Tropical Plant Pathology (2019) 44:183–191
https://doi.org/10.1007/s40858-018-0262-9

ORIGINAL ARTICLE

Multi-environment assessment of fungicide performance for managing wheat head blast (WHB) in Brazil and Bolivia

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Received: 17 June 2018 / Accepted: 25 September 2018 / Published online: 8 October 2018

Abstract

This study aimed to evaluate the performance of fungicides against wheat head blast (WHB) under various environments and to determine scenarios best suited for fungicide applications. Field experiments were conducted at 23 environments in Brazil and Bolivia from 2012 to 2015. Data from all trials within the same country were combined for estimating mean WHB control efficacy and yield benefits from using a set of fungicides. Experiments were classified, based on disease index in the check treatment, as having low (CDI = 10), moderate (CDI = 40), and high (CDI = 70) disease pressure and this variable was tested as a covariate in the model. In Brazil, greater disease reduction and yield increase, in trials with moderate to high disease pressure, were obtained when using mancozeb-based fungicides, but with yield gains below 1276 kg/ha. In Bolivia, all fungicides reduced the disease at moderate to high disease pressure, but specific QoI + DMI premixes led to higher yield gains averaging 1834 kg/ha. Based on the evidence provided, we concluded that current WHB chemical strategies could have radically different results depending on country and disease pressure. Although WHB chemical control can be effective even under environmental conditions that favor the disease, integrated management strategies should be explored. Our results are useful for aiding decisions on fungicide application and identifying priorities for future research.

Section Editor: Emerson M. Del Ponte

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s40858-018-0262-9) contains supplementary material, which is available to authorized users.

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Keywords Wheat blast · Brusone · *Magnaporthe oryzae* · *Pyricularia oryzae* · Head blast · Fungicide efficacy

Introduction

Wheat blast, caused by the fungal pathogen *Magnaporthe oryzae* (Couch and Kohn 2002) *Triticum* pathotype (MoT, synonym *Pyricularia oryzae Triticum* pathotype), is a major threat to wheat (*Triticum aestivum*) production worldwide (Cruz and Valent 2017). Wheat blast has been responsible for yield losses of up to 100% in Brazil (Goulart et al. 2007; Goulart and Paiva 2000), Bolivia (Barea and Toledo 1996), Paraguay (Kohli et al. 2011) and, more recently, Bangladesh (Islam et al. 2016; Malaker et al. 2016). MoT is known to cause explosive epidemics in wheat with greater yield losses occurring when first visual symptoms appear between head emergence and grain filling stages. Rachis infection and blockage of translocation of nutrients to the spike prevents normal formation of wheat grains (Goulart et al. 1996). The recent report of clonal fungal isolates from diverse wheat regions in Bangladesh and their relatedness to highly aggressive isolates from South America (Cruz and Valent 2017; Inoue et al. 2017; Malaker et al. 2016) have raised the alarms among the global wheat research community.

In Brazil, Bolivia, and Paraguay wheat blast is considered a difficult disease to control. A combination of factors such as high temperatures, heavy rainfall, long and frequent leaf wetness, high diversity in MoT virulence, lack of effective blast resistance, and poor fungicide coverage, timing, and/or efficacy has favored disease outbreaks in some regions, especially in the tropics (Cruz et al. 2011; Cruz and Valent 2017; Goulart 2005; Goulart et al. 2007; Urashima et al. 2004). In addition, the poor knowledge of ecological and epidemiological factors affecting wheat blast epidemics makes management of this disease a challenging task (Cruz and Valent 2017). Wheat head blast (WHB) symptoms are well described in the literature, but leaf blast symptoms are also prevalent on highly susceptible cultivars and certain environments (Cruz and Valent 2017).

