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Estimating the upper and lower limits of kernel weight under different water regimes in hybrid maize seed production



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ABSTRACT

In hybrid maize (Zea mays L.) seed production, both the kernel quality and the germination rate, which are positively related to kernel weight (KW), are very important. Water deficit can change the source-sink ratio (SSR) and thus affects KW. To create a water-saving irrigation program that facilitates the production of highquality seed, it is necessary to properly model the KW-water relationship. Irrigation experiments were conducted in 2014 and 2015 in an arid region of Northwest China to investigate the effects of deficit irrigation on maize plant biomass and yield; and pollination experiments were conducted in 2016 to obtain a wide range of SSR and KW data. Analysis of the results showed that water deficit at the vegetative or flowering stages reduced postflowering biomass gain (PBG) and kernel number (KN), thus significantly affecting SSR. At the grain-filling stage it reduced PBG but had no significant effect on KN, thus reducing SSR. Only the treatment of no irrigation in the grain-filling stage in 2015 significantly reduced KW. The Jensen model can accurately simulate the relationship between PBG and relative evapotranspiration at each growth stage. The water sensitivity index of PBG in the vegetative, flowering, grain-filling and ripening stages were respectively 0.48, 0.48, 0.97, and 0.16, Based on the experimental data of 2016, the hyperbolic upper (UpKW) and lower (LowKW) limit equations were created for KW as a function of SSR using boundary analysis. UpKW and LowKW increased as SSR increased, but the difference between UpKW and LowKW first increased and then decreased as SSR increased. When SSR was 0, UpKW was 178.39 mg and LowKW was 155.56 mg. When SSR is not less than 867.23 mg kernel⁻¹, UpKW and LowKW are both 326.97 mg, which is the potential KW. Combined with the KN-water model, the models developed in this study can be used to develop a water-saving and irrigation program that produces high-quality seed.

1. Introduction

In the Hexi Corridor, located in the arid region of Northwest China, water is a scarce resource due to the low rainfall and high rate of evaporation. The Hexi Corridor is well-suited for hybrid maize seed production with a large day–night temperature difference, sufficient thermal time, and isolated oases. Maize inbred lines have become the main irrigated crop in the region (Wang et al., 2017). To improve water use efficiency (WUE) and protect the ecology of this region, scientifically based irrigation programs need to be developed for maize inbred lines.

Hybrid maize seed quality and germination rate are very important and they are positively related to kernel weight (KW), which is a major factor in determining yield (Borrás et al., 2002; Guan et al., 2013). Water deficit can alter the post-flowering source–sink ratio (SSR) and

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https://doi.org/10.1016/j.agwat.2018.09.014 Received 24 April 2018; Accepted 6 September 2018 Available online 22 October 2018 0378-3774/ © 2018 Published by Elsevier B.V. thus affect KW. A satisfactory irrigation program for maize inbreds must not only ensure high yield and WUE but also guarantee that KW meets or exceeds the threshold for germination rate standards. Thus, it is important to study the relationship between KW and water deficit at each growth stage of the maize inbreds to create a high-quality watersaving irrigation program.

The effect of water deficit on maize KW has been extensively studied. Ouattar et al. (1987) found that short-term water deficit during the lag and linear-filling phases of kernel development and water deficit during the period after linear-filling up to physiological maturity did not significantly affect KW. However, long-term water deficit from after the lag phase to physiological maturity decreased KW by 50%. Çakir (2004) showed that water deficit at different growth stages could possibly reduce KW, but the effects differed in different years. Aydinsakir et al. (2013) showed that reducing the irrigation water amount by 50% over the whole growth period significantly decreased KW. Hammad et al. (2015) found that KW significantly decreased when water deficit occurred at the vegetative stages V2 and V16 and reproductive stage R1. Wang et al. (2017) found that there was no significant difference between full irrigation and water deficit irrigation during the vegetative and flowering stages. These studies show that the effect of water deficit on KW at different growth stages is complex. This complexity is because KW is largely governed by SSR, which is the ratio of post-flowering biomass gain (PBG) to kernel number (KN). Since PBG and KN are differently and individually affected by water deficit, their combined effect complicates the response of KW to water deficit. Quantification of the PBG–water, KN–water, and KW–SSR relationships will facilitate better analysis of the response of KW to water deficit at each growth stage.

