INTRODUCTION

Grain sorghum is an important crop in semi-arid regions around the world due to drought tolerance (Hattendorf et al., 1988), high nutrient use efficiency (Maranville et al., 1980), ethanol production (Zhao et al., 2008; Wu et al., 2007), and is used as feed and forage for livestock (Kriegshauser et al., 2006), and human food uses. Interest in white-grain sorghum for use in human food products has generated the need for research about the interaction effects of genotype and environment on grain quality. Sorghum grain is used to make thin or stiff porridges and fermented beverages (Lochte-Watson et al., 2000), as a partial replacement for maize (Zea mays L.) in tortilla production (Almeida-Domínguez et al., 1991) and wheat (Triticum aestivum L.) flour in leavened or unleavened breads, brewing (Figueroa et al., 1995), fuel ethanol (Zhao et al., 2008; Wu et al., 2007), and to make many types of snack foods (Rooney, 1996). Sorghum flour is gluten free, making it a desirable food product for humans with gluten intolerance (Fasano and Catassi, 2001).

Limited research on the interaction of genotype (G) and environment (E) influence on grain quality of sorghum has been conducted. Sorghum grain yield and protein concentration increases with increasing N supply (Kaye et al., 2007; Kamoshita et al., 1998). High temperatures and water stress lowers starch concentration (Johnson et al., 2010), and an increased N supply usually increases kernel hardness (Kaye et al., 2007). Irrigation results in softer kernels than under rainfed conditions (Taylor et al., 1997). Dry milling and alkaline cooking for human food products is best with hard kernels (Johnson et al., 2010; Shandera et al., 1997) while wet millers and brewers prefer soft to intermediate kernel hardness with low protein concentration (Fox et al., 1992).

Rapid visco starch analysis (RVA) is an instrument/method that relates biochemical components to hardness and density (Fox and Manley, 2009; Almeida-Domínguez et al., 1997; Barbosa Pinto et al., 2009; Narváez-González et al., 2007). This instrument measures the viscosity developed during hydration and subsequent gelatinization of starch granules during heating and stirring in excess water (Almeida-Domínguez et al., 1997). It measures the pasting temperature when gelatinization begins and peak viscosity at full gelatinization. When held at the maximum temperature and stirred, the starch polymers become oriented and the viscosity declines to the trough viscosity or holding strength. The difference between peak and trough viscosity is termed breakdown viscosity; a low breakdown viscosity indicates shear-force stability under heated conditions. As the
temperature is lowered, the viscosity increases to a final viscosity, with the difference between the final and trough viscosities being termed the setback viscosity. These starch viscosity properties help predict the functionality of food products.

High peak, final and setback viscosities has been associated with high ethanol yield from sorghum grain (Zhao et al., 2008); high pasting temperatures with the need for intensive cooking to produce high consumable alcohol yields (Agu et al., 2006); and low peak and final viscosities are associated with softer endosperm, greater expansion of starch during cooking, and production of less stiff porridges (Taylor et al., 1997). It has been used to determine the effect of processing on tortilla quality (Gomez et al., 1992); pasting characteristics of maize, wheat and potato (Solanum tuberosum L.) starch (Deffenbaugh and Walker, 1989); starch viscosity association with noodle quality made from sorghum grain (Beta and Corke, 2001); and to assess genetic diversity in South African sorghum land races for starch properties (Beta et al., 2001). Ragae and Abdel-Aal (2006) tested whole sorghum flours and found higher paste stabilities than for barley (Hordeum vulgare L.), pearl millet (Pennisetum glaucum (L.) R. Br.) or rye (Secale cereal L.), indicating sorghum grain’s high potential as an ingredient in food products with exposure to high temperatures and mechanical stirring. Most studies have used RVA to study sorghum kernel properties and/or genetic differences (Beta and Corke, 2001), and none have jointly studied genotype-by-environment interaction (GE) influence on starch concentration and viscosity.

