Euphytica (2021) 217:84
https://doi.org/10.1007/s10681-021-02816-w

Evaluation of wheat genotypes for field resistance to wheat blast caused by *Magnaporthe oryzae* pathotype Triticum (MoT) and correlation between yield loss and disease incidence in the Brazilian Cerrado

Alexei de Campos Dianese · **Ana Beatriz Zacaroni** · **Bruno Cézar Pereira de Souza** · **Ana Paula da Silva Pagani** · **Nelson Oliveira Pinheiro** · **Eduardo Monteiro de Castro Gomes** · **Gisele Abigail Montan Torres** · **Luciano Consoli** · **Adalberto Corrêa Café-Filho**

Received: 4 August 2020 / Accepted: 27 March 2021 / Published online: 9 April 2021

Abstract Wheat blast caused by *Magnaporthe oryzae* pathotype Triticum (MoT) has become an important fungal disease on wheat and is now present in most of the important wheat-producing tropical regions of the world. This study evaluated head blast incidence on the spikes of 281 hexaploid wheat genotypes and two *Triticum durum* cultivars across three years (2011–2013) in the Cerrado Biome in the Brazilian Midwest, a hotspot area and where the highest disease levels have been recorded. Forty eight host lines exhibiting moderate to high resistance to the disease included synthetic hexaploid wheat genotypes (SHW) and derivatives (17), breeding lines (16), landraces (2), and cultivars (13). Thirty early genotypes were identified to have head blast incidence levels similar to the moderately resistant cultivar BR 18. In addition, seven medium maturing genotypes and ten late maturing genotypes had average disease incidence scores on spikes below 35%. These were grouped separately from all other materials. This study also indicated a strong correlation between head blast incidence and yield loss, indicating that incidence

Supplementary information The online version contains supplementary material available at (https://doi.org/10.1007/s10681-021-02816-w).

A. de Campos Dianese (✉)
Embrapa Cerrados (Brazilian Agricultural Research Corporation, Embrapa Cerrados), Caixa Postal 08223, Rodovia BR 020, km 18, Planaltina, DF 73310-970, Brazil
e-mail: alexei.dianese@embrapa.br

A. B. Zacaroni · B. C. P. de Souza · N. O. Pinheiro
Brasília, Brazil

A. P. da Silva Pagani
Goiânia, Brazil

E. M. de Castro Gomes
Departamento de Estatística/UnB, Campus Universitário Darcy Ribeiro, Brasília, DF 70910-900, Brazil
e-mail: edumonteiro@unb.br

G. A. M. Torres · L. Consoli
Embrapa Trigo, PO Box 3081, Passo Fundo, RS 99001-970, Brazil
e-mail: gisele.torres@embrapa.br

L. Consoli
e-mail: luciano.consoli@embrapa.br

A. C. Café-Filho
Departamento de Fitopatologia, Instituto de Biologia/UnB, Campus Universitário Darcy Ribeiro, Brasília, DF 70910-900, Brazil
e-mail: cafefilh@unb.br

could be an appropriate selection parameter in breeding programs targeting blast resistance.

Keywords Brusone · *Pyricularia oryzae* · Blast reaction

Introduction

Wheat blast or 'brusone', caused by *Magnaporthe oryzae* pathothype Triticum (MoT) (Catt.) B.C. Couch 2002 (asexual morph *Pyricularia oryzae* Cavara 1892) (Couch and Kohn 2002; Zhang et al. 2016), was first detected in commercial wheat fields in 1985, in Paraná state in Brazil (Igarashi et al. 1986). Currently, the pathogen is present on all wheat-producing regions of the country, and also in Bolivia, Paraguay and Argentina (Barea and Toledo 1996). It was identified in Bangladesh in 2016 (Islam et al. 2016; Ceresini et al. 2019) and was reported in Zambia in 2020 (Tembo et al. 2020). The Lolium pathothype (MoL) was recovered from a single blasted wheat plant found in Kentucky, USA in 2011 (Farman et al. 2017), although it was of no subsequent concern.

The blast fungus can infect different aerial parts of the plant at various stages of development. The most severe disease symptoms occur on spikes as partial or complete bleaching. Dark lesions that develop on the rachis interrupt the translocation of sap. Depending on the developmental stage, the plant can be severely damaged, with the formation of small, wrinkled grains with low test-weight (Goulart and Paiva 2000; Goulart et al. 2007). Yield losses due to wheat blast in Brazil have ranged from 10.5 to 100% (Goulart and Paiva 1992, 2000; Goulart et al. 2007; Cruz and Valent 2017; Ferreira et al. 2020). Trials conducted in the Brazilian Cerrado, where conditions are particularly favorable for the disease (Trindade et al. 2006; Rocha et al. 2019), indicated lack of adequately resistant cultivars and low efficacy of available chemical control products (Pagani et al. 2014). Wheat blast is recognized as a threat to wheat production in tropical regions of the world (Rocha et al. 2019; Sharma and Singh 2020) and risk assessment studies were initiated in Brazil (Fernandes et al. 2017) and worldwide (Duveiller et al. 2016).

A number of studies, conducted under controlled conditions and field trials to evaluate the performance of wheat cultivars in areas where MoT is present (Goulart and Paiva 1992; Urashima et al. 1993; Urashima and Kato 1994; Goulart et al. 1995, 2007; Arruda et al. 2005; Prestes et al. 2007; Cruz et al. 2010), identified several cultivars as moderately resistant to wheat blast. As a consequence, cultivars BH 1146 and BR 18 were recommended for planting in the Cerrado area. BR 18 continues to be recommended in the region (Ferreira et al. 2020).

Finding wheat genotypes with both leaf and spike resistance to blast has proven to be a challenge, because these resistant types do not always correlate (Arruda et al. 2005; Ferreira et al. 2020). Cruz et al. (2011) reported a limited correlation of 64% between spike reaction and leaf reaction. Until recently, isolate-specific blast resistance genes were unknown in the MoT x wheat pathosystem (Trindade et al. 2006). However, between 2008 and 2015, four resistance genes, *Rmg2*, *Rmg3*, *Rmg7*, and *Rmg8*, were identified and shown to be effective in seedling trials against certain groups of MoT isolates obtained from wheat plants (Zhan et al. 2008; Tagle et al. 2015; Anh et al. 2015). Moreover, Cruz et al. (2016) showed a positive correlation between the resistance of some wheat accessions to MoT and the presence of a chromosomal translocation (2NS/2AS) involving chromatin from *Aegilops ventricosa*. Finally, Ferreira et al. (2018) identified several resistant wheat lines that did not have the 2NS/2AS translocation.

Breeding for resistance involves the evaluation and selection of host accessions with the highest levels of resistance traits under uniform inoculum levels. As disease intensity on a given host genotype varies with prevailing environmental conditions and magnitude of the pathogen population (often referred to as 'disease pressure'), 'hotspot' trials were established in locations where natural infection was most likely and genetic diversity of the pathogen was greatest in order to ensure detection of the most effective and stable resistance sources (Dias Neto et al. 2010; Urashima et al. 2004).