PBG is the difference between biomass at physiological maturity and biomass at the end of the flowering stage. There have been many studies of the effect of water deficit on maize biomass (Boote, 2013; Bouazzama et al., 2012; Çakir, 2004; Jurgens et al., 1978; Sinclair et al., 1990), but few studies of the effect of water deficit on PBG. Crop water production functions, which originally related crop yield to evapotranspiration at different growth stages, have been used to determine irrigation programs (Blank, 1975; Jensen, 1968; Kang et al., 2017; Minhas et al., 1974; Stewart et al., 1975). Chen et al. (2014) used the forms of crop water production functions to quantify the effects of water deficit at different growth stages on the fruit quality of tomato plants. We examine whether crop water production functions can be used to quantify the effects of water deficit on PBG at different growth stages. Then combined with KN, we can quantify the effects of water deficit on SSR. Wang et al. (2017) analyzed the effects of water deficit on maize inbred flowering and KN; based on the results, they developed a water-flowering model to estimate KN of maize inbreds under different irrigation treatments (Wang et al., 2018). Borrás and Otegui (2001) and Tanaka and Maddonni (2008) developed models of the KW-SSR relationships by examining the effects of defoliation, shading, different plant densities, and pollination methods. However, they did not consider the effect of water deficit, and, at a particular value of SSR, differences in KW were large and up to 100 mg. When the KW-SSR relationship is used as the basis of an irrigation program, there is a large probability that actual KW will be less than estimated KW, which will result in a large number of seeds having a low germination rate. Therefore, a KW-SSR relationship which can precisely maintain desired KW when creating an optimal irrigation program needs to be developed to guarantee KW and germination rate.

This study aims (1) to investigate the response of PBG to water deficit at each growth stage; (2) to model the PBG–water relationship; and (3) to develop upper and lower bounds for the KW–SSR relationship and so to create a foundation for a water-saving irrigation program for maize inbreds that produces high-quality hybrid seed.

2. Material and methods

2.1. Field experiment

The experiment was conducted from 2014 to 2016 with maize inbreds grown for hybrid seed (Funong series) at Shiyanghe Experimental Station of China Agricultural University, located in Wuwei City, Gansu Province of Northwest China. Detailed information of the station and crop management can be found in Wang et al. (2017). The female inbreds were planted on 15 Apr. 2014, 16 Apr. 2015, and 24 Apr. 2016. Kernels were harvested on 20 Sept. 2014, 15 Sept. 2015, and 15 Sept. 2016.

There were 9 irrigation treatments in 2014 and 11 irrigation treatments in 2015 during the vegetative (V), flowering (F), grainfilling (G), and ripening (R) stages. Table 1 shows the different irrigation treatments in 2014 and 2015. There was no irrigation during establishment stage because soil moisture had been recharged by winter

Table 1

Irrigation	treatments	at	the	establishment,	vegetative,	flowering,	grain-filling
and ripen	ing stages.						

Year	$Treatment^{\dagger}$	Establishment (%)	Vegetative (%)	Flowering (%)	Grain- filling (%)	Ripening (%)
2014	V2F2	0	100*	100	100	100
	V2F1 [™]	0	100	50	100	100
	V2F0 [*]	0	100	0	100	100
	V1F2	0	50	100	100	100
	V1F1	0	50	50	100	100
	V0F2	0	0	100	100	100
	V0F0	0	0	0	100	100
	G0	0	100	100	0	100
	R0	0	100	100	100	0
2015	V2F2	0	100	100	100	100
	V2F1	0	100	50	100	100
	V2F0	0	100	0	100	100
	V1F2	0	50	100	100	100
	V1F1	0	50	50	100	100
	V1F0	0	50	0	100	100
	V0F2	0	0	100	100	100
	V0F1	0	0	50	100	100
	V0F0	0	0	0	100	100
	G0	0	100	100	0	100
	R0	0	100	100	100	0
2016	V2F2	100	100	100	100	100
	V1F2	100	50	100	100	100
	V2F1	100	100	50	100	100
	G1	100	100	100	50	100

 † F, flowering stage; V, vegetative stage; G, grain-filling stage; R, ripening stage. Numbers 0, 1, and 2 indicate no irrigation, 50% of full irrigation, and full irrigation, respectively. In the control treatment (V2F2), the irrigation lower limit was maintained at 70 ± 2% of the field water capacity, and the upper limit was maintained at the field water capacity during the whole season.

