Monitoring risks of mycotoxin contamination caused by fusarium head blight pathogens in winter wheat

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Abstract

Fusarium head blight (FHB) of wheat can be caused by a number of different *Fusarium* species, including *F. culmorum*, *F. graminearum*, *F. avenaceum*, *F. poae*, *Microdochium nivale* and *M. majus*. All these pathogens, with the exception of the *Microdochium* spp. produce mycotoxins, which can have an adverse effect on human and animal health. The main aim of this project was to monitor and investigate fusarium disease in winter wheat and to advise industry of seasonal and regional risks of disease incidence and mycotoxin contamination.

National surveys of incidence of FHB disease and pathogen levels were carried out in co-operation with the Defra winter wheat disease survey between 2006 and 2008. Data showed that although FHB levels were low in 2006, disease levels in 2007 and 2008 were the highest, and third highest recorded respectively (86 and 64%), with the predominant pathogen being *M. nivale/majus*. Isolations of the toxin-producing *F. graminearum* were also high, with over 25% of crops infected in both years and an average of >2% of ears affected nationally in 2008 (the highest recorded). Due to the elevated levels of detection of this pathogen, alerts were issued via the CropMonitor website advising of the increased risk of toxin contamination in grain in 2007 and 2008. These predictions were validated by results from mycotoxin monitoring (RD-2006-3288) indicating that toxin levels were elevated in 2007 and 2008. Analyses of the data collected indicated that the most important factors in incidence of *F. graminearum* were region (17% of the variation accounted), weather, specifically spring temperature (28% variance accounted) and agronomic factors (previous crop, cultivation method and sowing date) (13.7% of the variation). Other weather factors such as temperature and rainfall at flowering need to be investigated and incorporated within the model to improve the predictive capability. In-season monitoring of FHB inoculum build-up and disease development was undertaken at five sites to try and provide an early indication of the risk from FHB, and thus provide intelligence on the likelihood of disease development on the ear. Annual differences in disease levels were evident, with levels in 2007 being particularly high. Alerts were issued each year indicating the likely risk from FHB infection, taking into account the weather forecast for the flowering period. Results indicate that this type of monitoring could assist in identifying risks of FHB earlier in the season, enabling growers to respond. Further work on investigation of the role of in-season monitoring in disease risk prediction and further development of the models is recommended.
Summary report

Introduction

Fusarium head blight (FHB) is a disease of the maturing ear of wheat and is caused by a number of different \textit{Fusarium} species, including \textit{F. culmorum}, \textit{F. graminearum}, \textit{F. avenaceum}, \textit{F. poae}, \textit{Microdochium nivale} and \textit{M. majus}. Most of these species produce mycotoxins, which can have an adverse effect on human and animal health. The levels of mycotoxins in grain was brought into focus in 2006 following the introduction of regulatory limits for fusarium mycotoxins, including deoxynivalenol (DON) and zearalenone (ZON) produced by \textit{F. culmorum} and \textit{F. graminearum}. Recent monitoring carried out within the CropMonitor project has shown that \textit{F. graminearum} is now the predominant DON/ZON producing species in England. This is of concern as \textit{F. graminearum} has been shown on the world scale to cause greater damage to wheat than \textit{F. culmorum} not only in terms of direct yield loss but also contamination of grain by mycotoxins.

Objectives

The main aim of this project was to monitor and investigate fusarium disease in winter wheat and to advise industry of seasonal and regional risks of disease incidence and mycotoxin contamination. This was achieved through building on the existing pilot risk schemes, by continued monitoring of FHB pathogens in winter wheat in order to provide further data to develop and improve prediction of risks of mycotoxin contamination of grain. The project involved thorough analysis of existing large-scale datasets, which were supplemented by new specific data generated by this project through in-season monitoring of inoculum build-up. The project also collaborated closely with the HGCA mycotoxin monitoring project (RD-2006-3288) to utilise all available data for analyses to improve risk predictions for the future.

Materials and Methods

\textbf{Fusarium survey}

Between 2006 and 2008, national (England) monitoring of commercially grown winter wheat crops was carried out through assessment of 300 crops at the early to medium milk development stage (GS73-75). From each crop, 50 fertile tillers were collected and 25 of these assessed for FHB and fusarium stem-base disease levels. Growers were asked to provide details of cultivar, tillage practice, sowing and harvest date, previous cropping and pesticide use; all factors, which influence pathogen levels.
**FHB pathogens isolation**
Wheat ears with FHB symptoms were collected during assessments for the fusarium survey and the species responsible isolated and identified. All isolates of *F. graminearum* and *F. culmorum* were purified by single spore isolation for chemotyping. Maps were produced to show the distribution of the FHB pathogens across the country. These allowed visualisation of the data and provided information, which assisted the development and validation of the FHB risk analyses.

**Chemotyping of *Fusarium graminearum* and *Fusarium culmorum***
Isolates of *F. graminearum* and *F. culmorum* collected between 2003 and 2008 were selected from the Fera culture collection, DNA extracted and their toxin profile established to determine whether they produced deoxynivalenol (DON) or nivalenol (NIV) respectively. Maps were produced to show annual chemotype distribution across the country.

**In-season development of fusarium inoculum**
For each year (2006 to 2008), five experimental sites were established to create a regional network and generate data relating to the build-up of FHB pathogens. Data collected throughout the growing season was used to provide early warnings of FHB pathogen development in the crop and hence the likelihood of FHB infection developing on the ear. Sites were located in Yorkshire (York), Lincolnshire (Louth in 2006 and 2007, and Caythorpe in 2008), Norfolk (Morley), Gloustershire (Cirencester) and Hampshire (Andover). At each site, three replicate plots of Robigus (1.5 x 18m) were sown; the target sowing date was typical for that region and the target plant population was 200-250 plants m⁻². No fungicide treatments were applied to any plots, all other treatments followed standard farm practice. Plots were sampled fortnightly from GS31 until GS75 and isolations were carried out to determine the proportion of stem bases infected by FHB pathogens. In the final year of the project, leaf layer isolations were also carried out to assess inoculum build-up and movement within the canopy. At GS75 and 85 the pathogens responsible for any FHB symptoms were identified. All results were posted on the CropMonitor web site together with interpretation as to the implications of the results in terms of FHB disease risk.

**Risk quantification using national monitoring data**
Analyses were carried out on a combined dataset containing data collected within this project (2006-2008) and those collected previously as part of the Defra national crop
surveys (2000 to 2005). Three approaches were used to quantify potential risk factors for incidence of FHB: 1) Regional effects, 2) effect of weather parameters on disease development and 3) effect of agronomic factors.

**Provision of sampling network for mycotoxin monitoring at harvest**
The project also acted as a vehicle for the provision of wheat samples to project RD-2006-3288 (Monitoring fusarium mycotoxins in harvested grain) via the CropMonitor winter wheat survey. Each year, grain sacks were sent with sampling and postage details to participating growers in mid July. It was hoped that at least 50% of samples would be returned for toxin analysis.

**Results**

**Fusarium survey and FHB pathogen isolation**
In 2006, the overall incidence of FHB symptoms was low, with *F. poae* and *F. langsethiae* being the predominant FHB pathogens isolated. In contrast, the incidence of FHB in 2007 was the highest seen in surveys to date. Isolations showed that the non-toxin producing species *M. nivale* and *M. majus* were responsible for the vast majority of the symptoms. Incidence of both *F. graminearum* and *F. culmorum* were the highest recorded, 26 and 13% of crops respectively, since the start of isolations in 1998. The within-crop incidence of both these species was also increased compared to 2006. In 2008, the incidence of FHB symptoms was lower than those of 2007 although levels were still the third highest recorded. As in 2007, *M. nivale/majus* were the predominant species isolated from symptoms, although levels were lower than in 2007. Overall, the incidence of *F. graminearum* (% crops) was the same as those found in 2007, however the within-crop incidence increased from 1.6% ears infected in 2007 to 2.1% in 2008. The incidence of *F. culmorum* reduced to a level similar to that seen in 2006. Maps produced to visualise the annual distribution of *M. nivale/majus, F. culmorum, F. graminearum, F. poae* and *F. langsethiae* showed that only *F. graminearum* had any discernable pattern to its distribution, with a greater proportion of isolations along the south and up the east coast of England than in other areas. No symptoms caused by *F. graminearum* were found beyond North Yorkshire. The precise areas of greatest *F. graminearum* aggregation, within the overall *F. graminearum* distribution, varied from year to year and indicated that the areas at greatest risk from toxin contamination of grain would vary from season to season.
Based on FHB pathogen isolations and distribution at GS73, alerts were issued to indicate the likely risk of toxin contamination in harvested grain. In essence they suggested that the overall risk would be low in 2006 and 2007, although in 2007 regional differences in *F. graminearum* isolations and delayed harvests due to wet weather could increase the risk at the field level. In 2008, it was predicted that as levels of *F. graminearum* infection were greater than 2007, the national risk from deoxynivalenol contamination was likely to be similar or slightly higher. It was again highlighted that the final toxin level was dependent on harvest conditions, with higher toxin levels likely if the harvest was delayed by wet weather.

**Chemotyping of *Fusarium graminearum* and *Fusarium culmorum***

In all years (2003 to 2008) both DON and NIV chemotypes were found in both the *F. graminearum* and *F. culmorum* populations. Overall, the NIV chemotype predominated within the *F. culmorum* population (59% of isolates), whereas the DON chemotype predominated in the *F. graminearum* population (94% of isolates). Maps showing the distribution of DON and NIV chemotypes for *F. culmorum* and *F. graminearum* between 2006 and 2008 indicated that neither chemotypes of either *Fusarium* species were restricted in distribution across the country.

