Efficacy and Economics of Integrating In-Field and Harvesting Strategies to Manage Fusarium Head Blight of Wheat

Jorge David Salgado, Laurence V. Madden, and **Pierce A. Paul,** Department of Plant Pathology, The Ohio State University, Ohio Agricultural Research and Development Center, Wooster 44691

Abstract

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Fusarium head blight (FHB), a fungal disease of wheat caused by *Fusarium graminearum*, and its associated toxins, particularly deoxynivalenol (DON), are best managed by integrating multiple strategies. Experiments were established in 2011 and 2013 to evaluate the effects of integrating cultivar resistance, fungicide application, and grain harvesting strategy on FHB index (IND; field severity), DON, grain yield (YLD), and grain test weight (TW; weight per unit volume). Plots of two moderately resistant and two susceptible cultivars were either treated with 19% tebuconazole + 19% prothioconazole or left untreated, and then inoculated with *F. graminearum*. IND was rated as the mean percentage of diseased spikelets per spike. Separate subsets of the plots of each cultivar–treatment combination were harvested with one of two combine harvester configuration: C1 (the default, set at a fan speed of 1,375 rpm and a shutter opening of 70 mm) and C4 (modified, with the same fan speeds but a wider shutter opening of 90 mm). YLD and TW data were collected, and grain samples were rated for percent Fusarium-damaged kernels (FDK) and tested for DON. Results from linear mixed-model analyses showed that the cultivar–treatment interaction was significant for all FHB-related responses, with the magnitude of the difference in mean arcsine-square-root-transformed IND and FDK (arcIND and arcFDK) and log-transformed DON (logDON) between treated and untreated being higher for susceptible than moderately resistant cultivars. Plots harvested with the C4 combine configuration had significantly higher mean TW than those harvested with C1. Treated plots had significantly higher YLD and TW than untreated plots, regardless of cultivar and configuration. Relative to the reference management program (untreated, susceptible cultivar, harvested with C1), the greatest percent reduction in FDK and DON and increase in YLD was observed for programs that included moderate resistance and fungicide treatment. The greatest percent increase in TW relative to the reference was observed when C4 adjusted combine setting was integrated with resistance and fungicide. Overall, the most effective management programs all included fungicide treatment, two included moderate resistance, and two included C4 combine setting. Relative to the reference management program, these programs resulted in 30 to 51% reduction in total estimated price discount, \$127 to 312 ha^{-1} increase in gross cash income, and economic benefit of \$31 to 272 ha^{-1}, depending on the level of FHB IND (5 to 15%), grain price (\$118 to 276 metric ton^{-1}), and fungicide application cost (\$40 to 96 ha^{-1}).

The integration of host resistance, chemical control, crop rotation, and other cultural practices is the most effective approach for managing Fusarium head blight (FHB), a disease of small grain crops caused by *Fusarium graminearum* Schwabe, and its associated toxins, particularly deoxynivalenol (DON) (6,7,12,22,23, 47,50). This is largely because no individual approach provides adequate FHB and DON reduction under highly favorable weather conditions (wet and humid weather before and during anthesis and early grain fill). For instance, whereas resistance may be the most economical, practical, and environmentally friendly approach for managing FHB, no soft red winter cultivar is immune to FHB and DON and, as such, even the most resistant cultivars may become infected (26,45) and accumulate DON above critical levels. Similarly, because fungicides are less than 100% effective against this disease, treated fields may still become infected and contaminated with DON (8,9,13,15,32,33).

A quantitative synthesis of data from more than 100 uniform fungicide trials showed that, when applied at anthesis, the demethylation inhibitor fungicides 8.6% metconazole (Caramba 90 SL; BASF Corporation Agricultural Products), 41% prothioconazole (Proline 480 SC; Bayer CropScience), and 19% tebuconazole + 19% prothioconazole (Prosaro 421 SC; Bayer CropScience) were the most effective products against FHB and DON, providing 50, 48, and 52% control of FHB index (IND) and 45, 43, and 42% control of DON, respectively (33). These fungicides were also most effective at increasing grain yield (YLD) and test weight (TW) relative to untreated controls (35). Willyerd et al. (51) subsequently reported that, when Prosaro was combined with a moderately resistant (MR) cultivar, percent reduction of both FHB IND and DON, relative to the untreated, susceptible (S) check, exceeded 70%. The combination of fungicide and resistance had an additive effect in terms of percent control for both responses. Analyses based on a nonparametric rank-based variance homogeneity test (17,21,36) showed that there was a significant interaction between management combination and environment for IND, indicating that the rank order of fungicide–resistance combinations in terms of the level of FHB control depended on the environment (51).

In some years, particularly when conditions are wet and humid during anthesis and early grain-fill, even when the best preharvest integrated management practices are implemented, Fusarium-damaged kernels (FDK) and DON contamination of grain cannot be avoided and grain YLD and quality losses may still occur (3,26,53). For instance, if the baseline level of DON is 8 ppm (in a nontreated, S cultivar), a 70% control with fungicide + resistance will reduce the toxin level to 2.4 ppm. This may still lead to price discounts and economic losses, because grain with DON in excess of 2 ppm and FDK greater than 1% may be priced down at grain elevators. In addition, FHB also has a negative effect on TW (weight per unit grain volume), a quality trait used by grain buyers to grade and price wheat. Grain with

Corresponding author: P. A. Paul, E-mail: paul.661@osu.edu

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low TW is considered of a low grade and, as such, may receive additional price discounts (24).

Because of the fact that the combination of fungicide and resistance may still not be sufficient to prevent losses due to FHB and the fact that the DON threshold is so low, other mitigation approaches need to be tested in combination with these two approaches to better control this disease. Grain harvesting and postharvest strategies such as modifying combine harvester settings and the use of screening, cleaning, and aspiration techniques to removal shriveled, light-weight, and small-sized kernels have also been recommended as ways of further reducing losses due to FHB and DON (16,22,24,39,52). Based on results from experiments in which a range of combine harvester configurations were evaluated for their effects on the YLD and quality of grain harvested from FHB-affected plots, Salgado et al. (39) showed that increasing the combine harvester fan speed (from 1,375 to 1,475 rpm) and the volume of air flowing through the combine to blow out diseased kernels significantly reduced FDK and DON and increased TW compared with the standard or default configuration. A cost/benefit assessment showed that estimated price discounts were lower ($10 to 40 metric ton^{-1} [MT^{-1}] less, depending on disease levels, associated grain damage, DON content, and grain prices) for grain harvested with modified compared with the default configuration.

Based on the aforementioned studies, is seems reasonable to hypothesize that FHB management programs that rely on cultivar resistance and a timely fungicide application in combination with grain harvesting strategies will provide a greater reduction in FHB-related grain YLD and quality losses than that achieved with fungicide plus resistance alone. However, the true benefit of integrating these approaches is still largely unknown. Certain combinations of baseline FHB, DON, grain YLD, grain prices, fungicide application costs, and price discounts for reduced grain quality may render even the most effective management strategies (in terms of disease and toxin reduction) uneconomical. Ultimately, economic calculations are required to integrate the combined effects of management programs (including cost of control) on grain YLD and quality (such as TW and DON) in order to determine the most cost-effective control strategy. Research is now needed to formally evaluate these factors in order to help growers make more informed FHB management decisions. Therefore, the objectives of this study were to (i) evaluate the integrated effects of fungicide treatment, MR cultivar, and adjustment to the combine harvester on FHB intensity, grain quality (DON, FDK, and TW), and grain YLD in soft red winter wheat (SRWW) and (ii) conduct an economic analysis of different integrated FHB management programs based on the field results from this study.

Materials and Methods

Field plots establishment and experimental design. Field plots were planted on 28 September 2010 and 25 September 2012 at the Snyder Research Farm, Ohio Agricultural Research and Development Center, near Wooster, OH. Plots of SRWW 'Truman' (MR to FHB, moderate YLD potential, and late maturing), 'Malabar' (MR to FHB, moderate YLD potential, and midseason), 'Hopewell' (S to FHB, moderate-to-high YLD potential, and midseason), and 'Cooper' or 'Bravo' (both S to FHB, moderate-to-high YLD potential, and early maturing) were planted into a field previously cultivated with soybean or oat and managed according to standard agronomics practices for Ohio (2,30). Cooper was used in 2011 and Bravo in 2013, due to the unavailability of Cooper seed. Truman and Hopewell were used here as the standard MR and S cultivar, respectively. Each plot consisted of seven 6-m-length rows, spaced 19 cm apart, and planted at a seeding rate of 4 $\times 10^6$ seeds ha^{-1}.

The experimental design was a randomized complete block with a split-split plot arrangement of combine harvester configuration as whole-plot (two levels), cultivar as subplot (four levels), and fungicide treatment as sub-subplot (two levels). There were four replicate blocks in 2011 and three in 2013, giving a total of 64 experimental units (plots) in the first year and 48 in the second. Each subplot was divided into two sub-subplots, one treated with the fungicide Prosaro (19% tebuconazole + 19% prothioconazole; Bayer CropScience) at a rate of 475 ml ha^{-1} plus Induce (a nonionic surfactant at 0.125% [vol/vol]; Helena Chemical Co.) and the other left untreated. Treatment applications were made when approximately 50% of the main tillers were at anthesis (Feekes growth stage [GS] 10.5.1), using either a backpack sprayer (R&D Sprayers) or tractor-mounted CO_2-pressurized sprayers equipped with three pairs of Twinjet XR8001VS nozzles (TeeJet Technologies) spaced 50 cm apart, mounted at an angle (45°) forward and backward, and calibrated to deliver approximately 187 liters ha^{-1}. Application dates varied with cultivar maturity. Early-maturing cultivars were treated on 27 May 2011 and 21 May 2013, midseason cultivars on 29 May 2011 and 24 May 2013, and late-maturing cultivar on 30 May 2011 and 27 May 2013.

Approximately 36 h after fungicide treatment application, plots were spray inoculated with a 1:1 mixture of macroconidia and ascospores from 10 highly aggressive isolates of *F. graminearum*, previously isolated from diseased wheat spikes collected from naturally infected fields across the state of Ohio. Media preparation, spore production, and inoculations were performed as previously described (11,18,39). In 2013, in addition to spray inoculation, *F. graminearum*-colonized corn spawn (prepared using the same 10 isolates) was spread in the field at full flag leaf emergence (Feeke's GS 9) and plots were overhead irrigated for approximately 3 weeks, as described by Sneller et al. (41,42).

Disease ratings, grain harvest, and grain quality assessment. FHB intensity was evaluated at soft dough (Feekes GS 11.2) during the third and second week of June 2011 and 2013, respectively, by quantifying the level of disease on 50 to 100 spikes sampled at multiple, arbitrarily selected locations within each plot. This was then used to calculate FHB incidence (INC, defined as percent diseased spikes out of the total number of spikes evaluated) and IND (field or plot level disease severity, defined as mean proportion of diseased spikelets per spike) (31,46).

Plots were harvested with an ALMACO SPC20 (ALMACO) research plot combine harvester on 25 July 2011 and 16 July 2013, when grain moisture was approximately 13 to 15%. Prior to harvest, the combine was calibrated on FHB-free plots, and the configuration was regulated by adjusting the fan speed and shutter opening, as described by Salgado et al. (39). In each block, half of the plots of each fungicide–cultivar combination (the whole-plot factor level) were harvested with the default combine configuration (C1, with a fan speed of 1,375 rpm and a shutter opening of 70 mm) and the other half with a modified configuration (C4, with a fan speed of 1,375 rpm and a shutter opening of 90 mm to increase the volume of air flowing through the combine). Grain YLD (kg ha^{-1}), TW (kg m^{-3}), and moisture (%) were determined directly on the combine using an electronic grain gage (HarvestMaster HM1000 GrainGage; Juniper Systems, Inc.), coupled with a field computer (Allegro MX Field PC; Juniper Systems, Inc.).

A sample of grain from each plot was used to estimate percent FDK (the percentage of small, shriveled, whitish-pink kernels) with the aid of a diagrammatic rating scale (10). Samples were then ground to resemble wheat flour using a laboratory mill (Laboratory Mill 3033; Perten Instruments) and sent to a U.S. Wheat and Barley Scab Initiative-funded laboratory at the University of Minnesota for DON quantification using a gas chromatography–mass spectrometry (GC/MS) method (39).

