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Agronomic and Quality Response of Hard Red Spring Wheat Genotypes to Management Systems in South Dakota

Jonathan Kleinjan
South Dakota State University

AGRONOMIC AND QUALITY RESPONSE OF HARD RED SPRING WHEAT GENOTYPES TO MANAGEMENT SYSTEMS IN SOUTH DAKOTA

BY

JONATHAN KLEINJAN

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AGRONOMIC AND QUALITY RESPONSE OF HARD RED SPRING WHEAT GENOTYPES TO MANAGEMENT SYSTEMS IN SOUTH DAKOTA

This dissertation is approved as a creditable and independent investigation by a candidate for the Doctor of Philosophy degree and is acceptable for meeting the dissertation requirements for this degree. Acceptance of this dissertation does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

Dr. Karl D. Glover Date
Thesis Advisor

Dr. David W. Wright Date
Head, Department of Agronomy, Horticulture, and Plant Sciences, South Dakota State University

Dr. Kinchel Doerner Date
Dean, Graduate School, South Dakota State University

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ABSTRACT

AGRONOMIC AND QUALITY RESPONSE OF HARD RED SPRING WHEAT GENOTYPES TO MANAGEMENT SYSTEMS IN SOUTH DAKOTA

JONATHAN KLEINJAN

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Intensive cereals management techniques such as multiple fungicide applications and in-season split N applications have been used to successfully improve wheat yields in Europe and in some winter wheat production areas of the USA. However, research on the effects of these management practices and their interaction with genotypes is limited in the hard red spring wheat (HRSW) production areas of the USA. The objectives of this study were to: (i) compare management treatments and (ii) quantify any interaction effects between management and genotype on the agronomic characteristics and relevant flour and dough properties of locally-adapted HRSW genotypes. A randomized complete block design in a split plot arrangement was implemented with five management treatments as the main plot and sixteen HRSW genotypes as the subplots over four site-years in South Dakota. While management strategies involving delayed N fertilizer application and fungicide application at anthesis seemed to have positive effects on grain yield and grain protein content, confounding environmental factors make these findings inconclusive. No predictable management by genotype interactions were observed for any of the agronomic traits. Differences between management treatments and genotypes alone were much more consistent than interaction effects between management system and genotype. Flour protein, flour yield, Mixograph envelope peak time, and Mixograph envelope peak value were also collected for two replications from each site-year. While management treatment seemed to have an effect on flour yield and flour protein content, effects were inconsistent. There were no management treatment effects on either of the mixing parameters. No management by genotype interaction was observed. Results from this study indicated that, for both agronomic characteristics and quality parameters (i) HRSW genotypes did not respond consistently to intensive management techniques in the rain-fed areas of central South Dakota, and (ii) any genotype by management interaction effects were minimal compared to the main effects of genotype and environment.

CHAPTER 1: LITERATURE REVIEW

I. Introduction

Common wheat (*Triticum aestivum* L.), a cereal grain crop belonging to family Poaceae, is grown in a wide range of environments throughout the world. More land is devoted to wheat production worldwide than any other crop (Briggle and Curtis, 1987) and it is harvested somewhere in the world in every month of the year (Briggle, 1980). In 2016/17, 221.8 million hectares (547.85 million acres) of wheat was harvested worldwide. Total world production in 2016/17 was 750.51 million metric tons (27,573.7 million bushels) with an average worldwide yield of 3.38 metric tons ha^{-1} (50.3 bu a^{-1}). In the same year, the United States produced 62.83 million metric tons of wheat (934.3 million bushels) from total harvested area of 17.75 million hectares (43.8 million acres) with an average yield of 3.54 metric tons ha^{-1} (52.6 bu a^{-1}) (www.fas.usda.gov). US producers received an average price of $3.89 per bushel placing the total value of US wheat production at $8.98 billion (www.ers.usda.gov). The above data represents all classes of wheat produced around the world and within the US including durum wheat (*Triticum durum*). In 2018, the US wheat production ranked fourth highest in the world behind China, India, and Russia (www.fao.org).

In the US, wheat is categorized into eight major classes: hard red winter, hard red spring, soft red winter, soft white, durum, hard white, unclassed, and mixed. The first six classes listed are classified on the basis of growing season, kernel hardness, and color; while 'unclassed' (any variety that cannot be classed under the criteria of the official US wheat standards) and 'mixed' (shipments that contain <90% of one wheat class and >10% of one or more other classes) do not meet these criteria. Hard red spring wheat

(HRSW) is characterized by a spring-sown growing pattern, high grain protein content (GPC) (12.0% - 15.0%), red bran, strong gluten, and high water absorption. It has excellent milling and baking characteristics and, while considered an important bread wheat, is also found in pan breads, hearth breads, rolls, croissants, bagels, hamburger buns, and pizza crusts (Wheat Marketing Center, Kansas State University, 2008). In the US, HRSW production is almost exclusively confined to the upper Great Plains states of Minnesota, Montana, North Dakota, and South Dakota. In 2017, South Dakota harvested 20,770,000 bushels of HRSW from 670,000 acres for a total estimated value of $129.8 million (www.nass.usda.gov). The primary HRSW production areas in South Dakota are the northeast and north central regions of the state. The top producing SD counties in 2017 were Potter, Day, Edmunds, Codington, and Roberts; with reported production of 1.55, 1.37, 1.19, 1.10, and 1.02 million bushels, respectively (www.nass.usda.gov).

II. Production Implications

The world population is expected to reach nearly 10 billion by the year 2050 (www.un.org). The necessity of increased food production and supply to keep pace with population growth is an implication of this eventuality. Wheat, along with maize and rice, provide about three-fourths of the calories and one-half of the protein requirements for the global population (Johnson, 1982). Other than reducing pre- and post-harvest grain losses, the only way to increase wheat supply is to increase production and correspondingly, the only way to increase production is to i) increase cultivated area, or ii) improve production on the area already under cultivation (higher yields) (Briggle and Curtis, 1987). Recent productivity gains have been realized by increasing yields, as the area under cultivation has actually been declining (Carter, 2002). Wheat grain yield

(GY) is comprised of a complex matrix of genetics, environment, and management practices (Ransom, et al., 2007) and achieving higher yields can be accomplished in two ways: i) developing better wheat plants (higher yield potential, better environmental stress tolerance, and improved disease resistance), and ii) using improved agronomic practices (i.e. management) (Briggle and Curtis, 1987). Some scientists believed that a genetic yield plateau was imminent as early as the mid-1980s (Briggle and Curtis, 1987). However, more realistic research indicates that wheat breeders have largely untapped the diverse genome of the wheat plant (Briggle, 1982; Johnson, 1982). This theory has been confirmed by modern research in areas such as marker-assisted selection, gene introgression, plant partitioning, and, photosynthesis; which has the promise to further increase the genetic potential of wheat (Foulkes et al., 2011; Reynolds et al., 2011). In addition to planting cultivars with enhanced genetic potential, to consistently improve wheat yields producers must employ all modern tools available; including new crop management techniques involving fertilizers, herbicides, insecticides, and fungicides. The importance of modern management techniques was noted over a half century ago by Reitz (1967) and continues to be relevant today (Peiretti, 2007).

III. Intensive Management

A. General Management Practices

Wheat yields in the European Union were 50% higher than those achieved in the US in 2017, due in part to differences in climate. However, some of this difference can be attributed to the more intensive management practices utilized in the EU (Beuerlein et al., 1989). As discussed in the previous section, producer-controllable components of yield include genotype, crop management, and their interactions (Ransom et al., 2007). Each of these components can contribute to yield in a variable manner, depending upon environmental conditions. There have been several attempts to separate the contribution of yield gains due to cultivar improvement (genetic gain) from those gains attributed to management practices (Feyerherm et al., 1988; Bell et al., 1995; Duvick and Cassman, 1999). Estimates for the rate of cultivar improvement are obtained by comparing an historic set of cultivars with uniform management on experiment stations at the end of a specific time period (i.e. 15 years). The gain between cultivars in relative terms is compared against the total gain in local producer's yields over the same time period and the difference is assumed to be attributed to management (Feyerherm et al, 1988). Hard red winter wheat (HRWW) yield increases in the Midwestern US have been estimated to be 61%, 27%, and 13% for genetics, applied nitrogen (N), and other sources, respectively for the time period 1954-1984 (Feyerherm et al., 1988). The increases in irrigated Mexican wheat yields in the Yaqui Valley region for the period 1968-1990 were estimated to be attributed to 72% improved management and 28% cultivar improvement (Bell et al., 1995). Approximately 48% of the yield gain due to management could be attributed to the increased use of N fertilizer and the other 24% of the gain could not be attributed to any specific factors. In this study, the incorporation of annual weather variation into the analysis allowed for a more accurate estimate of yield gain partitioning. Both Freyerherm and Bell report that N fertilizer application appears to be the single most effective management practice for yield improvement. Duvick and Cassman (1999) report that 50% of yield increases in dryland maize (*Zea mays* L.) in the US was due to better management and 50% was due to hybrid improvement. The complex myriad of factors affecting yield, including weather, make it difficult to identify management factors other than N application that provide for consistent yield increases.

There have been several attempts to identify the most critical management practices for increasing wheat productivity (Stapper and Fischer, 1990; Hobbs et al., 1998; Ransom et al., 2007; Vigani et al., 2015). In Australia, Stapper and Fischer (1990) found seeding rate, genotype, and seeding date to be the most important factors for increasing yields in irrigated wheat. Hobbs et al. (1998) identified N application, planting date, crop establishment, lodging, and weed control as the most critical practices for raising wheat yields in northern Mexico and the North Indian River Plains in Asia. In eastern North Dakota, Ransom et al. (2007) found that seeding rate and N application timing had no effect on yield while fungicide application at flowering consistently and dramatically increased yields in 2005. Ransom et al. also noted that i) genotype can sometimes be the primary factor impacting yield in intensive management research, and ii) it is often the careful application of a combination of several less obvious management practices that allow some producers to consistently achieve above average yields. A 2015 survey of French and Hungarian producers indicated that crop rotation, use of fertilizers, use of pesticides, and seed quality were all considered to be important management practices (Vigani et al., 2015). In Wisconsin, intensive cereal management (ICM) practices listed by Oplinger et al. (1985) include cultivar selection, split N application, fungicide application, higher seeding rates, narrow row spacing, and plant growth regulators. Management practices pertinent to the treatments used in this study will be discussed in the following paragraphs.

B. Nitrogen

1. Role in Wheat

Nitrogen is often the most limiting nutrient in a non-legume crop production system (Havlin et al., 1999). Nitrogen is an important component of many molecules, including proteins, nucleic acids, hormones, and chlorophyll. All of these molecules play essential roles within the plant and therefore, it should come as no surprise that the symptoms of N deficiency are slow, stunted growth and chlorosis of leaf tissue (Hopkins and Hüner, 2009). Many crops, such as maize and wheat, are considered "heavy feeders" and require large amounts of nitrogen fertilizers. It has been recognized in the literature that Nitrogen Use Efficiency (NUE) averages only 33% for these two crops (Freeman and Raun, 2007). In wheat, N is especially important due to its relation to GPC. Nitrogen is a primary component of protein and thus, the amount available to the plant during the growing season is strongly correlated to GPC. Grain protein content directly affects the nutritional quality of wheat flour, as well as the milling and baking characteristics (Daigger et al., 1976). There is a strong negative correlation between GY and GPC (Kibite and Evans, 1984; Fowler, 2003) and the use of N fertilizers to increase GY can have the unintended consequence of reducing GPC if the application levels are not adequate (Bly and Woodard, 2003). Daigger et al. (1976) reported a 41% loss of applied N following anthesis in winter wheat, most likely due to the emission of ammonium gas and concluded that the GPC of wheat could, in theory, be doubled if the N lost was instead translocated to the grain. Harper et al., 1987 confirmed N losses due to the emission of ammonium gas at senescence. Nitrogen in the grain is primarily the result of translocation from the vegetative portions of the plant (leaves, stem, anthers, etc.) and is influenced by N fertilizer applications (Boatwright and Haas, 1961).

2. Application Rate

Some of the earliest documented work on N fertilization in wheat was performed in England in the mid-1800s. Macy (1936) refers to research performed by Sir J.H. Gilbert (1895) who observed a 57.6% and 124.7% yield increase in a 'poor' and 'good' growing season, the years 1852 and 1863, respectively, with an unreported rate and source of N fertilizer. In the mid-1900s, much of the initial work to determine N recommendations for HRSW in the United States was performed on state agricultural experiment stations and the data from these trials is difficult to locate. In more recent times, there have been numerous other studies examining the effects of N fertilization on the yield and GPC of wheat in the Great Plains region of the United States and Canada. Much of this research has been conducted on HRWW but there are also a few studies involving HRSW. McNeal and Davis (1954) observed an average GY increase of 67.2% and 114.2% over the 0 N control when applying 50 lb a^{-1} and 100 lb a^{-1} of N, respectively to nine HRSW cultivars near Bozeman, MT. This study also noted that (i) earlier forming kernels were highest in GPC and (ii) the 50 lb a^{-1} N treatment invariably lowered GPC below that of the control treatment. As mentioned previously, in low soil N environments at lower N fertilizer application rates, the amount of N available to the wheat plant is often not adequate to support both increased GY and increased GPC. In Saskatchewan, Fowler et al. (1998) noted an 86.3% increase in average GY over the 0 N control for five HRSW cultivars when applying 134 lb a^{-1} of N. In the same study, the average GPC of the five cultivars ranged from 11.8% to 14.2% for the N rates of 0 and 214 lb a^{-1}, respectively. The GPC dropped from 11.8% to 11.0% as the N rate increased from 0 to 45 lb a^{-1}, while yields increased approximately 45% over the same range, almost exactly mirroring the earlier observations of McNeal and Davis. Bly et al. (2000; 2001; 2002) examined the effects of four N rates (0, 75, 150, & 225 lb a^{-1}) on two HRSW cultivars over three seasons in east-central South Dakota. Grain yield was increased by 34%, 9%, and 43% over the 0 N control treatment when applying 75 lb a^{-1} N for the years 2000, 2001, and 2002, respectively. Yields were not significantly increased by the higher 150 lb a^{-1} and 225 lb a^{-1} application rates. It should be noted that when the response levels were low (in 2001), initial soil N measurements were very high, at 145 lbs a^{-1} in the 0-24” profile. Grain protein content tended to increase at a near linear rate with N application rates over the three years of the study. Unlike the previously discussed studies, Bly et al. did not see a drop in GPC at low rates of N application. Most likely initial soil N levels were adequate to accommodate the increased vegetative and yield growth at the 75 lb a^{-1} ‘low’ rate without sacrificing GPC. In west-central Minnesota, Farmaha et al. (2015) examined the impact of nitrogen fertility on GY and grain nitrogen content (GN) in four cultivars of HRSW over three years. Grain nitrogen content in HRSW can be directly converted into GPC by multiplying by 5.7 or 5.75 (Dreccer et al., 2000). This study examined four N application rates: 0, 60, 120, and 180 lbs a^{-1}. Grain yield increased 4.4% from 60 to 120 lb $a-^{1}$ and another 8.5% from 120 to 180 lb a^{-1}.

Yields for the 0 N control treatment were not reported. Grain protein content (calculated from GN) increased from 13.2% to 14.8% from the 60 to 120 lb a^{-1} treatment but did not increase further from 120 to 180 lb a^{-1} treament.

3. Application Timing

It has been demonstrated that HRSW can respond to not only rate, but the timing of application of N fertilizer relative to plant development (Mossedaq and Smith, 1994). Generally, applications of fertilizer at planting or early in the growing season maximize GY and later applications enhance GPC (Fowler and Brydon, 1989). In theory, a split application, or "spoon-feeding" the wheat plant N throughout the season as crop needs dictate should allow for increased NUE (Otteson et al., 2008). In many cases, however, a single application of N prior to planting is the most economically viable alternative for producers. The relationship between N application timing and tiller formation has been examined by several researchers. A tiller is a stem or shoot produced after the initial parent shoot grows from the wheat seed. In HRSW, tiller formation can be affected by the rate and timing of N and can be enhanced when N is applied before planting or during the tillering process (Strong, 1986). Opinions vary as to whether or not more tillers are beneficial to GY. More tillers can result in more heads at harvest, although most research has shown that, regardless of the number of tillers produced, 85-100% of HRSW grain yield is produced by the main stem and the T1 and T2 tillers (McMaster et al., 1994; Goos and Johnson 2001; Otteson et al., 2008). Ransom et al. (2007) state "It has been hypothesized that, by delaying the N application until tillering has ceased combined with a higher seeding rate, there will be more main stems, greater yield potential, and more uniformity in the flowering of the spikes".

Several studies have examined the direct effects of N fertilization timing on GY and GPC in HRSW. While early season applications tended to maximize GY, late season applications still provided some yield benefit, confirming earlier work which indicates the necessity for adequate N nutrition during late development stages (Morris and Paulsen, 1985). While it is common to apply all N prior to planting, slightly later applications may actually increase GY. In Argentina, Melaj et al. (2003) documented a yield increase of 7.7% across tillage regimes when 107 lb a^{-1} N was applied at Zadoks growth stage 21 (GS 21; beginning of tiller formation) (Zadoks et al., 1974) versus at planting. Hobbs et al. (1998) cite Chinese scientists that recommend delaying N application until GS 31 (first node detectable) to reduce luxury biomass production and strengthen stems without sacrificing yield. Research in Morocco conducted by Mossedaq and Smith (1994) showed that N fertilizer application consistently increased GY compared to the 0 N control treatment when applied at various combinations to three different growth stages: GS 20 (floral initiation), GS 30 (the onset of stem elongation), and at GS 60 (anthesis). However, a two-way split at GS 20 and GS 30 resulted in the greatest GY increase, providing a 20% increase over a two-way split between GS 30 and GS 60, and a 13.3% increase over a three-way split between all growth stages. They concluded that N demand in wheat is highest just prior to GS 30, when plant growth is most rapid. This confirms earlier work by Darwinkel (1983) who noted that GS 30 to GS 60 is the period of greatest demand for N in wheat due to rapid leaf expansion, stem growth, and head development.