This present work reports the blast responses of 283 wheat genotypes in a hotspot location and attempts to quantify the relationship between wheat blast incidence and yield loss.

Materials and methods

Plant materials and experimental conditions

A collection of 281 hexaploid wheat genotypes and two *Triticum durum* cultivars, from Embrapa Trigo Germplasm Bank (BAG-Embrapa Trigo), was evaluated between 2011 and 2013 in the field in a hotspot at Embrapa Cerrados Experimental Station, located at Planaltina, DF, Brazil (17°35′03″S, 47°42′30″W, 1100 m altitude). The panel included landraces, commercial cultivars, breeding lines and synthetic hexaploid wheat (SHW) lines. Accessions identified as CBFusarium ENT are synthetic wheat derivatives from a crossing block (CB) distributed by CIMMYT.

Each genotype was manually sown with a density of 65 seeds m^{-1}. Each experimental unit consisted of one 3-m row, which was replicated three times per genotype. The distance between rows was 20 cm. The replications were distributed in a completely randomized design. There were one to three years of disease evaluation data per genotype (i.e., three to nine observations). One hundred and eighteen genotypes were sown on February 17, 2011, 146 on February 15, 2012, and 134 on February 15, 2013. The environmental conditions were also highly conducive to wheat blast infection (Torres et al. 2009). Weeds and pests were controlled by metsulfuron-methyl and chlorpyrifos, at recommended dosages, respectively. Four hundred kg of NPK 4-30-16 + boron fertilizer were applied at planting, followed by 80 kg ha^{-1} of N at 20 and 40 days after emergence.

Maturity status was based on the number of days between planting and 50% fully emerged spikes per genotype, and materials were classified as early maturing (up to 60 days post planting), medium maturing (61 to 75 days) or late maturing (over 75 days). Maturity status of the host genotype impacts blast intensity by affecting the duration of the epidemics of this polycyclic disease.

Disease and grain yield evaluation

Genotypes were classified according to maturity grouping, evaluated for blast incidence on the spikes, and yield. Blast incidence evaluation for each plot started at 50% total-spike emergence. Each spike showing bleaching symptoms was marked with a coloured ribbon and the plots were assessed weekly until maturity. For each year the average blast incidence (ratio between the number of bleached spikes/total number of spikes in the plot) X 100) per plot/per genotype was determined. The data were used to compare blast levels among genotypes within each maturity cycle.

The impact of wheat blast incidence on grain yield was verified twice by determining yield loss of the early cycle genotypes in 2011 and 2013. The harvest was performed manually separating healthy spikes from infected spikes. The number of healthy, infected, and total spikes of each plot was determined, healthy and infected spikes were threshed, and the grains weighed separately for each experimental unit. Synthetic wheat materials were not included due to hand threshing difficulties. In 2013 the genotypes with 100% spike blast incidence were not harvested.

Data analysis

The Scott-Knott method for unbalanced experiments (Conrado et al. 2017) was implemented in the R language to compare and classify genotypes for each maturation group. Conrado et al. (2017) presented and validated an adjustment of the Scott-Knott method with minimal loss of power and satisfactory control of type I error. The adjustments allowed balancing the standard error estimates in cluster analysis, by considering the unbalanced numbers of each treatment for all candidate partition subsets.

Yield loss (L) was determined by the difference between potential yield (PY) and actual yield (AY), according to calculations proposed by Goulart et al. (1993):

$$\begin{aligned} \mathrm{L} &= \mathrm{PY} - \mathrm{AY} \\ \mathrm{PY} &= (\mathrm{GWHS}/\mathrm{NHS}) \times \mathrm{NTS} \\ \mathrm{AY} &= \mathrm{GWHS} + \mathrm{GWIS} \end{aligned}$$

where

$$\begin{aligned} \mathrm{GWHS} &= \text{Grain weight of healthy spikes}/ \\ &\quad m^2\left(\text{assuming} \times \text{rows per m}^2\right) \\ \mathrm{NHS} &= \text{Number of healthy spikes/m}^2 \\ \mathrm{NTS} &= \text{Total number of spikes/m}^2 \\ \mathrm{GWIS} &= \text{Grain weight of infected spikes/m}^2 \end{aligned}$$

The data were extrapolated to kg ha^{-1}. Loss was defined as the reduction in the amount of grain (grain yield) caused by wheat blast and regression analysis between disease incidence and loss was performed. Head blast incidence was used as an independent variable and yield loss as the dependent variable.

Results and discussion

Field resistance of genotypes within each maturation cycle

One hundred and ninety four genotypes were classified as early, 60 as medium and 29 as late maturing. Considering the entire three-year period 97 genotypes reached 100% disease incidence and were not included in the statistical analysis (Online Resource 1, Table a). The analysis of variance for the remaining 186 genotypes is shown in Table 1.

There were significant differences among the genotypes for each maturity class for the average wheat blast incidence (Table 1). The analysis separated the genotypes into four clusters (a, b, c, and d) within the early (Table 2) and medium (Table 3) maturation groups and three clusters (a, b and c) for the late maturation genotypes (Table 4).

Early maturation group

Thirty-one genotypes formed cluster ‘a’ with mean blast incidence varying from 7.66 to 38.99% (Table 2). The lowest mean disease incidences in this cluster were 7.66 and 12.11% for CBFusarium ENT016 and CBFusarium ENT025, respectively. Genotypes marked CB were documented as having resistance to Fusarium head blight but had not been previously tested for blast reaction (Ferreira et al. 2020).

CPAC 07434 (19.37%), also in this cluster, carries the 2NS/2AS chromosome translocation (Ferreira et al. 2018, 2020), which has been associated with wheat blast resistance (Cruz et al. 2016). However, other genotypes in this cluster, including BR 18, BRS 229, BRS Angico, CPAC 07340, and Embrapa 27, also exhibited significant low blast incidence in this study and were classified as resistant by Ferreira et al. (2018, 2020), but do not carry that translocation. BR 18 and BRS 229 are two of the most important wheat cultivars in Brazil in terms of durable resistance to blast (Ferreira et al. 2018, 2020). BR 18 (38.78%) was released in 1986 and remains recommended for cultivation in the central region of Brazil, due to its blast resistance and baking quality (CBTT 2011, 2020; Ferreira et al. 2020). BRS 229 (32.26%) was commercially cultivated between 2004 and 2012 in Paraná state (Brazil) and was known for good resistance to blast and other major fungal diseases (Ferreira et al. 2018, 2020). BRS Angico (28.66%) and CPAC 07340 (34.88%) were also identified as sources of blast resistance in previous work (Ferreira et al. 2018). Embrapa 27 (35.03%) was frequently used as a breeding parent in the Embrapa wheat breeding program in the 1990s (Sousa et al., 2014). This cultivar also had the lowest blast severities on seedling leaves when inoculated with 18 M. *oryzae* isolates (Cruz et al. 2010), and showed spike resistance at the adult plant stage (Ferreira et al. 2018).