Data analysis. *Analysis of variance.* Linear mixed-model (LMM) analyses (19) were conducted using the GLIMMIX procedure of SAS (SAS Inc.) to determine the main and interaction effects of treatment factors on each of the measured responses. Each experiment (each year) was first analyzed separately and then, based on results from the initial analyses, which showed that trends and relationships were fairly consistent across years, the data were pooled and analyzed together. Prior to the analyses, all response variables quantified on a percentage scale (IND, INC, and FDK) were arcsine square root transformed (arcIND, arcINC, and arcFDK), and DON was log-transformed (logDON = log[DON +

1]) to stabilize variances. Separate analyzes were performed for each dependent variable. For responses quantified before harvest (arcIND and arcINC), the model fitted to the data could be written as:

$$y_{ijlm} = \theta + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \varphi_m + b(\varphi)_{lm} + \alpha(b\varphi)_{ilm} + e_{ijlm} \quad (1)$$

where y_{ijlm} is the response (dependent variable; arcIND, arcINC) for the *ith* cultivar (CV) and *j*th fungicide treatment (TRT) within in the *lth* block (BLK) and *mth* year (YEAR), θ is the constant (intercept), α_i is the effect of the *i*th CV, β_j is the effect of the *j*th TRT, $(\alpha\beta)_{ij}$ is effect of the *i*th CV × *j*th TRT interaction, φ_m is the effect of the *m*th YEAR, $b(\varphi)_{lm}$ is the effect of the *l*th BLK within the *m*th YEAR (the subplot error term), $\alpha(b\varphi)_{ilm}$ is the effect of the *ith* CV within the *l*th BLK within the *m*th YEAR, and e_{ijlm} is the residual (the sub-subplot error).

For responses quantified after harvest (arcFDK, logDON, YLD, and TW), equation 1 was expanded to include terms to account for the main and interaction effects of combine configuration:

$$y_{ijklm} = \theta + \alpha_i + \beta_j + \tau_k + (\alpha\beta)_{ij} + (\alpha\tau)_{ik} + (\beta\tau)_{jk} + (\alpha\beta\tau)_{ijk} + \varphi_m + b(\varphi)_{lm} + \tau(b\varphi)_{klm} + \alpha(\tau b\varphi)_{iklm} + e_{ijklm} \quad (2)$$

where, α_i, β_j and $(\alpha\beta)_{ij}$ are the effect of CV, TRT, and their interaction as describe above; τ_k is the effect of the *k*th combine configuration (CONFIG), $(\alpha\tau)_{ik}$ is the effect of the *i*th CV × *k*th CONFIG interaction, $(\beta\tau)_{jk}$ is the effect of the *j*th TRT × *k*th CONFIG interaction, $(\alpha\beta\tau)_{ijk}$ is the effect of the *i*th CV × *j*th TRT × *k*th CONFIG interaction, φ_m and $b(\varphi)_{lm}$ are as described above, $\tau(b\varphi)_{klm}$ is the effect of the *k*th CONFIG within the *l*th BLK within the *m*th YEAR (whole-plot error), $\alpha(\tau b\varphi)_{iklm}$ is the effect of *i*th CV within the *kth* CONFIG within the *l*th BLK within the *m*th YEAR (subplot error), and e_{ijklm} is the residual. CV, TRT, and CONFIG were treated as fixed effects and BLK, YEAR, and interactions involving the latter two variables were treated as random effects. Fixed effects were evaluated with *F* tests and random effects with standard normal test statistics. For all significant fixed effects and interactions of fixed effects, *contrast* and *lsmestimate* statements in GLIMMIX were used to compare main- and simple-effect means.

Management program effects on IND/FDK, IND/DON, IND/TW, and IND/YLD relationships. Each unique combination of CV resistance reaction (S or MR), TRT (treated or untreated), and CONFIG (default or modified) was considered a separate management program to reflect options that producers may use to manage FHB and DON. There were eight management programs: M1 = MR cultivar, treated with Prosaro, and harvested with the modified CONFIG (MR_TR_C4); M2 = MR cultivar, not treated with Prosaro, and harvested with the modified CONFIG (MR_UT_C4); M3 = S cultivar, treated with Prosaro, and harvested with the modified CONFIG (S_TR_C4); M4 = S cultivar, not treated with Prosaro, and harvested with the modified CONFIG (S_UT_C4); M5 = MR cultivar, treated with Prosaro, and harvested with the default CONFIG (MR_TR_C1); M6 = MR cultivar, not treated with Prosaro, and harvested with the default CONFIG (MR_UT_C1); M7 = S cultivar, treated with Prosaro, and harvested with the default CONFIG (S_TR_C1); and M8 = S cultivar, not treated with Prosaro, and harvested with the default CONFIG (S_UT_C1). M8 was used as the reference against which all other programs were compared.

Relationships between arcFDK and IND, logDON and IND, TW and IND, and grain YLD and IND, as influenced by management program, were modeled by treating IND as a continuous covariate and management program as a class variable in LMM regression analyses using PROC GLIMMIX. Equation 2 above was modified by replacing terms for CV, TRT, CONFIG, and their interactions with a single term for management program (PROG) and adding terms to account for the effect of IND and its interaction with PROG. The subscript $\acute{\imath}$ is used for $i{\times}j{\times}k$ and $\acute{m}$ for $l{\times}m$. All random effect terms were maintained as in equation 2 (with the appropriate subscript changes). The generic model fitted to the data, with the random effect terms suppressed for simplicity, was:

$$y_{\acute{\imath}\acute{m}n} = \theta + \rho_{\acute{\imath}} + \delta X_n + \Delta_{\acute{\imath}} X_n + \cdots + e_{\acute{\imath}\acute{m}n} \quad (3)$$

where $y_{\acute{\imath}\acute{m}n}$ is the response (logDON, arcFDK, YLD, or TW), θ is the intercept, $\rho_{\acute{\imath}}$ is the effect of *í*th PROG, X_n is the *n*th observation of the covariable disease IND, δ is the effect of the covariable, $\Delta_{\acute{\imath}}$ is the interaction effect of the covariable and PROG (the effect of PROG on the relationship between y and X), and $e_{\acute{\imath}\acute{m}n}$ is the residual. Here, the *n* subscript refers to each unique covariable observation within a block and year (e.g., for each PROG, this represents the two cultivars in each FHB resistance class).

Efficacy and economic benefit of FHB management programs. Grain YLD and quality (TW, FDK, and DON) responses for each FHB management program (PROG) were estimated using equation 3. Predicted arcFDK, logDON, TW, and YLD were determined for a range of IND values, and then predicted arcFDK and logDON were back-transformed to obtain FDK (%) and DON (ppm), respectively. Using M8 as the reference program (without any management intervention) percent FDK and DON reduction (C_M) and percent TW and grain YLD increase (I_M) were estimated using equations 4a and 4b as measures of the efficiency of the other seven programs for which at least one management strategy was used. *C* and *I* were estimated as:

$$C_m = \frac{\bar{y}^*_{M8} - \bar{y}^*_{M}}{\bar{y}^*_{M8}} \cdot 100 \quad (4a)$$

$$I_M = \frac{\bar{y}^*_{M} - \bar{y}^*_{M8}}{\bar{y}^*_{M8}} \cdot 100 \quad (4b)$$

where $\bar{y}^*_{\bullet}$ = mean predicted response (FDK, DON, TW, or YLD) at a fixed level of IND for the reference treatment (M8: S_UT_C1) and each management program (M). The values of $\bar{y}^*_{\bullet}$ were obtained, where appropriate, as back-transformation of the least squares means from the mixed models.

Based on predicted responses at each of three IND levels (see equation 3), price discounts for each grain quality trait (*twl*, *fdkl*, and *donl*) were estimated and used along a range of estimated grain prices and fungicide application costs to estimate the economic benefit of a given management approach as:

$$EB_M = NCI_M - NCI_{No} \quad (5)$$

where EB_M = economic benefit of using management program *M* ($\$ha^{-1}$); NCI_M = net cash income to the producer if FHB management strategy *M* is used ($\$ha^{-1}$), and NCI_{No} = net cash income to the producer if no management strategy is applied (i.e., M8). Assuming that the only source of cash income ($\$ha^{-1}$) is from the sale of wheat grain, if no FHB management is implemented, NCI_{No} depends on overall production costs not directly related to FHB ($Cost_p$, \$ ha^{-1}), grain YLD (*Y*; MT ha^{-1}), standard price per MT paid by the grain elevator (*P*, \$ MT^{-1}), and total price discount (*dct*, \$ MT^{-1}) based on the levels of TW, FDK, and DON. Therefore, NCI_{No} can be estimated as:

$$NCI_{No} = Y \cdot (P - dct) - Cost_p \quad (6)$$

The price discount is given by:

$$dct = twl + fdkl + donl \quad (7)$$

where *twl*, *fdkl*, and *donl* represent individual estimated price discounts due to TW below and FDK and DON contamination above thresholds established by grain elevators. Baseline thresholds established by grain elevators for TW, FDK, and DON are typically 746.6 kg m^{-3}, 1%, and 2 ppm, respectively.

If an FHB management program is used, net cash income with management can be written as:

$$NCI_M = Y \cdot (P - dct) - Cost_p - Cost_M \quad (8)$$

where $Cost_M$ represents the costs associated with the use of a management program. In equations 6 and 8, $Y \cdot (P - dct)$ = gross cash income (*GCI*; income before production costs are subtracted). Assuming that the amount of fuel burnt during harvest does not vary between CONFIGs C1 and C4 (increasing the air flow through the combine by switching shutter opening from 70 to 90 mm does not burn extra fuel) and that there is no additional cost for planting an MR cultivar (which is currently true in SRWW production), then $Cost_M$ equals the cost of TRT (the price of the product plus the cost of application).

Assuming that standard production costs (land preparation, planting, fertilization, insect and weed control, and so on) are the same with and without FHB management, $Cost_P$ becomes irrelevant in the estimation of EB_M (equation 5) because it cancels out. If NCI_{No} is less than NCI_M, EB_M is greater than 0 and there will be a net benefit to using a management program. Thus, equation 5 (together with equations 6 through 8) provides a logical framework for quantifying the effects of different management programs on the joint YLD quantity and quality responses.

Results

Effect of cultivar resistance and fungicide application on FHB intensity. Averaged across treatments and replicates, mean INC, IND, FDK, and DON were 23 (2 to 47%), 5 (0.2 to 16%), and 4% (1 to 12%) and 0.9 ppm (0 to 4 ppm), respectively, in 2011, and 37 (16 to 78%), 6 (1 to 18%), and 14% (4 to 42%) and 5 ppm (1 to 14 ppm) in 2013. Overall, INC and IND were higher in plots planted with an S cultivar (Cooper, Bravo, or Hopewell) than in those planted with MR Malabar or Truman. For all cultivars, Prosaro-treated plots had lower mean levels of INC and IND than untreated plots (Fig. 1). In both years, treated plots of the late-maturing, MR cultivar (MR_Late) Truman had the lowest mean

