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Waxy maize yield and components as influenced by environment, water regime, and hybrid

Jeremy J Milander[1], Stephen C Mason[1]*, Greg Kruger[1], Tomie D Galusha[1], Zaher Kmail[1]

[1]Department of Agronomy & Horticulture, University of Nebraska, Lincoln, NE, USA
*Corresponding author: E-mail: smason1@unl.edu

Abstract

Limited research on environment and production practices on grain yield and yield components of waxy maize (Zea mays L) has been conducted. Research was conducted in 2012 and 2013 at Mead and North Platte, NE under irrigated and rainfed water regimes with the objective to determine the influence of environment, water regime and hybrid on waxy maize yield and yield components. The waxy maize hybrids P0461EXR, P35F36, P1162EXR, and P1395EXR were grown. Grain yield, ears m^{-2}, kernels ear^{-1}, kernels row^{-1}, rows ear^{-1}, ear length, and circumference and kernel weight were determined. Average grain yield was 9.5 Mg ha^{-1} across environments and irrigation increased grain yield by 3.1 to 3.3 Mg ha^{-1} at Mead and 8.1 to 12.7 Mg ha^{-1} at North Platte. The highest irrigated grain yields of 14.2 Mg ha^{-1} were produced at North Platte in 2013 while the highest rainfed grain yields of 10.1 Mg ha^{-1} were produced in Mead in 2013. Kernel weight in Mead and North Platte irrigated environments had the highest correlation with grain yield (R = 0.67), while kernels ear^{-1} had the highest correlation (R = 0.78) with grain yield in the North Platte rainfed environment. Hybrid influenced yield and yield components, however the influence on yield was much less than for environment and water regime. Waxy maize had similar grain yield and yield components to previous studies with dent maize. Irrigated and higher rainfall environments produced high waxy maize yields, thus waxy maize should be a viable specialty crop option if minimal market incentives are available.

Keywords: Waxy maize, yield components, irrigation, rainfed

Introduction

Waxy maize (*Zea mays* L) is composed of 100% amylopectin starch compared to approximately a 75% amylopectin: 25% amylose ratio for normal dent maize (Fergason, 2001). This branched starch allows for unique end uses such as food thickeners and adhesives, and thus, is commonly marketed as a specialty grain. Production practices for waxy maize hybrids are similar to those used for normal hybrids with the only difference being the need for isolation and cleaning equipment for identity preservation.

The waxy trait is controlled by a recessive gene (Fergason, 2001) that is incorporated into normal dent maize inbred lines by backcrossing and recovered in future generations. Waxy maize hybrids are usually counterparts of dent hybrids popular a few years earlier, thus yields of waxy maize hybrids «lag» behind those of the best normal hybrids. However, newer waxy maize hybrids have less yield «lag» than was true for older hybrids (Thomison, 2011). For these reasons, yield components of waxy maize would be expected to be the same or similar to those of normal maize, but this has not been documented.

Maize yield is the product of yield components that are interrelated, have compensatory effects, and develop sequentially at different stages (Dofing and Knight, 1992). The yield components ears m^{-2}, kernels ear^{-1}, and kernel weight have direct effects on maize grain yield, and indirect effects via other yield components, while other components such as number of rows ear^{-1}, kernels row^{-1}, ear length and ear circumference have only indirect effects. Detailed yield components studies have been reported for many species but detailed yield component studies in maize are limited (Agrama, 1996; Mohammadi et al, 2003). Production practice research for waxy maize in the western maize belt is also limited.

The sequential development of yield components at different growth stages acts as a buffer against very low yields since the climate is rarely unfavorable throughout the entire growing season (Hay and Walker, 1989). The compensatory effect of yield components allows reductions in early developing yield components to be compensated for by increasing later yield components. Early-season growing conditions influence the number of ears m^{-2} (Evans et al, 2003), while mid-season (mid-vegetative to mid-grain fill stages) growing conditions tend to influence the number of kernels ear^{-1} (Cicchino et al, 2010; Pandey et al, 2000; Moser et al, 2006). The potential number of kernels ear^{-1} is a result of number of rows ear^{-1} determined at the V7 growth stage and kernels row^{-1} determined at the V16 growth stage (Abendroth et al, 2011). Number of rows ear^{-1} is strongly related to genetics and is only influenced by serious environmental stresses (Begna et al, 1997; Abendroth et al, 2011).

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Table 1 - Seasonal rainfall and temperatures at Mead, NE and North Platte, NE in 2012, and 2013 (High Plains Regional Climate Center. 2012-13).