Other research has shown no GY response to application timing. In three of four site-years, Subedi et al. (2007) noted that GY of wheat tended to be higher when a high rate of N was applied entirely preplant. However, treatment differences were only significant in one of those site-years. Treatments consisted of a 0 N check, a low rate (54 lb a^{-1}) and high rate (90 lb a-^{1}) preplant, and a 60:40 split high rate applied i) preplant and top-dressed at GS 40 (boot stage), and ii) preplant and foliar at GS 40. Grain protein content was directly related to N rate, but only responded significantly to late season N application (i.e. GS 40) in one of the four site-years. The GPC of the 0 N control treatment was consistently the lowest over the entire study. Otteson, etal. (2007) examined three N timings at various yield-based N rates in North Dakota over five site-years. The treatments were i) preplant, ii) a two-way split: preplant and GS 15 (five-leaf stage), and iii) a three-way split: preplant, GS 15, and GS 69 (post-anthesis). Otteson did not see any consistent GY response to application timing and noted applying all required N preplant frequently produced the highest yields. Grain protein content was highest for the three-way split application in three of the five site-years, equal to other treatments in one site-year, and lowest in the final site-year. The results of this study seem to confirm that late season N applications tend to increase GPC rather than GY. Other studies have shown that foliar application of N following GS 60 can be used as a way to increase NUE and GPC in wheat, especially when goals for GY are surpassed (Schatz et al., 1991; Bly and Woodard, 2003). It is important to note that environment often plays a large role in the response of both GY and GPC to N fertilization timing.

4. Effects on Wheat Quality

Wheat quality is often significantly affected by N rate and timing. Hard red spring wheat is used primarily in bread manufacture and desirable characteristics include high protein and strong gluten (Souza et al., 2002). Bread quality traits have been found to be highly related to GPC (Peterson et al., 1992; Lang et al., 1998) but until the 1970s, the relationship between N management and the milling and baking qualities of HRSW were not fully understood. McNeal et al. (1971) showed that applications of N significantly increased GPC and there was a corresponding increase in bread loaf volume and texture scores. Baking absorption and mixing time decreased as N application rates increased. However, Souza et al. (2004) reported that N application levels were rarely important for end use quality, noting that environment and genotype tended to have a much more influential impact. Otteson et al. (2008) also noted the importance of genotype but found that applying N in a three-way split throughout the season increased baking absorption and Mixograph scores and decreased mixing time when compared to applying all N preplant. All N treatments increased GPC and bread loaf volume while reducing flour extraction. Nitrogen management for increased GPC can have a positive effect on bread quality parameters although other factors such as genotype and environment generally have a larger impact.

C. Fungicide

1. Prevalent Diseases in South Dakota.

Several diseases can have a detrimental effect on the production of HRSW. Modern production practices often combine higher rates of N fertilizer with cultivars resistant to stem rust (*Puccinia graminis* Pers. f. sp. *tritici* Eriks. and Henn.) and leaf rust (*Puccinia triticina* Eriks.). These practices, along with others listed previously, often result in a wheat crop with lush green foliage that presents the perfect habitat for infection by not only rusts but other foliar pathogens such as tan spot [caused by *Pyrenophora tritici-repentis* (Died.) Drechs.], septoria nodum blotch [caused *by*

Phaeosphaeria nodorum (Muller) Hedja.], and fusarium head blight (FHB) [caused by *Gibberella zeae* Schw. Petch] (Stover et al., 1996). In South Dakota, the most common fungal diseases in HRSW are FHB in the eastern/central portion of the state and leaf rust in the central/western portion (Glover, 2018). FHB may cause direct reductions in yield and test weight, and further price discounting due to the presence of *Fusarium spp*. damaged kernels and the associated mycotoxin, deoxynivalenol (Jones, 2000). In the early 1990s, HRSW was affected more than other wheat classes in the United States, with production losses of up to 52% (Sayler, 1998). Humid climates tend to have higher incidences of FHB because prolonged wet periods during flowering are conducive to infection, which primarily begins on the extruded anthers (Cunfer, 1987). Leaf rust usually does not cause ‘spectacular’ damage but it probably causes more total loss than all other wheat rusts due to its broad climatic adaptation (Samborski, 1985). Wheat cultivars that are susceptible to leaf rust typically suffer yield reductions of 7-30%, depending on growth stage at the time of onset. Losses are due to the reduction in photosynthetic capacity which primarily causes a reduction in kernel weight (Huerta-Espino et al., 2011). Producers have been advised to use resistant cultivars as the first line of defense in fighting disease, as it is often considered the most economical means of disease control (Weirsma and Motteberg, 2005; Huerta-Espino et al., 2011). However, to most consistently reduce the effects of pathogens, it seems more prudent to use a balanced approach of cultural practices, cultivar selection, and chemical control (Jones, 2000; Ransom et al., 2007).

2. Chemical Disease Control.

The interest in effective and economical chemical control for wheat pathogens, specifically rusts, began in the United States during the 1950's due to multiple epidemics of stem rust (Rowell, 1985). The use of systemic fungicides for wheat diseases in the United States was very sporadic into the 1980s (Bissonnette et al., 1969; Rowell, 1985), while at the same time considered commonplace in Great Britain and Western Europe (Jenkins and Lescar, 1980). Delayed fungicide adoption in the US may have been, in part, due to the lack of economic returns to application (Buchenau, 1970). An outbreak of FHB in 1993 spurred renewed interest in using fungicide to protect HRSW production and usage has been on the rise since then (Weirsma and Mottenberg, 2005). There are several different active ingredients, or chemical families, providing some level of disease suppression or control (Byamukama et al., 2017). Historically, two of the most common are triazoles and strobilurins (Gooding, 2007). Triazoles inhibit the synthesis of ergosterol, which is the main fungal sterol; and strobilurins inhibit mitochondrial respiration. Wheat fungicides can be considered a protectant, where activity is limited to the site of pathogen infection, and systemic, where the active ingredient is active throughout the plant (Waller, 1985). Protectants must be applied prior to infection and repeatedly re-applied throughout the growing season to be effective while systemics have a greater period of efficacy and some 'curative' effects (Fry, 1982; Rowell, 1985). Fungicides vary in efficacy against specific pathogens and it is therefore recommended to use either a combination of active ingredients or an active ingredient with broad-spectrum control (Doll et al., 1988; Byamukama et al., 2017). There is some debate on whether the beneficial effects of fungicides are the result of i) recognized pathogen control (Ruske et al., 2003), ii) minor or unrecognized pathogen control (Bertelsen et al., 2001), or iii) direct physiological effects on the wheat plant (Grossman and Retzlaff, 1997). Observed yield improvements have been attributed to extended life of the flag leaf (Gooding, et al., 2000) and possibly physiological alterations such as the inhibition of ethylene formation and increased cytokinin levels (Grossman and Retzlaff, 1997).

3. Application Timing and Yield Response

In the Midwestern United States, several diseases have been suppressed and wheat yields increased by fungicide applications (Guy et al., 1989; Jones, 2000; Sweeney et al., 2000; Weirsma and Motteberg, 2005; Ransom et al., 2007). An application of fungicide at GS 37-39 (full extension) is generally considered appropriate for leaf rust and other foliar disease control (Byamukama et al., 2017). The basic principle of foliar disease control is keeping the flag leaf disease-free, as it provides more photosynthetic activity for grain-fill than any other leaf (Lupton, 1972). In Wisconsin, Guy et al. (1989) observed foliar disease reduction of up to 78% and yield increases from 9.5 to 36.3 bu/acre for several fungicide combinations on three HRWW cultivars in a cool, moist environment (conducive to disease development). Other environments with warmer and drier conditions also saw slight disease reductions and, in some cases, GY improvement. Sweeney et al. (2000) report a reduction of leaf rust severity from 49% to 29% on the flag leaf of two HRWW cultivars (resistant and susceptible to leaf rust) when applying propiconazole at GS 37-39, but the reduction was more pronounced in the susceptible cultivar. Grain yields averaged 71.4 bu a^{-1} for both cultivars when treated with fungicide, and 61.0 bu a^{-1} and 68.4 bu a^{-1} for untreated susceptible and resistant cultivars, respectively.

Findings by Wiersma and Motteberg (2005) contradict the timing recommendation of GS 39 for foliar leaf disease control. They report that an application at GS 60 tended to provide the best control of leaf-spot diseases and greatest improvement in grain yield and grain quality. Conditions were not conducive for leaf rust development in this study, so the pathogen-specific effects of fungicide timing were not quantified. The average grain yield increase for all fungicide applications was 11%, 31%, and 16% across eight HRSW cultivars in 2001, 2002, and 2003, respectively. They do note, however, that in some years leaf pathogens develop early and an early application of fungicide at GS 15 combined with a second application at GS 60 provides better disease control than a single application at GS 60.

The optimum fungicide application timing for suppressing FHB is reported to be GS 60 (Halley et al., 2001; Wiersma and Motteberg, 2005). Jones (2000) discusses unpublished trial results where he observed 18% fewer Fusarium spp.-damaged heads and 9.4% fewer Fusarium spp.-damaged kernels in three HRSW cultivars sprayed with mancozeb at GS 59 (100% of head visible) compared with earlier treatments (GS 30 or GS 37) or those not treated with fungicide. Treatments receiving applications at GS 59 showed a 6.1 bu a^{-1} yield increase. In the same paper, Jones reports yield response of 1.0 to 12.7 bu a^{-1} for four types of fungicides (benomyl, iprodione, mancozeb, and tebuconazole) applied to seven HRSW cultivars at GS 59 or a combination of GS 59 and GS 73 (early milk stage). Three of the four fungicides produced GY significantly higher than the non-treated control and the highest yields always occurred with a double treatment at GS 59 and GS 73. If the non-effective fungicide (iprodione) is omitted from the analysis, the average yield increase due to fungicide was 9.2 bu a^{-1}. Ransom, et al.

(2007) noted that fungicide significantly reduced FHB severity and greatly increased grain yields for HRSW in North Dakota in 2005. The average yield increase observed for twenty-seven HRSW cultivars was 13.4 bu a^{-1}. In Kansas, Kelley (2001) reports that grain yield and test weight responses to foliar fungicide depended on a combination of disease severity, cultivar resistance, and environmental conditions, but a significant yield increase occurred 77% of the time in HRWW and soft red winter wheat (SRWW) cultivars. Grain protein content, head density, and kernels per head were not affected by foliar fungicide applications.

4. Effects on Wheat Quality

There have been numerous studies documenting the effects on grain quality due to fungicide applications. Such studies either focus on i) the implications of improved plant health on grain quality (Herrman et al., 1996; Puppala et al., 1998; Blandino and Reyneri, 2008) or ii) the direct influences of fungicide on the wheat plant (Saunders and Salmon, 2000; Ruske et al., 2004; Wang et al., 2004).

Reduction in disease resulting from fungicide application often improves the physical qualities of wheat grain because the grain-fill period is maintained (Dimmock and Gooding, 2002) and the translocation of nitrogen into the kernels can be sustained (Hermann et al., 1996). Blandino and Reyneri (2008) observed significant reductions in FHB symptoms but no differences in test weight, GPC, or dough extensibility when applying a triazole to ‘Bologna’ HRWW at GS 60. The lack of response could be due to relatively low levels of disease, as Dexter et al. (1996) reports that FHB infected wheat in Manitoba in 1994 exhibited poor flour color, weak dough properties, and unsatisfactory bread quality. However, data shows that FHB levels of up to 3% do not affect baking quality in American HRWW (Seitz et al., 1986).

Leaf rust and other foliar diseases may have effects on quality that are easier to quantify. In a Kansas study of the HRWW cultivar ‘Karl’, Hermann et al. (1996) observed that fungicide treated plots had higher GPC, flour protein, single kernel size, single kernel weight, and flour absorption when compared to control plots with high incidence of leaf rust. There were no significant differences in mixing time, flour yield, or test weight. However, a 1995 study, also in Kansas involving twelve HRWW cultivars showed increases in test weight and single kernel weight but no consistent changes in kernel protein, flour extraction, flour absorption, or mixing time; as much of the quality response to fungicide was cultivar specific (Puppala et al., 1998).

Saunders and Salman (2000) found no clear differences in breadmaking quality between fungicide treatments for any of three wheat varieties. There was also no overall significant treatment effect on the microbiological condition of grain samples. In England, field experiments on ‘Malacca’ winter wheat showed increased yields, decreased GPC, Hagberg falling number, sulphur concentration, and loaf volume as the amount of fungicide applied increased. However, there were no deleterious effects of fungicide application on sodium dodecyl sulphate (SDS) sedimentation volumes, N:S ratios, or dough rheology. Effects on breadmaking quality were not product specific (Ruske et al., 2004). Wang et al. (2004) found similar results over three wheat cultivars in Germany, where they applied five fungicide products in four different combinations and observed lower falling numbers, crude protein content, water absorption, protease activity, viscosity, and free amino acid content in fungicide-treated grains. None of the fungicides caused any differences in dough properties or breadmaking qualities versus the untreated controls.

D. Insecticide

1. Prevalent Early Season Insect Pests in South Dakota

While there are several insect species capable of impacting production in SD spring wheat fields, the most prevalent found early in the growing season have been bird cherry oat aphid (*Rhopalosiphum padi*), and English grain aphid (*Sitobion avenae*) (Varenhorst, 2017). The aphids do not overwinter in the state and migrate in from the south (Varenhorst and Chirumamilla, 2015). In spring wheat, most early-season damage is caused by direct feeding on foliage (Szczepaniec, 2013). The early season threshold for chemical application is 5-10% damaged and infested tillers or 20 and 30 bird cherry oat and English grain aphids per stem, respectively (Hein and Thomas, 2006). However, in most seasons, aphid populations in the region are very low, slow to develop, or are simply controlled by a natural event such as a late frost (MacRae, 2018).

2. Chemical Control

A common insecticide used to treat these insects is cyfluthrin, belonging to the pyrethroid chemical family, which are a sodium channel inhibitors (Hein and Thomas, 2006; Varenhorst, et al., 2016). Trade names for these chemicals include Baythroid XL®, Baythroid 2EC® (Bayer CropScience), Tombstone®, and Tombstone Helios® (Loveland Products) (Varenhorst and Wagner, 2018). In Idaho, Johnston and Bishop (1987) noted that Baythroid 2EC® provided initial and residual aphid control at a rate of 0.125 lb AI/acre on spring wheat when applied at the end of flowering. Control plots in this study were kept aphid-free with a series of insecticide applications throughout the growing season and, although yields tended to be higher in the aphid-free plots, differences were not significant. Experiment station trials conducted in Minot, ND observed a general reduction in aphid populations when plots were treated with Baythroid XL®, but the reductions were not significant (Waldstein, 2010; Waldstein and Pederson, 2010). In eastern ND, over four site-years, Chyle (2012) observed a 1.5 bu a^{-1} increase in spring wheat yields when adding 0.125 lb AI a^{-1} of Baythroid XL® to an application of fungicide at GS 29, despite a lack of insect pressure. The author speculated that yield increases may have been due to the suppression of barley yellow dwarf virus (BYDV) but did not actually perform assessments of disease pressure. Another possibility is a positive synergistic effect on fungicide efficacy caused by the addition of the insecticide. In some cases, synergistic effects between fungicide and insecticide products, specifically, pyrethroids, have been noted to increase the toxicity of insecticides (Colin and Belzunces, 1992). However, similar studies have noted negligible increases in the level of fungicide toxicity (Pilling and Jepson, 1993). Yield increases in an insect-free environment is most likely the result of a beneficial prophylactic effect for insecticide on spring wheat, rather than a synergistic increase in fungicide efficacy.

3. Effects on Wheat Quality

Chyle (2012) found no treatment effect for insecticide on grain protein content and other grain quality parameters were not measured. Literature on the relationship between insecticide treatment and grain quality is generally limited to improved plant health and resulting grain quality improvements, rather than any overall plant physiological effects induced by insecticide applications.

E. Chloride

1. Role in the Plant

Chloride is often used interchangeably with 'chlorine' in literature. It must be noted, however, that chloride (Cl^-) is the anion form of the chemical element chlorine (Cl). Chloride salts are formed either by the reaction of hydrochloric acid (HCl) with an inorganic base, metal, or metal oxide or from the direct union of chlorine gas with metals (Tebbutt, 1998). Some of the earliest documented research involving chloride examined the use of table salt (NaCl) as a fertilizer in the mid-1800's (Fixen, 1993). Tottingham (1919) noted that NaCl applications in barley seemed to have a positive effect and concluded that chloride was the active element. Lipman (1938), while studying the effects of chlorine on buckwheat, stated that "if chlorine is not essential, it is certainly highly beneficial." Several other studies in the first half of the 20^{th} century have documented the beneficial effects of chlorine (and thus, chloride) in plant development (Broyer et al. 1954).

The chloride ion (Cl^-) is absorbed into plants through both root and leaf tissue (Havlin et al., 1999). While Cl^- is not present in any true metabolites in higher plants, it does provide an essential role in plant development and osmoregulation (Broyer et al., 1954; Havlin et al., 1999). The biochemical inertness of Cl^- allows it to balance the charge within plant cell membranes, which is important to chemical and physiological processes affecting factors such as leaf turgor and pH (Broadley et al., 2012). The regulation of guard cells, which cause stomata to open and close, is directly related to leaf turgor reactions relating to the concentrations of K^+, Cl^-, and malate (Maas, 1986). Leaf orientation is also controlled by turgor changes in motor cells (Satter and Galston, 1981), which seem to utilize the same mechanism as guard cells (Fixen, 1993). Taylor and Jackson (1980) noted that Cl- treatment can indeed affect wheat leaf orientation in test plots. It is also necessary for oxygen production as a component of the water-splitting reaction in photosynthesis (Izawa et al., 1969; Clarke and Eaton-Rye, 2000) and may be required for cell division in leaves and roots (Harling et al., 1997). The importance of Cl^- in photosynthesis has been confirmed by Terry (1977) and Robinson and Downton (1984). Both authors reported a large reduction in sugar beet and spinach growth, respectively, in Cl^- deficient conditions without a significant reduction in Cl^- concentrations measured in the chloroplasts. This suggests that plants prioritize available Cl^- for usage in the chloroplasts and that deficiency levels in the plant are set by processes other than photosynthesis, such as cell multiplication (Terry, 1977; Fixen, 1993).

