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Corn Grain Weight: Dependence upon Nitrogen Supply and Source-Sink Relations

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Summary

From a yield component perspective, final grain yield in corn (*Zea mays* L.) is the result of the number of grains per unit area and their final grain weight. The understanding of grain weight parameters, the rate and duration of grain growth, is critical to improve our rational design of management practices and breeding strategies. In this study, we attempted to determine the effect on grain weight and grain-filling parameters of source-sink modifications (i.e. the amount of assimilates available per grain) during linear grain fill under contrasting levels of nitrogen (N) fertilization in two commercially available US corn hybrids. Two hybrids (3394 and P1197) were evaluated under zero-N and two fertilized strategies at a N rate of 194 lb/a. Four levels of source-sink manipulations were implemented: 1) control; 2) reduced sink, with partially restricted pollination; 3) reduced source, with partial defoliation; and 4) both reduced sink and source. Final grain weight was significantly affected by N management and by modifications of the source-sink ratio during grain-filling. In addition, variations in grain filling rate were responsible for the major changes in grain weight. Results from this study suggest that grain weight is very responsive to reductions in the source capacity during grain-filling, but only marginally responsive to increments in the assimilate availability per seed during grain-filling.

Introduction

From a yield component perspective, final grain yield is the result of the number of grains per unit area and their final grain weight. While grain number per area is recognized as the most important component, grain weight is an important contributor to the final grain yield in corn. Grain weight parameters, the rate and duration of grain growth, have been studied under heat stress (Wilhelm et al., 1999), across planting dates (Melchiori and Caviglia, 2008), plant density (Borrás et al., 2003), and N fertilization (Melchiori and Caviglia, 2008; Fernandez and Ciampitti, 2019) to improve recommendations of best management practices and breeding strategies in corn.

The growth of corn grains can be separated into three key phases (Johnson and Tanner, 1972). After pollination, there is a short period of active cell division where the potential kernel size is defined, usually referred to as lag phase (Reddy and Daynard, 1983). The second growth phase, the linear grain fill, is characterized by a rapid dry matter accumulation and moisture decline (Ouattar et al., 1987). As starch is accumulated in the grain throughout this period, the grain milk line advances towards the tip through the dough stage. Water content continues to drop during the third and final phase, and grains are considered physiologically mature when they achieve their maximum dry weight. After this moment, grains continue to undergo a loss of water during the dry down period until harvest moisture (20-25%) is reached. From here, we can use a bi-linear model to effectively represent these three phases (Figure 1). Lag phase duration can be calculated as the period from flowering to the intersection of the curve with the x-axis, delineating the initiation of linear grain fill. The linear phase is described in terms of the grain filling duration and the rate of dry matter accumulation. Accordingly, the constant rate of water concentration decline can be assessed after grains enter the maturity state, referred to as dry down rate. The implementation of this simple approach to estimate physiological and harvest maturities is of value to both corn farmers and scientists.

The realization of the potential grain weight is determined by the balance between the post-flowering source capacity of the plant (i.e. assimilate production during the grain filling period) and the sink (i.e. total number of grains) (Reddy and Daynard, 1983; Jones et al., 1996). This balance represents the amount of assimilates available per grain during the linear grain fill and is commonly referred to as the source-sink ratio. A better understanding of the effect of source and sink limitations on grain growth in US hybrids, and thus on yield, is critical to outline and provide guidance toward adequate agricultural practices in corn. Therefore, the aim of this work was to determine the effect on grain weight and grain-filling parameters of source-sink modifications during linear grain fill under contrasting levels of N fertilization in two commercially available US corn hybrids.

Procedures

The study was conducted at the Ashland Bottoms Research Farm, Manhattan, KS, during the 2018 growing season. The soil pH was 6.13, soil organic matter (SOM) was 1.6%, and there was 48 ppm of phosphorus (P) (Mehlich) at the 6-inch soil depth, and available N was 54 lb/a at 24-inch soil depth.

Corn was planted on April 25, 2018, in plots of four rows, 30 in. apart, and 10-ft wide × 70-ft long. The previous crop was corn and furrow irrigation was applied using gated pipes. The experimental area was kept free of weeds, pests, and diseases during the growing season. The experimental design was a split-plot with factorial subplot structure, where hybrids were assigned to whole plots, and combinations of levels of N and source-sink treatment factors + a zero-n negative control were assigned to subplots. Two Pioneer (Corteva Agriscience, Johnston, IA, US) hybrids were evaluated [3394 and P1197, detailed description of hybrids in Fernandez et al. (2021) under zero-N and two fertilized strategies with an equal final N rate of 194 lb/a: 1) early N, split in two applications (50% planting and 50% V6); and 2) late N, split in three applications (50% planting, 20% V6, and 30% V12). Four levels of source-sink ratio were included (Figure 2): 1) control with normal pollination; 2) reduced sink, with partially restricted pollination; 3) reduced source, with partial defoliation; and 4) reduced both sink and source, combination of treatment 2 and 3. Reduced sink treatments were achieved using a bag to cover the entire ear when the silks were 2.5 cm long (Rajcan and Tollenaar, 1999). Partial defoliation was accomplished, two weeks after flowering, by removing the four topmost leaves. Lastly, a zero N (no N applied) with normal pollination was added as a negative control.