In regions where the disease is endemic in Brazil and Bolivia, growers rely on several fungicide applications (*i.e.* three or more) at the heading stage as a last resort to control WHB. However, the efficacy and profitability of fungicide sprays for controlling WHB is currently disputed. Although there is evidence that fungicides can provide some level of control (Cruz et al. 2015; Goulart et al. 1996; Hurtado and Toledo 2004; Kohli et al. 2011; Toledo 2015), other evidence suggests that the limited efficacy prevents from recommending fungicides for an economic disease control (Pagani et al. 2014; Castroagudín et al. 2015; Maciel 2011; Pagani et al. 2014; Rocha et al. 2014). In particular, the reported WHB control provided by quinone outside inhibitors (QoI) and sterol demethylation inhibitors (DMI) fungicides (premixes or solo product) is not consistent among studies (Pagani et al. 2014; Rios et al. 2016; Rocha et al. 2014). While Rios et al. (2016) reported high levels of control (88–95%) of WHB using a single premix (13.3% epoxiconazole +5% pyraclostrobin), in other studies the levels of control ranged from 48 to 72% (Pagani et al. 2014) and 5–25% (Rocha et al. (2014) with two sprays of the same fungicide. Rios et al. (2016) discussed that differences in the results may be due to differences in application timing, overall environmental conditions and possibly variation in sensitivity of MoT to the fungicides. Two decades earlier Goulart et al. (1996) recommended tebuconazole and mancozeb as best options for WHB control, especially two applications of the latter (Goulart et al. 1996). Recently, reduced efficacy of fungicides has been reported in Brazil together with reports of fungicide resistance in the fungal population. Castroagudín et al. (2015) reported widespread resistance of MoT populations to fungicides of the QoI group in important wheat growing areas of Brazil. Reduced efficacy of fungicides of the DMI group is also prevalent in Brazil (Goulart and Paiva 1993; Maciel, personal communication; Santana et al. 2013). However, no study has looked at the prevalence of fungicide-resistant strains in MoT Bolivian populations.

Although fungicides are commonly used in wheat blast management programs, the Brazilian Wheat and Triticale Research Committee concluded that, due to reports of low efficacy, no recommendations for fungicide control are warranted (CBPTT, 2013). Clearly, inconsistencies in fungicide efficacy related to wheat blast control required further investigation. The present study was carried out to determine i) which, if any, fungicides were effective at controlling wheat blast in Bolivia and Brazil, ii) if fungicide performance is affected by environmental conditions that favor the disease, and iii) if some fungicides may be recommended under specific scenarios.

Materials and methods

Multi-site (non-irrigated) experiments were carried out at 23 environments (location-years) in Brazil ($n = 17$) and Bolivia ($n = 6$) between 2012 and 2015. Fungicides were evaluated under natural occurrence of wheat blast. Cultivars susceptible to WHB, plot size, equipment, and methodology for disease evaluations varied slightly by country to conform to local practices, as follows.

Brazil Experiments were carried out at 17 location-years between 2012 and 2014 (Table 1). One Cultivar, BRS-208, highly susceptible to blast, was selected as the standard in most of

Table 1 List of experiments conducted at 23 location-years in Brazil and Bolivia between 2012 and 2015