Cultivar BH 1146 (36.96%) was recommended for the Cerrado in the 1980s, since it was considered moderately resistant to wheat blast (Goulart and Paiva 1992; Urashima et al. 1993; Urashima and Kato 1994;

Table 1 Analysis of variance (mean squares, MS) for average wheat blast disease incidence (%) on spikes for early, medium, and late maturing genotypes evaluated for three consecutive years (2011–2013)

Source of variation	Maturity group					
	Early		Medium		Late	
	Df[1]	MS	Df	MS	Df	MS
Genotypes	111	1593.0*	47	1715.4*	25	1729.5*
Error	491	292.4	183	293.1	109	359.1

[1] *Df* Degrees of freedom

*Significant at $p = 0.01$ by the *F* test

Table 2 Head blast incidence (%) of 112 early maturing wheat genotypes observed in 2011, and/or 2012, and/or 2013 evaluated in 'hotspot' assays at Embrapa Cerrados, Planaltina, DF, Brazil

Genotype	Pedigree	Mean	Years assessed
CBFusarium ENT016	No Information	7.66a*	2013
CBFusarium ENT025	No Information	12.11a	2013
Casw96y00538s	D67.2/P66.270//Ae.squarrosa (301)	15.05a	2013
T 50130	Cook*4/VPM 1	19.27a	2011, 2012, 2013
CPAC 07434	Taurum/BRS 254	19.37a	2012, 2013
Cigm921698	Garza/Boy//Ae.tauschii (374)	25.51a	2013
PF 940110	PF-83743/PF-813019//PF-84296/PF-83743	27.03a	2013
CPAC 07407	No Information	27.33a	2012
BRS Angico	PF 87107/2*IAC 13	28.66a	2011, 2012, 2013
CPAC 0544	Embrapa 22/CM 106793	31.63a	2012
Opata 85	Bluejay(SIB)/Jupateco 73	31.71a	2011, 2012, 2013
Cigm87.2771	Altar-84/(TR.TA)WX-211	31.97a	2013
BRS 229	Embrapa 27*3//BR 35/Buck Poncho	32.26a	2012, 2013
IPF 82880	W-3918-A/Jupateco-73	32.38a	2013
PF 030027/1	CEP 24 SEL/BRS 194	33.15a	2013
Giza	Landrace	33.85a	2011, 2012, 2013
CPAC 0787	BRS 208/PF 990607//PF 980354	34.17a	2012, 2013
CPAC 07340	CPAC 96306/CPAC 9985	34.88a	2012, 2013
Embrapa 27	PF 83743//PF 83182/F 25716	35.03a	2011, 2012, 2013
BRS 220	Embrapa 16/TB 108	36.05a	2011, 2012, 2013
Cigm93275	Arlin_1/Ae.tauschii (536)	36.23a	2013
Ônix	CEP 24/(SIB)/Rubi	36.30a	2011, 2012, 2013
CPAC 0761	Taurum/CPAC 98222//CPAC 96306/PF 973047	36.66a	2012
BH 1146	PG 1//Fronteira/Mentana	36.96a	2011, 2012, 2013
BRS 179	BR 35/PF 85946/3/PF 772003*2/PF 813//PF 83899	37.33a	2011, 2012, 2013
PF 100757	BH 1146/CEP 24//BRS 229	37.39a	2013
PF 993118-B	Graneiro INTA/CPAC 92108	37.71a	2012
PF 100660	MGS 1-Aliança/WT 99172	38.10a	2013
BRS Timbauva	BR 32/PF 869120	38.53a	2012, 2013
BR 18	D 6301/Nainari 60//Weique/Red Mace/3/Ciano 67*2/Chris	38.78a	2011, 2012, 2013
PF 023186ca	Klein H 3394 A 3110/PF 990744	38.99a	2013
PF 92482 (825518)	BR-35*5//BR-14*2/Largo	40.30b	2013
CPAC 0691	Iapar 17/CPAC 98222	41.61b	2012
CPAC 06298	Babax/3/Vee/PJN//2*Tui	41.77b	2012
Embrapa 40	PF 7650/NS 18 78//CNT 8/PF 7577	44.29b	2011, 2012, 2013
BRS Louro	PF 869114/BR 23	44.63b	2011, 2012, 2013
BRS 208	CPAC 89118/3/BR 23//CEP 19/PF 85490	44.98b	2011, 2012, 2013
PF 015733C/1	PF 99602/WT 98109	45.07b	2013
PF 990606	TB 951/TB 941	45.31b	2011, 2012
CPAC 05342	CPAC 931042/Diamante INTA	45.49b	2012
PF 020037	PF 89375*2/CEP 24	46.50b	2011, 2012, 2013
BR 24	IAS 58*2/Eagle	46.59b	2011, 2012, 2013
Lagoavermelha	Veranopolis*2//Marroqui/Newthatch	46.97b	2011, 2012, 2013
PF 050771	IPF 78786	47.15b	2012, 2013