Most soil Cl^- is most commonly found in the form of soluble salts (NaCl, $CaCl_2$, $MgCl_2$) and the quantity varies widely in a range of 0.5 ppm or less to 6,000 ppm or more. The majority of soil Cl^- has been in the oceans at some point in time and annual depositions of Cl^- from precipitation events are commonplace (Havlin et al., 1999). Due to the fact that the biochemical requirements of plants are less than 100 ppm, Cl^- is classified as a micronutrient. Despite this classification, Cl^- is often present in plant tissues at levels of 2,000 – 20,000 ppm (Fixen, 1993). Low nutrient requirement combined with relatively ample amounts in the soil has historically made it difficult to identify Cl^- deficiencies in plants, especially in arid environments where reduced infiltration rates can lead to relatively high concentrations in the root zone (Graham et al., 2017).

Although the potential benefits to crop production were first recognized as early as the mid-1800s, and confirmed in the early 1900s, the ubiquitous nature of Cl^- in the environment led the scientific community to believe that field crops would not benefit from Cl^- fertilization (Deliopoulos et al., 2010). Extensive studies involving the role of chloride in crop performance and, correspondingly, plant physiology, did not begin until a number of field studies the 1970s demonstrated the positive effects of Cl^- fertilization. Subsequent research involving Cl^- and crop production has primarily focused on two aspects: (i) the role of Cl^- in disease suppression, and, (ii) the effects of insufficient Cl^- levels on plant development (Fixen, 1993).

2. Disease Suppression

Although the mechanisms of interaction between plant pathogens and Cl^- are not completely understood, the effects have been well documented. It has been generally accepted that nutrients such as Cl^- reduce the effects of plant disease by (i) enhancing plant host tolerance, (ii) providing direct suppression of plant pathogens, and, (iii) altering the environment to make conditions less favorable for disease survival or infection (Huber and Wilhelm, 1980). Examples supporting each of these modes of action are listed in the following paragraph.

Cl^- induced suppression in HRSW has been reported for at least four diseases: common root rot [likely caused by *Cochliobolus sativus* or *Fusarium spp.*](Fernandez and Jefferson, 2004), tan spot, leaf rust, and septoria (*Septoria spp.*) (Fixen, et al., 1987). Field studies conducted in South Dakota showed that Cl^- applications resulted in the reduction of leaf rust, tan spot, and septoria on HRSW (Buchenau et al., 1988). A subsequent growth chamber study showed the application of Cl^- resulted in dramatic reductions of disease incidence and severity on five HRSW cultivars inoculated with leaf rust. The authors postulated that Cl^- appeared to affect the phenotypic expression of resistance genes (Rizvi et al., 1988). Deliopoulos et al. (2010) identified six inorganic Cl- salts that have been used to suppress fungal disease in wheat, although they should not be considered as a fungicide replacement as they are generally less effective. Mann et al. (1994) used a foliar application of KCl to suppress Septoria and powdery mildew in HRWW, suggesting that control was possibly the result of salt-induced negative osmotic effects on spore germination. The authors concluded that the mode of action for KCl is contact and that it is both protective and curative. Studies involving soil-applied KCl have shown some levels of disease suppression, however, authors note that the magnitude of disease control is often not of practical value (Deliopoulos et al., 2010). Christensen et al. (1990) hypothesize that Cl^- acts as a nitrification inhibitor, causing the plant to uptake NH_4 rather than NO_3^-, which in turn lowers the pH in the root zone. This lower pH may offer a competitive advantage to microorganisms that help to reduce the incidence and severity of diseases such as take-all root rot in HRWW.

3. Yield Response in Wheat

Heckman (2006) theorizes that any crop performance benefits due to Cl^- fertilization are most likely the result of disease suppression, rather than enhanced Cl^- nutrition. However, other researchers have noted that Cl^- fertilization increased wheat grain or forage yield without any noticeable effect on disease suppression (Fixen et al., 1987; Windels et al., 1992; Engel, et al., 1994). In South Dakota, Fixen et al. (1987) studied the influence of soil Cl^- concentrations on several HRSW parameters, including the diseases common root rot, leaf rust, and leaf spot. Yield increases were observed at testing sites both with and without discernable disease pressure. Studies of this type suggest the mechanisms for improving crop production due to Cl^- are more complex than disease suppression alone. This study also measured leaf relative water content at two testing sites. Both sites exhibited a significant increase in leaf water content due to Cl^- fertilization, suggesting potential effects on plant-water relations. This complements earlier research done by Christensen et al., (1985) and Powelson et al., (1985); who both noted Cl^- effects on water potential in wheat. Chloride also seems to have a positive effect on plant physiological development. Schumacher et al. (1990) saw consistently earlier anthesis in two varieties of HRSW in South Dakota when treated with KCl. Application of KNO_3 had no effect on plant development. Physiological maturity was not affected, leading to a slightly longer grain-fill period, which resulted in a 4% increase in kernel weights. Prior research on HRSW in South Dakota had shown kernel weight increases of up to 14% (Cholick et al, 1986). Environmental conditions such as temperature, moisture, and the timing of weather events can be critical to crop responses to Cl^- and may have a large impact on yield response (Fixen, 1993).

In general, yield responses in the Great Plains area of the United States have been less than those documented in the Pacific Northwest. A summary of several studies performed in the Pacific Northwest in early 1980s showed grain yield increases ranging from 7-32 bu a^{-1} with an average of 16 bu a^{-1} (Fixen, 1993). In contrast, a research summary compiled by Engel et al. (1992) showed that wheat and barley yield performance in Great Plains was significantly increased 42% of the time in 169 episodes, with an average response (over all studies) of 1.7 bu a^{-1}. Trials with significant responses showed an average yield increase of 4.5 a^{-1}. It is important to note that these studies included both non-responsive cultivars and testing sites with high levels of soil Cl^-. Later research, conducted by Graham et al. (2017) examined three HRSW cultivars over five seasons in eastern South Dakota. Response to Cl^- was significant for two of the three cultivars, and varied from 1-4 bu a^{-1}, with an overall average response of 2.5 a^{-1}. Yield responses observed in Saskatchewan, CA, have been largely similar to those of the Great Pains, with an average yield response in HRSW of 2.9 bu a^{-1} (Wang, 1987).

4. Effects on Wheat Quality

Research examining the effects of Cl^- on wheat grain quality have concentrated mainly on kernel weight, kernel plumpness, and test weight (Cholick et al., 1996; Engel et al., 1992; Mohr, 1992; Schumacher, 1990; Windels et al., 1992). In some studies, effects on quality parameters, such as kernel weight, were more evident than effects on final yield. Graham et al. (2017) found no discernable effects on test weight or protein content in HRSW. It has been observed in South Dakota that Cl^- application can reduce late-season lodging in HRSW (Fixen, 1993). Reduced lodging, when combined with the crop physiological effects and disease suppression characteristics discussed previously, may provide mechanisms of grain quality improvement. Literature involving the relationship between Cl^- treatments and more intensive wheat quality parameters such as mixing properties, dough rheology, or baking qualities is almost entirely absent.

F. Genotype by Management

1. Cultivar Response to Management Practices

Genotype by crop management interactions have been found to be significant and can complicate analysis of both the genetic yield potential of crops and the effects of various management practices on this genetic yield potential (Beuerlein et al., 1989; Guy et al., 1989; Harms et al., 1989; Ransom, et al., 2007). However, there have been studies involving individual management practices that resulted in little or no interaction effects. Investigations of the interaction of cultivar with seeding rate (Geleta et al., 2002; Gooding et al., 2002) and cultivar with nitrogen (Ma et al., 2004; Souza et al., 2004) did not find significant interaction effects between genotype and management. Studies examining fungicide and cultivar have found there to be varying interaction effects (Puppala et al., 1998; Varga et al., 2005; Koch et al., 2006). Koch et al. (2006) found that an application of tebuconazole significantly reduced DON concentrations in a cultivar rated as highly susceptible to FHB versus providing only slight reductions in a moderately resistant cultivar. However, here was no significant fungicide by cultivar effect on GY. Puppala et al. (1998) found that cultivar by fungicide interaction significantly affected test weight, kernel protein, and flour absorption but there was no effect on GY. The authors note that by substituting cultivar disease resistance ratings for the cultivar selections themselves, i.e. grouping cultivars by disease resistance, there was a significant cultivar group by fungicide interaction effect on GY. This confirms the theory that cultivar yield response to fungicide application is often partially dependent upon the inherent disease resistance of the cultivar combined with disease pressure (Kelley, 1993). Varga et al. (2005) found that cultivars differed in their response to fungicide applications across N fertilization rates. Some susceptible cultivars showed greater increases in GY versus resistant cultivars when treated with both high N rates and fungicide versus untreated control treatments. Cultivar also appears to have an effect on the magnitude of response to Cl^- fertilization. Average responses to Cl^- over five site-years for three hard red HRSW cultivars in South Dakota were 6.1, 4.9, and 0.1 bu a^{-1} for

'Butte', 'Marshall', and 'Guard', respectively (Fixen, 1987). Guard also showed minimal plant physiological response in Shumacher, et al. (1990). A similar lack of response was noted for the hard red HRSW variety 'Katepwa' during a study of four HRSW cultivars in Manitoba (Mohr, 1992).

2. Cultivar Response to Intensive Management Systems

There have been several attempts to investigate the effect of complete management systems on the magnitude of cultivar yield response (Beuerlein et al., 1989; Guy et al., 1989; Khan and Spilde, 1992; Ransom et al., 2007). Beuerlein et al. (1989) examined the effects of an Intensive Cereal Management (ICM) program (involving seeding rate, N management, and fungicide and growth regulator applications) on nine HRWW cultivars in the Great Lakes region of the US. To evaluate the cultivar by management interaction, the cultivars were split into four groups: 1) lodging prone, 2) lodging resistant, 3) leaf rust susceptible, and 40 leaf rust resistant. Lodging groups had a differing yield response to seeding rate, nitrogen rates, and fungicide application. Plant growth regulators provided a greater yield increase in the lodging-prone group versus the lodging resistant when all other intensive inputs were applied. In a comparison of low and high-input management systems for three soft white wheat and one HRWW cultivars in Idaho, Guy et al. (1989) noted significant cultivar by management GY and GPC effects in 1991 at one location, but there were no significant interaction effects at either of two locations in 1992. Under most circumstances, the low-input management system gave the best overall agronomic performance over environments and cultivars. In the upper Great Plains, Kahn and Spilde (1992) examined the effects of ICM on twelve HRSW lines in four site-years. They found a significant GY decrease due to ICM for five of the

12 cultivars with no response in the remaining seven. The results of this study suggest that ICM practices employed in more marginal production conditions, such as limited moisture and high temperatures, are in fact detrimental. In North Dakota, Ransom et al. (2007) examined twenty-seven HRSW cultivars under varying intensive management programs in 2004-2005. The top five yielding cultivars were grouped together and compared with the five lowest yielding cultivars. Mean GY and GPC for each group were compared under high input and low input crop production regimes. In 2005, the higher yielding cultivars were found to be significantly higher yielding and more responsive to management than the lower yielding cultivars. In 2004, under ideal growing conditions with no disease pressure, the same two groups of cultivars had no significant differences in yield. The authors attribute the responses observed in 2005 primarily to disease control associated with the application of fungicide.

The relative importance of management practices varies largely due to environmental conditions, making it difficult to recommend a universal management program that will apply for each season and location. Identifying and utilizing positive genotype by management interactions are important to maximizing wheat yields in the future and breeders should develop a better understanding of these relationships. Cooper et al. (2001) suggest applying interactive management practices to advanced breeding lines to identify which genotypes are responsive to a particular management practice.

IV. Objectives

The objectives of this study were i) to investigate the agronomic response of sixteen HRSW cultivars and breeding lines to five different management programs including N timing, fungicide at flowering (GS 60), early fungicide and insecticide (GS

15), and chloride fertilization in north-central South Dakota, and ii) to determine the potential impact of management on flour and dough characteristics for these cultivars.

Chapter 2 focused on the effect of five levels of agronomic inputs with increasing intensity or 'management' on the GY, test weight (TW), and GPC of sixteen HRSW genotypes in 2015 and 2016 at two South Dakota locations (four environments). The same genotypes and management treatments were used at all environments.

Chapter 3 examined the same management treatment effects on the protein content and extraction of wheat flour along with two dough mixing characteristics (Mixograph envelope peak time and peak value) for the same sixteen HRSW genotypes over the four testing environments.

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CHAPTER 2: AGRONOMIC RESPONSE OF HARD RED SPRING WHEAT GENOTYPES TO MANAGEMENT SYSTEMS IN CENTRAL SOUTH DAKOTA

ABSTRACT

Intensive management of hard red spring wheat (*Triticum aestivum* L.) in the upper Great Plains has produced variable yield response when compared to more humid production areas with higher yield potential. Information is limited on locally-adapted genotypic agronomic response to management systems in South Dakota. Our objectives in this study were to determine the efficacy of five intensive management systems in South Dakota and to investigate the response of sixteen hard red spring wheat (HRSW) genotypes to these different management systems. Grain yield, grain protein content, and test weight were collected in two South Dakota locations in 2015 and 2016. While N fertilizer application timing and fungicide application at anthesis seemed to have an effect on grain yield and grain protein content, confounding environmental factors made these findings inconclusive. The application of chloride had no effect on any of the agronomic traits. No predictable management by genotype interaction was observed for any of the agronomic traits. Differences between management systems and genotypes alone were much more consistent than interaction effects between management system and genotype. It appears that agronomic response to management system, and correspondingly, any interaction effects between genotype and management were highly correlated to environmental conditions.

Introduction

Regional fluctuations in wheat production are often highly correlated to environmental conditions. However, some of this variation can be attributed to agronomic management systems. Producer-controllable aspects of production include genotype, crop management, and their interactions (Ransom et al., 2007). Each of these components can contribute to production in a variable manner, depending upon environmental conditions. Genotypic selection typically has the highest impact on grain yield (GY), test weight (TW) and grain protein content (GPC). There have been several attempts to separate the contribution of GY gains due to cultivar improvement (genetic gain) from those gains attributed to management practices (Feyerherm et al., 1988; Bell et al., 1995; Duvick and Cassman, 1999). Hard red winter wheat (HRWW) yield increases in the Midwestern US have been estimated to be 61%, 27%, and 13% for genetics, applied nitrogen (N), and other sources, respectively for the time period 1954-1984 (Feyerherm et al., 1988). In contrast, the increases in irrigated Mexican wheat yields in the Yaqui Valley region for the period 1968-1990 were estimated to be attributed to 72% improved management and 28% cultivar improvement (Bell et al., 1995). The complex myriad of factors affecting GY, including weather, make it difficult to identify management systems other than nitrogen application that provide for consistent yield increases. Despite this complexity, there have been several attempts to identify the most critical management practices for increasing wheat productivity (Stapper and Fischer, 1990; Hobbs et al., 1998; Ransom et al., 2007; Vigani et al., 2015). Both Freyerherm et al. (1988) and Bell et al. (1995) report that N fertilizer application appears to be the single most effective management practice for yield improvement. In eastern North Dakota, Ransom et al. (2007) found that seeding rate and N application timing had no effect on yield while fungicide application at flowering consistently and dramatically increased yields in 2005. Ransom et al. also noted that i) genotype can sometimes be the primary factor impacting yield in intensive management research, and ii) it is often the careful application of a combination of several less obvious management practices that allow some producers to consistently achieve above average yields.

Though the impact of management systems on hard red spring wheat (HRSW) genotypes has been studied in North Dakota (Kahn and Spilde, 1992; Ransom, et al. 2007), published research from South Dakota seems to be absent from the literature. The objectives of this study were two-fold. The first was to identify the agronomic response of sixteen HRSW cultivars to five different management systems. The second was to determine any significant interaction effects between genotype and management system. The relative importance of management practices can vary largely due to environmental conditions, making it difficult to recommend a universal management program that will apply for each season and location. Knowledge gained by identifying and utilizing positive genotype by management interactions may be important to maximizing wheat yields in the future and both breeders and producers should develop a better understanding of these relationships.

Materials and Methods

Experimental Layout

Experiments were conducted at Agar and Northville, SD during the 2015 and 2016 growing seasons. Global Positioning System coordinates along with soil type and series information for each experimental site are given in Table 2-1. Soil samples (0-6") from each experimental site were collected and analyzed for soil pH and soil nutrient levels by Agvise Laboratories (Benson, MN). Soil test results along with other attributes of plot management are reported in Table 2-2. Climatological data was obtained from South Dakota State University Mesonet weather stations (https://climate.sdstate.edu) and is summarized for each experimental site in Table 2-3. Experimental design was a randomized complete-block design in a split-plot arrangement with four replications. Main plots were five management treatments and sub-plots were sixteen HRSW genotypes locally adapted to SD, including thirteen released varieties and three experimental lines. Genotype descriptions are reported in Table 2-4.