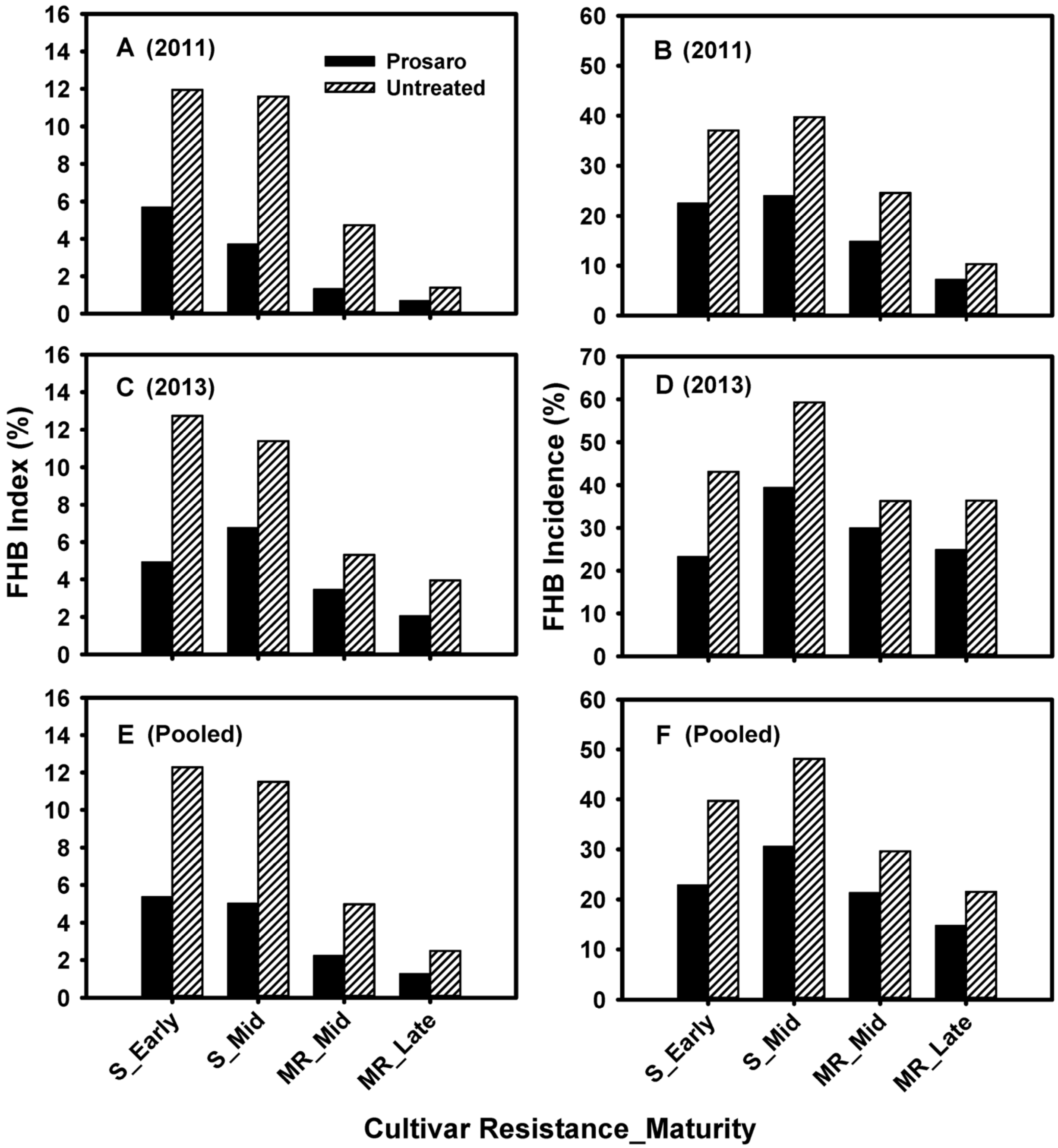

Fig. 1. A, C, and **E,** Mean Fusarium head blight (FHB) index (mean proportion of diseased spikelets per spike) and **B, D,** and **F,** incidence (mean proportion of diseased spikes) from wheat plots of four soft red winter wheat cultivars (S_Early = susceptible and early maturing, S_Mid = susceptible and midseason, MR_Mid = moderately resistant and midseason, and MR_Late = moderately resistant and late-maturing) treated with Prosaro (19% prothioconazole + 19% tebuconazole at 475 ml ha^{-1}) at early anthesis (Feekes growth stage 10.5.1) or left untreated and inoculated with a mixture of 10 highly aggressive isolates of *Fusarium graminearum* (*Gibberella zeae*) at a spore density of 4 × 10^4 spores/ml in 2011 (A and B) and 15 × 10^4 spores ml^{-1} in 2013 (C and D). Graphs E and F shows the pooled data. Each bar represents the mean of eight (A and B) and six (C and D) observations. Bars in graphs E and F represent the mean of 14 observations (pooled data from 2011 and 2013).

IND, whereas untreated plots of early-maturing S (S_Early) Cooper or Bravo had the highest. Averaged across years (Fig. 1E and F), plots of Truman and Malabar (the MR midseason [MR_Mid] cultivar) treated with Prosaro had mean INC of 14.7 and 21.3% and mean IND of 1.3 and 2.2%, respectively. The corresponding mean INC and IND for untreated plots of the midseason S cultivar (S_Mid) Hopewell and the S_Early cultivar were 48.1 and 39.7% and 11.5 and 12.3%, respectively.

Based on results from LMM analyses of pooled transformed INC and IND data, the main effects of CV and fungicide TRT and their interaction (CV × TRT) were statistically significant ($P < 0.05$; Table 1), suggesting that the effect of the TRT on INC and IND depended on the CV and vice versa. Differences in mean INC and IND between pairs of cultivars varied with TRT, with the magnitude of the differences being higher in untreated than in treated plots (Table 2). Differences between MR and S cultivars were higher than differences between cultivars of the same resistance class. For instance, in untreated plots, differences in mean INC and IND between the MR_Late and S_Mid cultivars were 26.6 and 9.0%, respectively, compared with differences between the MR_Late and MR_Mid cultivars (8.1 and 2.5%, respectively) and between the S_Early and S_Mid cultivars (8.5 and 0.8%, respectively). A similar trend was observed between cultivars in treated plots, with the magnitude of the difference in mean INC and IND being greater between MR and S cultivars than between cultivars of the same resistance class. In both treated and untreated plots, mean IND was not significantly different between the S cultivars; however, the MR_Late cultivar (Truman)

Table 1. Probability values (significance levels) from linear mixed-model analyses of the effect of cultivar (CV) and fungicide treatment (TRT) on arcsine-transformed Fusarium head blight incidence (arcINC) and index (arcIND) and the effect of CV, TRT, and combine harvester configuration (CONFIG) on arcsine-transformed Fusarium-damaged kernel (arcFDK) and log-transformed deoxynivalenol (DON) content of harvested grain (logDON), test weight (TW), and grain yield (YLD) for pooled data from experiments conducted in 2011 and 2013 in Wooster, OH

	Dependent variable[x]					
Factors[y]	**arcIND**	**arcINC**	**arcFDK**	**logDON**	**TW**	**YLD**
CV	<0.001	<0.001	<0.001	<0.001	<0.001	0.002
TRT	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
CV × TRT	0.001	0.024	0.015	0.028	0.486	0.442
CONFIG	…	…	0.960	0.424	0.014	0.174
CONFIG × CV	…	…	0.958	0.845	0.916	0.675
CONFIG × TRT	…	…	0.989	0.643	0.974	0.699
CONFIG × CV × TRT	…	…	0.320	0.407	0.781	0.917
YEAR[z]	0.517	0.490	0.481	0.480	0.480	0.727

[x] INC = mean percentage of diseased spikes in a sample, IND = mean percentage of diseased spikelets per spikes, FDK = percentage of visually diseased (small, shriveled, and discolored) kernels, DON = deoxynivalenol contamination (ppm), TW = grain weight per unit volume (kg m^{-3}), and YLD = grain yield (kg ha^{-1}).

[y] CV = soft red winter wheat cultivars (Cooper or Bravo = susceptible and early maturing, Hopewell = susceptible and midseason, Malabar = moderately resistant and midseason, and Truman = moderately resistant and late-maturing); TRT = fungicide treatment (19% prothioconazole + 19% tebuconazole [475 ml ha^{-1}] applied at anthesis and nontreated); CONFIG = combine harvester configuration (C1 = the standard configuration, with a fan speed of 1,375 rpm and a shutter opening of 70 mm; and C4 = modified configuration with a fan speed of 1,375 rpm and a shutter opening of 90 mm to increase the volume of air flowing through the combine).

[z] Probability values for the random effect of year were based on standard normal (*Z*) tests.

Table 2. Estimated differences (Diff) in mean Fusarium head blight (FHB) incidence and index, Fusarium-damaged kernel (FDK), and deoxynivalenol (DON) content of harvested grain between pairs of cultivar resistance-maturity and fungicide treatment combinations for pooled data from field experiments conducted in 2011 and 2013 in Wooster, OH[y]

	FHB incidence		FHB index		FDK		DON (ppm)	
Contrast[z]	**Diff**	***P***	**Diff**	***P***	**Diff**	***P***	**Diff**	***P***
MR_Late UT vs. MR_Mid UT	–8.1	0.012	–2.5	<0.001	0.1	0.874	0.6	0.903
MR_Late UT vs. S_Early UT	–18.2	<0.001	–9.8	<0.001	–4.9	0.001	–0.3	0.005
MR_Late UT vs. S_Mid UT	–26.6	<0.001	–9.0	<0.001	–13.2	<0.001	–2.0	<0.001
MR_Mid UT vs. S_Early UT	–10.1	0.014	–7.3	<0.001	–5.0	0.001	–0.9	0.006
MR_Mid UT vs. S_Mid UT	–18.5	<0.001	–6.5	<0.001	–13.4	<0.001	–2.6	<0.001
S_Early UT vs. S_Mid UT	–8.5	0.047	0.8	0.440	–8.4	0.002	–1.7	0.041
MR_Late TR vs. MR_Mid TR	–6.6	0.025	–1.0	0.028	–1.1	0.488	0.2	0.872
MR_Late TR vs. S_Early TR	–8.1	0.006	–4.1	<0.001	–0.9	0.245	0.4	0.703
MR_Late TR vs. S_Mid TR	–15.8	<0.001	–3.8	<0.001	–10.2	<0.001	–1.8	<0.001
MR_Mid TR vs. S_Early TR	–1.5	0.557	–3.1	<0.001	0.2	0.635	0.3	0.588
MR_Mid TR vs. S_Mid TR	–9.3	0.012	–2.8	<0.001	–9.1	<0.001	–2.0	<0.001
S_Early TR vs. S_Mid TR	–7.8	0.048	0.3	0.655	–9.3	<0.001	–2.2	<0.001
MR_Late TR vs. MR_Late UT	–6.8	0.003	–1.2	0.018	–2.4	0.012	–0.8	0.008
MR_Mid TR vs. MR_Mid UT	–8.3	<0.001	–2.8	<0.001	–1.1	0.076	–0.4	0.002
S_Early TR vs. S_Early UT	–16.9	<0.001	–6.9	<0.001	–6.3	<0.001	–1.6	<0.001
S_Mid TR vs. S_Mid UT	–17.5	<0.001	–6.5	<0.001	–5.4	<0.001	–1.1	<0.001
MR_Late TR vs. S_Mid UT	–33.4	<0.001	–10.2	<0.001	–15.6	<0.001	–2.9	<0.001
MR_Mid TR vs. S_Mid UT	–26.8	<0.001	–9.3	<0.001	–14.4	<0.001	–3.1	<0.001
S_Early TR vs. S_Mid UT	–25.3	<0.001	–6.2	<0.001	–14.6	<0.001	–3.3	<0.001

[y] Percentage of diseased spikes in a samples (FHB incidence), mean percentage of diseased spikelets per spike (FHB index), percentage of diseased (small, shriveled, and discolored) kernels (FDK), and DON content of grain. Diff = difference between means on the raw data scale. Differences were estimated using least square means based on transformation of the original data; however, for presentation, differences of original means are shown. *P* = probability value (level of significance) for pairwise differences from linear mixed-model analyses of arcsine-transformed INC, IND, and FDK and log-transformed DON data.

[z] Cultivar resistance-maturity and fungicide treatment: S_Early (susceptible and early maturing), S_Mid (susceptible and midseason), MR_Mid (moderately resistant and midseason), and MR_Late (moderately resistant and late-maturing), treated (TR) with fungicide Prosaro (19% prothioconazole + 19% tebuconazole [475 ml ha^{-1}]) at anthesis and nontreated (UT).

consistently had significantly lower levels of disease than the MR_Mid cultivar (Malabar) (Table 2).

Differences in mean INC and IND between treated (TR) and untreated (UT) plots were higher for S cultivars than for MR cultivars (Table 2). Mean differences between TR and UT for MR cultivars were 1.2 to 2.8% for IND and 6.8 to 8.3% for INC, whereas the corresponding differences for S cultivars were 6.5 to 6.9% for IND and 16.9 to 17.5% for INC. Relative to S_Mid_UT, used here as the reference resistance × TRT management combination (UT plots of the standard S cultivar [Hopewell]), all other combinations of CV and TRT significantly reduced infection (as measured by INC) and disease spread within the spike (as measured by IND) (Table 2). The greatest reductions were observed when S_Mid_UT was compared with MR_Late_TR (33.4 and 10.2% for INC and IND, respectively) (Table 2).

