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Fusarium head blight resistance in U.S. winter wheat cultivars and elite breeding lines

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Abstract

Fusarium (*Fusarium graminearum*) head blight (FHB) is a destructive disease of wheat (*Triticum aestivum* L.) worldwide. To characterize FHB resistance in U.S. wheat germplasm, 363 U.S. winter wheat accessions were repeatedly evaluated for FHB resistance. A high correlation (r = 0.73, P < 0.001) for mean percentages of symptomatic spikelets (PSS) was observed between greenhouse and field experiments. The majority of tested accessions were either moderately or highly susceptible; only 7% of the accessions in the greenhouse and 6% of the accessions in the field showed a high level of resistance. Mean PSS for 19 accessions that carry markers for *Fhb1*, a major quantitative trait locus (QTL) from 'Sumai3', are 29.8% in the greenhouse and 25.1% in the field experiments. Fifty-four wheat accessions lacking *Fhb1* showed at least a moderately high level of FHB resistance in the greenhouse and/or field. These included three resistant accessions, 35 moderately resistant accessions, and 16 accessions that showed different levels of resistance in greenhouse and field experiments. Accessions without *Fhb1* that showed consistent resistance in both field and greenhouse experiments may be good sources for pyramiding native resistance QTLs from U.S. wheat with *Fhb1*.

Abbreviations: FHB, Fusarium head blight; HWW, hard winter wheat; SWW, soft winter wheat; NIL, near-isogenic lines; PSS, percentage of symptomatic spikelets in a spike; QTL, quantitative trait locus; R, resistant; MR, moderately resistant; MS, moderately susceptible; S, susceptible

F. Jin, College of Agronomy, Northwest A&F University, Yangling, Shaanxi, China, 712100; F. Jin, D. Zhang, and G. Bai, Department of Agronomy, Kansas State University, Manhattan, KS 66506; W. Bockus, Department of Plant

Pathology, Kansas State University, Manhattan, KS 66506; P. S. Baenziger, University of Nebraska, Lincoln, NE 68583; B. F. Carver, Oklahoma State University, Stillwater, OK 74078; G-H. Bai, USDA-ARS Hard Winter Wheat Genetics Research Unit, Manhattan, KS 66506. *Corresponding author (guihua.bai@ars.usda.gov, gbai@ksu.edu).

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Fusarium head blight (FHB, incited by *Fusarium spp*.) of wheat (*Triticum aestivum*), also known as wheat scab, is one of the most destructive diseases in the humid and semi-humid wheat-growing areas worldwide (Parry et al., 1995; Osborne and Stein, 2007). *F. graminearum* Schwabe [teleomorph = *Gibberella zeae* (Schw.) Petch] is the prevailing wheat pathogen in the United States and many other countries (Bai and Shaner, 2004). Severe FHB epidemics occur when a susceptible host encounters abundant pathogen inocula in the presence of humid and warm weather during wheat anthesis (Osborne and Stein, 2007). FHB epidemics can cause significant losses in both grain yield and quality. Harvested grain contaminated with mycotoxins, especially deoxynivalenol (DON), produced by the pathogen is a serious safety concern to human and animal health (Bai and Shaner, 1994; Parry et al., 1995).

Use of resistant cultivars coupled with fungicide application is the most effective strategy to minimize disease losses. In China, a nationwide screening of germplasm and breeding lines identified 'Sumai 3' and its derivatives to have the best resistance (Reviewed by Bai and Shaner, 1994, 2004), which have become the major sources of FHB resistance in breeding programs worldwide. Quantitative trait loci (QTLs) for FHB resistance have been reported on all 21 chromosomes (Bai and Shaner 2004, Yu et al, 2008, 1963 Liu et al, 2009, Buerstmayr et al., 2009). However, only the *Fhb1* QTL on chromosome 3BS has a large effect mainly on type II resistance, resistance to fungal spread within a spike (Schroeder, and Christensen, 1963), that has been stable across various genetic backgrounds (Bai and Shaner, 2004). In the United States, FHB epidemics originally occurred mainly in hard spring wheat in the northern Great Plains and in soft winter wheat (SWW) regions, so extensive screening of breeding materials from those regions has identified several U.S. cultivars with FHB resistance, such as ‘Roane’, ‘Ernie’, and ‘Freedom’ (Rudd et al., 2001, Griffey et al., 2001). QTL haplotype analysis indicates that these cultivars do not carry *Fhb1*, which means they may carry resistance QTLs that are different from those in Chinese sources (Liu et et al., 2005). In the hard winter wheat (HWW) growing region of the Great Plains, FHB has not been a major issue until recent years; thus, systematic screening of HWW germplasm and breeding materials for FHB resistance has not been reported. Initial evaluation of some HWW identified several cultivars, including ‘Heyne’ and ‘Hondo’, with FHB resistance. QTLs in these cultivars may be different from those in Asian sources (Zhang et al. 2012). Combining U.S. native resistance genes with the resistance alleles at major QTLs from Asian sources may diversify the FHB resistance gene pool and significantly enhance FHB resistance levels in U.S. wheat. Therefore, characterizing U.S. winter wheat, especially HWW elite breeding lines, may provide important information to breeders for selecting good parents for breeding crosses. This study was designed to evaluate the effects of *Fhb1* on FHB resistance in U.S. winter wheat backgrounds, to identify native sources of FHB resistance, and to investigate wheat accessions with resistance type I (to initial infection) and type II by comparing reactions to FHB in greenhouse and field experiments.

MATERIALS AND METHODS

Plant materials

A total of 363 winter wheat accessions, including 289 HWW and 74 SWW accessions, were evaluated for FHB resistance in both greenhouse and field experiments. HWW accessions were selected from five hard winter wheat nurseries: the 2008 and 2010 Southern and Northern HWW Regional Performance Nurseries, the 2010 HWW Regional Germplasm Observation Nursery, the 2010 Tri-state FHB Nursery, and the 2008 Yield Trial Nursery from the wheat breeding program at Oklahoma State University. SWW accessions were selected from Uniform Eastern Soft Red Winter Wheat Nurseries and Uniform Southern Soft Red Winter Wheat Nurseries. The project consisted of two sets of materials tested in different experiments: set I had 207 accessions, including all of the HWW and SWW entries from the 2008 nurseries and breeding lines from Oklahoma; and set II had 191 accessions, including 156 new accessions from the 2010 HWW nurseries, and 35 selected accessions from experiment I. In both sets, Sumai3 (resistant), 'Wesley' (moderately susceptible), and 'Duster' (susceptible) were used as controls.

Evaluation of FHB resistance

In the greenhouse experiments, six plants per line were transferred into a 13 x 13 cm Dura-pot (Hummert Int., Earth City, MO) with a 12 h photoperiod after vernalization for 6 wk at 4 °C in a cold chamber. Set I was tested in 2009 (spring and fall) and 2010 (spring) greenhouse experiments, and set II was tested in 2011 (spring and fall) and 2012 (spring) greenhouse experiments. All experiments were arranged in a randomized complete block design with two replications (pots) of six plants in each experiment.

Conidial inocula of *F. graminearum* were prepared using field isolate GZ 3639 from Kansas. This isolate has showed consistent pathogenicity on a set of wheat cultivars for over a decade (G. Bai, unpublished data). Conidial suspension was adjusted to 100 spores per µL for inoculation.

About six spikes with similar flowering time in each pot were inoculated by injecting 10 μL of the conidial suspension into a central spikelet of a spike at anthesis using a syringe. After inoculation, plants were moved into a moist chamber with 100% relative humidity for 48 h at 21 ± 5 °C to initiate infection. Infected plants were then moved to a greenhouse bench for disease development at 21 ± 5 °C during the day and 17 ± 2 °C during the night. About 15 d post-inoculation, when the susceptible control was completely blighted, the numbers of infected and total spikelets in each inoculated spike were counted to calculate the percentage of symptomatic spikelets (PSS) in a spike.

Field experiments were conducted in the Rocky Ford FHB Nursery of the Department of Plant Pathology, Kansas State University (Manhattan, KS). Set I was evaluated for FHB in the springs of 2009, 2010, and 2011, and set II was evaluated in the springs of 2011 and 2012. About 40 seeds per accession were planted in a 1-m-long single-row plot, and each experiment had two replications. The FHB nursery was inoculated using spawn inoculation, in which *F. graminearum*-infected corn (*Zea mays* L.) kernels were scattered on the soil surface at the booting stage and 2 wk afterwards to facilitate initial infection. To ensure FHB infection in early flowering plants, needle inoculation was also conducted as described for greenhouse inoculation with six spikes per plot to assess type II resistance. From flowering through early dough stages, the nursery was misted by sprinklers 10 min per h from 1700 h to 0700 h daily. PSS was estimated for all plots on the basis of overall performance of a plot at 21 d after needle inoculation. PSS data were rechecked after 3 d.

All accessions were classified into one of four categories based on their PSS: resistant (R), moderately resistant (MR), moderately susceptible (MS), and susceptible (S). Classification decisions were made by comparing mean FHB rating of each accession with the 95% confidence intervals of R, MS, and S controls. Accessions falling between R and MS were classified as MR.

DNA extraction and marker analysis

Leaf tissue was collected at the two-leaf stage, and genomic DNA was isolated using a cetyltrimethyl ammonium bromide (CTAB) method (Zhang et al. 2012). A sequence tagged site marker, Xumn10, was used to identify whether the *Fhb1* resistance allele was present (Liu et al., 2008), and a single nucleotide polymorphism marker, Xsnp3BS-8, for *Fhb1* was analyzed to verify *Fhb1* resistance allele (Bernardo et al., 2012). DNA sequencing for Xsnp3BS-8 was done for these accessions that did not provide useful single nucleotide polymorphism results. Polymerase chain reaction was performed following Sun et al. (2010), and DNA sequencing was done using a BigDye® Terminator V1.1 sequencing kit (Applied Biosystems, Foster City, CA).

Data Analysis

Analysis of variance (ANOVA) and regression analysis were conducted using SAS ver. 9.2 (SAS Institute, Inc., Cary, NC). Because two sets of materials were selected from Regional Performance Nurseries in two different years (2008 and 2010), they were evaluated for FHB in different sets of greenhouse and field experiments. To investigate if any significant PSS differences existed between the two sets of experiments, ANOVA was conducted for both greenhouse and field PSS data for 35 common accessions that were tested in both sets of experiments.

Results

Wheat reactions to *Fusarium* head blight in greenhouses

The difference in PSS for the 35 accessions that were common to both sets of materials was not significant between the two sets of greenhouse experiments, nor among three tests of each set, nor between replications in each test (data not shown); thus, the two sets of materials were combined for further data analysis. Correlation coefficients of PSS for 363 accessions were highly significant among the three greenhouse experiments (r = 0.53-0.67, $P < 0.001$).

Wheat accessions showed significant variation in PSS after single floret inoculation (Fig. 1). Control cultivars Sumai3 (R), Wesley (MS), and Duster (S) had an average PSS of 8.6%, 51.5%, and 81.3%, respectively. Frequency distribution of PSS showed that most accessions (75.0%) were either as susceptible as Duster (43.0% with PSS ⩾ 70.1%) or as moderately susceptible (32.0% with PSS between 45.1% and 70.0%) as Wesley (Fig. 1 and Table 1). Among the 363 wheat accessions, only 25 (7.0%) were classified as resistant, with a PSS ⩽ 23.0%, and 64 (18.0%) were moderately resistant, with a PSS between 23.1% and 45.0% (Table 1).