**In-season development of fusarium inoculum**

The development of FHB inoculum was monitored at five sites between 2006 and 2008. Stem base isolations showed that in all three years *M. nivale* and *M. majus* were present in the crops from GS31 when the isolation work started. The level of *M. nivale* and *M. majus* isolated in each of the three years varied with the highest levels detected in 2007 and lowest in 2006. In 2007, the high levels of infection on the stem base prompted the issue CropMonitor alerts on the 02nd and 22nd May 2007. The high levels of *Microdochium* species detected at the stem base in 2007 were followed by the worst levels of FHB recorded since the start of the disease survey. Stem-base levels in 2008 were lower than those in 2007. This was followed by reduced levels of FHB recorded on the ear compared to 2007. Data from this three–year period indicate that data on levels of *Microdochium* species pathogens at the stem base correlate well with eventual disease levels on the ear. No correlation was evident between *Fusarium* species at the stem base and levels of infection by these pathogens on the ear, possibly due to very low isolation levels.
The leaf layer isolations carried out in 2008 indicated differences between the pathogens in timing and degree of movement within the leaf canopy. In general, *F. culmorum* was isolated from leaves throughout the season, whereas the *Microdochium* species and *F. graminearum* were generally not present on leaves in the early part of the season. However, by early June, when crops were starting to flower, and at their most susceptible to infection, both *Microdochium* species and *F. graminearum* could be isolated from the upper canopy (leaves 1-3). As for the stem base assessments, all data were reported on the CropMonitor website. FHB levels at the monitoring sites were highest in 2008 and lowest in 2006. Analyses of data from leaf layer assessments show a better correlation between detection of the *Microdochium* species/*F. graminearum* on the upper leaves and subsequent development of infection on the ear compared to isolations from the stem base. However, the data are from only a single year and more monitoring would be needed to investigate these relationships further.

**Risk quantification**

**Effect of region** - Cluster maps were produced for *F. graminearum* and *F. culmorum* (Figure1), which highlighted differences between the two species both in terms of overall risk and the areas at greatest risk of infection. In general terms, the overall risk from infections caused by *F. culmorum* was lower than for *F. graminearum*, with the north west and south east at highest risk of infection by *F. culmorum* and the east of England at greatest risk from *F. graminearum*. 
Due to the perceived changes in the risk from *F. graminearum* over recent years the clusters were recalculated for this species, with comparisons made for *F. graminearum* incidence between 2000-2004 (Figure 2a) and 2005-2008 (Figure 2b). Comparison of the two maps indicated how the risk from infection by *F. graminearum* has altered over time. Between 2000 and 2004, the overall risk from *F. graminearum* was 0.3% with areas at greatest risk in the south west and around the Wash (Figure 2a). However, data collected between 2005 and 2008 showed the overall risk had increased to 0.8%, with the areas at highest risk along the south and up the east coast, up to and including Lincolnshire. The risk to northern England was still low although the division of the large cluster (Figure 2a) into four smaller clusters (Figure 2b) suggested the risk of infection was increasing.
Figure 2. Cluster maps showing regional risk for *Fusarium graminearum* incidence at GS73-75 a) 2000-2004 and b) 2005-2008.

The risk clusters derived from the data for 2005-2008 on incidence of *F. graminearum*, were used in analyses to identify and quantify meteorological and agronomic factors which might increase the risk of *F. graminearum* development and hence mycotoxin contamination of grain.

**Effect of weather parameters** - Correlation analysis of weather data (from 35 met. stations) with risk region showed that the only significant weather parameter for the development of FHB caused by *F. graminearum* was average mean temperature between the beginning of February and the end of April, with higher than average temperatures resulting in higher disease. Using this parameter alone, 28% of the variance could be explained.

**Effect of agronomic factors** - Four agronomic factors, (previous crop, sowing date, resistance rating and method of cultivation) were analysed to determine their effect on the incidence of the FHB pathogens *F. graminearum* or *M. nivale/majus*. In all instances, data used were collected between 2005 and 2008.
Previous crop
Analysis indicated that maize as a previous crop led to significantly higher incidence of *F. graminearum* when compared to all other previous crops. For *M. nivale/majus* previous crops of pulse, grass or maize resulted in significantly higher disease incidence but only when compared to other cereals (crops other than winter wheat or maize).

Sowing date
For *F. graminearum*, there was a strong indication that sowing before 1st September resulted in a lower disease incidence, whereas sowing during October favoured a higher incidence, although the effect was not significant (Figure 3a). There was no clear effect of sowing date on the incidence of *M. nivale/majus* (Figure 3b); later sowing dates (November onwards) seemed to reduce disease incidence although this was not significant.

Cultivation method
Four cultivation methods (conventional plough, shallow plough, reduced cultivation and direct drill) were examined to determine their effect on *F. graminearum* and *M. nivale/majus* incidence. For both pathogens the use of reduced cultivation or direct drill increased disease incidence compared to conventional plough, with direct drill
having a greater effect than reduced cultivation. For \textit{F. graminearum}, there was no difference between shallow or conventional plough, whereas shallow plough reduced the incidence of \textit{M. nivale/majus}. Used in a model, cultivation method would explain 5.1 and 3.1\% of the variance for incidence of \textit{F. graminearum} and \textit{M. nivale/majus} respectively.

Cultivar resistance
Modelling of the effect of winter wheat FHB resistance rating indicated that a higher resistance rating (indicating greater resistance to FHB) did not have a significant effect in reducing the incidence of \textit{F. graminearum}, but did for \textit{M. nivale/majus}.

Analyses therefore identified previous crop, cultivation method and sowing date as the most significant agronomic factors affecting incidence of \textit{F. graminearum}. However, using these selected agronomic factors, only explained 13.7\% of the variation. Including cluster region and year increased this level of variation to 38\%, with cluster region being the dominant factor, explaining 17\% of the variance for \textit{F. graminearum} incidence at the farm scale. The inclusion of weather parameters would improve this further and although some weather factors have been identified i.e. mean temperature February-April the impacts of weather parameters at flowering still need to be quantified.

Analyses of the effects of agronomic factors on \textit{Microdochium} species identified three factors as being most important: previous crop, cultivation method and cultivar resistance. However, these explain only 6.7\% of the variation in incidence of \textit{M. nivale/majus} at the farm level. Currently cluster analyses have not yet been carried out for \textit{M. nivale/majus} and therefore cannot be included in the model. This has also precluded use of the approaches used for \textit{F. graminearum} to investigate the effects of weather parameters. This will be addressed in future work.

**Conclusions and implications**
- The risk from \textit{Fusarium graminearum} is increasing across England, with the area in which a crop is grown being the major risk factor in disease development.
- In-season monitoring of inoculum build-up could provide the intelligence required by consultants/growers to enable early and informed decisions on the likely risk of FHB infection occurring during crop flowering to be made.
• Monitoring of the FHB pathogens responsible for FHB symptoms in winter wheat crops at GS73 provides a good indication of the likely risk of mycotoxin contamination of grain, however it is the prevailing weather conditions between flowering and harvest that determine the final levels and type of toxin present.

• Agronomic factors that influence development of *F. graminearum* in a crop are previous crop (maize), sowing date and cultivation method. Effective sources of resistance to *F. graminearum* do not seem to be present in the winter wheat varieties currently grown in the UK.

• Further work investigating the role of in-season monitoring in disease risk prediction and further development of the models is recommended.
Full Project Report

Introduction

Fusarium head blight (FHB) is a disease of the maturing ear of wheat and can be caused by a number of different Fusarium species, including F. culmorum, F. graminearum, F. avenaceum, F. poae, Microdochium nivale and M. majus. All these pathogens, with the exception of the Microdochium species, produce mycotoxins. These are secondary metabolites produced by some fungi, which can have an adverse effect on human and animal health. They are of particular relevance since the introduction of EU legislation in 2006, setting limits for a number of toxins, including deoxynivalenol (DON) and zearalenone, produced by Fusarium species. Historically, F. culmorum was the predominant DON producing species in UK grain. However, recent monitoring carried out within the CropMonitor project has shown that F. graminearum now predominates over F. culmorum, and that its geographical distribution, once largely limited to the south west, has advanced north and east. This is of concern as F. graminearum has been shown on the world scale to cause greater damage to wheat than F. culmorum not only in terms of direct yield loss but also contamination of grain by mycotoxins.

During the past decade, analyses of monitoring data have contributed to the significant progress in understanding the epidemiology and control of FHB, and the relationship between fusarium pathogen levels and degree of mycotoxin contamination in grain. The epidemiology of the individual species and the environmental factors driving epidemics have been investigated, the toxigenic potential of the current UK population has been evaluated, and appropriate strategies for disease control have been developed. However, large gaps in our knowledge remain. As a consequence, reliable estimates of the likely risk from fusarium disease are not available to the industry in time to inform T3 spray decisions.