Code	Country	State or Department	Location	Season	Cultivar	CDI* (%)	CY** (kg/ha)	Pressure Category ***	Mean / Category Pressure****	
									CDI (%)	CY (kg/ha)
IT12	Brazil	São Paulo	Itaberá	2012	BRS-208	0.35	2148.3	L		
PA12	Brazil	Paraná	Palotina	2012	BRS-208	11.73	1219.4	L		
PL12	Brazil	Distrito Federal	Planaltina	2012	BRS-208	6.36	1747.4	L		
DO13	Brazil	Mato Grosso do Sul	Dourados	2013	BRS-208	9.17	506.0	L		
PdM13	Brazil	Minas Gerais	Patos de Minas	2013	BRS-208	2.91	1562.7	L		
PL13	Brazil	Distrito Federal	Planaltina	2013	BRS 208	10.40	3250.4	L		
IT14	Brazil	São Paulo	Itaberá	2014	Quartzo	14.48	2173.1	L		
PAL14A	Brazil	Paraná	Palmeira (A)	2014	Marfim	4.50	2761.0	L		
PA14B	Brazil	Paraná	Palmeira (B)	2014	TBio Tibagi	8.08	2937.1	L		
PdM14A	Brazil	Minas Gerais	Patos de Minas (A)	2014	BRS 208	0.73	2740.0	L		
PdM14B	Brazil	Minas Gerais	Patos de Minas (B)	2014	BRS 264	0.10	4276.3	L	6.3	2301.96
IT13	Brazil	São Paulo	Itaberá	2013	Quartzo	42.52	967.1	M		
PA14	Brazil	Paraná	Palotina	2014	CD 111	37.91	1281.3	M	40.2	1124.18
DO12	Brazil	Mato Grosso do Sul	Dourados	2012	BRS-208	68.65	1097.0	H		
LO12	Brazil	Paraná	Londrina	2012	Marfim	92.86	495.1	H		
LO14A	Brazil	Paraná	Londrina (A)	2014	Marfim	77.66	901.4	H		
LO14B	Brazil	Paraná	Londrina (B)	2014	Marfim	82.61	518.7	H	80.5	753.05
OK13	Bolivia	Santa Cruz	Okinawa	2013	Atlax	9.325	541.0	L		
OK14A	Bolivia	Santa Cruz	Okinawa (A)	2014	Atlax	9.90	1547.1	L	9.6	1044.05
OK14B	Bolivia	Santa Cruz	Okinawa (B)	2014	Atlax	25.67	2337.7	M/L		
QU15B	Bolivia	Santa Cruz	Quirusillas (B)	2015	Atlax	44.10	426.7	M	34.9	1382.19
QU14	Bolivia	Santa Cruz	Quirusillas	2014	Atlax	68.61	680.5	H		
QU15A	Bolivia	Santa Cruz	Quirusillas (A)	2015	Atlax	71.77	518.3	H	70.2	599.42

**CDI*, average untreated control disease index (DI) on a per environment (location/year) basis

***CY*, average untreated control yield on a per environment (location/year) basis

****L, M, and H*, low, medium, and high level of head blast, respectively, on a per environment (location/year) basis

****Average CDI and CY for each pressure category the locations. However, this cultivar was not adapted to all locations, and other susceptible cultivars were used (Table 1). Fungicides were applied using current commercial recommendations to control WHB according to doses registered at the Brazilian Ministry of Agriculture, Livestock and Supply (MAPA by its Portuguese acronym), (MAPA 2017). The check treatment consisted of unsprayed plots. The fungicide treatments used in these experiments included systemic mixtures alone, systemic mixtures combined with multi-site or multi-site fungicides alone (Table 2). Fungicides were each applied three times beginning at spike emergence and following at seven-to-ten-day intervals. The experimental design was a randomized complete block with four replicates. Each plot (experimental unit) was 12 m^2. Fungicide applications were made using a handheld compressed CO_2 sprayer calibrated to deliver a volume of 200 L/ha at 207 kPa using 110:03 double fan nozzles. Two-meter border rows were left unsprayed in an effort to minimize interplot interference. WHB intensity was rated as incidence (proportion of diseased head) and severity in a 100-head sample. Severity was assessed using an ordinal scale developed by Maciel et al. (2013). An overall WHB disease index (DI) was given by (severity*incidence)/100. Individual plots (4 m^2) were harvested and yields (kg/ha) were calculated.

Bolivia Experiments were carried out in the Santa Cruz Department, three at the Okinawa Municipality and three at the Quirusillas Municipality (Table 1). Experiments in Okinawa were set in 2013 and 2014 while experiments in Quirusillas were set in 2014 and 2015. Experimental treatments consisted of fungicides applied on the highly susceptible cultivar Atlax at the heading stage. The check treatment consisted of non-sprayed plots. Fungicides were each applied three times, at 20–30%, 70–80%, and 100% spike emergence (Cruz et al. 2015), which are the usual commercial rates and times in Bolivia recommended for highly susceptible cultivars (Table 2). The experimental design consisted of a randomized complete block with four blocks (1.5 m wide alleyways around blocks). Each plot (experimental unit) was 20 m^2. Seeds used in all experiments were treated with carboxin 20% + thiram 20% at a dose of 200 ml/100 kg of seeds. Each study was planted at 150 kg/ha at a depth of 2–3 cm. Prior to sowing, weed control was attained with glyphosate. Fungicides were applied with a handheld compressed air sprayer calibrated to deliver a volume of 100 L/ha at 207 kPa using TXA8001VK hollow cone nozzles spaced 50 cm apart on 2-m-long boom. The number of heads was recorded from two chosen samples of one-meter length rows per replicate. The two numbers were averaged and expressed as number per linear meter. Severity was assessed using an ordinal scale (0, 25, 50, 75, or 100% blast severity). The WHB disease index (DI) was calculated the same as in the Brazilian trials. Individual plots (4 m^2) were harvested and yields (kg/ha) were calculated.