To test for the presence of the *Fhb1*-resistant allele in the resistant wheat accessions, marker Xumn10 was analyzed in all accessions. A total of 23 wheat accessions had the 258-bp marker allele associated with the *Fhb1* resistance allele. Among them, 16 were backcross-derived *Fhb1* NILs from the USDA marker-assisted backcross project (G. Bai, unpublished data). In these accessions, the *Fhb1* resistance allele had been transferred into three U.S. HWW cultivars (Wesley, 'Trego', and 'Harding') and one SWW cultivar ('Clark') (Table

2). They all showed a high level of resistance in greenhouse experiments, except for single *Fhb1* lines from Trego and Clark, and two from Harding that had slightly higher PSS estimates. Among the seven other lines carrying the Xumn10 allele associated with *Fhb1* resistance, four lines (INW0411, P02444A1-23-9, NE08527, and P03112A1-7-14) were resistant or moderately resistant to FHB, and three (BC01007-7, VA05W-258, and NX03Y2489) were moderately susceptible or susceptible. To verify the presence of the *Fhb1* resistance allele in these accessions, the polymorphic nucleotide sequence at a recently developed single nucleotide polymorphism marker, Xsnp3BS-8, was assayed. All 16 *Fhb1* NILs had the Sumai3 allele G (Table 2). Among the other seven *Fhb1* lines with the Xumn10 marker allele associated with resistance, only three (INW0411, P02444A1-23-9, and P03112A1-7-14) carry the Xsnp3BS-8 allele that is associated with resistance. Two (NE08527 and VA05W-258) carry the allele C associated with a susceptible reaction, and two (BC01007-7 and NX03Y2489) did not produce PCR products. Seventeen accessions did not carry the *Fhb1* resistance allele, but still showed a high level of type II resistance, with a mean PSS of 17.4% (Table 2). These materials likely contain resistance QTLs other than *Fhb1*, and include wheat accessions SD05085-1, T154, SD05210, 'Century', Heyne, 'Lyman', 'Everest', 'Harry', Freedom, and 'Atlas66' (Table 2). The mean PSS for the wheat accessions with the *Fhb1* resistance allele was 29.8% based on the both markers Xumn10 or Xsnp3BS-8 (Table 2). Therefore, *Fhb1* can significantly improve FHB resistance in many genetic backgrounds.

The percentage of resistant or moderately resistant accessions was higher in SWW (43.0%) than in HWW (20.0%) (Table 1). In HWW, the percentage is even lower (17.0%) after removal of *Fhb1* NILs; thus, HWW appears to have a much lower percentage of breeding lines or cultivars with FHB type II resistance than SWW (Table 2, Supplemental Table S1).

Wheat reactions to Fusarium head blight in the field

In the two sets of field experiments, the difference in PSS for the 35 accessions common to both sets was not significant between the two sets of field experiments (data not shown) and the correlation coefficients of the 35 accessions were significant (Supplemental Table S2). Therefore, they were combined for further statistical analysis. The field mean PSS for the three controls, Sumai3 (R), Wesley (MS) and Duster (S), increased slightly from the greenhouse data, so PSS ranges for the four phenotypic classes were adjusted accordingly for field data, with a PSS of 0 to 25.0% classified as R, 25.1 to 50.0% as MR, 50.1 to 75.0% as MS, and above 75.0% as S. Among the 363 accessions, only 22 were R (10 HWW and 12 SWW), and 98 were MR. A majority of accessions (67.0%) were either MS (151) or S (92). For the 289 HWW accessions, about 71.0% were MS or S to FHB in the field conditions (Table 1).

The 19 wheat accessions containing the *Fhb1*-associated alleles of both markers Xumn10 and Xsnp3BS-8 all had FHB resistance, with a mean PSS of 25.1% in the field experiments (Table 2). Among them, 16 *Fhb1* NILs had consistent resistance similar to that observed in the greenhouse experiments. Results confirmed that the *Fhb 1* resistance allele had a stable effect on reducing FHB severity both in greenhouse and field conditions. Among the 22 resistant accessions identified in the field experiments, three HWW and seven SWW accessions did not have the Xumn10 allele associated with *Fhb1* resistance (Table 1, Table 2). The HWW entries consisted of both breeding lines and released cultivars from different states, including T154, ‘Hitch’, and KS08IFAFS1. Resistant SWW cultivars or breeding lines from several states included IL02-18228, Roane, USG3555, and KY96C-0769-7-3 (Table 2).

Relationship of FHB ratings between greenhouse and field experiments

A significant correlation coefficient (r = 0.73, P < 0.001) of mean PSS for 363 wheat accessions was observed between greenhouse and field experiments (Fig. 2), suggesting that most wheat accessions with a low PSS in the greenhouse usually had a low PSS in the field (Fig. 2, Table 2). Correlation coefficients of PSS were significant (r = 0.45 to 0.64, P < 0 .001) among the greenhouse experiments and among the field experiments. Significant correlations of PSS ratings were observed between three greenhouse and three field experiments, with r-values ranging from 0.40 to 0.96 (P < 0 .001).

Comparing the resistant accessions identified from greenhouse and field experiments showed that 15 out of the 17 HWW accessions that demonstrated resistance in greenhouse experiments also had resistance or moderate resistance in field experiments, including the accessions developed from institutions or companies in South Dakota (SD05085-1, SD05210, Lyman), Nebraska (Harry), Kansas (T154, Heyne, Everest, and AP05T2413), and the USDA Genotyping Lab in Kansas (*Fhb1* NILs in Wesley or Trego backgrounds). Seven out of eight SWW accessions (INW0411, Freedom, MO040152, Roane, ‘Bess’, KY96C-0769-7-3, Atlas66) showed low PSS in both greenhouse and field experiments (Table 2). Accessions with a low PSS in the field usually also showed a low PSS in greenhouse, with a few exceptions.

Under both environments (greenhouse vs. field), most lines carrying *Fhb1* showed consistent resistance to FHB. For example, all the *Fhb1*-carrying NILs of Wesley, two of the three Trego *Fhb1* NILs, three of the four Clark *Fhb1* NILs, and one of three Harding *Fhb1* NILs showed consistent resistance in both environments (Table 2), suggesting that *Fhb1* is a reliable QTL for reduced PSS, and that it may contribute to both type I and type II resistance in the field. However, several accessions that did not carry *Fhb1* according to marker data also showed a high level of resistance. For example, one HWW, T154, and two soft red wheats, Roane and KY96C-0769-7-3, did not have *Fhb1* according to the allele at Xumn10, but showed a high level of resistance in all greenhouse and field experiments (Table 2). In addition, 35 accessions without the *Fhb1* resistance allele consistently showed moderate resistance in both greenhouse and field environments (Table 2). Another 16 accessions lacking *Fhb1*, such as SD05085-1, Heyne, Lyman, Everest, Harry, Hitch, Freedom, Bess, and Atlas66, had resistance or moderate resistance in both greenhouse and field experiments (Table 2, Supplemental Table S1). These accessions can be used either as parents in further breeding crosses, or as FHB-resistant cultivars for commercial production to reduce FHB damage in epidemic years.

Discussion

Repeatability of FHB resistance in field and greenhouse experiments

Systematic evaluation of wheat germplasm for FHB resistance has been reported in China and many other countries (Snijders, 1990; Miller et al., 1998; Buerstmayr et al., 2003; Bai and Shaner, 2004; Zhang et al, 2008; Oliver et al., 2008), but not for U.S. HWW, especially elite HWW breeding lines, so this study is the first attempt to systematically evaluate FHB resistance in U.S. winter wheat (mainly HWW) cultivars and breeding lines in both greenhouse and field experiments. The results provide valuable information that breeders can use to select resistant parents for crosses or to select elite breeding lines that could be released as FHB-resistant cultivars or germplasm.

To evaluate FHB resistance accurately, an effective evaluation protocol is crucial. Needle inoculation of a single spikelet in a spike is a common practice used for type II resistance, and FHB severity usually is scored using either PSS per spike (Bai and Shaner, 2004) or a 1 to 10 visual scale (Stack and McMullen, 1995). Spraying spores over spikes or scattering Fusarium-infected wheat or corn spawn in field is used to evaluate both type I and type II resistance, and incidence is scored by estimating proportion of diseased spikes per experimental unit (plot) to estimate type I resistance (Stack and McMullen, 1995). In field experiments, it is often impossible to distinguish between type I and type II resistance, so an FHB index is often used to reflect overall resistance (Seem, 1984; Bai and Shaner, 2004; Paul et al., 2005).

In this study, the experimental materials were repeatedly evaluated for FHB resistance in both greenhouse and field experiments. In the greenhouse, needle inoculation was performed and type II resistance was measured. Among the three greenhouse experiments, the correlation coefficients were highly significant. In the field studies, plants were inoculated by a combination of both needle and spawn inoculations, and were misted hourly from heading to dough stages to ensure that there would be enough moisture for infection. This procedure significantly reduced disease difference caused due to plant heights and flowering times of different wheat accessions. In Manhattan, Kansas, spawn inoculation with misting usually is effective in most years for inducing sufficient infection of most plants with high repeatability (Bockus et al, 2007), but spring weather conditions vary from year to year, especially with regard to ambient temperature. A warm early spring, for example, may lead to an early heading date, which may result in infection escape in early maturing accessions due to lack of inoculum. The needle inoculation technique can ensure that early flowering plants have an appropriate initial infection and can minimize flowering time effect on FHB level. Also, we scored FHB based on flowering time (21 d after needle inoculation), needle-inoculated plants were scored when natural infection was low in these early flowering plants; thus, correlation coefficients among field experiments were similar to those among greenhouse experiments. The combination of needle and spawn inoculation methods can be recommended for field genetic studies, especially for genotypes with large differences in flowering times. Although we observed a slight difference in resistance ranking for some accessions between greenhouse and field experiments, the correlation coefficients between greenhouse and field experiments were still very high (Fig. 2). This result indicates that type II resistance is the major type of resistance for most accessions in field conditions, with a few exceptions, such as in Husker, Century, P03207A1-7, KS08IFAFS1, and IL02-18228 (Table 2 and Supplemental Table S1).

Husker, Century, and P03207A1-7 had a low PSS in the greenhouse experiments, indicating that they had type II resistance, but not type I resistance, as reflected by their high PSS in the field experiments, so they are not recommended for use in FHB resistance breeding. Only those accessions with low PSS in both field and greenhouse experiments should be used as resistant cultivars or breeding parents.

Impact of *Fhb1* on FHB resistance

To date, although many different sources of FHB resistance have been reported worldwide (Bai and Shaner, 2004), the *Fhb1* gene has shown the largest effect on type II resistance in diverse genetic backgrounds and environments. Unfortunately, in this study, none of released cultivars were shown to carry *Fhb1*, and only seven accessions (three HWW and four SWW) from regional nurseries carried the Xumn10 marker allele associated with *Fhb1*-mediated resistance (Liu et al., 2008). Among the seven accessions, NX03Y2489, VA05W-258, BC1007-7, and NE08527 are unlikely to carry *Fhb1* based on their pedigrees. One possible reason for the low frequency of *Fhb1* in U.S. winter wheat is that Sumai3 and its Chinese derivatives have many undesirable traits, so progenies with *Fhb1* usually inherit some of these. When breeders select for desirable agronomic trait and adaptation to North America, plants carrying the *Fhb1* gene might be discarded in field selection due to their poor agronomic traits. To solve this problem, the USDA Genotyping Laboratory in Manhattan, Kansas, successfully transferred *Fhb1* into four U.S. winter wheat backgrounds (Wesley, Trego, Harding, and Clark) using marker-assisted backcrossing. This successfully combined *Fhb1* with adapted agronomic traits and improved the resistance of U.S. winter wheat. Among the four recurrent parents, Clark is a soft red winter wheat, Trego is a hard white winter wheat, and Wesley and Harding are hard red winter wheats. In the greenhouse tests, four Wesley *Fhb1* resistant NILs had a mean PSS similar to Sumai3. Three Trego *Fhb1* resistant NILs and four Clark *Fhb1* resistant NILs had a slightly higher PSS than Sumai3, but had a significant reduction in PSS compared with their recurrent parents. Significant PSS reduction in these NILs was also observed in the field experiments (Table 2 and

Supplemental Table S1). These NILs have an appearance similar to their recurrent parents, so transfer of *Fhb1* to U.S. winter wheat can quickly improve the level of FHB resistance. These selected *Fhb1* NILs should be good parents for future breeding crosses; however, *Fhb1* was not equally effective at enhancing FHB resistance in all genetic backgrounds. For example, the Harding *Fhb1* NILs had a PSS similar to Harding. Thus, selecting appropriate recurrent parents is important for successful use of *Fhb1*.

Among potential *Fhb1* carriers from the Regional Nurseries, INW0411, P02444A1-23-9, and P03112A1-7-14 displayed a high level of FHB resistance, whereas BC01007-7, VA05W-258, and NX03Y2489 were highly susceptible. NE08527 had only type II resistance, as shown in greenhouse experiments, but not in field experiments (Table 2). High susceptibility in some lines with the *Fhb1* resistance-associated allele of the Xumn10 marker was possibly due to Xumn10 is not a diagnostic marker for *Fhb1*. This assumption is supported by two factors: 1) the pedigrees of those lines do not have any connection with Sumai3 sources, and 2) they all carry a susceptible allele that is associated with susceptibility or fail to amplify any PCR product at the Xsnp3BS-8 marker (Bernardo et al., 2012). All other lines with the Xumn10 allele linked to the *Fhb1* gene have the allele associated with resistance at Xsnp3BS-8 (Table 2). Thus, *Fhb1* as determined by both markers UMN10 and Xsnp3BS-8 significantly improved type II resistance in these U.S. wheat backgrounds.