In a companion study that included both white and red grain sorghums, E was found to have the largest effect on variation in grain yield, kernel mass, kernel density and composition and starch viscosity properties; G to have intermediate effect; and the GE had minor importance (Griess et al., 2010; 2011). This research indicated that dryland production environments with non-limiting N supply produced dense sorghum kernels with high protein and low starch concentrations as also reported by Johnson et al. (2010), Taylor et al. (1997) and Kaye et al. (2007), while irrigated production produced softer grain (Griess et al., 2010; Taylor et al., 1997). Unfortunately, the results of RVA starch viscosity properties indicated that it was difficult to predict the effect of location and year on resulting sorghum flour parameters (Griess et al., 2011). Although of secondary importance in terms of total variation, white-grained sorghums were grouped based upon viscosity properties into those best suited for dry mill and alkaline cooked product uses and those best suited for porridge, consumable alcohol and ethanol production.

Genotype performance research studies are conducted in multiple locations, generally to assist plant breeding programs to develop cultivars for broad adaptation or for a target “environment”. This same strategy should be useful for food processing companies to select production environments and genotypes to provide desired quantity and quality of grain for use for specific food end uses. Processors desire consistent grain quality to reduce adjustments required from use for different batches of grain. In some cases, consistency of grain quality is more important than the actual level of desired grain quality attributes. Bi-plots are a useful way to allow visual analysis of GE effects, and the G main effect and the GE interaction can jointly be graphed as the GGE simultaneously, thus allowing evaluation of genotypes for their performance in individual environments and across environments (Yan et al., 2000; Yan and Tinker, 2005).

The objective of this research was to visually analyze the GGE of white sorghum kernel mass, starch concentration, and starch viscosity properties. These results help processors in selection of the best production areas and genotypes for different end uses of white sorghum grain.

MATERIALS AND METHODS

Field experiments were conducted in 12 Nebraska environments, with each location-year combination being considered an environment (Table 1). The environments were selected to be representative of an array of environments typical for sorghum production in Nebraska (NE). Eastern Nebraska experiments were conducted at the University of Nebraska Agricultural Research and Development Center near Mead, NE under furrow irrigation, dryland, and dryland with low N environments in 2004 and 2005. Central Nebraska experiments were conducted under dryland and furrow irrigated environments at the South Central Agricultural Laboratory, near Clay Center, NE, and in a farmer’s dryland field at Hebron, NE in 2004 and 2005. In 2005, a dryland location in west-central Nebraska was added near Orleans, NE. All commercial white-grained sorghum genotypes available in 2004 and adapted to Nebraska were included in the experiment. Ten commercial white-grained genotypes, and Macia, a high quality white-grained sorghum variety from Africa (Dlamini et al., 2007) were produced and data collected for grain yield, kernel mass, kernel hardness (true density, bulk density and tangential abrasive dehulling device removal), starch and protein concentration, and RVA starch viscosity parameters [Table 2, for more details, see Griess et al. (2010, 2011)]. Analysis of variance was completed (Table 3) with G and E considered to be fixed effects in the model, while block effects within an E were considered random. Genotype plus genotype-by-environment interaction effects for percentage of the total variation was considered, with percent of variation >18% considered as important GGE effects. For these variables a GGE bi-plot along with a rank of genotypes were generated, and visually assessed following procedures of Yan and Tinker (2005). The origin in the GGE bi-plot
corresponded to the average response for an environment. The closer a genotypic or environmental vector was to the origin, the smaller its contribution to the significance of GGE. A longer genotypic and/or environmental vector indicated the potential for a significant deviation from the average response. Correlations between environments/genotypes (or a genotype and an environment) was determined by the relative directions and angles of their vectors (i.e., low angle indicated high positive correlation). The optimal genotypes for each environment were determined by identifying genotypic and environmental vectors in close proximity to each other. Interpretation was based upon the fact that PC1 is usually based largely on the genotypic effect while PC2 is usually a measure of residual GE variation or non-genotypic effects (Yan et al., 2001; Yan and Rajcan, 2002). Stable genotypic responses were indicated by low variation around the PC2 zero axis. 