Effect of CV, TRT, and CONFIG on grain quality and YLD. *FDK and DON*. Mean FDK and DON content varied between years and among CV × TRT × CONFIG combinations within each year (Fig. 2). Plots of MR cultivars treated with Prosaro had the lowest mean FDK and DON in 2011 (Fig. 2A and B), whereas UT plots of S cultivars had the highest means for both responses in that same year. In 2013, UT plots of the S_Mid cultivar had the highest

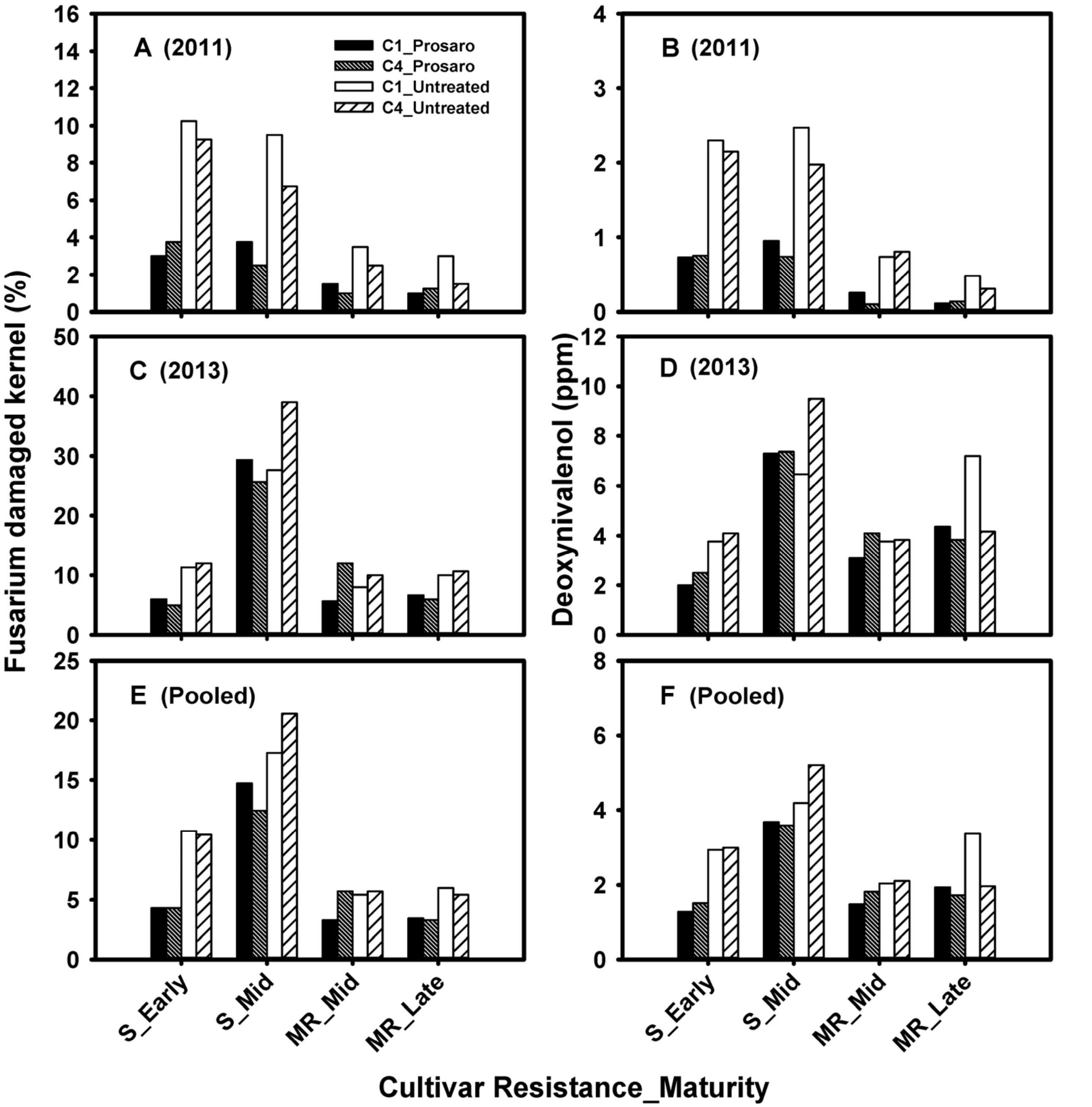

Fig. 2. A, C, and **E,** Mean *Fusarium*-damaged kernels (FDK) and **B, D,** and **F,** deoxynivalenol grain content from wheat plots of four soft red winter cultivars (S_Early (susceptible and early maturing), S_Mid (susceptible and midseason), MR_Mid (moderately resistant and midseason), and MR_Late (moderately resistant and late-maturing) treated with Prosaro (19% prothioconazole + 19% tebuconazole at 475 ml ha^{-1}) at early anthesis (Feekes growth stage 10.5.1) or left untreated, and grain harvested with two different combine harvester configurations (C1 and C4) in 2011 (A and B) and 2013 (C and D). FDK was recorded as the percentage of diseased kernels (shriveled, lightweight, and discolored). Graphs E and F represent data pooled across two years. C1 = the standard (default) combine setting with a fan speed of 1,375 rpm and a shutter opening of 70 mm; and C4 = the modified setting, with fan speed of 1,375 rpm and wide shutter opening of 90 mm (increased volume of air flowing through the combine). Each bar represents the mean of eight (A and B) and six (C and D) observations. Bars in graphs E and F represent the mean of 14 observations (pooled data from 2011 and 2013). For both responses, the scale on the y-axis was allowed to vary between the years to facilitate visualization of trends among the treatment factors within a given experiment.

mean FDK and DON. However, the S_Early cultivar had levels of mean FDK and DON comparable with the MR cultivars in both TR and UT plots (Fig. 2C and D).

For any given TRT × CV combination, mean FDK and DON tended to vary among CONFIGs, without a well-defined trend. For instance, in 2011, for UT plots of all cultivars, mean FDK and DON tended to be lower for those harvested with the modified configuration (C4) than with the default configuration (C1). However, for TR plots, a similar trend was observed for the two midseason cultivars (S_Mid and MR_Mid) but not for the MR_Late or S_Early cultivars (Fig. 2A and B). Trends were even more variable in 2013, with several instances of plots harvested with C4 having mean FDK and DON higher to or comparable with plots harvested with C1 (Fig. 2C and D). Averaged across years (Fig. 2E and F), TR plots of the S_Mid and MR_Late cultivars had lower mean FDK and DON for C4 than for C1. For the UT plots, the MR_Late cultivar had lower FDK and DON for C4 than for C1; however, an opposite trend was observed for the other cultivars (Fig. 2E and F).

LMM analyses of pooled transformed FDK (arcFDK) and DON (logDON) data (Table 1) showed that the main effects of CV and TRT and their interaction (CV × TRT) were statistically significant ($P < 0.01$) for both responses; however, the main effect of CONFIG and all interactions involving CONFIG were not significant ($P > 0.05$, Table 1). Differences in mean FDK and DON between pairs of cultivars varied with TRT (Table 2). For UT plots, differences between MR and S cultivars were statistically significant (on the transformed scale), with the greatest differences observed between the MR_Late and S_Mid cultivars and between MR_Mid and S_Mid (13.2 and 13.4% for FDK and 2.0 and 2.6 ppm for DON, respectively). When cultivars of the same resistance class were compared, differences between MR_Late and MR_Mid (0.14% for FDK and 0.6 ppm for DON) were not significant; how-

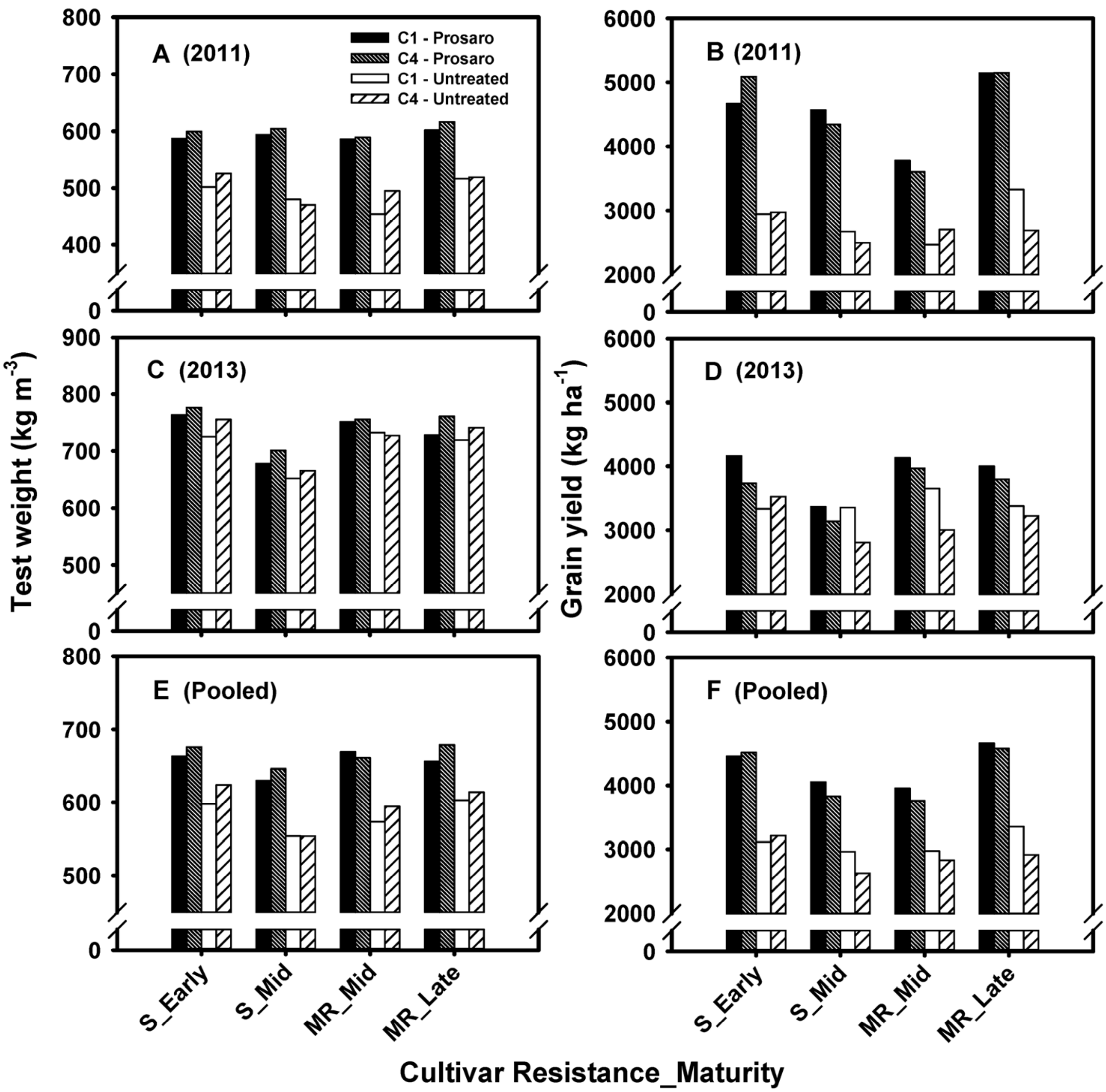

Fig. 3. A, C, and **E,** Mean test weight (kg m^{-3}) and **B, D,** and **F,** grain yield (kg ha^{-1}) from plots of four soft red winter wheat cultivars (S_Early = susceptible and early maturing, S_Mid = susceptible and midseason, MR_Mid = moderately resistant and midseason, and MR_Late = moderately resistant and late-maturing) treated with Prosaro (19% prothioconazole + 19% tebuconazole at 475 ml ha^{-1}) at early anthesis (Feekes growth stage 10.5.1) or left untreated, and grain harvested with two different combine harvester configurations (C1 and C4) in 2011 (A and B) and 2013 (C and D) Graphs E and F represent data pooled across two years. C1 = the standard (default) combine setting with a fan speed of 1,375 rpm and a shutter opening of 70 mm; and C4 = the modified setting, with fan speed of 1,375 rpm and a wider shutter opening of 90 mm (increased volume of air flow through the combine). Each bar represents the mean of eight (A and B) and six (C and D) observations. Bars in graphs E and F represent the mean of 14 observations (pooled data from 2011 and 2013).

ever, differences between S_Early and S_Mid (8.4% for FDK and 1.7 ppm for DON) were significant ($P < 0.05$, Table 2). For fungicide-TR plots, only comparisons between MR_Late and S_Mid, MR_Mid and S_Mid, and S_Early and S_Mid were statistically significant ($P < 0.001$), with differences of 10.2, 9.07, and 9.3%, respectively, for FDK and 1.8, 1.9, and 2.2 ppm, respectively, for DON (Table 2).

