Chapter 2

# Integration of Fungicide Application and Cultivar Resistance to Manage Fusarium Head Blight in Wheat

Stephen N. Wegulo, William W. Bockus, John F. Hernandez Nopsa, Kamaranga H. S. Peiris and Floyd E. Dowell

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/53096

## 1. Introduction

Fusarium head blight (FHB), also known as scab, is a destructive disease of wheat and other small grain cereals. Losses are compounded by the associated mycotoxin deoxynivalenol (DON) which contaminates grain. This chapter provides a brief review of FHB of wheat in North America including occurrence, symptoms, life cycle, economic importance, and integrated management with an emphasis on use of fungicides and host resistance. The review is followed by a presentation of selected research results from experiments conducted by the authors to determine the effects of integrating fungicide application with cultivar resistance on FHB. These results indicate that combining cultivar resistance with fungicide application is a more effective strategy for management of FHB and DON than using a single approach. In North America, a slow but steady progress has been made during the last decade in the development of wheat cultivars with improved resistance to FHB and DON. These cultivars are replacing or complementing older, FHB-susceptible cultivars. Availability of moderately resistant cultivars and new fungicide chemistries coupled with improved fungicide application technology has led to greater farmer adoption of an integrated strategy in the management of FHB and DON.

In North America, FHB occurs mainly in the eastern half of the United States (McMullen et al., 1997) and in eastern Canada (Gilbert & Tekauz, 2000), although surveys by the Canadian Grain Commission have increasingly found it in western Canada (Clear & Patrick, 2010). Several species of *Fusarium* and its allies are among the causal agents of FHB. They include *F. culmorum, F. avenaceum, F. graminearum, F. poae*, and *Microdochium nivale* (Liddell, 2003). Worldwide, *F. graminearum* is the major cause of FHB (Liddell, 2003; Parry, 1995) and predominates in North America (Parry, 1995; Sutton, 1982). Stack (2003) reviewed the history of FHB with emphasis on North America. The disease has occurred sporadically since the 1880s, with several major epidemics documented worldwide to date. In the U.S., major epidemics occurred in 1917, 1919, 1928, 1932, and 1935 (Stack 2003). More recently, the disease re-emerged in the early 1990s and since then outbreaks of varying intensity have been common and widespread in the U.S., particularly in areas with high moisture and abundant maize culture (McMullen et al., 1997).

In wheat, FHB symptoms are recognized by the premature bleaching of one or more spikelets on a head (spike). This bleaching can continue until the entire head is whitened. Bleached heads appear suddenly and are readily visible in a wheat field. *F. graminearum* sporulates on infected spikelets and glumes during prolonged wet weather, resulting in pink to salmon-orange spore masses which are a diagnostic feature of FHB. Infection of the stem (peduncle) immediately below the head may also occur, causing a brown or purple discoloration. If the peduncle is infected early, the entire head becomes sterile. Bleached spikelets are sterile or contain shriveled and/or chalky white or pink kernels commonly referred to as *Fusarium*-damaged kernels (FDK), scabby kernels, or "tombstones." Apparently healthy kernels also may be infected, especially if infection occurred late in kernel development.

*F. graminearum* overwinters as chlamydospores or mycelia in the soil or in host crop residues which serve as a source of primary inoculum in the spring (Dill-Macky, 2010). FHB primary inoculum consists mainly of ascospores produced in perithecia, which form on crop residues in the spring as temperatures warm up. Maize and wheat residues are particularly suitable for survival of the fungus. Khonga and Sutton (1988) observed perithecia formation on *F. graminearum*-inoculated maize and wheat residues placed on or above the soil surface for up to two years. Dill-Macky & Jones (2000) reported up to 45 and 94% recovery of *F. graminearum* from maize and wheat residue, respectively, in a single cropping cycle. In the spring, ascospores and/or conidia are released from crop residues and are spread by wind or splashing water. They land on wheat heads and during wet, warm weather they germinate and infect glumes, flower parts, or other parts of the head.

Infections occur mostly during anthesis. Wheat heads are susceptible from head emergence until harvest (Dill-Macky, 2010). Infections that occur during anthesis are the most damaging. During warm temperatures (25$^{o}$C to 30$^{o}$C) and wet conditions, blight symptoms develop within 2 to 4 days after infection. Therefore, an apparently healthy crop can show symptoms suddenly. Later in the growing season or after harvest, perithecia may form on wheat heads. FHB is considered a monocyclic or one cycle disease, that is, after the initial or primary infection, little or no secondary infection occurs by conidia formed on infected heads. FHB is favored by prolonged wet, warm weather prior to and during anthesis. Excessive rainfall during the growing season and especially during a one to three week period prior to anthesis can lead to severe epidemics of FHB. The disease usually is more severe in fields with corn and/or wheat residue on the soil surface and in irrigated fields.

In addition to lowering grain yield and quality, *F. graminearum* produces mycotoxins, primarily the trichothecenes deoxynivalenol (DON), nivalenol (NIV) and T-2 toxin

(McCormick, 2003; Gale, 2003). The sterol zearalenone (ZEA) is also commonly encountered (Gale 2003). These mycotoxins are harmful to humans and livestock. In North America, DON, also known as vomitoxin, is the most common and economically important mycotoxin found in *Fusarium*-infected wheat. Its acetylated derivatives, 3-ADON and 15-ADON, are commonly detected in contaminated grain. Grain with high concentrations of DON often is discounted or rejected at the elevator, which exacerbates the losses incurred by the farmer.

DON has been shown to be positively correlated with both FHB intensity (incidence, severity, or index) and FDK (Paul et al., 2005; Wegulo et al., 2011). In replicated field studies conducted over two years (2008 and 2009) in Manhattan, KS, USA (Wegulo et al., 2011), the authors of the current chapter generated different levels of FHB intensity by applying or not applying the fungicide Prosaro (prothioconazole + tebuconazole) to six cultivars differing in susceptibility to FHB. Grain samples from treated and check plots were ground to flour and submitted to the North Dakota Veterinary Diagnostic Laboratory at North Dakota State University for DON content determination using gas chromatography with electron capture detection (GC/ECD) (Tacke and Casper, 1996). Regression of DON concentration on FHB index revealed a strong positive linear relationship between the two variables. For every percent increase in FHB index, DON concentration increased by 0.31 ppm (Fig. 1).

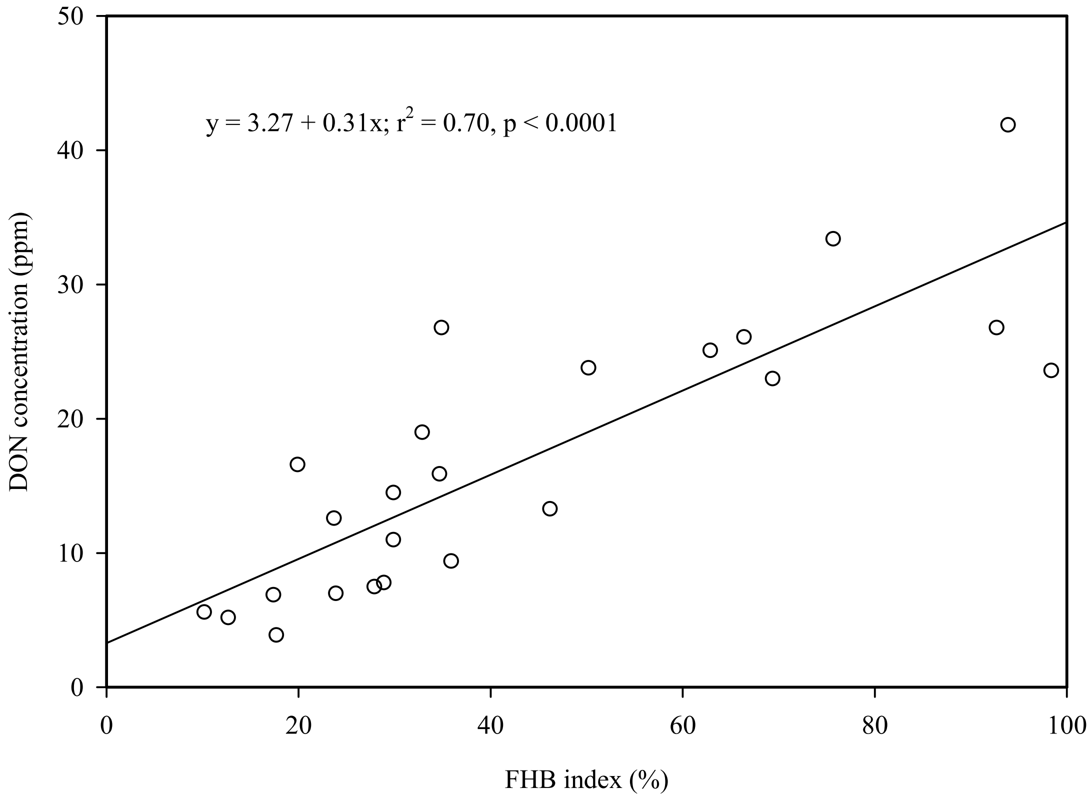


**Figure 1.** Relationship between Fusarium head blight (FHB) index and DON concentration determined from field experiments in which the fungicide Prosasro (prothioconazole + tebuconazole) was applied or not applied to six winter wheat cultivars differing in susceptibility to FHB. The experiments were conducted in Manhattan, Kansas, USA in 2008 and 2009.