Since 1998, seasonal and regional risk of mycotoxin contamination in grain has been predicted with some success using monitoring data on the incidence of ear blight pathogens and determination of their toxigenic potential (Sourced from Defra National Surveys). Risk predictions were first issued pre-harvest in 2004 and 2005 and were validated using data on actual mycotoxin levels in harvested grain sourced from an investigation funded by FSA/HGCA. Analyses at this stage showed a good correlation between the level of incidence of FHB pathogens in crops and mycotoxin contamination in harvested grain.
In the interests of food safety, it is important for government and industry to develop robust strategies to minimise the risks of mycotoxins entering the food chain and to ensure that the EU limits on mycotoxin levels in grain are not exceeded. The project reported here aimed to build on the existing pilot risk schemes by continuing to monitor FHB pathogens in winter wheat in order to provide further data to develop and improve prediction of risks of mycotoxin contamination of grain. The project aimed to thoroughly analyse existing large-scale datasets, and supplement them with new specific data generated by the project through in season monitoring of inoculum build up. The project collaborated closely with two related projects (1) on epidemiological research to inform development of risk predictions for mycotoxin contamination in winter wheat (funded by Defra) and (2) monitoring of mycotoxin contamination in harvested grain (funded by FSA/HGCA). Through this cluster project approach, all three projects aimed to collaborate and exchange data to develop new approaches to identify risks from mycotoxin contamination and develop strategies to minimise such risks under changing pathogen prevalence scenarios.

**Materials and Methods**

**Fusarium survey**
Between 2006 and 2008, national (England) monitoring of commercially grown winter wheat crops was carried out through assessment of 300 crops at the early to medium milk development stage (GS73-75, Tottman, 1987). The data collected provided statistically robust data on annual levels of fusarium pathogens on the ear and at the stem-base.

The winter wheat fields assessed were selected at random from a list of farms stratified by region and arable farm size taken from annual returns to the Defra Census Branch. A proportion of the sampling sites was fixed to improve farmer cooperation from year-to-year with a proportion (one third) of sites replaced each year to ensure no bias was introduced to the results through long term farmer participation. Contact was made with farmers in late spring and crops were sampled at GS73-75 by collecting 50 fertile tillers at random from a diagonal transect of the field. Statistical advice was sought to confirm that the number of samples taken was valid for national and regional disease estimates. Samples were collected by ADAS
and TAG, and sent to Fera for assessment. Fusarium head blight (FHB) and fusarium stem-base disease levels were assessed on a sub-sample of 25 tillers from the 50 tillers collected from each crop. The severity of FHB symptoms was recorded as the percentage of the ear area affected using NIAB keys (Anonymous, 1979). The crop growth stage was recorded using the scheme of Tottman (1987). The percentage of stems with slight, moderate and severe fusarium symptoms on the nodes and internodes were measured using the following key:

- **Slight**: lesion girdling less than half the circumference of the stem.
- **Moderate**: lesion girdling more than half the circumference of the stem.
- **Severe**: lesion girdling more than half the circumference of the stem, and tissue softened so that lodging would occur.

Growers were asked to fill in a focussed questionnaire to provide details of cultivar, tillage practice, sowing and harvest date, previous cropping and pesticide use, all factors, which may influence pathogen levels. All data was entered into the INFORMIX relational database at also held FHB data from previous surveys for the period 1986-2005.

**FHB pathogens isolation**

Wheat ears with FHB symptoms were collected during assessments for the fusarium survey. In general, three separate types of symptom were identified: ear bleaching, spikelet bleaching or blotches (Figure 1).

![Figure 1. Typical fusarium head blight symptoms, a) ear bleaching, b) spikelet bleaching and c) blotches.](image-url)
For each symptom type, the site of primary infection was removed from the infected ear (for ear bleach symptoms this was usually denoted by orange sporulation at a spikelet base), surface-sterilised for 10 minutes in a 10% sodium hypochlorite solution, rinsed twice in sterile distilled water and blot dried between sterile filter paper. The surface sterilised spikelets were placed onto potato dextrose agar (PDA) amended with streptomycin sulphate (120 mg l\(^{-1}\)) and incubated for five days at 25°C. All colonies with characteristic growth patterns of FHB pathogens were transferred on to fresh PDA; those with growth patterns typical of *Fusarium* species were also plated onto sucrose nutrient agar (SNA) (Nirenberg, 1976). Plates were incubated at 25°C under a 12h light/dark regime for 10 days and cultures identified to species level based on colony characteristics on PDA and spore morphology on SNA. All isolates of *F. graminearum* and *F. culmorum* were purified by single spore isolation. These and a proportion of the other isolates identified were placed in the Fera culture collection.

Maps were produced using Arc GIS to show the distribution of the FHB pathogens across the country. These allowed visualisation of the data and provided information, which assisted the development and validation of the FHB risk analyses.

**Chemotyping of *Fusarium graminearum* and *Fusarium culmorum***

**DNA extraction**

Isolates of *F. graminearum* and *F. culmorum* collected between 2003 and 2008 were selected from the culture collection and grown on PDA plates for 5-6 days. DNA was extracted using a method adapted from Chang et al. (1993). All centrifugation steps were carried out in a microcentrifuge at 3000 x g and 4°C. Mycelium (0.1 g) was harvested from the PDA plates, frozen in liquid nitrogen and ground to a fine powder. The ground mycelia were mixed with 1 mL of CTAB extraction buffer (2% hexadecyltrimethyl amonium bromide; 100 mM Tris-HCl, pH 8.0; 20 mM EDTA; 1.4 mM NaCl; 1% Na\(_2\)SO\(_3\); 1% polyvinylpolypyrrolidone; 0.4% bovine serum albumin) in a 2 mL centrifuge tube and incubated at 65°C for 20 min. The mixture was centrifuged for 5 min and the supernatant decanted into a fresh 2 mL centrifuge tube. An equal volume of chloroform-isoamyl alcohol (24:1) was mixed with the supernatant and centrifuged for 5 min. The aqueous layer was removed to a new tube and the chloroform-isoamyl alcohol step repeated. The aqueous layer was again removed to a new tube and a 0.5 volume of 5M NaCl and 1.5 volume of ice-cold isopropanol added,
the liquids were vortexed and chilled at -20°C for 30 min. The pellet obtained following centrifugation was washed in 70% ethanol, re-pelleted and dried. The pellet was re-suspended in 50μl of nuclease free water and stored at -20°C.

**Determination of *F. graminearum* and *F. culmorum* chemotype**

Three primer sets, *Tri303F/Tri303R, Tri315F/Tri315R* and *Tri3NIVF/Tri3NIVR* (Jennings et al., 2004) were used to characterise the *Tri3* gene of *F. culmorum* and *F. graminearum* isolates to determine whether they produced 3 acetyl-deoxynivalenol (3AcDON), 15-acetyl-deoxynivalenol (15AcDON) or nivalenol (NIV) respectively. Each isolate produced a PCR product with only one of these primer sets. PCR products were 586, 864 and 549 bp long for 3AcDON, 15AcDON and NIV chemotypes respectively. The cycling protocol consisted of denaturation at 94°C for 2 min followed by, 30 cycles of 94°C for 30 s, 60°C for 1 min and 72°C for 2 min, with a final extension step of 72°C for 10 min. PCR products were separated by electrophoresis in 2% agarose gels and DNA visualised with 1 μg mL⁻¹ ethidium bromide solution.

Maps were produced using Arc GIS to show annual chemotype distribution across the country. These allowed visualisation of the data and provided information to assist the development and validation of the FHB risk analyses.

**In-season development of fusarium inoculum**

For each year (2006 to 2008), five experimental sites were established to create a regional network and generate data relating to the build-up of FHB pathogens throughout the growing season. Sites were located in Yorkshire (York), Lincolnshire (Louth in 2006 and 2007, and Caythorpe in 2008), Norfolk (Morley), Gloucestershire (Cirencester) and Hampshire (Andover) as indicated in Figure 2. These data were used to develop analyses to provide early warnings of FHB pathogen development in the crop and hence the likelihood of FHB infection developing on the ear.
Figure 2. Location of experimental sites established between 2006 and 2008 to generate in-season data on the build-up of fusarium head blight pathogens.

At each site, three replicate plots of Robigus (each 1.5 x 18m) were sown. The target sowing date was typical for that region in that year (Table 1) with a target plant population of 200-250 plants m⁻². No fungicide treatments were applied to any plots, all other treatments (plant growth regulators, fertiliser, micronutrients, herbicides, insecticides, molluscicides) followed standard farm practice.

Table 1. Sowing dates for the five monitoring sites (2006 to 2008).

<table>
<thead>
<tr>
<th>Monitoring site</th>
<th>Sowing date for harvest year</th>
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<tr>
<td></td>
<td>2006</td>
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<td>York</td>
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<tr>
<td>Louth</td>
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<td>Caythorpe</td>
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<td>Morley</td>
<td>5th Oct</td>
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<tr>
<td>Cirencester</td>
<td>5th Oct</td>
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<tr>
<td>Andover</td>
<td>11th Oct</td>
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ina – information not available
Plots were sampled fortnightly from GS31 until GS75. At each visit ten shoots (main stems and tillers, representative of those likely to contribute to yield) were sampled from each plot, and sent to Fera for assessment and isolation. In each year of the project, isolations were carried out to determine the proportion of stem bases infected by FHB pathogens. Graphs showing the development of symptoms and the species responsible were posted on the CropMonitor web site throughout the season. Interpretation of the implications of the disease levels in terms of FHB risk later in the season was also provided.

In the final year of the project, leaf layer isolations were also carried out to assess inoculum build-up and movement within the canopy. Again, results were posted on the CropMonitor web site together with interpretation as to the implications of the results in terms of FHB disease risk.