Table 2 Fungicide treatments used in the field experiments in Brazil and Bolivia

Country	Fungicide	kg a.i./ha
Brazil	Pyraclostrobin 26% + epoxiconazole 16%	0.1 + 0.06
	Thiophanate methyl 14% + mancozeb 64%	0.350 + 1.60
	Trifloxystrobin 15% + prothioconazole 17.5	0.075 + 0.0875
	Azoxystrobin 12% + tebuconazole 2%	0.090 + 0.150
	Azoxystrobin 12.5% + tebuconazole 24%	0.075 + 0.144
	Trifloxystrobin 10% + tebuconazole 20%	0.05 + 0.1
	Pyraclostrobin 13.3% + epoxiconazole 5%	0.099 + 0.038
	Tebuconazole 20%	0.15
	Mancozeb 75%	1.875
Bolivia	Picoxystrobin 20% + cyproconazole 8%	0.1 + 0.04
	Trifloxystrobin 10% + tebuconazole 20%	0.1 + 0.2
	Azoxystrobin 20% + cyproconazole 8%	0.1 + 0.04
	Pyraclostrobin 26% + epoxiconazole 16%	0.1 + 0.06
	Tricyclazole 75%	0.225

Statistical analyses

Data sets from each country were analyzed separately due to differences in fungicide treatments and cultivars used. Fungicide treatment effects were tested by combining data from all trials within each country (Moore and Dixon 2015). The dependent variables were disease index (DI) and wheat yield. Additionally, an analysis of covariance (Littell et al. 2006) used a control disease index (CDI) as covariate to account for differences in disease severity and incidence among environments. The disease intensity in the check treatments defined three CDI levels as follows: low (CDI = 10), moderate (CDI = 40), and high (CDI = 70). All analyses were conducted using SAS PROC MIXED (SAS Institute Inc., v. 9.3) to fit a linear mixed model to the data. Fungicide treatment as the fixed effect, and environment, block within environment, and the environment × treatment interaction as random effects. For the covariate part of the analysis, equality of linear and quadratic covariate (*i.e.* CDI) slopes was tested, followed by fitting of an unequal or equal slopes model as appropriate (Littell et al. 2006). Fungicide treatment means were compared using SAS LSMEANS. Mean differences and their 95% confidence intervals were reported for three CDI categories.

Results

The mean disease index values on a per environment basis varied substantially, with similar ranges observed for both countries (Table 1). In Brazil, WHB mean CDI was 6.3%, 40.2%, and 80.5% at low, medium, and high CDI categories, respectively. In Bolivia, DI in these same categories averaged 9.6%, 34.9%, and 70.2%, respectively. These levels based our selection of covariate levels for reporting model results (*i.e.* CDI = 10, CDI = 40, and CDI = 70). Londrina (Brazil), and Quirusillas (Bolivia), locations with the highest levels of disease pressure, are typical hotspots for the wheat blast disease. Models with CDI as a covariate explained a high percentage of the variance (r^2 = 0.97–0.98) in DI across fungicides and environments (Table 3). Covariate models did a poorer job of explaining variance in wheat yield across fungicides and environments (r^2 = 0.45).

Brazil In Brazil, DI increased ($p < 0.0001$) with the covariate (CDI) as did differences among fungicides (Table 3). Estimated reductions in DI across treatments averaged 4% (95% C.I.: ±4%), 12% (95% C.I.: ±8%), and 27% (95% C.I.: ±6%) at low, moderate and high CDI levels, respectively (Fig. 1a). Wheat yields declined ($p = 0.0013$) with increasing baseline disease level (CDI; Table 3, Fig. 1b, Supplementary Fig. 1A). Average yield responses across treatments were 333 kg/ha (95% C.I.: ±141 kg/ha), 425 kg/ha (95% C.I.: ±128 kg/ha), and 517 kg/ha (95% C.I.: ±195 kg/ha) at low, moderate and high baseline disease levels, respectively (Fig. 1b).

