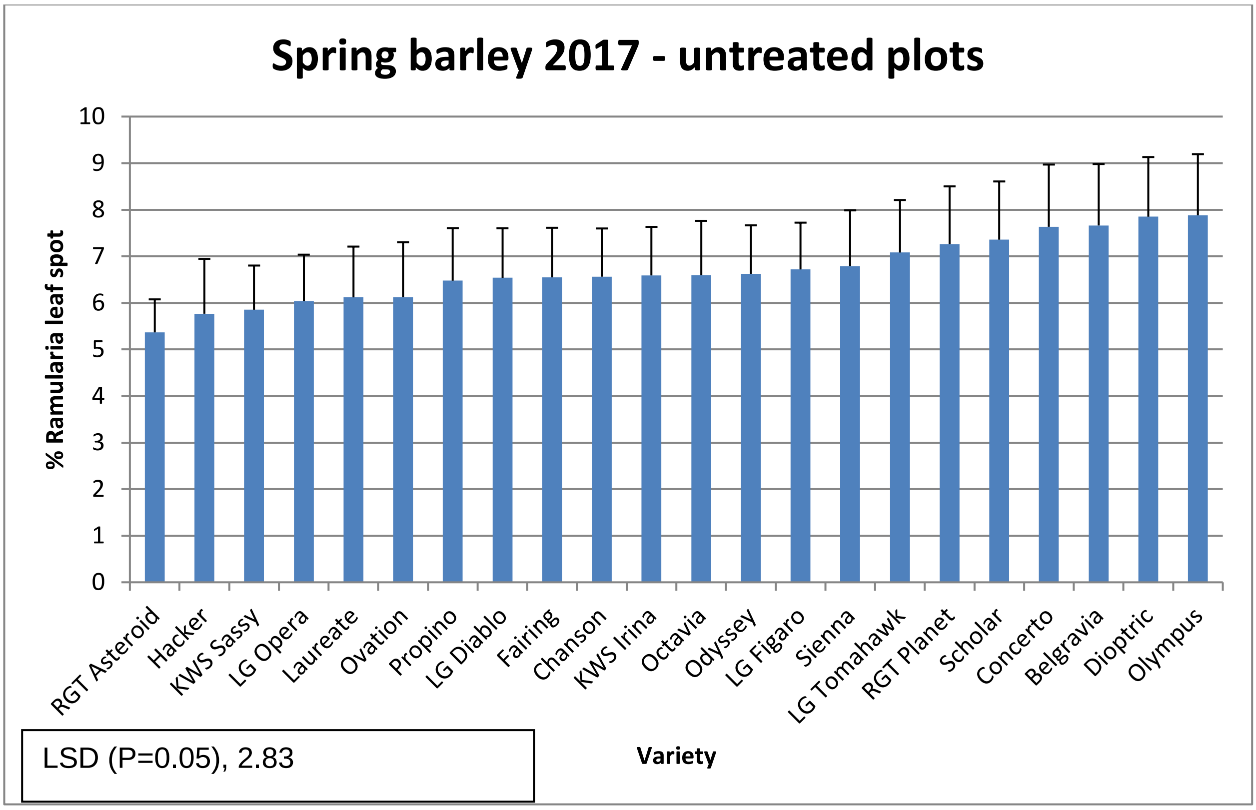

Figure 15. Mean RLS levels on F-1 leaf layer in untreated spring barley in 2017 across the UK. Error bars above bars in graph show variation in scores across all of the trials assessed.

Figure 15 shows that in the 2017 untreated spring barley trials, the highest RLS levels were observed in cvs Dioptric and Olympus (7.8% for both). Lowest levels were recorded in cvs RGT Asteroid and Hacker (5.3 and 5.7% respectively). Of the new varieties added to the RL, Laureate, Fairing and Ovation were in the lowest half for RLS disease scores. Hacker gave similar RLS levels to 2016 but moved from the most susceptible to one of the most tolerant. Trials were scored once between GS 75-85. Full data is shown in Supplementary Table 6A and 6B. There were no significant differences between varieties.

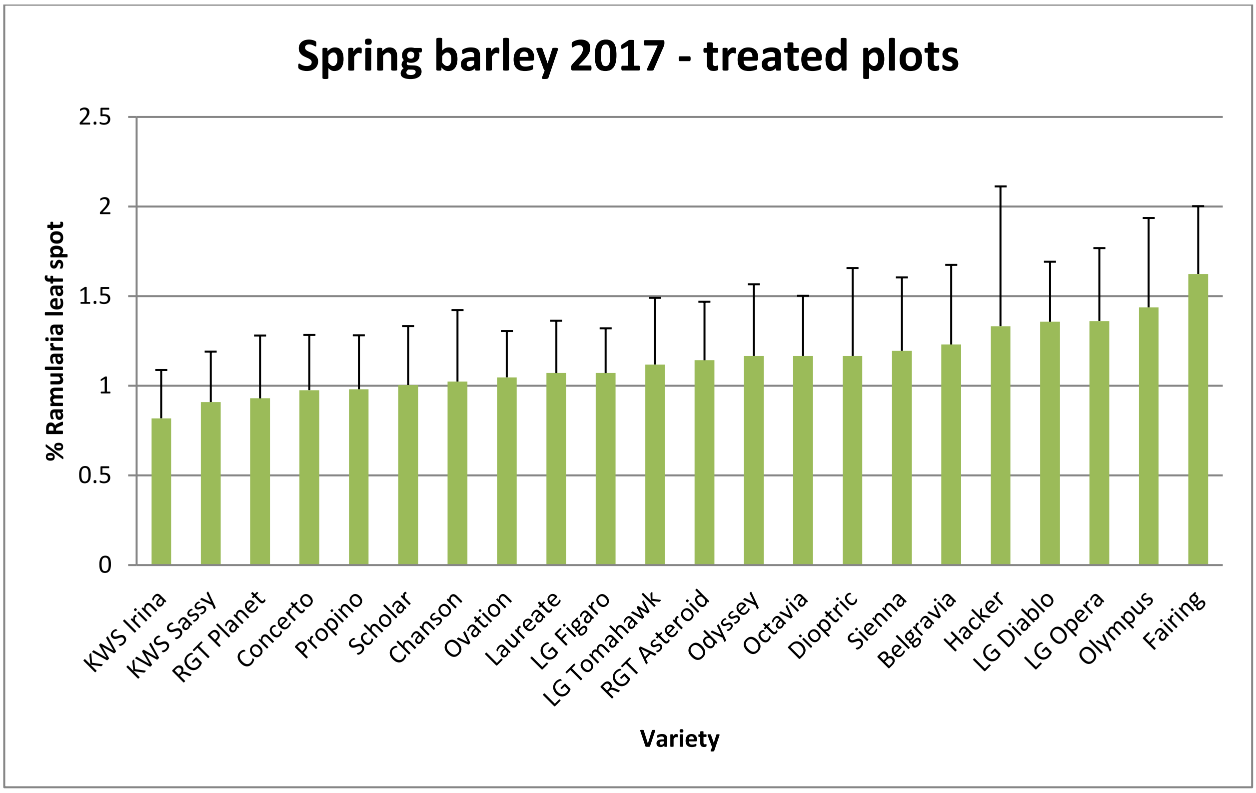

Figure 16. Mean RLS levels on F-1 leaf layer in treated spring barley in 2017 across the UK. Error bars above bars in graph show variation in scores across all of the trials assessed

Figure 16 shows that in the 2017 treated spring barley trials, highest levels were observed in cvs Fairing and Olympus (1.6 and 1.4% respectively). Lowest levels were recorded in cvs KWS Irina and KWS Sassy (0.8 and 0.9% respectively). Trials were scored once between GS 75-85. There were no significant differences between varieties.

In 2017 there were no differences in RLS disease scores between spring barley varieties in the treated and the untreated trials. In previous years, differences in disease levels were not always statistically significant but were still marked. This variability was not seen in 2017 across the RL sites. The disappearance of resistance to RLS in the spring barley varieties is unexplained at present. However, a number of scenarios are possible. Firstly there could have been significant changes in the race structure of *R. collo-cygni.* Recent changes in the race structure of the yellow rust pathogen, *Puccinia striiformis,* overcame host resistance in the wheat varieties on the RL. Little is known about a race structure in *R. collo-cygni* but the pathogen is known to be very variable within sites and has recently overcome two major groups of fungicides so is capable of rapid adaptation. The other possible scenario is that the environmental conditions may have affected the RLS genetic control in the spring barley varieties. Short term stress events on *mlo* varieties have been shown to effect genetic resistance to mildew in the short term. In previous years varieties have moved from the resistant end of the scale towards the susceptible end, for example cv. Optic. However this was usually observed over a number of years. Changes in *Rcc* diversity may have accelerated this process. However, without further experimentation it is not possible to confirm the reasons behind the changes observed in spring barley resistance to RLS.

4.2. Assessment of risk forecast

4.2.1. Historical analysis

Winter barley

Data were collected from two trial sites (Bush and Lanark), where winter barley trials had been done for over 10 years and RLS severity recorded late in the season in untreated plots.

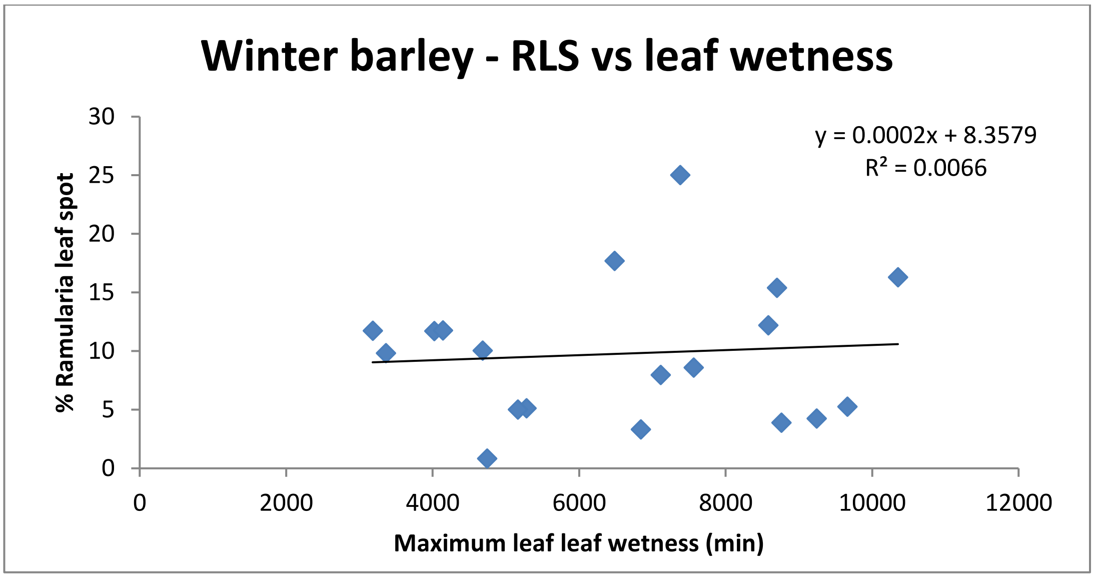

Figure 17. Correlation between RLS severity at GS 75-85 and leaf wetness for the 14 days after GS 30/31 in winter barley at two sites over 10 seasons.

Although previous work at SRUC had indicated a relationship between leaf wetness and disease severity within a cropping season, this analysis indicates a relationship could not be seen when multiple seasons were analysed together (Figure 17).

Spring barley

Data were collected from 2 trial sites (Bush and Lanark), where spring barley trials were done for over 10 years and RLS severity recorded late in the season in untreated plots.

