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GERMPLASM

Registration of Scab-Resistant KY06C-11-3-10 Soft Red Winter Wheat Germplasm

Anthony J. Clark, Jose M. Costa, Carl A. Griffey, Gina L. Brown-Guedira, Yanhong Dong, Edward J. Souza, J. Paul Murphy, and David A. Van Sanford*

ABSTRACT

Fusarium head blight (FHB) is a serious disease of wheat (*Triticum aestivum* L.) worldwide that has elicited a widespread resistance-breeding effort. One approach to breeding relies on deployment of exotic quantitative trait loci (QTL) from wheat outside North America. Germplasm line KY06C-11-3-10 (Reg. No. GP-965, PI 669817) is a soft red winter wheat that is a product of an accelerated backcrossing program performed jointly by the Kentucky Agricultural Experiment Station, Maryland Agricultural Experiment Station, Virginia Polytechnic Institute and State University, North Carolina State University, and the USDA–ARS. KY06C-11-3-10 carries exotic FHB resistance alleles from Chinese spring wheat 'Ning7840' at *Fhb1*, and at QTL on chromosomes 5A and 2DL. These QTL, backcrossed into 'McCormick'—which itself has nonexotic, native moderate resistance—reduced FHB spike symptoms, percentage Fusarium-damaged kernels, and concentration of the mycotoxin deoxynivalenol (DON). KY06C-11-3-10 has additionally been selected for yield, test weight, heading date, height, milling and baking quality, and resistance to lodging. The combination of exotic resistance QTL, moderately resistant genetic background, widespread adaptation, and competitive agronomic and quality characteristics makes KY06C-11-3-10 a useful germplasm for wheat breeders.

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5585 Guilford Rd., Madison, WI 53711 USA
*Corresponding author (dvs@uky.edu)

Fusarium head blight (FHB), caused primarily by *Fusarium graminearum* Schwabe [*Gibberella zeae* (Schwein.:Fr.) Petch] reduces wheat (*Triticum aestivum* L.) yield and volume weight and contaminates grain with trichothecene mycotoxins, notably deoxynivalenol (DON). The U.S. Food and Drug Administration (2010) has established advisory levels for DON. Fusarium head blight continues to seriously damage U.S. and world wheat production, and disease risks are predicted to increase as a result of climate change (Chakraborty and Newton, 2011; Goswami and Kistler, 2004).

To lower the risks of FHB damage, resistant varieties need to be grown more widely. Wheat varieties grown in Kentucky and the surrounding region not only need FHB resistance but also must have competitive yield, test weight, and acceptable milling and baking quality and must usually be sufficiently early maturing to be followed by double-crop soybean [*Glycine max* (L.) Merr.]. In addition, because harvest of grain less than 30 d after spraying with fungicide is prohibited, heading and anthesis must be early enough to allow this period before grain harvest.

The development and use of parents that carry FHB resistance in increasingly adapted backgrounds should accelerate the rate at which resistant varieties acceptable to growers are produced. Marker-assisted selection (MAS) for FHB-resistance QTL is now routinely used in public breeding programs, and there is a strategic need for continuous improvement in the background of these QTL sources.

We report here the development through marker-assisted backcrossing of germplasm KY06C-11-3-10 (Reg. No. GP-965, PI 669817), an FHB-resistant line that combines exotic QTL and native resistance in a well-adapted background.

A.J. Clark and D.A. Van Sanford, Univ. of Kentucky, Dep. of Plant and Soil Sciences, Lexington, KY 40546; J.M. Costa, Univ. of Maryland, PSLA Dep., 2102 Plant Sciences Bldg., College Park, MD 20742-4452; C.A. Griffey, Virginia Polytechnic Institute and State Univ., Blacksburg, VA 24061; G.L. Brown-Guedira, USDA–ARS, Plant Science Research Unit, Raleigh, NC 27695; Y. Dong, Plant Pathology Dep., Univ. of Minnesota, St. Paul, MN 55108; E.J. Souza, Bayer Crop Science, Lincoln, NE; J.P. Murphy, Dep. of Crop Science, North Carolina State Univ., Raleigh, NC 27695-7620. The information reported in this paper (no. 14-06-001) is part of a project of the Kentucky Agricultural Experiment Station and is published with the approval of the Director.

Abbreviations: DON, deoxynivalenol; FDK, Fusarium-damaged kernels; FHB, Fusarium head blight; GS, genomic selection; MAS, marker-assisted selection; QTL, quantitative trait loci; SRC, solvent retention capacity.