North American sources of FHB resistance in U.S. winter wheat

In this study, 17 accessions showed a similar or slightly lower level of type II resistance than

Sumai3 in the greenhouse experiments, even though they do not carry the Xumn10 marker allele associated with *Fhb1* resistance allele and do not relate to any Chinese sources of resistance in their pedigrees. This suggested that the resistance of these accessions to FHB might originate from North American sources. Among them, seven accessions are SWW types. Freedom (Gooding et al., 1997) and Roane (Griffey et al., 2001) have been major U.S. sources of FHB resistance of soft wheat in U.S. breeding programs (Liu et al., 2005). Other accessions, including MO040152, Bess, KY96C-0769-7-3, and Atlas66 had low PSS ratings in both greenhouse and field experiments. Those accessions are also good local sources of resistance for improvement of SWW FHB resistance. Ten such accessions were HWW. Among them, T154 showed the best resistance in both field and greenhouse experiments. SD05210, Heyne, Lyman, Everest, and Harry also had relatively low PSS in both greenhouse and field experiments. These accessions are well-adapted to the Great Plains growing environments and are resistant to different diseases. Some of them have been released as commercial cultivars in the region, and thus are good native sources of resistance in HWW. To date, resistance QTLs from these sources have not been characterized, and identification of markers for the QTLs in those accessions will facilitate marker-assisted pyramiding of these QTLs in U.S. winter wheat.

In addition, HWW cultivars such as Hitch had a high level of field resistance as well as moderate resistance in greenhouse experiments. The released cultivars mentioned above have not only the desired adaptation to HWW regions, but also reasonable yield and quality, making them ideal parents for pyramiding *Fhb1* with resistance QTLs from North American sources to attain transgressive segregation. This list can be expanded to SD08198, T153, CO04W210, OK05128, ‘Aspen’, U07-698-9, ‘Endurance’, N02Y5117, and HV9W02-942R in HWW, and IL00-8530, MD01W233-06-1, M04*5109, Ernie, OH02-12678, and KY97C-0519-04-07 in SWW (Table 2). These accessions had slightly higher PSS than previously mentioned highly resistant cultivars in both field and greenhouse experiments, but they were all moderately resistant, which means they could be important breeding parents for improvement of FHB resistance in U.S. winter wheat.

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Figures

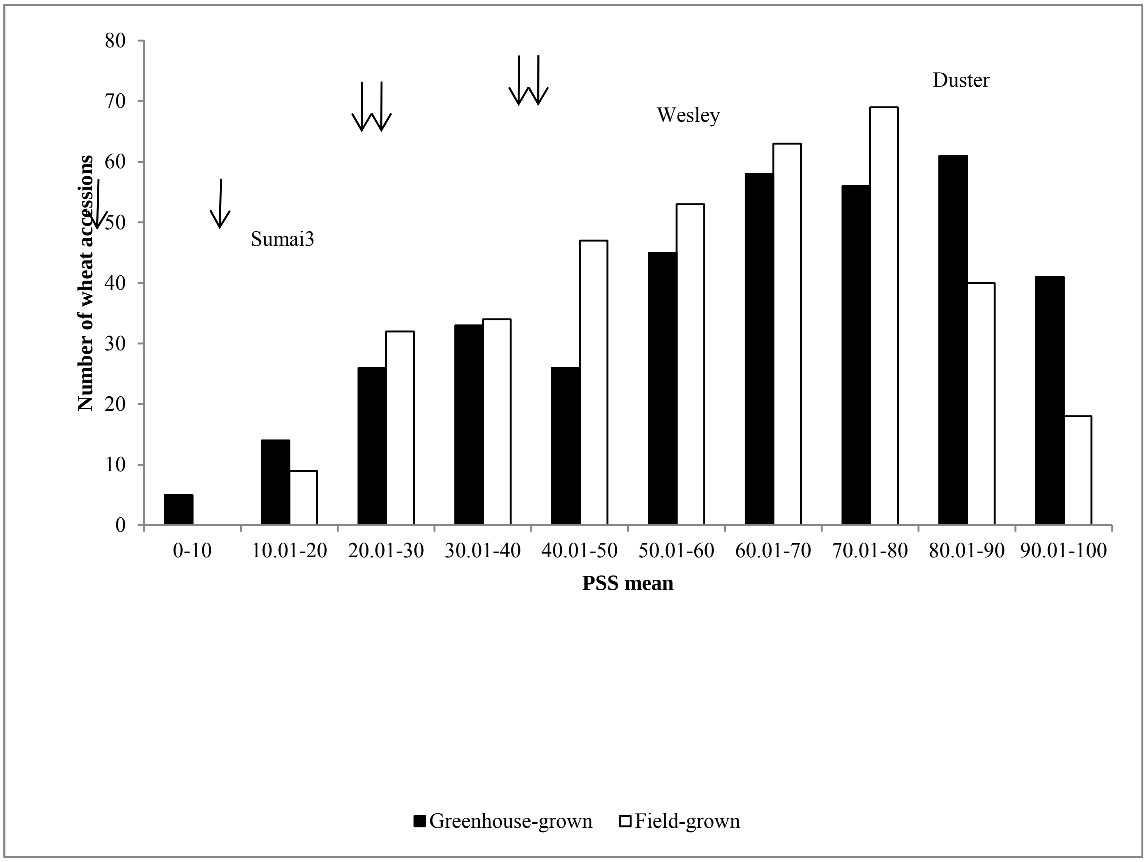

Figure 1. Frequency distribution of mean percentage of symptomatic spikelets (PSS) in a spike for 363 wheat accessions evaluated in greenhouse and field experiments at Manhattan, KS.

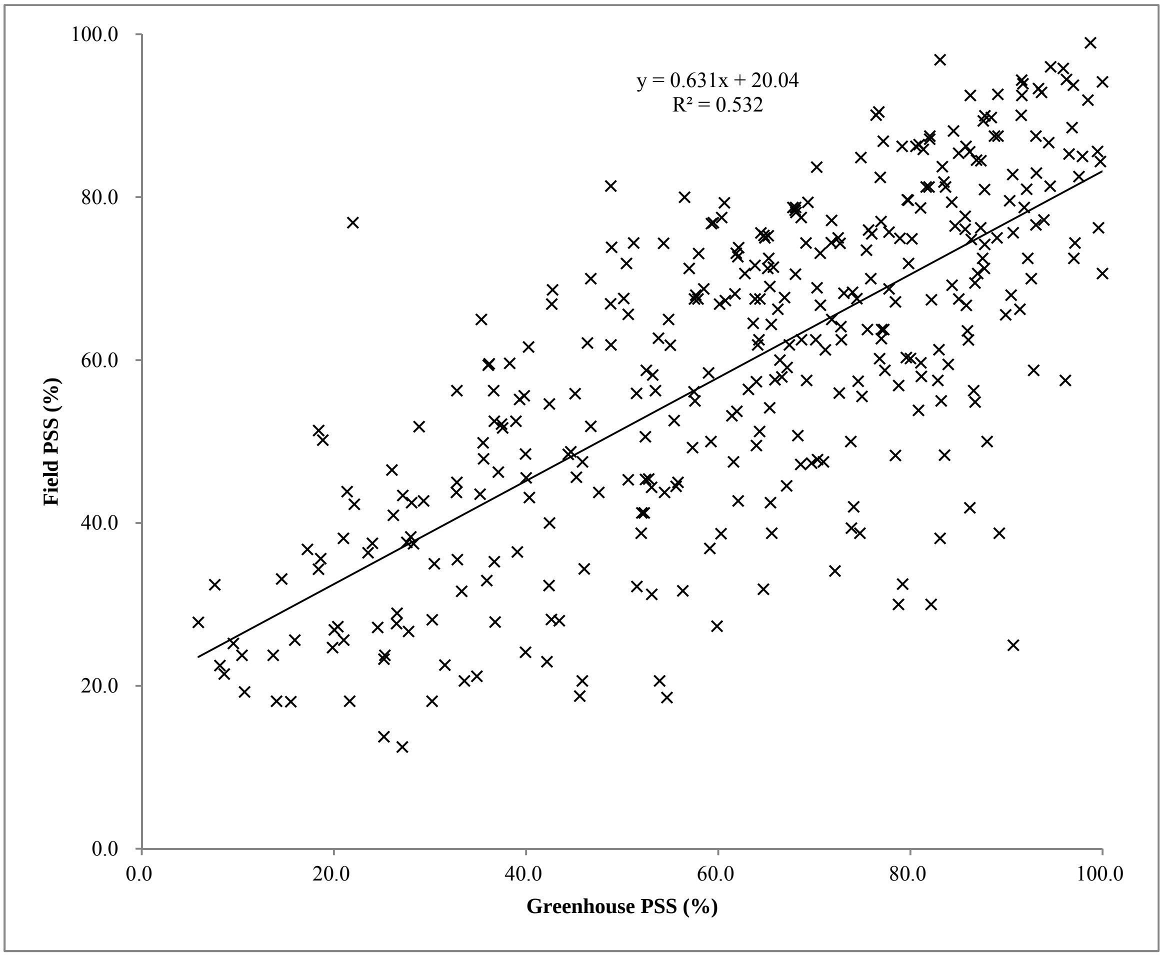

Figure 2. Correlation of percentages of symptomatic spikelets in a spike (PSS) of 363 U.S. winter wheat accessions between greenhouse and field experiments conducted in Manhattan, KS.

Table 1. Reactions of two classes of U.S. winter wheat accessions, hard winter wheat (HWW) and soft winter wheat (SWW), to Fusarium head blight inoculation in the greenhouse and field experiments.

Wheat Class	No. of accessions in greenhouse†					No. of accessions in field†				
	R (≤23.0%)	MR (23.1%-45.0%)	MS (45.1%-70.0%)	S (≥70.1%)	Total	R (≤25.0%)	MR (25.1%-50.0%)	MS (50.1%-75.0%)	S (≥75.1)	Total
HWW	17	40	97	135	289	10	75	125	79	289
SRWW	8	24	19	23	74	12	23	26	13	74
Total	25	64	116	158	363	22	98	151	92	363

†Phenotypic classification of accessions in greenhouse and field based on their reactions to *F. graminearum* by comparing their mean percentage of symptomatic spikelets (PSS) in a spike and 95% confidence intervals with resistant (R) control (Sumai3), moderately susceptible (MS) control (Wesley) and susceptible (S) control (Duster). Moderately resistant (MR) refers to accessions that had PSS between Sumai3 and Wesley.

Table 2. A list of accessions that showed resistance and moderate resistance to Fusarium head blight as reflected by mean percentage of symptomatic spikelets (PSS) in a spike evaluated in greenhouse (GH) and field (F) experiments in Manhattan, KS and that carry *Fhb1* marker allele associated with FHB resistance.