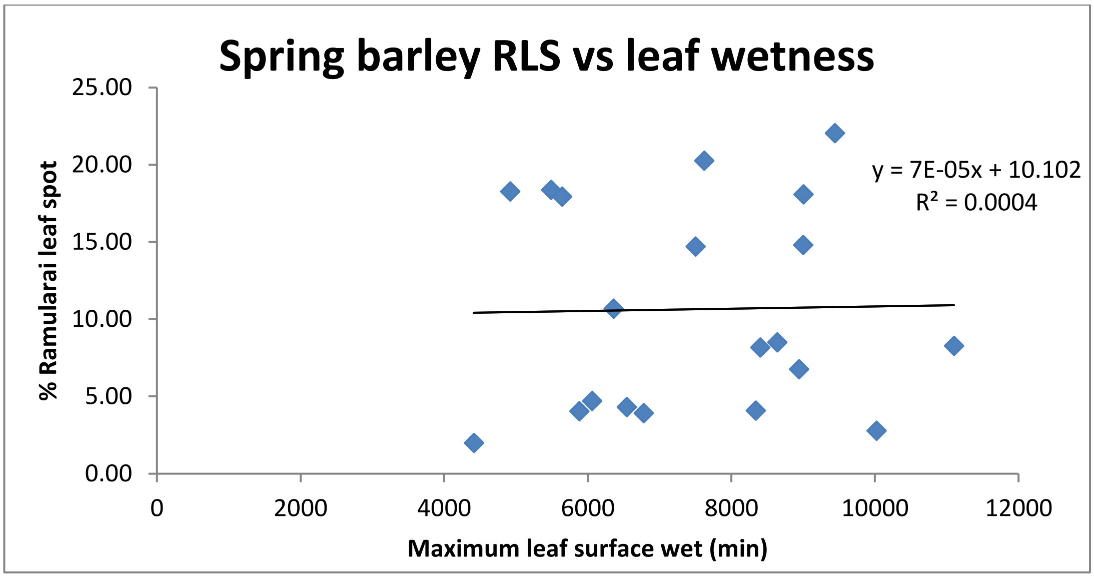

Figure 18. Correlation between RLS at GS 75-85 and leaf wetness for the 14 days after GS 30/31 in spring barley at two sites over 10 seasons.

As with winter barley, the correlation between leaf wetness and final disease levels in the crop disappeared when multiple seasons were analysed together (Figure 18).

4.2.2. 2015 UK data

Winter barley

Data on mean RLS severity at GS 75-85 from all the varieties at each trial site and maximum leaf wetness at GS 30/31 were collected for 16 winter barley trial sites in 2015 and analysed. Overall, there was no positive correlation between leaf wetness and final disease levels in the winter barley crop. Within the UK the sites in the southern region showed more of a positive correlation, but this was not significant ($y = 0.0003x + 0.4644$, $R^2 = 0.6877$; solid symbols on Figure 19).

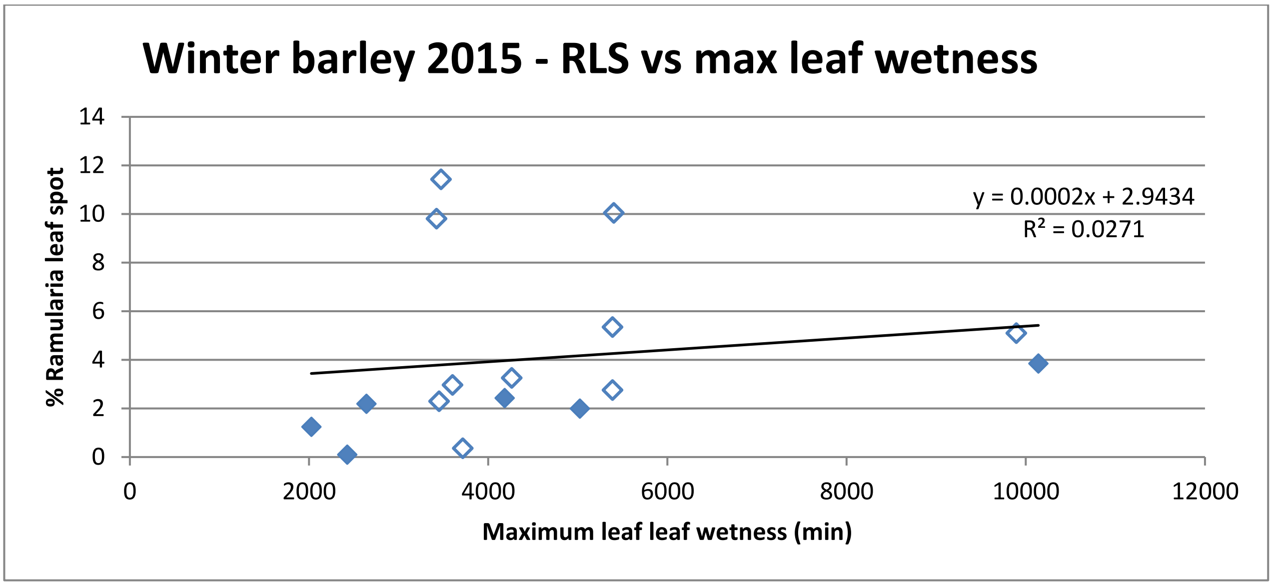

Figure 19. Correlation between RLS at GS 75-85 and leaf wetness for the 14 days after GS 30/31 in winter barley at 16 RL sites in 2015 (trend line describes all data). Solid symbols are sites in the south of UK. Hollow symbols are northern UK sites.

Spring barley

Data on mean RLS severity at GS 75-85 from all the varieties in the trial and maximum leaf wetness for the 14 days after GS 30/31 were collected for 9 trial sites and analysed. Although there was more of a positive correlation between leaf wetness and final disease levels in the spring barley crop compared to the winter barley data, the result was not significant (Figure 20).

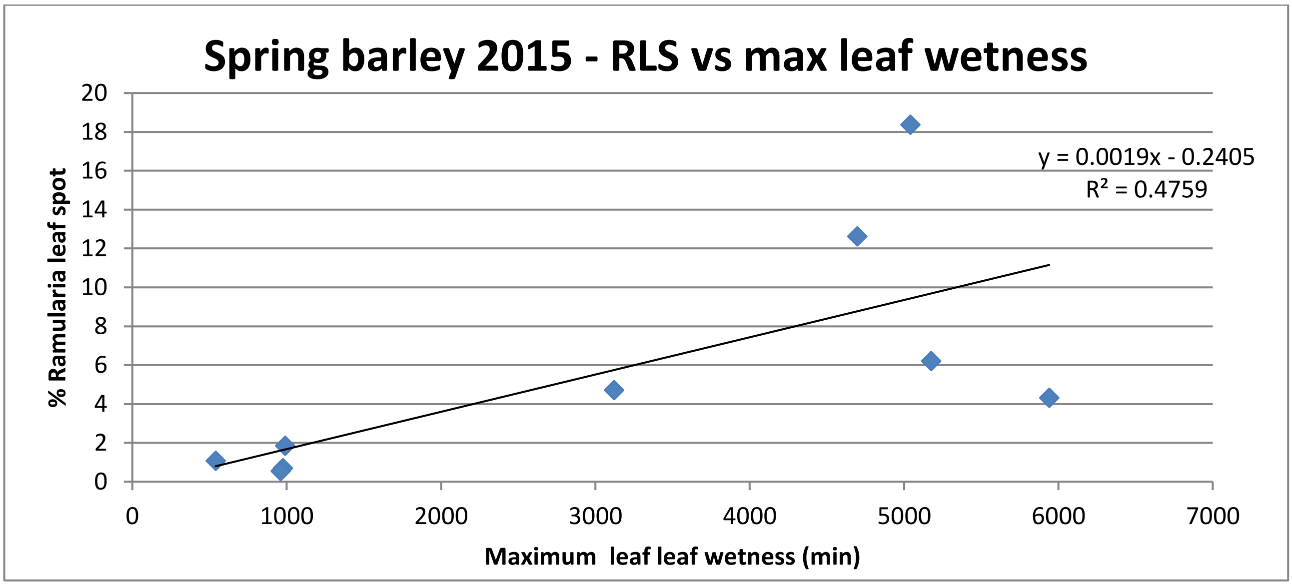

Figure 20. Correlation between RLS at GS 75-85 and leaf wetness for the 14 days after GS 30/31 in spring barley at 9 RL sites in 2015.

Although the relationship was not strong across the entire UK, when smaller geographical areas were analysed a positive correlation was observed (data not shown). Sites in the east of Scotland region showed more of a positive trend, although the results were not statistically significant.

4.2.3. Analysis of 2016 spring barley data

Exploratory analysis

Average disease levels for each variety were calculated from the multiple disease recordings from each plot. The mean values for RLS levels in all untreated spring barley crops from the RL at each trial site were analysed alongside a number of additional crop and environmental factors collected in 2016.

Table 2. Exploratory analysis on data from untreated spring barley plots in 2016. A correlation analysis was carried out on disease data from the untreated plots in 2016 spring barley RL trials and a number of environmental parameters tested for their influence on late season Ramularia in the crop.

Interaction	**Correlation R^2 value**
Maximum leaf wetness at GS 30/31 (measured for 14 days from GS 30/31)	$R^2 = 0.331$
Solar radiation 3 weeks post heading	$R^2 = 0.225$
Rainfall at GS 30/31 (measured for 14 days from GS 30/31)	$R^2 = 0.080$
Average temperature 3 weeks post heading	$R^2 = 0.044$
Number of days from sowing	$R^2 = 0.085$

There were no significant interactions between the parameters and final RLS severity. No further analysis of rainfall at GS 30/31, average temperature 3 weeks post-heading, or days from sowing was carried out because of the low correlation R^2 values in relation to final RLS severity. The greatest positive correlation between RLS levels and environmental parameters were for leaf wetness and solar radiation (Table 2). However, solar radiation post heading would not be a feasible component for a risk forecast therefore further analysis was carried out to investigate if any of the parameters experienced by the crop during the period from sowing to ear fully emerged had an influence on disease levels. Although analysis of a number of parameters was carried out, the majority of the analysis was carried out on cumulative maximum leaf wetness in the crop, cumulative rainfall and cumulative temperature (all from sowing to ear fully emerged), based on parameters associated with increased RLS in published papers (Havis *et al*., 2015) (see Table 1).

Table 3. Correlation analysis for RLS in untreated spring barley RL trials from 2016 and environmental parameters from sowing to GS 59.

Parameter	Cumulative temperature (sowing to GS 59)	Cumulative rainfall (sowing to GS 59)	Cumulative leaf wetness (sowing to GS 59)
Ramularia % disease (Pearson correlation)	-0.113	-0.322	-0.640
Ramularia % disease (P-value)	0.06	0.000	0.000

The analysis in Table 3 indicates that there is no response in disease levels to increasing temperature, a general but not significant decrease in disease levels as rainfall and leaf wetness in the crop increases. A series of contour plots were drawn (Figures 21 and 22) to examine any potential interaction between the variables and disease. Sometimes the variable of interest (RLS severity) may be related to explanatory variables in a way that does not yield a straightforward multiple linear regression analysis. In such cases, it is useful to investigate relationships via contour plots. In plant disease studies, disease severity is often related to variables related to "wetness" and to "temperature", measured appropriately. So these are useful axes for contour plots if we are going to look for relationships (Aegerter *et al*., 2003).

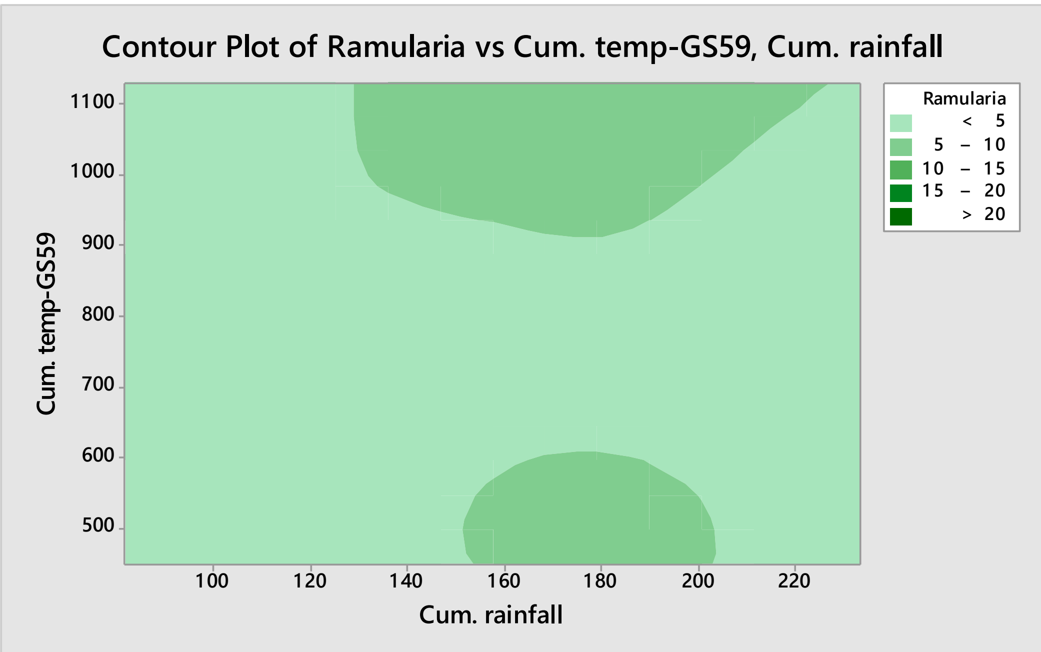

Figure 21. Contour plot of RLS disease severity recorded at GS 75-85 in untreated spring barley across RL sites in 2016 vs cumulative temperature (degrees Celsius) and rainfall (mm) from sowing to GS 59. No significant interaction is visible.