^{*} Irrigation amounts: 100, full irrigation; 50, 50% of full irrigation amount; 0, no irrigation.

* The irrigation pipe broke when irrigating the crop during the flowering stage in 2014, so the two treatments V2F1 and V2F0 were not administered according to plan; the two treatments were used only in model calibration and validation.

irrigation in the previous year. Border irrigation was used in 2014 and 2015 and all plots were irrigated in synchrony with treatment V2F2 (Wang et al., 2017). The irrigation pipe broke when irrigating during the flowering stage in 2014, so the two treatments V2F1 and V2F0 became invalid. The two treatments were not included when analyzing the effects of deficit irrigation on crop evapotranspiration (ET), PBG, SSR, or KW, but they were used in model calibration and validation.

The maize inbreds were irrigated every 10–15 d in 2016 using drip irrigation under plastic film mulch. There were four irrigation treatments (Table 1). The quantity of water used in the full irrigation treatment was the difference between evapotranspiration (ET) and rainfall during the interval before irrigation. ET was calculated by $ET = K_C ET_0$ (Allen et al., 1998), where K_C , the crop coefficient of each growth stage, was defined by Jiang et al. (2014), and ET_0 , reference crop evapotranspiration, was calculated by the Penman–Monteith equation (Monteith, 1965; Penman, 1948). Six pollination treatments were set up for each irrigation treatment at the flowering stage in 2016 to vary KN and give different SSR and KW values for subsequent analysis (Fig. 1). Pollination was performed manually, with sufficient pollen, between 09:00 and 10:00 h. Each treatment had six replicates.

PBG is the difference between biomass at the end of flowering and biomass at the stage of physiological maturity. At the end of the flowering stage and at the end of the ripening stage in each year from 2014 to 2016, six plants from each treatment were oven-dried to measure the above-ground biomass. KN and KW were measured according to the procedure described in Wang et al. (2017).

Meteorological data were obtained from an automatic weather



Fig. 1. Six pollination treatments in 2016. The white rectangles represent natural pollination, the grey rectangles represent that pollination was prevented by bagging silks and the yellow rectangles represent pollination was enhanced by hand.

station (Hobo, Onset Computer Corp.; Jiang et al., 2014). Soil water content was measured by a Trime-PICO probe (TDR, IMKO, Germany). Actual crop ET was calculated by the water balance method using average soil moisture change in the 0–100 cm soil layer (Kang et al., 2000). The contribution of groundwater to soil moisture was negligible in the study area as the groundwater table is > 25 m below the surface. There was no surface runoff or deep percolation during irrigation.

2.2. PBG-water relationship

Four crop water production functions were used as models: the Jensen model (Jensen, 1968), the Minhas model (Minhas et al., 1974), the Blank model (Blank, 1975), and the Stewart model (Stewart et al., 1975). Model predictions were compared to simulate the effects of water deficit at the vegetative, flowering, grain-filling, and ripening stages on PBG and the best one was chosen as an index of the PBG–water relationship:

Jensen model :

$$\frac{PBG}{PBG_{CK}} = \prod_{i=1}^{n} \left(\frac{ET_i}{ET_{CKi}}\right)^{\lambda_i}$$
(1)

Minhas model :

$$\frac{PBG}{PBG_{CK}} = \prod_{i=1}^{n} \left(1 - \left(1 - \frac{ET_i}{ET_{CKi}} \right)^2 \right)^{\delta_i}$$
(2)

Blank model :

$$\frac{PBG}{PBG_{CK}} = \sum_{i=1}^{n} K_i \left(\frac{ET_i}{ET_{CKi}}\right)$$
(3)

Stewart model :

$$\frac{PBG}{PBG_{CK}} = 1 - \sum_{i=1}^{n} Z_i \left(1 - \frac{ET_i}{ET_{CKi}} \right)$$
(4)

where: *PBG* is the post-flowering biomass gain; *PBG*_{CK} is the post-flowering biomass gain under full irrigation; ET_i is the evapotranspiration at the *i*th growth stage of each treatment; ET_{CKI} is the evapotranspiration at the *i*th growth stage of the full irrigation treatment; δ_{i} , λ_i , K_i , and Z_i are the water deficit sensitivity indexes of PBG at each growth stage; *i* is the growth stage; and *n* is the number of growth stages.