In a laboratory study to demonstrate the relationship between FDK and DON, the authors of the current chapter mixed FDK collected from winter wheat fields and grain elevators in 2007 and 2008 (when there were severe epidemics of FHB in Nebraska, USA) with healthy grain in 5% (by weight) increments from 0% FDK, 100% healthy grain to 100% FDK, 0% healthy grain. Samples were ground to flour and submitted for DON content determination as described above. Regression of DON on FDK revealed a strong linear relationship between FDK and DON in both years (Fig. 2). For every percent increase in FDK, DON concentration increased by 0.33 and 0.53 ppm in 2007 and 2008, respectively.

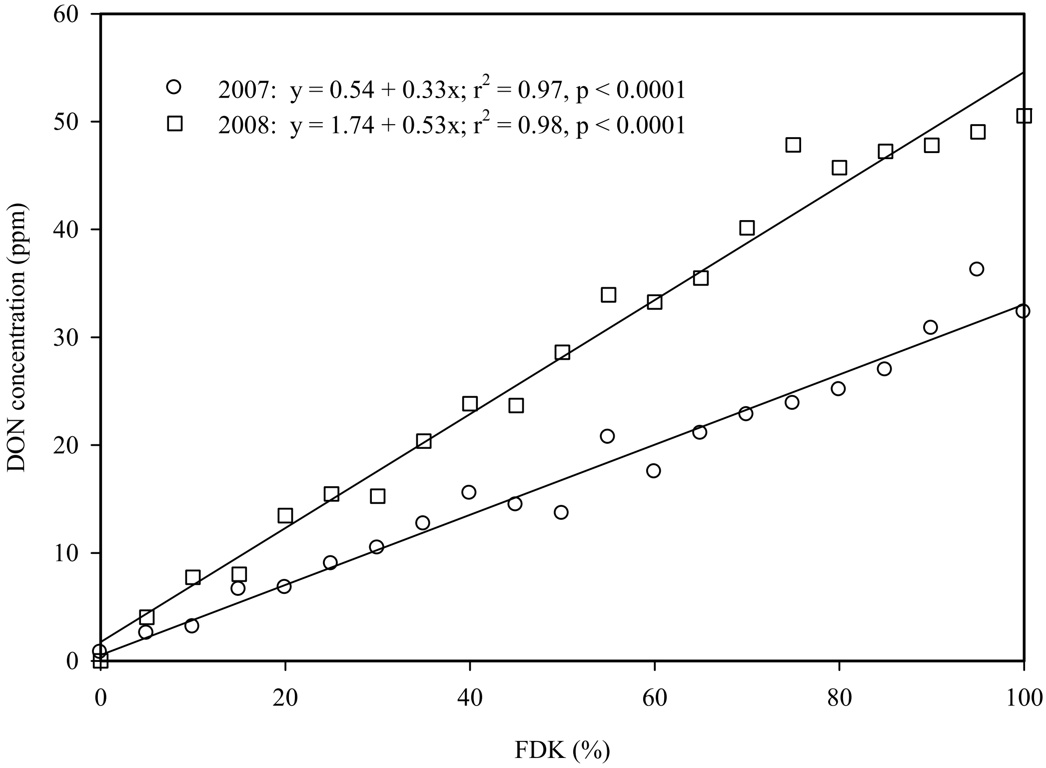


**Figure 2.** Relationship between *Fusarium*-damaged kernels (FDK) and deoxynivalenol (DON) concentration in grain samples with increasing proportions (5% increments) by weight of FDK from 0% FDK, 100% healthy grain to 100% FDK, 0% healthy grain. FDK were collected from fields and grain elevators in 2007 and 2008 when severe epidemics of Fusarium head blight occurred in winter wheat fields in Nebraska, USA.

## 2. Economic importance of FHB

FHB can cause substantial economic losses. In 1917, FHB caused losses estimated at 288,000 metric tons (10.6 million bushels) in 31 out of 40 states surveyed (Atanasof, 1920). Dickinson and Mains (1929) reported that the 1919 epidemic in the U.S. resulted in a loss of 2.18 million metric tons (80 million bushels) of wheat. Mains et al. (1929) estimated that the 1928 epidemic caused a 15% yield loss in wheat in Indiana. Significant additional losses occurred in the 1930s (Dickinson & Mains, 1942). Major economic losses occurred again in the 1980s (McMullen et al., 1997), with total losses in U.S. wheat production totaling 2.72 million metric tons (100 million bushels) in 1982 alone (Boosalis et al., 1983). Johnson et al. (2003) estimated that FHB caused direct losses in wheat and barley totaling more than $1.3 billion in the U.S. during the period from 1991 to 1997. They estimated the total economic impact in rural communities and businesses related to grain production and marketing to be three to four times this amount. To date, FHB continues to cause significant economic losses in the U.S. and other parts of the world.

## 3. The use of fungicides to control FHB in the United States

In the U.S., a less than desirable number of current commercial wheat cultivars have moderate resistance to FHB and this resistance can be overwhelmed in years with high disease intensity. Fungicides are often applied to control FHB when favorable conditions for disease development are forecast. In North America, the most commonly used fungicides are in the triazole class. They include metconazole, prothioconazole, tebuconazole, prothioconazole + tebuconazole, and propiconazole. Strobilurin fungicides are generally not recommended for control of FHB because some studies have shown them to be associated with elevated levels of DON in grain (Blandino et al., 2006; Mesterházy et al., 2003c; Zhang et al., 2009).

Although the triazole fungicides have been tested extensively in university trials, not all farmers apply them specifically for FHB control, in part due to the sporadic nature of the disease. There are several reasons why some farmers do not apply fungicides specifically for FHB control. Firstly, to be effective, fungicide application usually is timed to coincide with anthesis. By this time those farmers who apply fungicides will have treated their crop at least once to control foliar fungal diseases, making it economically unfeasible to apply a second spray. Secondly, the application window for effective control of FHB is only a few days during anthesis. Unfavorable weather conditions during this time will prevent timely fungicide application. Thirdly, most farmers who apply fungicides do so by contract with commercial applicators. Often these contracts are made long before it is known whether FHB will occur at epidemic proportions. Because of this uncertainty, risk-averse farmers do not sign the contracts. Fourthly, some farmers are discouraged by less than adequate control of FHB by fungicides.

### 3.1. Variability in fungicide efficacy

Studies have shown that results from fungicide application to suppress FHB are highly variable. This variability has been attributed to various factors including improper timing of application, inadequate coverage of wheat heads due to inefficient application technology, and poor fungicide efficacy (McMullen, 1997; Mesterházy, 2003b). In North Dakota, USA, Ransom and McMullen (2008) found that in a year with high FHB intensity, tebuconazole did not reduce FHB to acceptable levels in most of the winter wheat cultivars in the field trial. However, in a year with low disease intensity, tebuconazole + prothioconazole achieved almost 100% FHB control in all but the most susceptible cultivars. Paul et al. (2008)

analyzed over 100 FHB uniform fungicide studies across 11 years and 14 U.S. states. In these studies, metconazole, propiconazole, prothioconazole, tebuconazole, and prothioconazole + tebuconazole were applied at anthesis to suppress FHB. The analysis showed that although all fungicides significantly reduced FHB index and DON, there was substantial between-study variability. A given fungicide can vary in its efficacy in controlling FHB versus DON. Paul et al. (2007) showed that tebuconazole was more effective in controlling FHB than DON. The same study (Paul et al., 2007) showed that tebuconazole controlled FHB and DON more effectively in spring wheat compared to winter wheat.