	Rainfall			Potential evapotranspiration		Average temperature		
Month	2012	2013	30 yr average	2012	2013	2012	2013	30 yr average
				Mead				
	mm					°C		
April	71	92	73	164	128	12.8	6.9	10.3
May	97	163	112	238	173	18.9	15.2	16.3
June	108	119	106	243	180	22.5	21.1	21.9
July	7	16	76	271	201	27.3	23.1	24.3
Aug.	23	46	89	223	163	22.9	23.6	23.0
Sept.	30	98	73	175	154	17.9	20.7	18.2
Oct.	35	98	58	114	105	9.4	11.0	11.2
Total/Average	371	632	587	1428	1104	18.8	17.4	19.1
				North Platte				
April	68	22	55	133	141	11.4	6.4	8.6
May	17	73	85	211	175	16.7	15.1	14.3
June	21	40	94	271	226	23.9	21.1	19.9
July	34	50	73	258	223	26.5	23.3	23.4
Aug.	10	27	61	228	193	22.9	23.9	22.5
Sept.	2	36	40	182	167	17.6	20.0	17.2
Oct.	6	27	43	110	87	8.7	9.1	10.0
Total/Average	158	275	451	1393	1212	18.2	17.0	16.56

Pollen shed and its timing with silking determines whether or not ovules will be fertilized (Abendroth et al, 2011), and is the stage that is most sensitive to water and heat stress which can reduce the number of kernels ear^{-1} (Westgate et al, 2004). At silking the potential number of kernels ear^{-1} is determined; however pollination problems and kernel abortion during early grain fill can reduce kernel number (Andrade et al, 1999). Inadequate carbohydrate supply is usually the cause of kernel abortion which occurs during the reproductive stages of R2 (blister) and R3 (milk), and usually occurs at the tip of the ear (Abendroth et al, 2011). Late-season conditions influence kernel weight as the final kernel weight is determined at physiological maturity (Eck, 1986; Novacek et al, 2013). A stressful environment during grainfill can result in light kernel weights (Abendroth et al, 2011; Andrade et al, 1999; Tsimba et al, 2013) while increased kernel weight results from high irradiance level, long grain-fill duration, and rapid plant and kernel growth rate (Egli, 2011; Novacek et al, 2013).

Studies using environments, water regimes, and hybrids have been used to determine the relationship between grain yield and yield components. Hu and Buyanovsky (2003) determined that high yielding years were characterized by environments with (1) less than average rainfall and warmer temperatures prior to and during planting; (2) above average rainfall and temperatures in May; (3) above average rainfall and cooler than average temperatures June through Aug; and (4) lower than average rainfall and higher temperatures in the grain fill period of Sept through Oct. Time periods differences in heat and rainfall, timing of irrigation, and maize growth stages have been found to differentially influence yield components (Eck, 1986; Pandey et al, 2000; Moser et al, 2006). It has been found that yield reductions from water stress were mostly due to reduced number of kernels and kernel weight with number of kernels having the greatest correlation with yield reduction (Pandey et al, 2000; Moser et al, 2006). Eck (1986) indicated that yield component compensation may be present when water stress is applied as kernel weight increased when the number of kernels ear^{-1} was decreased as a result of water stress in the vegetative growth stages. Heat stress lengthens the time interval between anthesis and silking, thereby reducing the number of kernels ear^{-1} (Cicchino et al, 2010) and grain yield (Cárcova and Otegui, 2001). Extreme temperatures of <15°C and >35°C during grain fill reduced kernel weight (Jones et al, 1984). Yield components have been found to vary by hybrid and hybrid maturity (Reeves and Cox, 2013). Hybrids with different maturities reach critical stages such as silking and pollen shed at different times, thus timing of environmental stresses differentially influences the yield and yield components.

Maize plants in a field are influenced by inter-plant competition for solar radiation, nutrients, and water (Rajcan and Swanton, 2001). Optimal plant population varies across environments and water regimes (Klein and Lyon, 2011; Barr et al, 2013). As maize plant populations increase more ears m^{-2} are produced (Cox, 1996; Novacek et al, 2013; 2014). The number of rows ear^{-1} is not greatly affected by plant population (Begna et al, 1997) and kernels row^{-1}, ker-

Table 2 - Mean squares and level of probability for hybrid and water regime effects on maize grain yield and yield components in Mead and North Platte NE in 2012 and 2013