If water deficit occurs in the establishment stage, the maize will fail to develop, so water deficit sensitivity was calculated only over the vegetative, flowering, grain-filling, and ripening stages.

2.3. KW-SSR relationship: upper and lower limits

The relationship between KW and SSR was determined using boundary-line analysis (Li et al., 2016). KW-SSR points were grouped in intervals of 50 mg kernel⁻¹ of SSR. In each group KW in the 95th percentile or higher was considered to be an upper limit point and KW in the 5th percentile or lower was considered to be a lower limit point. Borrás and Otegui (2001) and Maddonni et al. (1998) used segmented linear functions to represent the relationship between KW and SSR. This is a straightforward method but the number of segments and the inflexion points are hard to determine. Moreover, segmented linear functions cannot reflect the continuity of crop growth. A continuous nonlinear model can overcome these drawbacks (Meade et al., 2013). Borrás et al. (2004) and Borrás and Gambín (2010) represented the dependence of kernel biomass accumulation on the availability of assimilates by a hyperbolic relationship, so in this study KW values within each set of limit points were fitted with hyperbolic curves through the least squares method using the corresponding SSR values:

$$UpKW = \frac{Up_m \times SSR + k_{up} \times Up_0}{SSR + k_{up}}$$
(5)

$$LowKW = \frac{Low_m \times SSR + k_{low} \times Low_0}{SSR + k_{low}}$$
(6)

where: *UpKW* and *LowKW* are respectively the upper and lower limits of kernel weight (mg); *SSR* is the post-flowering source–sink ratio (mg kernel⁻¹); *Up_m*, *Low_m*, *Up₀*, *Low₀*, *k_{up}* and *k_{low}* are fitting parameters, and *Up₀* and *Low₀* are respectively the upper and lower limits of kernel weight respectively when SSR = 0.

2.4. Calibration and validation

The PBG–water relationships were calibrated using the 9 sets of field experiment data from 2014 and validated using the 11 sets of field experiment data from 2015. As the ranges of KW and SSR in the experiment of 2016 were larger than the ranges of 2014 and 2015, the KW–SSR relationship was calibrated using the data from 2016 and validated using the data from 2014 and 2015.

The regression coefficient (b), the coefficient of determination (R^2) and the relative root mean square error (*RRMSE*) between the measured data and estimated results were used to evaluate the performance of the models. They were calculated by (Coucheney et al., 2015; Yang et al., 2014):

$$b = \frac{\sum_{i=1}^{n} M_i S_i}{\sum_{i=1}^{n} M_i^2}$$
(7)

Table 2				
Evapotranspiration at each	growth stage of the	maize inbreds for	hybrid seed produ	ction in 2014 and 2015.