Table 2 continued

Genotype	Pedigree	Mean	Years assessed
PF 909	PF 83743/PF 82252//PF 84433/BR 35	47.29b	2011, 2012, 2013
Menceki	LV TUR	47.65b	2011, 2012, 2013
CPAC 05406	Embrapa 22*3/Sonora 64	47.68b	2012
PAT 7392	J 12326 67/IAS 55	48.44b	2011, 2012, 2013
PF 040007	MRGA/Yecora Rojo-2	49.61b	2012
CPAC 07258	CPAC 96306/CPAC 9985	49.66b	2012
BRS 207	Seri 82/PF 813	49.84b	2011, 2012, 2013
PF 090452	PF 89375/PF 990607	50.60b	2013
Hartog	Vicam 71//Ciano 67(SIB)/Siete Cerros 66/3/Kalyansona/Bluebird	50.62b	2012, 2013
Brilhante	PF 8640/BR 24	50.70b	2011
CPAC 0549	Embrapa 41/PF 88414	51.02b	2012
BR 32	IAS 60/Indus 66//IAS 62/3/Alondra/4/IAS 59	51.70b	2011, 2012, 2013
Anahuac 75	II 12300//Lerma Rojo 64/II 8156/3/Norteno 67	52.01b	2011, 2012, 2013
Siete Cerros	Penjamo 62 SIB/Gabo 55	52.05b	2011, 2012
CPAC 04295	Embrapa 22/BR 33	52.26b	2012
BRS 254	Embrapa 22*3/Anahuac 75	53.13b	2012
CPAC 06266	Embrapa 42/TB 951	53.19b	2012
PF 100332	BR 18/MGS 1-Aliança	53.29b	2013
CPAC 0754	Taurum/BRS 207//PF 8190/BR 18	53.58b	2012
Morocco	Landrace	53.76b	2012
Quartzo	Ônix/Avante	55.24b	2013
IPF 79812	No Information	55.72c	2013
BRS 49	BR 35/PF 83619//PF 858/PF 8550	56.04c	2011, 2012, 2013
CPAC 04347	CPAC 8947/CPAC 8886	56.54c	2012
PF 9127	BR 32/BR23//BR 32/BR 35	56.76c	2011, 2012, 2013
CPAC 0770	Taurum/CPAC 98222//CPAC 96306/PF 973047	57.22c	2012
PF 030019	IPF 71449/2*BRS 177	58.31c	2011, 2012
Londrina	IAS 16 /4/ Norin 10 B17/Yaqui 53//Yaqui 50 /3/ Kentana 54B	58.72c	2011, 2012, 2013
IAS 20	Colonias//Frontana/Kenya 58	59.19c	2011, 2012, 2013
Casw94y00064s	Local Red/Ae.squarrosa (220)	60.55c	2011
CPAC 07265	CPAC 96306/CPAC 9985	60.65c	2012
Taurum	Bobwhite/Nacozari//Veery/3/Bluejay/Cocoraque	61.07c	2012
Tota 63	Yaqui 53//Bonza 55/Kenya AJ	61.10c	2011, 2012
BR 35	IAC 5*2/3/CNT 7*3/Londrina//IAC 5/Hadden	62.09c	2011, 2012, 2013
CPAC 04215	No Information	62.84c	2012
PF 92482 (825590)	BR-35*5//BR-14*2/Largo	63.19c	2013
CD 108	TAM 200/Turaco	63.84c	2013
W 185	Tobari 66//Ciano SIB/Tokwe	65.76c	2011, 2012
CPAC 07259	CPAC 96306/CPAC 9985	66.05c	2012
Ruminahui	Marne Desprez//McMurachy/Egipto/3/*2AF/Mayo	66.79c	2011, 2012
Cruza 0454	Romany//Gabo/Gamenya	66.91c	2011, 2012, 2013
CPAC 0794	Taurum/BRS 254	67.47c	2012
PF 92482	BR-35*5//BR-14*2/Largo	68.03c	2011, 2012
CPAC 05266	Embrapa 42/CPAC 9548	68.90c	2012
Iniaf 66	Lerma Rojo 64/Sonora 64	69.39c	2011, 2012

Table 2 continued

Genotype	Pedigree	Mean	Years assessed
CPAC 05164	BR 33/PF 91627	69.96c	2012
PF 040006	BH 1146/MAX 15	70.30c	2012
IPR 85	Iapar 30/BR 18	70.82c	2011, 2012
PF 980354	BR 35/CEP 24//PF 88522	71.29c	2011, 2012
Ning84n1406	No Information	71.52c	2011, 2012
PF 090299	WT 98109/TB 0001	71.93c	2013
PF 781198	Nadadores 63/3/Chris SIB//Gloriabamba	72.58c	2011, 2012, 2013
CPAC 06232	Embrapa 22/Taurum	73.20c	2012
Karamu	Lerma Rojo//Norin 10/Brevor/4/Yaktana 54//Norin 10/Brevor/3/3*Andes	75.28d	2011, 2012
CPAC 07449	No Information	75.76d	2012
CPAC 07292	PF 973047/Taurum	76.07d	2012
CPAC 07263	CPAC 96306/CPAC 9985	76.38d	2012
PF 93157	MS 7936/2*Jacui//PF 83147/BR 15	76.64d	2011, 2012
PF 100334	BR 18/Aliança	78.14d	2013
PF 980270	Embrapa 40/PF 89232	80.54d	2011, 2012
Cass03gh00084s	SHAG_22/Ae.squarrosa (721)	83.39d	2011
CPAC 05347	CPAC 93,175/Granero INTA	84.43d	2012
CPAC 05345	CPAC 93,175/Granero INTA	86.00d	2012
CPAC 05320	CPAC 93175/Granero INTA	87.42d	2012
Maiteninia	Tezanos Pintos Precoz/Paloma//Siete Cerros 66	88.07d	2011, 2012
PF 87849	Jupateco 73*6/Toropi	95.95d	2011
303	No Information	98.17d	2011
Embrapa 42	LAP 689/MS 7936	99.32d	2011

*Means followed by the same lower-case letter in the column did not differ significantly from each other (Scott-Knott's method for unbalanced experiments, $p < 0.05$)

Goulart et al. 1995, 2007; Arruda et al. 2005; Prestes et al. 2007; Cruz et al. 2010). Unfortunately, it was prone to lodging (Goulart and Paiva 1992). In the present study, its performance was similar to BR 18, indicating that it remains an important source of resistance to blast (Table2).

Cultivar Anahuac 75 (52.01%) was previously considered susceptible to wheat blast and was frequently used as a susceptible check in field trials. However, in the present study, Anahuac 75 fell into group b, along with 34 other genotypes with an average incidence varying from 40.30 to 55.24% (Table 2). This included PF 909 (47.29%), which was considered resistant by Ferreira et al. (2018, 2020). Although Anahuac 75 had a mean blast incidence above 50%, 47 other genotypes in clusters c and d had higher blast incidence (Table 2).

The wheat blast incidence observed for cultivar Embrapa 42 (99.32%) (Table 2) agrees with recent reports, in which it was classified as susceptible (CBTT 2013; IAC 2018). This contrasts with the report of Rocha et al. (2019), who described cultivars Embrapa 42, Anahuac 75, and BRS 254 (53.13%) to have lower AUDPC values than cultivar BR 18, based on vegetative stage assessments. These contrasting results indicate that leaf and spike resistance to blast might not be correlated.

Among the 39 genotypes in cluster a, there were four synthetic wheat genotypes (SHW), Cas-w96y00538s (15.05%), Cigm921698 (25.51%), Cigm87.2771 (31.97%), and Cigm93275 (36.23%). These genotypes are potentially important for extending the sources of blast resistance beyond that available in conventional hexaploid wheat germplasm.