Treatments

Seed was treated with a basal dose of pyraclostrobin (methyl (2-(((1-(4-chlorophenyl)-1H-pyrazol-3-yl)oxy)methyl)phenyl)(methoxy)carbamate) + triticonazole ((RS)-(E)-5-(4-Chlorobenzylidene)-2,2-dimethyl-1-(1H-1,2,4-triazol-1-ylmethyl) cyclopentanol) + metalaxyl (methyl-DL-N-(2,6-dimethylphenyl)-N-(methoxyacetyl)-alaninate) (Stamina F3 Cereals Fungicide Seed Treatment, BASF, Research Triangle Park, NC, USA) at a rate of 4.6 oz/cwt to control seedling diseases. Plots were no-till seeded with plot drills at a rate of 42 seeds ft^{-2}. Plots were sown in an area measuring 5 by 20 ft using seven 7-inch rows at Agar and six 8-inch rows at Northville. Starter fertilizer used was granular 9-42-12 (N-P-K) applied in-furrow with the plot drills at a rate of 7 lb N a^{-1}, 34 lb P_2O_5 a^{-1}, and 10 lb K_2O a^{-1}. Seeding dates and previous crop for each experimental site are reported in Table 2. Main plot management treatments consisted of:

1. 100 lb N a^{-1} surface broadcast as urea (46-0-0) immediately following seeding with a Gandy 42-inch variable rate drop spreader (Gandy Company, Owatonna, MN, USA).
2. 100 lb N a^{-1} streambar applied as urea ammonium nitrate (UAN) (28-0-0) at GS 21-22 (Zadoks et al., 1974) with Chafer streambars (Chafer Machinery Ltd., Gainsborough, Linconshire, UK).
3. Treatment 2 plus a foliar application of prothioconazole (2-[2-(1-Chlorocyclopropyl) -3-(2-chlorophenyl)- 2-hydroxypropyl]-1, 2-dihydro-3H-1, 2, 4-triazole-3-thione) + tebuconazole (alpha-[2-(4-chlorophenyl) ethyl]-alpha-(1, 1-dimethylethyl)-1H-1, 2, 4-triazole-1-ethanol) (Prosaro 421 SC Fungicide, Bayer CropScience, Research Triangle Park, NC, USA) at a rate of 6.5 oz $^{a-1}$ + 2.0 oz a^{-1} of Franchise adjuvant (lecithin, methylesters of fatty acids, and alcohol ethoxylate) (Loveland Products, Greeley, CO, USA). Products were broadcast applied at GS 60 with 15 gallons a^{-1} water carrier at 40 PSI with TeeJet 8001XR nozzles (TeeJet Technologies, Glendale Heights, IL, USA) set at 15 inch spacing.
4. Treatment 3 plus a foliar application of fluxapyroxad (3-(difluoromethyl)-1-methyl-N-(3',4',5'-trifluorobiphenyl-2-yl)pyrazole-4-carboxamide + pyroaclostrobin (Methyl (2-(((1-(4-chlorophenyl)-1H-pyrazol-3-yl)oxy)methyl)phenyl)(methoxy)carbamate) (Priaxor Fungicide, BASF, Research

Triangle Park, NC, USA) at a rate of 2.0 oz a^{-1} + cyfluthrin (cyano(4-fluoro-3-phenoxyphenyl)methyl 3-(2,2-dichloroethenyl)-2,2-dimethylcyclopropane carboxylate) (Tombstone Insecticide, Loveland Products, Greeley, CO, USA) at a rate of 1.5 oz a^{-1}. Products were broadcast applied at GS 15 with 10 gallons a^{-1} water carrier at 40 PSI with TeeJet 8001XR nozzles (TeeJet Technologies, Glendale Heights, IL, USA) set at 15 inch spacing.

5. Treatment 4 plus 33 lb Cl a^{-1} surface broadcast as Potassium chloride immediately following seeding with a Gandy 42-inch variable rate drop spreader (Gandy Company, Owatonna, MN, USA).

Bromoxynil (3,5-Dibromo-4-hydroxybenzonitrile) (Brox-M Herbicide, Albaugh, Inc., Ankeney, IA, USA) was applied with a tractor-mounted sprayer at all locations as needed to control weed pressure. Plots were trimmed to a length of 13 ft with a tractor-mounted mower and alley-cutting toolbar prior to harvest to eliminate border effects. Harvest was performed with a Kincaid 8XP plot combine (Kincaid, Haven, KS, USA) which provided plot weight, grain moisture, and test weight with an on-board weighing system. Grain protein content was measured using near-infrared reflectance with a Foss Infratec 1229 grain analyzer (Foss, Hilleroed, Denmark).

Data Analysis

Each location-year was considered a separate environment. Each environment was analyzed individually, with estimates of independent variables GY, TW, and GPC calculated using the split-plot model specified by Kuehl (2000).

$$y_{ijk} = \mu + \tau_i + \beta_k + d_{ik} + \upsilon_j + (\tau\upsilon)_{ij} + e_{ijk}$$

$$i = 1, 2, \ldots, 5 \quad j = 1, 2, \ldots, 16 \quad k = 1, 2, \ldots, 4$$

where μ is the general mean, τ_i is the effect of the ith level of management treatment, β_k is the effect of the kth block, d_{ik} is the whole-plot random error, υ_j is the effect of the jth level of genotype, $(\tau\upsilon)_{ij}$ is the interaction effect between management treatment and genotype, and e_{ijk} is the subplot random error. Genotype and MT were both considered fixed effects, as in several other studies involving genotype by management treatment interactions (Kahn and Spilde, 1992; Guy et al., 1995; Bly and Woodard, 2003; Farmaha et al., 2015; Corassa et al., 2018). Replications (blocks) are generally considered to be a random effect in agricultural experiments but arguments have been made that blocks may also be fixed (Allison, 2009; Dixon, 2016), especially in completely balanced designs. Effects on the aforementioned independent variables were tested for individual environments using a split plot model analysis vignette found in the ‘agricolae’ package in the R program (R Development Core Team, 2013). Calculations for this model are provided in detail by Gomez and Gomez (1984). An analysis of variance was also performed using the ‘anova’ function in the R program. A Tukey post-hoc means comparison test (alpha=0.05) using the ‘emmeans’ package in the R program was used to identify differences in means between treatments, varieties, and interaction effects. In cases where effect significance was shown at the ($P<0.10$) level in the analysis of variance, Tukey post-hoc means comparisons tests were re-run using a lower level of significance (alpha=0.10) for discussion purposes.

Environments were also combined and analyzed together, with estimates of independent variables GY, TW, and GPC calculated using a multi-environment split plot model specified by Carmer et al. (1989).

$$y_{ijk} = \mu + E_i + \beta_{l(i)} + \tau_j + (E\tau)_{ij} + d_{ijl} + \upsilon_k + (E\upsilon)_{ik} + (\tau\upsilon)_{jk} + (E\tau\upsilon)_{ijk} + e_{ijkl}$$

$$i = 1, 2, \ldots, 4 \quad j = 1, 2, \ldots, 5 \quad k = 1, 2, \ldots, 16 \quad l = 1, 2, \ldots, 4$$

where μ is the general mean, E_i is the effect of the ith level of environment, β_l is the effect of the lth block in environment i, τ_j is the effect of the jth level of management treatment, $(E\tau)_{ij}$ is the interaction effect between environment and management treatment, d_{ijl} is the whole-plot random error, υ_k is the effect of the kth level of genotype, $(E\upsilon)_{ik}$ is the interaction effect between environment and genotype $(\tau\upsilon)_{jk}$ is the interaction effect between management treatment and genotype, $(E\tau\upsilon)_{ijk}$ is the interaction effect between environment, treatment, and genotype and e_{ijkl} is the subplot random error. Effects on independent variables over combined environments were analyzed using the analysis of variance function in the R program. A Tukey post-hoc means comparison test (alpha=0.05) using the 'emmeans' package in the R program was used to identify differences in means between treatments, varieties, and interaction effects. In cases where effect significance was shown at the (P<0.10) level in the analysis of variance, Tukey post-hoc means comparisons tests were re-run using a lower level of significance (alpha=0.10).

Results and Discussion

Environment 1 – Agar 2015

The weather conditions at the Agar trial location in 2015 were characterized by a warm April and a cool, wet May followed by near-normal growing conditions for the remainder of the growing season (Table 2-3). Precipitation was 1.1 in below normal in April and temperatures were 3.8°F above normal. In May, precipitation was 2.2 inches above normal and temperatures were 2.1°F below normal. Throughout the remainder of the growing season, June and July were 1.6°F and 0.2°F above normal in temperature, respectively, and cumulatively 2.6 inches below normal in precipitation. Precipitation and temperatures were both near normal in August. Growing degree days (GDD) (F°) were above normal in April and June and near to slightly below normal in May, July, and August. Overall, Environment 1 had the lowest average GY, and the second lowest TW and GPC of the four environments.

Analysis of variance for agronomic characteristics showed a very highly significant response to both management treatment (MT) and genotype ($P < 0.001$) for GY and GPC (Table 2-5). There was a very highly significant response to genotype for TW ($P < 0.001$). Additionally, the interaction of MT and genotype was highly significant ($P < 0.05$) for TW and GPC. Unfortunately, block (repetition) was a significant source of variation for both GY and TW. Upon visiting with the cooperator, it was discovered that there was an old shelterbelt on the property which had been removed a few years prior. Block four happened to fall on the old shelterbelt area and thus GY and TW were negatively affected compared to blocks one through three.

Agronomic trait means for genotype are summarized in Table 2-6. Grain yields ranged from 39.1 bu a^{-1} for 'SD4451' to 54.9 bu a^{-1} for 'Faller'. Grain protein content varied from 13.3% for 'MS-Stingray' to 15.4% for 'SY-Soren'. Test weight varied from 54.9 lb bu^{-1} for MS-Stingray to 58.5 lb bu^{-1} for 'Focus'.

Management treatment effects are summarized in Table 2-7. Management treatment 1, which had all N applied as surface broadcast urea, had the lowest GY and GPC over all varieties. The dry and warm weather conditions in April may have prevented the movement of this surface broadcast N into the root zone and a portion may have been lost to volatilization. Clay et al. (1990) observed that NH_3 volatilization losses from urea are maximized at a time corresponding to warm soil temperatures and decreasing soil moisture. Jantalia et al. (2012) reported that irrigating immediately following fertilization could significantly limit NH_3 loss from urea-based fertilizers. In addition, Dillon et al. (2012) noticed that rice yields decreased proportionally with the time of urea application prior to water-induced movement into the root zone. Grain protein content is influenced by both the total N available during the growing season and N timing and method of application (Chen et al., 2008; Farmaha et al., 2015). Management treatments 2-5 were statistically similar for both GY and GPC. Management treatment had no effect on TW.

The interaction of MT and genotype was significant for three of the sixteen varieties for TW and eight of the sixteen varieties for GPC. Similar results were noted in the upper Great Plains, where Kahn and Spilde (1992) observed significant genotype by management interactions over four environments for TW and GPC in HRSW. However, Kahn and Spilde also observed a significant interaction effect on GY but there was no interaction effect on GY observed in Environment 1 in this study.

Environment 2 – Northville 2015

The weather conditions at the Northville trial location in 2015 were characterized by a warm April and a wet May followed by warm conditions in June and July (Table 2-3). Precipitation was 0.9 in below normal in April and temperatures were 5.9°F above normal. In May, precipitation was 2.8 inches above normal and temperatures were near normal. Throughout the remainder of the growing season, June and July were 2.8°F and 1.1°F above normal in temperature, respectively, and cumulatively 1.9 inches above normal in precipitation. Precipitation and temperatures were both near normal in August. Growing degree days (GDD) (F°) were above normal in April and June and near to normal in May, July, and August. Overall, Environment 2 had the second lowest average GY, the second highest average TW and the highest average GPC of the four environments (Table 2-6).

Analysis of variance for agronomic characteristics showed a very highly significant response to management treatment ($P < 0.01$) for GY and GPC (Table 2-5). There were very highly significant differences due to genotype for GY, TW, and GPC ($P < 0.001$). In addition, the interaction of MT and genotype was very highly significant ($P < 0.001$) for GY and TW and highly significant ($P < 0.05$) for GPC.

The HRSW genotypes varied widely for agronomic traits measured (Table 2-6). Grain yields ranged from 52.5 bu a^{-1} for SD4451 to 64.4 bu a^{-1} for 'Prevail'. Grain protein content varied from 13.3% for MS-Stingray to 15.7% for SY-Soren. Test weight varied from 56.6 lb bu^{-1} for MS-Stingray to 59.6 lb bu^{-1} for Focus.

Management treatment 1 had the lowest GPC and second lowest GY, although in both cases statistically similar to MT 2, suggesting that losses to NH_3 volatilization may not have been as marked as Environment 1. The timing of precipitation may have an effect on N losses, as weather station data shows both Environments 1 and 2 had about 0.4 inches of rain 18 days after planting. This rainfall amount is slightly less than the rate of 0.57 inches (14.6 mm) that Holcomb et al. (2011) reported adequate to incorporate surface broadcast urea into the soil. Soil temperature and the amount of surface residue may also have an effect on N losses (Clay et al., 1990). Treatments 3-5 were all statistically in the top group for GY and GPC, suggesting the application of fungicide at GS60 was beneficial at Environment 2. Previous research has also documented GY increases due to fungicide at GS60 (Wiersma and Motteberg, 2005; Ransom, 2007). Leaf rust (*Puccinia triticina* Eriks.) was observed at Environment 2, and may have affected GY and GPC, but severity ratings were not recorded. Management treatment had no effect on TW.

The interaction of MT and genotype was significant for eight of the sixteen varieties for GY, three of the sixteen for TW and two of the sixteen varieties for GPC. As discussed previously, similar results were observed by Kahn and Spilde (1992) over four North Dakota environments, with significant genotype by management interactions for GY, TW, and GPC in HRSW.

Environment 3 – Agar 2016

The weather conditions at the Agar trial location in 2016 were characterized by a wet April followed by warm and dry conditions for the remainder of the growing season. (Table 2-3). Precipitation was 4.0 inches above normal in April and temperatures were near normal. May, June, and July were -0.5, -2.2, and -1.8 inches below normal for precipitation, respectively, and temperatures were 1.8°F, 4.4°F, and 0.5°F above normal. Growing degree days (GDD) (F°) were above normal in April, May, and June before returning to near normal in July. Harvest occurred on August 3rd, so August weather had no influence on this trial location. Heat during and following anthesis can be very detrimental to grain production in wheat, primarily due to a reduction in the grain-fill period (Stone and Nicolas, 1994). However, the heat at Environment 3 seemed to occur early enough in the season that yield and grain quality were not affected. Overall, Environment 3 had the second highest average GY and GPC but the lowest TW of the four environments (Table 5).

Analysis of variance for agronomic characteristics showed a very highly significant response to management treatment for GY (P <0.01) and a significant response for GPC (P <0.10) (Table 2-5). There were very highly significant differences due to genotype for GY, TW, and GPC (P <0.001). Additionally, the interaction of MT and genotype was highly significant (P <0.05) for TW and GPC. Finally, the interaction of MT and genotype was significant (P <0.10) for TW.

As noticed in other environments, the HRSW genotypes varied widely for agronomic traits measured (Table 2-6). Grain yields ranged from 52.3 bu a^{-1} for SD4451 to 66.0 bu a^{-1} for ‘Surpass’. Grain protein content varied from 13.9% for MS-Stingray to 15.0% for ‘Forefront’, ‘SD4383’, and ‘WB-Mayville’. Test weight varied from 54.6 lb bu^{-1} for ‘Boost’ to 58.2 lb bu^{-1} for Focus.

There were no differences among management treatments for TW. Although treatment was found to have a significant effect on GPC (P<0.10), differences in treatments were inconsistent. Management treatment 1 had the lowest GPC but was statistically similar to MT 2, MT 3, and MT 5 demonstrating no predictable effect of N timing or fungicide/insecticide application. Management treatment 5 had the highest yield, but was statistically similar to MT 3 and MT 4, suggesting that fungicide application at GS60 may have had a positive effect on yield. However, MT 1 was similar to MTs 3-4, somewhat confounding this conclusion. The statistical similarities between MT 1 and MTs 3-4 also indicate that there was perhaps very little N lost to NH_3 volatilization. A rainfall event of 1.33 inches occurred 14 days after planting and should have been adequate to incorporate surface broadcast urea into the soil (Holcomb et al., 2011).

There was no MT by genotype interaction effect for GY or GPC but there was a significant interaction effect ($P<0.10$) for TW. Only one of sixteen varieties showed a significant interaction effect for TW.

Environment 4 – Northville 2016

The weather conditions at the Northville trial location in 2016 were very similar to those of Agar in 2016, and were characterized by a wet April followed by warm and dry conditions for the remainder of the growing season. (Table 2-3). Precipitation was 1.8 inches above normal in April and temperatures were 2.7°F above normal. June and July were -2.0 and -0.9 inches below normal for precipitation, respectively, and temperatures were 5.3°F, and 1.5°F above normal. Growing degree days (GDD) (F°) were above normal in April, May, and June before returning to near normal in July. Harvest occurred on August 3rd, so August weather had no influence on this trial location.

Overall, Environment 4 had the highest average GY and TW but the lowest GPC of the four environments (Table 2-6).

Analysis of variance for agronomic characteristics showed a very highly significant response to genotype (*P* <0.001) for GY and GPC (Table 2-5). There was also very highly significant response to genotype for TW (*P* <0.01). There were no significant MT effects or genotype by MT interaction effects for any of the response variables. Unfortunately, block (repetition) was a significant source of variation for all the response variables. Trial results were affected by soil variability (which cannot be accounted for in the soil series descriptions) which was brought on by warm and dry conditions in June and July. Blocks three and four were severely affected by soil variability. Soil variability is evident when examining average GY across the trial location where blocks one, two, three, and four averaged 75.0, 65.5, 62.1, and 56.8 bu a^{-1}, respectively. Grain protein content varied from 13.5% in block one to 14.1% in block four. The coefficients of variation (CV) for GY were 22.8% for the whole-plot treatments (MT) and 16.6% for the subplot treatments (genotype). Maximum acceptable CV values are thought to be 12-15% for management treatments and 6-8% for genotype trials (Gomez and Gomez, 1984).

Agronomic traits for the HRSW genotypes are summarized in Table 6. Grain yields ranged from 51.7 bu a^{-1} for SD4451 to 66.0 bu a^{-1} for MS-Stingray. Grain protein content varied from 12.6% for MS-Stingray to 14.5% for SD4451. Test weight varied from 57.7 lb bu^{-1} for Faller to 60.7 lb bu^{-1} for Focus.