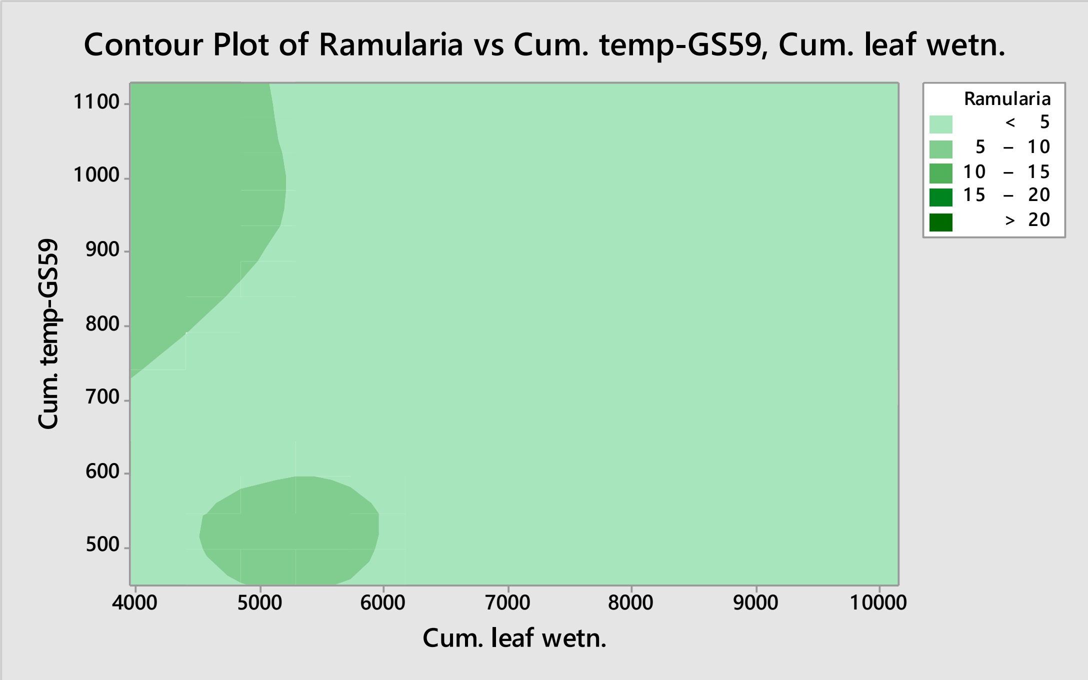

Figure 22. Contour plot of RLS disease severity recorded at GS 75-85 in untreated spring barley across RL sites in 2016 vs cumulative temperature (degrees Celsius) and cumulative leaf wetness (min) from sowing to GS 59. The graph shows a tendency to higher disease levels at lower leaf wetness levels.

In summary, there were no significant interactions between cumulative temperature and leaf wetness from sowing to GS 59 with final RLS disease severity from the 2016 data. The contour maps (Figures 21 and 22) did indicate higher disease levels were associated with lower leaf wetness levels, in contrast to the limited data used in the Scottish model i.e. leaf wetness for 14 days at stem extension, which indicated a positive correlation between RLS and higher leaf wetness in individual seasons.

Further analysis was carried out to determine the accuracy of the current AHDB risk area maps (Figure 23) in predicting RLS levels. In general, this involved correlation analysis between disease levels and either environmental parameters (outlined in Tables 1 and 2) and the geographical region in which the trials were carried out.

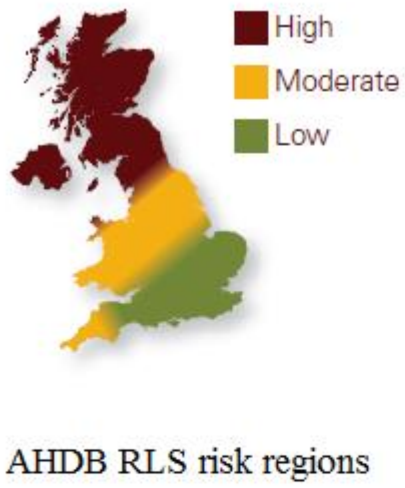

Figure 23. Current AHDB risk region area map for Ramularia (AHDB, 2017).

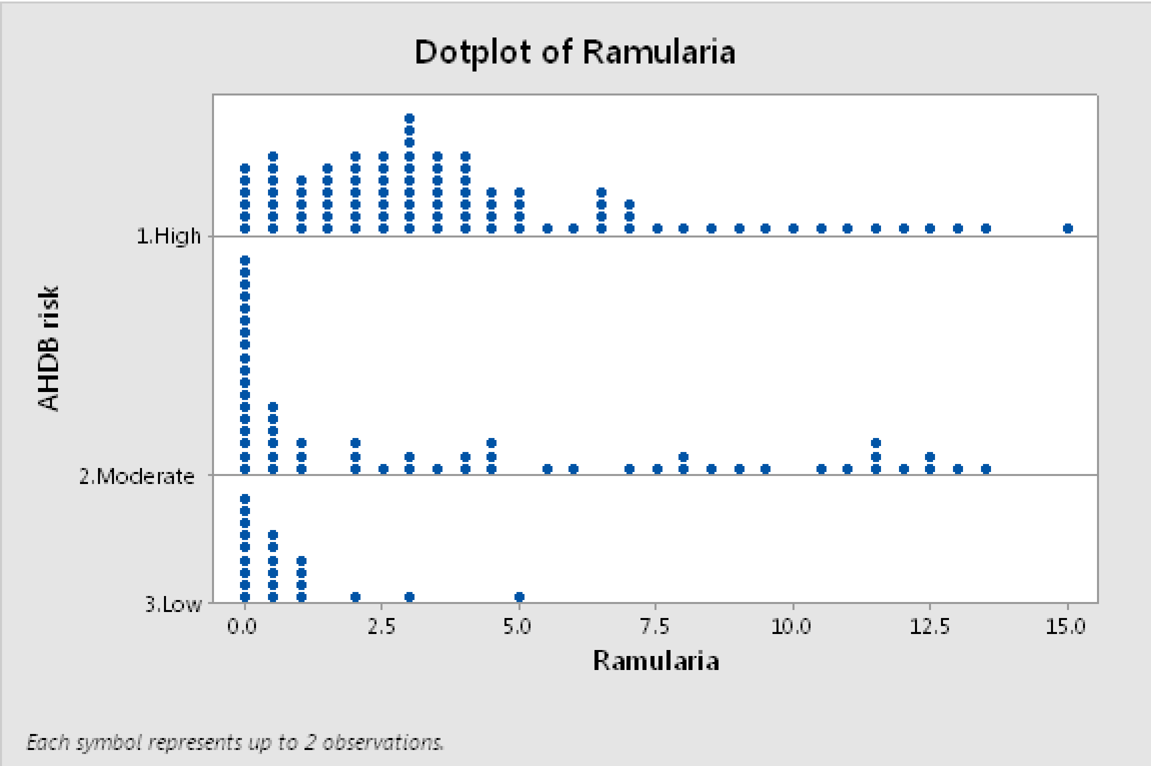

Figure 24. Dotplot of % RLS levels against risk area for spring barley in 2016. Each symbol on the dotplot represents the mean RLS levels in two separate varieties at each site.

The results in Figure 24 show that the existing published risk areas shown in Figure 23 are broadly indicative of the final disease severity recorded in this project. It should be noted that the high risk area does not mean high RLS disease but merely a greater chance of high disease. The moderate RLS risk area appears to fall between 'high risk' of RLS area and 'low risk' of RLS area. The results can be tabulated as follows (Table 4).

Table 4. Total counts of mean disease levels from untreated spring barley for each published risk area in the 2016 cropping season. The table groups disease levels in the AHDB risk areas into distinct bands and indicates the data range for each risk area

AHDB Risk area	**>10% RLS**	**5.1-10% RLS**	**≤ 5% RLS**	**All**
High	13	29	132	174
Medium	20	14	74	108
Low	1	0	42	43
All	34	43	248	325

In the 2016 RL trials RLS scores in the highest band (>10% RLS) were recorded in all three risk areas. The medium risk area actually had more scores in this high band than the high risk area (Table 4). The data reinforces the very general and broad nature of the existing published risk areas.

RLS disease levels in untreated spring plots from the RL trials in 2016 were also compared to the Met Office climate regions (Figure 25) to establish if disease levels corresponded to a defined climate region.

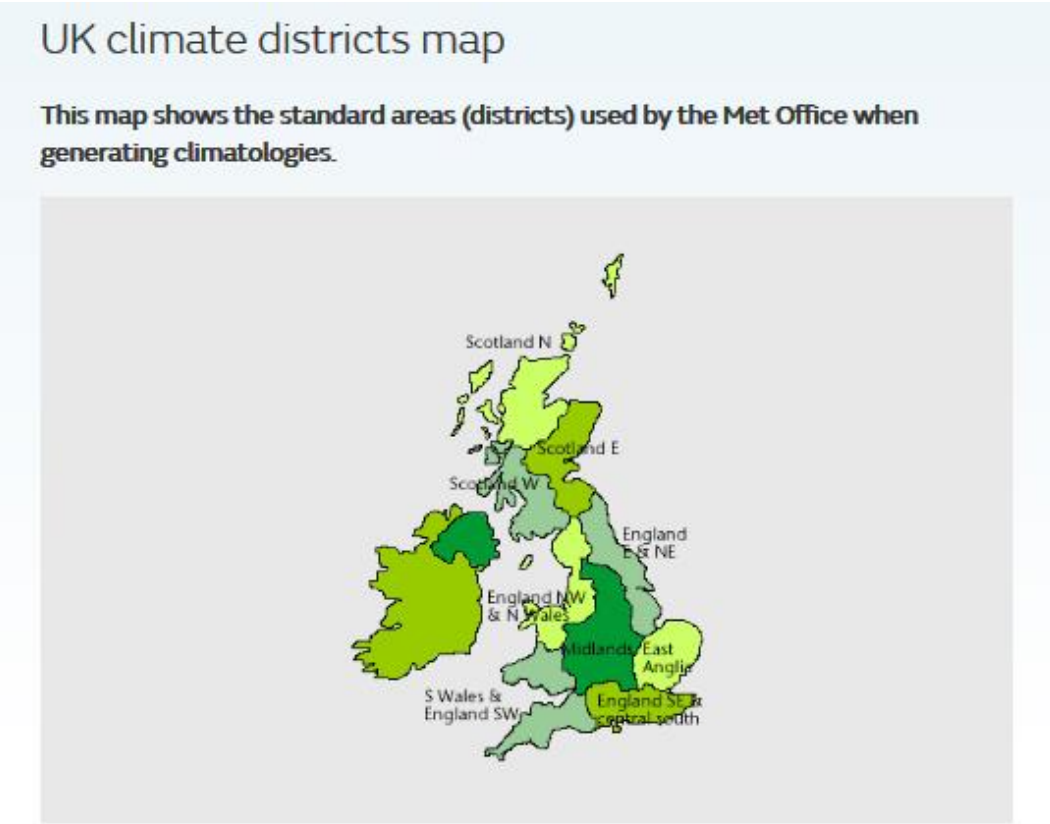

Figure 25. Met Office climate regions (Met Office, 2017).