Table 3 Wheat head blast incidence of 48 medium maturing wheat genotypes observed in 2011, and/or 2012, and/or 2013 evaluated in 'hotspot' assays at Embrapa Cerrados, Planaltina, DF, Brazil

Genotype	Pedigree	Mean	Years of observation
Casw94y00116s	Cerceta/Ae.tauschii (533)	00.68a*	2011
CBFusarium ENT014	No Information	05.69a	2013
Casw00gh00065s	Local Red/Ae.tauschii (221)	07.96a	2011
CBFusarium ENT006	No Information	09.34a	2013
Cigm921696	DOY1/Ae.tauschii (370)	10.85a	2013
OC 8154	IAS-64/Aldan	18.15a	2013
IPR 144	Seri*3/Buc/5/Bow/3/Car 853/Coc//Vee/4/OC22	19.83a	2013
IPR 130	Rayon//Vee#6/Trap#1	25.08b	2013
Weebill1	Babax/Amadina//Babax	25.26b	2013
Casw94y00063s	Local Red/Ae.tauschii (219)	28.82b	2011
CD 118	Veery/Koel//Siren/3/Arivechi M 92	30.22b	2013
Cigm89567	Cerceta/(TR.TA)WX-895	30.91b	2013
Sumai3	Funo/Taiwan Xiaomai	33.01b	2012, 2013
PF 926	Oasis/BR-5//BR-5/Coker-762	35.34b	2011, 2012, 2013
Safira	PF 9099/OR 1//Granito	35.86b	2011, 2012
Cigm921666	Rascon/T.tauschii (312)	36.99b	2013
Kleinlucero	Klein Progreso/Apulia Klein	38.53b	2012
Jesuita	Polyssu/Alfredo-Chaves-3.21	39.28b	2011, 2012
PF 020458	FL 72185A-A2-C1/Embrapa 40//CEP 24	39.77b	2011, 2012
Patriarca	Trintecinco/Minuano	40.74b	2011, 2012
PF 89156	Sullivan/PF-79777	41.84b	2011, 2012
Lovrin13	Bezostaya 1/Fiorello	42.65b	2011, 2012
302	No Information	44.75c	2011
IPR 128	Vee/Lira//Bobwhie/3/BCN/4/Kauz	44.97c	2013
PF 9052	PF-8237//LAP-689/3*CNT-10	45.90c	2011, 2012
Embrapa10	CNT 8*3/Sonora 64	46.54c	2012, 2013
PF 990283	PF 93232//Thatcher*8/VPM-1	47.78c	2011, 2012
PF 090318	IPF 78917/PF 940051	47.89c	2013
PF 080310	PF 980533/PF 970227//BRS Guamirim	48.27c	2013
Peladinho	No Information	48.98c	2011, 2012
Veery2	Kavkaz/(SIB)Buho//Kalyansona/Bluebird	49.16c	2013
Castico (*T. durum*)	USA-III-C/Ganso//Geier/Flamingo Mex	49.29c	2011, 2012
Casw94y00065s	Local Red/Ae.tauschii (221)	51.34c	2011
Toropi	Petiblanco 8 // Frontana 1971 37/Quaderna A	58.44c	2011, 2012
PF 090308	IPF 78917/PF 940051	58.45c	2013
CEP 24	BR 3/CEP 7887//CEP 7775/CEP 11	59.01c	2011, 2012, 2013
Colonista	Roxo SEL	59.25c	2011, 2012
PF 090447	PF 89375/BRS 208	59.56c	2013
BRS Pardela	BR 18/PF 9099	60.21c	2012
Rayonfn89	URES 81*2/Parula	60.76c	2013
IWT 08155	CMH74A.630/SX//CNO79/3/SW89-5124*2/Fasan	66.15d	2012
OR 1	Embrapa 27/Bagula	68.36d	2011, 2012
Colonias	Trintecinco/S.L.G.242–30	72.44d	2011, 2012
PF040183	BRS 194*2/IPF 71449	73.18d	2011, 2012

Table 3 continued

Genotype	Pedigree	Mean	Years of observation
Agatha	Agrus/6*Thatcher	78.95d	2011, 2012
NP 790	Pusa 165/Thatcher	79.47d	2013
IWT 08150	Milan/Kauz//Prinia/3/Babax	81.81d	2012
PF 010161	BR 23/Embrapa 16//Coker 80.33/PF 88522	88.94d	2011, 2012

*Means followed by the same lower-case letter in the column did not differ significantly from each other (Scott-Knott's method for unbalanced experiments, $p < 0.05$)

Medium maturation genotypes

Cluster a included seven genotypes with mean blast incidence lower than 20% (Table 3). Casw94y00116s (0.68%), CBFusarium ENT014 (5.69%), Casw00gh00065s (7.96%), CBFusarium ENT006 (9.34%) and Cigm921696 (10.85%) showed less than 15% blast incidence (Table 3). CBFusarium ENT014 was reported to carry the 2NS/2AS translocation and it was also resistant in trials reported by Ferreira et al. (2020). Cultivar Safira, (35.86%) previously considered a source of resistance by Ferreira et al. (2018), was included in group b, which had an average incidence ranging between 25.08 and 42.65% (Table 3). In the present study, it was not ranked with the best genotypes of this maturation group.

Late maturation group

The lowest and the highest blast incidence among the late maturing materials were observed in SHW genotypes (Table 4). The synthetic genotypes Casw02gh00002s (9.18%), Cass03gh00077s (13.99%), and Casw02gh00005s (19.38%), with the same pedigree, performed similarly and were placed in the same cluster (a) (Table 4). On the other hand, Cass03gh00099s (86.75%), with a different pedigree, had the highest blast incidence in this maturation group (Table 4). As in the previous maturation groups, SHW genotypes appeared to be a major source of resistance to wheat blast. The inclusion of CBFusarium ENT007 (20.68%) in the 'a' group also indicated the potential importance of CBFusarium ENT genotypes as sources of blast resistance. Cultivar Shanghai (43.32%) was in the intermediate cluster b, which had an average blast incidence ranging from 39.90% to 56.54% (Table 4), but was considered resistant by Ferreira et al. (2018).

Correlation between yield loss and wheat blast incidence

A positive correlation between wheat blast incidence on the spikes and yield loss was observed in the early cycle genotypes in 2011 and 2013 (Fig. 1).

Over three-quarters of the yield loss in 2011 was attributed to diseased spikes ($R^2 = 0.7646$) (Fig. 1), pointing to a strong correlation between blast incidence on the spikes and yield loss. Based on the data presented, we infer that once a spike is infected the disease severity on that spike will generally be very high, and that the yield loss for that spike will also be high. Some genotypes showing high susceptibility levels, such as IAC 24, PF 010,255, PF 020,062, PF 89,326 and PF 92,393, with 100% blast incidence had yield losses between 87 and 98% (Online Resource 1, Table b), whereas genotypes such as PF 909 and BH 1146, with mean incidence values of 79% and 64%, had very minor yield losses (1% and 2%, respectively) possibly indicative of tolerance.

In 2013, the yield loss-disease incidence correlation was even stronger and 80% of the yield loss was attributed to disease incidence on the spikes ($R^2 = 0.8005$) (Fig. 1) (Online Resource 1, Table c). The high correlations found in 2011 and 2013 show that blast incidence on wheat spikes is a particularly important parameter when evaluating genotypes for resistance to MoT. Not surprisingly, there is a direct effect on yield.

This study complements and corroborates previous response assessments conducted by Arruda et al. (2005) and confirms the effectiveness of quantifying the disease incidence on spikes as a simple and adequate variable to evaluate the blast reactions of wheat genotypes and their effects on yield loss.