At GS75 and 85, 25 ears were sampled per replicate plot; all ears were assessed for FHB and the pathogens responsible identified.

Data from all assessments were analysed to identify indicators of risk of head blight infection and subsequent risks of mycotoxin contamination in harvested grain.

**Risk quantification using national monitoring data**

Analyses were carried out on a combined dataset containing data collected within this project (2006-2008) and those collected previously as part of the Defra national crop surveys (2000 to 2005). Three approaches were used to quantify potential risk factors for incidence of FHB: 1) Regional effects, 2) effect of weather parameters on disease development and 3) effect of agronomic factors.

**Effect of region**

For accurate risk predictions of disease at a local level, or to model disease by risk parameter, it is important to aggregate ‘like’ samples together. Cluster analysis can be used to objectively determine spatially contiguous zones of disease (Luo, 2008). Four cluster analysis methods were used to determine the most appropriate for use with *F. graminearum* and *F. culmorum* incidence: 1) Complete linkage, 2) Average linkage, 3) Wards algorithm and 4) K-means. Initially, analyses were undertaken on
data for both species collected between 2000 and 2008. The analysis was repeated for
the *F. graminearum* data to determine any differences in effects over time i.e. 2000 -

**Effect of weather parameters**
Correlation analysis was used to test the relationship between weather parameters
and *F. graminearum* incidence. The analyses were carried out on data collected
between 2005 and 2008. A stepwise-partial least square regression analysis (Luo,
2008) was used to quantify any parameters identified as part of the correlation
analysis.

**Effect of agronomic factors**
Basic summary statistics and ANOVA were carried out on data collected during the
CropMonitor winter wheat surveys between 2005 and 2008, to determine the overall
impacts of differing agronomic factors on risk of development of FHB symptoms
caused by *F. graminearum* and *M. nivale/majus*. Factors analysed included previous
crop, sowing date, cultivation method and FHB resistance rating.

**Provision of sampling network for mycotoxin monitoring at harvest**
The project also acted as a vehicle for the provision of wheat samples to project RD-
2006-3288 (Monitoring fusarium mycotoxins in harvested grain) via the CropMonitor
winter wheat survey. Each year, grain sacks, sampling and postage details were sent
to participating growers around the middle of July in order for the information to
arrive in plenty of time before the start of harvest. It was hoped that at least 50% of
samples would be returned for toxin analysis.

**Results**
**Fusarium survey**
Data on the proportion of crops affected by FHB at GS 73 have been collected as part
of the Defra funded survey of winter wheat since 1986. Over the years covered by this
report (2006-2008), the proportion of crops affected by FHB was among the highest
seen during the survey, in particular during 2007 and 2008 when levels were the
highest and third highest respectively (Figure 3). Between 1991 and 2008 the overall
proportion of crops affected has increased. Generally, the increase has occurred since
the epidemic year in 1998. In the seven years pre 1998 (1991-1996), an average of
10% of crops were affected by FHB, however the average increased to 30% in the 8
years following the 1998 (1999-2006). The impacts of the 2007 epidemic year are difficult to predict but the early indications are that level of infection may increase because disease levels in 2008 were over 20% higher than those in the years immediately following 1998.

Figure 3. Level of fusarium head blight symptoms measured on winter wheat crops between 1991 and 2008. Black bars indicate the years covered by this project.

**FHB pathogen isolation**

Three symptom types, ear bleaching, spikelet bleaching and blotches, were associated with FHB pathogen infections. Typically, ear bleaching was associated with infections caused by *F. culmorum* or *F. graminearum*, spikelet bleaching by infections caused by *Microdochium nivale/majus* or *F. avenaceum*; or by early infections of *F. culmorum* or *F. graminearum*. Blotches were generally caused by *F. poae*, *F. langsethiae*, *F. sporotrichiodes* and *F. tricinctum*.

In 2006, the overall incidence of FHB symptoms was low, with *F. poae* and *F. langsethiae* being the predominant FHB pathogens isolated (Table 2). The deoxynivalenol producing species, *F. culmorum* and *F. graminearum*, were both isolated from less than 5% of crops; within crop levels of these species were also low with less than 1% of ears affected. In contrast, the incidence of FHB in 2007 was the highest seen in surveys to date (Table 2). Isolations showed that the non-toxin
producing species *M. nivale* and *M. majus* were responsible for the vast majority of the symptoms. Incidence of both *F. graminearum* and *F. culmorum* were the highest recorded, 26 and 13% crops respectively, since the start of isolations in 1998. The within-crop incidence of both these species was also increased compared to 2006. In 2008, the incidence of FHB symptoms was lower than those of 2007 although levels were still the third highest recorded (Table 2). As in 2007, *M. nivale/majus* were the predominant species isolated from ears displaying symptoms, although levels were lower than in 2007. Overall, the incidence of *F. graminearum* (% crops) was the same as those found in 2007, however the within-crop incidence increased from 1.6% ears infected in 2007 to 2.1% in 2008. The incidence of *F. culmorum* reduced to a level similar to that seen in 2006.

Table 2. Fusarium head blight pathogens responsible for disease symptoms 2006-2008.

<table>
<thead>
<tr>
<th>Year</th>
<th>FHB level (% crops)*</th>
<th>FHB pathogen isolated (% crops)*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><em>M. nivale</em>/majus</td>
<td><em>F. graminearum</em></td>
</tr>
<tr>
<td>2006</td>
<td>22 (4.4)</td>
<td>5 (0.9)</td>
</tr>
<tr>
<td>2007</td>
<td>86 (14.0)</td>
<td>70 (8.9)</td>
</tr>
<tr>
<td>2007</td>
<td>64 (10.5)</td>
<td>44 (6.5)</td>
</tr>
</tbody>
</table>

* Figures in parenthesis indicate within-crop incidence (% ears affected)

**Fusarium pathogen distribution**
Maps were produced to visualise the annual distribution of the main FHB pathogens, *M. nivale/majus* (Figure 4), *F. culmorum* (Figure 5), *F. graminearum* (Figure 6), *F. poae* (Figure 7) and *F. langsethiae* (Figure 8). For four of the five pathogens, *M. nivale/majus, F. culmorum, F. poae* and *F. langsethiae*, no discernable distribution pattern was identified. In each of the three years these pathogens were evenly distributed across the country. In contrast, *F. graminearum* (Figure 6) isolations in all three years showed a pattern to their distribution, with a greater proportion of isolations along the south and up the east coast of England than in other areas. No symptoms caused by *F. graminearum* were found beyond North Yorkshire. The precise areas of greatest *F. graminearum* aggregation, within the overall *F. graminearum* distribution, varied from year to year and indicated that the areas at greatest risk from toxin contamination of grain would vary from season to season.
Based on FHB pathogen isolations and distribution at GS73, alerts were issued (via the CropMonitor web site, e-mail and text messages) to indicate the likely risk of toxin contamination in harvested grain.

2006 - low incidence of FHB, in particular *F. graminearum* and *F. culmorum*, indicated that the overall effects on yield and grain quality (including mycotoxin contamination) caused by FHB pathogens was likely to be low.

2007 - predictions suggested that even though the level of FHB symptoms was the highest seen since the start of the survey, the relative prevalence of the species responsible for the symptoms i.e. predominance of the non-toxin producing *M. nivale/majus*, would result in a low overall risk of deoxynivalenol contamination of grain. However, it was also advised that regional differences in the distribution of *F. graminearum* and delayed harvests due to wet weather could increase the risk at the field level. As levels of *Microdochium* species were high, it was also highlighted that there would be an increased need for seed testing and use of appropriate seed treatments to control seedling blight caused by *Microdochium* species.

2008 - Overall, incidence of FHB symptoms was lower in 2008 than in 2007. However, the level of *F. graminearum* infection was greater, suggesting that the national risk from deoxynivalenol contamination was likely to be similar or slightly higher than in 2007. On a regional basis, crops in the South East and East Midlands regions were identified as being at greatest risk, followed by those in the East, South West, and Yorkshire & Humberside. Areas of low risk were in the North East, North West, and West Midlands. It was again highlighted that the final toxin level was dependent on harvest conditions, with higher toxin levels likely if the harvest was delayed by wet weather.
Figure 4. Distribution of *Microdochium nivale* and *M. majus* in 2006, 2007 and 2008. Small dots indicate location of fields sampled, large dots indicate location of fusarium head blight symptoms and large black dots the location of infections caused by *Microdochium* species.
Figure 5. Distribution of *Fusarium culmorum* in 2006, 2007 and 2008. Small dots indicate location of fields sampled, large dots indicate location of fusarium head blight symptoms and large black dots the location of infections caused by *F. culmorum*. 
Figure 6. Distribution of *Fusarium graminearum* in 2006, 2007 and 2008. Small dots indicate location of fields sampled, large dots indicate location of fusarium head blight symptoms and large black dots the location of infections caused by *F. graminearum*. 
Figure 7. Distribution of *Fusarium poae* in 2006, 2007 and 2008. Small dots indicate location of fields sampled, large dots indicate location of fusarium head blight symptoms and large black dots the location of infections caused by *F. poae*. 
Figure 8. Distribution of *Fusarium langsethiae* in 2006, 2007 and 2008. Small dots indicate location of fields sampled, large dots indicate location of fusarium head blight symptoms and large black dots the location of infections caused by *F. langsethiae*. 
Chemotyping of *Fusarium graminearum* and *Fusarium culmorum*

Between 2003 and 2008, a total of 161 *F. culmorum* isolates and 581 *F. graminearum* isolates, from 81 and 246 fields respectively, were analysed to determine whether they were deoxynivalenol (DON) or nivalenol (NIV) chemotypes (Table 3). In all years both DON and NIV chemotypes were found in both fusarium populations, however there were differences in the two populations in terms of the ratio of DON to NIV producing isolates and the predominant chemotype. Overall, the NIV chemotype predominated within the *F. culmorum* population, with 59% of isolates producing a PCR product with the *Tri3NIVF/Tri3NIVR* primer set, whereas it was the DON chemotype that predominated in the *F. graminearum* population, with 94% of isolates producing a PCR product with either of the DON primer sets (*Tri303F/Tri303R* or *Tri315F/Tri315R*). Non-NIV producing *F. culmorum* isolates all produced a PCR product with the *Tri303F/Tri303R* primer set indicating they produced 3-AcDON. In contrast,

Table 3. Proportion of deoxynivalenol (DON) and nivalenol (NIV) chemotypes determined in *Fusarium culmorum* and *Fusarium graminearum* populations between 2003 and 2008.

