Evaluating Methods of Screening for Pre-Harvest Sprouting in Soft Red Winter Wheat and the Effect of Delayed Harvest on Flour Properties

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ABSTRACT

High pre-harvest rainfall in 2006 caused significant pre-harvest sprouting (PHS) and weathering throughout the mid-Atlantic soft red winter wheat (SRWW) (*Triticum aestivum* L.) growing region. Sprouting and weathering caused decreased flour quality due to lowered dough viscosity and decreased ability to withstand mixing and processing for baked goods. Due to its decreased quality, severely sprouted grain is sold for feed, at a lower price per bushel. Pre-harvest sprouting negatively affects the chain of production from the field to baking operations. The purpose of this research was to evaluate the inherent dormancy and PHS resistance of current SRWW cultivars and to assess the relationship between falling number and flour quality after grain weathering.

Employing a weighted germination index (WGI), a large range in dormancy was observed across SRWW cultivars. Artificial weathering tests confirmed the use of WGI as a tool for screening for SRWW cultivar dormancy. The WGI consistently identified cultivars with significantly higher or lower inherent dormancy. 'Coker 9553' was highly dormant and resistant to PHS. This cultivar maintained an average falling number of 300 seconds even after receiving an average of 215 mm of rainfall, while the mean falling number for all SRWW cultivars after this amount of weathering was 131 seconds. After only moderate weathering, nine of 15 SRWW cultivars in the study exhibited severe sprouting, demonstrating the need for increased PHS resistance in SRWW wheat. Pre-harvest sprouting resistance groupings, based on average 2008 cultivar falling number were accurately predicted by WGI at both 10 (R^2=0.79) and 30°C (R^2=0.72) No consistent relationship was observed between head angle, glume tenacity or awn length and PHS resistance.

Water absorption, dough stability, farinograph arrival and departure times, peak, and 20-minute drop were measured from grain samples with varying degrees of weathering. All parameters were negatively affected by weathering in 2008. Flour quality parameters were more affected by genotype than falling number suggesting that falling number should not be used as the sole indicator of flour quality after grain weathering. It is clear that there are vast differences in dormancy levels and PHS resistance among SRWW cultivars and stronger dormancy and higher resistance to PHS does not automatically ensure higher quality flour.

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INTRODUCTION

Higher than average rainfall prior to wheat harvest in 2006 resulted in high levels of (PHS) of soft red winter wheat across Virginia and the mid- Atlantic region. Pre-harvest sprouting occurs when germination is initiated in the wheat spike. As a result of this abortive germination, starches and protein are degraded in the grain, and flour produced from such grain has a low falling number. Falling number is an industry-standard method used to quantify PHS damage in grains. Falling number indirectly measures α-amylase activity by measuring the viscosity of a flour slurry. With sound grain, a thick slurry indicates more intact starch because of low α-amylase activity and the result is a high falling number.

Low falling numbers (<250 seconds), which generally are considered to be an indirect measure of PHS damage, result in decreased price per bushel of grain for producers. Millers do not accept wheat with low falling number, because sprouted grain produces lower flour yield and sticky dough that cannot withstand intense mixing. The decrease in flour quality causes end use products to be sticky and have poor volume and crumb structure. Mixing sprout damaged and sound grain is a complex process; and, with the automation of the milling industry, the need for sound grain to prevent the need for blending grain is more important than ever.

The weighted germination index (WGI) was developed to measure the inherent seed dormancy of wheat. This test gives higher weights to seeds that germinate rapidly when seeds are counted over several days under controlled conditions. Many researchers have used the WGI coupled with environmental data to form predictive models for sprouting of white wheat. In white wheat, the interaction between genetic and environmental components makes the prediction of sprouting difficult. Environment plays a large role in seed dormancy levels across genotypes, particularly the environment during the grain fill period. Temperature from heading to physiological maturity has a large influence on the dormancy level that ultimately develops. Low temperature during maturation favors a strong, more prolonged dormancy; i.e. grain that can withstand more weathering in the field. Falling number measurements for cultivars over locations with various degrees of weathering may be necessary to understand environmental effects on individual cultivars.

Genetics naturally plays a large role in the PHS resistance of wheat cultivars. It is commonly known that dormancy is correlated with red seed coat color; red wheat typically has a higher level of dormancy than white wheat. The genes for seed coat color have been identified, and DNA markers are available for mapping this trait in hard red wheat. Recent research has also identified a gene related to embryo dormancy mechanisms.

Spike morphology has been reported to affect PHS resistance in some white-seeded cultivars. Characteristics such as head angle, awn length, and glume tenacity were reported to affect water shedding and retention.

Pre-harvest sprouting in SRWW is costly to the wheat industry but currently, little information exists concerning PHS and resistance mechanisms in SRWW cultivars. The objectives of this research were to quantify inherent seed dormancy at physiological maturity of current SRWW wheat cultivars and to estimate PHS resistance by grouping cultivars by falling number after delayed harvest.

REVIEW OF LITERATURE

Soft Red Winter Wheat

Wheat is grown in many regions of the U.S. and throughout the world. It also holds an important role in the U.S. economy and the world food supply. In 2007, U.S. winter wheat was valued at $9.48 billion dollars and wheat production in Virginia was valued at $71.5 million (USDA, 2008). In the fall 2007, high prices resulted in an increase in US winter wheat acreage of 1.4 million hectares (Sowers, 2007).

Winter wheat is an annual bunchgrass that reaches a 0.6 to 1.2 m height. Winter wheat is planted in the fall (September – October) and harvested in mid-June to mid-July in Virginia. Virginia wheat yields range from 3.4 to 7 Mg ha^{-1} (Brann, 2000) with many varieties in the 2008 variety trial yielding over 5.7 Mg ha^{-1} (Thomason et al., 2008).

In general, soft red winter wheat (SRWW) is the predominant wheat class grown in the mid-Atlantic region of the U.S. High relative humidity and high night temperatures in the Southeast make the region less suitable for production of hard wheat. Hard wheat requires low relative humidity and low night temperatures in order to produce the high protein content that make it particularly useful for bread making. Soft red winter wheat flour has relatively low protein and low gluten strength, making it more suitable for crackers, pie crusts, cookies, scones, pancakes, waffles, and cakes (Henry and Kettlewell, 1996).

Afternoon thundershowers and rainstorms are a common occurrence in the mid-Atlantic region in the summer (Watson, 2001). High temperatures during the day increase ground temperatures by late afternoon, which coupled with high relative humidity, cause warm, moist air to rise creating an updraft and thunderstorms. These storms can result in grain weathering.

Due to high energy costs, producers want grain to field dry as much as possible to avoid drying costs. Grain above 13.5% moisture is typically discounted at the buying point. Waiting for target moistures can delay harvest and increase chances of pre-harvest rainfall, which can reduce grain quality. Another factor extending wheat harvest in Virginia is total farm acreage. Producers with large acreages cannot harvest their entire wheat crop at the optimal time or harvest is delayed to attend to other farm duties such as soybean planting.

Pre- Harvest Sprouting Effects on Wheat Quality

There are many negative effects of PHS on end-use quality. Decreased flour water absorption due to degradation of starches and weakened dough strength are two effects of PHS on wheat flour. Flour water absorption is affected by protein content, starch damage, and non-starch carbohydrates (Finney et al., 1987). Dexter et al. (1994) reported that starch damage, which can be caused by PHS, was the predominant factor influencing water absorption, development time and stability in durum wheat. High water absorption is desired for high dough yield in bread wheat. Water absorption is correlated with sprouting but is reported to be influenced genetics more than environment (Mares, 1993). In soft red winter wheat low water absorption, high degree of kernel softness, short mixing time, and weak gluten strength are desirable for baking products (Finney, 1990; Pederson et al., 2004). The optimal water absorption is 51-55% for pastry flour and 52-56% for cracker and export flour (Souza et al., 2006). Johansson (2003) reported that both genotype and environment, e.g. weathering or the effects of rainfall and temperature on wheat post physiological maturity; affect starch quality and protein quality, both of which play a role in overall flour quality.

Sprouting does not have an equally detrimental effect on all flour products. For example, Cantonese noodles are affected much more than other products such as chapattis and pan bread (Orth and Moss, 1987). Starch damage can be separated into two separate categories, the first being biological starch damage, which occurs in the field prior to harvest; and the second is physical starch damage, which can occur during the milling process (Munck, 1987).

Hwang and Bushuk (1973) reported that germination transforms insoluble glutenin to soluble glutenin. It is important to note that loaf volume is inversely proportional to the amount of soluble glutenin and directly proportional to insoluble glutenin. In other words, as sprouting increases, soluble glutenin content increases resulting in decreased loaf volume and negatively affecting end-use products. Mixing sound and sprouted wheat to derive acceptable milling quality grain is a very complex process. The blend is based on the falling number of the sound and damaged grain and a specific ratio is applied (Weipert, 1987). Acidification of wheat flour has also been used to inhibit α-amylase activity and to give sprouted wheat acceptable quality.

There has also been some concern of the effect of sprouting on feed quality of grain. While Johnson and Taverner (1987) determined that the physical and chemical composition of wheat was altered by sprouting, they did not observe any negative effects on feed quality and pig growth rate was actually improved by the feeding sprout damaged wheat.

Recent research on SRWW in Virginia indicates that mild to moderately sprouted wheat with falling numbers from 150 to 330 seconds may produce significant decreases in flour quality

(Barbeau et al., 2006) In this research, only 35% of tested cultivars were classified as damaged based on falling number, but all 17 were considered low quality according to farinograph measurements. These authors concluded that falling number should not be used as the only criteria for determining PHS.

Dormancy

Dormancy is the device for optimizing the distribution of germination in time or space (Bewley and Black, 1982). Seeds are considered dormant if they are viable but fail to germinate when conditions are conducive to germination, i.e. adequate moisture, oxygen, and temperature (Bewley and Black, 1985). Dormancy is a positive and important trait in many plant species, including wheat, because it prevents pre-harvest sprouting or germination in the seed spike prior to distribution, or in wheat's case machine harvesting (Gubler et al., 2005). Dormancy level is one of many characteristics that contribute to PHS resistance in wheat, these characteristics also include: genetics, physical composition of seed coat, spike morphology, and embryo composition. Dormancy is usually initiated during seed maturation and maintenance in the mature seed depends on both environmental and genetic factors (Gubler et al., 2005). The proportion of gibberellic acid (GA) versus abscisic acid (ABA) in the embryo has an effect on seed dormancy in wheat. After-ripening, stratification and other dormancy-breaking mechanisms can rapidly decrease the ABA content of imbibed dormant seeds, and promote the germination process (Gubler et al., 2005). Garello and Le Page-Degivry (1999) discuss the role of ABA in dormant and non-dormant wheat cultivars and confirm that only ABA synthesized inside the embryo is responsible for the induction of dormancy. Abscisic acid developed during maturation in the mother plant only prevents germination before the seed can reach physiological maturity. They reported that the depth of dormancy is related to the ability of the embryo to synthesis ABA. Bewley (1997) states that GA is not directly involved in the development of dormancy, instead it has more of an influence on dormancy maintenance and promotion.

Some genotypes are more likely to contain pre-maturity α-amylase (PMAA). These cultivars can contain high levels of α-amylase in the absence of PHS. Farrell and Kettlewell, (2008) evaluated the effects of temperature shocks on PMAA and reported that cold and heat shocks during grain fill were effective at inducing PMAA activity with cold shocks being most effective.

Dormancy is a characteristic that has been identified in wild progenitors of wheat along with uneven ripening, and brittle rachis. Much greater genetic diversity for dormancy exists in wild progenitors than in modern wheat (Damania, 2008). In the domestication process, dormancy was indirectly selected against by breeding for rapid, even germination.

The Process of PHS

Mares (1987) lists the mechanisms involved in pre-harvest sprouting as: movement of water and gases to the grain surface, loss of germination inhibitors in vegetative parts of the spike in the presence of water, water and gas infiltration of the seeds, loss of seed dormancy, and production of germination enzymes. After-ripening is another process discussed previously that can break dormancy and influence PHS. These mechanisms can be manipulated or can naturally occur in ways that increase PHS resistance in wheat cultivars. Another factor affecting PHS susceptibility of mature wheat is water potential of mature wheat seeds. Water moves more readily into seeds having low versus high moisture content prior to harvest ripeness (approximately 12% moisture) (Duffus, 1987).