Table 4 Wheat head blast incidence of 26 late cycle wheat genotypes observed in 2011, and/or 2012, and/or 2013 evaluated in 'hotspot' assays

Genotype	Pedigree	Mean	Years of observation
Casw02gh00002s	68.111/Rugby-USA//Ward Resel/3/Stifftail/4/Ae.tauschii (617)	09.18a*	2011
PF 070475	WT 98109/TB 0001	09.49a	2013
Casw02gh00045s	D67.2/P66.270//Ae.tauschii (668)	11.22a	2011
Cass03gh00077s	68.111/Rugby-USA//Ward Resel/3/Stifftail/4/Ae.tauschii (700)	13.99a	2011
Casw00gh00019s	Cerceta/Ae.tauschii (425)	17.94a	2011
Casw02gh00005s	68.111/Rugby-USA//Ward Resel/3/Stifftail/4/Ae.tauschii (623)	19.38a	2011
CBFusarium ENT007	No Information	20.68a	2013
Frontana	Fronteira/Mentana	22.07a	2011, 2012
Trintecinco	Alfredo Chaves 3.21/Alfredo Chaves 4.21	30.98a	2011, 2012
Galegorapado	Landrace	33.79a	2011, 2012
BRS177	PF 83899/PF 813//F 27141	39.90b	2011, 2012
Karim (*T. durum*)	Jori 69(SIB)/(SIB)Anhinga//(SIB)Flamingo Mex	40.04b	2011
185583	Avrora//Kalyansona/Bluebird/3/(Sib)Woodpecker	41.46b	2013
HAR 604	4777*2//FKN/GB/3/Pavon F 76	42.79b	2011, 2012
Shanghai	(M)Yangmai-1	43.32b	2011, 2012
Embrapa 16	Hulha Negra/CNT 7//Amigo/CNT 7	45.37b	2011, 2012
BRS Umbu	Century/B 35	46.72b	2012
Frondoso	Polyssu/Alfredo-Chaves-6–21	46.88b	2011, 2012
IPR 84	Anahuac 75/PF 7455//PF 72556/3/Pamir SIB/Alondra SIB//Kavco SIB	50.60b	2011, 2012
PF 010069	OR 1/C 97.33//PF 92334/PF87451	50.83b	2011, 2012
Cigm89559-1b	ND-68–111/Rugby,USA//Ward/3/Flamingo Mex/4/Rabicorno/5/(TR.TA)WX-878	51.38b	2012
PF 040310/1	PF 88618/Coker 80.33//Frontana/Karl	56.54b	2013
Cotipora	Veranopolis*2/Egyptian 101	69.10c	2011, 2012
PG 1	Polissu Sel	73.06c	2011, 2012
Estanzueladorado	Estanzuela-Tarariras/3/Tobari-66//Klein-Petiso/Rafaela	74.20c	2011
Cass03gh00099s	Gan/Ae.tauschii (790)	86.75c	2011

*Means followed by the same lower-case letter in the column did not differ significantly from each other (Scott-Knott's method for unbalanced experiments, $p < 0.05$)

Conclusions

The difficulty to find commercial wheat cultivars with effective levels of resistance to blast, strengthens the hypothesis raised by Urashima and Kato (1994), that the widespread susceptibility of germplasm was due to lack of resistance in current wheat cultivars globally, and/or to a broad spectrum of virulence in MoT. However, other factors may also play important roles. Climatic conditions also seem to be important and the disease so far has become significant in the more tropical wheat growing areas (Sonder 2016). Head blast will likely be one of the main factors directly limiting grain yield, regardless of the blast resistance level of the cultivar.

In the present study, thirty early maturing genotypes were identified with statistically similar mean wheat blast incidences on spikes comparable to the moderately resistant cultivar BR 18. Seven medium maturity and ten late maturity genotypes also had average spike blast incidence levels less than 35%. Among the 48 genotypes in 'a' clusters across the three maturation groups, 17 were SHW or CBFusarium ENT entries, 16 were breeding lines, 13 were

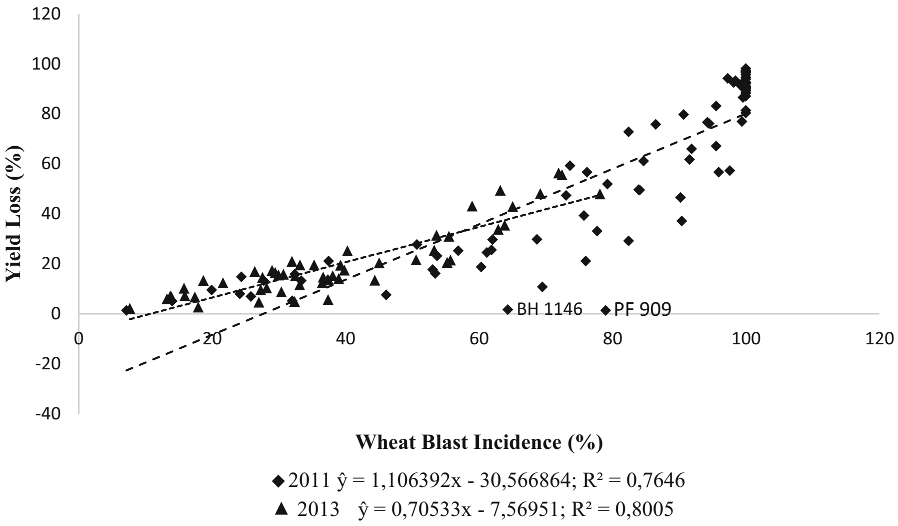

Fig. 1 Regression analysis between wheat blast incidence on the spikes and yield loss caused by *M. oryzae* in the early maturation group observed in 2011 and 2013. Lack of loss in BH 1146 and PF 909 may be indicative of tolerance

commercial cultivars, and 2 were landraces. Although no genotype fully immune to blast was identified, there were lines that performed with apparent levels of resistance in a disease 'hotspot'. We predict that most of these genotypes will perform similarly in other regions with high disease pressure. Finally, this study presents data confirming the strong correlation between spike blast incidence and yield loss. We suggest the use of blast incidence on spikes in field trials for the assessment of genotype response to blast.

References

Anh VL, Anh NT, Tagle AG, Vy TTP, Inoue Y, Takumi S, Tosa Y (2015) *Rmg8*, a new gene for resistance to *Triticum* isolates of *Pyricularia* oryzae in hexaploid wheat. Phytopathology 105:1568–1572. https://doi.org/10.1094/PHYTO-02-15-0034-R

Arruda MA, Bueno CRN, Zamprogno KC, Lavorenti NA, Urashima AS (2005) Reação do trigo à *Magnaporthe grisea* nos diferentes estádios de desenvolvimento. Fitopatol bras 30:121–126. https://doi.org/10.1590/S0100-41582005000200003

Barea G, Toledo J (1996) Identificación y zonificación de piricularia o bruzone (Pyricularia oryzae) en el cultivo del trigo en el Dpto. de Santa Cruz In: CIAT. Informe Técnico. Proyecto de Investigación Trigo, Santa Cruz, pp. 76–86.