### 3.2. Prospects for control of FHB with fungicides

Over the last two decades, there has been considerable improvement in the effectiveness of fungicides in controlling FHB and DON. This improvement is attributable in part to improved fungicide chemistries and greater knowledge gained through research on fungicide application rates, timing, and technology. A review of fungicide trials conducted over the last two decades clearly demonstrates this improvement. In trials conducted in 1992 and 1993 in Arkansas, USA, Milus and Parsons (1994) found that the fungicides benomyl, chlorothalonil, fenbuconazole, flusilazole, myclobutanil, potassium bicarbonate, propiconazole, tebuconazole, thiabendazole, and triadimefon + mancozeb) applied to the soft red winter wheat cultivar Florida 302 at the heading stage had no effect on FHB incidence, DON, yield, or test weight. The investigators concluded that prospects for chemical control of FHB were poor. Similar trials conducted between 1994 and 1997 by Jones (2000) in Minnesota led to the conclusion that although benomyl and tebuconazole significantly reduced FHB, FDK, and DON in the hard red spring wheat cultivars Norm and 2375, prospects for chemical control of FHB remained limited.

With the realization that the triazole fungicides are more effective than other fungicide classes in controlling FHB, and with newer chemistries and refinements in application timing, rates, and technology, the majority of fungicide trials conducted over the last decade have demonstrated improved effectiveness of triazole fungicides in controlling FHB and DON. In Minnesota, USA, Hollingsworth et al. (2006) showed that the then experimental products (now registered) metconazole and tebuconazole + prothioconazole significantly reduced FHB severity and FDK compared to tebuconazole. These results indicate that the prospects for chemical control of FHB and DON in wheat have improved over the last decade and continue to improve with the development of new fungicide chemistries and improvements in application timing, rates, and technology.

## 4. Management of FHB with host resistance

Genetic resistance is the most cost-effective management strategy for FHB (Ruckenbauer et al., 2001). Five categories of resistance to FHB have been described (Shroeder & Christensen, 1963; Wang & Miller, 1988; Mesterházy, 1995; Mesterházy, 2003a). They are resistance to initial infection (Type I), resistance to pathogen spread in infected tissue (Type II), resistance to kernel infection (Type III), tolerance (Type IV), and resistance to toxins (Type V).

Challenges to breeding for resistance to FHB include the quantitative nature of resistance to the disease (Ruckenbauer et al., 2001), the fact that there are up to five categories of resistance, the lack of well adapted and complete resistance sources, and confounding environmental effects (Anderson et al., 2001). In addition, because only a few sources of resistance (mainly Sumai 3 and its relatives) are widely used, the potential exists for *F. graminearum* and other FHB-causing pathogens to overcome this resistance that relies on a narrow genetic basis (Ruckenbauer et al., 2001). Recent progress in breeding for resistance to FHB is attributable to a combination of traditional breeding methods and molecular breeding techniques such as marker-assisted selection (Anderson, 2007). In the U.S., there are now several cultivars in most wheat classes with moderate resistance to FHB (Scab Smart, http://www.scabsmart.org/). These cultivars have been released as a result of concerted efforts in greenhouse and field screening of germplasm. In addition, many research programs at universities and private companies are devoted to screening commercially released cultivars whose reaction to FHB and DON was previously unknown.

## 5. Forecasting FHB

To facilitate the judicial and economical use of fungicide applications to control FHB and DON, several forecasting systems have been developed. In the U.S., the Fusarium Head Blight Risk Assessment Tool (http://www.wheatscab.psu.edu/riskTool_2011.html) is an Internet-based forecasting system deployed in at least 23 states. It was developed based on logistic regression models for FHB using information from 50 location-years in four states and three different wheat production regions (De Wolf et al., 2003). The system uses combinations of temperature, relative humidity, and rainfall during seven days before anthesis to calculate the risk of occurrence of FHB. Specifically, the predictor variables used are duration (hours) of precipitation 7 days before anthesis, duration (hours) when temperature is between 15 and 30$^{o}$C 7 days before anthesis, and relative humidity greater than or equal to 90%. Based on these variables for a particular location, the system outputs a risk category of low, moderate, or high. Farmers can then decide whether to apply a fungicide at early anthesis based on the risk predicted for their respective locations. In Canada, the DONcast® model was developed for use by wheat farmers to predict DON accumulation. Hence, farmers can make fungicide spray decisions more efficiently. The model uses weather forecast data supplemented by actual data from additional weather stations to make site-specific DON predictions based on wheat cultivar, crop rotation, tillage, heading date, and local weather conditions. The DONcast® prediction tool is Internet-based and is available on the weathercentral.ca website. In Switzerland, FusaProg is an Internet-based decision support system which provides information about local and regional risks of FHB outbreaks (Musa et al., 2007). In addition, it forecasts field-specific DON contamination of winter wheat. FusaProg uses a model that takes into account the effects of cropping factors, previous crops, soil and straw management, and cultivar susceptibility as driving variables which are combined with growth stage (anthesis) and prevailing weather conditions to predict DON in specific wheat fields. Hence, farmers can optimize the timing of fungicide applications to control FHB and DON. In Argentina, one of the forecasting systems for FHB index was recently modified into a new forecasting system that has potential to forecast annual DON content in mature wheat grain using primary meteorological daily data from surface stations (Martinez et al., 2012).

## 6. Integrated management of FHB

The best approach to managing FHB is to integrate multiple strategies (McMullen et al., 2008) including host resistance, fungicide application, crop rotation, residue management, and forecasting. A combination of two or more of these strategies can significantly reduce losses caused by FHB. Few studies have been done to determine the effect of multiple management strategies on FHB and DON. In Germany, Koch et al. (2006) found that tillage type, cultivar, and application of the fungicide tebuconazole had a significant effect on DON accumulation. Reduced tillage resulted in higher DON content in both a moderately resistant and a highly susceptible cultivar compared to clean tillage, with the highly susceptible cultivar accumulating more DON than the moderately resistant cultivar. Fungicide application reduced DON concentration only slightly in the moderately resistant cultivar, but significantly in the highly susceptible cultivar. In Hungary, Mesterházy et al. (2003c) found that fungicide efficacy in controlling FHB and DON accumulation was higher in the more resistant than in the more susceptible winter wheat cultivars. In Minnesota, USA, Hollingsworth et al. (2008) reported that in spring wheat, fungicide application resulted in higher economic returns in moderately susceptible cultivars than in moderately resistant cultivars when disease intensity was low. However, when disease intensity was moderate, economic returns did not differ between moderately susceptible and moderately resistant cultivars. In the same study (Hollingsworth et al., 2008), fungicide application reduced FHB intensity in moderately resistant cultivars, but had no effect on DON accumulation in both moderately resistant and moderately susceptible cultivars. McMullen et al. (2008) reported that in North Dakota, USA, FHB severity was reduced by 50, 80, and 92% with rotation, rotation + a tolerant cultivar, and rotation + a tolerant cultivar + fungicide application, respectively. Recently, Willyerd et al. (2012) used multivariate analysis to evaluate the integration of host resistance and application of the fungicide prothioconazole + tebuconazole in wheat using data from over 40 trials in 12 U.S. states. They found that the best control of FHB was provided by a combination of fungicide application and moderately resistant cultivars.

## 7. Experiments conducted to determine the effects of integrating cultivar resistance and fungicide application on FHB

From 2007 to 2009, the authors of the current chapter evaluated the effects of integrating cultivar resistance and fungicide application in hard winter wheat in two sets of experiments (Wegulo et al., 2011). In the first set (experiments 1-3) the fungicide Prosaro (prothioconazole + tebuconazole) was applied or not applied to three cultivars (Harry, 2137, and Jagalene) at full heading to early anthesis in 2007 to 2009. In the second set (experiments 4 and 5), the same two fungicide treatments were applied to six cultivars (Truman, Heyne, Roane, Karl 92, Overley, and Tomahawk) at full heading in 2008 and 2009. From these experiments we demonstrate the effects of combining cultivar resistance and fungicide application on FHB index, DON, FDK, and yield using four moderately resistant (based on FHB phenotype only) and four susceptible cultivars selected from the two sets of experiments in location-years that had high FHB intensity (Manhattan 2007, Mead 2008, Manhattan 2008, and Manhattan 2009).