Combined Environments

The significance of mean squares in the analysis of variance for agronomic traits as affected by environment, treatment, genotype, and their interactions are reported in Table 2-8. As mentioned in the previous sections, climatic conditions varied widely over all four locations, but tended to be warmer and drier than the 30-year averages. Analysis of variance showed environment to be a very highly significant source of variation for GY, TW, and GPC (P<0.001).

The effect of MT was very highly significant for GY and GPC (P<0.001) but not for TW (Table 2-8). Grain protein content was the lowest for MT1, while MTs 2-5 were all similar, suggesting that broadcasting all N as urea following planting is not the best management practice for optimizing GPC. Grain yields were also lowest for MT1, but MT2 was similar, suggesting that N timing may not be as important for GY as GPC. Previous studies have produced mixed results on N application timing and GY; some have shown no response (Otteson, et al., 2007; Subedi et al., 2007), while others conclude that in-season applications of N maximize GY (Mossedaq and Smith 1994; Melaj, et al., 2003). As discussed previously, environmental conditions such as soil temperature and the timing of precipitation may have an effect on N volatilization and movement into the root zone (Clay et al. 1990), which can confound N timing studies. Ransom (2018) noted that split applications of N can result in lower GY if there are rain delays following fertilizer application, due to N loss and 'stranding'. Management treatments 3-5 were all statistically in the top group for GY and GPC, suggesting the application of fungicide at GS60 was beneficial. This confirms results observed by previous research (Wiersma and Motteberg, 2005; Ransom, 2007). Ransom (2007) speculates that, in some years, fungicide is the only management practice that consistently improves yield and grain quality. Management treatment 4, which included early season (GS15) application of fungicide and insecticide, did not increase GY significantly over MT 3, which had a later season application (GS60). A later application (GS37-39) is actually recommended for leaf disease control (Byamukama, 2017) and therefore a fungicide application as GS15 may not have be timed correctly for pathogen control in this study. The addition of KCl in MT 5 had no effect on GY, and in fact was slightly lower than MT 4. Conversely, previous research conducted in South Dakota has documented GY increases from the application of chloride (Fixen et al., 1986; Graham et al., 2017). Neither fungicide or KCl applications had and discernable effect on GPC. In the upper Great Plains, Kahn and Spilde (1992) found a significant GY decrease due to intensive cereals management (ICM) for five of 12 cultivars with no response in the remaining seven. The results of this study suggest that ICM practices employed in more marginal production conditions, such as limited moisture and high temperatures, are in fact detrimental (note these are the predominant weather conditions at all environments in this study).

Environment by management interaction effects existed for GY ($P<.05$) and for GPC ($P<0.10$). Previous research has indicated similar results (Kahn and Spilde, 1992; Guy et al., 1995, Corassa et al., 2018). Differences in MT response between environments are due to weather variations such as heat and the timing and amount of precipitation. Disease pressure may also affect MT efficacy although disease analysis was not included in this study. There were no significant three-way interaction effects of environment by genotype by management.

The HRSW genotypes varied widely for agronomic traits measured (Table 2-9). In general, genotypes with the greatest GY had lower GPC, which agrees with previous research noting this negative correlation (Kibite and Evans, 1984; Fowler, 2003). For example, the highest yielding genotype, MS-Stingray, yielded 64.0 bu a^{-1} with an average GPC of 13.3%. The lowest yielding genotype, SD4451, yielded 48.9 bu a^{-1} with an average GPC of 14.9%.

Genotype by environment interaction effects existed for all response variables, ($P<.05$) for GY and ($P<0.001$) for TW and GPC, indicating that environment had an influence on genotype performance. It is commonly known to plant breeders that genotype by environment is a well-documented source of variation (Fehr, 1991). Other studies examining the relationship between management and genotype have also observed significant environment by genotype effects (Kahn and Spilde, 1992; Guy et al., 1995). Conversely, Corassa et al. (2018) noticed no differences in yields for genotype over three environments.

Genotype by management interaction was significant ($P<0.10$) for GY but not for TW or GPC. Ten of the sixteen genotypes had significant effects on GY due to MT, including ‘Advance’, Faller, Forefront, MS-Stingray, ‘SD4393’, SD4451, ‘Select’, Surpass, SY-Soren, and WB-Mayville. These genotypes are highly variable in a number of ways including the efficiency of starch and protein production, maturity, and disease resistance. Results from this study indicate that it is impossible to state which genotype characteristics have the potential to respond to the given management treatments. Ransom (2007) theorized that higher yielding cultivars should be significantly higher yielding and more responsive to management than the lower yielding cultivars in years with disease pressure. In contrast, under ideal growing conditions with no disease pressure, higher and lower yielding cultivars should respond in a similar manner.

Several studies have shown improvements in GY and GPC due to intensive management treatments in other areas of the United States (Beuerlein et al. 1989; Guy et al. 1989; Morris et al., 1989). However, results from this study seem to be agree with previously research conducted in North Dakota by Khan and Spilde (1992) where intensive management treatments had no positive effects on agronomic properties.

Conclusion

Hard red spring wheat genotypes were evaluated under five management regimes over years and locations in South Dakota to examine agronomic response to management and genotype by management interaction effects. While N fertilizer application timing seemed to have an effect on grain yield and grain protein content, confounding environmental factors make these findings inconclusive. In addition, an early season application of fungicide and insecticide combined with a late-season application of fungicide increased yields versus no fungicide but not versus a single late-season application of fungicide. The application of chloride had no effect on any of the agronomic traits. No predictable management by genotype interaction was observed for any of the agronomic traits.

Techniques for the intensive management of wheat were primarily developed for winter wheat producing areas with humid climatic conditions. Our study environments were predominantly warm and dry, therefore may explain why the intensive management techniques implemented in this study did not have consistent effects on the agronomic characteristics in any of the genotypes tested. Literature suggests that cultivar-specific responses to management inputs seem to be environmentally dependent, relating primarily to heat, precipitation, and the presence of disease. Therefore, results from this study should not be used to predict effects of management in areas with ideal growing conditions and/or heavy disease pressure.

Table 2-1. Trial locations along with soil types and soil series descriptions for four South Dakota environments.

Environment	Location	Year	GPS coordinates	Soil type	Soil series description
1	Agar	2015	44.948030° -100.083972°	Agar silt loam, 0-2% slopes	Fine-silty, mixed, superactive, mesic Typic Argiustoll
2	Northville	2015	45.158557° -98.565832°	Harmony-Aberdeen silty clay loams, 0-2% slopes	Harmony - fine, smectitic, frigid Pachic Argiudoll Aberdeen - Fine, smectitic, frigid, Glossic Natrudoll
3	Agar	2016	44.943959° -100.122906°	Eakin-Raber complex, 0-2% slopes	Eakin - Fine-silty, mixed, superactive, mesic, Typic Argiustoll Raber - Fine, smectitic, mesic, Typic Argiustoll
4	Northville	2016	45.158586° -98.570113°	Harmony-Aberdeen silty clay loams, 0-2% slopes	Harmony - fine, smectitic, frigid Pachic Argiudoll Aberdeen - Fine, smectitic, frigid, Glossic Natrudoll

Table 2-2. Summary of soil analyses and plot management at four South Dakota environments.

Environment	Location	Year	soil pH	N (lb a^{-1})	Bray P (ppm)	K (ppm)	Previous crop	Row spacing	Planting date	Harvest date
1	Agar	2015	6.4	8	20	364	soybeans	7"	4/1/15	8/14/15
2	Northville	2015	6.8	9	24	379	soybeans	8"	4/1/15	8/14/15
3	Agar	2016	6.2	18	12	407	field peas	7"	3/29/16	8/3/16
4	Northville	2016	6.7	12	27	388	soybeans	8"	3/29/16	8/3/16

Table 2-3. Average monthly temperatures and precipitation at four South Dakota environments.

Environment	Location	Year	Month	Temperature Avg	Temperature 30 yr Avg	Temperature Deviation	Precipitation Avg	Precipitation 30 yr Avg	Precipitation Deviation
				--------------------F°------------------			------------------ in -------------------		
1	Agar	2015	April	47.3	43.5	+3.8	0.7	1.8	-1.1
			May	53.0	55.1	-2.1	5.1	2.9	+2.2
			June	66.4	64.8	+1.6	2.1	3.5	-1.4
			July	71.6	71.4	+0.2	1.7	2.9	-1.2
			August	68.9	69.7	-0.8	3.2	2.4	+0.8
2	Northville	2015	April	50.2	44.3	+5.9	1.2	2.1	-0.9
			May	56.3	56.9	-0.6	6.0	3.2	+2.8
			June	69.3	66.5	+2.8	3.4	3.3	+0.1
			July	73.2	72.1	+1.1	4.9	3.1	+1.8
			August	69.4	69.6	-0.2	4.8	2.8	+2.0
3	Agar	2016	April	44.8	43.5	+1.3	5.8	1.8	+4.0
			May	56.9	55.1	+1.8	2.4	2.9	-0.5
			June	69.2	64.8	+4.4	1.3	3.5	-2.2
			July	71.9	71.4	+0.5	1.1	2.9	-1.8
			August	69.9	69.7	+0.2	3.3	2.4	+0.9
4	Northville	2016	April	47.0	44.3	+2.7	3.9	2.1	+1.8
			May	59.5	56.9	+2.6	3.9	3.2	+0.7
			June	71.8	66.5	+5.3	1.3	3.3	-2.0
			July	73.6	72.1	+1.5	2.2	3.1	-0.9
			August	71.9	69.6	+2.3	1.5	2.8	-1.3

Table 2-4. Descriptions of sixteen hard red spring wheat (HRSW) genotypes.

				Disease reactions†			
Genotype	Origin‡	Year of release	Maturity	Stem rust	Leaf rust	Tan spot	FHB§
Advance	SD	2011	Medium	MR	MR	S	MR
Boost	SD	2015	Late	MR	MR	MR	MS
Faller	ND	2007	Med. late	R	S	S	MR
Focus	SD	2014	Early	MR	S	MS	MR
Forefront	SD	2011	Med. early	MR	MS	S	MR
MS-Stingray	MS	2014	Late	MR	S	S	MR
Prevail	SD	2014	Early	MR	MS	MR	MR
SD4393	SD	-	Early	MR	MR	MR	MR
SD4451	SD	-	Early	MR	MR	MR	MR
SD4471	SD	-	Medium	MR	MS	S	MR
Select	SD	2009	Early	MR	MR-MS	S	MR
Surpass	SD	2015	Early	MR	MR	MS	MR
SY-Ingmar	AP	2014	Med. late	MS	MR	MR	MR
SY-Rowyn	AP	2013	Medium	R	MS	MS	R
SY-Soren	AP	2011	Med. late	R	MR	-	MR
WB-Mayville	WB	2007	Med. early	MS	S	S	S

†S - susceptible; MS - moderately susceptible; MR - moderately resistant; R - resistant

‡AP - Agripro; MS - Meridian Seeds; ND - North Dakota; SD - South Dakota; WB - Westbred

§Fusarium Head Blight

Table 2-5. Significance of mean squares in the analysis of variance for agronomic traits as affected by main factors and their interactions at four South Dakota environments.

Source of variation	df	GY†	TW	GPC	GY	TW	GPC
		Agar 2015 Environment 1			Northville 2015 Environment 2		
block (replication)	3	<0.001	<0.001	0.671	0.124	0.119	0.499
treatment	4	<0.001	0.250	<0.001	0.003	0.255	0.002
error(a)	12						
genotype	15	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
treatment:genotype	60	0.481	0.039	0.041	<0.001	<0.001	0.028
error(b)	225						
		Agar 2016 Environment 3			Northville 2016 Environment 4		
block (replication)	3	0.218	0.008	0.159	<0.001	<0.001	0.003
treatment	4	0.008	0.819	0.091	0.336	0.935	0.134
error(a)	12						
genotype	15	<0.001	<0.001	<0.001	<0.001	0.006	<0.001
treatment:genotype	60	0.295	0.089	0.688	0.539	0.881	0.750
error(b)	225						

†GY - Grain yield; TW - Test weight; GPC - Grain protein content

Table 2-6. Genotype means for the agronomic traits of sixteen hard red spring wheat genotypes for four South Dakota environments.

	Environment											
	Grain yield				Test weight				Grain protein content			
Genotype	1	2	3	4	1	2	3	4	1	2	3	4
	----------------bu a^{-1}---------------				----------------lb bu^{-1}--------------				---------------- % ---------------			
Advance	49.4	60.8	61.3	66.9	56.3	58.7	56.1	59.5	14.1	14.6	14.2	13.4
Boost	45.8	60.2	57.2	62.0	55.5	57.9	54.6	58.8	15.3	15.6	14.4	14.1
Faller	54.9	62.9	64.5	68.0	55.8	57.7	54.7	57.7	13.7	14.3	14.4	13.3
Focus	47.1	58.7	62.9	64.3	58.5	59.6	58.2	60.7	14.3	15.1	14.4	14.1
Forefront	43.2	54.2	57.7	58.8	56.2	58.5	56.4	60.0	14.6	15.1	15.0	13.6
MS-Stingray	52.8	64.1	64.7	74.2	54.9	56.6	55.6	59.8	13.3	13.3	13.9	12.6
Prevail	48.8	64.4	64.7	69.1	55.6	58.1	56.6	59.0	14.2	14.9	14.7	13.2
SD4393	48.4	58.4	61.9	64.7	56.7	57.8	56.9	59.0	14.6	15.3	15.0	14.3
SD4451	39.1	52.5	52.3	51.7	56.6	58.3	56.0	58.3	14.8	15.4	14.9	14.5
SD4471	46.7	58.3	59.0	62.9	56.1	57.6	55.8	59.4	14.8	15.0	14.5	14.2
Select	45.8	56.8	61.5	63.0	58.1	58.4	58.3	60.1	14.1	15.0	14.4	13.6
Surpass	51.5	61.3	66.0	71.7	55.8	57.0	55.8	58.9	14.3	15.3	14.5	13.5
SY-Ingmar	48.5	62.4	62.8	64.7	57.3	57.7	56.5	59.1	15.7	15.6	14.9	13.9
SY-Rowyn	46.7	61.2	60.7	60.9	55.7	58.3	56.0	58.9	14.3	14.6	14.7	13.0
SY-Soren	45.5	58.3	63.7	65.9	56.1	57.8	55.2	59.2	15.4	15.7	14.8	13.8
WB-Mayville	49.4	60.1	64.3	68.5	55.0	56.7	55.5	58.6	14.5	15.0	15.0	14.4
Average	47.7	59.7	61.6	64.8	56.3	57.9	56.1	59.2	14.5	15.0	14.6	13.7
HSD (0.05)	3.2	4.1	4.3	11.8	1.8	0.6	1.5	2.4	0.5	0.4	0.8	0.8
CV (%)	6.2	6.3	6.4	16.6	2.9	1.0	2.5	3.7	2.9	2.4	5.3	5.4

Table 2-7. Management treatment means for the agronomic traits of 16 hard red spring wheat genotypes at four South Dakota environments.

	Environment											
	Grain yield				Test weight				Grain protein content			
Treatment	1	2	3	4	1	2	3	4	1	2	3	4
	----------------bu a^{-1}---------------				----------------lb bu^{-1}--------------				---------------- % ---------------			
1	41.9	58.3	60.3	62.9	55.9	57.9	56.3	59.4	14	14.7	14.2	13.5
2	47.5	56	59.8	65.5	55.7	57.6	56.3	59.1	14.8	14.9	14.6	13.9
3	48.7	60.4	61.4	64.3	56	58.1	56	59.1	14.7	15.1	14.6	13.8
4	49.7	61.9	62.9	68.1	56.6	57.9	56.2	59.2	14.5	15.2	14.9	13.5
5	50.9	61.9	63.5	63.4	57.1	58.1	55.9	59.1	14.5	15.1	14.6	13.9
Average	47.7	59.7	61.6	64.8	56.3	57.9	56.1	59.2	14.5	15.0	14.6	13.7
HSD (0.05)	3.8	4.2	3	8.3	2.2	0.7	1.2	1.2	0.4	0.3	0.7	0.7
CV (%)	14.0	12.4	8.6	22.8	6.8	2.1	3.7	3.6	5.2	3.6	8.5	8.7

Table 2-8. Significance of mean squares in the analysis of variance as affected by main factors and their interaction for four combined South Dakota environments.

Source of variation	df	GY†	TW	GPC
environment	3	<0.001	<0.001	<0.001
treatment	4	<0.001	0.411	<0.001
environment:block	12	<0.001	<0.001	<0.001
environment:treatment	12	0.012	0.360	0.074
error (a)	48			
genotype	15	<0.001	<0.001	<0.001
genotype:environment	45	0.006	<0.001	<0.001
genotype:treatment	60	0.081	0.475	0.310
genotype:environment:treatment	180	0.426	0.134	0.611
error (b)	900			

†GY - Grain yield; TW - Test weight; GPC - Grain protein content

Table 2-9. Management treatment and genotype means on the agronomic traits for sixteen HRSW genotypes at four combined South Dakota environments.