Accession	**Class**	**PSS GH**‡	**PSS (F)**‡	**Xumn10**§	**SNP** §
Wheat accessions with *Fhb1* allele					
INW0411	SWW	5.9 ± 2.6	27.8 ± 32.8	+	G
WesleyFhb1NIL09S-103†	HWW	8.1 ± 3.4	22.5 ± 8.9	+	G
WesleyFhb1NIL09S-104†	HWW	10.4 ± 2.8	23.8 ± 5.9	+	G
KS08FHB-78†	HWW	13.7 ± 8.4	23.8 ± 11.8	+	G
Wesley FHB1†	HWW	14.0 ± 6.1	18.1 ± 4.7	+	G
WesleyFhb1NIL09S-105†	HWW	15.9 ± 7.6	25.6 ± 9.2	+	G
TregoFhb1NIL09S-98†	HWW	21.0 ± 5.5	25.6 ± 10.3	+	G
TregoFhb1NIL09S-99†	HWW	21.6 ± 9.4	18.1 ± 3.4	+	G
ClarkFhb1NIL-75†	SWW	26.7 ± 7.1	13.8 ± 2.5	+	G
ClarkFhb1NIL09F-23†	SWW	27.1 ± 3.3	12.5 ± 2.7	+	G
ClarkFhb1NIL09F-45†	SWW	30.2 ± 21.0	18.1 ± 5.1	+	G
KS08FHB-31†	HWW	33.6 ± 21.1	20.6 ± 4.1	+	G
P02444A1-23-9	SWW	34.9 ± 30.4	21.2 ± 14.7	+	G
NE08527	HWW	35.3 ± 15.1	65.0 ± 11.2	+	C
P03112A1-7-14	SWW	35.6 ± 30.4	47.9 ± 24.8	+	G
HardingFhb1NIL09S-107†	HWW	44.7 ± 18.9	48.8 ± 9.5	+	G
TregoFhb1NIL09S-100†	HWW	45.6 ± 10.8	18.8 ± 5.9	+	G
BC01007-7	HWW	52.5 ± 19.2	58.8 ± 6.8	+	N
ClarkFhb1NIL09F-4†	SWW	53.9 ± 14.8	20.6 ± 9.2	+	G
HardingFhb1NIL09S-109†	HWW	59.1 ± 18.5	36.9 ± 15.6	+	G
HardingFhb1NIL09S-108†	HWW	64.7 ± 11.0	31.9 ± 12.6	+	G
VA05W-258	SWW	68.3 ± 10.2	50.7 ± 20.3	+	C
NX03Y2489	HWW	93.7 ± 10.7	92.9 ± 9.9	+	N

Mean PSS (%)		35.5 ± 21.7	32.3 ± 19.3		
Resistant accessions without *Fhb1* allele in greenhouse experiments					
Freedom	SWW	7.6 ± 3.0	32.4 ± 25.2	-	-
MO040152	SWW	9.5 ± 1.7	25.2 ± 14.2	-	-
Roane	SWW	10.7 ± 4.8	19.3 ± 7.4	-	-
SD05085-1	HWW	14.6 ± 5.8	33.1 ± 11.6	-	-
T154	HWW	15.5 ± 7.8	18.1 ± 6.5	-	-
Bess	SWW	17.2 ± 14.4	36.8 ± 28.2	-	-
SD05210	HWW	18.4 ± 10.9	34.3 ± 20.1	-	-
Century	HWW	18.4 ± 9.6	51.4 ± 23.2	-	-
Heyne	HWW	18.6 ± 15.4	35.6 ± 7.4	-	-
P03207A1-7	SWW	18.8 ± 12.3	50.2 ± 26.7	-	-
KY96C-0769-7-3	SWW	19.9 ± 11.1	24.7 ± 7.9	-	-
Lyman	HWW	20.0 ± 8.8	26.9 ± 6.2	-	-
Everest	HWW	20.4 ± 12.5	27.3 ± 14.5	-	-
Harry	HWW	21.0 ± 13.0	38.1 ± 5.4	-	-
Atlas66	SWW	21.4 ± 13.4	43.9 ± 13.9	-	-
Husker	HWW	22.0 ± 14.9	76.9 ± 11.3	-	-
AP05T2413	HWW	22.1 ± 12.3	42.3 ± 25.3	-	-
Mean PSS (%)		17.4 ± 4.3	36.3 ± 13.8		
Additional accessions without *Fhb1* but with FHB resistance in field experiments					
IL02-18228	SWW	54.7 ± 27.5	18.6 ± 10.2	-	-
M03-3616-C	SWW	31.5 ± 17.1	22.6 ± 9.0	-	-
G41732	SWW	42.2 ± 27.1	23.0 ± 11.7	-	-
USG 3555	SWW	25.2 ± 13.7	23.3 ± 12.4	-	-
Hitch	HWW	25.3 ± 15.3	23.8 ± 4.6	-	-
G61505	SWW	39.9 ± 33.6	24.1 ± 8.8	-	-
KS08IFAFS1	HWW	90.7 ± 4.0	25.0 ± 7.2	-	-

Moderately resistant accessions without *Fhb1* in greenhouse and field					
IL00-8530	SWW	23.6 ± 15.6	36.4 ± 19.5	-	-
SD08198	HWW	24.0 ± 9.8	37.5 ± 8.9	-	-
MD01W233-06-1	SWW	24.6 ± 17.9	27.2 ± 10.7	-	-
NI04420	HWW	26.0 ± 21.7	46.5 ± 10.9	-	-
SD05118	HWW	26.2 ± 22.4	40.9 ± 26.9	-	-
T153	HWW	26.5 ± 9.8	27.7 ± 7.9	-	-
M04*5109	SWW	26.6 ± 23.6	28.9 ± 8.2	-	-
MTS0531	HWW	27.2 ± 11.9	43.4 ± 19.9	-	-
G69202	SWW	27.6 ± 30.4	37.6 ± 26.4	-	-
Ernie	SWW	27.8 ± 14.0	26.7 ± 14.3	-	-
CO04W210	HWW	28.0 ± 12.0	38.3 ± 13.7	-	-
2008-193 Jagger (FHB3)	HWW	28.1 ± 6.4	42.5 ± 12.7	-	-
OK05128	HWW	28.3 ± 12.4	37.4 ± 11.0	-	-
OK05134	HWW	29.3 ± 17.6	42.7 ± 16.5	-	-
Aspen	HWW	30.2 ± 11.6	28.1 ± 6.8	-	-
OH02-12678	SWW	30.5 ± 14.8	35.0 ± 14.9	-	-
NE06545	HWW	32.8 ± 16.9	43.8 ± 13.8	-	-
Camelot	HWW	32.8 ± 18.2	45.0 ± 9.7	-	-
OH02-7217	SWW	32.8 ± 7.7	35.5 ± 10.7	-	-
U07-698-9	HWW	33.3 ± 15.9	31.6 ± 20.6	-	-
MD99W483-06-9	SWW	35.2 ± 18.8	43.5 ± 16.9	-	-
OK05723W	HWW	35.5 ± 25.7	49.8 ± 25.9	-	-
KY97C-0519-04-07	SWW	35.9 ± 27.2	32.9 ± 9.4	-	-
P04287A1-10	SWW	36.7 ± 15.8	35.2 ± 4.6	-	-
Endurance	HWW	36.8 ± 22.2	27.9 ± 9.4	-	-
Winterhawk	HWW	37.1 ± 11.2	46.3 ± 8.1	-	-
N02Y5117	HWW	39.1± 27.4	36.4 ± 20.1	-	-

OK06528	HWW	39.9 ± 34.1	48.5 ± 23.8	-	-
NW05M6011-6-1	HWW	40.0 ± 22.9	45.5 ± 5.5	-	-
Arapahoe	HWW	40.3 ± 14.5	43.1 ± 6.4	-	-
M04-4715	SWW	42.4 ± 29.2	32.3 ± 12.4	-	-
Overland	HWW	42.4 ± 19.9	40.0 ± 15.6	-	-
HV9W02-942R	HWW	42.6 ± 18.2	28.2 ± 11.2	-	-
MO011126	SWW	43.5 ± 15.5	28.0 ± 13.5	-	-
Jerry	HWW	44.4 ± 18.9	48.4 ± 17.7	-	-
Control cultivars					
Sumai3	SWW	8.6 ± 3.6	21.5 ± 18.0	-	G
Wesley	HWW	51.5 ± 22.2	55.9 ± 18.0	-	-
Duster	HWW	81.3 ± 18.7	85.9 ± 8.3	-	-

†Hard and soft winter wheat *Fhb1* near-isogenic lines (NILs).

‡Mean of standard deviation.

§ In Xumn10, '+' refers as *Fhb1* allele associated with FHB resistance, and '-' refers as non-*Fhb1* associated with FHB susceptibility; In single nucleotide polymorphism (SNP) marker data derived from Xsnp3BS-8, G refers as *Fhb1* allele associated with FHB resistance, C refers as non-*Fhb1* associated with FHB susceptibility, and N refers as no polymerase chain reaction products in these lines carrying *Fhb1* resistant allele as predicted by *Xumn10*. '-' means that this marker was not analyzed for these lines without the resistance allele as predicted by *Xumn10*.

Supplemental Table S1.Wheat accessions resistance to Fusarium head blight in greenhouse and field experiments.

Accession	Type[‡]	Sources §	Pedigree	Greenhouse PSS (%) ¶	Field PSS (%) ¶
WesleyFhb1NIL09S-103	HWW	HWWGRU	ND2928/Wesley*3 F6	8.1 ± 3.4	22.5 ±8.9
WesleyFhb1NIL09S-104	HWW	HWWGRU	ND2928/Wesley*3 F6	10.4 ± 2.8	23.8 ± 5.9
KS08FHB-78	HWW	Tri-state FHB Nursery	Bulk Selection	13.7 ± 8.5	23.8 ± 11.8
Wesley FHB1	HWW	HWWGRU	ND2928/Wesley*3 F6	14.0 ± 6.1	18.1 ± 4.7
SD05085-1	HWW	Tri-state FHB Nursery	SD92107-2/TX96D2845	14.6 ± 5.8	33.1 ± 11.6
T154[†]	HWW	2008 SRPN	T88/2180//T811	15.5 ± 7.8	18.1 ± 6.5
WesleyFhb1NIL09S-105	HWW	HWWGRU	ND2928/Wesley*3 F6	15.9 ± 7.6	25.6 ± 9.2
SD05210	HWW	2008 NRPN	SD98444/SD97060	18.4 ± 10.9	34.3 ± 20.1
Century	HWW	PI 502912	Payne//TAM W-101/Amigo	18.4 ± 9.6	51.4 ± 23.2
Lyman	HWW	South Dakota State University	KS93U134/Arapahoe	20.0 ± 8.8	26.9 ± 6.2
Everest[†]	HWW	2008 SRPN	HBK1064-3/Betty 'S'//VBF0589-1/IL89-6483	20.4 ± 12.5	27.3 ± 14.5
Harry	HWW	PI 632435	NE90614/NE87612 198/Lancer/3/Newton/Brule	21.0 ± 13.0	38.1 ± 5.4
Husker	HWW	Tri-state FHB Nursery	NE96644//Pavon/*3 SCOUT66/3/Wahoo (sib)/4/Wesley	22.0 ± 14.9	76.9 ± 11.3
AP05T2413	HWW	2008 SRPN	(KS95U522/TX95VA0011)F1/Jagger	22.1 ± 12.3	42.3 ± 25.3
SD08198	HWW	Tri-state FHB Nursery	Wesley/NE93613	24.0 ± 9.8	37.5 ± 8.9
Hitch	HWW	WestBred LLC.	Unknown	25.3 ± 15.3	23.8 ± 4.6
NI04420	HWW	2008 NRPN	NE96644//PAVON/*3Scout 66/3/Wahoo sib	26.0 ± 21.7	46.5 ± 10.9
SD05118[†]	HWW	2008 NRPN	Wesley/NE93613	26.2 ± 22.4	40.9 ± 26.9
T153†	HWW	2008 SRPN	T136/T151	26.5 ± 9.8	27.7 ± 7.9
MTS0531	HWW	2008 NRPN	L'Govskaya 167/Rampart//MT9409 (solid stem)	27.2 ± 11.9	43.4 ± 19.9
2008-193 Jagger (FHB3)	HWW	Oklahoma State University	*Jagger-Leymus racemosus 7A translocation*	28.1 ± 6.4	42.5 ± 12.7
OK05128	HWW	Oklahoma State University	KS94U275/OK94P549 F4:10 RC	28.3 ± 12.4	37.4 ± 11.0
KS980512-2-2	HWW	2008 SRPN	T67/X84W063-9-45//K92/3/SNF/4/X86509-1-1/X84W063-9-39-2//K92	28.9 ± 14.5	51.8 ± 13.6
OK05134[†]	HWW	Oklahoma State University	OK97411/TX91D6825 F4:10	29.3 ± 17.6	42.7 ± 16.5
NE06545	HWW	2010 SRPN	KS92-946-B-15-1/Alliance	32.8 ± 16.9	43.8 ± 13.8
Camelot	HWW	University of Nebraska	KS91H184/Arlin sib//KS91HW29/3/NE91631/4/VBF0168	32.8 ± 18.2	45.0 ± 9.7
Bill Brown	HWW	Colorado State University	Yumar/Arlin	32.8 ± 10.7	56.3 ± 3.5
U07-698-9[†]	HWW	2008 RGON	Jagger*2/HD29	33.3 ± 15.9	31.6 ± 20.6