CBTT, Comissão Brasileira de Trigo e Triticale, (2011) Informações técnicas para trigo e triticale—safra 2012. Embrapa Agropecuária Oeste, Dourados, Brazil. https://www.embrapa.br/busca-de-publicacoes/-/publicacao/912499/informacoes-tecnicas-para-trigo-e-triticale—safra-2012. Accessed 26 February 2021

CBTT, Comissão Brasileira de Trigo e Triticale, (2013) Informações técnicas para trigo e triticale—safra 2014. Instituto Agronômico do Paraná, Londrina, Brazil. https://www.embrapa.br/documents/1355291/1729833/Livro+Trigo+e+Triticale+-+21-05-14.pdf/3be16e3a-1136-47bd-95ba-7439b09c23d7. Accessed 26 February 2021

CBTT, Comissão Brasileira de Trigo e Triticale, (2020) Informações técnicas para trigo e triticale—safra 2020. Biotrigo Genética, Passo Fundo, Brazil. https://www.embrapa.br/busca-de-publicacoes/-/publicacao/1123960/informacoes-tecnicas-para-trigo-e-triticale-safra-2020#:~:text=Autoria%3A%20REUNI%C3%83O%20DA%20COMISS%C3%83O%20BRASILEIRA,hihi%C3%B3ria%20tra%C3%A7ada%20por%20muitos%20desafios. Accessed 26 February 2021

Ceresini PC, Castroagudín VL, Rodrigues FÁ, Rios JA, Aucique-Pérez CE, Moreira SI, Croll D, Alves E, de Carvalho G, Maciel JLN, McDonald BA (2019) Wheat blast: from its origins in South America to its emergence as a global threat. Mol Plant Pathol 20:155–172. https://doi.org/10.1111/mpp.12747

Conrado TV, Ferreira DF, Scapim CA, Maluf WR (2017) Adjusting the Scott-Knott cluster analyses for unbalanced designs. Crop Breed Appl Biotechnol 17:1–9. https://doi.org/10.1590/1984-70332017v17n1a1

Couch BC, Kohn LM (2002) A multilocus gene genealogy concordant with host preference indicates segregation of a new species, *Magnaporthe oryzae*, from *M. grisea*. Mycologia 94:683–693. https://doi.org/10.1080/15572536.2003.11833196

Cruz CD, Bockus W, Pedley K, Peterson G, Stack J, Tang X, Valent B (2011) Resistance among U.S. wheat (*Triticum aestivum*) cultivars to the wheat pathotype of *Magnaporthe oryzae*. Phytopathology 101:S220. https://www.ars.usda.gov/research/publications/publication/?seqNo115=265342. Accessed 26 February 2021

Cruz CD, Peterson GL, Bockus WW, Kankanala P, Dubcovsky J, Jordan KW, Akhunov E, Chumley F, Baldelomar FD, Valent B (2016) The 2NS translocation from *Aegilops ventricosa* confers resistance to the *Triticum* pathotype of *Magnaporthe oryzae*. Crop Sci 56:990–1000. https://doi.org/10.2135/cropsci2015.07.0410

Cruz MF, Prestes AM, Maciel JLN, Scheeren PL (2010) Resistência parcial à brusone de genótipos de trigo comum e sintético nos estádios de planta jovem e de planta adulta. Tropical Plant Pathol 35:24–31. https://doi.org/10.1590/S1982-56762010000100004

Cruz CD, Valent B (2017) Wheat blast disease: danger on the move. Tropical Plant Pathol 42:210–222. https://doi.org/10.1007/s40858-017-0159-z

Dias Neto JJ, Santos GR, Silva LMA, Cunha ACR, Rangel PHN, Ferreira ME (2010) Hot spots for diversity of *Magnaporthe oryzae* physiological races in irrigated rice fields in Brazil. Pesq Agropec Bras 45:252–260. https://doi.org/10.1590/S0100-204X2010000300004

Duveiller E, He X, Singh PK (2016) Wheat Blast: An emerging disease in South America potentially threatening wheat production. In: Bonjean A, Angus WJ, van Ginkel M (eds) The world wheat book, a history of wheat breeding, vol 3. Lavoisier, Paris, pp 1107–1122

Farman M, Peterson G, Chen L, Starnes J, Valent B, Bachi P, Murdock L, Hershman D, Pedley K, Fernandes JM, Bavaresco J (2017) The Lolium pathotype of *Magnaporthe oryzae* recovered from a single blasted wheat plant in the United States. Plant dis 101:684–692. https://doi.org/10.1094/PDIS-05-16-0700-RE

Fernandes JMC, Nicolau M, Pavan W et al (2017) A weather-based model for predicting early season inoculum build-up and spike infection by the wheat blast pathogen. Trop plant pathol 42:230–237. doi:https://doi.org/10.1007/s40858-017-0164-2

Ferreira Jr, Vancini C, Torres GAM, Consoli L, Seixas CDS, Dianese AC, Goulart ACP, Soto-Gonzales HH (2018) Absence of 2NS/2AS in wheat resistance sources to *Magnaporthe oryzae* in Brazil. Passo Fundo: Embrapa Trigo (Boletim de Pesquisa e Desenvolvimento, no 91). https://www.embrapa.br/busca-de-publicacoes/-/publicacao/1095170/absence-of-2ns2as-in-wheat-resistance-sources-to-magnaporthe-oryzae-in-brazil. Accessed 26 February 2021

Ferreira JR, Torres GAM, Consoli L, Binneck E, Camilotti GA, Scagliusi SMM, Deuner CC, Dianese AC, Goulart ACP, Seixas CDS, Coelho MAO (2020) Genetic and molecular basis of wheat–*Magnaporthe oryzae* Triticum interaction. In: Kumar S, Kashyap P, Singh G (eds) Wheat Blast, 1st edn. Florida, Boca Raton, pp 69–104

Goulart ACP, Paiva FA (1992) Incidência da brusone (*Pyricularia oryzae*) em diferentes cultivares de trigo (*Triticum aestivum*) em condições de campo. Fitopatol bras 17:321–325. https://www.researchgate.net/publication/280882521_Incidencia_da_brusone_Pyricularia_oryzae_em_difdiferen_cultivares_de_trigo_Triticum_aestivum_em_condicoes_de_campo. Accessed 26 February 2021

Goulart ACP, Paiva F de A (1993) Losses in wheat (*Triticum aestivum* L.) caused by *Pyricularia grisea*. Annual Wheat Newsletter 39:108–109. https://www.researchgate.net/publication/326160011_Losses_in_wheat_Triticum_aestivum_L_caused_bb_Pyricularia_grisea. Accessed 26 February 2021