Physical Controls: Spike Morphology

Sprouting susceptibility is not homozygous across genotypes, plants of the same genotype, or even seeds within the same spike. Pre-harvest sprouting is most likely to occur on late tillers because these seeds are softer and less dense than those on earlier maturing spikes (Munck, 1987). Differentiation in dormant seeds on the same spike was observed by Gale et al., (1987). Seeds in the lower central area of the spike contained the most α-amylase activity, while those in distal florets displayed the lowest level of enzymatic activity. This research reported that seeds in the lower florets of the spike are the oldest and would be least likely to dry slowly after a wetting event, while seeds in the distal florets would be days younger and more likely to dry quickly following a rainfall event. This is due to the location within the spike and interception of sunlight and wind. When examining the wild progenitors of wheat, Key (1987) noted that dormancy never appears to have been synchronized within a genotype. The physical make up of the kernel itself plays a role in PHS tolerance. Barnard et al. (2005) reported a correlation of sprouting resistance with kernel hardness, kernels per spike, and kernel diameter when investigating kernel characteristics and their effects on sprouting in a greenhouse study. They also reported that PHS resistance was positively correlated with hardness and protein content of grain.

The morphological structure of the spike has been reported to have an effect on the sprouting resistance of wheat cultivars. King and Richards (1984) reported that the process of wetting is slower in awnless cultivars versus awned cultivars leading to higher PHS resistance in awnless wheat.

Physical Controls: Seed-Coat-Imposed Dormancy

Seed coat-imposed dormancy also plays a major role in PHS resistance. Bewley and Black (1985) demonstrated a seed coat-imposed dormancy in wheat by pricking the pericarp to allow gas exchange. Puncturing the pericarp allowed the dormant wheat seed to germinate. Mares (1993) noted, after exposure of seed to wetting and drying cycles that the shrinking and swelling of the grain decreased dormancy by weakening the pericarp. Strength of the pericarp directly correlates with seed coat-imposed dormancy in wheat.

When embryos of dormant wheat cultivars were extracted from the seed they still germinated. However, not all wheat cultivars germinated at the same rate, indicating that there is another component of dormancy in these cultivars, imposed within the embryo (Black et al., 1987).

Genetic Controls: Correlation of Dormancy with Seed Coat Color Genes

Degree of pigment color of the seed coat in wheat is controlled by three R genes; *R-A1*, *R-B1* and *R-D1* (Flintham et al., 1999; Metzger and Silbaugh, 1970; Sears, 1944). Flintham et al. (1999) have reported that these genes have direct effects on dormancy. The *taVp1* gene, which is orthologous to the *VP1* gene reported to influence dormancy in maize (*Zea Mays* L.) has been mapped on chromosome arm 3L (3A 3B AND 3D) of wheat at 30 cM from the R loci (Bailey et al., 1999). It is now thought that the relation between PHS and grain color is due to both a direct influence of the R genes on dormancy inducing mechanisms and to the linkage of the R genes with *taVp1*, which is related to the embryo mechanisms of dormancy and the ABA sensitivity of the embryo (Groos et al., 2002; Himi et al., 2002).

Red grain color is considered a major source of PHS resistance in wheat. While color was thought to affect the imbibition rate with white wheats imbibing water more readily than red wheats Himi et al. (2002) reported that this is only true for the first 24 hours, at which time the red wheat tested reached a plateau at 56% moisture. Clark et al. (1984) reported that the falling number of PHS resistant white wheat lines exceeded that of certain resistant red cultivars and concluded that there are two sets of genes controlling dormancy: one set related to seed coat color and another set not related to seed coat color. While red-seeded varieties are generally more resistant to PHS, than white seeded cultivars there are different levels of resistance among genotypes with the same number of red genes. Czarnecki (1987) suggested that these differences may be explained by the allelic composition of the red genes. Torada and Amano (2002) concluded that the effect of coat color is highly variable depending on environmental conditions during seed development.

Effects of Environment on PHS

Henry and McLean (1987) reported that relative rates of synthesis of α-amylase and other hydrolytic enzymes and their movement into the endosperm may be influenced by temperature. Temperature during grain development (flowering to physiological maturity) has a significant effect on dormancy (Mares, 1993). Reddy at al. (1985) verified previous reports that grain maturing under cool conditions expressed higher levels of dormancy than grain maturing at higher temperatures. They also noted that varieties that developed high dormancy during cool maturity temperatures did not necessarily maintain dormancy under cool conditions post-maturity. They suggested that selection of genotypes for dormancy is most effective when grain matures under warmer temperatures. This would increase the overall dormancy of the cultivars and therefore dormancy would be maintained under a wider range of environments. Nyachiro et al. (2002) reported that dormancy varies with germination temperature and that the range from 15 to 20°C was ideal to determine dormancy levels for spring wheat genotypes. Previous research also indicates that high temperatures during after-ripening (post physiological maturity) expedite dormancy loss in wheat (Hagemann and Ciha, 1987). Other researchers have reported that drought during grain fill increases susceptibility to PHS for hard white winter wheat (Auld and Paulsen, 2003). This is in contrast to the observations of Biddulph et al. (2005) who reported that drought conditions during grain fill increased dormancy and overrode any increase in dormancy due to low temperatures during grain fill. They accordingly recommended that selection of genotypes for PHS tolerance would not be effective for samples that experienced drought because embryo sensitivity can be induced in a non-dormant genotype. A low-dormancy genotype grown in a hot, dry environment can have the same phenotype as a dormant genotype grown in a cool, wet environment. Also, high temperatures after maturity increase the rate of dormancy decay, making wheat lines more susceptible to PHS as time, after-ripening, and temperatures increase (Mares, 1987).

Practices that Affect PHS and Quality of Damaged Grain

Previous research indicates that nitrogen fertilizer can indirectly affect PHS, most notably due to the increase in lodging caused by increased nitrogen application. Increased sprouting in lodged wheat is caused by proximity of the spikes to moist soil and decreased drying rate due to the lack of air circulation (Henry and Kettlewell, 1996). Nitrogen has been reported to reduce pre-maturity α-amylase formation; however, the mechanism behind this action is not fully understood (Kettlewell and Cooper, 1992). Morris and Paulsen (1985) reported that high nitrogen rates only affected the level of pre-harvest sprouting in low to moderately dormant wheat genotypes. The sprouting level of wheat with strong resistance to sprouting is unaffected by nitrogen rate.

Grain gravity separators have been used as a mass screening method to separate sprouted and non-sprouted wheat kernels. In theory, sprouted kernels will be less dense because of starch degradation and would be blown out and segregated away from the sound grain. However, some wheat cultivars exhibit low falling number and high α-amylase activity in the absence of weathering, suggesting genetic control of high α-amylase content (Gale et al., 1983; Mares, 1987). Kernel density would be unaffected in this situation and density separation methods would not be effective due to the inclusion of sprouted kernels having higher α-amylase content and lower falling number for the sample (Henry and Kettlewell, 1996). Bettge and Pomeranz (1993) reported that the overall quality of grain taken into the mill can be improved by running damaged grain shipments through an air-aspirated cleaning device to remove the more sprouted grain by removing lower test weight kernels. This method was reported to work best when handling grain with only moderately (200-300 falling number) sprouted grain.

Predicting PHS Tolerance/Susceptibility

Examining different laboratory or greenhouse methods of screening for sprouting resistance, Humphreys and Noll (2002) reported that artificial weathering consistently resulted in higher falling numbers than would be experienced in the field due to constancy of droplet intensity and uniform droplet size not experienced in the field. They also noted that a visual sprouting score (0-9) could be used to identify cultivars with low PHS resistance but only for cultivars with sprouting scores of 7.5 or higher. Falling numbers obtained from simulated rainfall studies can give insight into the dormancy and PHS resistance of a line. A major shortfall of rainfall simulators is the inability to deliver droplets at the same kinetic energy as natural rainfall (King, 1987).

Shorter et al. (2005) reported that use of a germination index (GI) to assess grain dormancy was consistent across years. They also determined that GI was the most reliable predictor of PHS tolerance and recommended its use to screen wheat cultivars for sprouting resistance among New Zealand cultivars. A strong correlation between increasing grain germinability and increasing PHS was reported among hard white wheat genotypes in Australia. Germinability data used to generate a sprouting index have also been coupled with environmental data to develop a model for predicting sprouting (Mares, 1993).

Genetic Resistance/Breeding for Resistance

Gorden (1987) reminds us that variation in harvest ripeness (approximately 12% moisture) and maturity can be attributed to general genetic combining ability while dormancy and germination variation is attributed to specific combining ability. DePauw and McCaig (1991) tested various assays to predict sprouting resistance and seed dormancy in both red-seeded and white-seeded wheat cultivars and concluded that these characteristics were highly heritable (0.59 to 0.9) and that 44 to 90% of the phenotypic variation was due to genotype. Paterson and Sorrells (1990) also concluded that improving PHS sprouting resistance in heterogeneous wheat populations is effective using spike- and seed-based mass selection techniques.

Pre-Harvest Sprouting Tolerance in Soft Red Winter Wheat Cultivars Assessed Via Weighted Germination Index, PHS Tolerance Groupings, and Spike Morphology

ABSTRACT

Pre-harvest sprouting (PHS) results in unacceptable flour quality for up to 30% of the mid-Atlantic soft red winter wheat (SRWW) (*Triticum aestivum L.*) crop annually. Flour milled from sprouted grain produces dough with poorer rheological properties due to starch breakdown and therefore produces inferior baked goods. The inherent dormancy of wheat might be expected to minimize PHS. This research evaluates inherent dormancy in current mid-Atlantic wheat cultivars, using grain falling number after delayed harvest and the weighted germination index (WGI) to see if WGI might serve as a predictor of PHS. Individual spikes from 15 wheat cultivars grown in Virginia in 2007 and 2008 were harvested at physiological maturity and seeds germinated under controlled conditions. A WGI was calculated that gave greater weight, and thus a higher score, to cultivars with seeds that germinated more quickly. When seeds were germinated at 30°C, soft red winter wheat cultivars exhibited a broad range of WGI scores, ranging from 5748 to 2082, 3168 to 333, and 1895 to 273 for samples from Warsaw in 2007 and 2008 and Blacksburg in 2008, respectively. The WGI can be used to identify very high and low dormancy SRWW cultivars, however the influence of environment must be considered, especially for cultivars with moderate dormancy. To evaluate PHS tolerance by line under natural conditions, plots were left standing in the field long after normal harvest date. Final harvest falling numbers were used to divide cultivars into PHS resistance groups ranging from very high to very low. The relationship between PHS resistance groups and WGI values was strong both the 10°C and 30° C treatments. This indicates that PHS resistance groups are good

predictors of dormancy and response of cultivars to delayed harvest. Neither head angle, glume tenacity, nor awn length significantly affected PHS in the current study. Artificial wetting resulted in a major loss of quality after just one rainfall event emphasizing the need for timely wheat harvest.

INTRODUCTION

In 2006, the mid-Atlantic SRWW growing region experienced higher than average rainfall and cool temperatures during grain fill and harvest resulting in PHS. As a result, falling numbers from wheat across the region were below acceptable levels (US Wheat Associates, 2006). The SRWW produced in this region is generally considered resistant to sprouting because red seed coat color is associated with grain dormancy. Problems experienced by the wheat industry in 2006 revived interest in further understanding of PHS in modern SRWW genotypes. Relatively little research has been conducted on dormancy level and sprout tolerance of red wheats compared to white wheats (Torada and Amano, 2002).

Falling numbers (AACC method 56-81B) are measured using a ground wheat sample which is mixed with water to create a slurry (AACC, 1995). The slurry is mixed in a test tube and placed in a hot water bath to gelatinize the starches in the flour. The falling number machine monitors a plunger as it falls through the slurry in the test tube and measures the time necessary for the plunger to move to the bottom of the tube. The longer it takes the plunger to reach the bottom of the tube, the thicker the slurry and the more intact the starch. This test indirectly measures α-amylase activity in grain. Alpha-amylase is released during seed germination to hydrolyze starches to nourish the seed.

The weighted germination index (WGI) has been used to quantifying the inherent dormancy of wheat cultivars (Nyachiro et al., 2002; Walker-Simmons, 1988). This test measures the time to germination for individual seeds at two temperature extremes, 10° and 30° C, with 10° C being the approximate dormancy-breaking temperature of wheat. If incubated at 10°C, most cultivars will germinate quickly and only those with high dormancy will show delay. The 30° C temperature treatment is not conducive to germination and under these conditions, only cultivars with very low dormancy will likely germinate.