Source	df	Grain yield	Ears m^{-2}	Rows ear^{-1}	Ear circumference	Kernels row^{-1}	Ear Length	Kernels ear^{-1}	Kernel weight
Environment (E)	3	261**	27.2**	5.2*	19.3**	468**	24.9*	213253**	298.9**
Water Regime (WR)	1	2214**	275.6**	9.8*	104.7**	496**	109.2**	340671**	2012.8**
E x WR	3	249**	31.6**	4.3	14.3**	114	18.6*	134519**	148.2**
Hybrid (H)	3	5*	6.9**	13.9**	9.7**	461**	88.3**	74623**	11.0**
E x H	9	2	0.8**	0.5	0.5**	9	2.7*	2361	15.6**
WR x H	6	1	0.1	0.4	0.8**	37	2.9	33140	31.5**
E x WR x H	3	2	0.1	0.8	0.2	16	1.6	3261	2.7
Block(WR x E)	16	1.3	0.1	1.4	1.0	40	4.9	12708	6.9
Residual	144	0.7	0.1	0.5	0.2	11	1.2	3237	2.7

nels ear^{-1} and kernel weight generally decrease with increasing plant populations (Novacek et al, 2013; 2014)

The objective of this research was to determine the influence of environment, water regime, and hybrid on the yield components of waxy maize, and to better determine the interrelationship of waxy maize yield and yield components.

Materials and Methods

Field experiments were conducted in 2012 and 2013 in rainfed and irrigated water regimes at the University of Nebraska Agriculture Research and Development Center (ARDC) near Mead, NE and the West Central Research and Extension Center (WCREC) North Platte, Nebraska. Environments were considered to be location x year combinations. Separate fields were used for irrigated and rainfed water regimes at both locations. The experimental design was a randomized complete block within water regimes (WR) and environments, with four hybrids and three replications. Plots were six-rows wide (4.6 m) by 9.1 m long. Irrigated water regimes were furrow irrigation at Mead and sprinkler irrigated at North Platte based on soil water depletion (Melvin and Yonts, 2009). The 2012 growing season in Nebraska was extremely hot and dry (Table 3.1), thus a single application of 100 mm ha-1 of irrigation was furrow-applied on 16 July at blister growth stage (R2) to reduce drought stress and approximate average growing conditions. The four Dupont Pioneer hybrids used were P0461EXR (104 day relative maturity), Pioneer P35F36 (105 day relative maturity), Pioneer P1162EXR (111 day relative maturity), and Pioneer P1395EXR (113 day relative maturity). These hybrids were selected to provide the widest variation in genetic background possible with commercially available waxy maize hybrids.

The predominant soil type at Mead was Tomek silt loam (fine, smectitic, mesic, Pachic, Argiudoll) with 0 to 1% slopes, while the soil in North Platte was a Holdrege silt loam (fine-silty, mixed, superactive, mesic Typic Argiustoll) with 1 to 4% slopes for rainfed and a Cozad silt loam (course-silty, mixed, superactive, mesic, Typic Huplustoll) with 0 to 1% for irrigated treatments. Soybean (*Glycine max* L Merrill) was the previous crop at Mead and irrigated North Platte environments. The previous crop in the rainfed North Platte treatments was winter wheat (*Triticum aestivum* L). At Mead all plots were planted on 25 April in 2012 and on 30 April 2013. At North Platte in 2012, the plots were planted on 4-5 May 2012 and on 14-15 May 2013. In Mead, seeding rates were 90,000 plants ha^{-1} for irrigated water regime and 75,000 plants ha^{-1} for the rainfed water regime. In North Platte, seeding rates were 80,000 plants ha^{-1} for the irrigated water regime and 35,000 plants ha^{-1} for the rainfed based upon recommendations of Barr et al (2013) and Klein and Lyon (2011).

Soil nutrients other than N and pH were above sufficiency levels except for P at Mead in 2012, thus N was the most limiting nutrient. Nutrient applications were made based upon University of Nebraska recommendations (Shapiro et al, 2008). At Mead, N fertilizer rates were based on an expected yield of 12.5 Mg ha^{-1} for the irrigated treatments and 9.4 Mg ha^{-1} for the rainfed treatments while North Platte rates were based on expected yields of 12.5 Mg ha^{-1} for irrigated and 7.5 Mg ha^{-1} for rainfed. At Mead, 170 kg N ha^{-1} was broadcast applied to the irrigated plots and 100 kg N ha^{-1} broadcast applied to the rainfed plots as dry urea (46-0-0) on 26 April 2012 and 19 April 2013. A broadcast application of 45 kg ha^{-1} P_2O_5 was applied 24 May 2012 based on soil test recommendation. At North Platte, 90 kg N ha^{-1} was applied to the rainfed plots and 200 kg N ha^{-1} was applied to the irrigated plots as surface application of urea ammonium nitrate solution (32-0-0). In addition, 46 l ha^{-1} of 10-34-0 starter fertilizer was also applied in the seed slice. Production practices were similar at both locations with conventional disk tillage used for soil preparation, and recommended pre-emergent and post-emergent herbicides used for weed control. Row spacing was 76 cm for both locations.