Goulart ACP, Paiva FA (2000) Perdas no rendimento de grãos de trigo causada por *Pyricularia grisea*, nos anos de 1991 e 1992, no Mato Grosso do Sul. Summa Phytopathol 26:279–282. https://www.researchgate.net/publication/280925324_Perdas_no_rendimento_de_graos_de_trigo_causadca_por_Pyricularia_grisea_nos_anos_de_1991_e_1992_no_Mato_Grosso_do_Sul. Accessed 26 February 2021

Goulart ACP, Paiva FA, Andrade PJM (1995) Relação entre a incidência da brusone de trigo e a presença de *Pyricularia grisea* nas sementes colhidas. Fitopatol bras 20:184–189. https://www.researchgate.net/publication/280741780_Relacao_entre_a_incidencia_da_brusone_em_espiges_de_trigo_e_a_presenca_de_Pyricularia_grisea_nas_sementes_colhidas. Accessed 26 February 2021

Goulart ACP, Souza PC, Urashima AS (2007) Danos em trigo causados pela infecção por *Pyricularia grisea*. Summa Phytopathol 33:358–363. https://doi.org/10.1590/S0100-54052007000400007

Igarashi S, Utiamada CM, Igarashi LC, Kazuma AH, Lopes RS (1986) *Pyricularia* em trigo. Ocorrência de *Pyricularia* sp. no estado do Paraná. Fitopatol bras 11:351–352

Instituto Agronômico de Campinas, IAC (2018) Cultivares de Trigo lançados de 1999 a 2008, pelo programa de Melhoramento Genético do IAC. http://www.iac.sp.gov.br/areasdepesquisa/graos/trigo.php. Accessed 27 July 2020

Islam MT, Croll D, Gladieux P, Soanes DM, Persoons A, Bhattacharjee P, Hossain MS, Gupta DR, Rahman MM, Mahboob MG, Cook N (2016) Emergence of wheat blast in Bangladesh was caused by a South American lineage of *Magnaporthe oryzae*. BMC Biol 14:84. https://doi.org/10.1186/s12915-016-0309-7

Pagani APS, Dianese AC, Café-Filho AC (2014) Management of wheat blast with synthetic fungicides, partial resistance and silicate and phosphite minerals. Phytoparasitica 42:609–617. https://doi.org/10.1007/s12600-014-0401-x

Prestes AM, Arendt PF, Fernandes JMC, Scheeren PL (2007) Resistance to *Magnaporthe grisea* among Brazilian wheat genotypes. In: Buck HT, Nisi JE, Salomón N (eds) Wheat production in stressed environments. (Developments in plant breeding, v. 12). Dordrecht, The Netherlands, pp119–123

Rocha JRASC, Paula IG, Gloria HB, Pimentel AJB, Ribeiro G, Souza MA (2019) Screening wheat genotypes for resistance to wheat blast disease in the vegetative and reproductive stages. Euphytica 215:59. https://doi.org/10.1007/s10681-019-2382-9

Sharma RK, Singh PK (2020) Wheat blast: A global threat to wheat production. In: Kumar S, Kashyap P, Singh G (eds) Wheat Blast, 1st edn. Florida, Boca Raton, pp 01–18

Sonder K (2016) Global map of wheat mega-environments. CIMMYT Research Data and Software Repository Network. https://hdl.handle.net/11529/10625. Accessed 26 February 2021

Sousa CNA, Caierão E (2014) Cultivares de trigo indicadas para cultivo no Brasil e instituições criadoras 1922 a 2014. Brasília, Distrito Federal. https://www.embrapa.br/busca-de-publicacoes/-/publicacao/1012761/cultivares-de-trigo-indicadas-para-cultivo-no-brasil-e-instituicoes-criadoras-1922-a-2014. Accessed 26 February 2021

Tagle AG, Chuma I, Tosa Y (2015) Rmg7, a new gene for resistance to *Triticum* isolates of *Pyricularia oryzae* identified in tetraploid wheat. Phytopathology 105:495–499. https://doi.org/10.1094/PHYTO-06-14-0182-R

Tembo B, Mulenga RM, Sichilima S, M'siska KK, Mwale M, Chikoti PC, Singh PK, He X, Pedley KF, Peterson GL, Singh RP, Braun HJ (2020) Detection and characterization of fungus (*Magnaporthe oryzae* pathotype Triticum) causing wheat blast disease on rain-fed grown wheat (*Triticum aestivum* L.) in Zambia. PLoS ONE 15:0238724. https://doi.org/10.1371/journal.pone.0238724

Torres GAM, Santana FM, Fernandes JMC, Silva MS (2009) Doenças da espiga causam perda de rendimento em trigo nos estados do Paraná, São Paulo e Mato Grosso do Sul, em 2009. Passo Fundo: Embrapa Trigo (Comunicado Técnico Online n° 255). https://www.embrapa.br/trigo/busca-de-publicacoes/-/publicacao/821793/doencas-da-espiga-causam-perda-de-rendimento-em-trigo-nos-estados-do-parana-sao-paulo-e-mato-grosso-do-sul-em-2009. Accessed 26 February 2021

Trindade MG, Prabhu AS, Só e Silva M (2006) Resistência parcial de genótipos de trigo a brusone nas folhas. Passo Fundo: Embrapa Trigo (Comunicado Técnico Online n° 201). https://www.embrapa.br/busca-de-publicacoes/-/publicacao/852394/resistencia-parcial-de-genotipos-de-trigo-a-brusone-nas-folhas. Accessed 26 February 2021

Urashima AS, Igarashi S, Kato H (1993) Host range, mating type, and fertility of *Pyricularia grisea* from wheat in Brazil. Plant Dis 77:1211–1216. https://doi.org/10.1094/PD-77-1211

Urashima AS, Kato H (1994) Varietal resistance and chemical control of wheat blast fungus. Summa Phytopathol 20:107–112

Urashima AS, Lavorenti NA, Goulart ACP, Mehta YR (2004) Resistance spectra of wheat cultivars and virulence diversity of *Magnaporthe grisea* isolates in Brazil. Fitopatol Bras 29:511–518. https://doi.org/10.1590/S0100-41582004000500007

Zhan SW, Mayamas S, Tosa Y (2008) Identification of two genes for resistance to *Triticum* isolates of *Magnaporthe oryzae* in wheat. Genome 51:216–221. https://doi.org/10.1139/G07-094

Zhang N, Luo J, Rossman AY, Aoki T, Chuma I, Crous PW, Dean R, Vries RP, Donofrio N, Hyde KD, Lebrun M-H, Talbot NJ, Tharreau D, Tosa Y, Valent B, Wang Z, Xu J-R (2016) Generic names in *Magnaporthales*. IMA Fungus 7:155–159. https://doi.org/10.5598/imafungus.2016.07.01.09