Methods

Breeding History

'Ning7840'/'McCormick' F_1 crosses were made at the University of Maryland in 2004. The first backcrosses were also made in Maryland in spring 2005 using McCormick (PI 632691) as female. Subsequent BC_2F_1 crosses were made in Maryland using McCormick (Griffey et al., 2005) as female, and BC_1F_1 lines were selected for *Fhb1* and QTL on chromosomes 5A and 2DL and for high percentage of recurrent parent background using 43 unlinked polymorphic simple sequence repeat (SSR) markers from throughout the genome (Kang et al., 2011). Additional BC_2F_1 crosses were made at the University of Kentucky in fall 2005–spring 2006 using similarly selected Maryland BC_1F_1s as females. In fall 2006, 118 BC_2F_1 head rows from these were planted at Lexington, KY. In 2007, 24 rows were selected on the basis of good agronomic characteristics. Seed from each row was bulked and planted in plots near Lexington in fall 2007.

Using remnant BC_2F_2 seed in 2008, 288 plants were genotyped for *Fhb1* (*Xumn10*), 5A (*Xbarc117, Xgwm304*), and 2DL (*Xcfd233, Xgwm539,* and *Xgwm608*) and advanced one generation in the greenhouse. KY06C-11-3-10 descends from a single resistant BC_2F_2 plant homozygous for resistance marker alleles at *Fhb1* and 5A, and heterozygous at 2DL from a bulk designated 11-3.

The head from which KY06C-11-3-10 BC_2F_2 was derived was planted as a row in fall 2008, and $BC_2F_{2:4}$ seed harvested in bulk in 2009 was used to seed a nonreplicated plot in a 2010 preliminary trial. This KY06C-11-3-10 plot was hand harvested and used as the seed source for 2011 experimental plots and increase rows. BC_2F_5 heads snapped from 2011 increase rows were planted as head rows in fall 2011, and seed from these heads was used for genotyping and greenhouse increase. Seed from a bulk of 37 greenhouse grown plants homozygous for all resistant marker alleles for all three QTL (*Fhb1*, *Xgwm533, Xumn10*; 5A, *Xbarc117, Xgwm304*; 2DL *Xcfd233, Xgwm539*, and *Xgwm608*) is available on request. *Xgwm533* was additional to the marker panel used to screen BC_2F_2 seed and was used to confirm the presence of *Fhb1*.

Fusarium Head Blight Testing

The 2010 Preliminary Scab Trial contained 38 nonreplicated rows of Ning7840/3*McCormick BC_2F_2–derived material, including KY06C-11-3-10 and eight McCormick check rows. As a prospective germplasm release containing resistant alleles at all three FHB QTL, line KY06C-11-3-10 was subsequently included as a check in a selection scab experiment (104 entries) in 2011 and 2012 and three other 2011 scab trials including genotypic and phenotypic selections of McCormick backcross-derived material. These trials were planted at Spindletop Farm near Lexington and had RCB designs with two replications. Lines were planted in rows 1.2 m long, spaced 30 cm apart. Severe scab epidemics were generated within the mist-irrigated FHB nursery inoculated with grain spawn at a rate of 12 g m^{-2} (Agostinelli et al., 2012; Balut et al., 2013). Inoculum comprised 27 isolates taken from scabby wheat seed collected from 2007 to 2010 at multiple locations across Kentucky.

KY06C-11-3-10 was also included in the 2012 Fungicide × Variety Trial, which comprised 24 entries, the other 23 of which were either widely grown wheat cultivars or advanced breeding lines. This was the only study in which FHB data were collected outside the scab nursery; it consisted of plots similar to those described below for yield testing. The Fungicide × Variety Trial plots were inoculated with 17.8 g m^{-2} grain spawn spread at Princeton, KY, on 29 Mar. 2012 and at Lexington on 31 Mar. 2012. In 2012, unusually dry conditions prevailed through much of the crop season, so grain spawn was kept moist using drip irrigation as necessary at Lexington. Prosaro (Bayer CropScience; prothioconazole {2-[2-(1-chlorocyclopropyl)-3-(2-chlorophenyl)-2-hydroxypropyl]-1,2-dihydro-3*H*-1,2,4-triazole-3-thione} and tebuconazole {α-[2-(4-chlorophenyl)ethyl]-α-(1,1-dimethylethyl)-1*H*-1,2,4-triazole-1-ethanol}) was applied at anthesis (Feekes 10.5.1) at a rate of 0.475 L ha^{-1}, followed 24 h later with application of conidial spray (100,000 spores mL^{-1} at a rate of 10 mL m^{-2}).