Grain yield was measured by mechanically harvesting the middle three rows of the plots, water content was measured, and grain yield for each plot adjusted to a water content of 155 g kg^{-1}. Number of plants m^{-2} and ears m^{-2} were counted prior to harvest in three of the middle rows of the plots in Mead and two of the middle rows in North Platte in 2012. However, the number of ears m^{-2} was not counted at North Platte in 2013. Regression analysis from the other environments in this study indicated that the number of plants m^{-2} and ears m^{-2} were essentially equal ($y = 0 + 1.008\,x$, $R^2 =$

Table 3 - Environment and water regime interaction effect on waxy maize grain yield and yield components ($P \leq 0.05$).

	Environment			
	Mead		North Platte	
Water Regime	2012	2013	2012	2013
Grain yield (Mg ha^{-1})				
Irrigated	12.9^{Ba†‡}	13.2^{Ba}	11.1^{Ca}	14.2^{Aa}
Dryland	9.6^{Ab}	10.1^{Ab}	3.0^{Bb}	1.5^{Cb}
Ears m^{-2} (No.)				
Irrigated	7.6^{Aa}	6.4^{Ca}	7.5^{Aa}	7.1^{Ba}
Dryland	6.4^{Ab}	5.5^{Bb}	3.6^{Cb}	3.4^{Cb}
Ear circumference (cm)				
Irrigated	14.5^{Ba}	15.2^{Aa}	14.5^{Ba}	15.0^{ABa}
Dryland	14.0Aa	14.5^{Ab}	12.4^{Bb}	12.3^{Bb}
Ear length (cm)				
Irrigated	16.7^{Aba}	16.5^{ABa}	15.6^{Ba}	17.2^{Aa}
Dryland	15.7^{Aa}	16.3^{Aa}	13.8^{Bb}	14.1^{Bb}
Kernels ear^{-1} (No.)				
Irrigated	634^{Aa}	549^{Ba}	599^{ABa}	587^{ABa}
Dryland	633^{Aa}	533^{Ba}	505^{Bb}	355^{Cb}
Kernel weight (g 100-kernels^{-1})				
Irrigated	32.0^{Ba}	34.9^{Aa}	30.7^{Ba}	34.1^{Aa}
Dryland	28.4^{Bb}	30.8^{Ab}	23.0^{Cb}	23.0^{Cb}

†Within each row, means followed by the same uppercase letters are not significantly different ($P > 0.05$) between the different environments under each water regime. ‡Within each column, means followed by the same lowercase letter are not significant different ($P > 0.05$) between water regimes for each environment.

0.97 with y indicating ears m^{-2} and x indicating plants m^{-2}). Visual observations confirmed this relationship. Thus, plants m^{-2} and ears m^{-2} were considered to be equal for the North Platte 2013 environments as also previously done by Norwood (2001a). Six ear samples were collected from each plot, stored and used to measure yield components. Yield components measured were rows ear^{-1}, kernels row^{-1}, ear length, ear circumference, kernels ear^{-1}, and kernel weight. Kernel rows, kernels row^{-1}, and kernels ear^{-1} were hand counted, and ear length and middle-of-the ear circumference were measured prior to hand shelling for each ear. The number of kernels ear^{-1} were hand counted and 100 kernels were randomly selected from each ear and were used to determine the kernel weight. Water content was measured and 100-kernel weight was adjusted 155 g kg^{-1} water content.

Data were analyzed using PROC Mixed of SAS (SAS Institute, 2014). Analysis of variance was conducted with environment (E), hybrid (H), and plant population (P) and their interactions considered fixed effects, and with replication and interactions considered random effects. Paired-wise comparisons were used to assist with mean separation of discrete variable responses. Analysis of variance indicated that the North Platte rainfed water regime had different yield component responses than the Mead rainfed, Mead irrigated and North Platte irrigated water regimes, thus Pearson correlations were determined separately.