### 7.1. Methods

The methods used in the experiments have been published previously (Wegulo et al., 2011). Briefly, the experiments were conducted near Mead, Nebraska and in Manhattan, Kansas, USA from 2007 to 2009. The experimental design was a split plot in randomized complete blocks with four to six replications with cultivars as the main plots and fungicide treatments as the subplots (Table 1). The fungicide treatments consisted of Prosaro (prothioconazole + tebuconazole) not applied (check treatment) or applied at a rate of 0.475 liters/ha at Zadoks growth stage 59 (GS 59) or 2 days before GS 65 (mid anthesis). Fungicide was applied at a rate of 187 liters/ha of spray volume and a pressure of 207 kPa using a back-pack sprayer equipped with flat-fan nozzles angled forward about $30^{o}$. Plots were inoculated with corn kernels colonized by *F. graminearum* two to four weeks before anthesis. At Mead, plots were additionally spray-inoculated with spores of *F. graminearum* ($1 \times 10^{5}$ spores $ml^{-1}$) at GS 65. Plots were over-head irrigated at Manhattan but not at Mead.

FHB index was assessed as the percentage of spikelets blighted in a plot or as (incidence (%) x severity (%))/100 three to four weeks after fungicide application. Plots were harvested with a small-plot combine and subsamples from the harvested grain were used to determine the percentage of FDK visually or with an automated single kernel near-infrared (SKNIR) system (Perten Instruments, Stockholm, Sweden) (Dowell et al., 2006). Ten-gram subsamples were ground to flour and sent to the North Dakota Veterinary Diagnostic Laboratory at North Dakota State University for DON content determination using gas chromatography with electron capture detection (GC/ECD) (Tacke and Casper, 1996).

The GLM and GLIMMIX procedures of SAS (SAS Institute, Cary, NC, USA) were used to analyze data. Treatments were considered significantly different at $p \leq 0.05$. Fungicide efficacy for index, DON, and FDK was calculated as

$$[(C - F)/C]*100$$

where $C$ is the check treatment value and $F$ is the fungicide treatment value. Fungicide efficacy for yield was calculated as

$$[(F - C)/F]*100$$

where $C$ and $F$ are as previously defined.

## 7.2. Results and discussion

### *7.2.1. Main effects and their interactions*

In experiments 1-3, the effects of location-year, cultivar, and fungicide were significant for index, DON, FDK, and yield (Table 1). The effect of location-year by cultivar interaction was also significant for all four variables. However, the effect of location-year by fungicide interaction was significant only for index and the effect of cultivar by fungicide interaction was not significant for any of the variables. The effect of the three-way interaction was significant for index, DON, and FDK, but not yield.

In experiments 4 and 5, the effects of location-year, cultivar, and fungicide were significant for index, DON, FDK, and yield (Table 1). The effect of location-year by cultivar interaction was significant for all four variables whereas the effect of location-year by fungicide interaction was significant only for yield and the effect of cultivar by fungicide interaction was significant for index and DON. The effect of the three-way interaction was significant for index and yield.

These results indicate that location-year, cultivar, and fungicide significantly affected FHB index, DON, FDK, and yield. The only interaction effect that significantly affected all four variables in both sets of experiments was that between location-year and cultivar, implying that the resistance or susceptibility of a given cultivar to FHB, DON accumulation, and *Fusarium* damage can be influenced by environmental conditions during the growing season. The location-year by fungicide and cultivar by fungicide interaction effects were inconsistent between the two sets of experiments and among the measured variables, suggesting that environment and cultivar did not always affect fungicide performance.

### *7.2.2. FHB index, DON, FDK, yield, and fungicide efficacy in moderately resistant and susceptible cultivars*

We selected from experiments conducted under high disease intensity four moderately resistant (based on FHB phenotype) (Truman, Harry, Heyne, and Roane) and four susceptible cultivars (Overley, Tamahawk, 2137, and Jagalene) for analysis and presentation in this chapter. Overall, FHB index was lower in the moderately resistant than in the susceptible cultivars in both the Prosaro and check treatments and Prosaro reduced index in both moderately resistant and susceptible cultivars (Fig. 3). For three of the moderately resistant cultivars (Truman, Heyne, and Roane), index in the check treatment was lower than index in the Prosaro treatment in all the susceptible cultivars whereas in Harry, index in the check treatment was similar to index in the Prosaro treatment in the susceptible cultivar 2137. These results indicate that the resistance in the moderately resistant cultivars was effective under high FHB intensity even in the absence of fungicide application. This implies that under low FHB intensity, resistance alone may be sufficient and no fungicide application may be needed in the moderately resistant cultivars.

Cultivar response to DON was less clear-cut compared to the response to FHB index. In the Prosaro treatment, cultivars Harry and Heyne (moderately resistant) had similar levels of

DON as cultivars 2137 and Jagalene (susceptible), indicating that some cultivars with a moderately resistant FHB phenotype may be susceptible to DON accumulation (Fig. 4). Within the check treatment, the four moderately resistant cultivars accumulated DON amounts similar to those in the susceptible cultivars 2137 and Jagalene. Overley and Tomahawk accumulated more DON than all other cultivars regardless of fungicide treatment. Overall, DON reduction due to fungicide application was greater in the moderately resistant than in the susceptible cultivars.

The response of both susceptible and moderately resistant cultivars to DON accumulation within the two fungicide treatments highlights the complexity of managing FHB and DON by integrating fungicide application and cultivar resistance. Fungicide efficacy for FHB intensity does not necessarily mirror efficacy for DON in a given cultivar. The authors of the current chapter have consistently observed the cultivar Harry to have a moderately resistant FHB phenotype. However, this cultivar appears to be susceptible to DON accumulation (Figs. 3 and 4; Wegulo et al., 2011; Hernandez Nopsa et al., 2012). These observations call for a consensus among FHB scientists to standardize the criteria by which to classify cultivars as resistant or susceptible to FHB, as well as the criteria for classifying fungicide efficacy. Should resistance to FHB refer to resistance to FHB intensity, DON, and FDK combined, or should resistance refer to each variable separately?

Among the moderately resistant cultivars, Truman, Heyne, and Roane had fewer FDK than the susceptible cultivars regardless of fungicide treatment (Fig. 5). Harry, on the other hand, had FDK levels similar to those in the susceptible cultivars. This result indicates that Harry, despite having a moderately resistant FHB phenotype, is susceptible when evaluated based on FDK. Because FDK and DON are positively related (Fig. 2), this result also suggests that the higher DON in Harry may be due to the cultivar's susceptibility to *Fusarium* damage.

Prosaro generally increased yield in both moderately resistant and susceptible cultivars (Fig. 6). There was no clear distinction in yield between the moderately resistant and susceptible cultivars, with Heyne (moderately resistant) having low yield and 2137 (susceptible) having high yield. The insignificant yield response to fungicide application and the inconsistency in yield response between moderately resistant and susceptible cultivars may be due to differences in genetics and the fact that yield, unlike the other three measured variables (index, DON, and FDK), is influenced by other factors in addition to FHB. These factors include other diseases (including foliar and root and crown diseases), nutrients, and weeds. This result indicates that among the four measured variables, yield may be the least accurate to use in assessing fungicide efficacy in controlling FHB.