RESULTS AND DISCUSSION

**Percentage of total variation**: The ANOVA indicated that the E, G and GE effects were all declared highly significant for all parameters measured (Table 3). However, the GGE (i.e., G plus GE) interaction effect only accounted for 2.4 to 3.5% of the total variation for yield, bulk and true density and TADD removal, while accounting for 18.8 to 23.3% of the total variation for kernel mass, protein and starch concentrations, and all starch viscosity parameters measured. Environment was clearly the most important factor in performance for all parameters, especially for yield, and all the hardness measures (bulk density, true density and TADD removal). For the range of environments and genotypes in this study, GGE effects were of importance for kernel mass, protein and starch concentrations, and starch viscosity parameters. 

**Kernel mass**: The GGE bi-plot (Fig. 1) indicated that the 2005 environments at Mead Dryland, Mead Irrigated, Clay Center Dryland, Clay Center Irrigated and Orleans were similar, with Pioneer 84Y00 having the greatest kernel mass (25.0 to 33.3 g 1000 kernels). In the Mead Dryland 2005 environment, both Pioneer 84Y00 and Dekalb DK41-44 had heavy kernel mass (33.3 and 30.2 g 1000 kernels), while Mycogen 14665 has the lightest kernel mass (22.3 g 1000 kernels). Mead Low N 2004, Clay Center Dryland 2004, Mead Irrigated 2004 and Hebron 2005 environments made little contribution in the significance of GGE and all sorghum genotypes performed similarly in those environments as indicated by short vector lengths. In the environments Hebron 2004 and Clay Center Irrigated 2004, the genotype NK1486 produced the heaviest kernel mass (22.8 and 26.8 g 1000 kernels). The GGE effects for the genotypes Asgrow Orbit, Macia and Dekalb DK41-44 were
Table 2. Characteristics of genotypes used in the study (Griess et al., 2010).

<table>
<thead>
<tr>
<th>Genotype</th>
<th>Bi-Plot Abbreviation</th>
<th>Glume Color</th>
<th>Maturity Class</th>
<th>Yield</th>
<th>Kernel Mass</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sorghum Partners NK8828</td>
<td>NK88</td>
<td>Tan</td>
<td>Full</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Asgrow Eclipse</td>
<td>Ecl</td>
<td>Tan</td>
<td>Medium</td>
<td>Low</td>
<td>Intermediate</td>
<td>Low</td>
</tr>
<tr>
<td>Asgrow Orbit</td>
<td>Orb</td>
<td>Tan</td>
<td>Medium</td>
<td>High</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Kelly Green Seed KG6902</td>
<td>KG</td>
<td>Tan</td>
<td>Full</td>
<td>High</td>
<td>Intermediate</td>
<td>Low</td>
</tr>
<tr>
<td>Fontanelle W-1000</td>
<td>Font</td>
<td>Tan</td>
<td>Medium</td>
<td>High</td>
<td>Intermediate</td>
<td>High</td>
</tr>
<tr>
<td>NC+ 7W92</td>
<td>NC+</td>
<td>Tan</td>
<td>Medium</td>
<td>Intermediate</td>
<td>Intermediate</td>
<td>Low</td>
</tr>
<tr>
<td>Sorghum Partners NK1486</td>
<td>NK14</td>
<td>Tan</td>
<td>Medium</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Dekalb 44-41</td>
<td>DK44</td>
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<td>Medium</td>
<td>High</td>
<td>Intermediate</td>
<td>High</td>
</tr>
<tr>
<td>Mycogen 14665</td>
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<td>Tan</td>
<td>Full</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Macia</td>
<td>Mac</td>
<td>Tan</td>
<td>Medium</td>
<td>Low</td>
<td>Intermediate</td>
<td>High</td>
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<tr>
<td>Pioneer 84Y00</td>
<td>PS4Y</td>
<td>Purple</td>
<td>Full</td>
<td>High</td>
<td>High</td>
<td>Intermediate</td>
</tr>
</tbody>
</table>

Table 3. Degrees of freedom and mean squares for environment and genotype effects on white sorghum grain yield and quality.