Results and Discussion

Seasonal Climatic Conditions

At Mead, the average rainfall was below the 30-yr average in 2012, while air temperatures were above average (Table 3). Rainfall was only 9% of average in July, 31% of average in Aug, and 41% of average in Sept during the critical pollination and grain fill growth stages, while temperatures were 0.6 to 3.0 °C greater in May through July. In 2013, seasonal rainfall was near the 30-yr average, but only 21% and 51% of average the in July and Aug. Although water stress was present in both years, it was far greater in 2012 than 2013 as reflected by the >30% greater potential evapotranspiration and visual observations. Thus in 2012, which led to the decision to apply a single irrigation application to reduce drought stress and approximate average growing conditions.

At North Platte, both 2012 and 2013 had lower than 30-yr average rainfall and higher temperatures (Table 1). In 2012, monthly rainfall was 6 to 47% of the 30-yr average in all months except April, and the growing season started with the soil profile at field capacity. Temperatures were greater than average, especially in May, June and July during vegetative growth and the critical pollination growth stages. In 2013, monthly rainfall was higher than 2012 but still well below the 30-yr average. Low rainfall in April combined with the very dry 2012 growing season resulted in the soil profile at the beginning of the growing season being below field capacity. Seasonal average temperatures were near the 30-yr average, but well above average in May, June and Sept. Potential evapotranspiration was greater in 2012 than 2013, but visual observations indicated that plants exhibited more water stress in 2013 than in 2012, likely due the soil water status at the beginning of the growing season.

Yield and Yield Components

Table 4 - Environment and hybrid interaction effect influence on waxy maize grain yield and yield components ($P \leq 0.05$).

	Environment			
	Mead		North Platte	
Hybrid (Relative Maturity)	2012	2013	2012	2013
		Grain yield (Mg ha^{-1})		
P0461EXR (104)	10.8^{Ab}[†][‡]	11.4^{Ab}	7.3^{Cab}	8.2^{Ba}
P35F36 (105)	10.6^{Ab}	11.3^{Ab}	6.7^{Bb}	7.7^{Bab}
P1162EXR (111)	11.8^{Aa}	12.1^{Aa}	6.9^{Bab}	7.5^{Bb}
P1395EXR (113)	11.9^{Aa}	11.8^{Aab}	7.4^{Ba}	8.1^{Bab}
		Ears m^{-2} (No.)		
P0461EXR (104)	7.2^{Aa}	6.0^{Bb}	5.6^{Ca}	5.6^{Ca}
P35F36 (105)	6.4^{Ab}	5.1^{Cc}	5.4^{Ba}	4.6^{Dc}
P1162EXR (111)	7.3^{Aa}	6.2^{Bb}	5.6^{Ca}	5.3^{Db}
P1395EXR (113)	7.1^{Aa}	6.5^{Ba}	5.5^{Ca}	5.6^{Ca}
		Ear circumference (cm)		
P0461EXR (104)	14.4^{Bab}	15.1^{Aa}	13.8^{Ca}	14.1^{BCa}
P35F36 (105)	14.1^{Bbc}	15.1^{Aa}	13.4^{Cb}	13.7^{BCb}
P1162EXR (111)	14.6^{Ba}	15.2^{Aa}	14.0^{Ca}	13.6^{Cb}
P1395EXR (113)	13.8^{Ac}	14.0^{Ab}	12.6^{Bc}	13.0^{Bc}
		Ear length (cm)		
P0461EXR (104)	14.7^{Ab}	15.1^{Ac}	13.2^{Bb}	14.6^{Ab}
P35F36 (105)	17.2^{ABa}	18.1^{Aa}	15.8^{Ca}	16.9^{BCa}
P1162EXR (111)	15.0^{Ab}	15.2^{Ac}	13.5^{Bb}	15.1^{Ab}
P1395EXR (113)	18.0^{Aa}	17.2^{ABb}	16.3^{Ba}	16.1^{Ba}
		Kernel weight (g 100-kernels^{-1})		
P0461EXR (104)	29.6^{Bb}	31.8^{Ac}	26.9^{Cb}	29.2^{Ba}
P35F36 (105)	28.9^{Bb}	34.0^{Aa}	25.7^{Cb}	29.3^{Ba}
P1162EXR (111)	31.0^{Ba}	33.1^{Aab}	28.9^{Ca}	28.3^{Cab}
P1395EXR (113)	31.2^{Aa}	32.6^{Abc}	25.8^{Cb}	27.6^{Bb}

[†] Within each row, means followed by the same uppercase letters are not significantly different ($P > 0.05$) between the different environments within each hybrid. [‡] Within each column, means followed by the same lowercase letters are not significantly different ($P > 0.05$) between the different environments within each hybrid.