Fungicide efficacy for index was generally higher in moderately resistant than in susceptible cultivars (Fig. 7). It was highest in Truman and lowest in Jagalene. Similarly, fungicide efficacy for DON was generally higher in moderately resistant than in susceptible cultivars except for Harry (moderately resistant) in which the efficacy was as low as in the susceptible Tomahawk and Jagalene (Fig. 7). The finding in this study that overall fungicide efficacy for index and DON was higher in moderately resistant than in susceptible cultivars is in agreement with the results of Mesterházy et al. (2003c). The finding suggests that integrating cultivar resistance with fungicide application can be an effective management strategy for FHB and DON.

| Source of variation | d.f.[a] | **Index[b] (%)** | | **DON (ppm)** | | **FDK (%)** | | **Yield (kg ha$^{-1}$)** | |
|---|---|---|---|---|---|---|---|---|---|
| | | **MS[c]** | ***P > F*** | **MS** | ***P > F*** | **MS** | ***P > F*** | **MS** | ***P > F*** |
| **Experiments 1-3[d], 2007-2009** | | | | | | | | | |
| Location-year (Y) | 2 | 27,296 | <0.0001 | 2,319 | <0.0001 | 2,512 | <0.0001 | 14,988,93 | <0.0001 |
| Rep (Y) | 14 | 199 | <0.0001 | 13 | 0.0353 | 103 | 0.5199 | 629,384 | 0.0058 |
| Cultivar (C) | 2 | 4,559 | <0.0001 | 80 | <0.0001 | 833 | 0.0014 | 4,163,646 | <0.0001 |
| Y * C | 4 | 2,794 | <0.0001 | 26 | 0.0066 | 1,101 | <0.0001 | 2,881,204 | <0.0001 |
| Error (a) | 28 | 71 | | 9 | | 163 | | 265,965 | |
| Fungicide (F) | 1 | 2,417 | <0.0001 | 89 | 0.0005 | 3,108 | <0.0001 | 5,697,574 | <0.0001 |
| Y*F | 2 | 2,032 | <0.0001 | 15 | 0.1060 | 44 | 0.6690 | 13,733 | 0.9419 |
| C*F | 2 | 68 | 0.2295 | 15 | 0.0974 | 127 | 0.3209 | 11,395 | 0.9515 |
| Y*C*F | 4 | 138 | 0.0249 | 21 | 0.0166 | 471 | 0.0050 | 232,551 | 0.4107 |
| Error (b) | 42 | 44 | | 6 | | 108 | | 229,164 | |
| Total | 101 | | | | | | | | |
| **Experiments 4 and 5, 2008-2009** | | | | | | | | | |
| Location-year (Y) | 1 | 11,484 | <0.0001 | 1,900 | <0.0001 | 7,368 | <0.0001 | 12,747,54 | <0.0001 |
| Rep (Y) | 6 | 76 | 0.0021 | 36 | 0.0973 | 48 | 0.7694 | 385,074 | 0.0061 |
| Cultivar (C) | 5 | 7,935 | <0.0001 | 1,072 | <0.0001 | 6,517 | <0.0001 | 14,500,24 | <0.0001 |
| Y * C | 5 | 1,336 | <0.0001 | 181 | <0.0001 | 732 | <0.0001 | 3,420,870 | <0.0001 |
| Error (a) | 30 | 72 | | 28 | | 132 | | 135,553 | |
| Fungicide (F) | 1 | 6,970 | <0.0001 | 678 | <0.0001 | 823 | 0.0041 | 6,816,701 | <0.0001 |
| Y*F | 1 | 24 | 0.2474 | 4 | 0.6467 | 27 | 0.5819 | 493,848 | 0.0367 |
| C*F | 5 | 69 | 0.0059 | 51 | 0.0309 | 63 | 0.6121 | 251,029 | 0.0569 |
| Y*C*F | 5 | 186 | <0.0001 | 28 | 0.2064 | 92 | 0.4042 | 308,975 | 0.0252 |
| Error (b) | 36 | 17 | | 18 | | 88 | | 104,686 | |
| Total | 95 | | | | | | | | |

[a]Degrees of freedom.

[b]Index was assessed as the percentage of spikelets blighted in a plot or calculated as [FHB incidence (%) x FHB severity (%)]/100.

[c]Mean square.

[d]Experiments 1-5 were conducted at Manhattan, KS in 2007; Mead, NE in 2008; Mead, NE in 2009; Manhattan, KS in 2008; and Manhattan, KS in 2009, respectively. There were 6, 6, 5, 4, and 4 replications in experiments 1-5, respectively.

**Table 1.** Analysis of variance from experiments conducted to determine the effect of combining cultivar resistance and fungicide application on *Fusarium* head blight (FHB) index, deoxynivalenol (DON) concentration, *Fusarium* -damaged kernels (FDK), and yield in winter wheat, 2007-2009

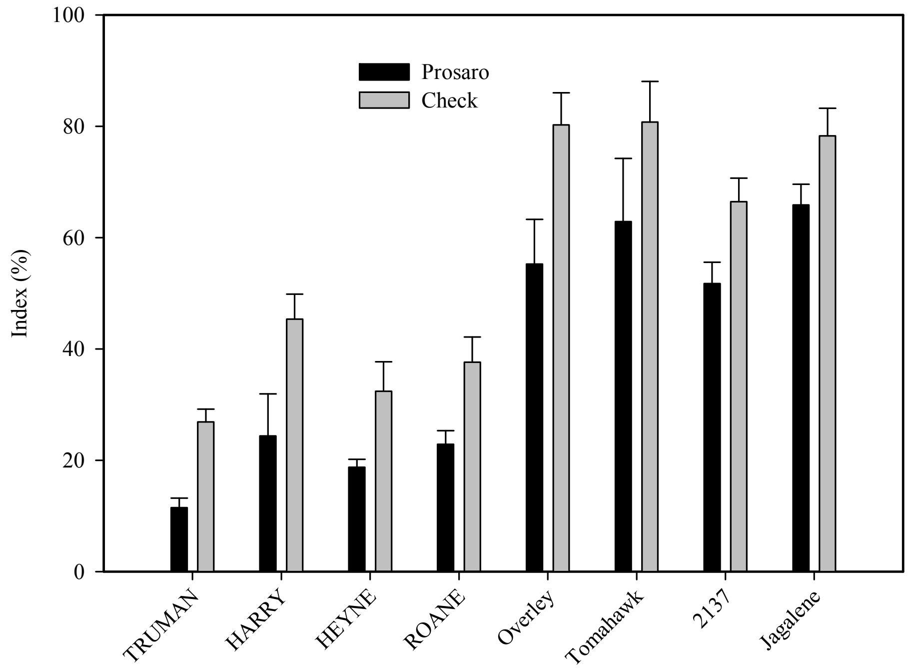


**Figure 3.** Fusarium head blight (FHB) index (percentage of blighted spikelets) in four moderately resistant (based on FHB phenotype) winter wheat cultivars (Truman, Harry, Heyne, and Roane) and four susceptible cultivars (Overley, Tomahawk, 2137, and Jagalene) treated with the fungicide Prosaro at full heading or not treated (check). Each mean was calculated from eight replications (four replications from each of two years). Error bars represent the standard error of the mean.

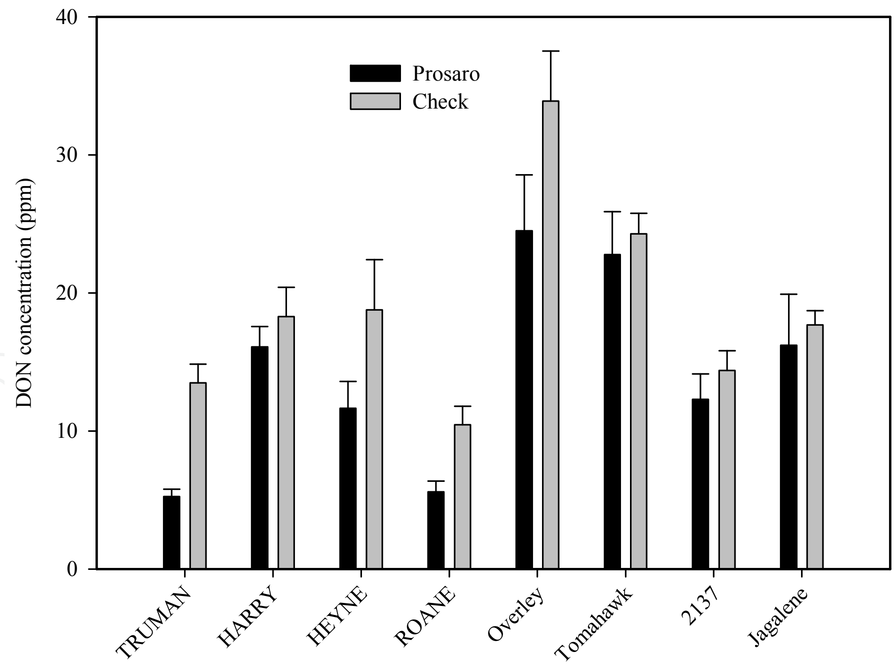


**Figure 4.** DON concentration in four moderately resistant (based on FHB phenotype) winter wheat cultivars (Truman, Harry, Heyne, and Roane) and four susceptible cultivars (Overley, Tomahawk, 2137, and Jagalene) treated with the fungicide Prosaro at full heading or not treated (check). Each mean was calculated from eight replications (four replications from each of two years). Error bars represent the standard error of the mean.