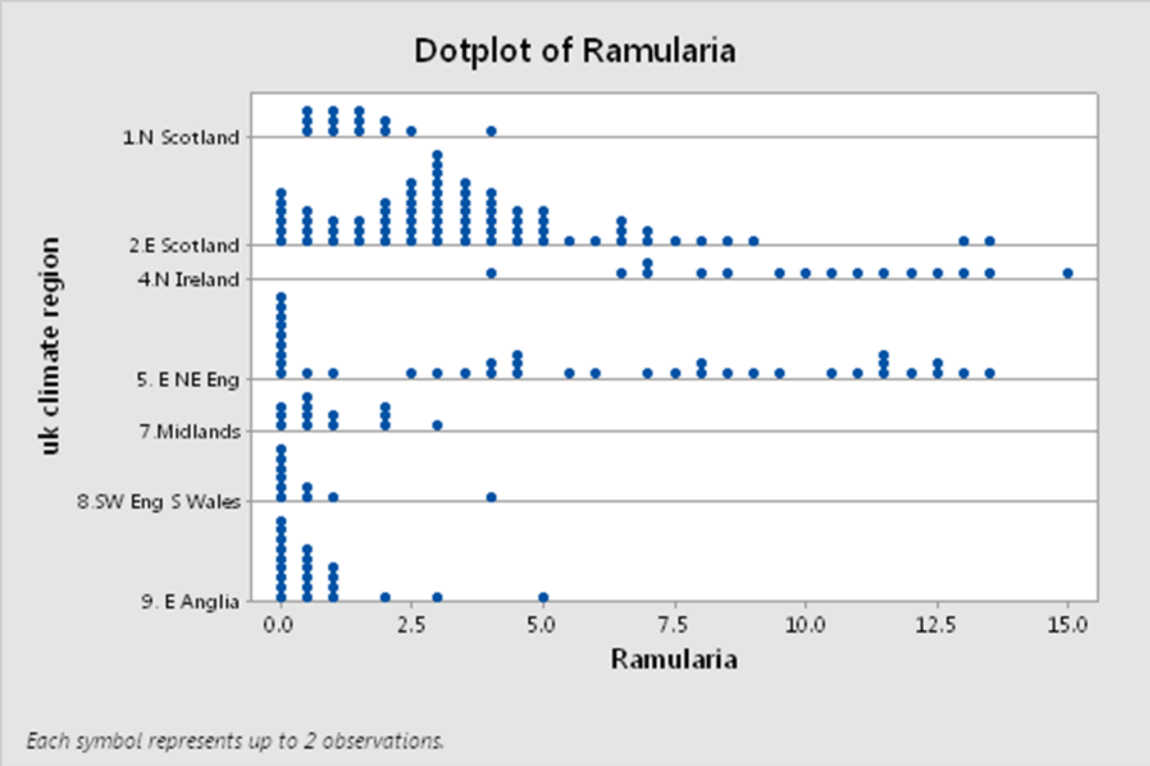

Figure 26. Dotplot of % Ramularia disease severity in untreated spring barley plots in 2016 against Met Office climate region. No RLS sets were available from West Scotland, North West England/North Wales and South East and Central South of England.

The dotplot graph suggests there may be some discrepancies in disease levels between the AHDB risk area and the Met Office climate regions. Highest disease levels were observed in eastern Scotland, Northern Ireland and east/northeast England. All of the Met Office regions which had disease data showed a wide range of disease levels. In particular, we might ask why the discrepancies arise between certain districts and the AHDB risk regions (particularly north Scotland, east and northeast England, midlands, southwest England and south Wales). In other words, there is no correlation between weather regions which lie in specific AHDB risk regions as some give disease levels very different from those seen in other parts of the same AHDB risk region. The discrepancies are clear from the data generated in this project but the underlying causes require further investigation.

Detailed analysis of the other parameters listed in Table 1 indicated they had no influence on RLS levels in the crops (data not shown).

4.2.4. Analysis of 2017 spring barley data

The same analysis methods from 4.2.3 were utilised on data generated from untreated spring barley plots in the 2017 cropping season. The same parameters were used as for the 2016 data (detailed in 4.2.3). The aim of this analysis was to determine if these parameters would influence disease levels in a year with completely different weather patterns. Time constraints limited the opportunity for an over year analysis. Ideally 3 years data would have been included in this analysis as 2015 data could also be incorporated.

Table 5. Correlation analysis for untreated spring barley % RLS data from 2017 cropping season and environmental parameters experienced by the crops from sowing up to GS 59.

Parameter	Cumulative temperature (sowing to GS 59)	Cumulative rainfall (sowing to GS 59)	Cumulative leaf wetness (sowing to GS 59)
Ramularia % disease (Pearson correlation)	0.442	0.646	0.168
Ramularia % disease (P-value)	0.000	0.000	0.011

The 2017 analysis indicates increasing disease levels in crops are associated with increasing temperature, rainfall and leaf wetness experienced by the crop from sowing up to GS 59. The relationship was significant for the spring barley trials in 2017.

Contour plots were drawn for the 2017 disease data as for the 2016 spring barley RLS data (detailed in 4.2.3)

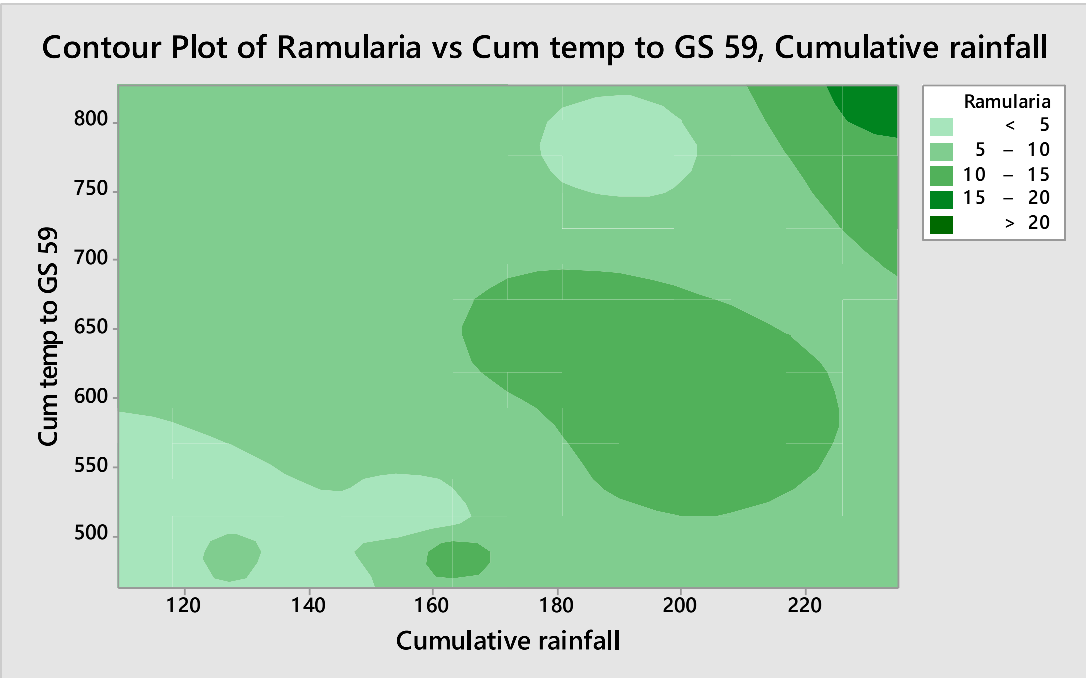

Figure 27. Contour plot of RLS disease severity recorded at GS 75-85 in untreated spring barley RL trials in 2017 vs cumulative temperature (degrees Celsius) and rainfall (mm) from sowing to GS 59. The graph appears to show that the highest disease levels are associated with higher rainfall in this season.

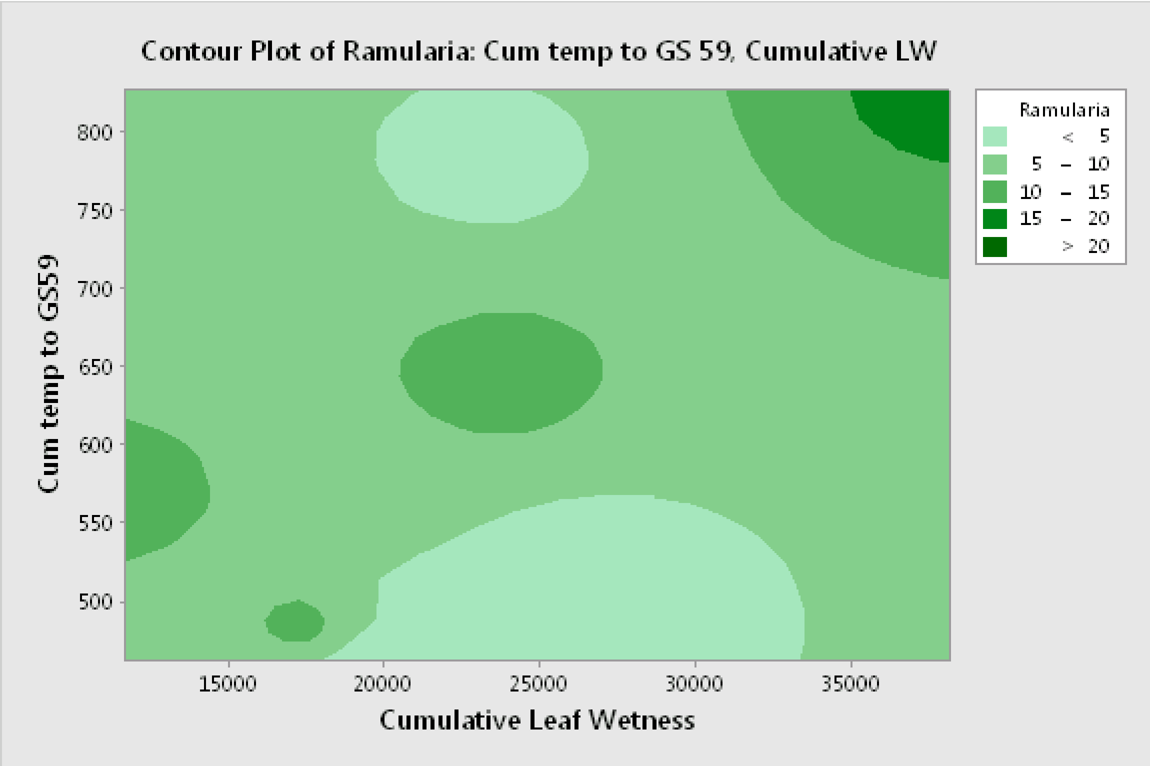

Figure 28. Contour plot of RLS disease severity recorded at GS 75-85 in untreated spring barley RL trials in 2017 vs cumulative temperature (degrees Celsius) and cumulative leaf wetness (min). The graph seems to indicate an underlying relationship between temperature, leaf wetness and RLS disease symptoms.

The contour plots drawn with the 2017 data showed a very different pattern to those from 2016. In 2017 there is an association between disease and high rainfall (Figure 27). This was not observed in 2016 (Figure 21). The relationship between cumulative temperature and cumulative leaf wetness from sowing to GS 59 and final RLS levels is very different between 2016 and 2017. In general disease levels were higher in untreated spring barley RL trials in 2017 (Figures 11 & 15). The highest disease levels were observed in areas with higher cumulative temperatures and higher cumulative leaf wetness (Figure 28). The effect of leaf wetness on disease levels was in line with the limited environmental data used in the Scottish prediction model but the contour plots have indicated that cumulative temperature will also play a part in determining final RLS levels. It is worth noting that this is leaf wetness over the entire vegetative crop growth stage (sowing to GS 59) rather than the limited data from 14 days after stem extension.

Scores for RLS in RL trials in 2017 were also broken down into counts for each of the AHDB risk areas (Table 6).

Table 6. Total counts for % RLS scores in untreated spring barley for each published risk area in 2017.

AHDB Risk area	>10% RLS	5.1-10% RLS	≤5% RLS	All
High	89	87	38	214
Medium	1	9	52	62
Low	0	16	44	60
All	90	112	134	336

In 2017 the highest RLS scores were almost exclusively recorded in the high risk area.