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>Df</th>
<th>Yield</th>
<th>Kernel Mass</th>
<th>Bulk Density</th>
<th>True Density</th>
<th>TADD*</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Protein</td>
<td>Starch</td>
<td>Peak</td>
<td>Trough</td>
<td>Break down</td>
<td>Final</td>
</tr>
<tr>
<td>E</td>
<td>11</td>
<td>293**</td>
<td>765**</td>
<td>95,341**</td>
<td>0.1110**</td>
<td>8432**</td>
<td>4294**</td>
</tr>
<tr>
<td>R(E)</td>
<td>24</td>
<td>9</td>
<td>5</td>
<td>323</td>
<td>0.0002</td>
<td>18</td>
<td>222</td>
</tr>
<tr>
<td>G</td>
<td>10</td>
<td>9**</td>
<td>169**</td>
<td>2595**</td>
<td>0.0018**</td>
<td>252**</td>
<td>1306**</td>
</tr>
<tr>
<td>G x E</td>
<td>110</td>
<td>2**</td>
<td>9**</td>
<td>722**</td>
<td>0.0009**</td>
<td>54**</td>
<td>80**</td>
</tr>
<tr>
<td>Residual</td>
<td>234</td>
<td>239</td>
<td>1</td>
<td>3</td>
<td>168</td>
<td>0.0001</td>
<td>13</td>
</tr>
</tbody>
</table>

% of Total Variation

- G x E 0.7 1.0 0.7 0.8 0.6 1.3 1.7 0.9 3.7 4.4 2.4 2.3 1.4 3.4
- G + G x 3.5 18.8 3.3 2.4 3.5 23.3 21.2 38.1 23.5 32.8 28.0 29.3 20.8 34.6

*TADD = Tangential abrasive dehulling device, E = Environment, R = Replication, G = Genotype

**Residual degree of freedom varies across parameters due to missing values

**Significant at P ≤ 0.01

Closest to the origin, thus were the most stable genotypes for kernel mass across environments.

Figure 1. GGE bi-plot for kernel mass of 11 white sorghum genotypes produced in 12 environments.

Mycogen 14665, NK8828 and Asgrow Eclipse has the lowest kernel mass and Fontanelle W-100, NC+7W92 and KG6902 produced similar kernel mass since their means were near zero for PC1. In general there was low genotypic stability for kernel mass across environments, however Pioneer 84Y00, Dekalb DK41-44, and Mycogen 14665 were more stable than the other genotypes since their means were near the PC2 zero axis. The rank of genotypes confirmed the bi-plot analysis, and also indicated that Pioneer 84Y00 consistently produced the heaviest kernels in all Mead environments, and also the heaviest or second heaviest kernels at Clay Center Irrigated 2005, Hebron Dryland 2004, and Orleans 2005 environments. Heavy kernels are either larger, more dense or a combination of both. In this study, there was only a small amount of G variation due to hardness (Table 3) thus these differences were largely related to kernel size. Kernel mass may have been larger under dryland production due to lower plant populations (M’Khaitir and Vanderlip, 1992). Large kernels have been shown to produce higher rates of gain by poultry (Kriegshauser et al., 2006). The other obvious conclusion from the rank of genotype means is that the genotype Mycogen 14665 produced low kernel mass, with this genotype ranking lowest in 10 out of the 12 environments. These results suggest that an end user desiring large, relatively stable kernel mass grain would choose the Pioneer 84Y00 genotype produced in one of the Mead environments. If a white-grained genotype with tan glumes was desired, then the DK41-44 produced in the Mead environments would be the best choice.
Starch and protein concentrations: The GGE bi-plots of protein and starch concentration were essentially mirror images of each other, at least partially due to the negative correlation between them (r = -0.36, P < 0.001) as also reported by Wang et al. (2008). Therefore, only the starch concentration bi-plot is presented and discussed. The GGE bi-plot showed that the Mead Dryland 2005, Clay Center Dryland 2004, and Hebron 2005 environments were similar, also the Mead Irrigated 2004 and 2005, and the Mead Low N 2005 belonged to the same cluster of environments (Fig. 2). The long vectors for Mead Low N 2004 Hebron 2004, and Clay Center Irrigated 2005 environments indicated variable starch concentration responses for genotypes, while Orleans and Hebron 2005 had small variations as indicated by the short vector length. The Mead Low N 2005 environment was positively associated with the starch concentration of fontanelle W-1000, NC+7W92 and Kelly Green seeds 6902 sorghum genotypes, while NK1486 was negatively correlated, and had the lowest starch concentrations (684 g kg\(^{-1}\)). The Hebron 2004 environment was directly associated with the Mycogen14665.