		Grain yield	Test weight	Grain protein
		bu a^{-1}	lb bu^{-1}	%
Treatment	1	55.8	57.3	14.1
	2	57.2	57.2	14.6
	3	58.7	57.3	14.6
	4	60.6	57.5	14.5
	5	59.9	57.6	14.5
	HSD (0.05)	2.3	0.6	0.2
	CV (%)	15.9	4.3	6.7
Genotype	Advance	59.6	57.6	14.1
	Boost	56.3	56.7	14.8
	Faller	62.6	56.5	13.9
	Focus	58.3	59.2	14.5
	Forefront	53.5	57.8	14.6
	MS-Stingray	64.0	56.7	13.3
	Prevail	61.8	57.3	14.2
	SD4393	58.4	57.6	14.8
	SD4451	48.9	57.3	14.9
	SD4471	56.8	57.2	14.6
	Select	56.8	58.7	14.3
	Surpass	62.6	56.9	14.4
	SY-Ingmar	59.6	57.6	15.0
	SY-Rowyn	57.4	57.2	14.1
	SY-Soren	58.4	57.0	15.0
	WB-Mayville	60.6	56.5	14.8
	HSD (0.05)	3.4	0.8	0.3
	CV (%)	10.6	2.7	4.1
	Mean	58.5	57.4	14.5

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CHAPTER 3: INFLUENCE OF ENVIRONMENT, GENOTYPE, AND MANAGEMENT SYSTEM ON HARD RED SPRING WHEAT QUALITY

ABSTRACT

Bread making is the primary end-use criterion selected for in the development of hard red spring wheat (*Triticum aestivum* L.) genotypes in the upper Great Plains. Information is limited on locally-adapted genotypic quality response to management systems in South Dakota. Our objectives in this study were to determine the relative influence of genotype, management system, and environment on the quality characteristics of sixteen hard red spring wheat genotypes in South Dakota. Flour protein, flour yield, mixograph envelope peak time, and mixograph envelope peak value were collected from two locations in 2015 and 2016. While management treatment seemed to have an effect on flour yield and flour protein content, responses were inconsistent. No management by genotype interactions were observed for any of the quality parameters. Overall, genotype, followed by environment, were the most important factors in determining flour quality and dough mixing performance.

Introduction

Hard red spring wheat (HRSW) (*Triticum aestivum* L.) is primarily grown for its high grain protein content and excellent milling and baking performance (Carson and Edwards, 2009). Many quality characteristics are important for the utilization of HRSW, particularly four extraction, flour protein content, dough handling characteristics, and breadmaking properties (Finney et al., 1987). The relatively short growing season for HRSW in the upper Great Plains typically allows for the production of high grain protein content (GPC) with very good milling and baking qualities (Otteson et al., 2008). One of the most commonly used methods used to predict dough properties is the Mixograph (National Mfg, Lincoln, NE), which is a recording dough mixer that measures flour mixing requirements and tolerance to overmixing (Finney and Shogren. 1972). During a Mixograph analysis, the sample dough shows three distinct phases; elongation, rupture, and relaxation (Gras et al., 2000). While mixing, the resistance imposed by the dough against the action of the mixing pins inside the bowl is recorded as a curve (mixogram). The height and the width of the mixogram during mixing time represent the dough mixing tolerance and consistency, respectively. Figure 3-1 shows examples of a mixogram for both strong and weak flour.

Quality characteristics are commonly known to be affected by both environmental conditions and genetic differences between cultivars (Souza, et al., 2004; Otteson et al., 2008; Caffe-Treml et al., 2010; Caffe-Treml et al., 2011). However, management treatments such as nitrogen (N) fertilizer application timing and fungicide application can also have an effect on HRSW quality. Nitrogen management for increased GPC can also have a positive effect on bread quality parameters including decreased mixing time and increased Mixograph scores (McNeal et al., 1971; Otteson et al., 2008). Lopez-Bellido etal. (2001) indicate N fertilizer application to be a key factor in determining bread-making quality in HRSW. Research involving the effects of fungicide application on grain quality generally either focuses on i) the implications of improved plant health on grain quality, or ii) the direct influences of fungicide on the wheat plant. Reduction in disease resulting from fungicide application may improve the physical qualities of wheat grain because the grain-fill period is maintained (Dimmock and Gooding, 2002. However, studies involving disease control with fungicide have had mixed results on grain quality (Hermann, et al., 1996; Puppala, et al, 1998). In addition, fungicide application in the absence of disease pressure does not appear to have any direct effects on grain quality (Saunders and Salmon, 2000; Ruske et al., 2004; Wang et al., 2004).

The differences in quality characteristics between HRSW genotypes has been well documented (Souza, et al., 2004; Otteson, et al., 2008; Caffe-Treml et al., 2010; Caffe-Treml et al., 2011). However, published research from South Dakota examining the effects of management treatment, genotype, environment, and their interaction on HRSW grain quality is limited. The objectives of this study were two-fold. The first was to identify the quality response of sixteen HRSW cultivars to five different management systems. The second was to determine any interaction effects between genotype, management system, and environment. The relative importance of management practices to grain quality can vary largely due to environmental conditions, making it difficult to recommend a universal management program that will apply for each season and location. Knowledge gained by identifying and utilizing positive genotype by management interactions may be important to maximizing wheat quality in the future and both breeders and producers should develop a better understanding of these relationships.

Materials and Methods

Experimental Layout

Experiments were conducted at Agar and Northville, SD during the 2015 and 2016 growing seasons. Global Positioning System coordinates along with soil type and series information for each experimental site are given in Table 3-1. Soil samples (0-6”) from each experimental site were collected and analyzed for soil pH and soil nutrient levels by Agvise Laboratories (Benson, MN). Soil test results along with other attributes of plot management are reported in Table 3-2. Climatological data was obtained from South Dakota State University Mesonet weather stations (https://climate.sdstate.edu) and is summarized for each experimental site in Table 3-3. Experimental design was a randomized complete-block design in a split-plot arrangement with four replications. Main plots were five management treatments and sub-plots were sixteen HRSW genotypes locally adapted to SD, including thirteen released varieties and three experimental lines. Genotype descriptions are reported in Table 3-4.

Treatments

Seed was treated with a basal dose of pyraclostrobin (methyl (2-(((1-(4-chlorophenyl)-1H-pyrazol-3-yl)oxy)methyl)phenyl)(methoxy)carbamate) + triticonazole ((RS)-(E)-5-(4-Chlorobenzylidene)-2,2-dimethyl-1-(1H-1,2,4-triazol-1-ylmethyl) cyclopentanol) + metalaxyl (methyl-DL-N-(2,6-dimethylphenyl)-N-(methoxyacetyl)-alaninate) (Stamina F3 Cereals Fungicide Seed Treatment, BASF, Research Triangle Park, NC, USA) at a rate of 4.6 oz/cwt to control seedling diseases. Plots were no-till seeded with plot drills at a rate of 42 seeds ft^{-2}. Plots were sown in an area measuring 5 by 20 ft using seven 7-inch rows at Agar and six 8-inch rows at Northville. Starter fertilizer used was granular 9-42-12 (N-P-K) applied in-furrow with the plot drills at a rate of 7 lb N a^{-1}, 34 lb P_2O_5 a^{-1}, and 10 lb K_2O a^{-1}. Seeding dates and previous crop for each experimental site are reported in Table 2. Main plot management treatments consisted of:

1. 100 lb N a^{-1} surface broadcast as urea (46-0-0) immediately following seeding with a Gandy 42-inch variable rate drop spreader (Gandy Company, Owatonna, MN, USA).
2. 100 lb N a^{-1} streambar applied as urea ammonium nitrate (UAN) (28-0-0) at growth stage (GS) 21-22 (Zadoks et al., 1974) with Chafer streambars (Chafer Machinery Ltd., Gainsborough, Linconshire, UK).
3. Treatment 2 plus a foliar application of prothioconazole (2-[2-(1-Chlorocyclopropyl) -3-(2-chlorophenyl)- 2-hydroxypropyl]-1, 2-dihydro-3H-1, 2, 4-triazole-3-thione) + tebuconazole (alpha-[2-(4-chlorophenyl) ethyl]-alpha-(1, 1-dimethylethyl)-1H-1, 2, 4-triazole-1-ethanol) (Prosaro 421 SC Fungicide, Bayer CropScience, Research Triangle Park, NC, USA) at a rate of 6.5 oz $^{a-1}$ + 2.0 oz a^{-1} of Franchise adjuvant (lecithin, methylesters of fatty acids, and alcohol ethoxylate) (Loveland Products, Greeley, CO, USA). Products were broadcast applied at GS 60 with 15 gallons a^{-1} water carrier at 40 PSI with TeeJet 8001XR nozzles (TeeJet Technologies, Glendale Heights, IL, USA) set at 15 inch spacing.
4. Treatment 3 plus a foliar application of fluxapyroxad (3-(difluoromethyl)-1-methyl-N-(3',4',5'-trifluorobiphenyl-2-yl)pyrazole-4-carboxamide + pyroaclostrobin (Methyl (2-(((1-(4-chlorophenyl)-1H-pyrazol-3-

yl)oxy)methyl)phenyl)(methoxy)carbamate) (Priaxor Fungicide, BASF, Research Triangle Park, NC, USA) at a rate of 2.0 oz a^{-1} + cyfluthrin (cyano(4-fluoro-3-phenoxyphenyl)methyl 3-(2,2-dichloroethenyl)-2,2-dimethylcyclopropane carboxylate) (Tombstone Insecticide, Loveland Products, Greeley, CO, USA) at a rate of 1.5 oz a^{-1}. Products were broadcast applied at GS 15 with 10 gallons a^{-1} water carrier at 40 PSI with TeeJet 8001XR nozzles (TeeJet Technologies, Glendale Heights, IL, USA) set at 15 inch spacing.

5. Treatment 4 plus 33 lb Cl a^{-1} surface broadcast as Potassium chloride immediately following seeding with a Gandy 42-inch variable rate drop spreader (Gandy Company, Owatonna, MN, USA).

Bromoxynil (3,5-Dibromo-4-hydroxybenzonitrile) (Brox-M Herbicide, Albaugh, Inc., Ankeney, IA, USA) was applied with a tractor-mounted sprayer at all locations as needed to control weed pressure. Plots were trimmed to a length of 13 ft with a tractor-mounted mower and alley-cutting toolbar prior to harvest to eliminate border effects. Harvest was performed with a Kincaid 8XP plot combine (Kincaid, Haven, KS, USA) which provided plot weight, grain moisture, and test weight with an on-board weighing system. Grain protein content was measured using near-infrared reflectance with a Foss Infratec 1229 grain analyzer (Foss, Hilleroed, Denmark).

Flour Sample Preparation

Grain samples from the first two replications at each location were used for flour and dough analysis. Samples were tempered to 15% moisture with distilled water (Approved Method 26-95.01 AACC International, 2010) and conditioned for at least 16 hrs overnight prior to milling with a Quadrumat Jr. (C.W. Brabender Instruments, South

Hackensack, NJ). Flour was collected by passing milled grain through a rotating US #60 (250 µm aperture) sieve. Flour yield (FY) was determined by weighing the flour that passed through the sieve after three minutes. Estimates of flour protein content (FPC) (14% moisture basis) were determined with a NIRSystems 6500 Monochromators (Foss, Laurel, MD). A Mixograph fitted with a 10-g bowl was used to measure dough rheological properties. Mixing speed was 88 rpm and test duration was 10 minutes. Water amounts added to each flour sample was based on water absorption estimates obtained with NIR spectroscopy. Mixograph parameters were obtained and recorded with MIXSMART software (v. 3.8). While over fifty parameters are recorded by the software, Caffe-Treml et al. (2010) identified six that have high reproducibility and the ability to successfully differentiate genotypes. From these six parameters, envelope peak time (EPT) and envelope peak value (EPV) were selected for analysis in this study.

Data Analysis

Each location-year was considered a separate environment. Each environment was analyzed individually, with estimates of independent variables FPC, FY, EPT, and EPV calculated using the split-plot model specified by Kuehl (2000).

$$y_{ijk} = \mu + \tau_i + \beta_k + d_{ik} + \upsilon_j + (\tau\upsilon)_{ij} + e_{ijk}$$

$$i = 1, 2, \ldots, 5 \quad j = 1, 2, \ldots, 16 \quad k = 1, 2$$

where μ is the general mean, τ_i is the effect of the ith level of management treatment, β_k is the effect of the kth block, d_{ik} is the whole-plot random error, υ_j is the effect of the jth level of genotype, $(\tau\upsilon)_{ij}$ is the interaction effect between management treatment and genotype, and e_{ijk} is the subplot random error. All effects were considered to be fixed effects. Replications (blocks) are generally considered to be a random effect in agricultural experiments but arguments have been made that blocks may also be fixed (Allison, 2009; Dixon, 2016), especially in completely balanced designs. Effects on the aforementioned independent variables were tested for individual environments using a split plot model analysis vignette found in the 'agricolae' package in the R program (R Development Core Team, 2013). Calculations for this model are provided in detail by Gomez and Gomez (1984). An analysis of variance was also performed using the anova function in the R program. A Tukey post-hoc means comparison test (alpha=00.05) using the 'emmeans' package in the R program was used to identify differences in means between treatments, varieties, and interaction effects. In cases where effect significance was shown at the (P<0.10) level in the analysis of variance, Tukey post-hoc means comparisons tests were re-run using a lower level of significance (alpha=0.10) for discussion purposes.

Environments were also combined and analyzed together, with estimates of independent variables FPC, FY, EPT, and EPV calculated using a multi-environment split plot model specified by Carmer et al. (1989).

$$y_{ijk} = \mu + E_i + \beta_{l(i)} + \tau_j + (E\tau)_{ij} + d_{ijl} + \upsilon_k + (E\upsilon)_{ik} + (\tau\upsilon)_{jk} + (E\tau\upsilon)_{ijk} + e_{ijkl}$$

$$i = 1, 2, \ldots, 4 \quad j = 1, 2, \ldots, 5 \quad k = 1, 2, \ldots, 16 \quad l = 1, 2$$

where μ is the general mean, E_i is the effect of the ith level of environment, β_l is the effect of the lth block in environment i, τ_j is the effect of the jth level of management treatment, $(E\tau)_{ij}$ is the interaction effect between environment and management treatment, d_{ijl} is the whole-plot random error, υ_k is the effect of the kth level of genotype, $(E\upsilon)_{ik}$ is the interaction effect between environment and genotype $(\tau\upsilon)_{jk}$ is the interaction effect between management treatment and genotype, $(E\tau\upsilon)_{ijk}$ is the interaction effect between environment, treatment, and genotype and e_{ijkl} is the subplot random error. Effects on independent variables over combined environments were analyzed using the 'anova' function in the R program. A Tukey post-hoc means comparison test (alpha=0.05) using the 'emmeans' package in the R program was used to identify differences in means between treatments, varieties, and interaction effects. In cases where effect significance was shown at the ($P<0.10$) level in the analysis of variance, Tukey post-hoc means comparisons tests were re-run using a lower level of significance (alpha=0.10). Pearson correlation coefficients and respective p-values were computed for all quality parameters using the 'rcorr' function in the 'misc' package in the R program.

Results and Discussion

Environment 1 – Agar 2015

The weather conditions at the Agar trial location in 2015 were characterized by a warm April and a cool, wet May followed by near-normal growing conditions for the remainder of the growing season (Table 3-3). Precipitation was 1.1 in below normal in April and temperatures were 3.8°F above normal. In May, precipitation was 2.2 inches above normal and temperatures were 2.1°F below normal. Throughout the remainder of the growing season, June and July were 1.6°F and 0.2°F above normal in temperature, respectively, and cumulatively 2.6 inches below normal in precipitation. Precipitation and temperatures were both near normal in August. Growing degree days (GDD) (F°) were above normal in April and June and near to slightly below normal in May, July, and August. Overall, Environment 1 had the lowest FY, the second lowest average FPC and the second highest EPT (tied with Environment 4) and EPV of the four environments.

Analysis of variance for quality parameters showed a very highly significant response to genotype for all parameters (P <0.001) (Table 3-5). The only significant response to management treatment (MT) was for FPC (P <0.05). There were no significant MT by genotype interaction effects. In addition, block (repetition) was a not a significant source of variation for any of the test parameters.

Quality parameter means for genotype are summarized in Table 3-6. Flour protein content varied from 12.1% for ‘MS-Stingray’ to 14.9% for ‘SY-Ingmar’. Flour yields ranged from 58.7% for ‘SY-Soren’ to 63.4% bu/acre for ‘Prevail’. Envelope peak time varied from 2.52 minutes for SY-Soren to 4.42 minutes for MS-Stingray. Envelope peak value varied from 58.5% for MS-Stingray to 71.3% for ‘WB-Mayville’.

Management treatment effects are summarized in Table 3-7. Management treatment 1, which had all N applied as surface broadcast urea, had the lowest FPC over all varieties. The dry and warm weather conditions in April may have prevented the movement of surface broadcast N into the root zone and a portion may have been lost to volatilization. Clay et al. (1990) observed that NH_3 volatilization losses from urea are maximized at a time corresponding to warm soil temperatures and decreasing soil moisture. Grain protein content is influenced by both the total N available during the growing season and N timing and method of application (Chen et al., 2008; Farmaha et al., 2015). Management treatments 4 and 5, however, which also had later-applied N, similar to MTs 2 and 3, were statistically similar to MT 1 for FPC. Thus, the N application methods used in this study seemed to have inconsistent results on FPC at Environment 1. In addition, none of the fungicide/insecticide applications or KCl treatments had any discernable effects on FPC. Management treatment had no effect on FY, EPT, or EPV. As mentioned previously, there were no significant MT by genotype interaction effects.

Environment 2 – Northville 2015

The weather conditions at the Northville trial location in 2015 were characterized by a warm April and a wet May followed by warm conditions in June and July (Table 3-3). Precipitation was 0.9 in below normal in April and temperatures were 5.9°F above normal. In May, precipitation was 2.8 inches above normal and temperatures were near normal. Throughout the remainder of the growing season, June and July were 2.8°F and 1.1°F above normal in temperature, respectively, and cumulatively 1.9 inches above normal in precipitation. Precipitation and temperatures were both near normal in August.

Growing degree days (GDD) (F°) were above normal in April and June and near to normal in May, July, and August. Overall, Environment 2 had the highest average FY and EPV, the second highest average FPC, and the lowest average EPT of the four environments.

Analysis of variance for quality parameters showed a significant response to management treatment (*P* <0.10) for FPC, FY, and EPT (Table 3-5). There were very highly significant effects of genotype for all parameters (*P* <0.001). While MT alone did not affect EPV, there was a very significant MT by genotype interaction effect for EPV (*P* <0.05). Block (repetition) was a not a significant source of variation for any of the test parameters at Environment 2.