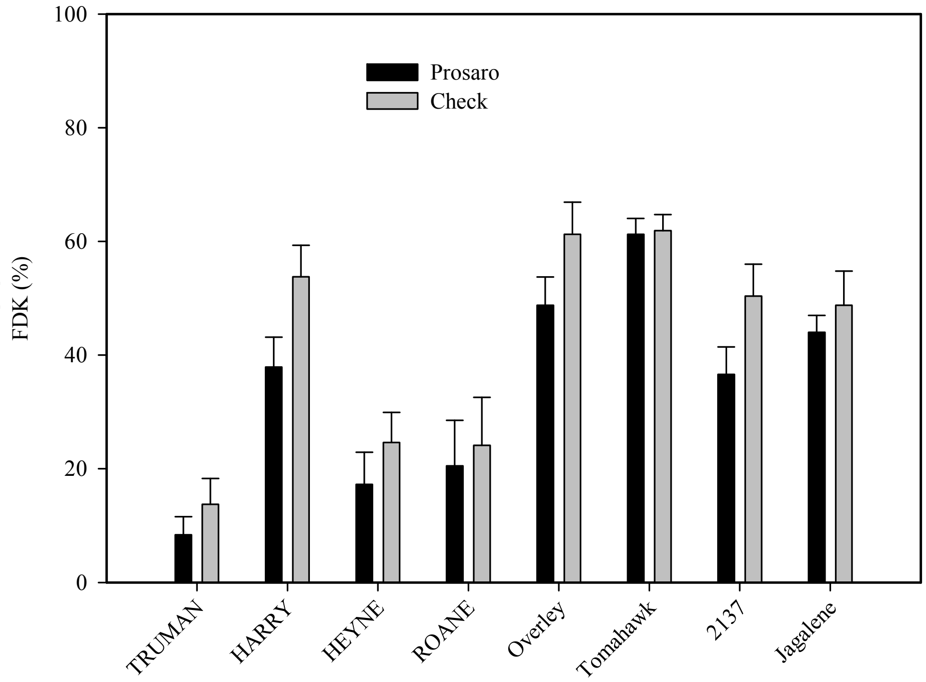


**Figure 5.** *Fusarium*-damaged kernels (FDK) in four moderately resistant (based on FHB phenotype) winter wheat cultivars (Truman, Harry, Heyne, and Roane) and four susceptible cultivars (Overley, Tomahawk, 2137, and Jagalene) treated with the fungicide Prosaro at full heading or not treated (check). Each mean was calculated from eight replications (four replications from each of two years). Error bars represent the standard error of the mean.

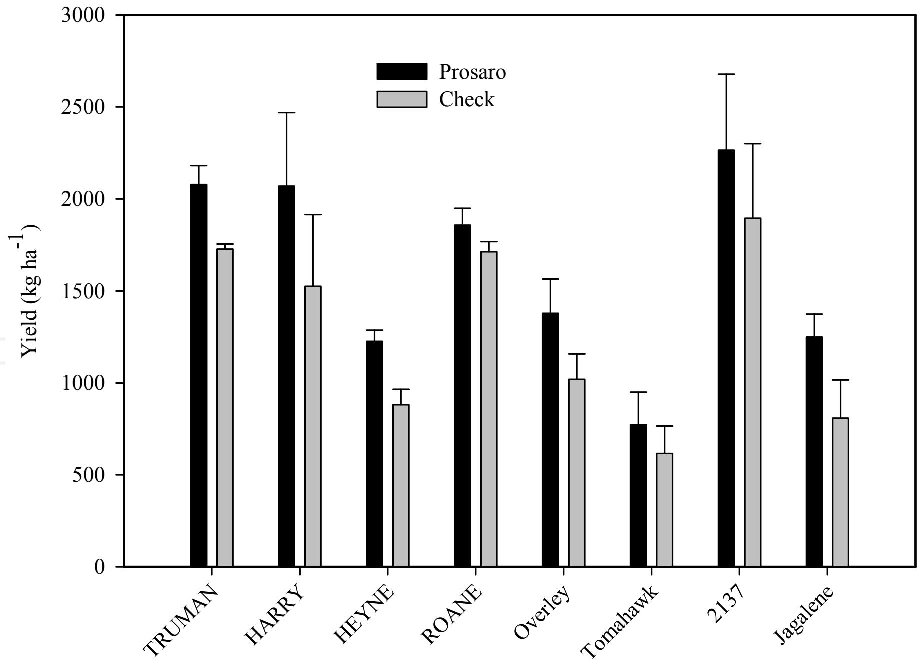


**Figure 6.** Yield in four moderately resistant (based on FHB phenotype) winter wheat cultivars (Truman, Harry, Heyne, and Roane) and four susceptible cultivars (Overley, Tomahawk, 2137, and Jagalene) treated with the fungicide Prosaro at full heading or not treated (check). Each mean was calculated from eight replications (four replications from each of two years). Error bars represent the standard error of the mean.

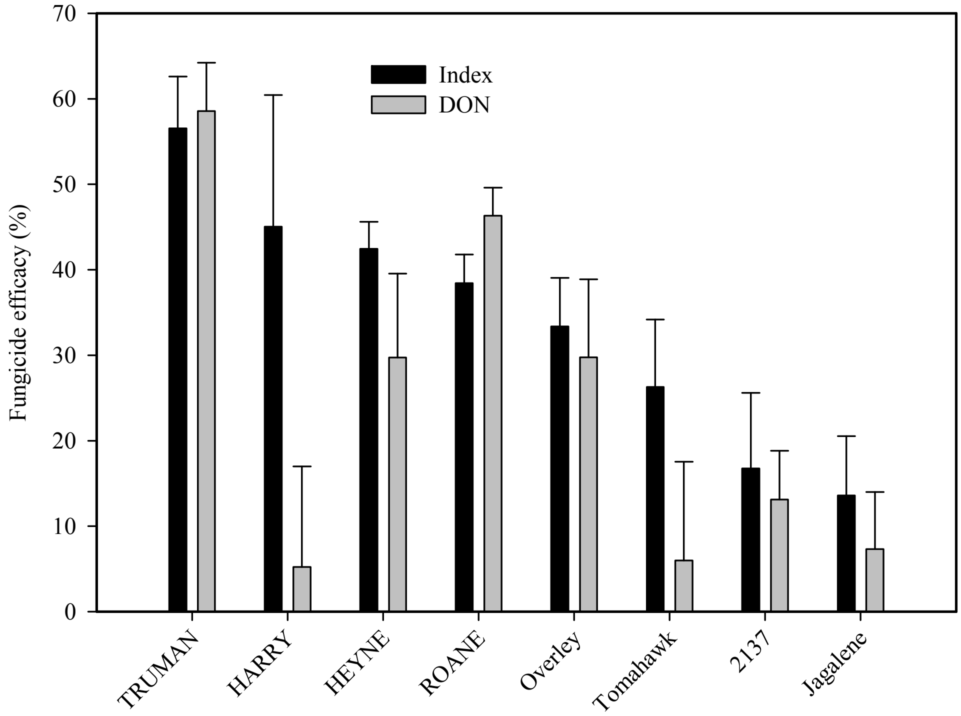


**Figure 7.** Fungicide efficacy for index and DON in four moderately resistant (based on FHB phenotype) winter wheat cultivars (Truman, Harry, Heyne, and Roane) and four susceptible cultivars (Overley, Tomahawk, 2137, and Jagalene) treated with the fungicide Prosaro at full heading. Error bars represent the standard error of the mean.