Disease ratings, taken 21 to 24 d post-heading, were recorded on a 0 to 9 scale, where 0 represents 0 to 10% bleaching of spikelets within the entire row and 9 signifies 90 to 100% of the spikelets in the row are symptomatic. Ratings were taken on all material grown in the 2010, 2011, and 2012 nurseries.

Detailed symptom readings included incidence (%), which is the proportion of 20 representative spikes that contained at least one bleached spikelet, and severity (%), which is the mean of the proportion of bleached spikelets of 10 spikes. The FHB index (%) is defined as incidence multiplied by severity and divided by 100. Detailed symptom readings were taken for the 2011–2012 Selection Experiment and the 2012 Fungicide × Variety Trial Lexington location.

Processing of scabby grain samples from the scab nursery for FDK and for DON analysis was performed as previously described (Agostinelli et al., 2012; Balut et al., 2013). The DON analysis was performed at the University of Minnesota DON Testing Laboratory using gas chromatography with mass spectrometry (Mirocha et al., 1998). For the Fungicide × Variety Trial, the grain was harvested with a mechanical combine. Subsequent cleaning used sieving and low airflow similar to scab nursery grain sample processing. Otherwise, FDK determination and sample preparation for DON analysis methods were similar to those used for material from the scab nursery (Agostinelli et al., 2012; Balut et al., 2013).

Both FDK and DON were measured for all entries in the Selection Experiment (2011 and 2012) and the 2012 Fungicide × Variety Trial. For the 2010 Preliminary Trial, only samples of line KY06C-11-3-10 and McCormick were analyzed for FDK and DON. For the remaining 2011 trials, FDK was measured on all entries, but only KY06C-11-3-10 and McCormick were submitted for DON analysis. Heading date and height data were collected on all entries in the scab nurseries in all years.

Yield Testing

In Kentucky, test plots had six rows and were 4.6 m long (trimmed to 3.0 m) and 1.3 m wide. In 2008, nonreplicated BC_2F_2–derived bulks and McCormick were planted at Spindletop Research Farm (38°7′37.81″ N, 84°29′44.85′ W; Maury silt loam [fine, mixed, active, mesic Typic Paleudalfs]) near Lexington. In 2009, 24 bulks of BC_2F_3 seed and McCormick were planted in a multistate (Kentucky, Virginia [Blacksburg and Warsaw], Maryland, and North Carolina) trial. The 2010 Preliminary Trial had 242 nonreplicated entries in an augmented

design with 60 McCormick checks. The experimental designs of the 2011 Selection Experiment yield trial and three other trials were RCB with two replications. The 2012 Fungicide × Variety Trial was also a RCB with three replications per treatment. The two treatments were with and without fungicide control. In 2011, the Selection Experiment and one other trial were seeded at Spindletop Research Farm, two other trials were grown at the C. Oran Little Animal Science Research Center (38°5′14.38″ N, 84°44′27.04″ W), Maury silt loam, Woodford County, KY. The second location of the Fungicide × Variety Trial was seeded in Princeton, KY, at the West Kentucky Research and Educational Center (37°6′7.37″ N, 87°52′13.62″ W; Crider silt loam [fine-silty, mixed, active Typic Paleudalfs]). Recommended cultural practices for wheat production in Kentucky were followed (Lee et al., 2009). Heading date and plant height measurements were taken in yield plots, and each plot was harvested with a mechanical combine for yield and test weight determination.

Quality Testing and Genotyping

Grain samples (500 g) of KY06C-11-3-10 and McCormick grown at Lexington in 2010 were tested for milling and baking quality at the USDA–ARS Soft Wheat Quality Laboratory at Wooster, OH, using methods approved by the American Association of Cereal Chemistry (AACC, 2000). KY06C-11-3-10 and all lines derived from the accelerated backcrossing study were genotyped at the Eastern Regional Small Grain Genotyping laboratory in Raleigh, NC (for protocols, see http://www.ars.usda.gov/Main/docs.htm?docid=19524). Marker data provided by the laboratory indicate that KY06C-11-3-10 carries resistance alleles to leaf rust [caused by *Puccinia triticina* Eriks. f. sp. *tritici* (Eriks. & E. Henn.)], stripe rust (caused by *P. striiformis* Westend. f. sp. *tritici* Eriks.), and stem rust [caused by *P. graminis* (Pers.:Pers. f. sp. *tritici* Eriks. & E. Henn.)] at the loci LR34/YR18 and SR24/LR24, as well as the RS:1AL translocation (as does the recurrent parent McCormick) along with Rht-D1b and the long vernalizing allele at VRN1.