The quality parameter means for each genotype are summarized in Table 3-6. Flour protein content ranged from 12.1% for MS-Stingray to 14.6% for 'Boost' and SY-Ingmar. Flour yields ranged from 60.5% for 'Select' to 65.0% for 'Faller'. Envelope peak time varied from 2.41 minutes for SY-Soren to 4.27 minutes for MS-Stingray. Envelope peak value varied from 59.0% for MS-Stingray to 72.1% for 'WB-Mayville'. It should be noted that the high- and low-ranking genotypes for both Mixograph parameters (EPT and EPV) were the same for both environments in 2015.

As occurred in Environment 1, MT 1 had the lowest FPC and the highest FY, and although MT had significant effects at the (*P*<0.10) value for FPC, FY, and EPT, differences between treatments were inconsistent. While the split application of N in MTs 2-5 appeared to increase FP, FY, and EPT, several of these MTs were statistically similar to MT 1 for all parameters. Due to these inconsistencies it is impossible to make any conclusions about the effects of MT. There were no MT by genotype interaction effects for FPC, FY, or EPT. However, five of the sixteen genotypes had a very significant MT by interaction effect for EPV. These five genotypes varied greatly maturity and disease resistance characteristics, and there is no discernable trend for interaction of MT and genotype for EPV. Other published research has noted that the main effects of genotype are much more important than any genotype by management interaction effects for quality traits (Gutierri, et al, 2000; Souza et al., 2004; Otteson et al., 2008).

Environment 3 – Agar 2016

The weather conditions at the Agar trial location in 2016 were characterized by a wet April followed by warm and dry conditions for the remainder of the growing season. (Table 3-3). Precipitation was 4.0 inches above normal in April and temperatures were near normal. May, June, and July were -0.5, -2.2, and -1.8 inches below normal for precipitation, respectively, and temperatures were 1.8°F, 4.4°F, and 0.5°F above normal. Growing degree days (GDD) (F°) were above normal in April, May, and June before returning to near normal in July. Harvest occurred on August 3rd, so August weather had no influence on this trial location. Heat during and following anthesis can be detrimental to both starch and protein production in wheat, and the effects may vary considerably between genotypes (Stone and Nicolas, 1994). However, the heat at Environment 3 seemed to occur early enough in the season that grain quality was not affected. Overall, Environment 3 had the highest average FPC and EPT, the second lowest FY and EPV of the four environments.

Analysis of variance for quality parameters showed a very highly significant response to genotype for all parameters (P <0.001) (Table 3-5). The only significant response to management treatment (MT) was for FPC (*P* <00.05). There were no significant MT by genotype interaction effects. In addition, block (repetition) was a not a significant source of variation for any of the test parameters.

Quality parameter means for genotype are summarized in Table 3-6. Flour protein content varied from 12.5% for MS-Stingray to 15.3% for 'SD4451'. Flour yields ranged from 59.2% for WB-Mayville to 64.9% bu/acre for Prevail. Envelope peak time varied from 2.52 minutes for 'SD4471' to 5.46 minutes for Prevail. Envelope peak value varied from 58.5% for MS-Stingray to 70.1% for Boost.

Management treatment effects are summarized in Table 3-7. Management treatment 1, which had all N applied as surface broadcast urea, had the lowest FPC over all varieties. However, while the FPC of MT 1 was significantly lower than MT 3 and 4, it was similar to MT 2 and 5, providing inconclusive results on the effects of MT on FPC at Environment 3. Management treatment had no effect on FY, EPT, or EPV. As mentioned previously, there were no significant MT by genotype interaction effects. The main and subplot coefficients of variation (CV) for the mixing parameters (EPT and EP were substantially higher than those observed at Environments 1 and 2. The CVs for EPV were only slightly higher than at Environment 4.

Environment 4 – Northville 2016

The weather conditions at the Northville trial location in 2016 were very similar to those of Agar in 2016, and were characterized by a wet April followed by warm and dry conditions for the remainder of the growing season. (Table 3-3). Precipitation was 1.8 inches above normal in April and temperatures were 2.7°F above normal. June and July were -2.0 and -0.9 inches below normal for precipitation, respectively, and temperatures were 5.3°F, and 1.5°F above normal. Growing degree days (GDD) (F°) were above normal in April, May, and June before returning to near normal in July. Harvest occurred early enough that August weather had no influence on this trial location. Overall, Environment 4 had the lowest average FPC and EPV and second-highest FY and EPT (tied with Environment 1) of the four environments.

Analysis of variance for agronomic characteristics showed a highly significant response to genotype (P <0.001) for all quality parameters (Table 3-5). There were no significant MT effects or genotype by MT interaction effects for any of the response variables. Unfortunately, block (repetition) was a significant source of variation (P<0.05) for both FY and EPT. Trial results were affected by soil variability (which cannot be accounted for in the soil series descriptions) which was brought on by warm and dry conditions in June and July. Blocks three and four were severely affected by this soil variability, which potentially confounded test results at this location. The coefficients of variation (CV) for FPC, FY, and EPV were higher than at any other trial location. The CVs for EPT were only slightly higher at Environment 3.

Quality parameters for the HRSW genotypes are summarized in Table 3-6. Flour protein content varied from 12.0% for MS-Stingray to 14.0% for 'SD4393'. Flour yields ranged from 59.7% for Select to 64.3% bu/acre for Prevail. Envelope peak time varied from 2.74 minutes for SD4471 to 4.21 minutes for SY-Ingmar. Envelope peak value varied from 57.9% for MS-Stingray to 70.1% for SD4451.

Combined Environments

The significance of mean squares in the analysis of variance for quality parameters as affected by environment, treatment, genotype, and their interactions are reported in Table 3-8. As mentioned in the previous sections, climatic conditions varied widely over all four locations, but tended to be warmer and drier than the 30-year averages. Analysis of variance showed environment to be a very highly significant source of variation for FPC, FY, and EPT ($P<0.001$), and a highly significant source of variation for EPV ($P<0.05$). Previous research in South Dakota has shown environment, and more specifically, heat and humidity following anthesis and during grain-filling, to be a significant source of variation for mixing properties and flour protein characteristics (Caffe-Treml et al., 2011). Karki et al. (2016) showed that weather data combined with FPC and EPT and other parameters could be used to improve prediction models for bread loaf volume at two South Dakota locations. Other studies examining the interaction of genotype and production environment in the upper Great Plains and Canada have also noted environmental effects on the quality of HRSW (Busch et al., 1969; McGuire et al., 1974; Lukow and McVetty, 1991).

The effect of MT was very highly significant for FPC ($P<0.001$) and highly significant for FY ($P<0.05$). Flour protein content was lowest for MT 1, and while MTs 2-5 were statistically similar, MT 4 was also similar to MT 1. Therefore, it is impossible to say that N application timing had a consistent effect on FPC. There were also no consistent effects on FY, other than that MT 5 was different than MT 1. Due to the step-up nature of the treatments in this study, it is impossible to isolate which of the treatments applied to MT 5 caused the differentiation in FP from MT 1. Other recent research has also shown that N application timing can have inconsistent effects on both flour characteristics and Mixograph parameters (Souza et al., 2004, Otteson, et al, 2008; Corassa, et al., 2018). However, research on hard red winter wheat (HRWW) performed in South Dakota suggested that N stress can result in weaker and less stable dough (Kharel et al., 2011). The lack of differences between MT 2 and MTs 3-5 suggest no response to fungicide for either FPC or FY. Effects on wheat quality when disease pressure is limited or even moderate have generally shown to be minimal (Hermann et al., 1996; Puppala et al., 1998; Saunders and Salman, 2000).

The effect of block nested within environment was significant ($P<0.001$) for FY only. There were no significant MT by environment effects. As mentioned previously, differences in MT response to quality between environments would typically be due to weather variations, such as heat and the timing and amount of precipitation, and other factors resulting from conducive weather conditions, such as disease pressure. It seems that, in this trial, weather differences between testing environments were not significant enough to affect response to management. Other research has shown similar results. Souza et al. (2004) did not notice any treatment by environment effects on FY, FPC, Mixograph tolerance, or bake mixing time when examining N application rates on seven HRSW genotypes over environments. This study examined both moisture-limited and irrigated conditions and found no significant MT by environment interactions for quality parameters under either moisture regime.

The HRSW genotypes varied widely for agronomic traits measured (Table 3-9) and the effect of genotype was very highly significant for all quality parameters ($P<0.001$). Genotype can often be the most significant factor in end-use quality in MT by genotype (Souza et al., 2004; Otteson et al., 2008) or genotype by environment studies (Lukow and McVetty, 1991). However, research by Caffe-Treml et al. (2011) suggests that as the amount of testing environments increases, environment may become a larger source of variation than genotype for quality parameters. In a study of 19 genotypes over 18 environments, environment was a larger source of variation than genotype for FPC and EPV and nearly the same for EPT.

Genotype by environment interaction effects were very highly significant for FP, EPT, and EPV (P<0.001), and highly significant for FY (P<0.05). Results from this study seem to agree with Canadian research that found highly significant cultivar by environment interactions for all quality parameters measured, including FPC, FY, and Mixograph development time (Lukow and McVetty, 1991). It should be noted that growing conditions for all environments in this study were nearly ideal. In contrast, Souza et al. (2004) did not see any genotype by environment interactions for FPC, FY, or Mixograph parameters on HRSW in Idaho. McGuire and McNeal (1971) suggest that genotype by environment interactions can only properly be assessed when several locations are examined.

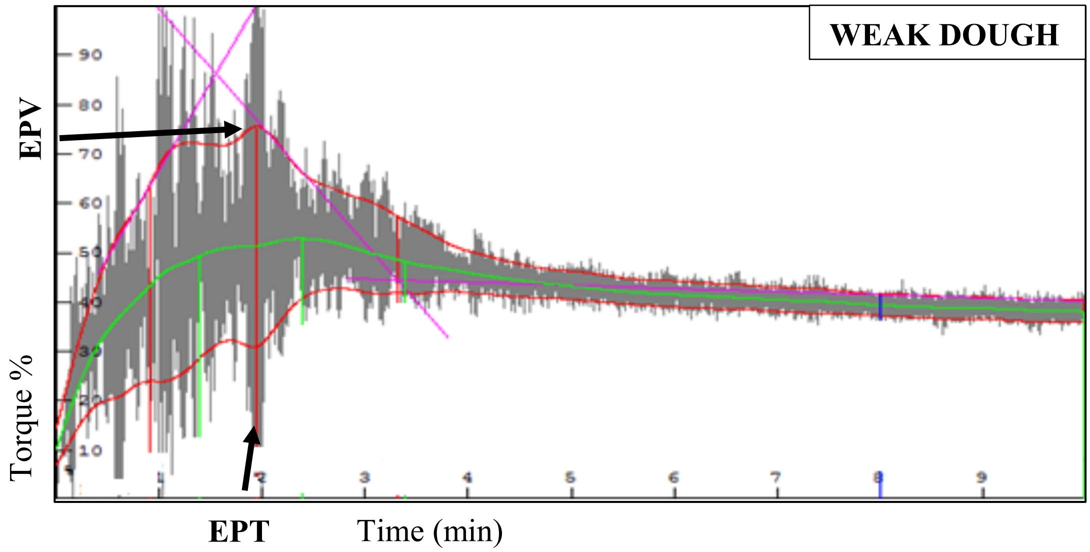
There were no significant interactions of genotype by management or three-way effects of genotype by environment by management. The literature suggests that the main effects of management and thus any interaction with these main effects seldom has an effect on quality parameters, especially with weather conditions are less than ideal for HRSW production. Results from this study seem to be agree with previously research conducted on HRSW in Idaho (Souza et al., 2004) and North Dakota (Otteson et al., 2008) where intensive management treatments had no effects on flour quality and Mixograph parameters.

Pearson correlation coefficients along with significance levels for the four quality parameters are summarized in Figure 3-2 where scatterplots fitted with regression lines are displayed along with distribution curves and correlation coefficients for each parameter. Flour protein content had a positive correlation (r = 0.52) with EPV and a negative correlation (r = -0.20) with EPT. These correlations are very similar to those observed previously in South Dakota by Caffe-Treml et al. (2010). While GPC, and correspondingly FPC, are often considered inadequate quality measurements in regards to breadmaking, they still may be the best overall crude indicator of the suitability of a genotype for certain end-use qualities (Souza et al., 2004).

Conclusion

Hard red spring wheat genotypes were evaluated under five management regimes over years and locations in South Dakota to examine quality parameter response to management, environment, and their interaction effects. While N fertilizer application timing and method seemed to have an effect on flour yield and flour protein content, responses were inconsistent. There were no consistent effects on any of the quality parameters by the application of any of the fungicide, insecticide, or chloride treatments. No management by genotype interaction was observed for any of the quality parameters. Overall, genotype, followed by environment, were the most important factors in determining grain quality and mixing performance. The significant interactions effects between genotype and environment observed in this study suggest these relationships should be studied by breeders and end-users when both developing and selecting HRSW genotypes for certain end-use qualities.

Techniques for intensive management of wheat were primarily developed for winter wheat producing areas with humid climatic conditions. Our study environments were predominantly warm and dry, which may explain why the intensive management techniques implemented in this study did not have consistent effects on the quality parameters in any of the genotypes tested. Literature suggests that cultivar-specific responses to management inputs seem to be environmentally dependent, relating primarily to heat, precipitation, and the presence of disease. Therefore, results from this study should not be used to predict effects of management in areas with ideal growing conditions and/or heavy disease pressure.



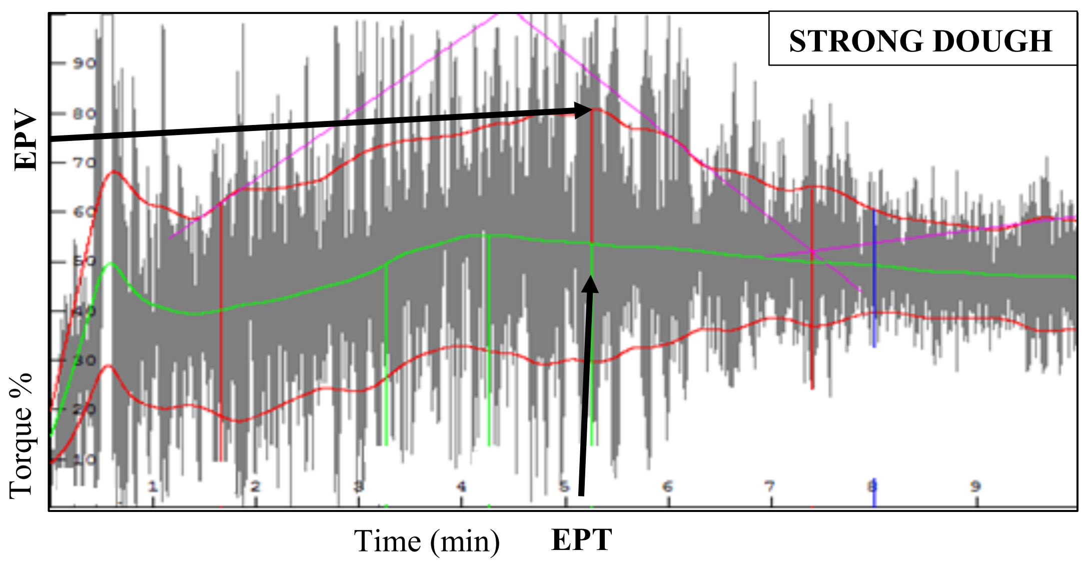


Figure 3-1. Annotated mixograms showing Envelope Peak Value (EPV) and Envelope Peak Time (EPT) for examples of weak and strong dough.

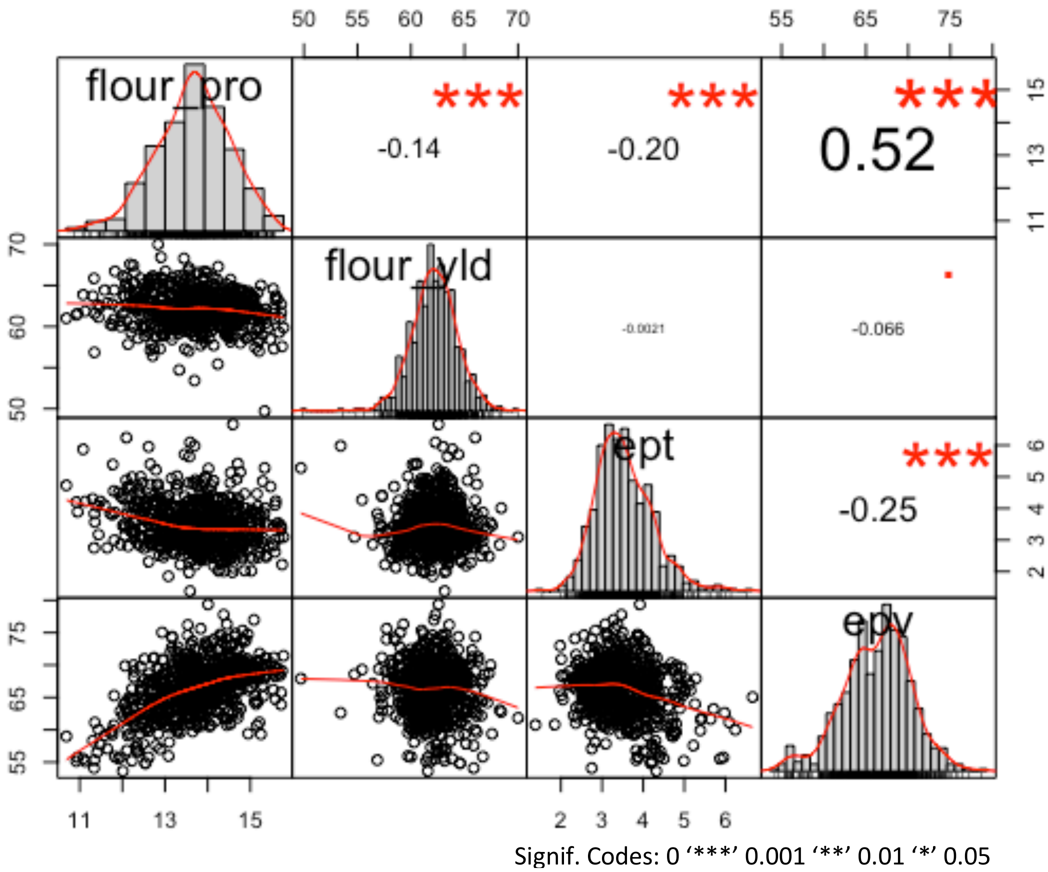


Figure 3-2. Lattice plot showing Pearson correlation coefficients along with significance levels, distribution curves, and scatterplots with regression lines for HRSW quality parameters.