Year	Treatment	Establishment (mm)	Vegetative (mm)	Flowering (mm)	Grain-filling (mm)	Ripening (mm)	Total (mm)
2014	V2F2	38 ± 7 a	113 ± 6 a	141 ± 6 ab	120 ± 7 a	59 ± 4 a	471 ± 8 a
	V2F1	37 ± 7 a	$100 \pm 10 \text{ ab}$	136 ± 13 ab	114 ± 8 ab	$52 \pm 5 a$	439 ± 16 b
	V2F0	35 ± 4 a	117 ± 7 a	129 ± 9 b	$109 \pm 4 ab$	50 ± 7 a	441 ± 12 b
	V1F2	37 ± 5 a	97 ± 5 b	$130 \pm 9 b$	113 ± 6 ab	52 ± 8 a	429 ± 11 b
	V1F1	35 ± 6 a	89 ± 7 b	134 ± 9 ab	$108 \pm 4 b$	51 ± 3 a	$417 \pm 10 \text{ b}$
	V0F2	35 ± 3 a	54 ± 8 c	137 ± 5 ab	$89 \pm 2 c$	54 ± 4 a	370 ± 7 c
	V0F0	32 ± 2 a	65 ± 3 c	77 ± 5 c	$86 \pm 2 c$	49 ± 12 a	$307 \pm 10 \text{ d}$
	GO	32 ± 5 a	118 ± 10 a	142 ± 8 ab	94 ± 13 c	54 ± 4 a	439 ± 23 b
	R0	34 ± 6 a	121 ± 6 a	149 ± 12 a	111 ± 6 ab	$35 \pm 6 b$	450 ± 2 b
2015	V2F2	42 ± 7 a	132 ± 2 a	152 ± 7 a	106 ± 7 ab	46 ± 5 a	478 ± 7 a
	V2F1	40 ± 3 a	$120 \pm 6 ab$	143 ± 5 a	98 ± 6 bc	44 ± 3 a	445 ± 18 b
	V2F0	43 ± 6 a	130 ± 5 a	128 ± 8 b	85 ± 6 cde	40 ± 5 ab	426 ± 12 bc
	V1F2	43 ± 1 a	111 ± 3 b	131 ± 5 ab	92 ± 5 bcd	39 ± 4 ab	417 ± 4 cd
	V1F1	40 ± 5 a	111 ± 3 b	126 ± 1 b	81 ± 5 ef	46 ± 4 a	405 ± 4 d
	V1F0	40 ± 6 a	108 ± 8 b	91 ± 7 c	81 ± 4 ef	50 ± 6 a	370 ± 8 e
	V0F2	42 ± 5 a	85 ± 4 c	128 ± 4 b	97 ± 8 bc	50 ± 2 a	401 ± 8 d
	V0F1	41 ± 3 a	$107 \pm 4 \text{ bc}$	87 ± 5 c	79 ± 5 ef	46 ± 3 a	360 ± 16 e
	V0F0	39 ± 5 a	74 ± 4 c	$100 \pm 6 c$	73 ± 5 f	47 ± 7 a	332 ± 17 f
	GO	39 ± 4 a	131 ± 3 a	$140 \pm 6 ab$	83 ± 4 de	31 ± 6 b	425 ± 13 c
	R0	41 ± 6 a	123 ± 2 a	151 ± 6 a	116 ± 4 a	$13 \pm 2 c$	443 ± 8 bc

$$R^{2} = \left[\frac{\sum_{i=1}^{n} (E_{i} - \overline{E})(O_{i} - \overline{O})}{\sqrt{\sum_{i=1}^{n} (E_{i} - \overline{E})^{2} \sum_{i=1}^{n} (O_{i} - \overline{O})^{2}}}\right]^{2}$$
(8)

$$RRMSE = \frac{1}{O} \sqrt{\frac{1}{n} \sum_{i=1}^{n} (E_i - O_i)^2}$$
(9)

where: E_i and O_i are respectively the estimated and observed values; \overline{E} and \overline{O} are the respective means of the estimated and observed values; and n is the number of measurements.

3. Results and discussion

3.1. Evapotranspiration, post-flowering biomass gain, kernel number, source-sink ratio and kernel weight

Table 2 shows the evapotranspiration (ET) at each growth stage of the maize inbreds in 2014 and 2015. Seasonal ET varied from 307 to 478 mm, depending on irrigation amounts and meteorological influences over two years. ET was highest for the full irrigation treatment (V2F2) and water deficit reduced ET at each corresponding growth stage. Seasonal ET varied among the different irrigation treatments: ET at the establishment, vegetative, flowering, grain-filling, and ripening stages, respectively, accounted for 7.32–11.60%, 14.53–30.88%, 24.29–37.03%, 19.47–27.96%, and 2.83–15.85% of seasonal ET.

Water deficit inhibits plant root water uptake and leads to reduced stomatal opening, thereby decreasing plant transpiration (Kang et al., 1998). It also increases soil resistance and thus decreases soil evaporation (Turner, 1975). ET decreases when water deficit inhibits photosynthesis through decreased leaf area (Li et al., 2018). Leaves grow rapidly during the vegetative and early flowering stages of maize development, so water deficit during these periods will inhibit leaf growth. Water deficit during the late flowering and grain-filling stages accelerates leaf senescence (Çakir, 2004). Clearly, water deficit at the vegetative, flowering, or grain-filling stages not only decreases ET at the time but also affects ET in subsequent stages.

Table 3 shows that PBG was greatest for the full irrigation treatment (V2F2) with values of 58.58–70.65 g. Treatments V1F1, V0F2, and V0F0 in 2014 and 2015 and treatments V2F0, V1F0, and V0F1 significantly decreased PBG. PBG was lowest for treatment V0F0, with a value of 17.78–22.72 g, which was 61.22–74.83% less than for the V2F2 treatment. There was no significant difference in PBG between

treatments G0 and V2F2 in 2014 due to sufficient rainfall in the grainfilling stage, but PBG for treatment G0 decreased significantly in 2015.