Among the genotypes, NK1486 had the lowest starch concentration (684 g kg\(^{-1}\), range 623 to 702 g kg\(^{-1}\)), and was ranked in the bottom 2 in 6 out of 12 environments, and never ranked in the top 5. Fontanelle W-1000 had the highest starch concentration (705 g kg\(^{-1}\), range of 657 to 726 g kg\(^{-1}\)), and was ranked in the top 3 for 9 out of 12 environments and was never ranked in the bottom 3. The genotypes Kelly Green Seeds KG 6902 (top 3 in 7 out of 12 environments, 705 g kg\(^{-1}\), range 674 to 723 g kg\(^{-1}\)), NC+7W92 (top 3 in 5 out of 12 environments, 703 g kg\(^{-1}\), range of 652 to 723 g kg\(^{-1}\)), and Asgrow Eclipse (top 3 in 7 out of 12 environments, 703 g kg\(^{-1}\), 670 to 725 g kg\(^{-1}\)) also had high starch concentrations. The genotypes Dekalb DK41-44 and Macia were more stable than the other genotypes since their means were near the PC2 zero axis, however, Dekalb DK41-44 had higher starch concentrations than Macia. The results suggest that high starch concentration sorghum grain would likely be produced by FontanellaeW-1000, Kelly Green Seeds KG 6902, NC+7W92, and Asgrow Eclipse any of in Nebraska environments with adequate N present, while Dekalb DK41-44, with intermediate starch concentration, would produce the most consistent starch concentration across environments.