Temperature during grain development (flowering to physiological maturity) has a significant effect on the dormancy level of developing grains (Mares, 1993). Lower temperatures during the grain fill period resulted in seeds with higher inherent dormancy than those exposed to temperatures of 26°C or more in the Pacific Northwest USA (Reddy et al., 1985). Similarly, Mares (1993) reported greater dormancy for cultivars exposed to a 26.5°C/8.5 °C temperature regime than those exposed to a 35.6°C / 17.5°C temperature regime. Other researchers have reported that drought during grain development increases PHS susceptibility, i.e. reduces dormancy, for hard white winter wheat (Auld and Paulsen, 2003). This is in contrast to the observations of Biddulph et al. (2005) who reported that drought conditions during grain fill increased dormancy and overrode any increase in dormancy resulting from low temperatures during grain fill. They accordingly recommended that selection for PHS resistance among genotypes would not be effective for samples that experienced drought, because embryo sensitivity can be induced in a non-dormant genotype. A non-dormant genotype grown in a hot, dry environment can develop the same level of dormancy as a typically dormant genotype grown in a cool wet environment.

Grain color has long been known to influence resistance or susceptibility to PHS, with red kernel wheat types more resistant than white kernel types (Torada and Amano, 2002). Historically, the association between PHS and grain color was thought to be due either to a pleiotropic effect of the genes controlling grain color or to genetic linkage between these genes and genes affecting dormancy. Degree of red pigment color of seed coats is controlled by three genes; *R-A1*, *R-B1* and *R-D1* (Flintham et al., 1999; Metzger and Silbaugh, 1970; Sears, 1944). Flintham et al. (1999) reported that these genes have direct effects on dormancy. The *taVp1* gene, which is orthologous to the *VP1* gene influencing dormancy in maize (*Zea Mays* L.), has been mapped on chromosome arm 3L of wheat at 30 cM from the R loci (Bailey et al., 1999). It is now thought that the relation between PHS and grain color is due to both a direct influence of the R genes on dormancy inducing mechanisms and to the linkage of the R genes with *taVp1*, which is related to the embryo mechanisms of dormancy (Groos et al., 2002).

The physical structure of the wheat spike has also been reported to affect PHS by impacting water uptake and drying. In a study of wheat–by-spelt recombinant inbred cultivars, individuals with a short, blocky spike were reported to be more susceptible to PHS than long, lax spikes (Zanetti et al., 2000). Awn length and club shaped spike are also noted by King (1989) as being related to PHS tolerance in wheat. Others have reported that the presence and thickness of epicuticular waxes affects water absorption rate and thus the likelihood of PHS (King and von Wettstein-Knowles, 2000).

DePauw and McCaig (1991) tested various assays to predict sprouting resistance and seed dormancy in both red- and white-seeded wheat cultivars and concluded that these characteristics were highly heritable (0.59 to 0.9) and that 44% to 90% of the phenotypic variation was due to genotype. Paterson and Sorrells (1990) also conclude that PHS resistance in heterogeneous wheat populations can be improved using spike- and seed-based mass selection techniques.

The occurrence of PHS in SRWW is costly to the industry and is becoming more of a concern due to automation in the baking industry. Relatively little information exists concerning PHS and resistance mechanisms in current SRWW cultivars. The objectives of this research were to evaluate methods to screen wheat cultivars for inherent dormancy, quantify inherent post-maturity seed dormancy of current SRWW cultivars, evaluate the effect of natural and simulated weathering through wetting/drying cycles on PHS and evaluate the effects of temperature, moisture, and morphological characteristics, collectively, on pre-harvest sprouting of current wheat varieties and cultivars.

MATERIALS AND METHODS

Field Experiments

In 2006-07, a single field experiment at the Eastern Virginia Agricultural Research and Extension Center (EVAREC) in Warsaw, VA was planted no-till into maize stover on October 19, 2006 at a rate of 300 seeds m^{-2} in 19 cm rows in plots of 4.1 m^{-2}. A total of 92 SRWW cultivars included in Virginia’s Official Variety Trial were evaluated in the initial study. Individual plots were divided into four randomly assigned quadrants to serve as four replications for this study. In 2008, a subset of 15 SRWW cultivars and lines (Table 1.2) representing a range of dormancy and four soft white wheat cultivars were planted in a RCBD with eight replications at Warsaw and Blacksburg, VA. The Blacksburg and Warsaw sites were planted into conventionally tilled seed beds on October 1, 2007 and October 30, 2007, respectively, at

300 seeds m^{-2} in 19 cm rows in plots of 4.1 m^{-2}. Management of the experiments followed recommendations from the Virginia Cooperative Extension Service in the Agronomy Handbook (Brann et al., 2000).

Inherent Dormancy Evaluation

Spikes were hand harvested at physiological maturity from four replications of 92 cultivars at Warsaw in 2007 and from four replications of 19 cultivars at Blacksburg and Warsaw in 2008. The stem was clipped approximately 3 cm below the spike at physiological maturity defined as the loss of color from the spike and the first 2 mm of stem below the peduncle (Hanft and Wych, 1982), dried to constant moisture and placed in a -20° C freezer to prevent an after ripening affect (Reddy et al., 1985; Nyachiro et al., 2002; Yanagisawa et al., 2005). Spikes were removed from the freezer and hand threshed to avoid mechanical injury. Twenty-five seeds of each line were placed crease down in a Petri dish lined with filter paper in 8 ml of water. Placing the seeds crease down ensured quick and consistent imbibition. Dishes were placed in dark germination chambers for 14 days at a constant 10°, 20°, or 30° C in 2007 and 10° or 30° C in 2008. Seeds were evaluated for germination every 12 hours for the first 5 days and daily for the remaining 9 days. A weighted germination index adapted from Nyachiro et al. (2002) was calculated giving a greater weight to cultivars with seeds germinating first. The sum of germinated seeds over the 14 days gave the weighted germination index (Equation 1.1).

Equation 1.1: $WGI = \{14*n_1 + 13*n_2 + \ldots + 1*n_{14}\}/N$

Where n= the number of germinated seeds counted daily and N=the number of total seeds and the integer = the daily weighting factor.

Artificial Wetting Effects on Falling Number

Also at physiological maturity, stems were clipped at 15 to 20 cm above the soil surface from all trials and placed into bundles of 100 spikes. Bundles were dried to constant moisture and placed into a -20°C freezer until tested to prevent any after-ripening affect. To simulate the effect of post-maturity rainfall on grain dormancy, stems with spikes intact were placed upright in a p.v.c. pipe 'honey comb" designed to allow spikes to sit upright and simulate field conditions (Figure 1.1).

Based on WGI in 2007, 15 cultivars from the original 92 were selected for further investigation. Cultivars were selected to represent a large range in WGI and a range in maturity with early, moderate, and late heading cultivars included. Four white-seeded cultivars were also included for comparison.

In 2007, simulated rainfall was applied using an existing greenhouse overhead misting system. Water volume output was calibrated so that the system applied 2.54 cm of water in 20-min at the lowest output area. It was assumed that, once seeds had imbibed adequate water to begin germination, additional water would not affect the level of germination. Treatments consisted of one, two, or three rainfall events, with plants allowed to dry 5 days between rainfall treatments, as this was the long-term frequency for rainfall events in eastern Virginia during wheat maturity and harvest. After the last treatment received simulated rainfall and was allowed to dry for 5 days, all bundles were threshed using a single-head thresher and grain ground to pass a 0.8 mm sieve with a Wiley mill (Thomas Scientific, Philadelphia, PA). As a control, one treatment harvested at physiological maturity did not receive simulated rainfall. This treatment was harvested from the field, dried to a constant weight, and similarly processed for falling number analysis using AACC method 56-81B (AACC, 1995).

In 2008 stems were once again harvested from the field at physiological maturity with the spike intact and placed in the same p.v.c. device. Water was applied to the spikes with a hand-held nozzle calibrated to apply 10.2 cm water three times daily for two days to ensure prolonged wetting of the grains. Five days of drying were allowed following each wetting treatment. The treatments were the same as the previous year's evaluation which included zero, one, two, and three simulated rainfall events. All samples were threshed using a single-head thresher and grain ground to pass through a 0.8 mm sieve with a Wiley mill (Thomas-Wiley, Swedesboro, NJ) and analyzed for falling number.

In-Field Weathering Studies

In 2007, 30 spikes were hand-harvested at physiological maturity from each of the four quadrants for each of the 19 selected cultivars (15 SRWW and four soft white cultivars). Thirty spikes were also collected at harvest maturity (approximately 12% moisture); two weeks post harvest maturity, and approximately one month post harvest maturity.

In 2008, the study was planted in Blacksburg and Warsaw, VA with 15 SRWW cultivars and 4 soft white cultivars and eight replications at each location. Thirty spikes were hand-harvested at physiological maturity and harvest maturity (estimated 12% moisture content) from the first four replications at each location. Thirty spikes were also hand harvested on two dates following harvest maturity from the last four replications (5-8) at each location. The first post-maturity harvest was conducted 10 days after harvest maturity while the final post-maturity harvest was conducted approximately six weeks after harvest maturity in 2008 and two weeks after harvest maturity in 2007. In both years, following hand harvest, samples were placed in a low temperature (21°C) dryer until a constant moisture was reached then placed into a -20°C freezer until processing. Each sample was removed from the freezer, threshed using a single-head thresher, and ground to pass a 0.8 mm sieve with a Wiley mill, and analyzed for falling number as previously noted.

PHS Resistance Grouping

Falling numbers from the final harvests at Blacksburg and Warsaw in 2008 were averaged to generate a mean falling number value for each cultivar. Cultivars with similar falling number after field weather were grouped together to better understand interactions with other measured parameters. Cultivars with average falling number >250 seconds were classified as VH or very high, 200-249 seconds H or high, 150-199 seconds M or medium, 100-149 seconds L or low, and <100 seconds VL or very low dormancy (Table 1.3).

Morphological Data

In 2007, field plots at Warsaw, VA were measured for head angle, glum tenacity, and awn length at physiological maturity. Three measurements were taken from each replication of each line for a total of 12 measurements per cultivar. Spikes were signified as awnless in the absence of awns. When awns were present, awn length was measured from the top of the head to the tip of the longest awn. Head angle was measured by holding the stem at the base of the head and lining a protractor so that the stem was at 90°. The head was allowed to fall naturally and the angle at which the tip of the wheat head fell was recorded. Glume tenacity was measured as the openness of the glume at the tip of the wheat grain using an electronic caliper. These measurement methods were developed to assign quantifiable values to evaluate their effects on PHS instead of the more qualitative measurements used by King and Richards (1984).

Statistical Analysis

A mean WGI for each cultivar was generated using PROC GLM of SAS (SAS Inst, 2004). Mean comparisons using a protected LSD test were made to separate treatment means when F-tests indicated that significant differences existed ($P<0.05$). The range of WGI values from all 92 entries in 2007 was separated into five groups: very low, low, medium, high, and very high based on the LSD and three cultivars in each group were selected for further study in simulated rainfall and delayed harvest testing. Falling number values obtained from these samples were also subjected to analysis of variance for each field sampling time and for each simulated rainfall wetting cycle. Only these 15 SRWW cultivars and four soft white wheats were grown for evaluation in 2008. Mean falling number values were similarly generated for all greenhouse and field samplings using PROC GLM of SAS and mean separation performed using a protected LSD test. Because of non-normal distribution of falling number data in 2008, data were arcsine transformed prior to analysis. Simple correlation analyses were performed with SAS, PROC CORR (SAS Inst, 2004) to evaluate PHS resistance grouping of field weathered samples based on falling number and falling number measured from the same cultivars after artificial wetting**.** Pearson correlation coefficients were considered significant if the probability was significant at $P \leq 0.05$. Morphological characteristics of head angle, glume tenacity, and awn length were compared to mean falling number of 2008 grain samples using simple linear regression. Regression was also used to evaluate the relationship between mean falling numbers of PHS resistance groups and mean WGI calculated over site-years at both 10°C and 30°C. Daily temperature and rainfall were recorded at each location and are presented in Figures 1.2 to 1.4.

RESULTS AND DISCUSSION

Delayed Harvest Effects on Falling Number

There was very little rainfall between physiological maturity and harvest maturity at Warsaw in 2007 (Figure 1.2). There was considerably more rainfall from heading to harvest at both locations in 2008 (Figures 1.3 and 1.4) with 245 mm falling in Blacksburg and 471 mm in Warsaw.