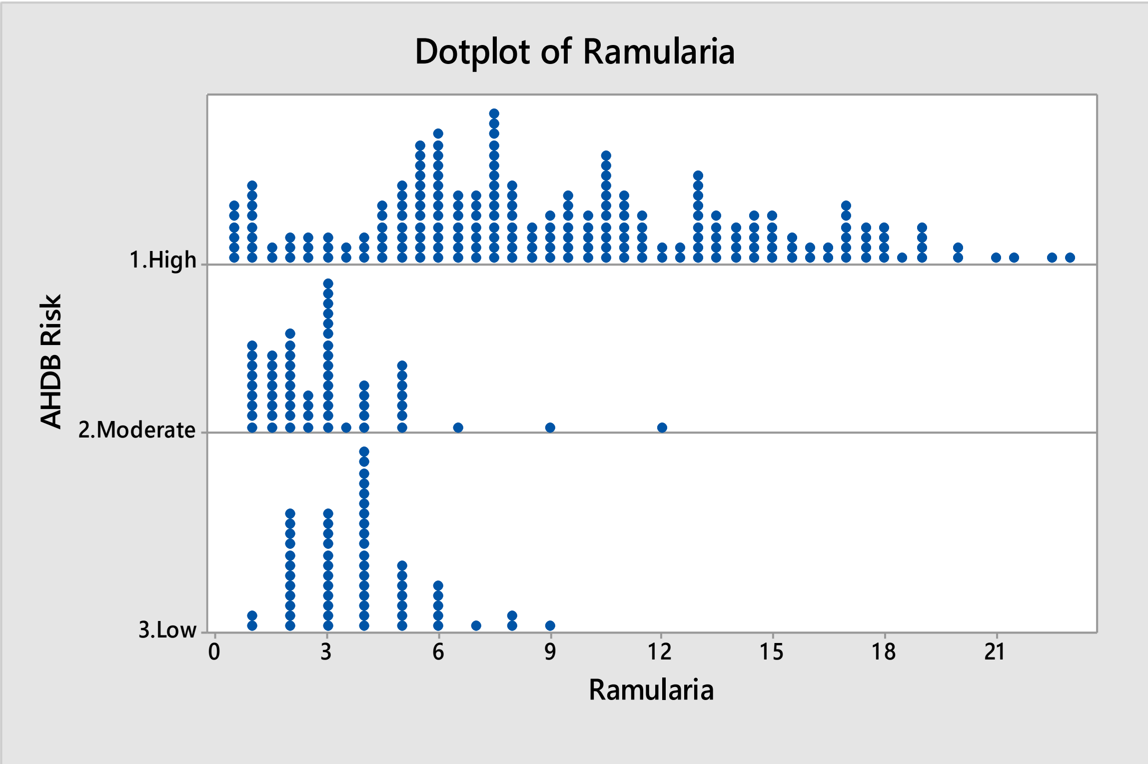

Figure 29. Dotplot of % RLS levels against published risk area for untreated spring barley in the 2017 cropping season.

The results in Figure 29 show that the risk areas are broadly indicative of final disease severity. It should be noted that the high risk area does not mean high disease but merely a greater chance of high disease. The moderate area appears to fall between ‘high’ and ‘low’.

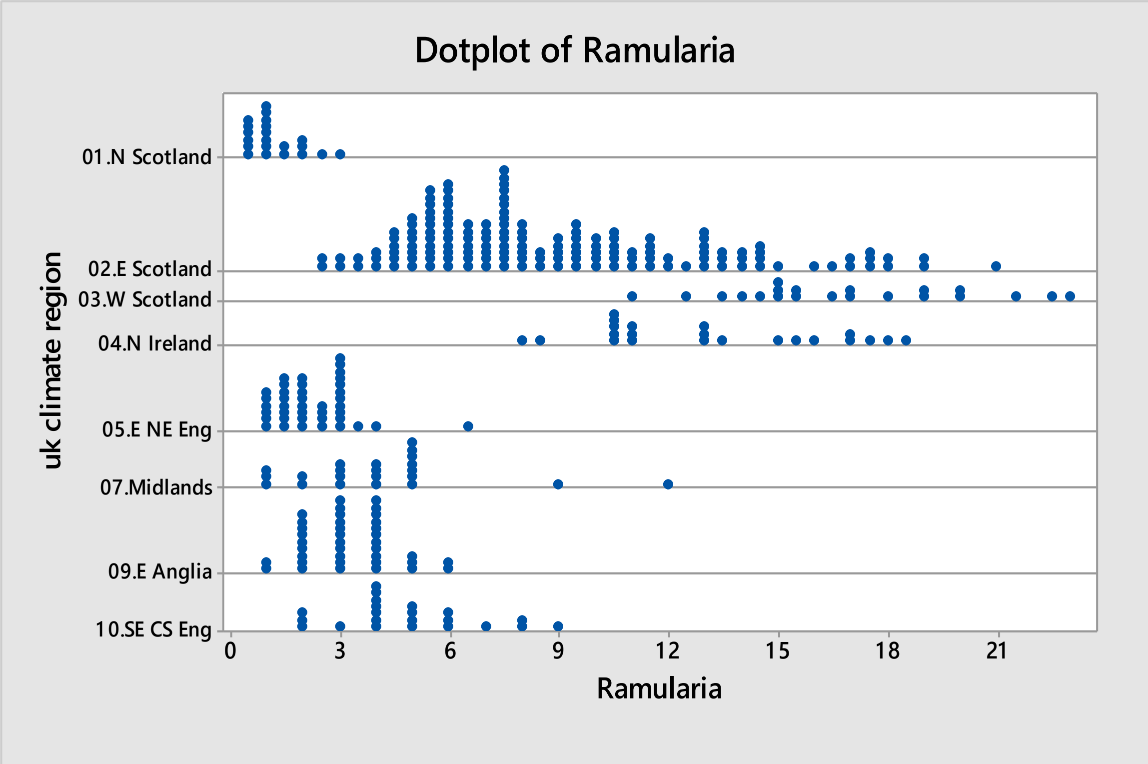

Figure 30. Dotplot of % RLS disease severity against Met Office region in 2017. There were no data sets from northwest England/north Wales and southwest England/south Wales. Each dot on the graph represents RLS levels in two varieties in the untreated spring barley RL trials.

As for 2016, Figure 30 suggests there may be some discrepancies between the published AHDB risk areas and the Met Office climate regions. In particular the north of Scotland climate region gives only low levels of RLS, despite being in the high risk area. This was also observed in 2016 (Figure 26). The east and northeast England climate region gave RLS levels similar to those in East Anglia, although they are in different risk regions.

4.3. Effect of environment on *Ramularia collo-cygni* DNA levels in spring barley crops

4.3.1. 2015 trial season

In this section of the report we will examine the influence of geographical location on movement of the fungal DNA within the crop. The samples tested using the qPCR assay were collected from a number of RL sites in 2015. Whole plants were sampled at GS 30, leaf F-1 was collected at the second sampling at GS 59, and just before harvest ear samples and flag leaves were collected from plots. DNA was extracted from leaf and ear samples and *Rcc* DNA levels quantified using a qPCR assay developed previously (Taylor et al., 2010). *Rcc* DNA levels were meaned across the same six varieties sampled at each site. DNA levels were correlated with maximum leaf wetness for 14 days after GS 30/31 and final disease severity in the varieties in the crop, measured between GS 75-85. Correlation analysis should be carried out on the effect of parameters experienced by the crop over vegetative growth stages and *Rcc* DNA levels. However this was not an initial aim of the project and will require more work.

Table 7. *Rcc* DNA levels in spring barley samples from 2015 cropping season. * indicates no data.

Site	Early *Rcc* DNA (GS 21) (pgrams)	Mid-season *Rcc* DNA (GS 59) (pgrams)	Late season *Rcc* DNA (GS 80) (pgrams)	Maximum leaf wetness (14 days after GS 30/31) (min)	% RLS in crop (GS 75-85)
Northeast Scotland	0.04	1.2	6.8	3120	4.71
Fife	0.1	0.7	5.4	4695	12.64
East Yorkshire	0.2	*	*	960	0.56
North Yorkshire	0.01	0.03	*	5175	6.22
Oxfordshire	4	*	*	975	0.7
Hampshire	1.2	2.1	2.1	1905	*
Norfolk	0.2	1	0.5	540	1.08
Herefordshire	0.1	*	5.7	2940	*
Lincolnshire	*	0.01	1.04	960	0.56
East Lothian	*	*	9.9	990	1.85

The data indicate that *Rcc* DNA levels were low early in the growing season. The highest levels were in the Oxfordshire site (Table 7). Unfortunately no other samples were sent from this site. *Rcc* DNA levels increased at the second sampling date with the highest levels in Hampshire. Highest late season levels were recorded at two Scottish sites (East Lothian and northeast Scotland). Correlation analysis between DNA levels and leaf wetness was carried out (Figure 31).

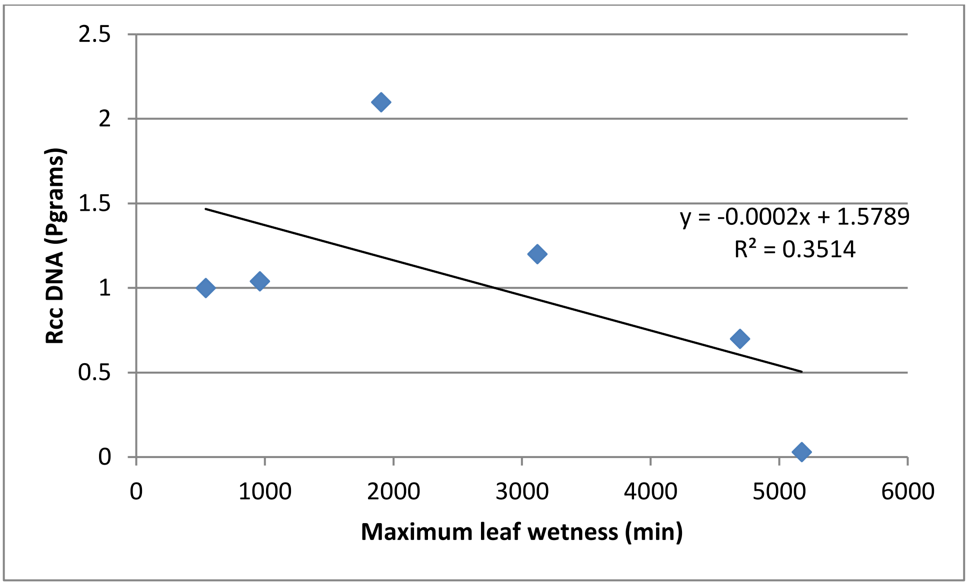

Figure 31. Correlation between *Rcc* DNA levels in F-1 leaf layer collected at GS59 and duration of maximum leaf wetness for the 14 days after GS 30/31 in spring barley crops in 2015. Line shows linear relationship between the two variables.

The data appear to indicate a decrease in mid-season *Rcc* DNA with increasing leaf wetness but the relationship is not statistically significant (p=0.39). This goes against the expectations from the Scottish model where increased leaf wetness correlated with higher disease incidence and by inference higher *Rcc* DNA levels in the upper canopy. Higher RLS levels have been correlated with higher *Rcc* DNA levels previously (Taylor *et al.,* 2010).

4.3.2. 2016 Data

Given the weak relationship observed in 2015 and the reluctance of some of the RL site managers to supply leaf samples it was decided to focus the sampling and DNA testing on SRUC sites, where samples could be taken and dates for crop development were more readily available. Three sites with varying environmental conditions were chosen. Drumalbin Farm, Lanarkshire is a high rainfall and high disease pressure site (West Scotland Met Office region). Boghall Farm in Midlothian is an intermediate disease risk farm; while Cauldshiel Farm in East Lothian is a low rainfall site with a climate more similar to cereal growing areas across the UK. Six spring barley varieties (Propino, Laureate, Concerto, Olympus, Scholar, and RGT Planet) were sown at each site and samples collected throughout the growing season. Plant samples were collected at GS 30 prior to stem extension and leaf F-1 at GS 59 when the ears had emerged. Late plant samples were not taken in 2016. An increasing number of environmental variables were collected and correlation analysis was carried out.

Table 8. *Rcc* DNA levels in spring barley samples from the 2016 cropping season. Environmental data collection was expanded to mirror the analysis carried out on the varietal means from sites (Section 4.2.3). No harvest samples were available for testing in 2016.

Site	Early *Rcc* DNA (pgrams) (GS 24)	Mid-season *Rcc* DNA (pgrams) (GS 59)	% RLS levels (GS 85)	Maximum leaf wetness (for 14 days after GS 30/31) (min)	Cumulative rain (mm) (sowing to GS 59)	Cumulative temperature (°C) (sowing to GS 59)	Cumulative leaf wetness (min) (sowing to GS 59)
Bush	0.18	181.0	1.2	10980	216	951.6	57300
Drumalbin	0.05	4.02	4.6	8820	219.4	661.7	36900
Cauldshiel	0.15	0.07	2.05	14580	157	793.6	56100

The sites were sown on 23rd March, 11th April and 3rd April respectively. GS30/31 was reached at 6th, 8th and 9th June respectively. Ears were fully emerged at 9th, 12th and 1st of July respectively. Correlation analysis indicated no significant interaction between mid-season *Rcc* DNA levels in the F-1 leaf layer and the environmental parameters recorded for the crop (Table 8).