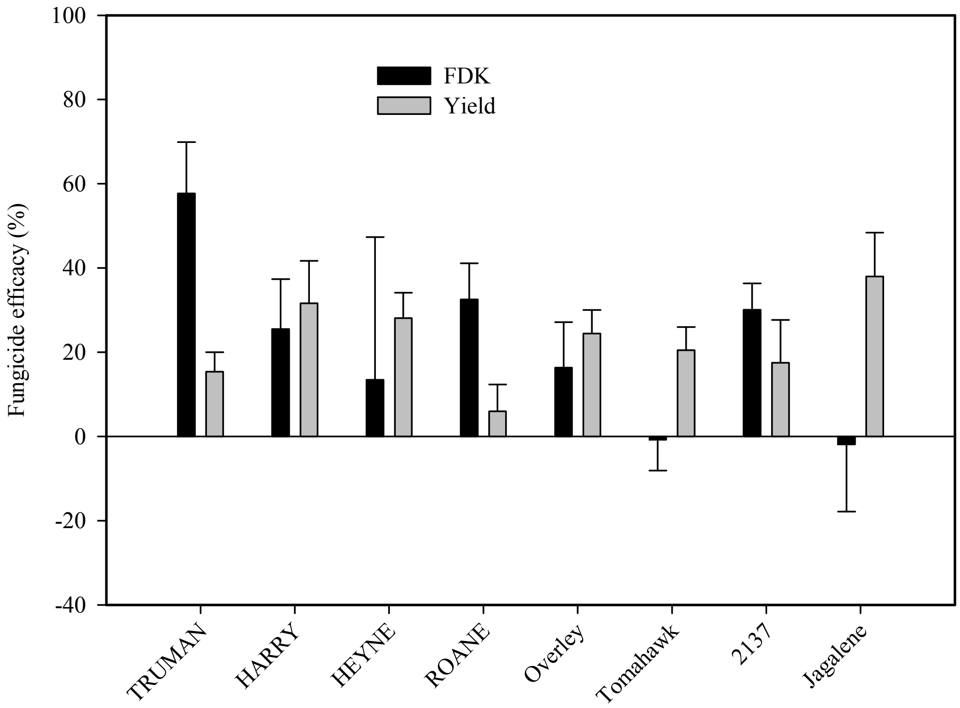


**Figure 8.** Fungicide efficacy for FDK and yield in four moderately resistant (based on FHB phenotype) winter wheat cultivars (Truman, Harry, Heyne, and Roane) and four susceptible cultivars (Overley, Tomahawk, 2137, and Jagalene) treated with the fungicide Prosaro at full heading. Error bars represent the standard error of the mean.

In contrast to index and DON, fungicide efficacy for FDK and yield was similar between moderately resistant and susceptible cultivars (Fig. 8) except for Truman in which fungicide efficacy for FDK was higher than that in the rest of the cultivars and Tomahawk and Jagalene in which fungicide efficacy for FDK was lower than that in all other cultivars. The similarity between moderately resistant and susceptible cultivars in fungicide efficacy for FDK and yield may be due in part to the fact that in contrast to index and DON which are more directly affected by fungicide treatment, FDK and yield are indirectly affected. In addition, the loss of significant quantities of FDK during machine harvesting can lead to inaccurate measurements of FDK and yield.

## 8. Conclusions

FHB continues to be an economically devastating disease of wheat in the U.S. and other parts of the world. Management strategies include the use of fungicide application timed at anthesis, planting resistant/tolerant cultivars, crop rotation, and residue management. Forecasting systems can facilitate the judicial and economical use of fungicides to control FHB and DON. Recent progress in the development of new chemistries of fungicides and improvements in fungicide application technology have improved the prospects for chemical control of FHB. Development of new cultivars with resistance using traditional and molecular breeding techniques has led to commercial availability of cultivars with moderate resistance and desirable agronomic characteristics. The best approach to managing FHB is to integrate available management strategies. Research has shown that integrating cultivar resistance with fungicide application can be an effective management strategy for FHB.

## Author details

Stephen N. Wegulo and John F. Hernandez Nopsa
*Department of Plant Pathology, University of Nebraska-Lincoln, USA*

William W. Bockus
*Department of Plant Pathology, Kansas State University, USA*

Kamaranga H.S. Peiris
*Department of Biological and Agricultural Engineering, Kansas State University, USA*

Floyd E. Dowell
*USDA ARS Center for Grain and Animal Health Research, Engineering and Wind Erosion Unit, Manhattan, USA*

## 9. References

Anderson, J. A. (2007). Marker-assisted selection for Fusarium head blight resistance in wheat, *International Journal of Food Microbiology*, Vol. 119, pp. 51-53, ISSN 0168-1605

Anderson, J. A., Stack, R. W., Liu, S., Waldron, B. L., Fjeld, A. D., Coyne, C., Moreno-Sevilla, B., Mitchel Fetch, J., Song, Q. J., Cregan, P. B. & Frohberg, R. C. (2001). DNA markers for Fusarium head blight resistance QTLs in two wheat populations, *Theoretical and Applied Genetics*, Vol. 102, pp 1164-1168, ISSN 0040-5752

Atanasof, D. (1920). Fusarium-blight (scab) of wheat and other cereals, *Journal of Agricultural Research*, Vol. 20, pp. 1-32, ISSN 2228-7973

Blandino, M., Minelli, L. & Reyneri, A. (2006). Strategies for the chemical control of Fusarium head blight: effect on yield, alveographic parameters and deoxynivalenol contamination in winter wheat grain. *European Journal of Agronomy*, Vol. 25, pp. 193-201, ISSN 1161-0301

Boosalis, M. G., Doupnik, B. L., Wyson, D. & Watkins, J. (1983). The wheat scab epidemic of 1982, *University of Nebraska Farm, Ranch, and Home Quarterly*, Vol. 29, pp. 7-9

Clear, R & Patrick, S. (2010). Fusarium head blight in western Canada, *Canadian Grain Commission*, Online, http://www.grainscanada.gc.ca/str-rst/fusarium/fhbwc-foc-eng.htm

De Wolf, E. D., Madden, L. V. & Lipps, P. E. (2003). Risk assessment models for wheat Fusarium head blight epidemics based on within-season weather data, *Phytopathology*, Vol. 93, No. 4., pp. 428-435, ISSN 0031-949X

Dickinson, J. G. & Mains, E. B. (1929). Scab of wheat and barley and its control, *U.S. Department of Agriculture Farmers Bulletin*, No. 1599, pp. 1-17

Dickinson, J. G. & Mains, E. B. (1942). Scab of wheat and barley and its control, *U.S. Department of Agriculture Farmers Bulletin*, No. 1599 (revised), pp. 1-22

Dill-Macky, R. (2010). Fusarium head blight (scab), *Compendium of Wheat Diseases and Pests*, APS Press, pp. 34-36, ISBN 978-0-89054-385-6 , St. Paul, Minnesota, USA

Dill-Macky, R. & Jones, R. K. (2000). The effect of previous crop residues and tillage on Fusarium head blight of wheat, *Plant Disease*, Vol. 84, No. 1, pp. 71-76, ISSN 0191-2917

Dowell, F. E., Maghirang, E. B., Graybosch, R. A., Baenziger, P. S., Baltensperger, D. D. & Hansen, L. E. (2006). An automated near-infrared system for selecting individual kernels based on specific quality characteristics. Cereal Chemistry, Vol. 83, pp.537-543, ISSN 0009-0352

Hollingsworth, C. R., Mottenberg, C. D. & Thompson, W. G. (2006). Assessing fungicide efficacies for the management of Fusarium head blight on spring wheat and barley, Online, *Plant Health Progress*, doi 10.1094/PHP-2006-0906-01-RS

Hollingsworth, C. R., Mottenberg, C. D., Wiersma, J. V. & Atkinson, L. M. (2008). Agronomic and economic responses of spring wheat to management of Fusarium head blight, *Plant Disease*, Vol. 92, No. 9, pp. 1339-1348, ISSN 0191-2917

Gale, L. R. (2003). Population biology of Fusarium species causing head blight of grain crops, *Fusarium Head Blight of Wheat and Barley*, APS Press, pp. 120-143, ISBN 0-89054-302-X, St. Paul, Minnesota, USA

Gilbert, J. & Tekauz, A. (2000). Review: recent developments in research on Fusarium blight of wheat in Canada, *Canadian Journal of Plant Pathology*, Vol. 22, No. 1, pp. 1-8, ISSN 0706-0661

Hernandez Nopsa, J., Baenziger, P. S., Eskridge, K. M., Peiris, K. H. S., Dowell, F. E., Harris, S. D. & Wegulo, S. N. (2012). Differential accumulation of deoxynivalenol in two winter wheat cultivars varying in FHB phenotype response under field conditions. *Canadian Journal of Plant Pathology,* Vol. 34, pp. 380-389, ISSN 0706-0661