KS08FHB-31	HWW	Tri-state FHB Nursery	Bulk Selection	33.6 ± 21.1	20.6 ± 4.1
NE08527	HWW	Tri-state FHB Nursery	1998 Roane/Culver	35.3 ± 15.1	65.0 ± 11.2
OK05723W	HWW	Oklahoma State University	SWM866442/Betty F4:10 HW	35.5 ± 25.7	49.8 ± 25.9
KS020822-M-5	HWW	Tri-state FHB Nursery	KS950409-P-4/KS940786-17-3//KS920709-B-5-2-2	36.1 ± 6.3	59.4 ± 6.4
Centerfield	HWW	Oklahoma State University	TAM 110/2174*2	36.2 ± 25.7	59.6 ± 21.8
SD06156-1	HWW	Tri-state FHB Nursery	Wesley/Falcon	36.6 ± 15.7	56.3 ± 9.3
OK06336	HWW	Oklahoma State University	Magvars/2174//Enhancer F4:9	36.7 ± 13.8	52.5 ± 24.0
Endurance†	HWW	Oklahoma State University	HBY756A/Siouxland//2180	36.8 ± 22.2	27.9 ± 9.4
Winterhawk	HWW	WestBred LLC.	Unknown	37.1 ± 11.2	46.3 ± 8.1
NE07444	HWW	2010 SRPN	KS96HW10-3/Wahoo/NE99585	38.9 ± 15.3	52.5 ± 6.6
N02Y5117	HWW	2008 RGON	Yuma//T-57/3/CO850034/4/4*Yuma/5/KS91H184/Arlin S/KS91HW29//NE89526	39.1 ± 27.4	36.4 ± 20.1
TX06A001376	HWW	2008 RGON	NE94482/TX95A1161	39.3 ± 29.1	55.2 ± 16.7
OK06528	HWW	Oklahoma State University	Vilma/Hickok//Heyne F4:9 A	39.9 ± 34.1	48.5 ± 23.8
OK06313	HWW	Oklahoma State University	Emma/Karl 92//2174 F4:9	40.3 ± 25.7	61.6 ± 12.9
Arapahoe	HWW	PI 518591	Brule/3/Parker*4/Agent//Belocerkovskaja 198/Lancer	40.3 ± 14.5	43.1 ± 6.4
SD06069†	HWW	2008 NRPN	Harry/Wesley//Jerry	42.4 ± 19.2	54.6 ± 16.2
Overland	HWW	2010 NRPN	Millennium sib//ND8974	42.4 ± 19.9	40.0 ± 15.6
HV9W02-942R†	HWW	2008 SRPN	53/3/Abl/1113//K92/4/Jag/5/KS89180B	42.6 ± 18.2	28.2 ± 11.2
SD07165	HWW	Tri-state FHB Nursery	SD97250/SD99W006//Avalanche	42.7 ± 11.9	66.9 ± 14.8
Jerry†	HWW	PI 632433	Roughrider//Winoka/NB66425/3/Arapahoe	44.4 ± 18.9	48.4 ± 17.7
HardingFhb1NIL09S-107	HWW	HWWGRU	Sumai3/Harding*3 F4	44.7 ± 18.9	48.8 ± 9.5
KS970187-1-10†	HWW	2008 SRPN	TAM107*2/TA759//HBC197F-1/3/2145	45.2 ± 11.1	45.6 ± 16.1
2174	HWW	HWWGRU	IL71-5662, VA66-54-10, Arthur, PL145, NB34, Scout, Sturdy, MoW7510	45.9 ± 28.1	47.5 ± 5.0
Millennium	HWW	University of Nebraska	Arapahoe/Abilene/4/Colt/3/Warrior *5/Agent//Kavkaz	46.0 ± 11.1	34.4 ± 8.0
KS010143K-11	HWW	2008 RGON	TAM-400/KS950301-DD-4	46.4 ± 26.7	62.1 ± 23.9
OK07231	HWW	2010 SRPN	OK92P577-(RMH 3099)/OK93P656-(RMH 3299) F4:10	46.7 ± 11.7	70.0 ± 8.2
ART	HWW	AgriPro Seeds Inc.	Jagger related	47.6 ± 18.3	43.8 ± 14.7
MTS0713	HWW	2010 NRPN	93X312E14/NuHorizon	48.8 ± 29.3	61.9 ± 16.7
OK02522W	HWW	Oklahoma State University	KS96WGRC39/Jagger	48.9 ± 25.5	73.8 ± 21.9
OK06319	HWW	Oklahoma State University	Enhancer/2174 F4:9	50.2 ± 24.5	67.6 ± 16.2
SD07W053	HWW	Tri-state FHB Nursery	Wendy/SD00W073//KS01HW54-4	50.5 ± 28.8	71.9 ± 16.1

KS020947-K-13	HWW	Tri-state FHB Nursery	01ROMIG-9/Jagger//KS940786-17-3	50.6 ± 33.8	65.6 ± 9.4
Wesley†	HWW	PI 605742	KS831936-3/NE86501//Colt/Cody	51.5 ± 22.2	55.9 ± 18.0
SD07220†	HWW	2008 RGON	Tandem/Goodstreak	51.5 ± 21.3	32.2 ± 16.8
KS031027-FHB~8	HWW	Tri-state FHB Nursery	MN99112/KS970226-5-4//KS970104-3-13	51.6 ± 16.7	71.3 ± 14.8
CA9W08-856	HWW	2010 NRPN	Jerry/CDC Falcon	52.0 ± 17.1	38.8 ± 14.7
Harding	HWW	HWWGRU	Brule//Bennett/Chisholm/3/Arapahoe	52.0 ± 14.6	41.3 ± 15.9
BC01007-7	HWW	2010 NRPN	W99-331/97x0906-8	52.5 ± 19.2	58.8 ± 6.8
NE02533	HWW	2008 NRPN	NE94458/Jagger	52.8 ± 24.8	45.4 ± 16.1
Hondo	HWW	Tri-state FHB Nursery	Unknown	53.1 ± 20.4	44.4 ± 10.4
Shocker	HWW	AGSECO	Unknown	53.1 ± 16.8	31.3 ± 4.6
NE07627	HWW	2010 NRPN	KS96HW10-3/Wahoo//NE99585	53.5 ± 6.9	56.3 ± 13.1
NE06430	HWW	Tri-state FHB Nursery	Wesley (N95L158)/3/KS9U241//Ike/TXGH12388-120*4/FS2	54.8 ± 30.9	65.0 ± 13.7
Kharkof†	HWW	PI 5641	Unknown	55.0 ± 26.6	61.8 ± 16.0
NE06619	HWW	2008 RGON	Wesley/Wahoo	55.4 ± 32.4	52.6 ± 27.9
TXHT001F8-CS06/325-PRE07/75	HWW	2008 RGON	TX01M5009/Halberd	55.6 ± 13.6	44.5 ± 8.9
09-25-11 rec-124	HWW	Kansas State University	*CS-Leymus racemosus 7A translocation*	55.8 ± 10.2	45.0 ± 0.0
BZ9W05-2039	HWW	2010 NRPN	Vanguard/BZ9W96-895	56.5 ± 9.0	80.0 ± 12.2
CO04499	HWW	2010 SRPN	Above/Stanton	57.5 ± 8.5	67.5 ± 20.6
NE06469	HWW	2010 NRPN	Unknown	57.6 ± 14.3	55.0 ± 20.6
OK05312	HWW	2008 RGON	TX93V5919/WGRC40//OK94P549/WGRC34	57.7 ± 21.5	68.0 ± 19.3
Hawken	HWW	AgriPro Seed Inc.	Unknown	57.9 ± 10.1	67.5 ± 17.1
SD06158	HWW	Tri-state FHB Nursery	Wesley/Falcon	58.5 ± 22.5	68.8 ± 7.5
NE05569	HWW	2008 NRPN	Wesley//Pronghorn/Arlin	59.0 ± 27.9	58.4 ± 31.7
HardingFhb1NIL09S-109	HWW	HWWGRU	Sumai3/Harding*3 F4	59.1 ± 18.5	36.9 ± 15.6
CA9W06-788	HWW	2010 NRPN	Jerry/CDC Falcon	59.2 ± 16.7	50.0 ± 5.6
OK Bullet†	HWW	Oklahoma State University	KS96WGRC39/Jagger	59.3 ± 21.7	76.8 ± 17.5
BC01139-1	HWW	2010 SRPN	W99-188$-1/BC950285G-1-2	59.5 ± 16.0	76.9 ± 9.4
CO050322	HWW	2010 SRPN	CO980829/TAM 111	60.1 ± 19.9	66.9 ± 16.4
OK01420W	HWW	Oklahoma State University	KS93U206/Jagger RC	60.4 ± 29.5	77.5 ± 15.3
NE06472	HWW	2008 RGON	CO95043 /KS89180B-2-1//NE98574	60.6 ± 11.1	79.3 ± 18.4
OK00514-05806	HWW	2008 SRPN	KS96WGRC39/Jagger	61.4 ± 31.5	53.2 ± 21.7

09-27-28 rec-989	HWW	Kansas State University	*CS-Leymus racemosus 7A translocation*	61.6 ± 14.1	47.5 ± 2.5
NE07688	HWW	Tri-state FHB Nursery	OK93P656-RMH3299/NW97S278	61.7 ± 12.3	68.1 ± 12.1
Ike	HWW	PI 574488	Dular/Eagle//2* Cheney/Larned/3/Colt	61.9 ± 16.2	73.1 ± 6.7
MTS04120	HWW	2008 RGON	L'Govskaya 167/Rampart	61.9 ± 20.8	53.7 ± 25.6
NE04424	HWW	2008 SRPN	KS92H363-2/Cougar sib	62.0 ± 26.4	72.7 ± 10.1
SD03164-1	HWW	2008 NRPN	89118RC1-X-9-3-3/TX96D2845//Expedition	62.1 ± 23.6	42.7 ± 22.1
KS020304K~3	HWW	2008 RGON	Jagger/2137//KS940786-6-9	62.1 ± 29.4	73.8 ± 15.4
TX05V7259	HWW	2010 SRPN	T107//TX78V3620/Ctk78/3/TX87V1233/4/Arap//TX86V1540/T200	62.8 ± 13.0	70.6 ± 10.1
OK06848W	HWW	Oklahoma State University	OK94P461/Oro Blanco F6:11	63.8 ± 34.2	71.6 ± 11.1
JackPot	HWW	AgriPro Seeds Inc.	Unknown	63.8 ± 16.7	67.5 ± 5.6
OK05212†	HWW	Oklahoma State University	OK95616-1/Hickok//Betty F4:10	64.0 ± 15.2	49.5 ± 15.1
OK03522	HWW	2008 SRPN	N566/OK94P597	64.0 ± 18.0	57.3 ± 12.4
NE06607	HWW	2010 NRPN	NE98466/Wesley	64.1 ± 16.5	61.9 ± 7.0
T-136	HWW	Trio Seed Research.	Unknown	64.2 ± 23.0	62.5 ± 14.4
NI07703	HWW	2010 SRPN	R-148 (G97343) /NI00436	64.3 ± 20.6	51.3 ± 10.9
Chisholm†	HWW	PI 486219	Sturdy sib/Nicoma	64.3 ± 20.2	67.5 ± 12.4
HardingFhb1NIL09S-108	HWW	HWWGRU	Sumai3/Harding*3 F4	64.7 ± 11.0	31.9 ± 12.6
NE06436	HWW	2008 RGON	Wesley/OK98699	64.8 ± 32.5	75.3 ± 20.7
TX06A001386	HWW	2010 SRPN	TX99A6030/Custer	64.9 ± 18.3	75.0 ± 16.0
Scout 66†	HWW	CItr 13996	Nebred//Hope/Turkey/3 Cheyenne/Ponca	65.2 ± 26.2	75.3 ± 14.2
2008-184 Overley (FHB3)	HWW	Kansas State University	*Overley-Leymus racemosus 7A translocation*	65.3 ± 9.7	72.5 ± 2.5
MT0495†	HWW	2008 NRPN	MT9640/NB1133	65.4 ± 29.5	54.1 ± 21.1
SD06165	HWW	2008 NRPN	Wesley/SD97049	65.4 ± 9.2	69.0 ± 5.0
HV9W06-1046	HWW	2010 SRPN	M97-1171/G980039//G982238	65.4 ± 10.8	42.5 ± 3.3
KS980554-12-~9	HWW	2008 SRPN	2180*K/2163//?/3/W1062A*HVA114/W3416	65.5 ± 19.0	64.4 ± 16.6
NH03614 (SETTLER)	HWW	Tri-state FHB Nursery	Wesley sib//Millennium sib/Above sib	65.6 ± 18.0	38.8 ± 10.1
CO03064	HWW	2008 SRPN	CO970547/Prowers 99	65.9 ± 32.1	57.6 ± 15.1
T-140	HWW	Trio Seed Research	Unknown	66.2 ± 15.2	66.3 ± 6.1
Infinity CL	HWW	AGSECO	Unknown	66.4 ± 5.7	60.0 ± 22.2
T151†	HWW	2008 SRPN	T81/KS93U206	67.1 ± 23.2	44.6 ± 10.8
SD08138	HWW	Tri-state FHB Nursery	SD92107-5/OK94P549-99-6704//Jagalene	67.4 ± 14.5	61.9 ± 7.5