Analysis of variance was performed on individual locations and years using JMP version 10 (SAS Institute). Mean comparisons of traits using a protected LSD ($P < 0.05$) were made to identify differences among entries.

Characteristics

Botanical Description

KY06C-11-3-10 is a soft red winter wheat with red coleoptiles. Its juvenile growth is prostrate. Plant color is green and similar in appearance to McCormick. Spikes are tapering and awnleted. Grain is similar in appearance to McCormick; it is ovate with rounded cheeks, the brush is mid-sized and short to medium, the embryo is mid-sized, and the crease is narrow and shallow to mid-deep.

Fusarium Head Blight Resistance

In the 2010 Preliminary Scab Trial, KY06C-11-3-10 had significantly ($P < 0.05$) lower DON concentration compared with McCormick (3.5 vs. 8.1 mg kg^{-1}; Table 1). In the 2011 Selection Scab Experiment, DON of KY06C-11-3-10 was 41% of McCormick, significantly lower ($P < 0.05$) (Table 2). In the same test in 2012, overall DON levels were lower; although KY06C-11-3-10 was still 50% that of McCormick, the difference was not significant ($P < 0.05$) (Table 2). In the 2011 test, DON of KY06C-11-3-10 was not significantly different than that of 'Truman' (a cultivar widely used as a parent in FHB resistance breeding; McKendry et al., 2005; Table 2). In the 2012 test, however, DON of KY06C-11-3-10 was significantly ($P < 0.05$) lower than that of Truman (Table 2). In 2011 but not 2012, DON of KY06C-11-3-10 was significantly lower than 'Pembroke', a moderately resistant cultivar produced by the University of Kentucky wheat-breeding program (Table 2). In three other 2011 scab nursery trials, average DON of KY06C-11-3-10 was 4.9 mg kg^{-1}, significantly lower ($P < 0.05$) than the McCormick mean 10.3 mg kg^{-1} (Table 1). In those three individual tests, DON reductions in KY06C-11-3-10 relative to McCormick ranged from 60 to 38% (data not shown). In the 2012 Fungicide × Variety Trial control treatment, DON of KY06C-11-3-10 (0.6 mg kg^{-1}) was significantly lower than that of Truman (1.6 mg kg^{-1}) as well as seven other lines, despite low overall DON levels in the test (Table 3). Deoxynivalenol in line KY06C-11-3-10 was numerically, although not significantly, lower than that of Pioneer Brand 25R32, which has resistance alleles at *Fhb1* (Greg Marshall, personal communication, 2012). In the fungicide treatment, KY06C-11-3-10 had the joint lowest DON, 0.2 mg kg^{-1}, with Truman. Six of the seven lines, other than Truman, with significantly ($P < 0.05$) higher DON than KY06C-11-3-10 in the control treatment were also significantly ($P < 0.05$) higher than KY06C-11-3-10 in the fungicide treatment (Table 3).

The FDK of KY06C-11-3-10 was significantly ($P < 0.05$) lower than McCormick in the 2010 Preliminary Scab Trial, although the 18% reduction was less than the reduction in DON relative to the recurrent parent (Table 1). In the three 2011 trials, FDK of KY06C-11-3-10 was significantly ($P < 0.05$) lower than Pembroke but not significantly ($P < 0.05$) different than that of the resistant check Truman (Table 1). In the 2011 Selection

Table 1. Characteristics of wheat germplasm KY06C-11-3-10 and checks in 2010 McCormick Backcross Preliminary Scab Nursery Trial and mean of three 2011 Scab Nursery Trials of McCormick-backcrossed lines.

Entry	DON†	FDK†	FHB†	Days to heading	Plant height
	mg kg^{-1}	%	0–9‡	d	cm
			2010		
KY06C-11-3-10	3.5	9.2	1.0	130.0	78.7
McCormick	8.1	11.2	2.8	128.3	79.4
LSD (0.05)	1.6	1.6	0.5	1.5	7.1
			2011		
KY06C-11-3-10	4.9	12.4	2.0	135.3	77.0
McCormick	10.3	13.7	3.0	133.0	76.6
Pembroke	–	18.2	3.2	133.7	83.4
Truman	–	10.5	1.0	145.0	94.4
LSD (0.05)	3.5	3.6	0.7	1.5	4.6

† DON, deoxynivalenol concentration; FDK, Fusarium-damaged kernels; FHB, Fusarium head blight.