Differences ($p < 0.05$) in linear (F × CDI) and/or quadratic (F × CDISQ) trends among fungicide treatments were observed for both disease index (DI) and wheat yield (Table 3; Fig. 1). Maximum efficacy (42–44% reduction in DI) was observed for mancozeb 75% at the high baseline disease level, followed by thiophanate methyl 14% + mancozeb 64% with 37–39% reductions in DI, and azoxystrobin 12% + tebuconazole 24%, with 27–39% reductions in DI (Fig. 1a). Reductions were lower than 30% for the remaining fungicide treatments.

Thiophanate methyl 14% + mancozeb 64%, and mancozeb 75% were consistently associated with the largest yield increases at the moderate to high baseline disease levels (Fig. 1b, Supplementary Fig. 1A). Yield responses to mancozeb 75%, in particular, were consistently greater ($p < 0.05$) than all other fungicide treatments, except thiophanate methyl 14% + mancozeb 64%, at moderate to high baseline disease levels (Fig. 1b). Yield increases for thiophanate methyl 14% + mancozeb 64%, and mancozeb 75% were, respectively, 705 kg/ha (95% C.I.: ±145 kg/ha) and 750 kg/ha (95% C.I.: ±132 kg/ha) at moderate disease levels, and 880 kg/ha (95% C.I.: ±212 kg/ha) and 1061 kg/ha (95% C.I.: ±215 kg/ha) at high disease levels (Fig. 1b). The remaining fungicide treatments produced yield increases less than 600 kg/ha.

Bolivia As observed for the Brazilian data, DI increased ($p < 0.0001$) with increasing CDI levels (Table 3). Estimated reductions in head blast across fungicide treatments averaged 7% (95% C.I.: ±7%), 36% (95% C.I.: ±5%), and 64% (95% C.I.: ±8%) at low, moderate and high baseline disease levels, respectively (Fig. 2a). A common linear trend associated with baseline disease level was not detected for wheat yield ($p = 0.59$; Table 3). Yield did decline rapidly with increasing CDI (*i.e.* disease pressure), but only for the control treatment (Supplementary Fig. 1B). Declines in yield were small for the fungicide treatments, resulting in a F x CDI interaction (Table 3), but no overall linear CDI effect. Average yield response across fungicide treatments was 767 kg/ha (95% C.I.: ±553 kg/ha), 1288 kg ha (95% C.I.: ±371 kg/ha), and 1809 kg/ha (95% C.I.: ±592 kg/ha) at low, moderate and high baseline disease levels, respectively (Fig. 2b).

Differences ($p < 0.05$) in linear (F × CDI) trends among fungicide treatments were observed for disease index (DI) and wheat yield (Table 3). Differences in predicted fungicide efficacy were, nonetheless, minor, with all fungicides reducing ($p = 0.0001$) head blast DI 32–38% and 58–68% from moderate and high baseline disease levels, respectively (Fig. 2a).

All fungicides increased yield at moderate to high baseline disease levels (Fig. 2b, Supplementary Fig. 1B). Picoxystrobin

Table 3 Covariate analysis summary tables. Dependent variables for the traditional combined experiment analyses included disease index and wheat yield

	Disease index (DI)				Wheat yield			
	Bolivia		Brazil		Bolivia		Brazil	
Effect	F value	Pr > F	F value	Pr > F	F value	Pr > F	F value	Pr > F
Fungicide (F)	0.32	0.8985	0.75	0.6655	2.04	0.0764	5.24	<0.0001
Linear trends								
Control disease index (CDI)	55.95	<0.0001	78.57	<0.0001	0.29	0.5882	10.5	0.0013
F x CDI	35.78	<0.0001	1.65	0.0977	2.76	0.0208	3.73	0.0001
Quadratic trends								
CDI-squared (CDISQ)	NS	.	8.03	0.0048	NS	.	NS	.
F x CDISQ	NS	.	3.34	0.0006	NS	.	NS	.
R^2 for model	0.983		0.966		0.454		0.452	