The vegetative stage is the most important period for the growth of maize stem and leaves. Water deficit at this stage can inhibit the growth of vegetative organs and thus reduce photosynthate at the late growth stage (Cakir, 2004). When water deficit occurs during the vegetative and flowering stages, a decrease in KN can affect leaf synthesis of dry matter and result in lower plant biomass at physiological maturity (Borrás and Otegui, 2001; Kiniry et al., 1992). Çakir (2004) showed that water deficit at flowering accelerated leaf senescence and thus decreased biomass accumulation after flowering. Plant biomass increases rapidly after flowering because the grain-filling stage is the most important and active period for kernel biomass accumulation. Water deficit during this growth stage can decrease leaf photosynthesis (Chaves et al., 2009; Corrêa de Souza et al., 2013; Saglam et al., 2014) and accelerate leaf senescence (NeSmith and Ritchie, 1992), thus resulting in decreased biomass after flowering. By the ripening stage, dry matter in the kernel is almost at its maximum; the main activities are dehydration and drying, so water deficit has little influence on plant biomass during this stage.

The effect of water deficit during the vegetative and flowering stages on KN was demonstrated by Wang et al. (2017). Different water treatments produced significant differences in SSR. However, the responses of SSR to different irrigation treatments were inconsistent between 2014 and 2015 because water deficit at the vegetative and flowering stages can differentially and separately affect both PBG and KN. Water deficit at the grain-filling and ripening stages had no significant effect on KN, but at the grain-filling stage, it significantly reduced PBG. Thus, SSR for treatment G0 was low in 2014 and 2015. There was no significant difference in KW among all treatments in 2014, and the average KW was 257.24 mg. In 2015, the average KW for treatment G0 was 248 mg and was significantly less than the average KW for treatment V2F2. There was no significant difference in KW among other treatments in 2015. Photosynthate and assimilate stored in stems and leaves can be released and transported to kernels (Borrás et al., 2004), which explains the similarities in KW.

3.2. PBG-water relationship

Table 4 shows the water sensitivity indexes of PBG at the vegetative, flowering, grain-filling, and ripening stages given by the Jensen, Minhas, Blank, and Stewart models (Eq. 1–4), which were calibrated

Table 3

Effects of different irrigation treatments on post-flowering biomass gain (PBG), kernel number (KN), post-flowering source-sink ratio (SSR) and kernel weight (KW) in 2014 and 2015.

Year	Treatment	PBG (g)	KN	SSR (mg kernel ⁻¹)	KW (mg)
2014	V2F2	58.58 ± 2.68 a	166 ± 21 a	357 ± 54 ab	269 ± 5 a
	V2F1	$52.22 \pm 4.94 \text{ ab}$	161 ± 26 a	317 ± 54 ab	260 ± 15 a
	V2F0	$51.03 \pm 3.83 \text{ ab}$	161 ± 55 a	339 ± 98 ab	268 ± 9 a
	V1F2	55.41 ± 4.78 ab	141 ± 48 ab	417 ± 87 a	256 ± 12 a
	V1F1	42.80 ± 6.57 bc	120 ± 37 b	370 ± 78 ab	25119 a
	V0F2	30.33 ± 5.62 c	116 ± 3 b	263 ± 55 b	259 ± 23 a
	V0F0	22.72 ± 4.00 c	66 ± 7 c	345 ± 59 ab	255 ± 10 a
	G0	47.43 ± 5.70 ab	165 ± 21 a	289 ± 23 b	264 ± 10 a
	R0	52.40 ± 5.87 ab	166 ± 20 a	$317 \pm 30 \text{ ab}$	269 ± 9 a
2015	V2F2	70.65 ± 7.99 a	223 ± 22 a	317 ± 19 abc	272 ± 10 a
	V2F1	56.28 ± 9.02 abcd	167 ± 38 b	342 ± 50 abc	261 ± 13 ab
	V2F0	46.11 ± 11.89 cd	$130 \pm 34 \text{ bcd}$	356 ± 19 abc	274 ± 15 a
	V1F2	64.20 ± 8.22 ab	176 ± 30 ab	367 ± 33 abc	266 ± 4 a
	V1F1	47.79 ± 5.01 cd	159 ± 22 bc	302 ± 10 bcde	266 ± 13 a
	V1F0	40.02 ± 0.20 de	109 ± 38 d	402 ± 108 a	269 ± 5 a
	V0F2	45.23 ± 7.46 d	136 ± 29 bcd	336 ± 29 abc	278 ± 13 a
	V0F1	27.18 ± 3.85 ef	$118 \pm 14 cd$	232 ± 29 e	268 ± 1 a
	V0F0	17.78 ± 5.91 f	47 ± 17 e	382 ± 76 ab	264 ± 5 a
	G0	51.80 ± 6.20 bcd	214 ± 10 a	242 ± 35 de	248 ± 5 b
	RO	61.29 ± 8.54 abc	219 ± 22 a	$282~\pm~23~cde$	269 ± 4 a