<table>
<thead>
<tr>
<th><em>Fusarium</em> species</th>
<th>Year</th>
<th>Isolates tested</th>
<th>Chemotype (% isolates)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>DON</td>
</tr>
<tr>
<td><em>F. culmorum</em></td>
<td>2003</td>
<td>20</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td>2004</td>
<td>4</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>2005</td>
<td>17</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td>2006</td>
<td>17</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>2007</td>
<td>91</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>2008</td>
<td>12</td>
<td>67</td>
</tr>
<tr>
<td><em>F. graminearum</em></td>
<td>2003</td>
<td>72</td>
<td>83</td>
</tr>
<tr>
<td></td>
<td>2004</td>
<td>31</td>
<td>94</td>
</tr>
<tr>
<td></td>
<td>2005</td>
<td>86</td>
<td>93</td>
</tr>
<tr>
<td></td>
<td>2006</td>
<td>12</td>
<td>83</td>
</tr>
<tr>
<td></td>
<td>2007</td>
<td>202</td>
<td>93</td>
</tr>
<tr>
<td></td>
<td>2008</td>
<td>178</td>
<td>98</td>
</tr>
</tbody>
</table>

non-NIV chemotypes of *F. graminearum* either produced a PCR product with *Tri303F/Tri303R* or *Tri315F/Tri315R* indicating that both 15AcDON and 3AcDON
chemotypes existed within the population; the vast majority of isolates (95%) were 15AcDON producers.

The predominant chemotype within the *F. culmorum* population varied between years, with the DON chemotype predominating in 2003, 2005 and 2008 and the NIV chemotype in 2004, 2006 and 2007 (Table 3). No such variation was seen in the *F. graminearum* population, with the DON chemotype predominating in all years.

Maps showing the distribution of DON and NIV chemotypes for *F. culmorum* and *F. graminearum* between 2006 and 2008 are shown in Figure 9. Both maps show that neither chemotypes of either *Fusarium* species were restricted in distribution across the country.

Figure 9. Maps showing the distribution of a) *Fusarium culmorum* and, b) *Fusarium graminearum* chemotypes between 2006 and 2008. Fields infected with nivalenol (NIV), deoxynivalenol (DON) or mixed DON+NIV chemotypes are shown as white, black, or grey dots respectively.
**In-season development of fusarium inoculum**

The development of FHB inoculum was monitored at five sites between 2006 and 2008. The data collated gave an indication of inoculum build-up in the crop and provided an indication of whether FHB pathogen inoculum was present at the ear as the crop approached flowering. Inoculum levels were measured through stem base isolations between GS31 and 65 (2006-2008) and by leaf layer isolations (in 2008 only). All isolation data were presented on the CropMonitor web site within two weeks of samples arriving at the laboratory.

Stem base isolations showed that in all three years *M. nivale* and *M. majus* were present in the crops from GS31 when the isolation work started (Figure 10). The level of *M. nivale* and *M. majus* isolated in each of the three years varied with the highest levels detected in 2007 and lowest in 2006. By the end of April 2007 (GS37), the proportion of stem bases infected by the *Microdochium* species ranged from 35% in plots at Morley and Andover, to 80% at York; by the beginning of June, levels had risen to between 70 and 100% at all sites with perithecia present on most infected stem bases. The high levels of infection on the stem base prompted the issue of CropMonitor alerts on the 02nd and 22nd May 2007. The high levels of *Microdochium* species detected at the stem base in 2007 were followed by the worst levels of FHB recorded since the start of the disease survey (see earlier section on FHB pathogen isolation). Stem-base levels in 2008 were lower than those in 2007 and, by the beginning of June, the proportion of stem bases infected by the *Microdochium* species ranged from 30-80%, with highest levels at Morley and Andover. The lower levels of stem base infection in 2008 were followed by reduced levels of FHB recorded on the ear compared to 2007. Data from this three–year period indicate that data on levels of *Microdochium* species pathogens at the stem base correlate well with eventual disease levels on the ear.
By the beginning of June, low levels of true *Fusarium* species (<10%) were isolated from stem-bases at most sites in all three years (Figure 11). In all three years the predominant species isolated were *F. culmorum* and *F. avenaceum*. No *F. graminearum* or *F. poae* were isolated from stem bases at any monitoring site in any of the three years. Due to the very low levels, no correlation was evident between stem base levels of these fusarium species and levels of infection by the pathogens on the ear.
The leaf layer isolations carried out in 2008 indicated differences between the pathogens in timing and degree of movement within the leaf canopy (Table 4). In general, *F. culmorum* was isolated from leaves throughout the season, whereas the *Microdochium* species and *F. graminearum* were generally not present on leaves in the early part of the season. However, by early June, when crops were starting to flower, and at their most susceptible to infection, both *Microdochium* species and *F. graminearum* could be isolated from the upper canopy (leaves 1-3). As for the stem base assessments, all data were reported on the CropMonitor website. Figure 12 provides an example of how the leaf layer data were presented.
Figure 12. Screen dump to illustrate how the leaf isolation data was presented on the CropMonitor web site.

FHB levels at the monitoring sites were highest in 2008 (all 5 sites showed ear symptoms (Table 4)) and lowest in 2006 (only Cirencester showed ear symptoms). Analyses of data from leaf layer assessments show a better correlation between detection of the *Microdochium* species/*F. graminearum* on the upper leaves and subsequent development of infection on the ear compared to isolations from the stem base. However, the data are from only a single year and more monitoring would be needed to investigate these relationships further.
Table 4. Leaf layer and ear isolations from live monitoring sites in 2008.

<table>
<thead>
<tr>
<th>Site</th>
<th>Species</th>
<th>Leaf layer isolations (Numbers indicate leaf layer examined, numbers in bold indicate the presence of that Fusarium head blight pathogen)</th>
<th>Ear disease (GS75 (% ears affected))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>GS31-32</td>
<td>GS33-37</td>
</tr>
<tr>
<td>York</td>
<td>M. nivale/majus</td>
<td>6 5 4 3</td>
<td>5 4 3 2</td>
</tr>
<tr>
<td></td>
<td>F. culmorum</td>
<td>6 5 4 3</td>
<td>5 4 3 2</td>
</tr>
<tr>
<td></td>
<td>F. graminearum</td>
<td>6 5 4 3</td>
<td>5 4 3 2</td>
</tr>
<tr>
<td>Caythorpe</td>
<td>M. nivale/majus</td>
<td>7 6 5 4 3</td>
<td>6 5 4 3 2</td>
</tr>
<tr>
<td></td>
<td>F. culmorum</td>
<td>7 6 5 4 3</td>
<td>6 5 4 3 2</td>
</tr>
<tr>
<td></td>
<td>F. graminearum</td>
<td>7 6 5 4 3</td>
<td>6 5 4 3 2</td>
</tr>
<tr>
<td>Morley</td>
<td>M. nivale/majus</td>
<td>7 6 5 4</td>
<td>5 4 3 2</td>
</tr>
<tr>
<td></td>
<td>F. culmorum</td>
<td>7 6 5 4</td>
<td>5 4 3 2</td>
</tr>
<tr>
<td></td>
<td>F. graminearum</td>
<td>7 6 5 4</td>
<td>5 4 3 2</td>
</tr>
<tr>
<td>Cirencester</td>
<td>M. nivale/majus</td>
<td>7 6 5 4</td>
<td>5 4 3 2</td>
</tr>
<tr>
<td></td>
<td>F. culmorum</td>
<td>7 6 5 4</td>
<td>5 4 3 2</td>
</tr>
<tr>
<td></td>
<td>F. graminearum</td>
<td>7 6 5 4</td>
<td>5 4 3 2</td>
</tr>
<tr>
<td>Andover</td>
<td>M. nivale/majus</td>
<td>7 6 5 4 3</td>
<td>5 4 3 2</td>
</tr>
<tr>
<td></td>
<td>F. culmorum</td>
<td>7 6 5 4 3</td>
<td>5 4 3 2</td>
</tr>
<tr>
<td></td>
<td>F. graminearum</td>
<td>7 6 5 4 3</td>
<td>5 4 3 2</td>
</tr>
</tbody>
</table>
Risk quantification
Effect of region
Four cluster analysis methods (complete linkage, average linkage, Ward’s algorithm and K-means) were used to analyse the incidence data for *F. graminearum/ F. culmorum* collected between 2000 and 2008. Initial analyses evaluated each cluster method for both matching of disease pattern and predictive ability, with greatest emphasis placed on the latter. From these analyses it was concluded that Ward’s algorithm and K-means were superior to the complete linkage and average linkage methods for the datasets for both species, so further analyses were restricted to these two methods. The use of the ‘elbow criterion’ showed that the most appropriate cluster method for use with both the *F. graminearum* and *F. culmorum* incidence data collected between 2000 and 2008 was Ward’s algorithm. Using this method, cluster maps were produced with nine and eight disease risk regions for *F. graminearum* and *F. culmorum* respectively (Figure 13).