Differences in mean arcFDK and logDON between TR and UT plots were statistically significant for S_Early, S_Mid, and MR_Late and marginally significant for MR_Mid ($P = 0.08$). The magnitude of the difference between TR and UT was greater for the S_Early (6.3% and 1.6 ppm) and S_Mid (5.4% and 1.1 ppm) cultivars than for the MR_Mid (1.1% and 0.4 ppm) and MR_Late (2.4% and 0.8 ppm) cultivars. The greatest reductions in both FDK and DON were observed when TR plots of both MR cultivars and the S_Early cultivar were compared with S_Mid_UT, the reference management combination, with differences of 15.57, 14.43, and 14.6%, respectively, for FDK and 2.9, 3.1, and 3.3 ppm, respectively, for DON. The magnitude of the differences in FDK and DON between S_Mid_TR and S_Mid-UT was lower than for other comparisons (5.36% and 1.07 ppm for FDK and DON, respectively).

TW and YLD. Mean TW and grain YLD tended to vary between years and among CV × TRT × CONFIG combinations (Fig. 3). In 2011, averaged across treatment combinations and replicates, TW was 407 to 630 kg m^{-3} (mean 546 kg m^{-3}) and YLD was 2,214 to 5,869 kg ha^{-1} (mean 3,660 kg ha^{-1}) whereas, in 2013, TW was 607 to 791 kg m^{-3} (mean 727 kg m^{-3}) and YLD was 2,431 to 4,913 kg ha^{-1} (3,539 kg ha^{-1}). In both years, Prosaro-TR plots of all cultivars tended to have higher mean TW and YLD than UT plots, and mean TW was generally higher in plots harvested with the modified CONFIG (C4) than with the default (C1) (Fig. 3A, C, and E). However, mean YLD was generally higher for C1 than for C4 (Fig. 3B, D, and F) for several of the CV × TRT combinations. For the pooled data, the MR_Late_TR_C4 management combination had the highest mean TW (679 kg m^{-3}) and S_Mid_UT_C1 the lowest (554 kg m^{-3}) (Fig. 3E), whereas MR_Late_TR_C1 had the highest mean YLD (4,657 kg ha^{-1}) and S_Mid_UT_C4 the lowest (2,627 kg ha^{-1}) (Fig. 3F).

Table 3. Least square means from linear mixed analyses of the effect of cultivar, fungicide treatment, and combine harvester configuration on test weight and yield for grain harvested from Fusarium head blight affected plots for pooled data from field experiments conducted in 2011 and 2013 in Wooster, OH

	Response variable[y]	
Management[z]	**Test weight (kg m^{-3})**	**Grain yield (kg ha^{-1})**
Cultivar		
S_Early	652.96 a	3,821.59 a
MR_Late	650.85 ab	3,875.04 a
MR_Mid	634.15 b	3,383.77 b
S_Mid	608.78 c	3,368.43 b
Fungicide		
Treated	671.09 a	4,225.62 a
Untreated	602.28 b	2,998.79 b
Configuration		
Modified	643.83 a	3,532.16 a
Default	629.54 b	3,692.25 a

[y] For each management approach, values with different letters are significantly ($P < 0.05$) different from each other at the 5% level of significance.

[z] Cultivar resistance_maturity: S_Early = susceptible and early-maturing, S_Mid = susceptible and midseason, MR_Mid = moderately resistant and midseason, and MR_Late = moderately resistant and late-maturing; fungicide treatment: Treated = Prosaro (19% prothioconazole + 19% tebuconazole [475 ml ha^{-1}]) applied at anthesis and Untreated = nontreated check; and Configuration: plots were harvested using two combine harvester configurations (Default = the standard configuration, with a fan speed of 1,375 rpm and a shutter opening of 70 mm; and Modified = a fan speed of 1,375 rpm and a shutter opening of 90 mm to increase the volume of air flowing through the combine).

LMM analyses of pooled data showed that the main effects of CV and TRT were statistically significant for both TW and YLD, and the main effect of CONFIG was only significant ($P < 0.05$, Table 2) for TW. None of the two- or three-way interactions were statistically significant for either response. Mean comparisons for the main effects of CV, TRT, and CONFIG are shown in Table 3. The S_Early and MR_Late cultivars had the highest mean TW and YLD, and there were not significant differences between each other for either response. The difference between MR cultivars was statistically significantly for YLD but not for TW, whereas the S_Early cultivar had significantly higher mean YLD and TW than the S_Mid cultivar. Significantly higher mean TW and YLD were observed in fungicide-TR than UT plots. Plots harvested with the modified CONFIG (C4) had significantly higher mean TW than those harvested with the default (C1) but the difference in mean YLD between the C1 and C4 was not significant ($P < 0.05$) .

Effects of FHB management programs on IND–grain quality and IND–grain YLD. Results from LMM covariance analyses (equation 3) showed evidence of linear relationships between FHB IND and all measures of grain quality (arcFDK, logDON, and TW) and between IND and grain YLD. For all relationships, the IND–PROG interactions were not statistically significant ($P = 0.128$ to 0.742), suggesting that the rates of change in arcFDK, logDON, TW, and YLD per unit increase in IND (slopes of the regression lines) were not influenced by management program. Therefore, a generic model for all evaluated relationships can be written as $y = a_i + \delta(IND)$, plus the design-based random effect, where a_i = intercept for each management program and δ = common slope (rate of change in arcFDK, logDON, TW, or YLD per unit increase in IND). The estimated slopes and intercepts (heights of the regression lines) for the relationships are presented in Table 4.

Using *lsmestimate* statements in Proc GLIMMIX, intercepts (estimated arcFDK, logDON, TW, and YLD when IND is zero) were compared among management programs, with emphasis on comparisons between each program and the reference (M8) (Table 4). The heights of the IND/arcFDK and IND/logDON regression lines were highest for M8 and lowest for M5. M1 had the second lowest regression lines for both of these relationships. Because of the lack of interactions, differences in predicted values for any level of IND must be the same as differences in estimated intercepts. Thus, the reference treatment (M8) had a higher predicted level of FDK and DON (on the transformed scale) at any level of disease in the field, while the M5 management program had the lowest predicted FDK and DON. The difference between the height of the regression lines (intercepts) for each program and M8 was statistically significant for M5 and marginally significant for M1 and M2 for the IND/arcFDK relationship. For the IND/logDON relationship, intercept differences relative to M8 were significant for M1 and M5 and marginally significant for M2, M3, and M7 (Table 4). For the IND/TW and IND/YLD relationships, the intercepts for M8 were significantly lower than those for M1, M3, M5, and M7 management programs, in which an anthesis application of Prosaro was made. The greatest differences in intercepts between IND/TW regression lines were observed when M8 was compared with M1 (61.7 kg m^{-3}) and M3 (63.6 kg m^{-3}), management programs in plots that received a TRT at early anthesis and harvested with the modified CONFIG (C4) (Table 4). YLD and TW intercepts for programs without a fungicide application were not significantly different from M8 (Table 4).

Efficacy and economic benefit of FHB management programs. Intercepts for the IND/arcFDK and IND/logDON regression lines were back-transformed to obtain FDK (%) and DON (ppm) and used along with intercepts for IND/TW and IND/YLD relationships to determine the efficacy of the management programs. Using equations 4a and 4b, percent reduction (C_M) in FDK and DON, and percent increase (I_M) in TW and YLD relative to M8 were estimated as measures of the efficacy of each program. Based on the estimated C_M and I_M values, the top (most effective) four management programs (M1, M3, M5, and M7, based collectively on the highest percent control of FDK and DON and percent increase in YLD and TW, relative to M8) all included fungicide treatment, two included moderate resistance (M1 and M5), and two included modified harvester configuration (M1 and M3) (Table 5). These programs provided between 25 (M7) and 62% (M5) reduction in FDK, 33 (M3 and M7) and 51% (M5) reduction in DON, 8 (M5 and M7) and 10% (M1 and M3) increase in TW, and 18 (M1) and 26% (M7) increase in YLD relative to the reference program (M8). Of the other programs, M2 performed well in terms of FDK and DON reduction but resulted in a 15% YLD reduction. M6 also performed reasonably well in terms of FDK reduction but not in terms of DON reduction, and also resulted in TW (2%) and YLD (7%) reductions relative to M8. Although M7 resulted in the highest YLD increase, this program did not do as well as M1 and M5 in terms of FDK and DON reduction. M4 was the least effective program in terms of FDK and DON reduction at 7.5 and 4%, respectively, relative to M8 (Table 5).

Using the equations summarized in Table 4, predicted YLD, TW, and back-transformed predicted FDK and DON were obtained for three IND levels (5, 10, and 15%). Price discounts for each grain quality trait (*twl*, *fdkl*, and *donl*) were then estimated using the discount schedule in Table 6. Total estimated price discounts (*dct*, equation 7) and net cash income with (NCI_M, equation 8) and without (NCI_{No}, equation 6) management were estimated and used to calculate the economic benefit (EB_M) for each management program based on equation 5, as described above. Price discounts and *GCI* (before subtracting the cost of management) for three IND levels and three grain market prices are presented in Table 7. Estimates of the EB_M for the four most efficacious programs (M1, M3, M5, and M7) are displayed in Figure 4 for a range of fungicide application costs ($Cost_M$).

For a given level of IND, the lowest price discounts due to TW (*twl*) were for M1 and M3 (management programs that included a Prosaro application at anthesis [TR] and the modified grain harvesting method [C4]), whereas the lowest discounts due to FDK (*fdkl*) and DON (*donl*) were for M5 (management option that integrated resistance cultivar [MR] and treatment with Prosaro). M7 (S_TR_C1) had the highest price discounts due to FDK and DON compared with the other three programs (M1, M3, and M5) that included a Prosaro application at anthesis. The overall lowest total discount in grain price (*dct* = twl + *fdkl* + *donl*) based on all three quality traits (TW, FDK, and DON) was observed for M5 (MR_TR_C1) at low IND (5%) and M1 (MR_TR_C4) at higher IND levels (10 and 15%) (Table 7). As expected, in all cases, *dct* increased as IND increased. For instance, at an IND of 5%, for M5, with a predicted TW of 659.2 kg m^{-3}, FDK of 4.6% and DON of 1.5 ppm, the estimated *dct* was calculated by adding \$20.5 (*twl*) + \$7.28 (*fdkl*) + \$0 (*donl*; no discount for DONm which is below 2 ppm), giving a total price discount of \$27.8 MT^{-1}. However, at 15% IND, *dct* for M5 was \$50.0 MT^{-1} (\$29.9 for *twl* + \$18.1 for *fdkl* + \$2.0 for *donl*), which was higher than the *dct* for M1 (\$48.8 MT^{-1} = \$26.8 for *twl* + \$20.1 for *fdkl* + \$2.0 for *donl*). Overall, management programs without a fungicide application at anthesis (M2, M4, M6, and M8) had the highest price discounts at all IND levels.

Table 5. Percent reduction of Fusarium damaged kernels (FDK) and deoxynivalenol (DON) content of grain and percent increase in test weight and grain yield with different cultivar, fungicide treatment, and combine harvester configuration combinations relative to the reference management combination for pooled data from experiments conducted in 2011 and 2013 in Wooster, OH[x]

	Reduction (%)		Increase (%)	
Program[y]	FDK	DON	TW	YLD
M1 (MR_TR_C4)	52.2	50.1	9.8	17.6
M2 (MR_UT_C4)	48.1	38.7	0.6	–15.2
M3 (S_TR_C4)	32.7	32.6	10.2	22.4
M4 (S_UT_C4)	7.5	4.3	3.0	–0.7
M5 (MR_TR_C1)	62.4	50.9	7.9	22.9
M6 (MR_UT_C1)	42.0	26.6	–2.0	–7.0
M7 (S_TR_C1)	25.4	32.6	8.2	25.7
M8 (S_UT_C1)[z]	6.9	2.4	626.8	3,614.5

[x] FDK = percentage of visually diseased (small, shriveled, and discolored) kernels, DON = DON of grain (ppm), TW = grain weight per unit volume (kg m^{-3}), and grain yield (kg ha^{-1}). Percent reduction or increase were calculated relative to reference management combination (M8) based on estimated intercepts from linear mixed-model covariance analysis.