Table 4

Water sensitivity indexes of post-flowering biomass gain (PBG) at each growth stage for different models that were calibrated from the 9 irrigation treatments in 2014; R^2 is the coefficient of determination.

Model	Sensitivity In		R^2		
	Vegetative	Flowering	Grain-filling	Ripening	
Jensen Minhas Blank	0.48 1.23 0.47	0.48 1.36 0.10	0.97 4.34 0.52	0.16 0.58 0.19	0.98 0.96 0.99
Stewart	0.43	0.22	0.98	0.17	0.98

using the 9 irrigation treatments for 2014. The Blank model gave the highest value of R^2 , but it showed negative water sensitivity in the ripening stage, which is not realistic. For the Jensen and Stewart models, $R^2 = 0.98$, which is higher than for the Minhas model. The water sensitivity indexes, which were calibrated using the field data of 2014, were validated with the field experimental data obtained in 2015. Fig. 2 compares observed PBG and the values predicted by the four models. The Jensen model was determined to be the best one to predicted the PBG–water relationship, with b = 1, $R^2 = 0.65$, and RRMSE = 0.1360.

Table 4 shows that the PBG water sensitivity indexes at the vegetative, flowering, grain-filling, and ripening stages were respectively 0.48, 0.48, 0.97, and 0.16. Water deficit during the vegetative and flowering stages can affect biomass both at the end of flowering and at physiological maturity, while it can significantly decrease biomass after flowering. The results show that PBG was most sensitive to water deficit during the grain-filling stage (Table 5).

3.3. KW-SSR relationship: upper and lower limits

The upper (*UpKW*; $R^2 = 0.79$, RRMSE = 0.0493) and lower (*LowKW*; $R^2 = 0.96$, RRMSE = 0.0368) limits for the KW–SSR relationship were calibrated using the experimental data of 2016 (Fig. 3). Observed KW of for each treatment in 2014 and 2015 was between UpKW and LowKW, which were calculated from observed SSR. UpKW and LowKW both increased as SSR increased, but the difference between UpKW and LowKW first increased and then decreased as SSR increased. When SSR = 0, UpKW = 178.39 mg and LowKW = 155.56 mg. When SSR ≥ 867.23 mg kernel⁻¹, UpKW = LowKW = 326.97 mg, which is the potential KW.

Borrás and Otegui (2001) and Tanaka and Maddonni (2008) modeled the relationship between KW and SSR as a two-stage linear function. When SSR was below the break point value, KW increased as SSR increased. When SSR was above the break point value, KW was constant. But in the two studies, there was a large range of KW values for a single SSR value, especially when SSR was in the range 200–300 mg kernel⁻¹. Borrás et al. (2004) investigated the relationship between relative changes in KW and relative changes in SSR. They showed that the model in which KW was most sensitive to SSR was very different from the model in which KW was most insensitive to SSR. This suggests that the upper- and lower-bounded KW–SSR model is better than the single KW–SSR model when creating an irrigation program to maximize maize kernel quality for seed production.

Kernel growth is limited by the assimilate supply (source) or by the assimilate storage capacity (sink). Some studies have used a hyperbolic model for the KW-SSR relationship. When SSR was small, the growth of the kernel was source limited. When SSR was larger, kernel growth was source-sink limited. As SSR continues to increase, kernel growth becomes sink limited (Borrás and Gambín, 2010; Borrás et al., 2004). Assimilate stored in the leaves and stem will be transported to kernels if SSR = 0 (Daie, 1988; Maddonni et al., 1998; Uhart and Andrade, 1995). The transport capability may differ between plants and thus will result in differences in KW. We found that the UpKW was 178.39 mg and LowKW was 155.56 mg when SSR was 0, which is similar to the results (~175 mg) by Ouattar et al. (1987) when photosynthesis during the grain-filling stage had stopped because of water deficit. When SSR was greater, the kernel was source-sink limited. The storage and release of assimilates is more complicated (Daie, 1988; Maddonni et al., 1998) and may differ among individual plants, which will result in larger differences between UpKW and LowKW. As SSR continues to increase, photosynthates remain stored in the leaves and stem, except for what is required for grain-filling. In this condition, kernels are sink limited, shown by a smaller difference between UpKW and LowKW.