AP06T3621	HWW	2010 SRPN	X920232-5/Karl 92//X920750A-13-1	67.8 ± 22.1	78.8 ± 7.9
TX05A001334	HWW	2008 RGON	TX87V1233-3/U1254-4-6-6//K92/3/T200*2/TA2460*2//T202	68.0 ± 31.2	78.4 ± 11.5
OK03716W	HWW	Oklahoma State University	Oro Blanco/OK92403 F4:11	68.0 ± 25.9	70.6 ± 25.7
Fuller†	HWW	Kansas State University	Unknown	68.6 ± 16.3	47.2 ± 19.5
Hatcher	HWW	Colorado State University	Yuma/PI 372129//TAM 200/3/4* Yuma/4/KS91H184/Vista	68.6 ± 16.8	77.5 ± 8.3
NE07531	HWW	2010 NRPN	HBK0630-4-5/NE98574	68.7 ± 13.2	62.5 ± 18.5
Armour	HWW	WestBred LLC.	Unknown	69.2 ± 21.7	57.5 ± 11.4
Alliance	HWW	University of Nebraska	Arkan/Colt//Chisholm sib	69.3 ± 11.5	79.4 ± 5.1
OK05903C	HWW	Oklahoma State University	TXGH12588-120*4/FS4//2174/3/Jagger F4:10 RC	69.7 ± 12.3	47.3 ± 15.6
BZ9W05-2043	HWW	2010 NRPN	Rampart/Kestrel	70.2 ± 15.6	62.5 ± 6.6
NE06549	HWW	2008 RGON	Hallam/Wesley	70.3 ± 22.8	68.9 ± 21.7
MTS0721	HWW	2010 NRPN	DMS/Rampart//Pronghorn/3/2*Rampart	70.6 ± 7.0	73.1 ± 7.9
NE02558†	HWW	2008 NRPN	Jagger/Alliance	70.6 ± 22.5	66.7 ± 20.9
HV9W04-1594R	HWW	2010 NRPN	KS89180B-2-1-1/CMBW91M02959T//Jagger	71.0 ± 12.4	47.5 ± 7.5
TAM 112	HWW	Taxes A&M University	TAM 200/TA2460//TXGH10440	71.2 ± 15.4	61.3 ± 9.2
KS010379M-2	HWW	2008 RGON	KS920709-B-5-2-2/TAM-400	71.8 ± 12.5	74.4 ± 13.2
OK03825-5403-6	HWW	2008 SRPN	Custer*3/94M81	71.8 ± 10.6	77.1 ± 16.2
T167	HWW	2010 SRPN	T136/T151	71.8 ± 13.5	65.0 ± 9.6
CO050303-2	HWW	2010 SRPN	CO980829/TAM 111	72.5 ± 15.0	75.0 ± 12.7
NE05548†	HWW	2008 NRPN	Brigantina.2/Arapahoe//CO850267/Rawhide	72.6 ± 10.1	56.0 ± 21.4
NI04427	HWW	2008 NRPN	KS98HW22//W95-615W/N94L189	72.8 ± 13.7	64.1 ± 10.1
T166	HWW	2010 SRPN	T81/KS93U206	73.9 ± 19.3	39.4 ± 12.8
NE04490†	HWW	University of Nebraska	Unknown	74.0 ± 23.1	68.3 ± 16.5
OK02405†	HWW	2008 RGON	Tonkawa/GK50	74.1 ± 27.5	42.0 ± 18.6
TX04A001246	HWW	2008 SRPN	TX95V4339/TX94VT938-6	74.4 ± 20.7	67.6 ± 20.2
T168	HWW	2010 SRPN	T81/T137	74.8 ± 17.0	38.8 ± 10.6
HV9W05-881R	HWW	2008 RGON	Mason/Ogallala-vr/Betty	74.8 ± 26.4	84.9 ± 9.4
AP04T8211†	HWW	2008 SRPN	W98-232/KS96WGRC38	75.0 ± 18.9	55.5 ± 18.6
TAM-107†	HWW	2008 SRPN	TAM 105*4/Amigo	75.4 ± 23.3	73.5 ± 21.7
2008-191 Jagger (FHB3)	HWW	Kansas State University	*Jagger-Leymus racemosus 7A translocation*	75.5 ± 5.6	63.8 ± 6.3
KS010957K~4	HWW	2008 RGON	2145/Karl 92//KS940786-6-11	75.6 ± 27.3	76.0 ± 21.0

HV9W05-1125R	HWW	2010 NRPN	00KSULR-73/G980039	75.9 ± 14.8	70.0 ± 5.4
MT0552	HWW	2008 NRPN	N95L159/CDC Clair	76.0 ± 18.6	75.5 ± 12.5
N98L20040-44	HWW	2008 NRPN	CS/PI467024//CS/3/SXLD/4/TAM202/5/SXLD	76.7 ± 21.0	90.5 ± 12.4
AP06T3832	HWW	2008 SRPN	HBK0935-29-15/KS90W077-2-2/VBF0589-1	76.8 ± 27.6	60.2 ± 19.1
TX01V5134RC-3	HWW	2008 SRPN	TAM-200/Jagger	77.0 ± 17.3	62.6 ± 18.0
00X0100-51	HWW	2010 NRPN	W95-301/W98-151	77.0 ± 17.4	63.8 ± 9.5
NE07521	HWW	2010 NRPN	(Yuma/T-57//Lamar/3/4*Yuma/4/New516)/NI00436	77.2 ± 13.0	86.9 ± 8.5
HV9W03-539R	HWW	2008 SRPN	KS94U275/1878//Jagger	77.2 ± 17.1	63.7 ± 21.2
TX05V7269	HWW	2010 SRPN	HBG0358/4/T107//TX78V3620/Ctk78/3/TX87V1233	77.3 ± 12.5	58.8 ± 8.8
TX04M410164	HWW	2008 SRPN	MIT/TX93V5722//W95-301	77.8 ± 28.8	75.7 ± 27.6
OK05204	HWW	2010 SRPN	SWM866442/OK95548 F4:12	77.8 ± 12.3	68.8 ± 13.6
SD06173	HWW	2008 NRPN	Bulk02R2B	78.4 ± 14.5	48.3 ± 16.0
CA9W07-817	HWW	2010 NRPN	CDC Falcon/Jerry	78.8 ± 12.4	30.0 ± 5.7
CO050270	HWW	2010 SRPN	Hatcher/NW97S295	78.8 ± 15.2	56.9 ± 14.6
TX05V5614	HWW	2008 RGON	TX96V2427/TX98U8083	78.9 ± 15.1	75.0 ± 14.5
PHS2008F206bab	HWW	Kansas State University	Rioblanco/NW97S187	79.1 ± 16.3	86.3 ± 3.7
Karl 92	HWW	PI 564245	Plainsman V/3/Kaw/Atlas 50//Parker *5/Agent	79.2 ± 18.5	32.5 ± 5.4
OK05830	HWW	Oklahoma State University	OK93617/Jagger F6:12	79.6 ± 18.9	60.3 ± 17.8
OK06345	HWW	Oklahoma State University	Fawwon 06/2174//OK95548-26C F4:9	79.7 ± 14.8	79.7 ± 14.8
CO050337-2	HWW	2010 SRPN	CO980829/TAM 111	79.8 ± 12.9	71.9 ± 10.7
NE05430	HWW	2008 SRPN	IN92823A1-1-4-5/NE92458	80.0 ± 19.8	60.2 ± 18.5
TX05A001822	HWW	2010 SRPN	2145/X940786-6-7	80.6 ± 20.7	86.3 ± 8.9
NE05549	HWW	2008 NRPN	NE90614/NE87612//NE87612//Wesley	80.9 ± 9.1	53.8 ± 29.9
NE05496	HWW	2008 SRPN	KS87H325/Rioblanco//Hallam	80.9 ± 16.1	86.5 ± 9.8
Duster[†]	HWW	Oklahoma State University	W0405/NE78488//W7469C/TX81V6187	81.3 ± 18.7	85.9 ± 8.3
TX06A001263	HWW	2010 SRPN	TX97V3006/TX98V6239	81.9 ± 12.9	81.3 ± 8.7
NE01481	HWW	Tri-state FHB Nursery	OK83201/Redland//Ike	82.0 ± 9.6	87.5 ± 2.2
KS030024-K-3	HWW	Tri-state FHB Nursery	KS89180B-2-1-2/3/Karl 92*2/Ravi-36	82.2 ± 17.9	30.0 ± 6.5
TAM 110[†]	HWW	Taxes A&M University	TAM105*4/Amigo*5/Largo	82.2 ± 15.9	67.4 ± 29.6
SD07204	HWW	2008 RGON	Harding//SD98243/Alliance	83.0 ± 10.3	61.3 ± 26.6
KS011327M~2	HWW	2010 SRPN	KS940748-2-4/TX97V4311//Overley	83.1 ± 12.0	96.9 ± 2.8

Santa Fe	HWW	AGSECO	Unknown	83.1 ± 17.0	38.1 ± 5.3
Jagger	HWW	PI 593688	KS82W418/Stephens	83.2 ± 14.5	55.0 ± 16.7
Keota	HWW	Westbred LLC.	Unknown	83.5 ± 9.1	81.9 ± 15.8
OK06518	HWW	Oklahoma State University	Palma/Hickok//2174 F4:9	83.6 ± 17.9	48.3 ± 24.1
Jagalene	HWW	AgriPro Seeds Inc.	Jagger/Abilene	83.7 ± 20.3	81.3 ± 5.3
OK04525	HWW	Oklahoma State University	FFR525W/Hickok//Coronado F4:11	83.9 ± 15.0	59.5 ± 8.5
OK04505	HWW	2008 SRPN	OK91724/2*Jagger	84.3 ± 12.2	69.2 ± 12.7
KS021006-NT-9	HWW	Tri-state FHB Nursery	KS920709-B-5-1-1/Cutter//Jagger	84.5 ± 11.0	88.1 ± 3.6
TXHT006F8-CS06/472-STA34	HWW	2008 RGON	Lockett/Halberd	84.7 ± 14.4	76.5 ± 18.3
KS010514-9TM-10	HWW	2008 RGON	CM98-42/3/HBF0290/X84W063-9-39-2//ARH/4/KS940786-6-4	85.0 ± 25.8	85.4 ± 11.7
TXHT023F7-CS06/607-STA07/40	HWW	2008 RGON	TX99U8544/Ogallala	85.7 ± 20.4	76.1 ± 25.8
Protection CL	HWW	AGSECO	Unknown	85.8 ± 17.0	86.3 ± 5.8
HV9W96-1271R-1	HWW	2008 SRPN	HV9W00-1551WP/KS94U326	85.9 ± 13.2	63.6 ± 17.0
OK04507	HWW	2008 RGON	OK95593/Jagger//2174	86.2 ± 13.6	85.6 ± 15.4
OK05526	HWW	2010 SRPN	KS94U275/OK94P549 F4:12	86.2 ± 11.8	41.9 ± 13.6
SD08174	HWW	Tri-state FHB Nursery	Ransom/Cutter/NW99L7068	86.2 ± 13.2	92.5 ± 4.8
KS030101-M-2	HWW	Tri-state FHB Nursery	KS00F5-20-3/KS00F5-14-4	86.6 ± 19.3	56.3 ± 7.3
TX03A0148	HWW	2008 SRPN	TX89A7137/Tipacna	86.7 ± 21.2	69.5 ± 20.4
T158	HWW	2008 SRPN	KS93U206/2*T81	86.9 ± 16.7	84.6 ± 9.8
TX06A001281	HWW	2010 SRPN	TX98VR8422/U3704A-7-7	87.0 ± 8.9	70.6 ± 11.5
NE08452	HWW	Tri-state FHB Nursery	(Brigantina/2*Arapahoe)/OK96717-99-6756	87.3 ± 12.0	76.3 ± 16.3
TX04V075080	HWW	2008 SRPN	Jagger/TX93V5722//TX95D8905	87.3 ± 9.0	84.5 ± 7.1
TAM-304	HWW	Taxes A&M University	(WO541A/W2440//W2407/Arkan)/(TX85V1326/TX86D1312)	87.5 ± 9.8	72.5 ± 8.3
HV9W06-509	HWW	2010 SRPN	G982231/G982159//KS920709W	87.6 ± 16.3	89.4 ± 4.3
Smoky Hill	HWW	Westbred LLC.	Unknown	87.7 ± 10.6	71.3 ± 18.4
HV9W03-696R-1	HWW	2008 SRPN	N94L027/Tbolt//KS89180B	87.7 ± 15.7	74.2 ± 21.3
TX05A001188	HWW	2010 SRPN	T107//TX98V3620/Ctk78/3/TX87V1233/4/N87V106//TX86V1540/T200	87.8 ± 13.2	90.0 ± 6.1
KS08P1-108	HWW	Tri-state FHB Nursery	KS89180B-2-1-2/3/Karl 92/Ravi-36	88.0 ± 7.7	50.0 ± 5.4
SD07056	HWW	Tri-state FHB Nursery	Falcon/SD97060//Jagalene	88.8 ± 18.0	87.5 ± 11.5
PHS2008F212bbb	HWW	Kansas State University	Rioblanco/NW97S186	89.1 ± 9.8	87.5 ± 2.5
KS030024-K-4	HWW	Tri-state FHB Nursery	KS89180B-2-1-2/3/Karl 92*2/Ravi-36	89.3 ± 13.3	38.8 ± 6.6