‡ Rating: 0 = 0–10% infected spikelets; 9 = 90–100% of spikelets infected.

Table 2. Characteristics of wheat germplasm KY06C-11-3-10 and checks in the McCormick Backcross Selection Scab Experiment.

Entry	DON†	FDK†	FHB†			Days to heading	Plant height
			Severity	Incidence	Index		
	mg kg^{-1}	%	%			d	cm
			2011				
KY06C-11-3-10	8.1	13.2	29.8	50.0	14.9	137.0	78.7
McCormick	19.7	23.3	47.3	75.0	35.9	133.5	74.9
Pembroke	19.5	22.7	47.5	70.0	36.8	132.0	83.8
Truman	6.4	10.2	26.7	60.0	16.5	146.0	94.0
LSD (0.05)	4.3	6.5	16.1	25.6	18.0	4.8	9.4
			2012				
KY06C-11-3-10	2.7	7.2	15.1	40.0	6.0	116.5	90.2
McCormick	5.4	8.8	22.5	50.0	12.8	111.0	94.0
Pembroke	3.8	7.2	16.2	50.0	8.1	109.0	92.7
Truman	7.2	11.9	19.9	50.0	10.3	125.0	104.1
LSD (0.05)	4.0	3.9	12.2	24.9	8.7	2.6	9.6

† DON, deoxynivalenol concentration; FDK, Fusarium-damaged kernels; FHB, Fusarium head blight.

Table 3. Characteristics of wheat germplasm KY06C-11-3-10 and checks in 2012 Fungicide Variety Trial.†

Entry	Lexington, KY											Princeton, KY		
	DON	FDK	FHB			LR	SR	GY	VW	DTH	PH	GY	VW	PH
			Sev	Inc	Ind									
	mg kg^{-1}	%	%			0–9‡	0–9‡	kg ha^{-1}	kg hL^{-1}	d	cm	kg ha^{-1}	kg hL^{-1}	cm
						Control								
KY06C-11-3-10	0.6	3.0	8.4	13.3	1.1	1.0	1.7	5317	74.2	118.3	81.3	5057	78.5	81.3
Beck 135	2.5	5.2	21.9	38.7	8.6	2.3	0.0	5765	70.0	118.7	81.3	5597	71.4	88.1
Dyna-Gro 9911	0.5	1.9	22.9	17.4	4.1	5.0	0.0	5719	74.4	111.3	81.3	4781	73.3	85.5
Exsegen Dinah	0.9	1.9	21.7	19.7	4.2	0.0	0.0	5899	74.0	116.3	76.6	5245	74.1	87.2
KAS 5058	0.7	1.5	21.4	14.8	3.2	0.0	0.0	6137	74.4	115.3	77.0	4929	73.2	86.4
KAS 1200	2.2	7.0	33.9	27.5	9.3	1.7	0.0	5738	68.7	110.7	70.3	5692	68.4	83.0
Pembroke	1.7	6.4	30.8	40.6	12.5	3.0	0.0	5106	71.5	113.7	77.9	5223	74.2	83.8
Pioneer 25R32	0.9	5.1	13.4	25.0	3.7	2.3	0.0	5524	72.5	117.3	77.9	5645	73.5	85.5
Pioneer 26R15	2.1	6.3	28.0	29.6	8.1	1.0	0.0	5829	69.9	117.3	79.6	5137	73.3	89.7
Southern States 8302	1.4	3.7	28.6	28.3	8.3	2.3	0.0	5517	73.6	117.0	85.5	5235	73.2	88.1
Southern States 8700	1.9	7.4	23.8	41.7	10.3	4.7	0.0	5438	68.4	118.7	83.8	6184	72.3	88.9
Syngenta W1104	1.7	5.2	21.7	27.2	5.5	4.7	0.0	5356	68.9	118.0	77.9	5428	73.3	90.6
Truman	1.6	1.5	27.1	19.4	5.3	1.7	0.0	5212	69.8	125.3	92.3	3849	74.6	97.4
USG 3251	2.6	3.4	22.5	37.2	8.5	1.7	0.0	5611	71.1	119.0	80.4	6063	71.2	88.1
LSD (0.05)	0.9	2.6	9.4	14.8	6.2	1.5	1.2	714	1.5	2.6	3.5	854	1.1	9.4
						Fungicide-treated								
KY06C-11-3-10	0.2	0.4	6.4	6.1	0.4	0.0	0.0	6109	76.7	117.3	78.7	4787	78.2	79.6
Beck 135	1.4	2.0	10.3	17.8	1.8	0.0	0.0	6676	72.5	118.7	83.0	5061	72.5	81.3
Dyna-Gro 9911	0.5	1.4	9.4	7.8	0.7	0.0	0.0	5956	75.7	111.3	82.1	5406	73.3	91.4
Exsegen Dinah	0.4	0.6	8.4	5.0	0.4	0.0	0.0	6149	75.7	118.3	77.9	5730	73.5	88.1
KAS 5058	0.3	0.6	8.8	5.0	0.5	0.0	0.0	6689	75.6	118.7	77.0	5194	74.3	86.4
KAS 1200	1.6	4.9	8.8	10.0	0.9	0.0	0.0	6363	70.2	112.3	70.3	6174	69.8	78.7
Pembroke	1.2	2.3	13.9	12.8	1.9	0.0	0.0	5727	73.0	117.0	75.4	5253	73.2	79.6
Pioneer 25R32	0.4	1.0	8.2	11.1	0.9	0.0	0.0	5392	76.0	118.0	79.6	5862	73.6	89.7
Pioneer 26R15	1.6	2.6	11.0	10.6	1.1	0.0	0.0	6476	72.6	118.7	77.9	5788	73.5	91.4
Southern States 8302	1.0	1.4	9.6	8.5	0.9	0.0	0.0	6296	76.7	119.0	87.2	4715	73.7	78.7
Southern States 8700	1.8	4.1	16.2	18.3	3.1	0.0	0.0	6661	71.6	119.3	81.3	6509	72.9	91.4
Syngenta W1104	0.8	1.5	10.3	8.3	0.9	0.0	0.0	5742	72.9	118.7	73.7	6690	73.2	88.1
Truman	0.2	0.5	18.7	3.7	0.7	0.0	0.0	4283	74.7	127.0	93.1	4140	74.2	95.7
USG 3251	2.0	2.7	11.0	16.1	1.8	0.0	0.0	6055	74.0	119.7	80.4	5826	71.7	88.1
LSD (0.05)	0.6	1.4	6.6	8.3	1.5	–	–	1155	1.5	2.1	1.4	727	1.2	6.1