Average falling number by location averaged over 400 seconds for the mean of all SRWW cultivars at all physiological maturity (PM) harvests (Table 1.2). A few cultivars did have falling number below 400 seconds at the PM harvest at Warsaw and Blacksburg in 2008, however none were below the threshold of 300 seconds. The same was true for the white-seeded cultivars except VA97W375WS, which had a falling number of 191 seconds at the PM harvest in Blacksburg in 2008. Grain from this sample would have been considered seriously damaged, even prior to any post-maturity weathering. The lack of rainfall at Warsaw in 2007 is exemplified by the maintenance of high falling number for all SRWW and white cultivars at the final harvest (Table 1.2). While values for some lines like AGS 2060 and Southern States 520 decreased appreciably, there would likely be no impact on grain quality. Other researchers have also noted good flour quality associated with high falling number (Kozmin, 1933). Greater impact of PM rainfall on grain quality was observed for samples from 2008. At over 300 seconds, falling number for Coker 9553 at Warsaw 2008 was higher than for any other cultivar measured at the final harvest, indicating strong resistance to PHS. Southern States 8309, WB03016G, Southern States 8302, and Vigoro Tribute also all had PM falling number values higher than the remaining group of SRWW cultivars at Warsaw in 2008. Cayuga is a soft white cultivar with relatively high PHS resistance (Sorrells and Anderson, 1998) and after delayed harvest the falling number was significantly higher than for the other white cultivars tested (Table 1.2). Across locations in 2008, Coker 9553, Southern States 8302 and 8309, and WB03016G maintained the highest falling numbers. Pioneer Brand 26R31 and Southern States 520 had the lowest mean falling numbers, indicating little resistance to PHS (Table 1.2). Mares (1993) also reported variability among cultivars for falling number response to weathering.

Weighted Germination Index

A large range in dormancy levels, based on WGI, across SRWW cultivars and locations was observed (Table 1.4). Mean WGI averaged over cultivars sampled at Warsaw in 2007 was 5846 and 3283 when germinated at 10 and 30° C, respectively (Table 1.4). Average WGI for cultivars in the 10° C treatment in 2008 were similar in magnitude to 2007; but at 30° C, WGI at both sites in 2008 averaged less than 1300 compared to over 3000 in 2007 (Table 1.4).

Coker 9553 exhibited a very low WGI indicating very high dormancy in all three site years (Table 1.4). The high dormancy characterization is reinforced by the final harvest falling numbers which were consistently high across site-years (Table 1.2). Even at Warsaw in 2008 where over 215 mm of rainfall fell between physiological maturity and final harvest, Coker 9553 still maintained a sound falling number. Conversely, some cultivars consistently exhibited a high WGI indicating very low dormancy. Vigoro 9713 consistently exhibited very high or high WGI in every site year and had average falling numbers of 94 and 65 seconds at Blacksburg and Warsaw, respectively, in the 2008 final harvest where considerable post-maturity weathering had occurred (Table 1.2). Nyachiro et al. (2002) also report wheat cultivars with consistently high or low dormancy across a range of germination-inducing conditions.

The fact that certain cultivars consistently exhibited the same extreme WGI indicates that this screening method may be used to identify cultivars with very high or low inherent dormancy. Rodriguez et al. (2001) used temperature during the grain fill period to form models that predict the PHS resistance of cultivars. In that research, certain cultivars consistently exhibited extreme WGI values across very diverse environments, indicating a strong genetic component influencing the WGI. The findings of Rodriguez et al. (2001) were similar to the present research, in that most cultivars did not consistently produce the same WGI when grown in different environments. However, cultivars with very strong or very weak inherent dormancy, regardless of environment, consistently exhibited a very high or very low WGI. While WGI cannot act as a concrete characterization of dormancy level across locations and years, it may identify those cultivars most and least likely to experience sprouting.

PHS Resistance Grouping

Cultivar falling number from final harvest grain samples from both locations (Blacksburg and Warsaw) in 2008 (Table 1.2) were used to assign PHS resistance groupings (Table 1.3). Only one cultivar, Coker 9553 had a mean falling number of over 250 seconds (Table 1.3). Coker 9553 also consistently exhibited very low or low WGI in our inherent dormancy evaluation over locations and years. Several cultivars, 6 of 15, exhibited intermediate PHS resistance and were placed into high or medium PHS resistance categories. These samples, while below the industry standard for sound grain, still exhibit falling numbers intermediate to acceptable and severely spouted grain (Table 1.3). Finally, eight of the SRWW cultivars had falling numbers below 150 seconds and are considered very low in PHS resistance. Six of these cultivars exhibited falling numbers similar to the white cultivars evaluated, all of which fell below 100 seconds (Table 1.2). Walker-Simmons (1988) also concluded that grouping lines based on PHS resistance was valuable and resulted in reliable, consistent patterns.

In an effort to evaluate WGI as a method to predict relative cultivar dormancy, the average falling number for each PHS resistance group was compared to the mean WGI for cultivars classified into each group (Figure 1.5). A strong negative relationship existed for PHS group falling number and WGI determined at both 10 and 30°C. At 10°C, for every second decrease in falling number, WGI was estimated to decrease by 8.8 units while at 30 °C, this decrease was 9.2 units. While the coefficient of determination was significant for WGI at both temperatures, there was less range in variability and slightly higher R^2 for the 10°C WGI (Figure 1.5).

Artificial Wetting

In the 2007 artificial wetting study, significant PHS damage was not induced via artificial wetting of wheat spikes. Falling numbers across cultivars and wetting applications were well above 350 seconds and all grain would be expected to produce acceptable quality flour (Figure 1.6). Maximum relative humidity inside the greenhouse was considerably lower than was observed at Warsaw during the summer of 2007. There were large fluctuations in the relative humidity in the greenhouse ranging between 35% and 90% with a mean of approximately 70%.

Examining in-field weathering conditions in Warsaw, VA for the last two weeks of June (approximate time of harvest maturity for the area), relative humidity usually fluctuates between 50% and 100% humidity with a mean of approximately 75 to 80%. It is likely that the water applied to the spikes evaporated and spikes were not soaked long enough for water to penetrate the seed coat and be imbibed by the seed.

In 2008, prior to artificial wetting, falling numbers were similar for all PHS resistance groups (Figure 1.7). After one rainfall event there was a significant decrease in falling number for all groups except the very high PHS resistance group. DePauw and McCaig (1991) also concluded that artificial wetting is a reliable method to assess PHS resistance and reported differences among cultivars. Three groups, medium, low, and very low, all exhibited severe sprouting and falling number below the 250 second cut-off for acceptable flour quality after this single rainfall event. White-seeded cultivars were particularly affected by the initial wetting event with falling numbers for all cultivars but Cayuga, considered to be a PHS resistant white wheat, dropping to 62 seconds (Figure 1.7). Sixty-two seconds is the lowest value measurable with the falling number machine. A sharp decline in falling number was observed for the very high and high PHS resistance groups after the second rainfall event. However falling number for the very high and high PHS resistant groups were still significantly higher than the other SRWW categories. Cayuga exhibited a falling number similar to the other soft white cultivars tested after the second rainfall. The large decrease in falling number the first to second rainfall event, in the very high and high PHS resistance groups, illustrates the substantial need for timely wheat harvest. After rainfall event three, all lines exhibited high levels of sprouting with falling numbers well below 250 seconds (Figure 1.7). The very high and high PHS resistance groups maintained significantly higher falling numbers than the other PHS resistance groups, however, not to the extent that it would ensure a higher price standard.

The relationship between the PHS resistance rank order of cultivars and the falling numbers after each artificial wetting event in 2007 and 2008 was evaluated to compare the reliability of using artificial wetting to estimate field PHS resistance (Table 1.5). Pre-harvest sprouting resistance level consistently correlated with the falling number after each wetting event in both years. Stronger correlations were observed with falling number at physiological maturity, or no wetting events, after the third wetting in 2007 and after the second wetting in 2008 (Table 1.5). This is likely because differences in falling number among cultivars were most consistent at these timings.

Morphology

Previous research has indicated that head angle, the presence of awns, and strong glume tenacity have a positive effect on falling number of weathered grain by shedding water and decreasing seed imbibition. The benefit of identifying morphological traits associated with high falling number after weathering is that these phenotypic traits are easy to select for in traditional breeding programs and would allow for easy introgression of increased PHS resistance. In the current study, neither head angle, glume tenacity, nor awn length had a significant impact on grain falling number after field weathering of SRWW cultivars (Table 1.6). In 2007, R^2 values measuring the effect of head angle, glume tenacity and awn length on falling number were: 0.04, 0.07, and 0.01, respectively. In 2008 R^2 values for effects on falling number after weathering were: 0.07, 0.01, and 0.02 for head angle, glume tenacity, and awn length, respectively (Table 1.6).

CONCLUSIONS

The morphological characteristics of head angle, glume tenacity, and awn length did not reliably predict PHS resistance and thus will likely not be easily selectable phenotypic traits for breeding for increased resistance to pre-harvest sprouting. A large range in dormancy levels, based on WGI, was observed across SRWW cultivars and test locations. This is likely indicative of the wide range of genetic variation and lack of selection for this particular trait within SRWW cultivars. Prediction of cultivar response to weathering and conditions that favor PHS could be estimated, but only for those cultivars with very high or very low seed dormancy. While the WGI did not accurately predict dormancy level of all SRWW cultivars across locations and years, it did identify cultivars most and least likely to experience sprouting across environments in Virginia. Pre-harvest sprouting resistance groupings more accurately predicted the response of cultivars to artificial wetting. Cultivars falling into the very high and high PHS resistance groups exhibited falling numbers that were consistently much higher than other groupings, including white wheats, over wetting events. Cultivars in these groups maintained sound falling numbers after the first artificial wetting event in 2008. The PHS resistance categories strongly correlated with the three-year cultivar mean for WGI at the 10°C and 30°C treatments. The PHS resistance categories, coupled with the WGI can help quantify the PHS resistance of SRWW cultivars in Virginia. This information, in turn, can be used by growers to choose cultivars with greater dormancy and resistance to PHS and identify cultivars to avoid if delayed harvest is a potential problem. Coker 9553 was identified as a PHS-resistant cultivar across environments. The large number of low-dormancy and/or low PHS resistant cultivars suggests a need for increased attention to dormancy and PHS resistance characteristics in Virginia cultivars and for Virginia producers to consider PHS resistance when selecting cultivars. The sharp decrease in falling number after only one artificial wetting event in 2008 illustrates the need for producers to make timely harvest a priority in farming operations. Having machinery ready and making wheat harvest a priority can mean the difference between flour quality and feed quality grain. Further understanding of the mechanisms governing seed dormancy in SRWW cultivars would facilitate breeding for increased PHS resistance. Identification and characterization of genes that control dormancy in SRWW wheat will facilitate breeding for increased seed dormancy and presumably reduced PHS in SRWW.

Table 1.1. Wheat cultivars and seed source for PHS resistance testing.

Cultivar	Seed Source
AGS 2060	AgSouth Genetics, PO Box 72246, Albany, GA 31721-2246
Vigoro Tribute	Crop Production Services, Box 1467, Galesburg, IL 61402-1467
Vigoro 9713	Crop Production Services, Box 1467, Galesburg, IL 61402-1467
Southern States 520	Southern States Cooperative, PO Box 26234, Richmond, VA 23260
VA05W258	experimental, Virginia Tech, Department of CSES, 330 Smyth Hall, Blacksburg, VA 24061
Southern States 8309	Southern States Cooperative, PO Box 26234, Richmond, VA 23260
Pioneer Brand 26R31	Pioneer Hi-Bred International, Inc., 7501 Memorial Pkwy SW, Suite 205, Huntsville, AL 35802
Coker 9436	AgriPro COKER, PO Box 411, 520 East 1050 South, Brookston, IN 47923
USG 3342	Uni-South Genetics, 2640-C Nolensville Road, Nashville, TN 37211
USG 3209	Uni-South Genetics, 2640-C Nolensville Road, Nashville, TN 37211
Southern States 8302	Southern States Cooperative, PO Box 26234, Richmond, VA 23260
VA05W414	experimental, Virginia Tech, Department of CSES, 330 Smyth Hall, Blacksburg, VA 24061
Coker 9553	AgriPro COKER, PO Box 411, 520 East 1050 South, Brookston, IN 47923
USG 3665	Uni-South Genetics, 2640-C Nolensville Road, Nashville, TN 37211
WB03016G	WestBred, LLC, 8 West Park St. Suite, 210, Butte, MT 59701
Pearl	Michigan Crop Improvement Association, P.O. Box 21008; Lansing, MI 48909
Cayuga	Cornell University, Department of Plant Breeding and Genetics, Ithaca, NY 14853
VAN98W-170WS	experimental, Virginia Tech, Department of CSES, 330 Smyth Hall, Blacksburg, VA 24061
VA97W375WS	experimental, Virginia Tech, Department of CSES, 330 Smyth Hall, Blacksburg, VA 24061

Table 1.2. Mean falling number by cultivar at physiological maturity and final (delayed) harvest, Warsaw 2007 and 2008, and Blacksburg, 2008.