OK05511[†]	HWW	2008 RGON	TAM 110/2174	89.9 ± 8.0	65.6 ± 26.3
KS030124-K-4	HWW	Tri-state FHB Nursery	Fuller/Jagalene	90.0 ± 9.4	75.0 ± 9.6
Overley[†]	HWW	Kansas State University	U1275-1-4-2-2/Heyne'S'//Jagger	90.3 ± 18.5	79.6 ± 22.2
NW03666	HWW	2008 NRPN	N94S097KS/NE93459	90.5 ± 11.5	68.0 ± 15.2
NX04Y2107	HWW	2008 NRPN	NW98S081/99Y1442	90.6 ± 7.5	82.8 ± 16.1
OK05122	HWW	Okalahoma State University	KS94U337/NE93427 F4:10	90.7 ± 4.0	75.6 ± 20.3
KS08IFAFS1	HWW	Tri-state FHB Nursery	Karl 92*5/McVey	90.7 ± 4.0	25.0 ± 7.2
T81	HWW	Trio Seed Research	Unknown	91.4 ± 10.9	66.3 ± 7.9
OK03305	HWW	2008 SRPN	N40/OK94P455	91.5 ± 8.1	90.1 ± 12.2
NE05426	HWW	2008 SRPN	W95-091 (=KS85-663-8-9//WI81-133/Thunderbird)/Akron	91.7 ± 6.7	93.9 ± 4.8
KS06O3A~50-3	HWW	2010 SRPN	Overley*3/Amadina	91.9 ± 10.5	78.8 ± 8.8
TX06A001239	HWW	2008 RGON	Ogallala/KS94U275	92.1 ± 12.8	81.0 ± 12.6
TAM111	HWW	Taxes A&M University	TAM 107//TX78V3630/Centurk 78/3/TX87V1233	92.2 ± 11.0	72.5 ± 6.6
HV9W06-262	HWW	2010 SRPN	TX98U8134/3/Karl 92*2/Ravi-36	92.6 ± 10.7	70.0 ± 7.4
KS07F5BULK01-K-7	HWW	Tri-state FHB Nursery	Bulk Selection	92.8 ± 9.3	58.8 ± 10.4
OK07209	HWW	2010 SRPN	OK93P656-(RMH 3299)/OK99621 F4:10	93.1 ± 6.3	87.5 ± 9.4
TX06A001084	HWW	2008 RGON	KS90WGRC10//U1275-1-11-8/TA2455/3/KS93U69/4/Ogallala/TX89V4133	93.1 ± 11.0	83.0 ± 14.1
TX06A001431	HWW	2008 RGON	T107//TX98V3620/Ctk78/3/TX87V1233/4/N87V106//TX86V1540/T200	93.3 ± 14.9	93.3 ± 7.5
NX03Y2489	HWW	2008 NRPN	BaiHuo/Kanto107//Ike/3/KS91H184/3*RBL//N87V106	93.7 ± 10.7	92.9 ± 9.9
Deliver	HWW	Oklahoma State University	OK91724/Karl	93.9 ± 6.2	77.2 ± 13.4
TX04M410211	HWW	2008 SRPN	Mason/Jagger//Ogallala	94.6 ± 4.4	96.0 ± 4.5
BC01138-5	HWW	2010 SRPN	W99-188$/BC950814-1-1	96.1 ± 8.6	57.5 ± 7.9
Guymon	HWW	Oklahoma State University	Intrada/Platte	96.3 ± 5.1	94.5 ± 6.7
SD06W117	HWW	2008 NRPN	Alice/SD00W024	96.5 ± 5.3	85.3 ± 13.5
TX03A0563	HWW	2008 SRPN	X96V107/Ogallala	96.8 ± 3.2	88.5 ± 10.3
TX06A001132	HWW	2010 SRPN	HBG0358/4/T107//TX78V3620/Ctk78/3/TX87V1233	97.0 ± 4.3	93.8 ± 8.8
KS06O3A~58-2	HWW	2010 SRPN	Overley*3/Amadina	97.0 ± 4.2	72.5 ± 11.2
Postrock	HWW	AgriPro Seeds Inc.	Unknown	97.1 ± 4.9	74.4 ± 7.8
09-26-6 rec-679	HWW	Kansas State University	*CS-Leymus racemosus 7A translocation*	97.9 ± 3.6	85.0 ± 0.0
TX02A0252	HWW	2008 SRPN	TX90V6313//TX94V3724/TX86V1405	98.5 ± 3.4	91.9 ± 6.0
KS020648-M-6	HWW	Tri-state FHB Nursery	Overley/Karl 92//Jagalene	99.5 ± 0.7	85.6 ± 4.2

BC01131-24	HWW	2010 SRPN	W99-429-1/W98-422	99.6 ± 0.9	76.3 ± 5.6
SD08145	HWW	Tri-state FHB Nursery	SD92107-5/OK94P549-99-6704//Jagalene	99.8 ± 0.5	84.4 ± 10.0
KS030049-NT-7	HWW	Tri-state FHB Nursery	TX97V4311/3/Karl 92*2/Ravi-36	100.0 ± 0.0	70.6 ± 9.7
OK06210	HWW	Oklahoma State University	KS90175-1-2/CMSW89Y271//K92/3/ABI86*3414/X86035*-BB-34//HBC 302E RC F4:9 RC	100.0 ± 0.0	94.2 ± 8.4
Heyne	HWW	PI 612577	KS82W422/SWM754308/KS831182/KS82W422	18.6 ± 15.4	35.6 ± 7.4
TregoFhb1NIL09S-98	HWW	HWWGRU	ND2710/Trego/Trego F4	21.0 ± 5.5	25.6 ± 10.3
TregoFhb1NIL09S-99	HWW	HWWGRU	ND2710/Trego/Trego F4	21.6± 9.4	18.1 ± 3.4
CO04W210	HWW	2008 RGON	NW97S343/Akron	28.0 ± 12.0	38.3 ± 13.7
Aspen	HWW	WestBred LLC.	Unknown	30.2 ± 11.6	28.1 ± 6.8
KS07HW25	HWW	2008 RGON	KS025580(Trego/CO960293)/KSO1HW152-6(Tgo/Bty sib)	38.3 ± 16.2	59.6 ± 24.4
SD07184	HWW	Tri-state FHB Nursery	Expedition/SD97W650//KS00H10-32-1-1	39.8 ± 8.5	55.6 ± 9.0
NW05M6011-6-1	HWW	2008 RGON	Nuplains/Arrowsmith	40.0 ± 22.9	45.5 ± 5.5
TregoFhb1NIL09S-100	HWW	HWWGRU	ND2710/Trego/Trego F4	45.6 ± 10.8	18.8 ± 5.9
MTS0532	HWW	2010 NRPN	L'Govskaya 167/Rampart//MT9409	46.7 ± 18.1	51.9 ± 7.6
SD05W030[†]	HWW	2008 NRPN	SD98W302/NW97S186	48.8± 34.2	81.4 ± 11.7
SD05W148-1	HWW	2008 RGON	SD98153/SD98W117	50.6 ± 31.5	45.3 ± 21.5
CO04393	HWW	2010 SRPN	Stanton/CO950043	51.2 ± 25.3	74.4 ± 14.3
Lakin	HWW	PI 617032	KS89H130/Arlin	52.3 ± 8.5	41.3 ± 8.6
SD07126	HWW	Tri-state FHB Nursery	SD92107-2/SD99W042	54.4 ± 11.2	43.8 ± 6.6
KS05HW121-2	HWW	2008 SRPN	KS99-5-16//Stanton/KS98HW423	58.0 ± 17.7	73.1 ± 18.5
CO03W139[†]	HWW	2008 SRPN	CO980862/Lakin	59.9 ± 25.8	27.3 ± 13.9
KS05HW15-2	HWW	2008 SRPN	KS98HW452/CO960293//KS920709B-5-2	60.7 ± 24.1	67.3 ± 26.2
CO03W054	HWW	2008 SRPN	KS96HW94//Trego/CO960293	63.6 ± 34.8	64.5 ± 19.1
NX05M4180-6	HWW	2010 NRPN	92201D5-2-29 X 99 waxy bulk	64.4 ± 25.8	75.6 ± 10.4
T150-1	HWW	2010 SRPN	T81/T201	65.2 ± 15.4	71.3 ± 13.6
CO03W043	HWW	2008 SRPN	KS96HW94/CO980352	65.7 ± 25.9	71.4 ± 19.0
NW07534	HWW	Tri-state FHB Nursery	KS920709-B-5-2/NW98S061	68.1± 12.3	78.1 ± 7.4
2137	HWW	Kansas State University	W2440/W9488A//2163	69.1 ± 13.2	74.4 ± 15.5
CO02W237	HWW	2008 SRPN	98HW519/96HW94	70.3 ± 22.3	83.7 ± 18.3
NW05M6015-25-4[†]	HWW	2008 RGON	NW97S186/Rioblanco	72.1 ± 25.6	34.1 ± 28.5