Borrás and Otegui (2001) and Tanaka and Maddonni (2008) found that when SSR > 312–588 mg kernel⁻¹, potential KW was actualized at 295.6–338.3 mg. However, Borrás et al. (2004) showed that when there was sufficient photosynthate, KW only increased by 15% as SSR doubled. These results show that KW gradually reaches the potential KW value. We found that when the SSR \geq 867.23 mg kernel⁻¹, KW was 326.97 mg, which is similar to the results (295.6–338.3 mg) by Borrás and Otegui (2001) and Tanaka and Maddonni (2008), but the SSR value



Fig. 2. Comparison between the observed (Obs) plant biomass gain (PBG) in 2015 and the values predicted (Pre) by four different models; model parameters were calibrated using data from 9 irrigation treatments in 2014. R^2 is the coefficient of determination; RRMSE is the relative root mean square error; the solid line is the 1:1 line.

Table 5

Comparation of observed kernel weight with the upper (UpKW) and lower limits (LowKW) of kernel weight for each irrigation treatment in 2014 and 2015; kernel weight limits were calculated from the observed source–sink ratio in 2014 and 2015.

Year	Treatment	LowKW (mg)	Observed KW (mg)	UpKW (mg)
2014	V2F2	241	269	303
	V2F1	233	260	299
	V2F0	237	268	301
	V1F2	253	256	308
	V1F1	244	251	304
	V0F2	221	259	292
	V0F0	239	255	302
	G0	227	264	296
	R0	233	269	299
2015	V2F2	233	272	299
	V2F1	238	261	302
	V2F0	241	274	303
	V1F2	243	266	304
	V1F1	229	266	297
	V1F0	250	269	307
	V0F2	237	278	301
	V0F1	214	268	287
	V0F0	246	264	305
	G0	216	248	289
	R0	225	269	295



Fig. 3. The relationship between kernel weight (KW) and post-flowering source–sink ratio (SSR) of maize inbreds for hybrid seed production. Squares represent upper limit data points and the dashed line is the upper limit of KW (UpKW); triangles represent lower limit data points and the dotted line is the lower limit of KW (LowKW); the red solid line shows the difference between UpKW and LowKW (KWD). R^2 is the coefficient of determination; RRMSE is the relative root mean square error.

corresponding to potential KW was greater in this study.

4. Conclusions

In this study, we estimated the potential and minimum KW under different water regimes in hybrid maize seed production. This is important in the development of water-saving irrigation program that produces high-quality seed. Because the minimum KW can strictly constrain KW. To this end, we did three aspects of work. Firstly, we analysis the effect of water deficit on KW, and found water deficit during the vegetative or flowering stages reduced post-flowering biomass gain (PBG) and kernel number (KN), and thereby significantly affected SSR. Water deficit during the grain-filling stage reduced PBG, but had no significant effect on KN, and thereby reduced SSR. Only the treatment with no irrigation in the grain-filling stage in 2015 significantly reduced KW. Secondly, the Jensen model was selected to accurately represented the relationship between PBG and relative evapotranspiration for each growth stage. The water sensitivity index of PBG in the vegetative, flowering, grain-filling and ripening stages is respectively 0.48, 0.48, 0.97, and 0.16. Thirdly, based on the experimental data of 2016, a hyperbolic boundary analysis model was developed to estimate the upper (UpKW) and lower (LowKW) limits of KW at different SSR values. UpKW and LowKW both increased as SSR increased, but the difference between UpKW and LowKW first increased and then decreased as SSR increased. When SSR was 0, UpKW was 178.39 mg and LowKW was 155.56 mg. When SSR was not less than $867.23 \text{ mg kernel}^{-1}$, UpKW and LowKW are both equal to 326.97 mg, which is the potential KW.

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