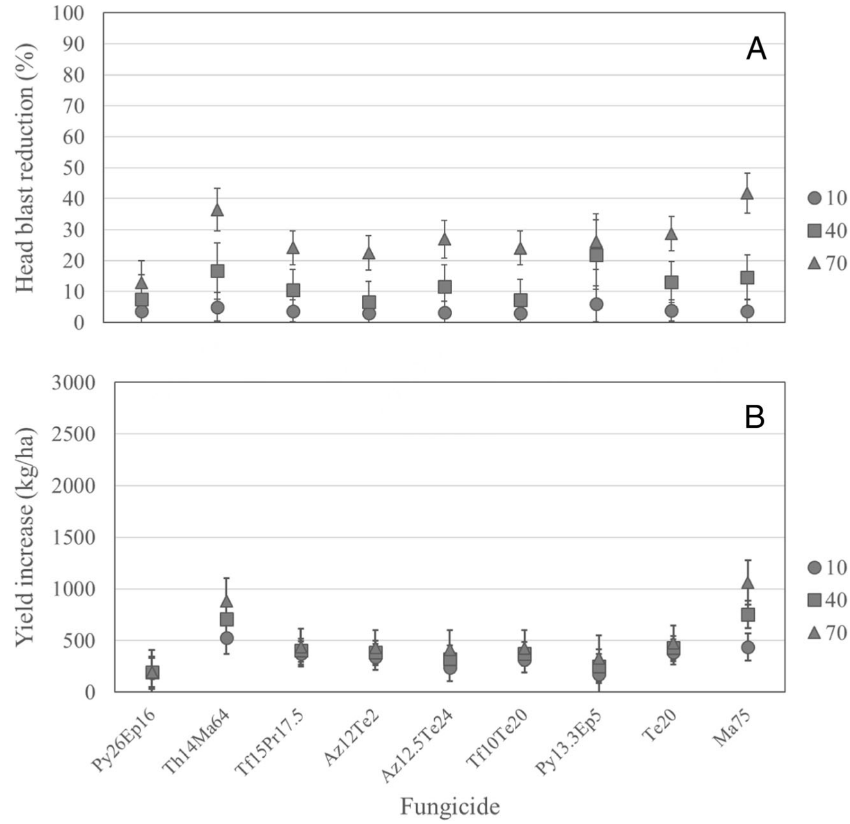

Fig. 1 Predicted fungicide effect sizes for wheat head blast **a** and wheat yield **b** at three levels of disease pressure (*i.e.* control disease indices of 10, 40, and 70) in Brazil. Bars represent 95% confidence intervals. Py26Ep16= pyraclostrobin 26% + epoxiconazole 16%; Th14Ma64= thiophanate methyl 14% + mancozeb 64%; Tf15Pr17.5= trifloxystrobin 15% + prothioconazole 17.5; Az12Te2= azoxystrobin 12% + tebuconazole 2%; Az12.5Te24= azoxystrobin 12.5% + tebuconazole 24%; Tf10Te20= trifloxystrobin 10% + tebuconazole 20% ; Py13.3Ep5= pyraclostrobin 13.3% + epoxiconazole 5%; Te20= tebuconazole 20%; Ma75= mancozeb 75%