Grain filling was measured since blister stage (R2) of growth, collecting one ear per plot every week from each treatment combination, until harvest. Ten grains from the central portion of the ear were sampled to track changes in dry weight and water volume during the period. Grain filling rate and duration were estimated on a day-time basis from flowering to harvest maturity, fitting a bi-linear model [equations (1) and (2)] in each hybrid × nitrogen × source-sink treatment combination:

$$\text{Grain weight (mg grain}^{-1}) = a + b * x \qquad \text{for } x < c \quad [1]$$
$$\text{Grain weight (mg grain}^{-1}) = a + b * c \qquad \text{for } x > c \quad [2]$$

where *x* are the days after flowering, *a* is the y-intercept (mg grain^{-1}), *b* is the grain growth rate (mg grain^{-1} day^{-1}), and *c* is the total duration of grain filling (in days). In addition, the source/sink ratio during effective linear grain fill was calculated as the quotient of biomass accumulated from 15 days after flowering to physiological maturity and the total grain number per unit of land area.

The effect of treatments on all variables under study was determined through three-way analyses of variance (ANOVA). Multiple pairwise comparisons were performed using Fisher's least significant difference (LSD) method at a 5% level of significance. Relationships between variables were described through linear regression analysis.

Results

Final grain weight was significantly affected by N management and by modifications of the source-sink ratio during grain-filling ($P \leq 0.001$, Table 1). Under N fertilization, control treatments averaged 294 mg (hybrid 3394) and 304 mg (hybrid P1197) per grain. Small increments in grain weight were observed when pollination was restricted (i.e. source-sink ratio was increased), increasing up to 340 and 320 mg, respectively, for 3394 and P1197 hybrids. In contrast, when defoliations occurred (i.e. source-sink ratio was reduced), grain weight was dramatically impacted and averaged 231 and 251 mg, respectively, for 3394 and P1197 hybrids.

Furthermore, grain filling rate followed a similar behavior pattern as that observed for grain weight. A bi-linear relationship within these two variables showed that variations in grain filling rate were responsible for the major changes in grain weight until a plateau of 341 mg was achieved at a rate of 10.2 mg day^{-1} (Figure 3A). For grain filling rate, main effects for N fertilization and source-sink treatments were identified. While it is known that N deficiency produces a significant impact in the number of grains set (Fernandez et al., 2020), here we have also observed that N deficiency affects the source-sink ratio during grain-filling (Figure 3B). These results show that N stress impacted corn grain weight essentially through reductions on the grain filling rate.

In this study, we showed that grain weight, and in particular the rate of dry matter accumulation, is very responsive to reductions or deteriorations in the source capacity during grain-filling (Figure 3B). However, it also shows that grain weight (and thus crop yield) is only marginally responsive to increments in the assimilate availability per seed during grain-filling, plateauing at a source-sink ratio of 380 mg grain^{-1}. It is also critical to highlight the importance to maintain an adequate source strength with respect to the number of grains via adequate management practices (N supply), in particular, for the period around flowering in corn (Borrás et al., 2004).

We also revealed that grain moisture at maturity (%) was significantly modified across the evaluated treatments, but in a different manner in each genotype ($P \leq 0.001$, Table 1). The hybrid 3394 resulted in lower grain moisture of 32.4% when reductions in the source capacity through defoliations were implemented. Instead, the P1197 hybrid showed lower plasticity for grain moisture when maturity was reached, ranging from 34.4 to 39.3% across all treatments. Lastly, the rate of post-maturity (maturity to harvest) dry down exhibited a decline or an increment in response to either source or sink reductions, respectively. However, modifications in the rate of dry down were less important than other variables, demonstrating that this period is highly dependent on the prevailing weather conditions—mainly related to humidity, temperature, and precipitation.