Waxy maize grain yield differences were attributed to the three-way interaction E x WR x H (Table 2), however, this interaction was broken down into environment x water regime (E x WR) and environment x hybrid (E x H) interactions to facilitate data presentation (Tables 3 and 4). The E x WR interaction indicated that grain yields were greater under the irrigated water regime than rainfed across environments (Table 3). Rainfed yields were greater at Mead than North Platte as would be expected by higher seasonal rainfall (Table 3) and 2012 irrigation at Mead to reduce water stress and approximate average growing conditions. With irrigation, grain yields were highest in North Platte in 2013, intermediate for Mead 2012 and Mead 2013, and lowest for North Platte 2012, the latter likely associated with high temperatures during the early and mid-growing season (Table 1). North Platte 2013 irrigated yields were likely higher due to fewer cloudy days as less seasonal precipitation occurred in this environment. In rainfed environments, Mead produced higher grain yields than North Platte, but grain yields across years were similar at both locations (Table 3). At Mead, the late-maturity waxy maize hybrids P1162EXR and P1395EXR produced higher yields than other hybrids, while at North Platte the hybrids P1162EXR and P0461EXR produced the highest grain yields (Table 4). Larson and Clegg (1999) and Tsimba et al (2013) found that late-maturity hybrids were affected negatively more by water stress than early-maturity hybrids. However, yield potential and water stress tolerance are important criteria to consider along with maturity classification for reducing potential for low grain yields under water-limited environments. In general, E and WR had a larger influence on grain yield than did hybrid.

Differences in the number of ears m^{-2} were attributed to the E x WR and WR x H interactions (Table 2). More ears m^{-2} were produced under irrigated and Mead rainfed environments than in the North Platte rainfed environment (Table 3) at least partially due to higher seeding rates used under irrigated and higher rainfall conditions than in the North Platte rainfed environment. More ears m^{-2} were produced in 2012 than in 2013 under both water regimes at Mead and under irrigated conditions at North Platte. The waxy maize hybrid P35F36 produced the fewest ears m^{-2} in three out of four environments, with no difference among hybrids in the North Platte 2012 environment (Table 4). Since the germination percentage of seed was similar, this implies that either this P35F36 hybrid had seed with lower vigor or was less tolerant to interplant competition during the growing season. The number of ears m^{-2} was associated with grain yield in the Mead and North Platte 2012 environments and

Table 5 - Correlation coefficients between yield components measured in the Mead Irrigated and Dryland Environments and North Platte Irrigated environments combined (above the diagonal) and the North Platte Dryland Environments (below diagonal).

	Grain yield	Ears m^{-2}	Rows ear^{-1}	Ear circumference	Kernels row^{-1}	Ear length	Kernels ear^{-1}	Kernel weight
Grain Yield	---	0.43**	-0.08	0.38**	-0.13	0.25**	0.07	0.67**
Ears m^{-2}	0.21	---	0.00	-0.04	-0.20*	-0.17*	0.11	0.10
Rows ear^{-1}	0.32*	0.12	---	0.43**	-0.19*	-0.42**	0.08	-0.12*
Ear circumference	0.59**	-0.06	0.77**	---	-0.23**	-0.11	-0.16	0.68**
Kernels row^{-1}	0.72**	0.03	0.40**	0.64**	---	0.70**	0.61**	-0.04
Ear length	0.31*	-0.11	0.43**	0.53**	0.72**	---	0.50**	0.32**
Kernels ear^{-1}	0.78**	0.05	0.46**	0.71**	0.94**	0.62**	---	-0.20*
Kernel weight	0.51**	-0.10	0.49**	0.84**	0.44**	0.39*	0.45**	---

* and ** indicate $P \leq 0.05$ and 0.01.

water regimes (Table 5) suggesting that early season stress impacted grain yield (Evans et al, 2003). In contrast, the number of ears m^{-2} was not associated with grain yield in the North Platte 2013 rainfed environment and water regime when more visual plant water stress was observed, suggesting that late-season stress was more important than early-season stress in this environment (Pandey et al, 2000).