Jones, R. K. (2000). Assessments of Fusarium head blight of wheat and barley in response to fungicide treatment, *Plant Disease,* Vol. 84, No. 9, pp. 1021-1030, ISSN 0191-2917

Johnson, D. D., Flaskerud, G. K., Taylor, R. D. & Satyanarayana, V. 2003. Quantifying economic impacts of Fusarium head blight in wheat, *Fusarium Head Blight of Wheat and Barley,* APS Press, pp. 461-483, ISBN 0-89054-302-X, St. Paul, Minnesota, USA

Khonga, E. B. & Sutton, J. C. (1988). Inoculum production and survival of *Gibberella zea*e in maize and wheat residues, *Canadian Journal of Plant Pathology,* Vol. 10, pp. 232-239, ISSN 0706-0661

Koch, H.-J., Pringas, C. & Maerlaender, B. (2006). Evaluation of environmental and management effects on Fusarium head blight infection and deoxynivalenol concentration in the grain of winter wheat, *European Journal of Agronomy,* Vol. 24, pp. 357-366, ISSN 1161-0301

Liddell, C. M. (2003). Systematics of Fusarium species and allies associated with Fusarium head blight, *Fusarium Head Blight of Wheat and Barley,* APS Press, pp. 35-43, ISBN 0-89054-302-X, St. Paul, Minnesota, USA.

Mains, E. B., Vestal, C. M. & Curits, P. B. (1929). Scab of small grains and feeding trouble in Indiana in 1928, *Proceedings of the Indiana Academy of Science,* Vol. 39, pp. 101-110

Martinez, M., Moschini, R., Barreto, D. & Comerio, R. (2012). Effect of environment on Fusarium head blight intensity and deoxynivalenol content in wheat grains: development of a forecasting system, *Cereal Research Communications,* Vol. 40, No. 1, pp. 74-84, ISSN 0133-3720

McCormick, S. (2003). The role of DON in pathogenicity, *Fusarium Head Blight of Wheat and Barley,* APS Press, pp. 165-183, ISBN 0-89054-302-X, St. Paul, Minnesota, USA

McMullen, M., Halley, S., Schatz, B., Meyer, S., Jordahl, J. & Ransom, J. (2008). Integrated strategies for Fusarium head blight management in the United States, *Cereal Research Communications,* Vol. 36, pp. 563-568, ISSN 0133-3720

McMullen, M., Jones, R. & Gallenberg, D. (1997). Scab of wheat and barley: a re-emerging disease of devastating impact, *Plant Disease,* Vol. 81, No. 12, pp. 1340-1348, ISSN 0191-2917

Mesterházy, Á. (1995). Types and components of resistance to Fusarium head blight of wheat, Plant Breeding, Vol. 114, pp. 377-386, ISSN 1439-0523

Mesterházy, Á. (2003a). Breeding wheat for Fusarium head blight resistance in Europe, *Fusarium Head Blight of Wheat and Barley,* APS Press, pp. 211-240, ISBN 0-89054-302-X, St. Paul, Minnesota, USA.

Mesterházy, Á. (2003b). Control of Fusarium head blight of wheat by fungicides, *Fusarium Head Blight of Wheat and Barley,* APS Press, pp. 363-380, ISBN 0-89054-302-X, St. Paul, Minnesota, USA.

Mesterházy, Á., Bartok, T. & Lamper, C. (2003c). Influence of wheat cultivar, species of Fusarium, and isolate aggressiveness on the efficacy of fungicides for control of Fusarium head blight. *Plant Disease* 87:1107-1115.

Milus, E. A. & Parsons, C. E. (1994). Evaluation of foliar fungicides for controlling Fusarium head blight of wheat, *Plant Disease,* Vol. 78, No. 7, pp. 697-699, ISSN 0191-2917

Musa, T., Hecker, A., Vogelgsang, S. & Forrer, H. R. (2007). Forecasting of Fusarium head blight and deoxynivalenol content in winter wheat with FusaProg, *Bullen OEPP/EPPO Bullettin,* Vol. 37, No. 2, pp. 283-289

Parry, D. W., Jenkinson, P. & McLeod, L. (1995). *Fusarium* ear blight (scab) in small grain cereals - a review. Plant Pathology Vol. 44, pp. 207-238

Paul, P. A., Lipps, P. E. & Madden, L. V. (2005). Relationship between visual estimates of Fusarium head blight intensity and deoxynivalenol accumulation in harvested wheat grain: A meta-analysis, *Phytopathology,* Vol. 95, No. 10, pp. 1225-1236, ISSN 0031-949X

Paul, P. A., Lipps, P. E., Hershman, D. E., McMullen, M. P., Draper, M. A. & Madden, L. V. (2007). A qunantitative review of tebuconazole effect on Fusarium head blight and deoxynivalenol content in wheat, *Phytopathology,* Vol. 97, No. 2, pp. 211-220, ISSN 0031-949X

Paul, P. A., Lipps, P. E., Hershman, D. E., McMullen, M. P., Draper, M. A. & Madden, L. V. (2008). Efficacy of triazole-based fungicides for Fusarium head blight and deoxynivalenol control in wheat: A multivariate meta-analysis, *Phytopathology,* Vol. 98, No. 9, pp. 999-1011, ISSN 0031-949X

Ransom, J. K. & McMullen, M. P. (2008). Yield and disease control on hard winter wheat cultivars with foliar fungicides, *Agronomy Journal,* Vol. 100, No. 4, pp. 1130-1137, ISSN 0002-1962

Ruckenbauer, P., Buerstmayr, H. & Lemmens, M. (2001). Present strategies in resistance breeding against scab (Fusarium spp., *Euphytica,* Vol. 119, pp. 121-127, ISSN 0014-2336

Schroeder, H. W. & Christensen, J. J. 1963. Factors affecting resistance of wheat to scab by *Gibberella zeae*, *Phytopathology,* Vol. 53, pp. 831-838, ISSN 0031-949X

Stack, R. W. 2003. History of Fusarium head blight with emphasis on North America, *Fusarium Head Blight of Wheat and Barley,* APS Press, pp. 1-34, ISBN 0-89054-302-X, St. Paul, Minnesota, USA.

Sutton, J. C. (1982). Epidemiology of wheat head blight and maize ear rot caused by *Fusarium graminearum, Canadian Journal of Plant Pathology* Vol. 4, pp. 195-209, ISSN 0706-0661

Tacke, B. K. & Casper, H. H. (1996). Determination of deoxynivalenol in wheat, barley, and malt by column cleanup and gas chromatography with electron capture detection, *Journal of the Association of Analytical Chemiststs,* Vol. 79, pp. 472-475, ISSN 1060-327

Wang, Y. Z. & Miller, J. D. (1988). Screening techniques and sources of resistance to Fusarium head blight, *Wheat Production Constraints in Tropical Environments,* CIMMYT, Lisboa, Mexico, ISBN 9686127224

Wegulo, S. N., Bockus, W. W., Hernandez Nopsa, J., De Wolf, E. D., Eskridge, K. M., Peiris, K. H. S. & Dowell, F. E. (2011). Effects of integrating cultivar resistance and fungicide application on Fusarium head blight and deoxynivalenol in winter wheat, *Plant Disease,* Vol. 95, No. 5, pp. 554-560, ISSN 0191-2917

Willyerd, K. T., Li, C., Madden, L. V., Bradley, C. A., Bergstrom, G. C., Sweets, L. E., McMullen, M., Ransom, J. K., Grybauskas, A., Osborne, L., Wegulo, S. N., Hershman, D.

E., Wise, K., Bockus, W. W., Groth, D., Dill-Mackey, R., Milus, E., Esker, P. D., Waxman, K. D., Adee, E. A., Ebelhar, S. E., Young, B. D. & Paul, P. A. (2012). Efficacy and stability of integrating fungicide and cultivar resistance to manage Fusarium head blight and deoxynivalenol in wheat, *Plant Disease,* in press

Zhang, Y. J., Fan, P. S., Zhang, X., Chen, C. J. & Zhou, M. G. (2009). Quantification of *Fusarium graminearum* in harvested grain by real-time polymerase chain reaction to assess efficacies of fungicides on Fusarium head blight, deoxynivalenol concentration, and yield of winter wheat. Phytopathology, Vol. 99, No. 9, (September 2009), pp. 95-100, ISSN 0031-949X