	-----Warsaw, 2007-----		-----Warsaw, 2008-----		-----Blacksburg, 2008-----	
	Physiological Maturity Harvest	Final Harvest	Physiological Maturity Harvest	Final Harvest	Physiological Maturity Harvest	Final Harvest
Red-seeded cultivars	-------------------------------Falling Number, sec--------------------------------					
Coker 9436	458.7	439.3	459.0	95.3	428.0	96.0
Coker 9553	428.0	455.0	428.3	300.3	422.3	219.3
AGS 2060	444.7	357.7	424.0	65.0	383.7	83.7
Pioneer Brand 26R31	451.7	408.7	383.7	62.0	420.0	62.0
Southern States 520	452.0	392.0	387.3	62.3	410.0	71.7
Southern States 8302	411.7	409.7	382.0	222.0	373.7	233.3
Southern States 8309	440.0	421.7	425.0	247.7	453.3	235.7
Vigoro Tribute	446.3	442.3	442.7	219.7	431.0	182.3
USG 3209	467.0	457.3	446.3	125.7	447.0	144.7
USG 3342	488.3	468.7	422.3	195.3	386.3	140.0
USG 3665	450.7	484.7	457.7	171.3	439.0	235.0
Vigoro 9713	418.7	403.3	403.3	65.3	416.0	93.7
VA05W258	425.7	444.0	403.7	109.7	397.7	150.0
VA05W414	468.7	488.3	449.0	69.3	429.0	93.3
WB03016G	427.3	434.3	390.7	225.7	421.7	244.7
Mean	445.3	433.8	420.3	149.1	417.2	152.4
LSD	20.2	44.5	30.2	41.4	54.0	68.1
White-seeded cultivars						
Cayuga	483.3	466.7	447.7	70.0	450.7	80.0
Pearl	446.7	421.7	398.7	62.0	351.0	62.0
VAN98W-170WS	442.0	431.0	424.7	62.0	338.0	62.0
VA97W375WS	481.3	445.7	405.0	62.0	191.3	62.0
Mean	463.3	441.3	419.0	64	332.75	66.5
LSD	25.5	31.2	23.8	4.2	80.2	10.1
Overall Mean	449.1	435.4	420.1	131.2	399.5	134.3

Table 1.3. Relative PHS resistance groupings for soft red winter and soft white cultivars based on mean falling number from 2008 final (delayed) harvest samples.

Red-seeded cultivars	Falling Number Range	Relative Dormancy Group
	--sec--	
Coker 9553	>250	VH
Southern States 8309	200-249	H
WB03016G	200-249	H
Southern States 8302	200-249	H
USG 3665	200-249	H
Vigoro Tribute	200-249	H
USG 3342	199-150	M
USG 3209	149-100	L
VA05W258	149-100	L
Coker 9436	<100	VL
VA05W414	<100	VL
Vigoro 9713	<100	VL
AGS 2060	<100	VL
Southern States 520	<100	VL
Pioneer Brand 26R31	<100	VL
White-seeded cultivars		
Cayuga	<100	VL
Pearl	<100	VL
VAN98W-170WS	<100	VL
VA97W375WS	<100	VL

VH = very high relative dormancy.
H = high relative dormancy.
M = moderate relative dormancy.
L = low relative dormancy.
VL = very low relative dormancy.

Table 1.4. Mean weighted germination index (WGI) determined at 10 and 30°C for SRWW and soft white wheat cultivars grown at Warsaw, 2007 and 2008, and Blacksburg, 2008.

	Warsaw, 2007				Blacksburg, 2008				Warsaw, 2008				Mean	
Red-seeded cultivars	10° C		30° C		10° C		30° C		10° C		30° C		10° C	30° C
							WGI							
Coker 9553	5090	-	524	-	5075	-	273	-	4970		717		5045	505
USG 3665	4194	-	1056	-	5564		306	-	3657	-	314	-	4472	559
Southern States 8302	5481		1524	-	4785	-	519		5049		663		5105	902
VA05W414	6183		1877	-	6331		783		5682	+	318	-	6065	993
USG 3209	6191		2129	-	5979		306	-	5088		1209		5753	1215
USG 3342	5280		2403		6125		1847		5239		711		5548	1654
WB03016G	5220	-	2082	-	6113		2232	+	3549	-	1095		4961	1803
Pioneer Brand 26R31	5586		3438		6747	+	1653		4501		1299		5611	2130
Coker 9436	5891		3177		6657		409	-	5833	+	3169	+	6127	2252
Vigoro Tribute	6354	+	3753	+	6066		693		5361		2801	+	5927	2416
AGS 2060	6591	+	5746	+	6333		1515		2805	-	333	-	5243	2531
VA05W258	6104		4644	+	6567		1656		4215	-	1452		5629	2584
Southern States 520	6354		5312	+	6705		1896		6216	+	1183		6425	2797
Southern States 8309	6442		5408	+	5907		2241	+	5001		1341		5783	2997
Vigoro 9713	6729	+	6174	+	6300		2973	+	5985	+	1766		6338	3638
Mean	5846		3283		6084		1287		4877		1225		5602	1932
LSD	519		1191		665		838		564		870			
White-seeded cultivars														
Cayuga	5700	-	1662	-	6528		1542	-	5700	-	1662	-	5976	1622
Pearl	7251	+	7734	+	7138		6348		7251	+	7734		7213	7272
VAN98W-170WS	6585		6582		6876		7263		6852		6582		6771	6809
VA97W375WS	6852		7215	+	6696		7125		6585		7215		6711	7185
Mean	6597		5798		6810		5570		6597		5798		6668	5722
LSD	413		1333		659		3436		416		2376			

WGI = Weighted germination index
- = WGI significantly (one LSD) below the mean of all entries and
+ = WGI significantly (one LSD) above the mean of all entries

Table 1.5. Relationship of cultivar falling number rank order based on mean falling number from 2008 final (delayed) harvest samples and falling number measured after each artificial wetting for samples from Warsaw, 2007 and Blacksburg, 2008.

Site Year	No Rain	One Rain Event	Two Rain Events	Three Rain Events
	---------------------Pr>r---------------------			
Warsaw 2007	0.94	0.64	0.56	0.94
Blacksburg 2008	0.94	0.67	0.99	0.66

Table 1.6. Influence of wheat spike morphological characteristics on falling number at final post maturity harvest, Warsaw, 2007, and mean of Blacksburg and Warsaw, 2008.

Spike measurement	2007	2008
	---------R^2---------	
Head Angle	0.04	0.07
Glume Tenacity	0.07	0.01
Awn Length	0.01	0.02

Figure 1.1. Honey-comb device used to administer simulated rainfall.

Figure 1.2. Daily rainfall and average temperature from wheat heading to final harvest at Warsaw, 2007. Arrows indicate individual harvest; P.M.=physiological maturity, H.M.=Harvest Maturity, 1 Post= 1st post-harvest maturity harvest 2 Post= 2nd post-harvest maturity harvest.

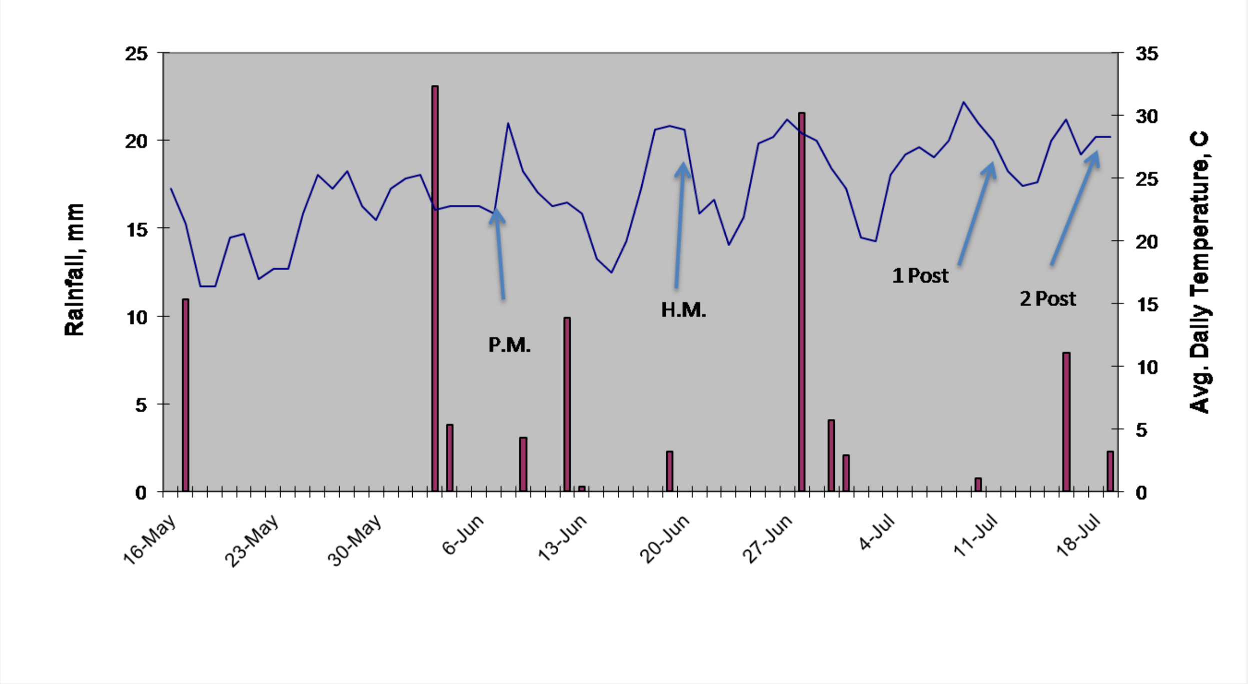


Figure 1.3. Daily rainfall and average temperature from heading to final harvest at Blacksburg, 2008. Arrows indicate individual harvest; P.M.=physiological maturity, Final= final post-harvest maturity harvest (4 weeks after harvest maturity).

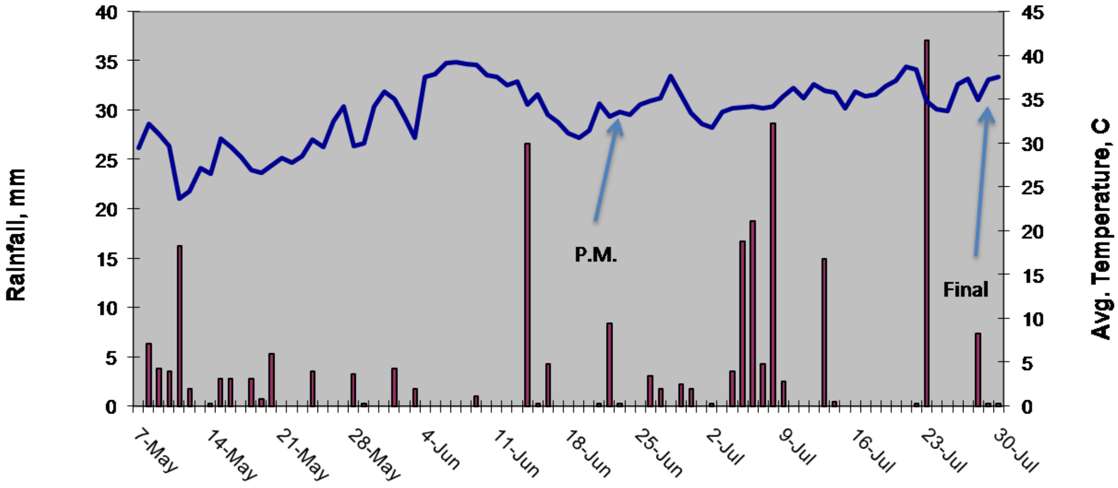


Figure 1.4. Daily rainfall and average temperature from heading to final harvest at Warsaw, 2008. Arrows indicate individual harvest; P.M.=physiological maturity, Final= final post-harvest maturity harvest (5 weeks after harvest maturity).