The number of rows ear^{-1} was attributed to the main effects of E, WR, and H (Table 2). Hybrid had the largest influence on the number of rows ear^{-1} with P0461EXR > P1162EXR = P35F36 > P1395EXR (16.1 > 15.6 = 15.3 >14.8 rows ear^{-1}). The number of rows ear^{-1} was greatest in the Mead 2012 = 2013 > North Platte 2013 > North Plate 2012 environments (15.7 = 15.7 > 15.3 = 15.0 rows ear^{-1}). The irrigated WR produced 0.5 more rows ear^{-1} than rainfed. These results confirm expectations that differences in the number of rows ear^{-1} would be small and largely genetically controlled (Abendroth et al, 2011; Lack et al, 2012).

Ear circumference differences were attributed to E x WR, E x H, and WR x H interactions (Table 2). Irrigation increased ear circumference over rainfed (Tables 3 and 6), with the increase being greater in the drier North Platte environments than at Mead where ear circumferences were similar in 2012 (Table 3) at least partially due to the irrigation application to save the crop. The waxy maize hybrid P1395EXR produced the smallest ear circumference in all environments, while no hybrid consistently produced the greatest ear circumference (Table 4). The hybrid P1395EXR also produced lowest number of rows ear^{-1}, and the number of rows ear^{-1} was highly correlated with ear circumference (Table 5).

Kernels ear^{-1} is a product of the number of rows ear^{-1} and kernels row^{-1}. Since the number of rows ear^{-1} is largely genetically controlled (Abendroth et al, 2011) variation in the number of kernels ear^{-1} would be expected to be largely due to the number of kernels row^{-1} and to be related to ear length as shown by correlations in this study (Table 5) and as observed in previous experiments (Begna et al, 1997; Lack et al, 2012). Differences in the number of kernels ear^{-1} were attributed to E x WR interaction, and H main effects (Table 2). In the higher rainfall Mead environments, differences in kernels ear^{-1} between irrigated and rainfed water regimes was minor as previously found while irrigation resulted in large increases in kernels ear^{-1} in North Platte environments, especially in 2013 (Table 3). Likely the more stressful North Platte environments encountered greater kernel abortion during early grain fill stages than at Mead (Abendroth et al, 2011). The Mead 2012 environment produced the greatest number of kernels ear^{-1} both in irrigation and rainfed WR, while the rainfed North Platte 2013 environment produced the fewest number of kernels ear^{-1}. The number of kernels produced ear^{-1} was greatest for P35F36 > P1395EXR = P1162EXR > P0461EXR (601 > 549 = 546 > 501 kernels ear^{-1}). P35F36 produced the lowest number of ears m^{-2} (Table 4) thus yield component compensation may have resulted in the larger number of kernels ear^{-1}.

Differences in ear length were attributed to E x WR and E x H interactions (Table 2). Irrigated WR produced longer ears than under rainfed in the North Platte 2012 and 2013 environments, while irrigated and rainfed ear lengths were similar in the Mead 2012 and 2013 environments (Table 3) likely the result of less seasonal rainfall in North Platte (Table 1). The Mead environments generally produced the longest ear lengths (Tables 3 and 4). The waxy hybrids P35F36 and P1395EXR produced longer ear lengths than P0461EXR and P1162EXR (Table 4). The hybrid P35F36 produced the fewest number of ears m^{-2} and P1395EXR produced the lowest number of rows ear^{-1} and circumference, thus if yield component compensation was present, longer ears would be expected for this hybrid. Correlation analysis (Table 5) indicated that the ear length was negatively correlated with the number of rows ear^{-1} for the Mead and North Platte irrigated environments. In the North Platte environments under the rainfed water regime, the ear length was positively associated with both the number of rows ear^{-1} and ear circumference.

The number of kernels row^{-1} was attributed to WR x H interaction and E main effects (Table 3). Environments influenced the number of kernels row^{-1} with Mead 2012 = Mead 2013 = North Platte 2012 > North Platte 2013 (35.6 = 35.3 = 33.5 > 28.9 kernels row^{-1}), largely a reflection of dry conditions and a single irrigation in the Mead 2012 environment (Table 1). The WR x H interaction indicated that P35F36 produced the greatest number of kernels row^{-1} and P1395EXR the second greatest number of kernels row^{-1} in both water regimes, while P1162EXR produced the fewest kernels row^{-1} under the rainfed water regime and

Table 6 - Hybrid and water regime interaction effect influence on waxy maize grain yield and yield components ($P \leq 0.05$).