5. Discussion

Ramularia leaf spot (RLS) is a pathogen which has emerged from being a newly described disease in the UK to a major barley pathogen within 13 years (Havis *et al*, 2015). As with other diseases epidemics can vary between years. Variability in RLS levels between years was also seen during the course of this project (Figures 7-16, Table 9). Standard error bars for disease levels in each year also indicate variability across sites (Figures 2-11).

Table 9. Mean Ramularia leaf spot levels (% severity) in untreated plots across UK sites in project years.

Year\crop	**% RLS in winter barley (mean)**	**% RLS in spring barley (mean)**
2015	4.6	6.34
2016	2.41	2.95
2017	2.1	6.7

Over the course of the project RLS levels were generally higher in spring barley crops than winter crops. The reasons for this are as yet unknown, although the use of *mlo* based resistance is widespread in spring barley (AHDB, 2018). Previous research has suggested that there is a link between *mlo* and increased RLS severity (Brown *et al,* 2015).

In the absence of significant varietal resistance, in either winter or spring barley (AHDB, 2018), effective control relies on the application of a fungicide prior to symptom expression (HGCA, 2013). Until recently the number of fungicides available for growers to use included products from 3 major groups, the Succinate dehydrogenase inhibitors (SDHIs), the demethylation inhibitors (DMIs) and the multi-site chloronitriles. However, recent reports of reduced efficacy and the detection of mutations within the fungus to the SDHI fungicides in a number of countries (FRAC, 2016) have raised concerns about the use of some fungicides. These were proved to be well-founded as the AHDB-funded Fungicide Performance trial in 2017 and similar trials showed a collapse in efficacy of the SDHI and DMI fungicides against the pathogen (AHDB, 2017). Growers are therefore relying on the timely use of chlorothalonil to control disease symptoms in their crops. More than ever then they will be interested to know the potential risk their barley crop is at from Ramularia leaf spot.

The aims of this project were threefold; i) to refine the Scottish model by comparing leaf wetness after stem extension with disease levels in the crop over years and sites, rather than a calendar based forecast (see Section 3.2; Supplementary Table 7A&B), ii) to extend the forecast used in Scotland to the rest of the UK by using information from the meteorological network funded by AHDB and disease scores from RL and other trials, and iii) to gather information on disease levels across the UK and quantify levels of fungal DNA in grain and plant samples using a real time PCR.

The first project aim was investigated using disease and meteorological data from Scottish trials carried out at SRUC trial sites over the last 12 years. Although a positive correlation had been observed in Scottish trials between RLS and maximum leaf wetness for the 14 days after stem extension in individual seasons over a number of years (Havis *et al*., 2013), when data were analysed over a number of years for the first time the relationship disappeared for both winter and spring barley (Figures 17 and 18). There was considerable variation in dates at which the crop reached the stem extension stage over the years and this could have caused the loss of the relationship. There is also the possibility that environmental factors later in the growing season could influence disease levels. The positive relationship between final disease levels and maximum leaf wetness was seen for the winter barley crop in southern sites in 2015 (data not presented) but the lack of a significant relationship over seasons led to a re-evaluation of the risk forecast away from using leaf wetness as the sole predictor of RLS severity. A comprehensive review of the limited published material on the effect of environmental variables on RLS was undertaken. A number of papers suggested a link between RLS levels and environmental conditions experienced by the growing crop. High humidity throughout crop growth was reported as influencing disease epidemics (Formayer *et al*, 2004). This was also reported by Salamati & Reitan (2006). Formayer *et al,* 2004 also reported that high radiation levels in the period after flowering increased RLS epidemics. Other post-heading conditions were also suggested to influence disease levels. Marik *et al*, (2011) found that higher temperatures and lower rainfall after flowering reduced disease symptoms. This could be due to accelerated senescence. As a result, the parameters on which data were collected in 2016 were expanded to include additional meteorological data and also crop-related data (see Table 1). None of the crop factors had a significant interaction with disease levels from the untreated spring barley trials in 2016 (data not presented). Of the environmental factors tested, the most significant interactions were maximum leaf wetness at GS 30/31 (measured for 14 days from GS 30/31) and solar radiation 3 weeks post heading (Table 2). It was decided to focus further analysis on the environmental factors experienced by the crop, which could be added into a risk forecast during the growing season. In addition, more focus was given to the conditions experienced by the crop up to the latest available date for fungicide application (GS 59). Correlation analysis indicated no significant interaction between these variables in the untreated spring barley plots across the UK in 2016. One contour plot presented showed a general decline in RLS with increasing cumulative leaf wetness from sowing to GS 59 (Figure 22). In contrast, in 2017 there was an increase in disease levels with increasing cumulative temperature, cumulative leaf wetness and cumulative rainfall from sowing to GS 59 (Figures 27 and 28), but the interactions were not significant. This underlies the problems in the construction of a robust Ramularia risk forecast, as the current risk forecasts used by UK cereal growers are based on statistically significant interactions between the pathogen and environment and crop factors (Burnett *et al*, 2012; Edwards *et al,* 2016). Both of these risk forecasts required the analysis of many years of trials data and multiple projects. It is apparent that the development of a robust Ramularia risk forecast will require further research.

The priority is to identify one or more risk factors (based on crop, environment or pathogen characteristics) that can be used to predict the need for treatment (or otherwise) in barley crops at an early enough stage for a reliable decision on fungicide use (or otherwise) to be made. The emphasis, for farm-level decision-making, is on reliability, especially in relation to predictions which would suggest fungicide use might not be warranted. This is a higher level of acceptability than for the identification of a trend towards higher disease levels when there are higher levels of a particular risk factor or combination of factors. Currently, this higher level of acceptability has not been met in the data presented here nor in other published data on RLS disease risk.

While farm-level decision guidance is not yet supported, region-level guidance may be possible. Current RLS risk areas presented by AHDB split the UK in 3 distinct regions (Figure 23). Our analysis of the RLS levels in spring barley RL trials in 2016 and 2017 indicated that each area corresponds more to a potential range of disease levels rather than distinct narrow band of disease levels (Figures 24 & 29). Each area contained sites with low levels of disease, whilst in 2016 the RLS levels in the moderate area covered a range similar to the high risk area. In order to see if these risk areas could be refined we carried out an analysis of RLS levels within the official Met Office climate districts (Figure 25). There is an approximate correspondence between the 10 Met Office climate districts and the AHDB RLS risk regions (Figure 26) as follows: RLS 'high risk' (north Scotland, east Scotland, west Scotland, Northern Ireland), RLS 'moderate risk' (east and northeast England, northwest England and north Wales, Midlands, southwest England and south Wales), 'low risk' (East Anglia). A comprehensive data set from across the UK would allow a more robust comparison between the AHDB risk regions and Met Office regions as some areas have no RL trials e.g. southeast and central southern England. The RLS data for 2016 (Figure 26) and 2017 (Figure 30) indicate some variability in described results. In both years, RLS severity was relatively low in the north Scotland climate district (part of the RLS 'high risk' region). In the east and northeast England climate district (RLS 'moderate risk'), RLS severity was more similar to RLS 'high risk' region in 2016, while it was more similar to the RLS 'low risk' region in 2017. No simple explanation for these discrepancies was identified from a further examination of the project data, but they clearly merit further investigation as they do appear to represent the effects of factors modifying risk which need to be identified. Overall, in the absence of any clear explanation of within-region variation of RLS risk, we do not recommend any changes to the AHDB RLS risk regions at this stage. However, we re-iterate that the data indicate that location in the high-risk region does not mean that RLS risk exposure for crops is universally and invariably high.

In 2015 leaf samples were tested for *Rcc* DNA concentration from a number of sites across the UK (Table 7). Late season DNA levels were negatively correlated with leaf wetness conditions in the crop at stem extension (Figures 31, but this was not statistically significant. High leaf wetness and humidity are used to improve RLS infection on barley in controlled environment experiments (Brown *et al,* 2014). In 2015 higher levels of leaf wetness in the crop at GS 30/31 did not appear to have promoted RLS infection. This is still a small temporal window to examine during crop development, however. It was concluded that a robust risk forecast would have to incorporate more environmental variables than maximum leaf wetness over a 14 day period. In 2016, samples were collected from 6 spring barley varieties grown at SRUC trial sites in Scotland. Environmental parameters were also collected at each of the sites (Table 7). Correlation analysis of *Rcc* DNA in the F-1 leaf layer and the environmental parameters showed no significant interaction (data not shown). No significant relationship between the environment and *Rcc* movement in the developing crops has yet been established. The influence of a number of environmental conditions on *Rcc* movement in plants is being examined in studies at SRUC as part of the current RESAS research programme. The movement of the fungus in field crops has been reported previously (Havis *et al,* 2014). The primary inoculum source for the fungus appears to be infected barley seed and *Rcc* DNA has been shown to move up the developing host plant in the absence of spore movement. Examination of the conditions experienced by the crops in these experiments could yield information that could contribute to our understanding of the relationship between the host plant and the fungus.

In conclusion, the project was successful in furthering our understanding of disease levels across the UK and data from the RL trials has contributed towards the production of official resistance ratings for winter and spring barley. The development of an Integrated Pest Management system to control RLS, including an evaluation of risk from environmental variables, will also require information on varietal susceptibility. However, the complexity of the host-pathogen interaction and gaps in our knowledge of *Rcc* fungal biology has contributed to the inability to produce a robust forecast scheme within the time period of the project. Although the project has suggested that some environmental variables can positively influence final disease severity in barley crops, more research is needed to establish if this relationship applies across numerous seasons, sites and crops.

6. KT activity

The research project was promoted at a number of events and in articles:

January 2016 AHDB/SRUC Winter disease roadshows (Carfraemill, Perth, Aberdeen and Inverness)

February 2016 Crop Protection in Northern Britain Conference

April 2016 Uruguayan Barley Meeting, Colonia, Uruguay

June/July 2016 SRUC Trial Open days

August 2016 IPCC Satellite Meeting Berlin

October 2016 Bayer Crop Focus article

January 2017 AHDB/SRUC Winter disease roadshows (Carfraemill, Perth, Aberdeen and Inverness

February 2017 Farmers Weekly Ramularia Academy

March 2017 Bayer Crop Magazine

June 2017 Cereals Event

June/July 2017 SRUC Trial Open days

January 2018 AHDB/SRUC Winter disease roadshows (Carfraemill, Perth, Aberdeen and Inverness)

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Supplementary Tables

Table 1. % RLS in untreated winter barley varieties in RL trials in 2015. * indicates no data for variety at this site.

Variety\Site	Bainton	Bush	Fife	Crofts	Downpatrick	Ellon	Limavady	Borders	North Yorkshire	Broughton	Cheshire	Cornwall	Cowlinge	Cornwall
Bazooka	*	*	4.4	*	*	*	*	*	*	*	*	*	*	*
Belfry	*	*	3.2	0	6.3	*	2.8	*	*	*	0	0.3	0.3	2.1
California	8.8	*	3.3	0	4.4	*	3.1	3	*	0	0	0.3	0	0
Cassata	12.7	9.5	2.4	*	10.9	0.3	3.2	2.8	2.8	2.4	0	17.3	3.2	0.5
Cavalier	*	9.7	3.4	2	*	0.8	*	8.9	13.3	1.2	*	*	*	*
Craft	15.2	9.2	1.9	*	5.7	0.1	3.6	3.8	4	5	0.3	4.6	1.5	3.6
Daxor	8.5	16.5	4.6	1	8.5	0.3	3.3	1.4	*	0.5	0	0.4	0.2	0.6
Florentine	22.5	*	2.7	0	6	*	4.5	4.2	*	5.7	0	0	0	0
Khatmandu	*	*	8	*	*	*	*	*	*	*	*	*	*	*
KWS-Cassia	5.3	6.2	0.7	0	3.1	0.7	1.1	2.6	2.6	2.4	0.3	0.9	3	1.1
KWS-Glacier	12	11.1	1.1	0	1.4	0.9	1.7	4.4	10.5	1.7	0.3	5.7	5.8	1
KWS-Infinity	9.7	10.3	3.2	1	4.8	0	3.4	1.9	3.2	1.9	0.3	0.8	0	0.6
KWS-Meridian	5.1	6.9	2.8	0	2.8	0.5	1.4	2.6	0.4	6.2	0	0.2	5.7	1.9
KWS-Orwell	*	*	3	0	3.6	*	3.1	*	2	0	0	0.8	1.3	0.5
KWS-Tower	15	14	2.8	1	5.4	0.3	1.7	3.5	2.6	2.5	0	0.7	1.4	4.1
Pearl	*	*	2.4	*	*	*	*	3.6	*	*	*	*	*	*
Perseus	*	9	1.5	*	*	*	*	3.1	*	*	*	*	*	*
Retriever	*	11.4	2.1	*	*	0.1	*	5.4	*	*	*	*	*	*
Shadow	16.6	12.7	3.2	5	8.8	0.4	6.1	5.9	2.7	6.1	0	9.3	5	5
SJ091049	24.6	15.8	*	6	5.4	0.7	2.8	2.6	11.4	6	0.1	3.2	3.1	0.2
Surge	8.2	9.3	4.9	6	6.6	0	1.2	2.8	2.3	0.4	0	9.1	4.1	1.5
SY212-118	5.8	5.8	*	0	5.2	0.9	1.8	1.9	3	4.6	0	0.3	0.3	0.7
SY212-124	*	6.1	*	*	*	0.5	*	1.6	7.4	*	*	*	*	*
SY-Venture	13.9	3.2	0.6	3	5.6	0.2	2.2	1.8	10.2	1	0	4.3	0.4	2.8
Talisman	11.8	18.6	3.9	0	4.7	0.1	4.3	3.3	7.4	0	0.2	18.2	1.5	14.3
Verity	3.4	2.8	1.6	1	2.7	0.2	1.4	2.1	1.9	1	0	0.5	2.7	1.5
Volume	6.6	12.2	3.8	2	5.1	0.2	2.6	2.6	4.2	0	0.2	0.3	0.6	1.3

Table 2. % RLS levels in untreated spring barley varieties in RL trials in 2015. * indicates no data for variety at this site.