Figure 13. Cluster analyses, as produced by Ward’s algorithm showing risk regions for: a) *Fusarium graminearum* and b) *F. culmorum* disease incidence using data collected at GS73-75 between 2000 and 2008.
The maps clearly show differences between the two species both in terms of the overall risk and the individual areas at highest risk. In general terms, the overall risk from infections caused by \textit{F. culmorum} was lower than for \textit{F. graminearum}, with an average cluster incidence of 0.4\% for \textit{F. culmorum} compared to 0.6\% for \textit{F. graminearum}. The areas of highest risk of infection by \textit{F. culmorum} were in the north west (around Cheshire and Lancashire) and south east (Kent and East Sussex) of England, whereas the east of England (in particular Lincolnshire) was at greatest risk from \textit{F. graminearum}. The majority of the north of England showed little risk of infection by \textit{F. graminearum}.

Due to the perceived changes in the risk from \textit{F. graminearum} over the last few years the clusters were recalculated for this species, with comparisons made for \textit{F. graminearum} incidence between 2000-2004 and 2005-2008. Using the methodologies described previously, it was shown that Ward’s algorithm with 8 cluster groups best described the data set 2000-2004 (Figure 14a), whereas K-means clustering with 12 groups gave best fit for the data set 2005-2008 (Figure 14b).

![Figure 14. Cluster analyses showing risk regions for \textit{Fusarium graminearum} incidence at GS73-75 a) 2000-2004 and b) 2005-2008 using Ward’s algorithm and K-means respectively.](image)
Comparison of the two risk maps for *F. graminearum* (Figure 14a and b) gives a clear indication of how the risk from infection by *F. graminearum* has altered over recent years. Between 2000 and 2004, the overall risk from *F. graminearum* was 0.3% with areas at greatest risk in the south west and around the Wash (Figure 14a), however, the vast majority of England was at low risk from infection by *F. graminearum*. Data collected between 2005 and 2008 shows that the overall risk from infections caused by *F. graminearum* had increased from 0.3% to 0.8%, with the areas at highest risk being along the south and up the east coast, up to and including Lincolnshire. The risk to the north of England was still low although the division of the large cluster (Figure 14a) into four smaller clusters (Figure 14b) suggested the risk of infection by this species was increasing.

The risk clusters derived from the data for 2005-2008 on incidence of *F. graminearum*, were used in analyses to identify and quantify meteorological and agronomic factors which might increase the risk of *F. graminearum* development and hence mycotoxin contamination of grain.

**Effect of weather parameters**

Meteorological data were obtained for 35 meteorological stations. Their geographical relationship to the *F. graminearum* cluster regions is shown in Figure 15.

![Figure 15. Location of the 35 meteorological stations in relation to the 12 Fusarium graminearum risk regions](image)
Correlation analysis of the weather data with risk region indicated four weather parameters were worth further investigation - average maximum temperature (Tmax_avg), average minimum temperature (Tmin_avg), average mean temperature (Tmean_avg) and average rainfall (Rain_avg) (Table 5).

Table 5. Correlation range and number of significant correlations for four weather parameters.

<table>
<thead>
<tr>
<th>Weather functions</th>
<th>Correlation range</th>
<th>Number (p&lt;0.01)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tmax_avg</td>
<td>-0.36 – 0.48</td>
<td>79</td>
</tr>
<tr>
<td>Tmin_avg</td>
<td>-0.27 – 0.48</td>
<td>66</td>
</tr>
<tr>
<td>Tmean_avg</td>
<td>-0.35 – 0.51</td>
<td>90</td>
</tr>
<tr>
<td>Rain_avg</td>
<td>-0.37 – 0.50</td>
<td>12</td>
</tr>
</tbody>
</table>

Correlations were investigated and indicated that all significant temperature correlations occurred before the middle of May and the majority of correlations for rainfall occurred between early January and mid March; weak positive correlations were found for rainfall functions after May but these were not significant. The weather parameters determined as important by correlation analyses were subjected to stepwise-partial least square (PLSR) analysis, which showed that the only weather parameter significant for the development of FHB caused by *F. graminearum* was the average mean temperature between the beginning of February and the end of April (Figure 16), with higher than average temperatures resulting in higher disease. Using this parameter alone, 28% of the variance could be explained.

Figure 16. Diagrammatic representation of the weather parameters determined as important for Fusarium head blight development caused by *Fusarium graminearum*. 
Similar analyses for the two *Microdochium* species were not undertaken as the cluster analyses for these pathogens were not available.

**Effect of agronomic factors**

Four agronomic factors, (previous crop, sowing date, resistance rating and method of cultivation) were analysed to determine their affect on the incidence of the FHB pathogens *F. graminearum* or *M. nivale/majus*. In all instances data used were collected between 2005 and 2008.

**Previous crop**

The effect of previous crop on incidence of *F. graminearum* and *M. nivale/majus* are shown in Table 6 and Table 7 respectively. The use of a pairwise t-test with multiple comparison correction indicated that use of maize as a previous crop led to significantly higher incidence of *F. graminearum* ($p= <0.001$) when compared to all other previous crops. For *M. nivale/majus* previous crops of pulse, grass or maize resulted in significantly higher disease incidence ($p= 0.05$) but only when compared to other cereals (crops other than winter wheat or maize). Used in a model to predict incidence, previous crop explained 2.6 and 1.8% of the variance for *F. graminearum* and *M. nivale/majus* respectively.


<table>
<thead>
<tr>
<th>Crop</th>
<th>Sample size</th>
<th>Mean incidence</th>
<th>Variance</th>
<th>% crops infected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter Wheat</td>
<td>287</td>
<td>0.82</td>
<td>4.47</td>
<td>20.2</td>
</tr>
<tr>
<td>Other Cereals</td>
<td>51</td>
<td>0.24</td>
<td>0.42</td>
<td>11.8</td>
</tr>
<tr>
<td>Pulse</td>
<td>142</td>
<td>0.54</td>
<td>2.83</td>
<td>12.7</td>
</tr>
<tr>
<td>Potato</td>
<td>63</td>
<td>1.08</td>
<td>8.49</td>
<td>22.2</td>
</tr>
<tr>
<td>Grass</td>
<td>40</td>
<td>0.75</td>
<td>5.88</td>
<td>17.5</td>
</tr>
<tr>
<td>Fallow</td>
<td>6</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>Other</td>
<td>101</td>
<td>1.43</td>
<td>23.79</td>
<td>18.8</td>
</tr>
<tr>
<td>Oilseed rape</td>
<td>354</td>
<td>0.55</td>
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<td>14.1</td>
</tr>
<tr>
<td>Set-aside</td>
<td>38</td>
<td>0.63</td>
<td>3.27</td>
<td>18.4</td>
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<tr>
<td>Maize</td>
<td>45</td>
<td>3.29</td>
<td>70.76</td>
<td>28.9</td>
</tr>
</tbody>
</table>
Table 7. Summary data for the effect of previous crop and *Microdochium nivale/majus* incidence (2005-2008).

<table>
<thead>
<tr>
<th>Crop</th>
<th>Sample size</th>
<th>Mean incidence</th>
<th>Variance</th>
<th>% crops infected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter Wheat</td>
<td>288</td>
<td>2.17</td>
<td>26.79</td>
<td>29.5</td>
</tr>
<tr>
<td>Other Cereals</td>
<td>51</td>
<td>1.45</td>
<td>12.33</td>
<td>25.5</td>
</tr>
<tr>
<td>Pulse</td>
<td>143</td>
<td>4.83</td>
<td>110.38</td>
<td>36.4</td>
</tr>
<tr>
<td>Potato</td>
<td>63</td>
<td>3.17</td>
<td>66.92</td>
<td>28.6</td>
</tr>
<tr>
<td>Grass</td>
<td>40</td>
<td>4.90</td>
<td>71.37</td>
<td>45.0</td>
</tr>
<tr>
<td>Fallow</td>
<td>6</td>
<td>1.67</td>
<td>7.07</td>
<td>33.3</td>
</tr>
<tr>
<td>Other</td>
<td>103</td>
<td>2.14</td>
<td>20.8</td>
<td>27.2</td>
</tr>
<tr>
<td>Oilseed rape</td>
<td>354</td>
<td>3.18</td>
<td>58.19</td>
<td>30.8</td>
</tr>
<tr>
<td>Set-aside</td>
<td>38</td>
<td>3.42</td>
<td>82.57</td>
<td>36.8</td>
</tr>
<tr>
<td>Maize</td>
<td>46</td>
<td>4.65</td>
<td>87.48</td>
<td>30.4</td>
</tr>
</tbody>
</table>

Sowing date

Plotting a frequency histogram for sowing date (Figure 17) indicated the data followed a poisson distribution with the majority of sowings occurring between 21\(^{st}\) September and 10\(^{th}\) October. Analysis of the data using a generalised additive model with a poisson distribution indicated a non-linear effect of sowing date on incidence of both *F. graminearum* and *M. nivale/majus* (Figure 18a and b).