[y] Fusarium head blight (FHB) management programs (M1–M8) consisting of combinations of fungicide treatment, cultivar resistance, and combine harvester configuration. MR = moderately resistant cultivar, TR = treated with the fungicide Prosaro (19% prothioconazole + 19% tebuconazole [475 ml ha^{-1}]) at anthesis, C4 = grain harvested using a modified combine configuration (a fan speed of 1,375 rpm and a shutter opening of 90 mm to increase the volume of air flowing through the combine), UT = not treated with Prosaro, S = susceptible cultivars, and C1 = grain harvested using a default combine configuration (with a fan speed of 1,375 rpm and a shutter opening of 70 mm). M8 is the reference management combination.

[z] Predicted mean FDK (%), DON (ppm), TW = grain weight per unit volume (kg m^{-3}), and grain yield (kg ha^{-1}) for the reference management combination (M8) based on estimated intercepts from linear mixed-model covariance analysis.

Table 4. Estimated intercepts and slopes and their corresponding standard errors (se) for relationships between arcsine-transformed Fusarium damaged kernels (arcFDK), log-transformed deoxynivalenol (logDON), test weight, grain yield, and Fusarium head blight (FHB) index (IND) of wheat for different FHB management programs (M1 to M8) for pooled data from experiments conducted in Wooster, OH in 2011 and 2013

	Response variable, predictor = IND[y]							
	arcFDK		logDON		Test weight (kg m^{-3})		Grain yield (kg ha^{-1})	
Program[z]	Intercept	se	Intercept	se	Intercept	se	Intercept	se
M1 (MR_TR_C4)	0.182*	0.086	0.778**	0.542	688.5**	92.8	4,250.9*	184.7
M2 (MR_UT_C4)	0.190*	0.087	0.894*	0.544	630.3	93.0	3,067.1	210.9
M3 (S_TR_C4)	0.216	0.088	0.951*	0.546	690.4**	93.1	4,422.7**	230.8
M4 (S_UT_C4)	0.255	0.100	1.180	0.574	645.8	94.9	3,589.3	428.2
M5 (MR_TR_C1)	0.161**	0.086	0.769**	0.542	676.3**	92.9	4,441.0**	193.9
M6 (MR_UT_C1)	0.201	0.087	1.004	0.544	614.3	93.0.	3,360.8	211.5
M7 (S_TR_C1)	0.228	0.089	0.951*	0.548	678.5**	93.2	4,541.7**	245.2
M8 (S_UT_C1)	0.265	0.096	1.211	0.566	626.8	94.3	3,614.5	379.2
Slope (se)	0.011 (0.004)		0.028 (0.015)		–3.4 (1.5)		–52.4 (30.4)	

[y] Intercept and common slope and their standard errors were estimated from linear mixed-model covariance analysis. Intercepts marked with asterisks are significantly different from the intercept of the reference management program (M8) at the 5% (**) and 10% (*) levels of significance, based on *F* tests from pairwise comparisons (contrasts). FDK = percentage of visually diseased (small, shriveled, and discolored) kernels, DON = DON contamination of grain (ppm), test weight and grain yield as response variables, and IND = FHB IND (%) as predictor variable.

[z] FHB management programs (M1–M8) consisting of combinations of fungicide treatment, cultivar resistance, and combine harvester configuration. MR = moderately resistant cultivar, TR = treated with the fungicide Prosaro (19% prothioconazole + 19% tebuconazole [475 ml ha^{-1}]) at anthesis, C4 = grain harvested using a modified combine configuration (a fan speed of 1,375 rpm and a shutter opening of 90 mm to increase the volume of air flowing through the combine), UT = not treated with Prosaro, S = susceptible cultivars, and C1 = grain harvested using a default combine configuration (with a fan speed of 1,375 rpm and a shutter opening of 70 mm). M8 is the reference management combination.

Relative to M8, all management programs had lower *dct* values, with the magnitude of the difference for the most efficacious programs (M1, M3, M5, and M7) increasing as IND increased from 5 to 15%. For instance, at 5% IND, the differences were $28.9, 25.6, 29.3, and 20.5 MT^{-1} for M1, M3, M5, and M7, respectively; whereas, at 15% IND, the corresponding differences were $39.7, 30.5, 38.6, and 26.4 MT^{-1}, respectively (Table 7). Differences relative to M8 were much smaller for programs without fungicide application (M2, M4, and M6), ranging from $5.7 (for M4 at 5% IND) to $21.3 MT^{-1} (for M2 at 10% IND), depending on the level of IND.

For all management programs, *GCI* (Table 7) increased as grain prices increased and decreased as disease IND increased. By virtue of their effects on grain YLD and quality, management programs that included a Prosaro application (M1, M3, M5, and M7) generally resulted in the highest *GCI* and were the most economically beneficial (Fig. 4). For all tested IND levels and grain price scenarios, M5 consistently had the highest *GCI*, followed by M1 at moderate to high IND levels (10 and 15%) and low and medium grain prices ($118 and 197 MT^{-1}), M7 at the highest tested grain price ($276 MT^{-1}) at all three IND levels, and M3 at the low IND level (5%) and low to medium grain prices ($118 and 197 MT^{-1}). Among programs without a Prosaro application (M2, M4, and M6), M4, the program with the highest YLD, had the highest *GCI*, except when the low grain price ($118 MT^{-1}) was combined with moderate to high IND levels. For programs that relied on moderate resistance without applying fungicide (M2 and M6), the benefit (in terms of cash income) of using the modified grain harvesting method (M2 = MR_UT_C4) was observed at moderate to high disease levels (10 and 15%) when grain price was low ($118 MT^{-1}). Among programs that did not include moderate resistance (M3, M4, and M7), M3, the program that included the modified combine harvesting method plus Prosaro at anthesis, had the highest *GCI* at the low grain price ($118 MT^{-1}) for almost all tested IND levels. However, M7, the program with the Prosaro application and the default grain harvesting method, had *GCI* comparable with M3 at the medium grain price ($197 MT^{-1}), and higher *GCI* than M3 at the highest tested grain price considered ($276 MT^{-1}) for all three IND levels. Comparing harvesting methods in the absence of moderate resistance and fungicide treatment (M4 versus M8), management option M4 consistently had higher *GCI* compared with M8 at all IND levels and grain prices.

Based on these results, the economic benefit of implementing FHB management programs (EB_M), calculated using equation 5, was greater than 0 for all management options at the lowest grain price ($118 MT^{-1}) and at all IND levels. For instance, at a grain price of $118 MT^{-1} and IND of 10%, the *GCI* for the reference program (M8), which is equivalent to NCI_{No} (if we assume that production costs unrelated to FHB are the same for all management programs and, as such, will cancel out), is $134.1 ha^{-1}, while the corresponding *GCI* for M5 is $315.7 ha^{-1} (Table 7). After subtracting the fungicide application cost ($50 ha^{-1}, for example), the NCI_{M5} is $265.7. Subtracting $134.1 ($NCI_{No}$) from $265.7 ($NCI_{M5}$) gives an EB_{M5} of $131.6 ha^{-1} (Fig. 4). However, at the highest grain price ($276 MT^{-1}), M2 and M6 (MR_UT options, with and without the modified grain harvesting method) were not economically beneficial compared with M8 at any of the tested IND levels (Fig. 4; Table 7). All of the top four management programs (those that included a Prosaro application; M1, M3, M5, and M7) were economically beneficial at all of the IND levels, grain prices, and fungicide application costs evaluated in this study, because NCI_M was higher than NCI_{No} in all cases (Fig. 4). As expected, for all of these programs, *EB* increased as grain price increased and decreased as IND and fungicide application cost increased.

As shown in the ranking of the programs in Table 8, M7 (fungicide alone) had consistently higher *EB* than M6 (resistance alone) and M4 (configuration alone) at all IND levels and grain prices evaluated in this study. However, relative to programs that included fungicide integrated with moderate resistance or combine harvesting method (M1, M3, and M5), M7 had the lowest *EB* values at all three IND levels when the grain price was $118 MT^{-1} (Table 8). Contrastingly, M7 had the second highest *EB* values (after M5) when the grain price was high ($276 MT^{-1}) compared with M1 and M3. On the other hand, M1, which was, in most cases, second to M5 in terms of *EB* at the low grain price, had the lowest *EB* of the four fungicide-based programs at the high grain price. Compared with M8, M4 (CONFIG alone) was economically beneficial at all IND levels and grain prices; however, the estimated *EB* values for this program were relatively low (ranging from $13.5 to 25.5 ha^{-1}) compared with the top management programs, which ranged from $31.1 to 272.2 ha^{-1}, depending on fungicide costs (Fig. 4).

Discussion

Over the last several years, there have been numerous reports, both in general literature reviews (1,22,24,48) and in publications from original research (14,37,47,50), alluding to the value of integrating multiple strategies to manage FHB and DON in small grain crops. However, none of the previous reports addressed the integration of in-field and grain-harvesting strategies, and few have evaluated the *EB* of FHB management strategies. The work presented

Table 6. Example grain elevator discount schedule for wheat due to test weight, Fusarium-damaged kernels (FDK), and deoxynivalenol (DON) contamination of grain[z]

Test weight				FDK			DON		
		Discount			Discount			Discount	
lb/bu	kg m^{-3}	$ bu^{-1}	$ MT^{-1}	%	$ bu^{-1}	$ MT^{-1}	ppm	$ bu^{-1}	$ MT^{-1}
58.0	746.57	0.00	0.00	0.9	0.00	0.00	0.0	0.00	0.00
57.5	740.13	0.04	1.57	1.0	0.02	0.79	2.0	0.05	1.97
57.0	733.70	0.08	3.15	1.5	0.06	2.36	2.5	0.10	3.94
56.0	720.82	0.16	6.30	2.0	0.10	3.94	3.0	0.20	7.87
55.0	707.95	0.24	9.45	3.0	0.13	5.12	3.5	0.30	11.81
54.0	695.08	0.32	12.60	4.0	0.16	6.30	4.0	0.40	15.75
53.0	682.21	0.40	15.75	5.0	0.21	8.27	4.5	0.50	19.69
52.0	669.34	0.48	18.90	6.0	0.26	10.24	5.0	0.60	23.62
51.0	656.46	0.56	22.05	7.0	0.31	12.20	6.0	0.80	31.50
50.0	643.59	0.64	25.20	8.0	0.36	14.17	7.0	1.00	39.37
49.0	630.72	0.72	28.35	9.0	0.41	16.14	8.0	1.20	47.24
48.0	617.85	0.80	31.50	10.0	0.46	18.11	9.0	1.40	55.12
47.0	604.98	0.88	34.65	11.0	0.51	20.08	10.0	1.60	62.99
46.0	592.11	0.96	37.80	12.0	0.56	22.05	11.0	1.80	70.87
45.0	579.23	1.04	40.94	13.0	0.61	24.02	12.0	2.00	78.74

[z] Price discounts estimated using 746.57 kg ha^{-1} (58 lb bu^{-1}), 1%, and 2 ppm as grain quality thresholds for test weight, FDK, and DON, respectively. Grain with FDK and DON below and test weight above these thresholds will not receive price discounts. Price discount schedules vary from year to year and from one grain elevator to another. (Source: Courtesy of Dr. M. McMullen, North Dakota State University.)

herein constitutes the first formal evaluation of the efficacy and cost-benefit of integrating chemical control, cultivar resistance (coupled with maturity and YLD potential), and grain harvesting strategies to manage FHB and DON in SRWW. In addition, this is the first large-scale comparative assessment of a new, commercially available MR SRWW, Malabar, relative to the standard MR SRWW Truman and S Hopewell, a reference SRWW cultivar in terms of grain YLD and quality (TW).

In this study, both the main and interaction effects of CV and TRT were statistically significant for all FHB-related responses (IND, INC, FDK, and DON). In all cases, the CV × TRT interaction was manifested as differences in the magnitude of the fungicide effect from one cultivar to another and the magnitude of the difference among cultivars in either TR or UT plots. On average, as expected, the MR cultivars had significantly lower levels of disease and toxin than the S cultivars, with the magnitude of the difference being greater in UT than Prosaro-TR plots. In terms of the fungicide effect, for all measures of FHB (INC, IND, FDK, and DON), differences between TR and UT plots were greater for S than for MR cultivars. These results seem to suggest that both the magnitude of the resistance and the fungicide effects vary with the baseline level of disease and toxin, with the greater reduction occurring at relatively high than at low baseline levels of FHB and DON. This is consistent with results from previous studies conducted by Paul et al. (33) and Willyerd et al. (51). In the latter investigation, the authors showed that the efficacy of Prosaro, based on mean percent control of IND from a meta-analysis of data from more than 40 studies from all major wheat classes, was greater between UT and TR plots of S cultivars (with higher baseline levels of disease) than between TR and UT plots of MR cultivars (with low baseline levels). However, these findings were contrary to those reported by Wegulo et al. (47) and Ransom and McMullen (37), based on data from hard red winter wheat (HRWW) studies in Nebraska and North Dakota, respectively. Hollingsworth et al. (14) also reported that the efficacy of Folicur, a fungicide that is considerably less effective against FHB than Prosaro (33), was higher in resistant than in S hard red spring wheat (HRSW) cultivars.