† DON, deoxynivalenol; FDK, Fusarium-damaged kernels; FHB, Fusarium head blight; Sev, severity; Inc, incidence; Ind, index; LR, leaf rust; SR, stripe rust; GY, grain yield; VW, volume weight; DTH, days to heading; PH, plant height.

‡ 0 = 0% of flag leaf covered with pustules, 9 = >90% of flag leaf covered with pustules.

Scab Experiment, FDK of KY06C-11-3-10 was reduced 43% relative to McCormick (Table 2). In that test, the difference was significant ($P < 0.05$) in 2011 but not in 2012. In 2012, FDK of KY06C-11-3-10 was significantly ($P < 0.05$) lower than Truman (Table 2). In the 2012 Fungicide × Variety Trial control treatment, FDK of KY06C-11-3-10 did not differ significantly ($P < 0.05$) from Truman but was different from FDK of Pembroke and three other lines (Table 3). In the fungicide treatment, those four lines and one other also had significantly ($P < 0.05$) higher FDK than did line KY06C-11-3-10.

The FHB rating of line KY06C-11-3-10 in the 2010 Preliminary Scab Trial was 1.0, significantly ($P < 0.05$) lower than 2.8 for the McCormick checks (Table 1). The FHB ratings from three 2011 scab nursery trials also were indicative of the significant ($P < 0.05$) increase in resistance of KY06C-11-3-10, having a mean rating of 2.0 compared with 3.0 for McCormick (Table 1).

In the 2011 Selection Scab Experiment, FHB severity of line KY06C-11-3-10 was significantly different (37% less) than McCormick. In that test in 2012, KY06C-11-3-10 had a 33% reduction in severity compared with McCormick. KY06C-11-3-10 had 10% higher severity than did Truman in 2011 but was 24% lower in 2012. Neither difference was significant (Table 2). In the 2012 Fungicide × Variety Trial control treatment, KY06C-11-3-10 had significantly ($P < 0.05$) lower (69%) severity than did Truman and similarly, was significantly different than 11 of 12 other released varieties tested (Table 3). In the fungicide treatment, KY06C-11-3-10 had severity reductions that were significantly different ($P < 0.05$) from three lines, including Pembroke (Table 3).