For *F. graminearum* (Figure 18a), there was a strong indication that sowing before 1\(^{st}\) September resulted in a lower disease incidence, whereas sowing during October favoured a higher incidence, although the effect was not distinct.

There was no clear effect of sowing date on the incidence of *M. nivale/majus* (Figure 18b). Later sowing dates (November onwards) seemed to reduce disease incidence, although the effect was not significant.

The use of a sowing date parameter within the model for *F. graminearum* incidence would explain 3.2% of the variance.
Figure 17. Frequency histogram for sowing dates between 2005 and 2008. (Sowing date 1st September = 0.)

Figure 18. Effect of sowing date on incidence of: a) *Fusarium graminearum* and b) *Microdochium nivale/majus*. (Sowing date 1st September = 0).
Cultivation method

Four cultivation methods (conventional plough, shallow plough, reduced cultivation and direct drill) were examined to determine their effect on *F. graminearum* and *M. nivale/majus* incidence (Table 8 and Table 9 respectively). For both pathogens the use of reduced cultivation or direct drill increased disease incidence compared to conventional plough, with direct drill having a greater effect than reduced cultivation. For *F. graminearum*, there was no difference between shallow or conventional plough, whereas shallow plough reduced the incidence of *M. nivale/majus*.

Used in a model, cultivation method would explain 5.1 and 3.1% of the variance for incidence of *F. graminearum* and *M. nivale/majus* respectively.

Table 8. Summary statistics and results from linear regression for effect of cultivation on *Fusarium graminearum* incidence.

<table>
<thead>
<tr>
<th>Predictors</th>
<th>Summary statistics</th>
<th>Linear regression</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sample size</td>
<td>Mean incidence</td>
</tr>
<tr>
<td>Conventional</td>
<td>697</td>
<td>0.61</td>
</tr>
<tr>
<td>Shallow</td>
<td>17</td>
<td>0.59</td>
</tr>
<tr>
<td>Reduced</td>
<td>403</td>
<td>1.06</td>
</tr>
<tr>
<td>Direct Drilled</td>
<td>17</td>
<td>6.24</td>
</tr>
</tbody>
</table>

Table 9. Summary statistics and results from linear regression for effect of cultivation on *Microdochium nivale/majus* incidence.

<table>
<thead>
<tr>
<th>Predictors</th>
<th>Summary statistics</th>
<th>Linear regression</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sample size</td>
<td>Mean incidence</td>
</tr>
<tr>
<td>Conventional</td>
<td>700</td>
<td>2.39</td>
</tr>
<tr>
<td>Shallow</td>
<td>18</td>
<td>1</td>
</tr>
<tr>
<td>Reduced</td>
<td>404</td>
<td>4.27</td>
</tr>
<tr>
<td>Direct Drilled</td>
<td>17</td>
<td>5.06</td>
</tr>
</tbody>
</table>
Cultivar resistance

Modelling of the effect of winter wheat FHB resistance rating indicated that a higher resistance rating (indicating greater resistance to FHB) did not have a significant effect in reducing the incidence of *F. graminearum*, but did for *M. nivale/majus* (Table 10 and Table 11 respectively). Resistance ratings of 3, 4 and 8 were not included in the analyses as there were less than 5 samples in each category over the test period. Use of resistant cultivars accounted for 2% of variation in incidence of *M. nivale/majus*.

Table 10. Summary statistics for effect of Fusarium head blight (FHB) resistance rating on *Fusarium graminearum* incidence.

<table>
<thead>
<tr>
<th>FHB resistant rating</th>
<th>Sample size</th>
<th>Mean incidence</th>
<th>Variance</th>
<th>% infected</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>286</td>
<td>0.87</td>
<td>8.96</td>
<td>18.9</td>
</tr>
<tr>
<td>6</td>
<td>355</td>
<td>0.81</td>
<td>7.43</td>
<td>16.3</td>
</tr>
<tr>
<td>7</td>
<td>293</td>
<td>0.86</td>
<td>11.75</td>
<td>15.4</td>
</tr>
</tbody>
</table>

Table 11. Summary statistics and results from linear regression for effect of Fusarium head blight (FHB) resistance rating on *Microdochium nivale/majus* incidence.

<table>
<thead>
<tr>
<th>FHB resistant rating</th>
<th>Summary statistics</th>
<th>Linear regression</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sample size</td>
<td>Mean incidence</td>
</tr>
<tr>
<td>5</td>
<td>286</td>
<td>3.64</td>
</tr>
<tr>
<td>6</td>
<td>356</td>
<td>2.85</td>
</tr>
<tr>
<td>7</td>
<td>296</td>
<td>1.83</td>
</tr>
</tbody>
</table>

Analyses therefore identified previous crop, cultivation method and sowing date as the most significant agronomic factors affecting incidence of *F. graminearum*. However, using these selected agronomic factors, only 13.7% of the variation could be explained. Updating the model to take into account spatial (cluster region) and temporal (year) components generated a model which explained 38% of the variation, with cluster region being the dominant factor, explaining 17% of the variance for *F. graminearum* incidence at the farm scale. The inclusion of weather parameters would
improve the model further and although some weather factors have been identified i.e. mean temperature February-April the impacts of weather parameters at flowering still need to be quantified.

Analyses of the effects of agronomic factors on Microdochium species identified three factors as being most important: previous crop, cultivation method and cultivar resistance. However, these explain only 6.7% of the variation in incidence of M. nivale/majus at the farm level. Currently cluster analyses have not yet been carried out for M. nivale/majus and therefore cannot be included in the model. This has also precluded use of the approaches used for F. graminearum to investigate the effects of weather parameters. This will be addressed in future work.

Discussion

National monitoring of Fusarium head blight pathogens, undertaken within this project as part of the CropMonitor winter wheat survey, has provided clear evidence indicating how the incidence of FHB disease, geographical distribution and prevalence of individual species has progressed over the last three years. The data have shown that this disease is still increasing in prevalence not only in terms of proportion of crops affected but also the proportion of plants within a crop, which are infected. The overall incidence of FHB symptoms in 2006 was relatively low, but in 2007 the proportion of crops affected reached the highest recorded levels since monitoring began in 1991. Between 1998 and 2006, F. graminearum was isolated at low levels from diseased ears, but in 2007 isolations of F. graminearum increased to record their highest levels to date, with 26% of crops affected, and an in-crop incidence of 1.6% of ears affected. In 2008, the percentage of crops affected by F. graminearum was the same as in 2007. However, the proportion of plants infected within a crop had increased to an average of over 2% ears infected. This increase in proportion of crop affected is of particular concern as this will lead to greater yield loss and higher levels of mycotoxin contamination at a national level. Incidence of F. graminearum has also changed geographically in the last three years with more infections being recorded in the east and North than in earlier years. These changes all point to an evolving heightened risk from FHB for the future.
The increasing risk posed by FHB pathogens has been evident in the UK for some time, with the threat from the toxin producing species *F. graminearum* increasing dramatically over the last five years. At the start of the FHB pathogen isolation work in 1998, *F. culmorum* was the predominant mycotoxin (deoxynivalenol (DON)/zearalenone) producing species, with *F. graminearum* responsible for only a small percentage of FHB infections. In 2002, for the first time, *F. graminearum* caused more FHB symptoms than *F. culmorum*; this predominance by *F. graminearum* has continued to the present time. The emergence of *F. graminearum* as the most prevalent mycotoxin producer in England is of concern as this species has the potential to cause greater damage to the crop both in terms of loss to yield and mycotoxin production than *F. culmorum*. This difference can mainly be attributed to differences in the type of spores produced by each of the species. *F. culmorum* only produces splash dispersed macroconidia which have been shown to move only small distances (a few centimetres up to just over a meter) in a wheat crop (Fernando *et al*., 1997; Fernando *et al*., 2000; Jenkinson and Parry 1994; Parry *et al*., 1995). In addition to splash dispersed macroconidia *F. graminearum* also produces ascospores, which are predominantly wind dispersed and can disperse distances of between several metres and several kilometres (Fernando *et al*., 1997; Maldonado-Ramirez and Bergstrom, 2000). Thus a single unit of *F. graminearum* inoculum is able to infect a greater area of a field than a similar level of *F. culmorum* inoculum. The increase in prevalence of *F. graminearum* is not unique to the UK. Similar changes in population have also been reported in parts of Germany (Obst *et al*., 1997 and the Netherlands (Waalwijk *et al*., 2003).

The increased levels of *F. graminearum* in 2007 and 2008 led to alerts being issued by CropMonitor indicating that crops were at greater risk from mycotoxin contamination than in previous years, and that the risk in 2008 was higher than 2007 (due to the greater prevalence of *F. graminearum*). However, it was advised that the final level would ultimately depend on levels of rainfall prior to harvest. Results from the HGCA project RD-2006-3288 indicated that the mean level of DON in 2007 was higher than in previous years (mean level 317 ppb), with 4% of samples exceeding the EU limit of 1250 ppb. DON levels in 2008 were higher than in 2007 with a mean of 670 ppb with 14% of samples exceeding the limit. Levels of a second mycotoxin, zearalenone, also varied between 2007 and 2008. Low levels of zearalenone were detected in 2007 (mean 17 ppb and no sample exceeding the 100 ppb EU limit), whereas in 2008 the mean level detected was 127 ppb with 30% of samples exceeding the limit. The
difference in zearalenone levels seen between the two years is related to differences in rainfall prior to harvest, with 2008 being a much wetter year than 2007 at this time. Comparison of the data on FHB pathogen incidence with the data on toxin contamination (HGCA project RD-2006-3288), indicates that the use of information on pathogen levels at GS73 could be used to predict the likely risk of toxin contamination, however further information such as rainfall levels prior to harvest would be required before a final risk of contamination could be determined.