Varieties\Site	Coleriane	Ewingston	Laurencekirk	Newtonards	Stockbridge	Strabane	Banbury	Docking	Balgonie
Belgravia	*	1.4	4.7	*	*	*	*	*	12.2
Concerto	2.9	1.7	5.6	20	6.1	2.8	1.7	*	16.6
Deveron	3.8	1.8	4.4	19.6	7.5	1.3	0.4	2.8	11
Fairing	7.7	3.4	3.4	12	3.6	9	0.5	*	11.9
Garner	5.4	*	*	*	*	5.1	*	*	*
Hacker	4.4	1.8	6.5	20.1	*	3.6	0	*	*
Kelim	1.8	1.8	2.1	9.5	9.1	5.2	1.8	*	11.1
KWS-Irina	2.7	1.6	3.5	19.4	4	3	0.9	*	10.9
KWS-Sassy	4.6	0.6	4.5	10.1	*	2.8	0.2	*	12.4
Laureate	2.3	1.5	5.1	12.9	5	3.5	0.5	*	14.9
NFC-Tipple	2.6	1.4	5.8	*	5.7	2.6	0.5	1	11.9
Octavia	2.8	2.2	6.3	22.2	4.5	5.6	0.3	*	15.3
Odyssey	4.5	2.8	5.8	12.5	4.4	3.9	0.8	*	14.6
Olympus	2.7	3	6.3	18.3	9.4	9	1.2	*	14.6
Origin	3.2	1.7	3.7	14.9	3.6	2.8	0.8	*	13.3
Ovation	2.9	2.7	6.8	13.6	4.1	5.8	0.3	*	11.5
Overture	2.3	*	*	*	*	4.1	*	*	*
Propino	3.6	2.5	4.7	9.7	9.2	1.7	0.3	0.6	12.8
Quench	8.6	*	*	*	*	4.8	*	*	*
RGT-Planet	5	1.9	2.9	20.3	5.8	2.3	1	*	10.3
Sanette	2.8	1.1	4.8	13.1	6.4	2.3	0.4	0.6	13.4
Scholar	2.2	1.7	4.8	12.1	10.6	4.7	0.8	0.4	10.8
Shada	2.9	2.2	4	16.2	3.3	1.2	0.7	*	11.9
Sienna	2.8	1.4	5.8	16.9	8.4	2	0.7	*	10.7
Tesla	3	2.4	5.1	16.1	7.7	2.5	0.6	*	14.2
Vault	3.1	1.5	3.7	11.5	5.9	1.5	1	*	11.8
Waggon	*	1.3	2.9	*	*	4.3	*	*	*
Westminster	*	0.9	4.6	*	*	2.8	*	*	*

Table 3. % RLS levels in untreated winter barley varieties in RL trials 2016. * indicates no data for variety at this site.

Variety\Site	Auchnagatt	Balgonie	Banbury	Bush	Cowlinge	Crofts	Hereford	Kinross	Lanark	Limavady	Borders	North Yorkshire
Bazooka	2.6	9.1	3	9.4	0.5	4.1	0.5	9.6	3.5	14.9	3.9	4
Belfry	9.1	8.6	2	7.6	1	3.4	0.3	8.4	4.3	20.8	4.8	9.7
Cassata	1.7	7.1	*	4.1	*	3.7	0.4	6.1	0.2	14.9	5.8	10.8
Craft	7.8	8.1	0.1	4.2	1	2.1	0.6	2.7		12.2	8	9.6
Daxor	15.8	7.9	0.1	8.4	3	2.2	0.4	7.1	1.8	11.1	8.8	6.9
Funky	*	3.6	*	6.3	*	*	1.7	3.4	*	*	*	*
KWS Cassia	6.2	4.8	1	2.7	0.1	3.3	0.7	1.9	2.2	21	3.1	4.5
KWS Cresswell	*	5.9	1	2.4	*	*	1	4.3	*	*	*	*
KWS Glacier	4.7	7	0.1	1.1	0.1	3.6	0.7	2.6	2.1	6.6	7.6	11.8
KWS Infinity	1.4	9.9	0	5.4	0.5	4.4	0.8	5.2	1.8	8.7	6.7	8.7
KWS Meridian	3.9	10	0.1	7.2	2	5.9	0.5	4.8	5.1	14.4	6.3	10.4
KWS Orwell	2.7	8	3	3.9	0.5	2.3	0.3	5.3	2.5	11.4	6.8	12.7
KWS Tower	2.8	19.5	0	3	0.1	3.3	0.3	2.7	*	13	7.2	1.8
KWSB114	1.7	*	0	*	*	3	0.2	*	*	7.1	13.8	3.8
MH08KU37	8.5	*	*	*	*	4.6	*	*	*	19.9	9.1	10.8
SC82909NH	7.5	*	*	*	*	1.7	*	*	*	10.6	5.1	4.2
Rubinesse	*	8	5	2.6	*	*	0.4	2.4	*	*	*	*
Sunningdale	2.8	6.2	3	14.1	3	5.8	0.9	5.9	*	16.4	6.3	5
Surge	3.9	5.1	3	4.8	1	2.1	0.9	8.7	3.1	20.8	14	8.4
SY Venture	1.5	5.8	0.5	0.7	0.5	3.2	0.7	2.6	1	9.2	8.5	3.9
Talisman	2.8	6.3	0.1	4.5	0.5	3.5	0.5	3.2	1.8	8	5.9	9
Volume	1.8	4	*	2.6	*	2.6	0.5	6.1	1.9	10.6	5.2	2.7

Table 4A. % RLS levels in untreated spring barley varieties in RL trials 2016. * indicates no data for variety at this site.

Variety\Site	Tayside	Cornwall	East Lothian	Shropshire	Norfolk	Norfolk	Northern Ireland	Laurencekirk
Acorn	8.9	0.1	1.2	0.5	0.1	3	12.3	4
Belgravia	4	*	0.2	0.1	0.1	1	6.3	2
Chanson	8.7	0	0.7	0.5	0.5	0.1	4.2	1
Concerto	3.3	*	0.7	0.5	0.5	0	7	3
Dioptric	3.1	0	2.6	0.1	0.1	1	7	0
Fairing	4.3	0	2.6	2	0.1	5	15.1	0
Hacker	1.7	0	4.6	2	*	*	12.4	2
Kelim	*	*	*	*	*	*	*	*
KWS Irina	6.1	0	0.5	0.5	0.5	0	12.8	0
KWS Sassy	9	0	0.5	0	0.5	0.5	11.6	0
Laureate	3.8	*	3	1	0.5	1	10.9	0
LG Okapi	6.4	0.1	2.3	0.5	0.1	2	13.6	3
LG Opera	7.9	0.5	6.5	1	0	0.5	7	0
Octavia	1.5	0.5	1.2	0.5	0.1	1	10.7	3
Odyssey	4.8	4	3.3	0.5	0	0.5	9.9	3
Olympus	13	1	1	2	0.1	1	9.5	3
Origin	1.9	0.1	2.7	2	0.5	0.1	10.6	0
Ovation	6.5	*	4	0.1	0.5	1	8.3	7
Propino	5.4	0.1	0.7	1	0.1	0.1	10.9	0
RGT Planet	7.4	0.1	0.7	0	0.1	0.5	8.2	2
Sanette	3.4	0	3.3	2	1	0.1	6.7	0
Scholar	4.9	1	1.7	3	0	2	9.8	2
Sienna	1.4	0.5	1.2	2	0.5	1	11.9	0

Table 4B. % RLS levels in untreated spring barley varieties in RL trials in 2016. * indicates no data for variety at this site.

Variety\Site	Lincolnshire	Banffshire	North Yorkshire	East Ross	Kinross	Borders	Bainton
Acorn	0.1	6.4	8.6	*	2.4	3.9	11
Belgravia	0	3.5	3.3	1.7	13.6	3.1	11.7
Chanson	0.5	2.8	4.6	*	2	4	9.2
Concerto	0.1	1.8	11.6	2	2.4	2.9	11.2
Dioptric	0	3.3	2.9	*	4.7	4.1	11.8
Fairing	1	3.4	4.1	1.4	3.7	4.6	6.2
Hacker	*	*	*	*	*	6	12.7
Kelim	*	*	*	0.6	*	*	*
KWS Irina	0	2.7	8	0.5	3	4.8	7.3
KWS Sassy	0.5	0.7	3.9	0.7	3	2	9.6
Laureate	0	5.3	4.5	0.8	2.9	2.4	8.5
LG Okapi	0	2.3	7	*	1.9	2.5	12.6
LG Opera	0.1	3.2	5.7	*	4.9	4.5	6.9
Octavia	0.1	2.4	11.7	1.9	2.9	7.2	13.1
Odyssey	0	4.5	3	0.5	1.6	3.6	12.3
Olympus	0.1	4.1	8.1	0.6	7.6	3.6	11.4
Origin	0.1	4.8	4.6	4.1	3.3	3.4	11.6
Ovation	0	2.6	2.6	1.4	2.8	2.9	8
Propino	0.1	4.2	4.7	1.3	5.2	2.1	12.1
RGT Planet	0	3.9	4.2	1.3	3.5	2.9	8.9
Sanette	0	4.8	3.7	1.6	4.9	3.3	10.3
Scholar	0.1	4.7	4.7	1.2	6.5	7.2	10.6
Sienna	0.1	4	7.8	0.5	2.3	3.2	13.6

Table 5A. % RLS levels in untreated winter barley varieties in RL trials in 2017. * indicates no data for variety at this site.

Variety/Site	Suffolk	Hampshire	Dorset	Norfolk 1	Fulbourn	Warwickshire	Hereford	Lincolnshire	Glamorgan	Cheshire	Gleadthorpe	Aberdeenshire
Cassata	3	7	5	3	4	8	3	4	1	9	2	1.8
Volume	1	3	5	4	3	3	2	6	2	2	1	0.4
KWS Cassia	1	2	2	3	2	2	2	5	4	8	1	0.2
KWS Meridian	1	2	3	4	6	5	3	4	3	7	2	0.7
SY Venture	3	4	2	5	2	2	1	8	4	3	2	0.3
Talisman	7	3	2	7	6	2	3	12	6	5	1	1.9
KWS Glacier	3	1	2	4	5	2	1	2	2	10	2	0.9
KWS Infinity	2	6	6	6	3	3	4	6	2	5	2	0.7
KWS Tower	2	2	2	4	4	1	2	7	4	1	3	1.9
KWS Orwell	1	4	5	4	7	2	1	12	5	7	1	0.7
Bazooka	1	4	3	4	2	2	2	4	2	6	1	1.2
Belfry	1	3	2	6	5	1	4	4	3	4	3	1.7
Craft	1	6	2	2	4	4	3	5	2	9	1	1.8
Surge	3	5	3	5	6	3	3	12	2	12	2	1.1
Funky	1	4	2	3	2	5	2	9	3	5	3	1.9
Sunningdale	3	3	3	4	4	3	3	9	4	4	1	2.2
Rubinesse	4	3	3	5	3	1	3	10	5	7	1	0
SY 614009	2	5	7	6	2	2	2	*	2	6	5	1.6
SY 614014	2	1	2	4	4	2	2	10	6	5	2	1.7
SY213139	6	4	5	5	3	3	3	7	5	10	4	1.3
Belmont	4	2	3	3	4	2	3	*	5	12	*	1.3
AC10/181/16	1	5	4	2	3	2	7	3	3	7	5	0.7
California	*	3	6	*	2	2	2	8	1	12	*	*
KWS Creswell	*	4	3	*	4	*	*	8	1	*	*	0.6
KWS Astaire	*	3	3	*	3	1	1	7	5	7	*	*

Table 5B. % RLS levels in untreated winter barley varieties in RL trials in 2017. * indicates no data for variety at this site.