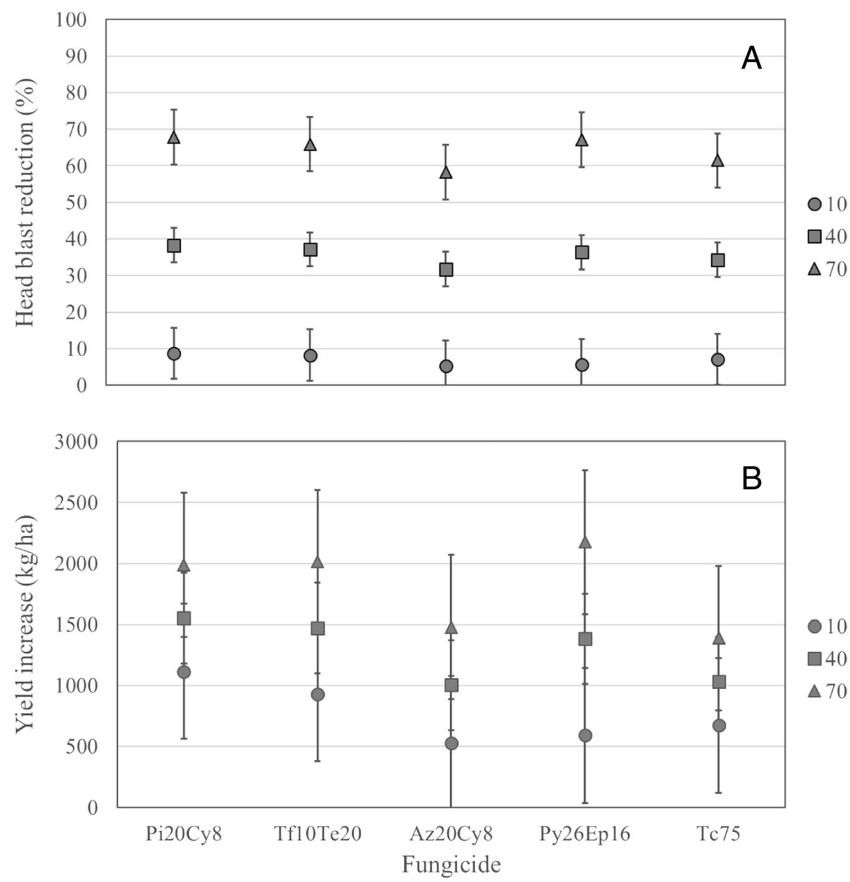

Fig. 2 Predicted fungicide effect sizes for wheat head blast **a** and wheat yield **b** at three levels of disease pressure (*i.e.* control disease indices of 10, 40, and 70) in Bolivia. Bars represent 95% confidence intervals. Pi20Cy8= picoxystrobin 20% + cyproconazole 8% ; Tf10Te20= trifloxystrobin 10% + tebuconazole 20%; Az20Cy8= azoxystrobin 20% + cyproconazole 8%; Py26Ep16= pyraclostrobin 26% + epoxiconazole 16% ; Tc75= tricyclazole 75%

20% + cyproconazole 8%, trifloxystrobin 10% + cyproconazole 8%, and pyraclostrobin 26% + epoxiconazole 16% produced average yield increases of 1542 kg/ha and 2125 kg/ha at moderate and high baseline disease levels, respectively, and 1834 kg/ha across environments. Azoxystrobin 20% + cyproconazole 8% and tricyclazole 75% produced average yield increases of 1033 kg/ha and 1449 kg/ha at moderate and high baseline disease levels, respectively.

Discussion

Fungicide efficacy for the management of WHB is currently disputed. No previous study has attempted to reconcile contradictory evidence on the efficacy of WHB chemical control under broad conditions for blast development. Recent outbreaks of WHB in South America and South Asia have led to a renewed interest in chemical control. In the present study, fungicide performance was evaluated and compared in 23 environments across Brazil and Bolivia to determine the conditions under which certain fungicides might be recommended for WHB control. Disease development varied substantially across environments, with a broad range of epidemic levels observed for both countries. This provided a uniquely robust data set for examining the consistency of fungicide efficacy against WHB. The results support the use of fungicides for WHB control at moderate to high disease pressure in both countries. However, we demonstrated that current chemical strategies in South America to control WHB could have radically different results depending on country and disease pressure. Although there were significant differences among fungicides for both disease reduction and yield increase in both countries, it was clear that fungicide efficacy was lower in Brazilian compared to Bolivian environments. Overall fungicide efficacy increased as disease pressure increased, but fungicides performed particularly poorly at high disease pressure in Brazil compared to Bolivia. Correspondingly, wheat yields declined with increasing disease pressure in both countries, but less so in Bolivia compared to Brazil (for fungicide treatments; declines were similar in both countries for control plots). Such striking differences in responses between countries warrant further investigation. Possible explanations include differences in environments, fungicide use, and differential sensitivity among MoT populations. The existence of less sensitive MoT populations in Brazil with less sensitivity to fungicides of the QoI chemical group and lower fungicide efficacy of fungicides of the DMI chemical group have been reported (Castroagudín et al. 2015; Goulart and Paiva 1993; Oliveira et al. 2015; Santana et al. 2013). In our study, pyraclostrobin 26% + epoxiconazole 16% and trifloxystrobin 10% + tebuconazole 20%, QoI plus DMI premixes, were the only treatments evaluated in both countries. However, only pyraclostrobin 26% + epoxiconazole 16% was used at the exact same concentration in both countries. Consistent to the general pattern described above, the efficacy of pyraclostrobin 26% + epoxiconazole 16% was more limited in Brazil than in Bolivia, especially under moderate and high levels of disease pressure. A definitive conclusion, however, must await characterization of fungicide sensitivity among Bolivian MoT isolates, as well as experiments that directly link fungicide sensitivity of MoT isolates to fungicide efficacy in both countries.