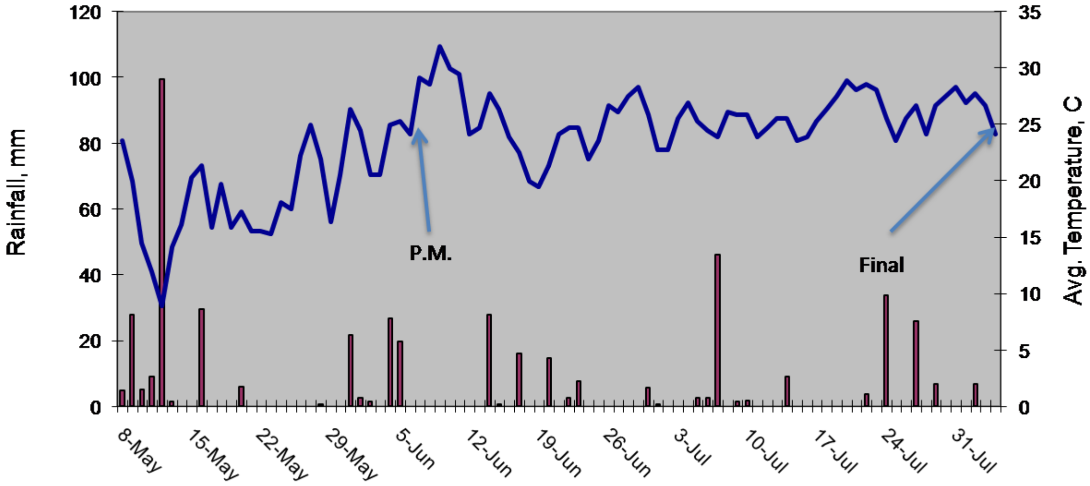
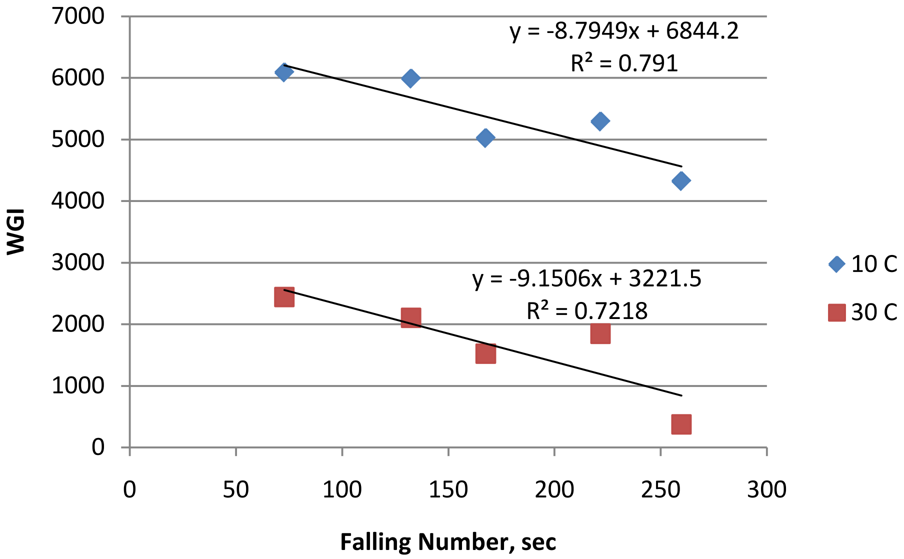


Figure 1.5. Relationship of relative dormancy group, as determined by mean 2008 final harvest falling number, and average weighted germination index (10 and 30°C treatments) by relative dormancy group, from Warsaw, 2007 and 2008, and Blacksburg, 2008.



WGI = Weighted Germination Index

Figure 1.6. Artificial wetting effects on mean falling number by relative PHS resistance group, Warsaw, 2007. Where VH=very high, H= High, M=Medium, L=Low, and VL=Very Low. White-seeded lines are listed by cultivar.

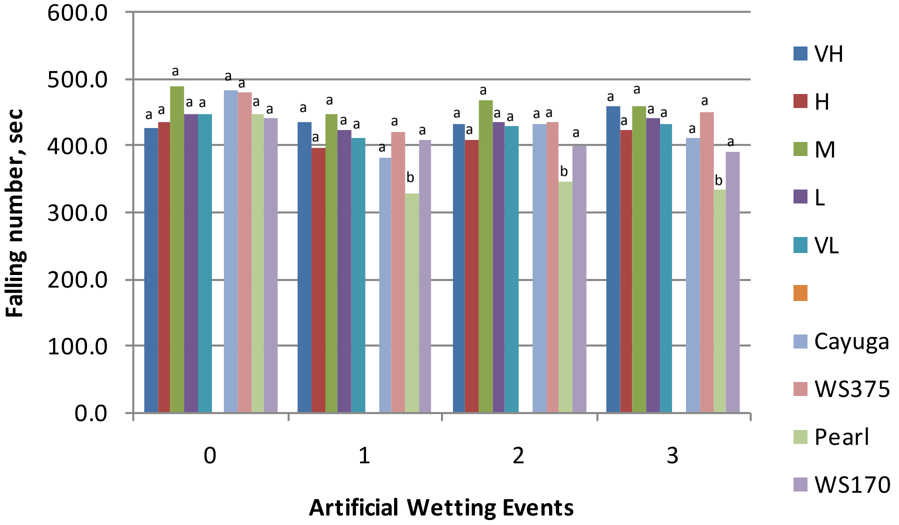
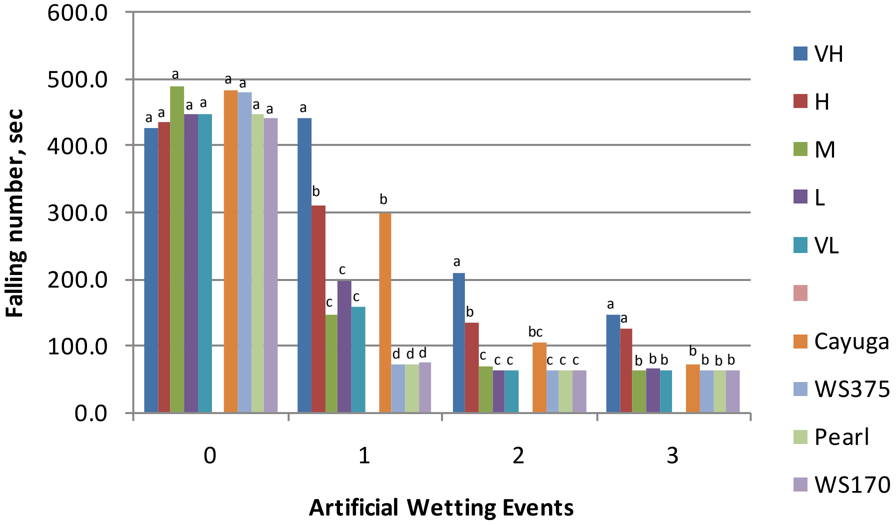


Figure 1.7. Artificial wetting effects on mean falling number by relative PHS resistance group, Blacksburg, 2008. Where VH=very high, H= High, M=Medium, L=Low, and VL=Very Low. White-seeded lines are listed by cultivar.



Effect of Pre-Harvest Sprouting on Soft Red Winter Wheat Flour Properties

ABSTRACT

Pre-harvest sprouting (PHS) in wheat (*Triticum aestivum L.*) can result in adverse rheological properties (as measured by farinograph) including: decreased flour water absorption, below acceptable levels for departure time and stability, and an increase in the 20- minute drop which negatively affects dough mixing tolerance and texture. Sprouted wheat can result in low dough yield, decreased cookie diameter and cake volume, and a sticky dough consistency. Five soft red winter wheat (SRWW) cultivars, chosen based on expected PHS resistance and sample availability, were grown in three diverse locations over two growing seasons. Samples were harvested after experiencing different environmental conditions with some exposed to high cumulative rainfall after physiological maturity and some experiencing little rainfall. This resulted in variable levels of grain sprouting and flour from these samples were subjected to Brabender Farinograph testing. Cumulative rainfall from heading to harvest was 190 mm, 54 mm, 245 mm, and 471 mm at Blackstone in 2007, Blacksburg in 2007, Blacksburg in 2008, and Warsaw in 2008, respectively. Falling numbers remained above the threshold of 300 seconds at both locations in 2007 but considerable spouting occurred in 2008, as evident by a mean falling number of 163 seconds across sites. Water absorption was almost 4% lower at sites where significant sprouting occurred and varied by wheat cultivar. Farinograph peak, arrival, and departure values all followed a similar trend with higher values obtained from sites with less sprouting. The cultivar Tribute generally displayed less impact of sprouting on flour quality than other cultivars. Flour quality parameters were more influenced by wheat genotype than by mean

falling number. Genotype appears to be more important in determining flour quality factors such as water absorption than are falling numbers.

INTRODUCTION

It is important to maintain high quality in Virginia's soft red winter wheat (SRWW) to obtain high prices for milling quality wheat versus lower value feed wheat. The increase in amylase and protease activity associated with seed germination causes damage to the starch and protein of wheat flour. Pre-harvest sprouting is quantified using the Haberg Falling Number test which indirectly measures the α-amylase activity in wheat flour by measuring the viscosity of a heated flour slurry (Hagberg, 1961). However, there are no official grading standards set for falling number in wheat (FGIS, 2006). Wheat with a falling number of less than 250, to as high as 300 seconds, can be categorized as sprouted wheat and graded suitable only for feed grain. Historically, bakers dealt with wheat having marginal falling number by blending flours or adjusting other recipe components. Due to mechanization of the milling industry, falling number standards are being raised to compensate for being less capable to manually mix grain or flour of sound and sprouted wheat.

It is difficult to predict the baking quality of wheat flour without performing actual baking tests and some researchers have pointed out the need for additional measurements to accurately assess end-use quality (Tulbek et al., 2002). Instruments such as the farinograph (C. W. Brabender, Hackensack, New Jersey) have been developed to quantify dough quality characteristics. The farinograph uses rotating blades spinning in a zigzag pattern to measure the torque on the dough. The farinograph was used to generate data for water absorption, arrival time, peak time, departure time, stability, and 20-minute drop in this study. Water absorption is defined as the amount of water required to center the farinograph curve on the 500-B.U. (Brabender unit) line (D'Appolonia and Kunerth, 1984). Arrival time is the time, in minutes, required for the top of the farinograph curve to reach the 500-B.U. line. This measurement evaluates the rate at which the flour takes up water. Departure time is the time in minutes for the top of the farinograph curve to fall below the 500-B.U. line and is used in the calculation of dough mixing stability. Gupta et al. (1992) reported a significant positive relationship between farinograph departure time and percent protein. Stability is the difference between the departure time and the arrival time in minutes and gives an indication to the mixing tolerance of the flour. Peak time gives an approximate optimal mixing time and is the time that the peak of the farinograph curve remains at its highest point and is measured in minutes. Finally, 20-minute drop (TMD) is the change in the height of the farinograph curve from the peak to the center of the curve at 20 minutes. This value indicates the rate of breakdown and strength of the flour (D'Appolonia and Kunerth, 1984); the higher the value the weaker the dough (Walker and Hezelton, 1996).

Flour water absorption is affected by protein quality and quantity, starch damage, and non-starch carbohydrates (Finney et al., 1987). Dexter et al. (1994) reported that starch damage is the predominant factor influencing water absorption, development time and stability in durum wheat. High water absorption is desired for high dough yield in bread wheat but lower water absorption is desirable in soft red winter products. However, PHS can decrease water absorption to an unacceptable level in SRWW; any water absorption below 52% is below the optimal level for SRWW products such as crackers or pastry flours (Souza et al., 2006). Johansson (2003) reported that both genotype and environment affected starch and protein quality, both of which play a role in flour quality.

Soft red winter wheat is generally used for production of cakes, cookies, crackers and other pastry type baked goods because of weak gluten strength and lower protein content (Henry and Kettlewell, 1996). Soft red winter wheat cultivars with a high level of inherent dormancy are suggested to be less likely to sprout prior to harvest and therefore more likely to preserve quality even after weathering. Falling number is used to quantify sprouting damage in wheat by indirectly measuring α-amylase activity via assessment of the viscosity of a flour slurry. In the previous chapter falling number and weighted germination index (WGI) were used to quantify the inherent dormancy of SRWW cultivars grown in Virginia. Recent research on SRWW in Virginia indicates that mild to moderately sprouted wheat with falling numbers from 150 to 330 seconds produces decreased flour and end use product quality (Barbeau et al., 2006). These authors concluded that falling number should not be used as the sole criteria for determining sprouting damage and recommended also including farinograph data.

Pre-harvest sprouting of wheat has been a major contributor to decreased wheat quality in the mid-Atlantic region of the U.S and while this phenomenon has been extensively studied in white wheat and in other areas of the world, little is currently known about PHS resistance of eastern SRWW and the effect of this resistance on wheat flour properties. The objectives of this research were to evaluate the impact of PHS on flour quality parameters and to investigate potential differences in flour quality of cultivars with varying levels of PHS.