Peak, trough and breakdown starch viscosities: The GGE bi-plots for peak and trough starch viscosities were similar, and were a mirror image with breakdown starch viscosity, as would be expected based upon these parameters being highly correlated (r = 0.81 to 0.86; P < 0.001) as previously reported by Beta et al. (2000), thus only the GGE plot for peak viscosity is presented (Fig. 3). The Mead Low N 2004 environment had the greatest E influence on the GGE, producing an intermediate peak viscosity (1529cP). The Hebron 2004 environment was associated with the genotype Asgrow Eclipse, the Clay Center 2004 environments with Fontonelle W-1000 and inversely with NK1486, Mead low N 2005 and Mead Irrigated 2004 and 2005 environments with NC+7W92, and Clay Center and Mead Dryland 2005 with DekalbDK41-44 and Mycogen 14665, and inversely with Asgrow Orbit. The Clay Center and Mead 2005 Irrigated and Orleans 2005 environments were similar. The genotypes Macia, Asgrow Orbit, NK1486 and NK8828 produced the lowest peak viscosities, however NK8828 was more sensitive to GE. Clay Center Dryland 2005 exhibited the most stable peak viscosity as indicated by the short vector, and Pioneer 84Y00, Asgrow Eclipse and Kelly Green Seeds KG6902 were more stable than the other genotypes since their means were near the PC2 zero axis. Macia (1241 cP, range of 602 to 1596 cP), Asgrow Orbit (1324 cP, range of 914 to 1728cP) and NK1486 (1326 cP, range of 988 to1785) had the lowest peak viscosities and were in the bottom 3 in 7 to 9 environments and never ranked in the top 2. In contrast, NC+7W92 (1687 cP, range of 1415 to2129 cP), Kelly Green Seeds KG6902 (1678 cP, range of 1050 to 2117 cP) and Fontanelle W-1000 (1655cP, range of 1049 to 2142 cP) produced high peak viscosities, however NC+7W92 was the only genotype to rank in the top 3 in 9 out of 12 environments and never ranked in the bottom 4. Dry mill and alkaline cooked processors desiring low peak viscosities (Shandera et al., 1997; Johnson et al., 2010) should contract for production of Macia, Asgrow...
Orbit or NK1486 genotypes (Fig. 3), and Pioneer 84Y00 for intermediate peak viscosities not greatly influenced by GE. Selection of G and E combinations for high peak viscosity desired for canned products (Beta et al., 2000), ethanol (Wu et al., 2007) and porridge (Taylor et al., 1997) is complicated as location, year and genotype interactively influenced the high peak viscosity. However, the genotypes Asgrow Eclipse and Fontonelle W-1000 appeared to be logical genotypes of grain with stable, high peak viscosities.

**Figure 3.** GGE bi-plot for peak viscosity of 11 white sorghum genotypes produced in 12 environments.

**Final and setback viscosities:** Bi-plots of the final and setback viscosities were mirror images, thus only the final viscosity which measures the stiffness of the final gel (Taylor et al., 1997) is presented (Fig. 4). The Clay Center Irrigated and Orleans 2005 environments and the genotype Pioneer 84Y00 exhibited the lowest variability as indicated by short vectors in the GGE bi-plot. The Hebron 2004 environments were the least stable, and closely followed by the Mead Low N 2004, Clay Center Irrigated 2004, and Mead Irrigated 2004 and 2005 environments. The Mead Low N 2004 environment was associated with Asgrow Eclipse and inversely with NK8828, Clay Center Irrigated 2004 with Kelly Green seeds 6902 and Fontanelle W-1000 and inversely with Macia, Mead Irrigated 2004 with Fontanelle W-1000 and inversely with NK1486, Mead Irrigated 2005 with NC+7W92, and Clay Center Dryland 2004 and 2005, Mead Low N and Dryland 2005 environments Dekalb DK 44-41, and inversely with NK8828.

**Figure 4.** GGE bi-plot for final viscosity of 11 white sorghum genotypes produced in 12 environments.

**Peak time and pasting temperature:** Peak time and pasting temperature are measures of the time required for starch cooking (Agu et al., 2006). The Orleans 2005 and Clay Center Dryland 2004 environments had the largest effect on peak time as indicated by long vectors, while Mead Low N was most stable (Fig. 5). The genotypes Asgrow Eclipse, Kelly Green Seeds KG6902 and Macia were more stable than the other genotypes since their means were near the PC2 zero axis. Macia had the highest peak time and NC+7W92, NK8828, Fontanelle W-1000 and Kelly Green seeds 6902 had the lowest peak times, and these were not
GGE bi-plot analysis to evaluate sorghum grain attributes

directly associated with any particular environment. Clay Center Dryland 2005, Mead Irrigated 2004 and Low N 2005, and Hebron 2004 were similar environments, as were Clay Center Irrigated 2004 and 2005 and Mead Dryland 2005. The Clay Center Dryland 2004 environment was associated with the genotype NK1486 and inversely related to Fontanelle W-1000, while Mycogen 14665 was directly associated with Mead Irrigated 2005 and inversely related with NK8828.