As it relates to the influence of TRT on cultivar resistance response, Hollingsworth et al. (14) reported findings that were contrary to those observed in this study, with greater differences in all measures of FHB between MR and moderately susceptible cultivars in TR rather than UT plots. These contrasting results could be due to several factors, including the fact that the Hollingsworth study was conducted using HRSW (different cultivars under different growing conditions) and, most importantly, using 41.8% propiconazole (Tilt 3.6 EC; Syngenta) and 38.7% tebuconazole (Folicur 3.6 F; Bayer CropScience), fungicides that are considerably less effective against FHB and DON than Prosaro (33).

In both TR and UT plots, the reference MR Truman had significantly lower levels of IND and INC than the new MR Malabar, suggesting that both infection (based on INC) and disease spread within the spike (based on IND), at least under the conditions of this study, were greater for Malabar than Truman. Although both

Table 7. Gross cash income (GCI) for different Fusarium head blight (FHB) management programs for a range of FHB index levels and grain prices

	Grain quality and price discounts[w]					GCI ($ha^{-1})/grain price ($MT^{-1})[x]		
IND, PROG[y]	YLD (MT ha^{-1})	TW (kg m^{-3})	FDK (%)	DON (ppm)	*dct* ($MT^{-1})[z]	118	197	276
5								
M1	4.0	671.3 (18.9)	5.5 (9.3)	1.5 (0.0)	28.2	358.4	673.6	988.7
M2	2.8	613.2 (33.1)	5.9 (10.2)	1.8 (0.0)	43.3	209.5	431.1	652.7
M3	4.2	673.3 (17.3)	7.2 (12.2)	2.0 (2.0)	31.5	360.0	688.7	1,017.4
M4	3.3	628.7 (28.4)	9.3 (17.1)	2.8 (5.9)	51.4	221.6	484.5	747.4
M5	4.2	659.2 (20.5)	4.6 (7.3)	1.5 (0.0)	27.8	377.2	707.3	1,037.5
M6	3.1	597.2 (36.2)	6.4 (11.2)	2.1 (2.0)	49.4	212.6	457.4	702.2
M7	4.3	661.3 (20.5)	7.8 (14.2)	2.0 (2.0)	36.6	348.3	686.4	1,024.6
M8	3.4	609.7 (33.1)	9.9 (18.1)	2.9 (5.9)	57.1	204.2	469.1	733.9
10								
M1	3.7	654.2 (22.1)	8.3 (14.2)	1.9 (0.0)	36.2	304.8	599.3	893.7
M2	2.5	596.1 (36.2)	8.7 (15.2)	2.3 (2.0)	53.4	164.4	365.4	566.3
M3	3.9	656.2 (22.1)	10.3 (18.1)	2.4 (3.9)	44.1	288.1	596.2	904.2
M4	3.1	611.6 (33.1)	12.7 (23.0)	3.3 (9.8)	65.9	159.6	401.8	644.0
M5	3.9	642.1 (25.2)	7.2 (12.2)	1.9 (0.0)	37.4	315.7	625.2	934.7
M6	2.8	580.0 (40.9)	9.3 (17.1)	2.6 (3.9)	62.0	158.8	383.0	607.1
M7	4.0	644.2 (25.2)	11.0 (20.1)	2.4 (3.9)	49.2	276.4	593.8	911.2
M8	3.1	592.6 (37.8)	13.4 (25.0)	3.5 (11.8)	74.6	134.1	378.3	622.5
15								
M1	3.5	638.8 (26.8)	11.2 (20.1)	2.3 (2.0)	48.8	241.5	517.4	793.2
M2	2.3	580.7 (40.9)	11.7 (21.1)	2.7 (5.9)	67.9	115.6	297.9	480.2
M3	3.7	640.8 (25.2)	13.4 (25.0)	2.9 (7.9)	58.1	219.5	509.0	798.4
M4	2.8	596.2 (36.2)	16.1 (29.9)	3.9 (13.8)	79.9	107.8	331.3	554.9
M5	3.7	626.7 (29.9)	9.9 (18.1)	2.3 (2.0)	50.0	250.4	541.2	832.1
M6	2.6	564.6 (44.1)	12.4 (23.0)	3.1 (9.8)	77.0	106.8	312.3	517.8
M7	3.8	628.8 (28.4)	14.2 (26.0)	2.9 (7.9)	62.2	211.1	509.9	808.7
M8	2.9	577.2 (40.9)	16.9 (31.9)	4.1 (15.8)	88.6	84.0	309.6	535.1

[w] Grain yield (YLD) and quality measures—test weight (TW), percent Fusarium damaged kernels (FDK), and deoxynivalenol contamination of grain (DON)—estimated at each level of IND based on the estimated parameters from linear mixed-model covariance analyses. Values in parentheses represent estimated price discount values for each quality trait (*twl*, *fdkl*, and *donl*) based on the example discount schedule in Table 6.

[x] GCI, estimated as $GCI = Y{\cdot}(P - dct)$. Y is grain yield, P is grain price, and dct = total price discount; $dct = twl + fdkl + donl$, where *twl*, *fdkl* and *donl* represent price discounts due to test weight below and FDK and DON contamination above thresholds established by grain elevators.

[y] IND = FHB index (mean percentage of diseased spikelets per spike) and PROG = FHB management programs, consisting of combinations of fungicide treatment, cultivar resistance, and combine harvester configuration. M1 = moderately resistant (MR) cultivar, treated with the fungicide Prosaro at anthesis and grain harvested using a modified combine configuration (C4; a fan speed of 1,375 rpm and a shutter opening of 90 mm to increase the volume of air flowing through the combine), M2 = MR cultivar, not treated with Prosaro, and harvested with C4, M3 = susceptible (S) cultivar, treated with Prosaro at anthesis, and harvested with C4, M4 = S cultivar, not treated with Prosaro and harvested with C4, M5 = MR cultivar, treated with Prosaro at anthesis, and grain harvested using a default combine configuration (C1; with a fan speed of 1,375 rpm and a shutter opening of 70 mm), M6 = MR cultivar, not treated with Prosaro and harvested with C1, M7 = S cultivar, treated with Prosaro at anthesis, and harvested with C1, and M8 (the reference management combination) = S cultivar, not treated with Prosaro, and harvested with C1.

[z] Total estimated total price discount (*dct*).

cultivars are classified as MR based on results from FHB screening nurseries (43,44), Truman appeared to have higher levels of both type I (resistance to infection) and type II (resistance to spread within the spike) resistance (40) than Malabar. The fact that Malabar is midseason and Truman late-maturing also could have contributed to the differences, because resistance to FHB is a partial and quantitative trait and genotype–environment interaction has been known to affect cultivar reaction (4,26,28). However, the weather conditions at the time Malabar reached anthesis were not very different from those when Truman reached anthesis (2 to 3 days later), suggesting that maturity likely had little effect on the observed FHB reaction. Interestingly, Malabar was not significantly different from Truman for FDK and DON, indicating that the two cultivars probably have similar levels of type III (resistant to DON accumulation) (27) and type IV (resistant to kernel infection) resistance (1,25,38).

Under the conditions of this study, CONFIG did not have a statistically significant effect on DON (on a log-transformed scale) or FDK (on an arcsine-square root-transformed scale). Plots harvested with the modified CONFIG (with increased air flow through the combine to remove diseased, light-weight kernels) tended to have numerically lower DON and FDK, on average, then plots harvested with the default configuration but, contrary to what was reported by Salgado et al. (39), the differences were not statistically significant. This could be attributed to the fact that IND was much lower in this study than in the study by Salgado and collabo-

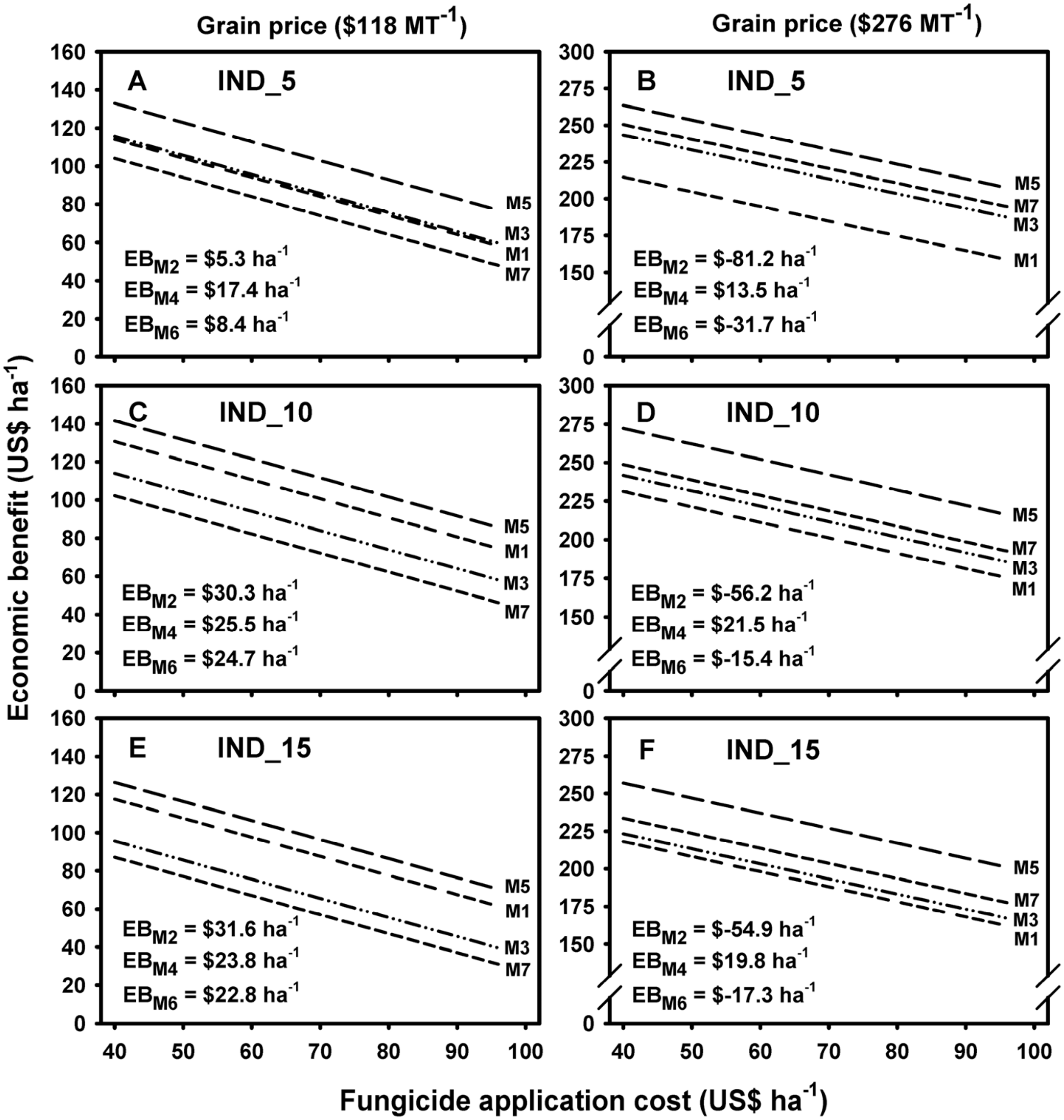

Fig. 4. Estimated economic benefit for (EB_M) for a range of fungicide application costs, three index (IND) levels (**A** and **B,** 5%; **C** and **D,** 10%; and **E** and **F,** 15%) and two grain prices (**A, C,** and **E,** US$118; and **B, D,** and **F,** 276 MT^{-1}) for different Fusarium head blight management programs relative to M8. M1 = moderately resistant (MR) cultivar, treated with the fungicide Prosaro at anthesis, and grain harvested using a modified combine configuration (C4; a fan speed of 1,375 rpm and a shutter opening of 90 mm to increase the volume of air flowing through the combine); M2 = MR cultivar, not treated with Prosaro, and harvested with C4; M3 = susceptible (S) cultivar, treated with Prosaro at anthesis and harvested with C4; M4 = S cultivar, not treated with Prosaro, and harvested with C4; M5 = MR cultivar, treated with Prosaro at anthesis and grain harvested using a default combine configuration (C1; with a fan speed of 1,375 rpm and a shutter opening of 70 mm); M6 = MR cultivar, not treated with Prosaro, and harvested with C1; M7 = S cultivar, treated with Prosaro at anthesis and harvested with C1, and M8 (the reference management combination) = S cultivar not treated with Prosaro and harvested with C1.

rators. In that particular investigation, only an S cultivar was used and plots were not treated with a fungicide; therefore, mean IND was much higher, ranging from 5 to 35%, compared with 0 to 17% (average across CV and TRT) in this study. Although Salgado et al. (39) reported that the effect of CONFIG was consistent across IND levels, their data did not allow them to evaluate the CONFIG effect at IND below 5%. In the current study, 66% of the observations had IND ≤ 5%.