The FHB incidence of KY06C-11-3-10 was lower than that of McCormick and Truman in both years of the Selection Scab Experiment (Table 2), although the difference was not significant. In the 2012 Fungicide × Variety Trial control treatment, incidence of line KY06C-11-3-10 was also not significantly different from Truman but significantly ($P < 0.05$) lower than Pembroke and five other varieties tested (Table 3). Of those six varieties, incidence was significantly ($P < 0.05$) reduced in three varieties in the fungicide treatment (Table 3).

FHB index of line KY06C-11-3-10 was significantly lower than McCormick ($P < 0.05$) in 2011 (Table 2). In the 2012 Fungicide × Variety Trial, FHB Index of KY06C-11-3-10 was significantly ($P < 0.05$) lower than seven varieties in the control treatment and one in the fungicide treatment (Table 3).

In the 2012 Fungicide × Variety Trial, line KY06C-11-3-10 had significantly lower leaf rust severity ratings than varieties Dyna-Gro 9911, Pembroke, Southern States 8700, and Syngenta W1104 (Table 3). KY06C-11-3-10 showed some susceptibility to stripe rust (Table 3).

Agronomic Characteristics of Early Generation Bulks

Yield of the BC_2F_2–derived bulks in 2008 varied from 2872 to 4835 kg ha^{-1}. Yield of bulk 11-3 (from which KY06C-11-3-10 was derived) was 4393 kg ha^{-1}. Height of bulk 11-3 averaged 83.8 cm compared with 78.7 cm for McCormick.

In 2009, the mean yield of the bulks ranged from 4620 to 3544 kg ha^{-1}; the mean yield of McCormick was 4391 kg ha^{-1}. The mean yield of bulk 11-3 was 4291 kg ha^{-1}. Mean grain volume weight of the bulks varied from 75.7 to 72.2 kg hL^{-1}. Mean grain volume weight of McCormick and bulk 11-3 were 74.1 and 74.3 kg hL^{-1}. Mean height between the two Virginia locations of bulk 11-3 was 91.4 cm compared with 87.1 cm for McCormick. The difference was not significant ($LSD_{0.05}$ = 10.4 cm).

The 2010 Preliminary Trial yield of KY06C-11-3-10 was 4102 kg ha^{-1}, significantly ($P < 0.05$) lower than the mean of McCormick checks (4873 kg ha^{-1}) (Table 4). The grain volume weight of KY06C-11-3-10 (78.8 kg hL^{-1}), however, was significantly higher than McCormick at 76.6 kg hL^{-1} (Table 4). Although the mean grain yield of KY06C-11-3-10 was lower than McCormick in four tests, the difference was not significant ($P < 0.05$) (Table 4) in 2011. Mean 2011 grain volume weight of KY06C-11-3-10 was significantly ($P < 0.05$) lower than McCormick but not significantly different ($P < 0.05$) than Pembroke or Truman (Table 4). In 2012, Kentucky had an unusually warm spring followed by relatively limited moisture, which favored rapid grain fill and dry down, especially in western Kentucky (Bruening et al., 2012). Under these conditions, KY06C-11-3-10 had significantly higher yields than Truman ($P < 0.05$) for the fungicide treatment in Lexington and for the control treatment in Princeton (Table 3). For both treatments in Princeton, KY06C-11-3-10 had a significantly ($P < 0.05$) higher grain volume weight than all 13 varieties tested (Table 3). At Lexington, the grain volume weight of line KY06C-11-3-10 was the highest in the fungicide treatment and significantly different ($P < 0.05$) from 8 out of 13 varieties. In the control treatment, the same 8 varieties plus Pioneer 25R32 had significantly lower grain volume weight than did KY06C-11-3-10.

From 2010 to 2012 in the Kentucky trials at Lexington and Princeton, KY06C-11-3-10 headed, on average, 3 d later than McCormick and 7 d earlier than Truman (Tables 1, 3, 4).

In the 2010 Preliminary Trial, KY06C-11-3-10 was 83.8 cm tall and significantly ($P < 0.05$) taller (2.1 cm) than McCormick (Table 4). However, in the four 2011 replicated yield trials,

Table 4. Characteristics of wheat germplasm KY06C-11-3-10 and checks in 2010 McCormick Backcross Preliminary Trial and mean of four 2011 yield trials, two at Lexington, KY, and two at Woodford, KY.