MATERIALS AND METHODS

Field Studies

Grain samples for quality evaluation were collected from Virginia's Official Variety testing sites at Blacksburg and Blackstone in 2007 and in Warsaw and Blacksburg in 2008 (Figure 2.1). Plots were planted in a RCBD and seeded at 300 seeds m^{-2} in 19 cm rows in plots of 4.1 m^{-2}. Planting and harvest dates are listed in Table 2.1. All trials were managed according to Virginia Cooperative Extension recommendations for wheat production (Brann et al., 2000).

Wheat spikes were harvested at physiological maturity from four replications of 92 cultivars in 2007 and from four replications of 15 cultivars in 2008. The stem was clipped approximately 3 cm below the spike at physiological maturity, defined as the loss of color from the spike and the first 2 mm of stem (Hanft and Wych, 1982), dried to constant moisture and, placed in a -20° C freezer to prevent after-ripening (Reddy et al., 1985; Nyachiro et al., 2002; Yanagisawa et al., 2005). Prior to processing, spikes were removed from cold storage and hand-threshed to avoid mechanical injury. Twenty-five seeds of each line were placed crease down in a Petri dish lined with filter paper in 8 ml of water. Placing the seeds crease down ensured quick and consistent imbibition. Dishes were placed in dark germination chambers for 14 days at a consistent 10°, 20°, or 30° C in 2007 and 10° or 30° C in 2008. Seeds were evaluated for germination every 12 hours for the first 5 days and daily for the remaining 9 days. A weighted germination index (WGI) adapted from Nyachiro et al. (2002) was calculated giving a greater weight to cultivars with seeds germinating first. The sum of germinated seeds over the 14 days gave the WGI (Equation 2.1).

Equation 2.1. $WGI = \{14*n_1 + 13*n_2 + \ldots + 1*n_{14}\}/N$

Where n= the number of germinated seeds counted each day and N=the total number of seeds and the integer = the daily weighting factor.

In 2007, 30 spikes were hand-harvested at physiological maturity from the 19 cultivars (15 SRWW and four soft white cultivars) from each replication selected for further testing. Thirty spikes were also collected at harvest maturity (approximately 12% moisture), two weeks post harvest maturity, and approximately one month post harvest maturity.

In 2008, the study was planted in Blacksburg and Warsaw, VA with 15 SRWW cultivars and 4 soft white cultivars and eight replications at each location. Thirty spikes were hand-harvested at physiological maturity and harvest maturity (estimated 12% moisture content) from the first four replications at each location. Thirty spikes were also hand harvested on two dates following harvest maturity from the last four replications (5-8) at each location. The first post-maturity harvest was 10 days after harvest maturity while the final post-maturity harvest was six weeks after harvest maturity in 2008 and two weeks after harvest maturity in 2007. In both years following hand harvest, samples were placed in a low temperature (21°C) dryer until a constant grain moisture was reached then placed into a -20°C freezer until processing. Each sample was removed from the freezer, threshed using a single-head thresher, grain ground to pass a 0.8 mm sieve with a Wiley mill (Thomas-Wiley, Swedesboro, NJ), and analyzed for falling number.

Five cultivars were selected from the 2007 field study for Brabender farinograph analysis based on expected relative PHS resistance and availability of a sufficient grain sample. Of these five, three cultivars: Southern States 8302, Southern States 8309, and Tribute had high falling numbers after field weathering while two cultivars: Vigoro 9713 and Southern States 520 had very low falling numbers (Table 2.2). Plots of 4.1 m^{-2} were harvested using a small plot combine and entire samples were retained. Samples were dried to a constant moisture and ground to pass a 0.8 mm sieve using a Wiley mill. Samples were divided, with a portion of the mixture reserved for falling number analysis, while the remainder was partitioned into triplicate 50-gram samples of each cultivar for farinograph measurements. Daily temperatures and rainfall were collected on-site at each location.

Laboratory Analyses

A Brabender farinograph (AACC Method 54-21, 2000) (C. W. Brabender, Hackensack, New Jersey) was used to measure water absorption, peak time, arrival time, departure time, stability, and 20-minute drop. The first of three triplicate samples was used to obtain an estimate of water absorption for each sample (data not shown). Having an estimation of water absorption for each line allowed more accurate measurement in subsequent runs. Falling number (AACC Method 56-81B, 1995) was also measured for each sample using the previously reserved material.

Statistical Analysis

Mean falling number, water absorption, peak time, arrival time, departure time, stability, and 20-minute drop for each cultivar were subjected to analysis of variance using PROC GLM in SAS (SAS Inst, 2004). Mean comparisons using a protected LSD test were made to separate treatment means where F-tests indicated that significant differences existed ($P<0.05$). Linear regression was used to evaluate the relationship of falling number with water absorption, peak time, arrival time, departure time, stability, and 20-minute drop.

RESULTS AND DISCUSSION

There was very little rainfall at either experimental location in 2007 (Figures 2.2 and 2.3) with only 54 mm falling in Blacksburg and 190 mm falling in Blackstone from heading to harvest. There was considerably more rainfall from heading to harvest at both locations in 2008 (Figure 2.4 and 2.5) with 245 mm falling in Blacksburg and 471 mm in Warsaw.

Analysis of variance revealed an interaction of line and environment for falling number, peak time, departure time, and stability (Table 2.3). The main effects of environment and cultivar significantly impacted water absorption and 20-min drop (Table 2.3).

Falling number at harvest was similar for all cultivars across both locations in 2007 (Table 2.2). This is likely a result of the limited weathering experienced by these samples during this harvest season, with an average falling number value of 428 seconds across cultivars and locations. Falling number differences were measured among cultivars in 2008 with values significantly lower for Southern States 520 and Vigoro 9713 than for other cultivars (Table 2.2). While none of the evaluated cultivars maintained falling number values greater than 250 seconds in 2008, Southern States 8302, 8309, and Vigoro Tribute were all above 200 seconds, indicating a better likelihood of blending with sound grain to achieve an acceptable falling number time. Overall, the lowest falling number values were observed for Southern States 520 (62 sec) and Vigoro 9713 (65 sec) at the Warsaw site in 2008 (Table 2.2). This dataset consisted of extremes of falling numbers between sound and weathered samples, with few data points in the range of 350 to 150 seconds. Intermediate falling number samples were not available for testing.

Flour water absorption varied significantly by site-year, when values were averaged over wheat cultivars (Figure 2.6). Water absorption values were similar for sites within a year, but different between years (67.8 % in 2007 and 63.8% in 2008). Again this is likely attributable to greater overall weathering and sprouting in the 2008 crop. Finney et al. (1987) also reported flour water absorption to be significantly impacted by degree of starch damage. Cultivar also affected flour water absorption (Table 2.3). Over locations, absorption was highest for Southern States 520 (69.2%) and was significantly lower for Vigoro 9713 (61.7%) than for all other cultivars (Table 2.4). Johansson (2003) also concluded that genotype and environment affect starch and protein quality, both of which play a role in flour quality. Over years, the relationship of falling number and water absorption was not significant (Table 2.5). The present research agrees with previous work by Barbeau et al. (2006), that falling number is not a good indicator of flour quality. Barbeau et al. found only six of 17 lines were considered poor quality based on falling number but farinograph measurements showed that 17 wheat lines exhibited low gluten strength. This is seemingly in contrast to the findings of Finney et al. (1987) and others but may reflect the extremes in falling number values in this study.

Twenty-minute drop averaged 79 B.U. in 2007 and 210 B.U. in 2008 (Table 2.2). Again this is reflective of very different conditions between years. Southern States 8302 and 8309 had the highest value across sites of 158 B.U., while Tribute had the lowest, at 105 B.U. Twenty-minute drop ranged from 162.5 to 105 B.U. by cultivar, when averaged over site years (Table 2.4). Twenty-minute drop measures the rate of breakdown and dough strength, with higher values denoting weaker flours (Walker and Hezelton, 1996). Twenty-minute drop and falling number were significantly correlated when examined over locations (Table 2.5).

Departure time was lower, an average of 5.7 minutes, in 2008 than in 2007 and there were no differences among cultivars in 2008 (Table 2.2). Tribute had the highest departure of 18.5 minutes at Blacksburg in 2007, which was significantly higher than other cultivars at that site. Tribute also had departure values higher than Vigoro 9713, Southern States 8302 and 8309 at Blackstone in 2007 (Table 2.2). Strong flours exhibit a long departure time, so flour was stronger overall in 2008 than 2007 and stronger for Tribute than other lines. This is to be expected based on gluten strength of this line (Griffey et al., 2005). Departure time was significantly correlated with falling number when examined across locations (Table 2.5). This is also to be expected based on degree of starch damage and coincides with the classic findings of Kozmin (1933).

Stability was higher for Tribute, Southern States 520 and 8309, than other cultivars at Blacksburg in 2007 (Table 2.2). Tribute and Southern States 520 also had higher stability that Southern States 8302 and Vigoro 9713 at Blackstone in 2007. Values for other line by site-year combinations were similar. Stability was significantly correlated with falling number when examined across locations (Table 2.5). Our finding agree with those of Dexter et al. (1994) who also report flour stability to be closely rated to falling number, and thus to degree of PHS.

CONCLUSIONS

Environment plays a major role in the quality parameters of SRWW flour as indicated by the sharp decline of all quality parameters with delayed harvest in 2008. Pre-harvest sprouting had a significant effect on important quality parameters such as water absorption and 20- minute drop but there was a distinct separation of sound and sprouted samples by year with weathered samples having a mean falling number below 200 seconds and sound samples well above 400 seconds. High and low falling number samples generated high and low values for water absorption, departure time, and stability. Flour from one cultivar, Tribute, did not seem to be as adversely affected by PHS as other cultivars. Tribute exemplifies the strong genetic component of flour quality and the ability of genetics to mask the effects of starch degradation that takes place with PHS. The correlation of falling number with peak time, departure time, stability, and 20-minute drop is indicative of the extreme differences in falling number observed in this study. Our observed correlation between quality parameters and falling number within harvest year; agrees with previous research that falling number is not a totally inclusive method of quantifying flour performance.

Tables

Table 2.1. Planting, heading, flowering, and harvests date of wheat cultivars used in farinograph studies by site-year.

	Planting Date	Heading Date	Flowering Date	Harvest Maturity Date	Final Harvest Date
Blacksburg 2007					
Southern States 520	5-Oct	9-May	14-May	27-Jun	27-Jun
Southern States 8302	5-Oct	14-May	19-May	27-Jun	27-Jun
Southern States 8309	5-Oct	12-May	17-May	27-Jun	27-Jun
Vigoro Tribute	5-Oct	8-May	13-May	27-Jun	27-Jun
Vigoro 9713	5-Oct	13-May	18-May	27-Jun	27-Jun
Blackstone 2007					
Southern States 520	24-Oct	25-Apr	30-Apr	26-Jun	26-Jun
Southern States 8302	24-Oct	1-May	6-May	26-Jun	26-Jun
Southern States 8309	24-Oct	1-May	6-May	26-Jun	26-Jun
Vigoro Tribute	24-Oct	26-Apr	1-May	26-Jun	26-Jun
Vigoro 9713	24-Oct	30-Apr	5-May	26-Jun	26-Jun
Blacksburg 2008					
Southern States 520	1-Oct	4-May	9-May	30-Jun	30-Jul
Southern States 8302	1-Oct	8-May	13-May	30-Jun	30-Jul
Southern States 8309	1-Oct	9-May	14-May	30-Jun	30-Jul
Vigoro Tribute	1-Oct	6-May	11-May	30-Jun	30-Jul
Vigoro 9713	1-Oct	9-May	14-May	30-Jun	30-Jul
Warsaw 2008					
Southern States 520	30-Oct	22-Apr	27-Apr	18-Jun	4-Aug
Southern States 8302	30-Oct	24-Apr	29-Apr	18-Jun	4-Aug
Southern States 8309	30-Oct	25-Apr	30-Apr	18-Jun	4-Aug
Vigoro Tribute	30-Oct	23-Apr	28-Apr	18-Jun	4-Aug
Vigoro 9713	30-Oct	25-Apr	30-Apr	18-Jun	4-Aug

Table 2.2. Mean falling number and farinograph measurements by cultivar for samples from Blacksburg and Blackstone, 2007 and Blacksburg and Warsaw, 2008.