KS07HW52-5	HWW	2010 SRPN	KS025580(Trego/CO960293)/KS02HW25(Tgo/Jgr 8W)	72.8 ± 11.7	62.5 ± 19.5
NI08708	HWW	2010 SRPN	CO980829 (=Yuma/T-57//CO850034/3/4*Yuma/4/NEWS1)/Wesley	73.8 ± 16.6	50.0 ± 5.6
KS05HW136-3	HWW	2008 SRPN	KS98HW518(93HW91/93HW255)//KS98H245(Ike/TA2460//*3T200)/Trego	77.0 ± 15.5	77.0 ± 11.1
NW04Y2188	HWW	2008 NRPN	MO8/Redland//KS91H184/3*Rioblanco	78.4 ± 20.0	67.1 ± 26.2
SD07W041	HWW	2008 RGON	Falcon/SD99W042//Trego	79.8 ± 14.4	79.6 ± 16.8
Danby	HWW	Kansas State University	Trego/KS84063-9-39-3-8w	81.6 ± 24.6	81.3 ± 6.0
Rioblanco	HWW	PI 531244	OK11252A/W76-1226	83.3 ± 23.9	83.8 ± 9.3
KS07HW81	HWW	2008 RGON	KS02HW25/KS00HW114-1-1	84.3 ± 13.7	79.4 ± 16.0
Antelope	HWW	PI 633910	Pronghorn/Arlin	85.8 ± 9.3	66.7 ± 21.8
KS07HW117	HWW	2008 RGON	KS00HW151-4//KS98HW151-6/00HW114-1	86.3 ± 20.3	74.8 ± 17.1
Trego[†]	HWW	2008 SRPN	KS87H325/Rioblanco	87.7 ± 15.6	80.9 ± 15.6
KS010990M~8	HWW	2010 SRPN	Trego/Ventnor//KS940786-6-4	91.6 ± 7.6	94.4 ± 6.8
KS08HW176-4	HWW	2010 SRPN	Trego/Jagger 8W	91.6 ± 13.2	92.5 ± 2.2
CO03W239	HWW	2008 SRPN	KS01-5539/CO99W165	98.8 ± 2.5	99.0 ± 2.3
INW0411	SWW	UESRWWN	96204A1-12//Goldfield/92823A1-11	5.9 ± 2.6	27.8 ± 32.8
Freedom	SWW	PI 531244	OK11252A/W76-1226	7.6 ± 3.0	32.4 ± 25.2
MO040152	SWW	UESRWWN	MO 12278/Pio2571	9.5 ± 1.7	25.2 ± 14.2
Roane	SWW	UESRWWN	VA71-54-147/C68-15//IN65309C1-18-2-3-2	10.7 ± 4.8	19.3 ± 7.4
Bess	SWW	PI 642794	MO11769/Madison	17.2 ± 14.4	36.8 ± 28.2
P03207A1-7	SWW	UESRWWN	INW0304*2/RSI5//981281/3/INW0315/99794	18.8 ± 12.3	50.2 ± 26.7
KY96C-0769-7-3	SWW	UESRWWN	2552/Roane	19.9 ± 11.1	24.7 ± 7.9
Atlas66	SWW	CItr 12561	Frondoso//Redhart 3/Noll 28(sister selection of Atlas 50)	21.4 ± 13.4	43.9 ± 13.9
IL00-8530	SWW	UESRWWN	IL89-1687//IL90-6364/IL93-2489	23.6 ± 15.6	36.4 ± 19.5
MD01W233-06-1	SWW	USSRWWN	McCormick/Choptank	24.6 ± 17.9	27.2 ± 10.7
USG 3555	SWW	USSRWWN	VA94-52-60/Pio2643//USG3209	25.2 ± 13.7	23.3 ± 12.4
M04*5109	SWW	UESRWWN	VA94-54-479/Pio2628	26.6 ± 23.6	28.9 ± 8.2
ClarkFhb1NIL-75	SWW	HWWGRU	Ning7840/Clark*7	26.7 ± 7.1	13.8 ± 2.5
ClarkFhb1NIL09F-23	SWW	HWWGRU	Ning7840/Clark*7	27.1 ± 3.3	12.5 ± 2.7
G69202	SWW	UESRWWN	VA91-54-219/OH413	27.6 ± 30.4	37.6 ± 26.4
Ernie	SWW	PI 584525	Pike/MO9965	27.8 ± 14.0	26.7 ± 14.3
ClarkFhb1NIL09F-45	SWW	HWWGRU	Ning7840/Clark*7	30.2 ± 21.0	18.1 ± 5.1

OH02-12678	SWW	UESRWWN	Foster/Hopewell//OH581/OH569	30.5 ± 14.8	35.0 ± 14.9
M03-3616-C	SWW	USSRWWN	Hopewell/Patton	31.5 ± 17.1	22.6 ± 9.0
OH02-7217	SWW	UESRWWN	92118B4-2/OH561	32.8 ± 7.7	35.5 ± 10.7
P02444A1-23-9	SWW	UESRWWN	981129/99793//INW0301/92145	34.9 ± 30.4	21.2 ± 14.7
MD99W483-06-9	SWW	UESRWWN	VA97W358/Renwood 3260	35.2 ± 18.8	43.5 ± 16.9
P03112A1-7-14	SWW	USSRWWN	INW0411//INW0315/99794	35.6± 30.4	47.9 ± 24.8
KY97C-0519-04-07	SWW	UESRWWN	SS555W/2540//2552	35.9 ± 27.2	32.9 ± 9.4
P04287A1-10	SWW	USSRWWN	INW0315*2/4/INW0304//9346/CS 5Am/3/91202//INW0301/INW0315	36.7 ± 15.8	35.2 ± 4.6
W06-202B	SWW	UESRWWN	Ashland/Hopewell//OH546/L930605	37.4 ± 20.3	52.1 ± 13.9
AR96077-7-2	SWW	USSRWWN	Jackson/Pio2643	37.6 ± 18.6	51.7 ± 24.0
G61505	SWW	USSRWWN	ABI89-4584A/T814	39.9 ± 33.6	24.1 ± 8.8
G41732	SWW	USSRWWN	T814/L900819	42.2 ± 27.1	23.0 ± 11.7
M04-4715	SWW	USSRWWN	Mason/Ernie	42.4 ± 29.2	32.3 ± 12.4
B030543	SWW	USSRWWN	VA93-54-429/LA85422	42.8 ± 29.5	68.6 ± 67.5
MO011126	SWW	UESRWWN	MO94-103/Pio2552	43.5± 15.5	28.0 ± 13.5
Mocha exp.	SWW	UESRWWN	OH489/OH490	45.1± 21.8	55.9 ± 20.5
AR97124-4-3	SWW	USSRWWN	P88288C1-6-1-2/Terra SR204	48.8 ± 13.0	66.9 ± 8.5
LA01*425	SWW	UESRWWN	P2571/Y91-6B	52.4 ± 36.9	50.6 ± 14.3
NC04-15533	SWW	USSRWWN	NC94-6275/P86958//VA96-54-234	52.4 ± 22.2	45.3 ± 9.8
D04*5513	SWW	UESRWWN	DK1551W/D94-50228	53.2± 28.1	58.2 ± 19.4
AR97044-10-2	SWW	UESRWWN	Elkhart/AR494B-2-2	53.8 ± 25.9	62.7 ± 13.8
ClarkFhb1NIL09F-4	SWW	HWWGRU	Ning7840/Clark*7	53.9 ± 14.8	20.6 ± 9.2
VA04W-259	SWW	USSRWWN	VA97W-533 /NC95-11612	54.3 ± 28.7	74.4 ± 14.0
IL02-18228	SWW	UESRWWN	Pio25R26/IL9634-24437(IL90-4813/L85-3132/Ning7840)//IL95-4162	54.7 ± 27.5	18.6 ± 10.2
G59160	SWW	USSRWWN	T812/VA91-54-219	56.3 ± 12.7	31.7 ± 12.6
Branson	SWW	UESRWWN	Pio2737W/891-4584A	57.3 ± 22.7	49.3 ± 22.6
M04-4802	SWW	UESRWWN	FFR518//Elkhart/MV-18	57.5 ± 33.5	56.1 ± 17.3
India exp.	SWW	UESRWWN	KY85C-35-4/Karl/Madison	60.3 ± 28.2	38.7 ± 33.6
Pioneer Brand 26R61	SWW	USSRWWN	Omega78/S76/4/Arthur71/3/Stadler//Redcoat/Wisc1/5/Coker747/6/2555 sib	63.1 ± 40.5	56.4 ±34.8
IL02-19463	SWW	UESRWWN	Patton/Cardinal//IL96-2550	66.6 ± 28.6	57.9 ± 25.6
M04-4566	SWW	UESRWWN	Bradley/Roane	66.9 ± 16.0	67.7 ± 22.2

W98007V1	SWW	USSRWWN	F2IN82104B1-3-2(H14H15)	67.2 ± 28.2	59.1 ± 25.6
TN801	SWW	USSRWWN	Cardinal/FL302//AR Exp 494B-2-2/3/Fillmore/Cardinal//Jackson	68.1 ± 29.8	78.7 ± 17.0
VA05W-258	SWW	USSRWWN	VA98W-130//Coker9835/SS520	68.3 ± 10.2	50.7 ± 20.3
VA05W-414	SWW	UESRWWN	Pio25W60//VA96W-606WS/Pio2691	70.3 ± 18.4	47.8 ± 18.1
KY97C-0321-02-01	SWW	UESRWWN	Kristy/VA94-52-25//2540	72.7 ± 23.9	74.3 ± 14.7
MO040192	SWW	UESRWWN	IL85-2872/MO10501	73.1 ± 19.6	68.2 ± 21.7
GA991209-6E33	SWW	USSRWWN	GA901146/GA96004//AGS2000	74.6 ± 31.6	57.4 ± 34.7
LA99005UC-31-3-C	SWW	USSRWWN	Pio2548/Coker9835//AGS2000	76.4 ± 32.5	90.1 ± 9.4
LA02-923	SWW	UESRWWN	PS8424//XY90-1B/TX851212	76.9 ± 23.6	82.4 ± 10.2
NYCalR-L	SWW	UESRWWN	reselection out of Caledonia	80.2 ± 12.1	74.9 ± 17.1
VA05W-78	SWW	USSRWWN	Tribute/AGS2000	81.1 ± 17.2	78.7 ± 16.0
NC03-6228	SWW	USSRWWN	A92-4452//NC96BGTD1sib/NC96BGTA6sib	81.1 ± 14.0	59.7 ± 16.9
W98008J1	SWW	USSRWWN	IN82104B1-3-2/Williams	81.1 ± 25.7	58.0 ± 23.6
OH03-41-45	SWW	UESRWWN	IL91-14167/OH599	82.0 ± 13.8	87.1 ± 4.3
Arena exp.	SWW	UESRWWN	NASW84-345/Coker9835//OH419/OH389	82.9 ± 20.8	57.5 ± 21.6
ClarkFhb1NIL-98	SWW	HWWGRU	Ning7840/Clark*7	85.0 ± 7.8	67.5 ± 16.9
VA03W-412	SWW	UESRWWN	Roane/Pio2643//SS520	85.7± 18.5	77.7 ± 11.6
Clark	SWW	PI 512337	Beau//65256A1-8-1/67137B5-16/4/Sullivan/3/Beau//5517B8-5-3-3/Logan	86.0 ± 15.2	62.5 ± 21.9
Coker 9553	SWW	USSRWWN	89M-4035A /Pio2580	86.7 ± 14.6	54.9 ± 23.9
D04-5012	SWW	USSRWWN	NC96BGTD1/Mason	88.4 ± 14.9	89.8 ± 9.2
GA991371-6E13	SWW	USSRWWN	GA931521/2*AGS2000	89.1 ± 14.9	92.6 ± 8.6
GA991227-6A33	SWW	USSRWWN	VA97W-24/AGS2000	93.1 ± 8.5	76.6 ± 21.5
LA01138D-52	SWW	USSRWWN	LA841/LA422//AGS2000	94.4 ± 9.7	86.7 ± 11.0
AGS 2000	SWW	USSRWWN	Pio.2555/PF84301//FL 302	94.5 ± 12.2	81.4 ± 17.5
LA98214D-14-1-2-B	SWW	USSRWWN	Shelby/LA87167D8-10-2	95.9 ± 6.2	95.8 ± 6.3
GA991336-6E9	SWW	USSRWWN	GA92432//AGS2000/Pio26R61	97.5 ± 5.5	82.5 ± 16.4

[†]35 common cultivars with average PSS of set I and set II in greenhouse and field experiments.

[‡]HWW, and SWW refer to hard red winter wheat, and soft winter wheat, respectively.

[§] HWWGRU=USDA-ARS, Hard Winter Wheat Genetics Research Unit, Manhattan, KS; Tri-state FHB Nursery=2010Tri-state FHB Nursery; SRPN= Southern HWW Regional Performance Nursery; NRPN= Northern HWW Regional Performance Nursery; RGON= HWW Regional Germplasm Observation Nursery; UESRWWN=Uniform Eastern Soft Red Winter Wheat Nurseries; USSRWWN=Uniform Southern Soft Red Winter Wheat Nurseries.

[¶]Mean of standard deviation

Supplemental Table S2. Correlation coefficients of percentage of symptomatic spikelets (PSS) of FHB based on 35 common accessions evaluated in 2009 fall (2009), 2010 fall (2010) and 2011 fall (2011I) field experiments with the first set, and 2011 (2011II) and 2012 (2012) field experiments with the second set.

	2009	2010	2011I	2011II
2010	0.345*	–		
2011I	0.499**	0.665***	–	
2011II	0.415*	0.685***	0.608***	–
2012	0.401*	0.720***	0.681***	0.849***

*, **, and ***Significant at the 0.05, 0.01 and 0.001 probability level, respectively.