The genotypes NK1486 (88.4°C, range of 85.4 to 90.5°C) and Asgrow Orbit (88.2°C, range of 83.2 to 90.8°C) had the highest pasting temperatures, ranking in the top 3 in 10 or 11 out of 11 environments. Macia had the third highest pasting temperature (87.6°C, range of 84.2 to 90.9), but ranked in the top 3 in only 6 environments. Fontanelle W-1000 (84.5°C, range from 80.6 to 89.9°C) and NC+7W92 (85.1, range from 80.1 to 89.5°C) had the lowest pasting temperatures, ranking in the bottom 3 in 7 or 9 out of 12 environments. Asgrow Orbit, Pioneer P84Y00 and NC+7W92 were more stable than the other genotypes since their means were near the PC2 zero axis (Fig. 6).

Macia (11.1 s, range of 10.0 to 12.0 s) and NK1486 (11.0 s, range of 9.9 to 11.7 s) had the highest peak times, ranking in the top 3 in 9 to 12 out of 12 environments. In contrast, the genotype NC+7W92 had the lowest peak time (10.5 s, range from 10.0 to 11.3 s), ranking in the bottom 3 in 9 out of 12 environments.

The Mead Low N environments, and Asgrow Eclipse, Fontanelle W-1000 and NC+7W92 genotypes created the most variation in the GGE bi-plot for pasting temperature (Fig. 6). The genotype NK1486 was associated with the Clay Center Dryland 2004 and Hebron 2004 environments, Asgrow Orbit was associated with the Clay Center Dryland 2005 environment and inversely with NC+7W92, Dekalb DK41-44 with the Mead Irrigated 2004 and Clay Center Irrigated 2004 environments, and Mycogen 14665 with Orleans 2005, Hebron 2005, and Mead Dryland 2005 environments. The Mead Irrigated 2005 environment had the stable response as indicated by the short vector.

An alkaline cook processor would desire a slow and consistent cook time (i.e. high peak time and pasting temperature) in order to obtain uniform steeping (Johnson et al., 2010), thus would desire the genotype Asgrow Orbit. A rapid cook time (i.e. low peak time and pasting temperature) would be desired for consumable and fuel ethanol production (Agu et al., 2006), thus NC+7W91 would be best for this end use. Unfortunately, pasting temperature was not consistent across years or locations, thus making selection of the best environment impossible from this data set.

**Conclusion:** The results of this study demonstrate that use of GGE bi-plot analysis can help processors and producers of specialty sorghum grain by selection of G and E for production to meet kernel mass, protein and starch concentration, and starch viscosity desired for different end
uses, but not for grain yield and hardness parameters since the GGE bi-plot composed only a small percentage of total variation for these parameters. Large kernel mass sorghum grain would be best using Pioneer P84Y00 or Dekalb DK41-44 produced in Mead environments. Fontannelle W-1000, Kelly Green Seeds KG6902 and Asgrow Eclipse would produce high starch concentrations environments with adequate N supply. High peak and final viscosities would be produced by Fontannelle W-1000 and NC+7W92 under Mead irrigated environments.

Consistent grain quality is also of importance to processors. In this study Pioneer 84Y00 and Dekalb DK41-44 produced small GGE variation around the PC2 zero axis for kernel mass; Dekalb DK41-44 for starch concentration; Pioneer 84Y00, Asgrow Eclipse and Fontonelle W-1000 for peak viscosity; Pioneer 84Y00, Macia and Asgrow Orbit for final viscosity; Asgrow eclipse, Kelly Green Seeds KG6902 and Macia for peak times; and Asgrow Orbit, Pioneer 84Y00 and NC+7W92 for pasting temperatures. The use of GGE bi-plot analysis for environment-by-genotype selection for quality traits for specific end uses is useful, but limited by difficulty in quantifying the environment and lack of ability to control climatic conditions, which is a major issue in the Nebraska and rest of the Central Great Plains.

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