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Table 1. Analysis of variance and means for grain weight, grain filling rate and duration, moisture percentage at maturity, and dry down rate for two hybrids (H) and four source-sink treatments (SS) across three nitrogen (N) levels in 2018 field experiment

Hybrid	Source-sink	Nitrogen	Grain weight		Grain filling rate		Grain filling duration		Moisture at maturity		Dry down rate	
			mg		mg day^{-1}		days		%		% day^{-1}	
3394	Control	0N	257	cd	7.5	cd	43		36.6	c	-0.86	b
		Early 194N	297	b	8.8	bc	43		37.4	bc	-0.87	bc
		Late 194N	291	bc	8.6	bcd	43		39.2	abc	-0.9	bcd
	Restricted pollination	Early 194N	344	a	10.9	a	41		39.8	ab	-0.91	cd
		Late 194N	337	a	10.7	a	41		40	ab	-0.91	cd
	Defoliated	Early 194N	236	d	7.1	d	41		32.6	d	-0.81	a
		Late 194N	233	d	7.1	d	41		32.2	d	-0.81	a
	Restricted pollination + defoliation	Early 194N	336	a	9.9	ab	43		37.5	bc	-0.87	bc
		Late 194N	340	a	11	a	40		41.1	a	-0.92	d
P1197	Control	0N	235	c	6.6	e	43	ab	37.3	abc	-0.87	abc
		Early 194N	302	b	8.5	cd	44	a	36.5	abc	-0.86	abc
		Late 194N	306	b	9.1	bc	43	ab	38.7	ab	-0.89	bc
	Restricted pollination	Early 194N	320	ab	10.5	ab	40	bc	36.5	abc	-0.86	abc
		Late 194N	320	ab	10.2	ab	41	abc	35.6	bc	-0.85	ab
	Defoliated	Early 194N	251	c	7.5	de	42	ab	34.4	c	-0.83	a
		Late 194N	252	c	7.5	de	42	ab	36.7	abc	-0.86	abc
	Restricted pollination + defoliation	Early 194N	345	a	10.3	ab	42	ab	35.8	bc	-0.85	ab
		Late 194N	325	ab	11.3	a	38	c	39.3	a	-0.9	c
Sources of variation												
Hybrid (H)			ns		ns		ns		ns		ns	
Nitrogen (N)			***		***		ns		*		*	
Source-sink (SS)			***		***		+		***		***	
H × N			ns		ns		ns		ns		ns	
H × SS			ns		ns		ns		***		***	
N × SS			ns		ns		ns		+		+	
H × N × SS			ns		ns		ns		ns		ns	

Within each hybrid, different letters indicate significant differences at $P \le 0.05$.
+ Significant at $P \le 0.1$; * significant at $P \le 0.05$; ** significant at $P \le 0.01$; *** significant at $P \le 0.001$.
Ns: non-significant.

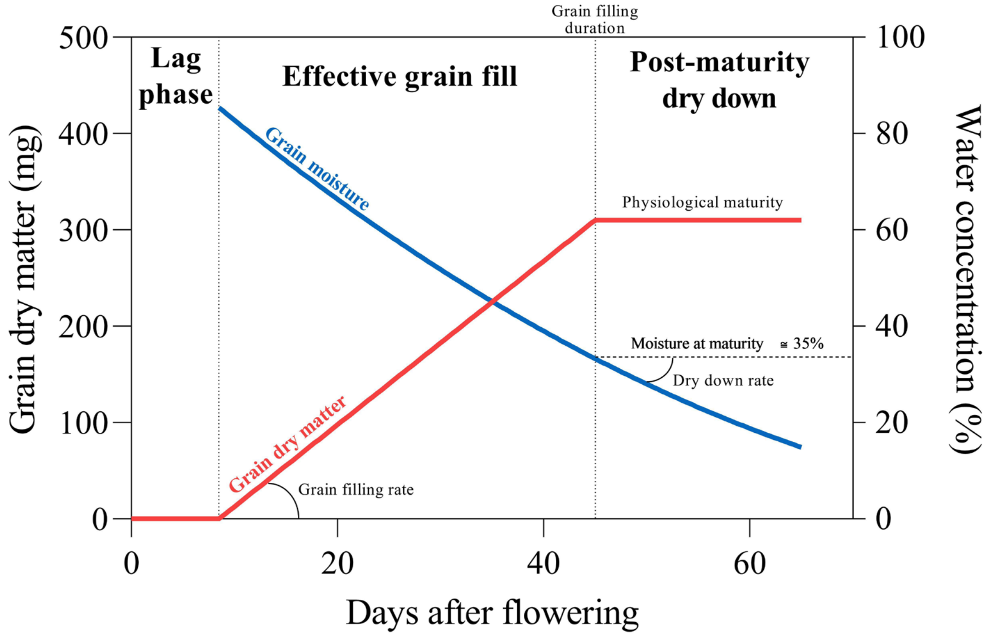

Figure 1. Graphical representation of the grain dry matter accumulation and water concentration decline on a day-time basis.