	---Southern States 520---				---Southern States 8302---				---Southern States 8309---				-------Vigoro Tribute-------				-------Vigoro 9713-------					
	----2007----		----2008----		----2007----		----2008----		----2007----		----2008----		----2007----		----2008----		----2007----		----2008----			
Parameter	BB[†]	BS[‡]	BB	WR[§]	BB	BS	BB	WR	BB	BS	BB	WR	BB	BS	BB	WR	BB	BS	BB	WR	Mean	LSD
Falling Number, sec	420	463	72	62	379	379	233	222	416	459	236	248	445	467	182	220	423	425	94	65	295	1.8
Water Absorption, %	67	67	62	64	68	67	67	64	63	65	60	58	72	71	67	67	70	68	66	64	66	1.5
Peak Time, min	4	5	2	2	5	4	3	2	5	5	2	2	11	7	2	3	5	4	2	2	4	0.4
Arrival Time, min	2	2	2	2	2	2	2	2	2	2	2	1	7	4	2	2	2	3	2	2	2	0.3
Departure Time, min	12	9	4	4	9	7	5	4	11	8	4	4	19	12	6	5	9	7	5	4	7	0.9
Stability, min	10	7	3	2	7	4	4	3	9	6	3	3	12	8	4	3	7	5	3	2	5	0.9
20-Minute Drop, BU[¶]	60	90	190	220	90	110	230	200	60	90	250	230	20	60	150	190	80	130	200	240	145	21.1

† - BB = Blacksburg

‡ - BS = Blackstone

§ - WR = Warsaw

¶ - Brabender Units

Table 2.3. ANOVA for wheat flour quality parameters across environments and cultivars tested.

	d.f.	Falling Number	Water Absorption	Time Peak	Departure Time	Stability	20-min Drop
Replication	1	-	-	-	-	-	-
Environment	3	**	**	**	**	**	**
Line	4	**	**	**	**	**	**
Environment by Line	12	**	ns	**	**	*	ns

* - indicates significance at the 0.05 level
** - indicates significance at the 0.01 level
ns - no significant difference

Table 2.4. Wheat cultivar effect on flour water absorption and 20-minute drop, average of four site-years.

Line	Water Absorption	20-min Drop
	----%----	--B.U.--
Southern States 520	69.2	128.6
Southern States 8302	66.9	157.5
Southern States 8309	66.4	157.5
Vigoro Tribute	65.1	105.0
Vigoro 9713	61.7	162.5
LSD	1.5	21.2

Table 2.5. Correlation of falling number with wheat quality parameters over cultivars and testing environments.

Quality Parameter	Coefficient of Determination
	-----R^2-----
Water Absorption	0.27
Peak Time	0.55
Arrival Time	0.25
Departure Time	0.56
Stability	0.62
20-Minute Drop	0.71

FIGURES

Figure 2.1. Study locations in 2007 and 2008.

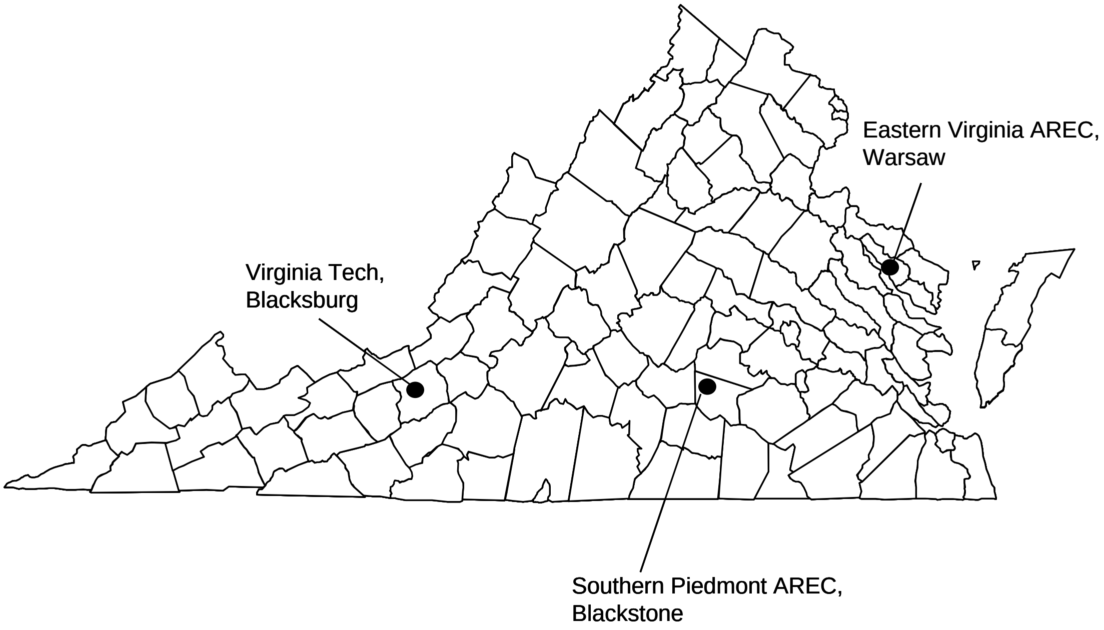


Figure 2.2. Daily rainfall and temperatures from mean heading date to harvest at Blackstone, VA 2007.

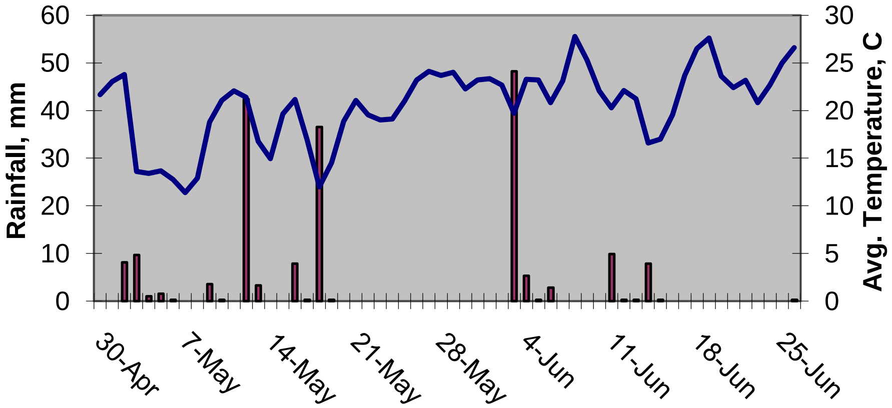


Figure 2.3. Daily rainfall and temperature from mean heading date to harvest at Blacksburg, VA 2007.

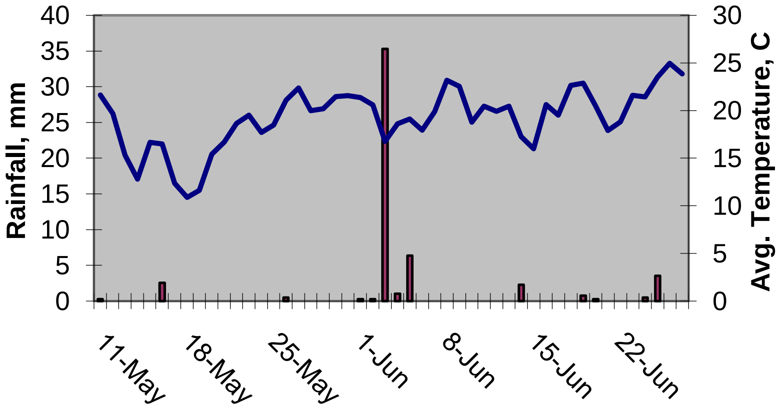


Figure 2.4. Daily rainfall and temperature from mean heading date to harvest at Blacksburg, VA 2008.

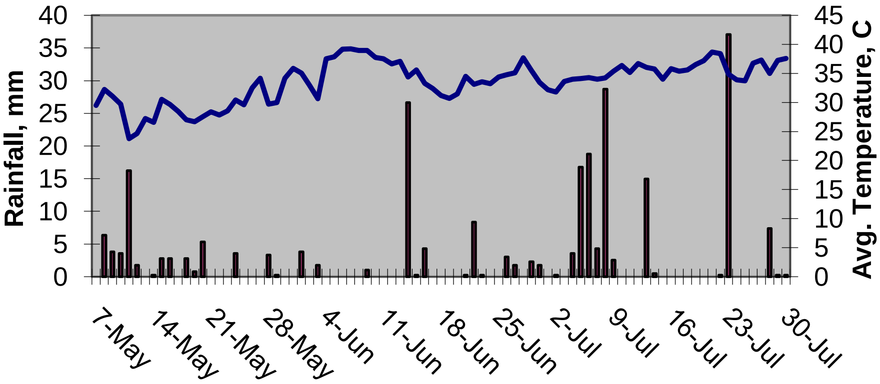


Figure 2.5. Daily rainfall and temperature from mean heading date to harvest at Warsaw, VA 2008.

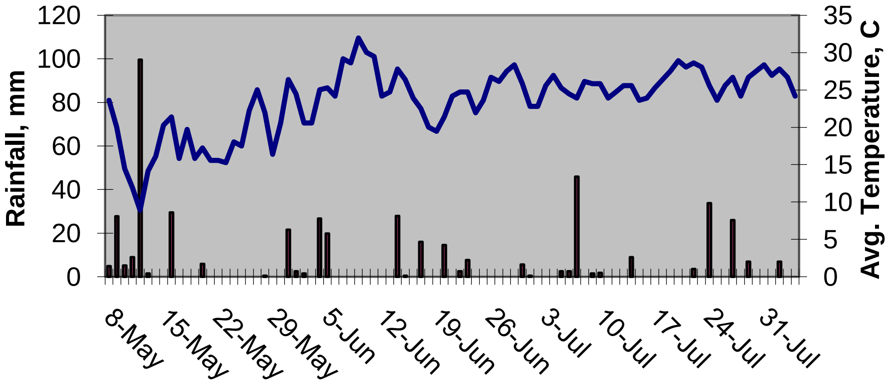
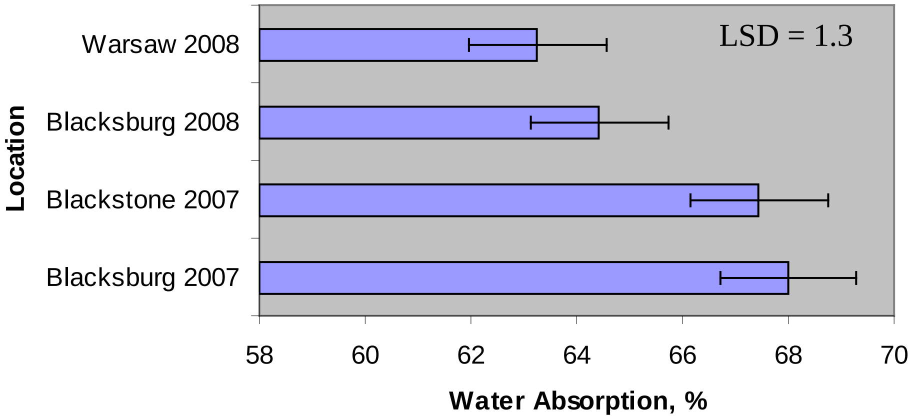


Figure 2.6. Flour water absorption by site-year, averaged over five wheat cultivars, error bars indicates one LSD.



SUMMARY AND CONCLUSION

A large range in dormancy levels across soft red winter wheat cultivars and experimental locations was observed**,** likely due to the lack of historic selection for the dormancy trait. The use of the WGI to estimate PHS resistance of SRWW cultivars can only be reliably applied to cultivars with extremely high or low dormancy. The use of PHS resistance groupings was effective at predicting the response of cultivars to artificial wetting and was also strongly correlated with the WGI averages over locations and years. The large number of low dormancy cultivars indicates that dormancy is a trait that needs to be addressed by wheat breeders in the region. Coker 9553 has been identified as a resource for PHS resistance that may be used to integrate sprout resistance into eastern SRWW cultivars. Spike morphology did not play a significant role in PHS resistance in soft red winter cultivars and cannot be use as a phenotypic trait for breeding for increased resistance to pre-harvest sprouting.

Environment has a significant effect on all quality parameters measured for SRWW flour. As weathering increased from 2007 to 2008, flour quality greatly decreased. One line, Tribute, did not seem to be as adversely affected by weathering as other cultivars in 2008. Overall, mean cultivar falling number values were not highly correlated with flour response to weathering. Genotype had a much greater effect than did falling number. Weathering significantly affected water absorption and 20 minute drop but there was a distinct separation of the sound and sprouted samples by year. Weathered samples had a mean falling number below 200 seconds and sound samples with a mean well above 400 seconds. The extremes in falling number resulted in extremes in flour quality.

Our observed correlation between quality parameters and falling number within harvest year; agrees with previous research that falling number is not a totally inclusive method of quantifying flour performance. The ability to consistently identify cultivars with high and low dormancy will hopefully allow producers to use this information to select cultivars with high dormancy when delayed harvest is a potential problem. Further understanding of the mechanisms governing seed dormancy and characterization of genes that control dormancy in SRWW wheat will facilitate breeding for increased seed dormancy and presumably reduced PHS in SRWW in the future.

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