The modified CONFIG did, however, result in significantly higher TW and numerically but not significantly lower grain YLD than the default (P = 0.17). This indicates that, even at relatively low IND and FDK levels, the removal of light-weight, low-density materials did contribute to an increase in TW (grain density) of 14 kg m^{-3} over plots harvested with the default CONFIG but was not sufficient to remove a substantial amount of healthy kernels, a common drawback of harvesting grain with combine harvesters regulated to higher fan speeds and wider shutter openings (39). In fact, the greatest contributors to YLD differences in this study were CV and TRT, regardless of CONFIG, corroborating previous findings (14,35,37,47).

For all measured responses (YLD, TW, arcFDK, and logDON), there was a straight-line functional relationship with IND, and there was no evidence that FHB management programs affected the rate of change in arcFDK, logDON, TW, and YLD per unit increase in IND. This is consistent with the findings reported by Madden and Paul (20), Salgado et al. (39), and Willocquet et al. (54) in terms of the nature of the functional relationship between FHB and grain YLD, and by Salgado et al. (39), Paul et al. (34), and Wegulo et al. (48) in terms of relationships between FHB and DON and FHB and FDK. The heights of the IND/arcFDK, IND/logDON, IND/TW, and IND/YLD regression lines (intercepts), which were used here to evaluate the efficacy of different management programs, varied among programs. In general, relative to the reference management program (M8), programs that included a fungicide application (M1, M3, M5, and M7) were the most efficacious overall, with significantly higher YLD and TW regression lines and lower arcFDK and logDON lines than M8. Correspondingly, these same programs resulted in the highest percent reduction in FDK and DON and percent increase in YLD and TW. Among these programs, those that included a cultivar resistance were the most efficacious in terms of reducing FDK and DON, whereas those that included the modified grain harvesting method resulted in the highest percent increase in TW.

Variation in grain YLD and quality among management programs translated into variations in estimated price discounts, cash income, and, ultimately, in differences in terms of the estimated *EB* of the programs based on our results. This is to be expected because wheat grain is graded and priced based on quality traits (TW, DON, and FDK) (14,22,24,37), and the total cash income received for a given grain lot is a function of the total YLD and the final grain price after adjusting for quality. Consequently, programs that resulted in the lowest total price discounts (*dct*) and highest YLDs were generally the most economically beneficial. However, there is a balance between grain YLD and quality in determining net cash income and, ultimately, the *EB* of a management program. Several interesting variations were observed in terms of *EB*, likely reflecting the influence of grain price and FHB intensity on the relative contribution of *dct* and YLD to the overall *EB*. Fungicide-based programs had the highest *EB* across all tested grain prices and IND levels. Studies conducted in Minnesota and North Dakota using HRSW and HRWW, respectively, show similar results, indicating that the profitability of using fungicides to manage FHB (as well as other disease, as was the case in North Dakota) is consistent across locations and wheat market classes (14,37). However, not surprisingly, the profit margin varied considerably among the HRSW in Minnesota, HRWW in North Dakota, and the SRWW in this study, likely reflecting the fact that grain YLD was considerably higher in our SRWW cultivars than in the HRWW and HRSW cultivars; some of the North Dakota experiments had fairly high levels of foliar diseases (over 80% severity in some cases) which, in combination with FHB, could have a greater effect on grain YLD and quality than FHB alone (*unpublished*); baseline levels of FHB varied among the experiments; and, most importantly, both the North Dakota and Minnesota studies included fungicide treatments (pyraclostrobin [Headline] before jointing [Feekes GS 6] and tebuconazole [Folicur] and a tank mixture of Folicur and prothioconazole [Proline] at anthesis in North Dakota; and Tilt and Folicur before jointing and at anthesis in Minnesota) that are generally less effective against FHB and DON than Prosaro (5,33,35).

The M5 program (MR_TR; resistance + fungicide) consistently had the highest ranking in terms of *EB* across all tested grain prices and IND levels in this investigation; however, the ranking of other fungicide-based programs (M1, M3, and M7) relative to M5 varied considerably with grain market price and FHB IND. M1 (MR_TR_C4), the fungicide-based program with the lowest mean YLD but second lowest *dct* at 5% IND, had the third highest *EB* when grain price and IND were low (\$118 MT^{-1} and 5%, respectively). However, at that same grain price, M1 resulted in the highest grain quality (lowest *dct*) and had the second highest *EB* at 10 and 15% IND. This suggested that the gain in grain quality at higher IND levels compensated for some of the YLD reduction that

Table 8. Ranking of Fusarium head blight (FHB) management programs based on the economic benefit (EB; \$ ha^{-1}) for a range of FHB index levels and grain market prices

	Ranking (1= best to 8 = worst) based on EB for each program (M)[y]							
IND, price (\$/MT)[z]	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
5								
Low (118)	M5	M3	M1	M7	M4	M6	M2	M8
Medium (197)	M5	M3	M7	M1	M4	M8	M6	M2
High (276)	M5	M7	M3	M1	M4	M8	M6	M2
10								
Low (118)	M5	M1	M3	M7	M2	M4	M6	M8
Medium (197)	M5	M1	M3	M7	M4	M6	M8	M2
High (276)	M5	M7	M3	M1	M4	M8	M6	M2
15								
Low (118)	M5	M1	M3	M7	M2	M4	M6	M8
Medium (197)	M5	M1	M7	M3	M4	M6	M8	M2
High (276)	M5	M7	M3	M1	M4	M8	M6	M2

[y] M1 = moderately resistant (MR) cultivar, treated with the fungicide Prosaro at anthesis and grain harvested using a modified combine configuration (C4; a fan speed of 1,375 rpm and a shutter opening of 90 mm to increase the volume of air flowing through the combine); M2 = MR cultivar, not treated with Prosaro and harvested with C4; M3 = susceptible (S) cultivar, treated with Prosaro at anthesis, and harvested with C4; M4 = S cultivar, not treated with Prosaro, and harvested with C4; M5 = MR cultivar, treated with Prosaro at anthesis and grain harvested using a default combine configuration (C1; with a fan speed of 1,375 rpm and a shutter opening of 70 mm); M6 = MR cultivar, not treated with Prosaro, and harvested with C1; M7 = S cultivar, treated with Prosaro at anthesis, and harvested with C1, and M8 (the reference management combination) = S cultivar, not treated with Prosaro, and harvested with C1.

[z] FHB index (IND; mean percentage of diseased spikelets per spike) and grain price.

resulted from the use of M1. The monetary value of the 0.2 MT ha^{-1} reduction in YLD with M1 relative to M5 was 20% of the low grain price (\$118 MT^{-1}) at all tested IND levels; however, the monetary value of the gain in grain quality (mainly through higher TW due to grain harvest with the modified configuration) represented a slightly higher percentage of the grain price at 10 and 15% IND than the value of the gain in grain quality with M5, leading to the two programs having comparable *EB* at the 15% IND level. However, this was not the case at the highest tested grain price (\$276 MT^{-1}), where the gain in grain quality with M1 relative to M5 was not sufficient to offset the reduction in YLD, leading to M1 having the lowest *EB* (lowest ranking) of the four fungicide-based programs. Apparently, at the high grain prices, the benefit of M1 having the highest grain quality at high IND levels did not compensate for it having the lowest YLD among the fungicide-based programs.

The opposite trend was observed for M7 (S_TR_C1, fungicide application alone), the fungicide-based programs with the highest mean grain YLD but lowest grain quality (highest *dct*). Without the benefit of host resistance and a grain harvesting strategy to improve grain quality, M7 had the lowest *EB* at the low grain price at all three IND levels. However, at the highest tested grain price, the higher grain YLD compensated for the relatively low grain quality, leading to M7 having the second highest *EB*, again reflecting differences in the relative contribution of YLD and grain quality to *EB*, as influenced by grain price. When compared with M2 (MR_UT_C4; moderate resistance without fungicide but harvested with modified CONFIG) and M6 (MR_UT_C1; moderate resistance alone), the two programs with the lowest grain YLD and TW, M7 had consistently higher *EB* across a range of application costs, grain prices, and disease levels. Willyerd et al. (51) previously showed (as was the case here) that resistance alone (a program similar to M6) provided superior control of IND and DON relative to the UT S reference program (similar to M8) than fungicide alone (a program similar to M7); however, the results presented here showed that this superior disease- and toxin-control benefit does not always translate into *EB* when the resistant cultivar is of lower YLD and quality than the S TR cultivar. In fact, M2 and M6 were less economically beneficial than the reference management program (M8; S_UT_C1) when the grain price was \$276 MT^{-1}. This was probably because, at the IND levels (5 to 15%) and fungicide application costs evaluated here (\$40 to 96 ha^{-1}), the relatively lower-yielding MR cultivar with lower TW was likely less economically beneficial than the TR S, high-yielding cultivar, with relatively higher TW, especially at high grain market prices. Our results further suggested that harvesting an S cultivar with the aforementioned agronomic traits with the modified CONFIG (as was the case in M4) may be just as or even more economically beneficial than a resistant, relatively lower-yielding, low-TW cultivar, under the conditions of this study.

Here, we demonstrated the superior efficacy as well as the *EB* of integrating a well-timed Prosaro application with an FHB-MR cultivar to manage FHB and DON in SRWW. We showed that under the disease levels of this study (IND of 0 to 17%), the integration of moderate resistance and a fungicide application was sufficient to minimize the effect of FHB on grain YLD and quality losses, without the need to change the combine harvester configuration. However, we also provided estimates of the *EB* of other combinations of management strategies to account for situations when either moderate resistance or Prosaro are not (or cannot be) used for FHB management. As discussed by Ozberk et al. (29) and Hollingsworth et al. (14), wheat cultivars are often selected based on grain YLD rather than quality traits, with producers often inclined to select high-yielding, low-quality cultivars over lower-yielding, higher-quality cultivars. We showed here that an FHB-S cultivar with YLD and quality characteristics similar to those of Hopewell, Cooper, and Bravo may still be economically beneficial at low to moderate FHB levels if treated with Prosaro (M7). Moreover, harvesting FHB-affected, Prosaro-TR plots of these cultivars with the modified CONFIG (M3) may further improve grain quality (TW in particular) and, consequently, the *EB*, particularly when the value of the crop (grain market prices) is low. Using a lower-yielding FHB-resistant cultivar alone (M6) or in combinations with modified grain harvest (M2) (which may further reduce YLD) will likely be a less economically viable option for managing FHB and DON than planting and treating a high-yielding S cultivar similar to those used here. As argued by Ozberk et al. (29), paying premiums for quality traits may increase the *EB* of using resistant cultivars with relatively low YLD potential, particularly if weather or some other factor prevents an anthesis application of Prosaro from being made or when FHB levels end up being low.

The assessments and conclusions made here are based the conditions of this study. However, although we anticipate that the absolute value of the *EB* of FHB management programs will likely vary under conditions different from those observed here, we believe that, with the currently available FHB management options, the trends observed in this investigation will likely be consistent across environments (in the generic sense). We anticipate that the combination of moderate resistance and Prosaro at anthesis will also be the most effective and economically beneficial approach for managing FHB and DON in other regions and grain marketing classes.

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