Alerts based on monitoring of disease and pathogen incidence at GS73-75 have been shown within this project to be indicative of risks of mycotoxin contamination at harvest. However, the late-season availability of these data precludes any action on the part of the grower to reduce the risk. In order to investigate possible indicators of risk of FHB and toxin contamination at a more appropriate point in the growing season, in-season monitoring of FHB pathogens was established at five sites to provide relevant data to aid the growers decision. Stem base isolations showed clear seasonal differences in the development of stem base disease, in particular those infections caused by the two Microdochium species, with the level of disease appearing to be related to weather conditions in the spring; warm dry conditions in early spring led to higher disease levels. Analyses of the equivalent data for stem base infections caused by fusarium species was much less clear. Data gained from the leaf layer isolations (2008 only) provided information indicating the possible risks from all FHB pathogens, in particular it showed whether fusarium inoculum had reached the ear during crop flowering. Further work is needed to explore these relationships further as leaf layer isolations were carried out in only the final year of the project. However, the use of these in-season data shows strong potential as a basis for providing the intelligence required by consultants/ growers to make earlier and more informed decisions on the likely risk of FHB infection during crop flowering.

Novel methodologies have been applied to the monitoring data for 2000-2008 on pathogen incidence to generate new risk maps for the key FHB pathogens. Maps generated through use of cluster analysis indicated how the distribution of F. graminearum incidence in England had developed and was still changing. Between 2000 and 2004, eight cluster regions were described for F. graminearum, with the areas at greatest risk of infection in the south west of England and around the Wash; the average incidence of F. graminearum infection in these areas was 0.6%. In more recent times (2005 to 2008) the number of clusters increased to 12 of which 6 had an
incidence of 0.6 or more. The areas shown to be at highest risk were similar to those highlighted in the earlier analyses, however the higher risk area had expanded further north. Cluster risk region had the main influence on the *F. graminearum* risk model (explaining 17% of the variance). However, all the evidence suggests that the geographical spread of *F. graminearum* is still changing and evolving. In order to develop definitive risk maps for *F. graminearum* for use in risk prediction it will be necessary to continue the monitoring of FHB pathogens until the cluster risk regions for *F. graminearum* become more stable.

The enhanced dataset for the years 2000-2008 was used to investigate and quantify the impact of agronomic factors on infection of crops by *F. graminearum* and *M. nivale/majus*. Of the factors examined, the greatest variance, 5.1 and 3.1% for *F. graminearum* and *M. nivale/majus* respectively, was explained by the method of cultivation used, with direct drill and reduced cultivation increasing the risk of infection by both pathogens. Reduced or no-tillage systems have previously been shown to favour the development of *F. graminearum* within a crop (Dill-Macky and Jones, 2000). Such systems leave crop debris on soil surface allowing its colonisation by FHB pathogens. Crop debris colonisation in the case of *F. graminearum* and *M. nivale/majus* results in the production of perithecia which have been shown to survive for 18 months on crop residues buried in soil and up to three years on crop residues left at the soil surface (Khonga and Sutton, 1988; Sutton, 1982). Only perithecia found at the soil surface contained ascospores, thus leaving the crop at risk from infection (Khonga and Sutton, 1988; Sutton, 1982).

Previous cropping also had a significant effect on the incidence of both *F. graminearum* and *M. nivale/majus* explaining 2.6 and 1.8% of the variance respectively. For *F. graminearum*, maize as a previous crop resulted in significantly higher disease incidence than any other crop examined; on average *F. graminearum* incidence was 5 times higher following maize. The effect of previous crop on *F. graminearum* incidence has also been previously reported by Teich and Nelson (1984) and Dill-Macky and Jones (2000). Teich and Nelson (1984) reported that incidence of FHB following maize was 6-7 times greater than for either wheat or soybean. The higher incidence of *F. graminearum* in the Teich and Nelson survey compared to the results found here may relate to differences in the type of maize grown i.e. mostly grain maize compared to mostly fodder maize, with grain maize leaving behind greater levels of crop debris than fodder maize. The area of grain maize grown in
England, in particular in the south, is increasing as new early maturing varieties are introduced. This increase in grain maize production may ultimately lead to a higher risk and incidence of *F. graminearum*.

The use of winter wheat varieties with a higher FHB resistance rating was shown to significantly reduce the incidence of only *M. nivale/majus*; their use did not affect *F. graminearum* incidence. One possible explanation for the difference could be the very limited prevalence of *F. graminearum* during the development of current winter wheat varieties. Varieties on the market now were being developed 10-15 years ago, when *M. nivale* and *M. majus* were the main FHB pathogens to which resistance would have been selected during trials. However, the difference may be a reflection of the type of FHB resistance present within UK varieties. Type I resistance indicates resistance to initial infection and is effective against FHB pathogens where symptoms do not spread after infection e.g. *M. nivale/majus* or nivalenol producing strains of *F. culmorum* or *F. graminearum*, whereas Type II resistance prevents spread within the cereal head and is effective against deoxynivalenol producing strains of *F. graminearum* and *F. culmorum*. As the response within the data is to *M. nivale/majus*, not *F. graminearum*, it is indicated that FHB resistance in UK wheat varieties is Type I and not Type II. Some researchers have suggested that wheat resistance to FHB appears to be horizontal and non-species specific with no clear evidence for host by pathogen species interaction (van Eeuwijk *et al.*, 1995; Mesterhazy *et al.*, 2005), however the data presented here indicates this is not the case.

The influence of sowing date on disease incidence also differed between *F. graminearum* and *M. nivale/majus*. There was no influence of sowing date on *M. nivale/majus* whereas sowing before mid September reduced disease incidence and sowing in October increased incidence for *F. graminearum*. This effect with *F. graminearum* may be related to early sown crops flowering earlier than the timing of inoculum release, thus escaping the main ascospore infection period. This is less likely to happen for *M. nivale/majus*, which, because it is mostly a seed-borne disease, which establishes in the crop as it develops and is not subject to conditions in soil which may slow down perithecial maturation.

Analysis of meteorological data between 2005 and 2008 indicated that the main parameter for incidence of *F. graminearum* was the mean temperature in the spring, which will affect the development of inoculum. Examination of meteorological anomaly
data (Source: UKMO), which compares actual temperature and rainfall data with the long-term average for 1971-2000, showed that temperatures in 2006 were 0.8°C below average, whereas in 2007 and 2008 they were 6.1°C and 1.5°C above average respectively. Stem base data for these years showed that highest disease levels occurred in 2007 and lowest in 2006. This simple comparison may indicate that growing conditions in spring warrant further examination in terms of effect on later development of FHB and toxins. The analyses only gave a weak positive correlation for rainfall in June, the factor generally regarded as most important. This lack of correlation may be related to the weather data available to the project team being too limited to reflect any differences in rainfall between cluster regions or it could be that even though June conditions were different across the years, they were similar across the majority of the country and therefore were not highlighted as a critical factor. Alternatively, this could be the first indication that rainfall in June is less important for the establishment of FHB symptoms caused by *F. graminearum* than for those caused by the other FHB pathogens. Further analysis is required to fully establish this.

Considerable progress has been made in the objectives to better understand the risks posed by FHB pathogens to winter wheat production. New risk maps have been produced and in-season monitoring has proved a potential role in identifying risks from the disease at a stage in the season, which will allow growers to respond in terms of implementing control strategies. Analyses of data have further identified and quantified risk factors and have advanced progress towards the development of robust models for the prediction of risks of FHB pathogens and mycotoxin contamination in winter wheat. However, using selected agronomic factors, only explained 13.7% and 6.7% of the variation for incidence of *F. graminearum* and *M. nivale/majus* respectively at the farm level. Updating the model to take into account spatial (cluster region) and temporal (year) components was shown to generate far more robust models, increasing the variance explained to 38% for *F. graminearum* incidence at the farm scale (cluster models are not yet available for *Microdochium* species). The inclusion of weather parameters would improve the models still further and although some weather factors have been identified i.e. mean temperature February-April the impacts of weather parameters at flowering still need to be fully quantified. These aspects will be addressed in future work.
Conclusions

- The risk from *Fusarium graminearum* is increasing across England, with the area in which a crop is grown being the major risk factor in disease development.

- In-season monitoring of inoculum build-up could provide the intelligence required by consultants/growers to enable early and informed decisions on the likely risk of FHB infection occurring during crop flowering to be made.

- Monitoring of the FHB pathogens responsible for FHB symptoms in winter wheat crops at GS73 provides a good indication of the likely risk of mycotoxin contamination of grain, however it is the prevailing weather conditions between flowering and harvest that determine the final levels and type of toxin present.

- Agronomic factors that influence development of *F. graminearum* in a crop are previous crop (maize), sowing date and cultivation method. Effective sources of resistance to *F. graminearum* do not seem to be present in the winter wheat varieties currently grown in the UK.

- Further work on investigation of the role of in-season monitoring in disease risk prediction and further development of the models is recommended.
References