	Waxy maize hybrid (relative maturity)			
Water Regime	P0461EXR (104)	P35F36 (105)	P1162EXR (111)	P1395EXR (113)
	Ear circumference (cm)			
Irrigated	15.0B^{a†‡}	14.8^{Ba}	15.2^{Aa}	14.2^{Ca}
Dryland	13.7^{Ab}	13.4^{Bb}	13.5^{ABb}	12.5^{Cb}
	Kernels row-1 (n°)			
Irrigated	31.7^{Ca}	39.2^{Aa}	31.6^{Ca}	37.4^{Ba}
Dryland	30.9^{Ba}	34.7^{Ab}	28.7^{Cb}	32.6^{ABb}
	Kernel weight (g 100 kernels^{-1})			
Irrigated	31.9^{Ba}	32.2^{Ba}	34.3^{Aa}	33.4^{Aa}
Dryland	26.8^{Ab}	26.8^{Ab}	26.4^{Ab}	25.2^{Bb}

[†] Within each row, means followed by the same uppercase letters are not significantly different ($P > 0.05$) between the different hybrids within each water regime.[‡] Within each column, means followed by the same lowercase letters are not significantly different ($P > 0.05$) between the different water regimes within each hybrid.

P0461EXR and P1162EXR produced the fewest under the irrigated water regime (Table 6).

Kernel weight differences were attributed to E x WR, E x H, and WR x H interaction effects (Table 2) Irrigation increased kernel weights in all environments (Table 3), with the difference in North Platte 2013 > North Platte 2012 > Mead 2013 > Mead 2012 environments reflecting differences in late-season water availability (Table 1). Kernel weight of drought stressed plants is usually lower than those of well watered plants (Moser et al, 2006; Lack et al, 2012). The hybrid P0461EXR produced one of the lightest kernel weights in Mead and North Platte 2012 environments, while the lowest in the North Platte 2013 environment was P1395EXR (Table 4). Late-maturing hybrids produced greater kernel weights under irrigation due to little or no water stress during grain fill, while earlier maturity hybrids produced greater kernel weights under all rainfed environments (Table 6). Apparently early-maturing hybrids reached the critical flowering time and maturity earlier, thereby using less water and reduced late-season water stress. Norwood (2001b) found less water use by early-maturity maize hybrids, but that late-maturing hybrids in his study produced the heaviest kernels under rainfed conditions in less severe environments than those in North Platte in this study (Norwood, 2001a).

Correlation analysis indicated different associations between grain yield and yield components in the Mead and North Platte irrigated environments and water regimes, and the North Platte rainfed environment and water regime (Table 5). Grain yield in the Mead and North Platte irrigated environments and water regimes was positively associated with the number of ears m^{-2}, ear circumference and ear length, and kernel weight, with kernel weight having the highest correlation while the number of kernels ear^{-1} was not correlated. Tsimba et al (2013) have also found kernel weight to have a high correlation with grain yield however they found kernels m^{-2} (ears m^{-2} x kernels ear^{-1}) was more correlated with grain yield. These results suggest that late-season stress and water availability, and early season stress were present, with desirable conditions being present during mid-season due to rainfall, irrigation, and/or presence of soil stored water in the high available water holding capacity soils used in this study.

In the North Platte rainfed environment and water regime, grain yield was associated with all yield components except the number of ears m^{-2} (Table 5). The number of kernels ear^{-1} and kernels row^{-1} had the highest correlation with grain yield, suggesting that early-season stress was minimal, perhaps due to the near normal rainfall in April 2012 and May 2013 (Table 1). These results suggest that the North Platte rainfed environments experienced mid-season stress that extended into the late-season, consistent with results of Pandey et al (2000) and Moser et al (2006), who found maize yield reductions were associated with reductions in the number of kernels ear^{-1} and to a lesser extent, with kernel weight.

Conclusion

Grain yield and yield components of waxy maize was influenced greatly by environment and water regime, as is true for dent maize. Response of Mead and North Platte irrigated environments was similar for grain yield and components while the very dry North Platte rainfed environments were different. Grain yield and all yield components except for the number of rows ear^{-1} were markedly reduced in the North Platte rainfed environment and water regime and all yield components except ears m^{-2} were found to be associated with grain yield while only ears m^{-2}, ear circumference, ear length and kernel weight were found to be associated with grain yield under the other environments and water regimes used in the study. High yields of waxy maize were produced at Mead and North Platte when irrigated, thus if small price premiums are present, this is a viable specialty crop that has only few production practice differences from those for commodity field maize. Waxy maize has an equal feeding value to dent corn (Fergason, 2001), so production above the contracted amount can easily be marketed for livestock feed.

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