Table 3-1. Trial locations along with soil types and soil series descriptions for four South Dakota environments.

Environment	Location	Year	GPS coordinates	Soil type	Soil series description
1	Agar	2015	44.948030° -100.083972°	Agar silt loam, 0-2% slopes	Fine-silty, mixed, superactive, mesic Typic Argiustoll
2	Northville	2015	45.158557° -98.565832°	Harmony-Aberdeen silty clay loams, 0-2% slopes	Harmony - fine, smectitic, frigid Pachic Argiudoll Aberdeen - Fine, smectitic, frigid, Glossic Natrudoll
3	Agar	2016	44.943959° -100.122906°	Eakin-Raber complex, 0-2% slopes	Eakin - Fine-silty, mixed, superactive, mesic, Typic Argiustoll Raber - Fine, smectitic, mesic, Typic Argiustoll
4	Northville	2016	45.158586° -98.570113°	Harmony-Aberdeen silty clay loams, 0-2% slopes	Harmony - fine, smectitic, frigid Pachic Argiudoll Aberdeen - Fine, smectitic, frigid, Glossic Natrudoll

Table 3-2. Summary of soil analyses and plot management at four South Dakota environments.

Environment	Location	Year	soil pH	N (lb/ a^{-1})	Bray P (ppm)	K (ppm)	Previous crop	Row spacing	Planting date	Harvest date
1	Agar	2015	6.4	8	20	364	soybeans	7"	4/1/15	8/14/15
2	Northville	2015	6.8	9	24	379	soybeans	8"	4/1/15	8/14/15
3	Agar	2016	6.2	18	12	407	field peas	7"	3/29/16	8/3/16
4	Northville	2016	6.7	12	27	388	soybeans	8"	3/29/16	8/3/16

Table 3-3. Average monthly temperatures and precipitation at four South Dakota environments.

				Temperature			Precipitation		
Environment	Location	Year	Month	Avg	30 yr Avg	Deviation	Avg	30 yr Avg	Deviation
				------------------F°-----------------			----------------- in ----------------		
1	Agar	2015	April	47.3	43.5	+3.8	0.7	1.8	-1.1
			May	53.0	55.1	-2.1	5.1	2.9	+2.2
			June	66.4	64.8	+1.6	2.1	3.5	-1.4
			July	71.6	71.4	+0.2	1.7	2.9	-1.2
			August	68.9	69.7	-0.8	3.2	2.4	+0.8
2	Northville	2015	April	50.2	44.3	+5.9	1.2	2.1	-0.9
			May	56.3	56.9	-0.6	6.0	3.2	+2.8
			June	69.3	66.5	+2.8	3.4	3.3	+0.1
			July	73.2	72.1	+1.1	4.9	3.1	+1.8
			August	69.4	69.6	-0.2	4.8	2.8	+2.0
3	Agar	2016	April	44.8	43.5	+1.3	5.8	1.8	+4.0
			May	56.9	55.1	+1.8	2.4	2.9	-0.5
			June	69.2	64.8	+4.4	1.3	3.5	-2.2
			July	71.9	71.4	+0.5	1.1	2.9	-1.8
			August	69.9	69.7	+0.2	3.3	2.4	+0.9
4	Northville	2016	April	47.0	44.3	+2.7	3.9	2.1	+1.8
			May	59.5	56.9	+2.6	3.9	3.2	+0.7
			June	71.8	66.5	+5.3	1.3	3.3	-2.0
			July	73.6	72.1	+1.5	2.2	3.1	-0.9
			August	71.9	69.6	+2.3	1.5	2.8	-1.3

Table 3-4. Descriptions of sixteen hard red spring wheat genotypes.

Genotype	Origin‡	Year of release	Maturity	Disease reactions† Stem rust	Leaf rust	Tan spot	FHB§
Advance	SD	2011	Medium	MR	MR	S	MR
Boost	SD	2015	Late	MR	MR	MR	MS
Faller	ND	2007	Med. late	R	S	S	MR
Focus	SD	2014	Early	MR	S	MS	MR
Forefront	SD	2011	Med. early	MR	MS	S	MR
MS-Stingray	MS	2014	Late	MR	S	S	MR
Prevail	SD	2014	Early	MR	MS	MR	MR
SD4393	SD	-	Early	MR	MR	MR	MR
SD4451	SD	-	Early	MR	MR	MR	MR
SD4471	SD	-	Medium	MR	MS	S	MR
Select	SD	2009	Early	MR	MR-MS	S	MR
Surpass	SD	2015	Early	MR	MR	MS	MR
SY-Ingmar	AP	2014	Med. late	MS	MR	MR	MR
SY-Rowyn	AP	2013	Medium	R	MS	MS	R
SY-Soren	AP	2011	Med. late	R	MR	-	MR
WB-Mayville	WB	2007	Med. early	MS	S	S	S

†S - susceptible; MS - moderately susceptible; MR - moderately resistant; R - resistant

‡AP - Agripro; MS - Meridian Seeds; ND - North Dakota; SD - South Dakota; WB - Westbred

§Fusarium Head Blight

Table 3-5. Significance of mean squares in the analysis of variance for HRSW quality parameters as affected by main factors and their interactions at four South Dakota environments.

Source of variation	df	FPC†	FY	EPT	EPV	FPC	FY	EPT	EPV
		Agar 2015 - Environment 1				Northville 2015 - Environment 2			
block (replication)	3	0.423	0.880	0.864	0.363	0.450	0.146	0.218	0.128
treatment	4	0.009	0.622	0.274	0.508	0.089	0.099	0.079	0.126
error(a)	12								
genotype	15	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
treatment:genotype	60	0.343	0.358	0.709	0.290	0.302	0.175	0.872	0.025
error(b)	225								
		Agar 2016 - Environment 3				Northville 2016 - Environment 4			
block (replication)	3	0.760	0.060	0.487	0.303	0.627	0.019	0.038	0.548
treatment	4	0.032	0.550	0.480	0.620	0.531	0.231	0.372	0.724
error(a)	12								
genotype	15	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
treatment:genotype	60	0.751	0.196	0.336	0.192	0.989	0.331	0.986	0.655
error(b)	225								

†FPC - Flour protein content; FY - Flour yield; EPT - Mixograph Envelope Peak Time;
EPV - Mixograph Envelope Peak Value

Table 3-6. Genotype means for the quality parameters of sixteen hard red spring wheat genotypes over four South Dakota environments.

	Environment															
	Flour protein content				Flour yield				Envelope peak time				Envelope peak value			
Genotype	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
	------------ % ------------				------------ % ------------				------------ min ------------				---------- torque % ---------			
Advance	13.3	13.5	13.7	12.7	61.1	62.4	61.1	62.7	3.71	3.46	4.14	3.25	64.25	66.3	65.3	64.5
Boost	14.2	14.6	14.8	13.7	59.5	62.0	61.8	61.0	3.19	2.99	3.68	3.36	69.74	70.4	70.1	68.4
Faller	12.6	12.8	13.6	12.6	62.7	65.0	63.6	62.8	3.30	3.33	3.97	3.29	63.33	66.2	64.5	66.0
Focus	13.5	14.0	14.1	13.5	62.2	63.4	63.1	63.1	3.38	3.14	3.88	3.42	65.27	67.9	66.1	66.0
Forefront	13.5	13.8	14.3	13.1	61.7	63.9	63.3	62.6	3.17	2.95	3.41	3.00	66.92	68.5	66.2	66.1
MS-Stingray	12.1	12.1	12.5	12.0	61.7	63.3	63.0	63.0	4.42	4.27	4.76	3.99	58.47	59.0	58.5	57.9
Prevail	13.2	13.6	14.0	12.6	63.4	64.5	64.9	64.3	3.12	2.83	3.81	3.27	66.02	66.3	66.8	62.4
SD4393	13.6	14.1	14.8	14.0	61.5	63.0	62.6	63.1	3.33	3.28	3.98	3.42	66.24	67.9	67.9	67.0
SD4451	14.2	14.5	15.3	13.9	60.7	63.5	62.3	62.8	2.96	2.92	3.53	2.94	67.60	68.3	65.0	67.7
SD4471	13.8	13.6	14.2	13.4	59.7	61.6	62.6	62.8	2.78	2.65	2.72	2.74	65.76	64.6	62.9	63.3
Select	13.2	13.9	13.5	13.0	60.4	60.5	60.5	59.7	3.26	3.31	3.99	3.34	62.94	65.9	61.7	66.0
Surpass	13.2	13.9	14.1	13.0	61.7	63.0	61.8	62.7	4.40	4.16	5.46	3.95	65.10	67.7	64.3	65.4
SY-Ingmar	14.9	14.6	15.1	13.4	61.1	62.8	60.7	62.7	3.08	3.63	4.15	4.21	68.58	69.0	68.4	66.7
SY-Rowyn	13.6	13.8	14.2	12.5	62.0	64.1	62.8	62.9	3.61	3.67	4.51	3.77	69.66	71.5	69.5	66.5
SY-Soren	14.7	14.5	15.0	13.5	58.7	61.7	61.3	60.6	2.52	2.41	3.03	3.30	68.18	67.6	67.3	66.4
WB-Mayville	13.2	13.6	15.1	14.0	59.1	61.8	59.2	59.8	3.51	3.34	3.09	3.65	71.33	72.1	69.4	67.4
Average	13.6	13.8	14.3	13.2	61.1	62.9	62.2	62.3	3.4	3.3	3.9	3.4	66.2	67.4	65.9	65.5
HSD (0.05)	0.6	0.55	0.7	1.2	1.3	1.7	2.5	3.4	0.57	0.59	0.66	1.13	4.04	3.9	4.2	5.2
CV (%)	2.7	2.5	2.9	5.9	1.3	1.7	2.5	3.5	10.8	11.3	10.8	20.9	3.9	3.7	4.0	5.0

Table 3-7. Treatment means for the quality parameters of sixteen hard red spring wheat genotypes over four South Dakota environments.

	Environment															
	Flour protein content				Flour yield				Envelope peak time				Envelope peak value			
Treatment	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
	------------ % ------------				------------ % ------------				------------ min ------------				---------- torque % ---------			
1	13.1	13.4	13.9	13.0	61.6	63.2	62.3	63.5	3.43	3.34	3.96	3.35	65.4	68.6	66.3	64.7
2	14.0	13.8	14.3	13.3	60.8	62.8	62.4	63.0	3.20	3.27	3.77	3.41	67.7	67.1	67.0	64.8
3	13.8	13.9	14.5	13.4	60.9	62.7	62.1	62.0	3.32	3.38	3.80	3.57	66.2	67.5	65.5	67.0
4	13.4	14.0	14.4	12.8	61.3	62.9	62.1	61.8	3.37	3.15	3.74	3.52	65.5	68.0	66.3	64.9
5	13.4	14.0	14.2	13.5	60.8	62.9	61.8	61.2	3.47	3.22	4.14	3.31	66.3	66.0	64.3	65.9
Mean	13.6	13.8	14.3	13.2	61.1	62.9	62.2	62.3	3.36	3.27	3.88	3.43	66.2	67.4	65.9	65.5
HSD (0.05)	0.5	0.8	0.5	1.9	2.6	0.5	1.7	4.0	0.48	0.26	0.86	0.60	5.8	3.2	7.5	8.5
CV(%)	3.4	5.0	3.0	13.1	3.8	0.8	2.4	5.8	12.9	7.1	23.9	14.8	7.9	4.3	10.3	11.6

Table 3-8. Significance of mean squares in the analysis of variance as affected by main factors and their interaction for four combined South Dakota environments.

	df	FPC†	FY	EPT	EPV
environment	3	<0.001	<0.001	<0.001	0.048
treatment	4	<0.001	0.034	0.396	0.697
environment:block	4	0.842	<0.001	0.111	0.406
environment:treatment	12	0.217	0.398	0.225	0.516
error (a)	16				
genotype	15	<0.001	<0.001	<0.001	<0.001
genotype:environment	45	<0.001	0.006	<0.001	0.003
genotype:treatment	60	0.905	0.147	0.584	0.120
genotype:environment:treatment	180	0.986	0.155	0.998	0.145
error (b)	300				

†FPC - Flour protein content; FY - Flour yield; EPT - Mixograph Envelope Peak Time; EPV - Mixograph Envelope Peak Value

Table 3-9. Management treatment and genotype effects on the flour and mixing parameters of sixteen HRSW genotypes at four combined South Dakota environments.

		Flour protein	Flour yield	Envelope peak time	Envelope peak value
		%	%	min	torque %
Treatment	1	13.4	62.7	3.52	66.3
	2	13.8	62.3	3.41	66.6
	3	13.9	61.9	3.52	66.5
	4	13.7	62.0	3.44	66.2
	5	13.8	61.7	3.54	65.6
	HSD (0.05)	0.4	0.9	0.22	2.3
	CV (%)	7.2	3.7	16.8	8.9
Genotype	Advance	13.3	61.8	3.64	65.1
	Boost	14.3	61.1	3.30	69.7
	Faller	12.9	63.5	3.47	65.0
	Focus	13.8	62.9	3.45	66.3
	Forefront	13.7	62.9	3.13	67.0
	MS-Stingray	12.2	62.7	4.36	58.5
	Prevail	13.4	64.3	3.26	65.4
	SD4393	14.1	62.6	3.50	67.3
	SD4451	14.5	62.3	3.09	67.2
	SD4471	13.8	61.7	2.72	64.2
	Select	13.4	60.3	3.48	64.1
	Surpass	13.5	62.3	4.49	65.6
	SY-Ingmar	14.5	61.8	3.77	68.2
	SY-Rowyn	13.5	62.9	3.89	69.3
	SY-Soren	14.4	60.6	2.81	67.4
	WB-Mayville	14.0	60.0	3.40	70.0
	HSD (0.05)	0.4	1.6	0.38	2.1
	CV (%)	3.7	2.4	14.0	4.2
	Average	13.7	62.1	3.49	66.3

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CHAPTER 4: SUMMARY AND CONCLUSIONS

Wheat is an essential food crop throughout the world and one of the most important cereal crops in South Dakota. Hard red spring wheat (HRSW) grain yields in South Dakota are often lower than other parts of the country, due in part to environmental conditions. However, both HRSW grain yield and quality are a complex function of not only environment, but genotype, management, and their interactions. Intensive agronomic management programs have been used to increase wheat yields with success in Europe and other parts of the United States. Response to management and environment is often genotype-specific. Identifying positive genotype by management interactions offers a potential avenue for increasing wheat yield potential and both plant breeders and producers should understand these relationships. Studies carried out to construct this dissertation concentrated on the agronomic and end-use qualities of HRSW grown in South Dakota as affected by management treatment and environment.

Studies involving intensive management and HRSW in South Dakota seem to be entirely absent from the literature. Due to this fact, sixteen hard red spring wheat genotypes were evaluated under five management regimes over years and locations in South Dakota to examine agronomic response to management and genotype by management interaction effects. While N fertilizer application timing and method seemed to have an effect on grain yield and grain protein content, confounding environmental factors make these findings inconclusive. It has been theorized that N fertilizer application methods and timing often do not have an effect in HRSW due to the relatively short growing season. Fungicide application, especially at anthesis, is often considered to have a positive effect on yield and quality. However, treatments involving fungicide were also inconclusive. An early season application of fungicide and insecticide combined with a late-season application of fungicide increased yields versus no fungicide but not versus a single late-season application of fungicide. The application of fungicide at anthesis did not increase grain yields, or affect test weight or grain protein content versus no fungicide. Although positive yield effects resulting from the application of potassium chloride to HRSW have been well documented in South Dakota, the application of chloride had no effect on any of the agronomic traits in this study. No predictable management by genotype interaction was observed for any of the agronomic traits. Techniques for intensive management of wheat were primarily developed for winter wheat producing areas with humid climatic conditions. Our study environments were predominantly warm and dry, which may explain why the intensive management techniques implemented in this study did not have consistent effects on the agronomic characteristics in any of the genotypes tested. Our findings support the previously documented suggestions that genotype-specific responses to management inputs are environmentally dependent, relating primarily to heat, precipitation, and the presence of disease.

One of the most common uses for HRSW is bread production. Millers and bakers understand that environment and management can have an impact on the quality characteristics intrinsic for consistent and quality breadmaking. The quality response of HRSW genotypes to environment in South Dakota has been well documented. However, this study sought to examine both environmental and management treatment effects on HRSW genotypes. Flour protein content and flour extraction are two commonly measured traits in wheat flour. Dough rheological properties can be measured by a number of instruments. Because of its relatively small flour requirement (10g), the Mixograph is a widely preferred method of evaluating genotypes for their mixing properties. This method is fairly quick (10 min) and distinguishes flour samples for their mixing time, consistency and tolerance to over-mixing. While the Mixograph measures several parameters, envelope peak time and envelope peak value have been shown to be good indicators of dough consistency and mixing tolerance, respectively. Grain samples from the previously discussed agronomic study were processed and analyzed for flour and dough parameters. There were no consistent effects on any of the quality parameters by the application of any of the N fertilizer timing, fungicide, insecticide, or potassium chloride treatments. In addition, no management by genotype interaction was observed for any of the quality parameters. Overall, genotype, followed by environment, were the most important factors in determining flour quality and mixing performance. Results of this study suggest that genotype and environment are significantly more important determinants of wheat end-use quality than management practices in the relatively arid production region of central South Dakota.