Variety/Site	Teeside	East Yorkshire 1	Northern Ireland	East Yorkshire 2	Borders	North Yorkshire	Tayside
Cassata	4.1	3.6	2.6	0	1.9	3.1	0.6
Volume	2.3	2.2	2.1	1.1	1.8	0.9	1.4
KWS Cassia	3.2	3.3	1.1	0.2	0.7	2.6	0.7
KWS Meridian	3.5	3.3	4	0.9	1.6	1.6	2
SY Venture	2.9	3.0	4.2	0.4	2.6	0.1	0.4
Talisman	4.4	4.8	3.5	0.1	1.7	1.6	1.1
KWS Glacier	2.8	3.0	4	0.2	1.8	1.3	0.2
KWS Infinity	3.2	3.3	4.3	0.7	0.8	1.5	0.3
KWS Tower	2.8	3.1	2.6	0.4	2.3	0.3	0.2
KWS Orwell	4.1	4.4	3.9	0.3	2.4	3.1	0.2
Bazooka	2.6	2.7	3.9	0.6	1.5	2.8	0.9
Belfry	3.0	3.2	3	0.4	1.8	2.6	0.2
Craft	3.7	3.6	3.5	0.1	0.9	3.2	0.9
Surge	5.0	5.3	2.6	0.2	2.2	3.4	0.6
Funky	4.1	4.0	3.3	0.3	1.7	4	1.5
Sunningdale	3.7	3.8	2.5	0.4	2.3	2.5	0.6
Rubinesse	3.9	4.3	2.1	0.6	1.5	1.8	0.6
SY 614009	3.1	4.9	3.9	0.5	2	1.3	0.4
SY 614014	4.1	4.9	2.8	0	1.7	3.1	1.4
SY213139	4.8	4.4	3	0.7	1.3	2.4	1.4
Belmont	4.7	3.3	3.3	1	1.5	2.1	0.7
AC10/181/16	4.0	4.2	4.4	0	2	2.1	0.8
California	5.0	*	5.7	0.3	2.3	*	*
KWS Creswell	3.2	*	4.7	0	1.8	*	*
KWS Astaire	4.2	*	*	0.3	1.4	*	*

Table 6A. % RLS levels in untreated spring barley varieties in RL trials in 2017. * indicates no data from variety at site.

Variety/Site	Cheshire	Kent	Cornwall	Herefordshire 1	Norfolk 1	Lincolnshire	Hampshire	Norfolk 2	Herefordshire 2	Lincolnshire
Belgravia	*	*	*	*	*	*	5	*	3	*
Concerto	16	3	0	5	4	0	6	4	5	3
Propino	8	3	1	3	8	2	4	3	1	3
Odyssey	14	5	2	3	10	1	4	4	4	2
KWS Irina	12	5	0.5	2	12	3	2	3	5	4
RGT Planet	16	8	0	3	14	3	5	2	5	4
Sienna	7	4	0	3	9	1	4	3	3	6
Octavia	12	3	2	3	7	1	4	4	5	3
Olympus	10	4	1	5	7	2	5	5	9	4
Scholar	12	3	2	8	4	1	2	3	12	3
KWS Sassy	5	7	1	1	8	2	2	4	3	5
Fairing	12	3	0	8	6	3	4	4	5	2
Laureate	10	3	1	3	3	2	6	4	4	2
Ovation	10	4	3	0.5	4	2	6	2	1	1
Chanson	9	2	1	4	6	5	7	5	1	2
LG Opera	10	3	2	3	5	3	4	3	2	2
Dioptric	*	*	*	*	*	*	5	*	4	*
LG Tomahawk	12	3	0	6	6	3	8	4	3	3
LG Figaro	7	4	0	2	7	3	8	3	5	6
LG Diablo	12	3	0	4	6	2	9	1	5	4
RGT Asteroid	8	4	1	4	5	5	3	2	4	2
Hacker	9	*	1	3	*	*	4	*	2	*

Table 6B. % RLS levels in untreated spring barley varieties in RL trials in 2017. * indicates no data from variety at site.

Variety/Site	Tayside	Fife 1	Northeast Scotland	North Scotland	East Lothian	Fife 2	Central Scotland	Aberdeenshire	Borders	North Yorkshire 1	Northern Ireland	East Yorkshire
Belgravia	10.4	16.3	8.1	1.4	6.6	8.8	15	10.4	4.3	3.1	8.6	1.6
Concerto	5.9	20.9	10.6	2.8	17.6	15.1	16.3	5.6	6.4	1.4	10.4	3
Propino	5.2	18.8	11.3	2	13.8	11.7	15.1	11.5	5.5	2.8	10.3	1.2
Odyssey	3	13.1	8.9	1.1	12.6	8.9	17.2	4.4	7.2	3.1	10.6	2.8
KWS Irina	3.4	14.5	7.5	1	9.8	9.6	14.2	6.5	4.2	1.6	15.5	2
RGT Planet	4.5	13.2	5.7	1	8.4	9.3	19.8	8.1	5.5	4	17.3	1.9
Sienna	3	13.1	7.6	0.6	17.5	11.8	17	5.8	6.1	3.1	17.1	2.2
Octavia	2.7	13	7.9	0.6	8.9	12	19.2	6.3	3.9	2.7	17.8	1.3
Olympus	6.1	15.9	7.6	0.9	18	18.2	22.4	8.3	6.3	2.5	10.3	1.6
Scholar	4.9	13.7	7.7	1.4	17.1	17.4	10.8	5.5	5.3	2.2	18.5	1.2
KWS Sassy	5.2	10	4.4	0.4	10.2	13.6	15.1	6.2	6.7	2.9	13	1.7
Fairing	3.7	8	5.8	1	14.3	11.5	17.9	7.6	5.1	6.7	14.8	2
Laureate	5.3	9.6	5.8	0.9	6.9	9.5	23	8.6	4.9	2.3	12.8	1.1
Ovation	7.1	10.5	6	0.3	9.7	8	21.3	7.5	7.3	3	16.8	1.1
Chanson	7	10.5	7.2	0.8	18.9	11.3	14.5	5.9	7.6	1.6	11.1	0.9
LG Opera	7.6	9.3	5.6	0.3	13.6	13.1	12.4	6	5.6	*	15.8	2
Dioptric	7.3	11	4.5	1.8	8.1	12.9	15.7	4.1	5.6	2.8	13.6	3.2
LG Tomahawk	7.1	9.9	5.5	0.9	14.1	14.7	20.1	6	7.2	2.3	12.9	1.8
LG Figaro	7.4	11	5.2	2.4	16.8	14	15.6	7.7	5	3.3	10.9	0.8
LG Diablo	7.5	10.1	4.5	0.6	14.5	10.8	19	6.1	5.2	3.1	10.3	1.6
RGT Asteroid	6.5	7.8	2.7	2	10.6	9.4	13.6	6	5.5	*	8.2	2.1
Hacker	*	*	*	*	8.9	*	*	7.6	7.6	*	11.1	1.9

Supplementary Table 7A. Data for times of growth stages in winter barley at Scottish sites (2005 to 2015).

Year	Site	Sowing date	Date GS 30 reached	Leaf wetness (14 days after GS 30/31) (min)	% Disease levels (GS 75-85)	Area under disease progress curve (unit)	Harvest date
2005	Bush	08-Oct-04	01-Apr-05	6480	17.7	223	03-Aug-05
2006	Bush	14-Sep-05	01-Apr-06	4020	11.7	123	27-Jul-06
2007	Bush	17-Sep-06	01-Apr-07	3180	11.72	239.6	09-Aug-07
2007	Lanark						
2008	Bush	19-Sep-07	01-Apr-08	7380	25	121.5	15-Aug-08
2008	Lanark	22-Sep-07	01-Apr-08	8701	15.38	121.4	05-Aug-08
2009	Bush	22-Sep-08	01-Apr-09	5280	5.12	43	31-Jul-09
2009	Lanark	26-Sep-08	01-Apr-09	8581	12	114	06-Aug-09
2010	Bush	23-Sep-09	08-Apr-10	4140	11.77	80.75	04-Aug-10
2010	Lanark	25-Sep-09	08-Apr-15	7113	7.97	43.3	14-Aug-10
2011	Bush	16-Sep-10	01-Apr-11	5160	5	71	05-Aug-11
2011	Lanark	27-Sep-10	05-Apr-11	7560	8.6	92.25	20-Aug-11
2012	Bush	22-Sep-11	05-Apr-12	5160	5	43.3	12-Aug-12
2012	Lanark	23-Sep-11	10-Apr-12	10353	16.3	154	10-Aug-12
2013	Bush	22-Sep-12	01-Apr-13	4740	0.84		06-Aug-13
2013	Lanark	08-Oct-12	14-Apr-13	6840	3.3		26-Aug-13
2014	Bush	18-Sep-13	01-Apr-14	9660	5.25	62.5	24-Jul-14
2014	Lanark	23-Sep-13	14-Apr-14	9240	4.25	24.3	05-Aug-14
2015	Bush	18-Sep-14	04-Apr-15	3360	9.82		07-Aug-15
2015	Lanark	19-Sep-14	07-Apr-15	4680	10.05		19-Aug-15

Supplementary Table 7B. Data for times of growth stages in spring barley at Scottish sites (2005 to 2015).

Year	Site	Sowing date	Date GS 30 reached	Leaf wetness (14 days after GS 30/31) (min)	% Disease levels	Area under disease progress curve	Harvest date
2005	Bush	21-Mar-05	01-Jun-05	7500	14.71	339.5	31-Aug-05
2006	Bush	10-Apr-06	20-May-06	9000	14.81	137	30-Aug-06
2007	Bush	20-Mar-07	25-May-07	7620	20.27	257.9	04-Sep-07
2007	Lanark	26-Mar-07	01-Jun-07	6360	10.69	190.75	12-Sep-07
2008	Bush	17-Apr-08	25-May-08	8400	8.18	92.62	21-Sep-08
2008	Lanark	17-Apr-08	01-Jun-08	5640	17.96	143.5	02-Sep-08
2009	Bush	02-Apr-09	25-May-09	4920	18.28	177.1	11-Sep-09
2009	Lanark	20-Mar-09	21-May-09	9439	22.05	316	11-Sep-09
2010	Bush	18-Mar-10	28-May-15	10020	2.80	127.4	02-Sep-15
2010	Lanark	14-Apr-10	25-May-15	8940	6.78	58.4	09-Sep-10
2011	Bush	21-Mar-11	21-May-11	6060	4.73	109.4	30-Aug-11
2011	Lanark	24-Mar-11	01-Jun-11	5880	4.05	93.30%	15-Sep-11
2012	Bush	15-Mar-12	24-May-12	9002	18.10	361.9	04-Sep-12
2012	Lanark	22-Mar-12	01-Jun-12	8340	4.10	42.16	19-Sep-12
2013	Bush	15-Apr-13	22-May-13	4413	2.00		03-Sep-13
2013	Lanark	04-Apr-13	04-Jun-13	6780	3.93		10-Sep-13
2014	Bush	25-Mar-14	25-May-14	8640	8.52		18-Aug-14
2014	Lanark	11-Apr-14	27-May-14	11101	8.28		09-Sep-14
2015	Bush	25-Mar-15	25-May-15	5490	18.38		22-Sep-15
2015	Lanark	27-Mar-15	28-May-15	6540	4.32		01-Oct-15