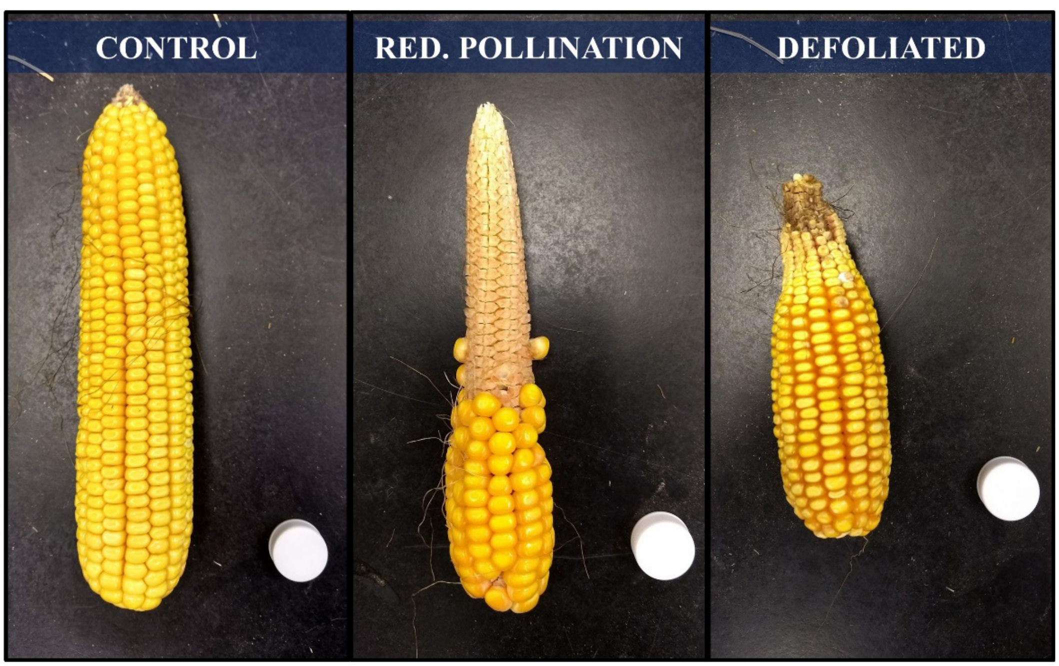

Figure 2. Picture of corn ears across three source-sink ratio manipulations evaluated in 2018 field experiment.

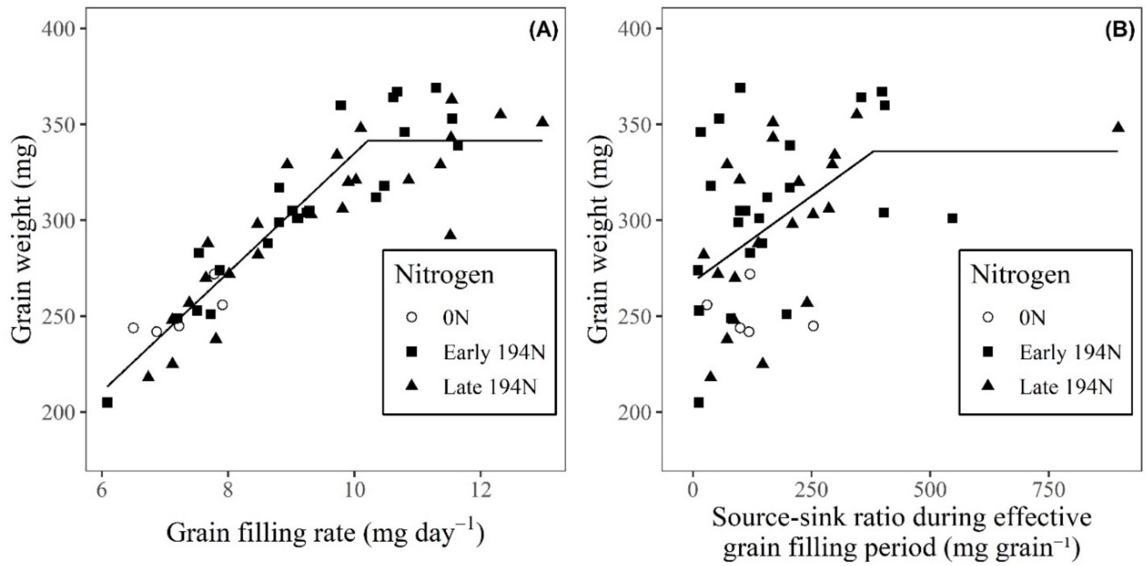

Figure 3. Relationship between grain weight and grain filling rate (A), and source-sink ratio during effective grain-filling (B). Symbols represent replicates across two hybrids, four source-sink treatments, and three nitrogen (N) levels in 2018 field experiment.