Entry	Grain yield	Vol. weight	Days to heading	Plant height	Lodging
	kg ha^{-1}	kg hL^{-1}	d	cm	%
			2010		
KY06C-11-3-10	4102	78.8	127.0	83.8	0.0
McCormick	4873	76.6	125.6	81.7	0.0
LSD (0.05)	141	0.6	0.2	0.8	0.0
			2011		
KY06C-11-3-10	3357	70.2	133.5	84.6	27.5
McCormick	3874	72.0	129.1	84.6	30.0
Pembroke	4043	69.7	129.1	88.9	1.3
Truman	4465	71.2	138.9	96.3	11.3
LSD (0.05)	578	1.2	1.6	4.8	23.0

there was no significant ($P < 0.05$) difference in height between KY06C-11-3-10 (84.6 cm) and either McCormick or Pembroke, but line KY06C-11-3-10 was significantly ($P < 0.05$) shorter than Truman by 11.7 cm (Table 4). In both locations and treatments of the Fungicide × Variety Trial in 2012, KY06C-11-3-10 was not significantly ($P < 0.05$) different than Pembroke, and overall it was significantly ($P < 0.05$) shorter than Truman (Table 3). Comparisons of height data collected in the scab nursery showed no significant ($P < 0.05$) difference in the Preliminary Scab Trial between line KY06C-11-3-10 and McCormick in 2010 or in the mean of three scab trials in 2011. In the latter experiments, KY06C-11-3-10 (77 cm) was significantly ($P < 0.05$) shorter than both Pembroke at 83.4 cm and Truman at 94.4 cm (Table 1). In the Selection Scab Experiment in 2011 and 2012, KY06C-11-3-10 was not significantly ($P < 0.05$) different than McCormick or Pembroke in height but was significantly ($P < 0.05$) shorter than Truman by 15.3 cm in 2011 and 13.9 cm in 2012 (Table 2).

Quality Testing

Milling and baking quality of KY06C-11-3-10 was consistent with soft wheat quality standards set by the USDA–ARS Soft Wheat Quality Laboratory. The flour yield was similar (68.0%) to a McCormick check (68.9%) grown alongside, with a modified milling quality score of 61.3 compared with 65.2 for McCormick. KY06C-11-3-10 had significantly coarser flour as measured by a softness equivalent score of 54.6, compared with 64.1 for McCormick. The softness equivalence, however, was within the normal range of soft wheat genotypes. The sucrose solvent retention capacity (SRC) value (95.3%), a measure of arabinoxylan water absorption, was similar to McCormick (93.5%), and the cookie diameter of 18.0 cm was the same as McCormick. The flour protein of KY06C-11-3-10 was 10.0% compared with 9.2% for McCormick. KY06C-11-3-10 has a moderate to weak gluten genotype based on lactic acid SRC value of 106.4% compared with 112.0% for McCormick and as such is within the normal range of gluten strength for soft wheat germplasm.

Discussion

Increased FHB resistance conferred by gene *Fhb1* and a QTL on chromosome 2DL in the cross Ning7840/3*McCormick has been well documented (Kang et al., 2011). This was also the case for KY06C-11-3-10, which contains these FHB-resistance QTL as well as one on chromosome 5A. Populations having KY06C-11-3-10 as a parent should be well suited for enrichment for *Fhb1* and the major resistance QTL on 5A and 2DL. Genomic selection (GS) in wheat is an active area of research; however, most molecular breeding for FHB resistance currently depends on enrichment via MAS for major resistance QTL. Comparing GS and MAS, breeding for low DON, the most important aspect of FHB resistance, was most efficiently performed using MAS of major QTL (Rutkoski et al., 2012), although an approach of selection for essential QTL followed by genomic selection has also been suggested (Heffner et al., 2010). Several populations in which line KY06C-11-3-10 was used as FHB-resistant parent are currently under development in the University of Kentucky wheat breeding program. The likelihood of recovering FHB-resistant lines with acceptable yield, grain volume weight, heading date, height, and quality characteristics should be greater than would be expected if unimproved sources of these QTL were used as parents. Resistant soft red winter wheat varieties with yield potential approaching or exceeding susceptible varieties that are currently grown and that also have other desirable agronomic and end use characteristics are needed as these would be more likely to be planted widely by growers.

Availability

Until the seed supply is exhausted, small quantities of seed of KY06C-11-3-10 are available on written request to the corresponding author. Seed of KY06C-11-3-10 has been deposited in the National Plant Germplasm System.

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