Based on the evidence provided in this manuscript, we conclude that fungicide performance for WHB control can be effective even under environmental conditions that favor the disease. Specific fungicides showed significant level of WHB control at moderate to high disease pressure in Brazil and Bolivia. In Brazil, mancozeb-based fungicides were consistently associated with greater WHB reductions and yield increases at moderate and high disease levels. However, these fungicides were not sufficient to reduce WHB and to increase yields to levels comparable to those observed in Bolivia. For example, in Brazil, under all conditions tested, no fungicide treatment resulted in yield gains higher than 1276 kg/ha. Even the best fungicides in Brazil might not be sufficient to reduce WHB and increase yields to satisfactory levels, and it is unlikely that three fungicide applications would protect plants sufficiently to offset the costs. In Bolivia, in contrast, all fungicides reduced head blast and produced yield increases from moderate and high baseline disease levels, and provided an average yield gain of 1834 kg/ha, 43.7% higher than the highest yield gain reported in Brazil with mancozeb 75%. It would, therefore, be advisable for Bolivian producers to use QoI plus DMI premixes, which produced the highest yield increases; however, the known existence of reduced sensitivity to fungicides of the QoI and DMI chemical groups in Brazilian populations (Castroagudín et al. 2015; Goulart and Paiva 1993; Oliveira et al. 2015; Santana et al. 2013) provides a caveat. Proactive fungicide resistance avoidance in Bolivia is needed. Given that multiple effective fungicides exist in Bolivia, the establishment of a fungicide rotation program is highly recommended.

Although there was no compelling evidence in this study to support general fungicide recommendations for WHB management, we encourage researchers to address the effect of fungicide timing to anticipating sprays to target MoT infections on leaves. Understanding the dynamics of MoT inoculum buildup and the significance of auto-infection (Cruz et al. 2015) could aid in determining optimal fungicide application timing. Even though a fundamental question concerns the source of inoculum, it is well documented that MoT sporulation on leaves of highly susceptible cultivars can coincide with spike emergence (Cruz et al. 2015; Cruz and Valent 2017). Regardless of the source of inoculum, whether within or outside fields, the heads should be protected. However, earlier fungicide applications that target MoT infections on leaves could provide a potential reduction and better control of

WHB in some cultivars (Cruz et al., 2015). Additionally, integrated approaches in other pathosystems have proven to be more effective than the simple use of fungicides alone (Bayer et al. 2006; Paul et al. 2007). Further studies are needed to assess the impact of fungicides in integrated management programs under a range of cultivars with known resistance or susceptible reactions to leaf blast, head blast, or both. Combining blast genetic resistance with fungicide protection tactics might be more effective than either approach alone. The results presented in this manuscript can help guide producers, extension educators, and national emergency first responders regarding fungicide application decisions, and help scientists identify priorities for future research.

Acknowledgements Our research on wheat blast disease has been funded by Agriculture and Food Research Initiative Competitive Grants 2009-55605-05201 and 2013-68004-20378 (Blast Integrated Project) from the United States Department of Agriculture National Institute of Food and Agriculture (USDA-NIFA). This work was supported by the USDA National Institute of Food and Agriculture, Hatch Project 1016253. We thank Purdue University start-up funds for supporting this work.

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