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Ashlyn Kessler
Iowa State University

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Planting date, cultivar maturity, and environment effects on soybean yield and crop stage

by

Ashlyn Kessler

A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the

MASTER OF SCIENCE

Major: Crop Production & Physiology

Program of Study Committee:
Mark Licht, Co-major Professor
Sotirios Archontoulis, Co-major Professor
Peter (Petro) Kyveryga

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ABSTRACT

Selecting soybean (*Glycine max* (L.) Merr.) planting date and maturity group are important agronomic decisions that are often affected by unfavorable weather. The objective of this study was to quantify how the selection of maturity groups and later than optimal planting dates effected soybean seed yield and crop development over time across Iowa, US. Field experiments were conducted at seven locations between 2014 and 2016 for a total of 21 environments. Cultivar maturities varied by location (ranging from 2.2 to 2.5 MG) and planting dates were scheduled for 20-day intervals from early May to early July. Studied planting date and maturity group combinations that resulted in grain yields ranging from 0.27 to 7.54 Mg ha^{-1}. Analyses showed that the main effect of maturity group had little (3.28 to 4.30 Mg ha $^{-1}$) to no effect on grain yield at 4 of 7 sites while the main effect of planting date was significant ($p < 0.001$) at all sites. The interaction of planting date and cultivar maturity was not significance. With delayed planting dates, the length of the non-grain filling (VE-R3) and grain filling (R3-R7) period were shortened by up to 15-20 days, resulting in less radiation, smaller growing degree day accumulation, and lower yields. Across northern Iowa, there was a critical radiation accumulation of 946 MJ whereas the critical radiation accumulation (1074 MJ) was much higher across southern Iowa. These results show that yield potential would be maximized by planting before May 20 using a cultivar maturity group that is well-adapted to specific location or geography. To maximize yield, planting soybean earlier in the growing season was a better management practice than maturity selection, and the duration of the grain filling period was critical in determining potential yield each growing season.

CHAPTER 1

INTRODUCTION

In Iowa, the second largest soybean producing state in the US (USDA-NASS, 2018), soybean planting delays occur because corn (*Zea mays* L.) planting is a priority for farmers, and logistical issues become common due to cool and wet soil conditions and increasing farm size (De Bruin and Pedersen, 2007b). Based on the current soybean planting recommendations, for southern Iowa, an optimum planting date is considered during the last week of April and for northern Iowa, optimum planting date falls within the first week of May (De Bruin et al., 2007b; Nafziger, 2015). To mitigate the negative effect of delayed planting date on grain yield, researchers have studied the effect of planting date and interaction of cultivar maturity selection on yield but little to no significant effect or interaction between planting date and maturity group have been found (Anderson and Vasilas, 1985; Barreiro and Godsey, 2013; Johnson and Major, 1979; Raymer and Bernard, 1988; Wilcox and Frankenberger, 1987).

Weather variability can greatly change the magnitude of the planting date effect on yield (Egli and Cornelius, 2009). Weather, in particular temperature, and photoperiod, which is a measure of time each day from sunrise to sunset at a given location, determine the length of the growing season from the first day of suitable planting conditions to the first suitable day for harvest. Weather and photoperiod can affect all phenological stages or periodic stages of plant development that are affected by seasonal variations in climate and environmental factors, through heat stress, water stress, the progressive initiation of crop growth stages, and photosynthesis. Photosynthesis being the process by which chlorophyll containing organisms, such as soybean, convert light energy to chemical energy, and chemical energy is then used to carry out vital processes or stored as carbohydrates. Decreased photoperiod and radiation lead to decreased photosynthesis which delays crop development. Delayed planting shifts the grain filling period, time from pod set initiation to physiological maturity, into a less favorable period with less photoperiod and lower temperatures.

Across the US, farmers select crop cultivars several months prior to the optimal planting time. Their decisions for the coming growing season must be based on recommendations given by seed dealers or Extension guides, assuming an average weather in the coming year. With increased year-to-year climate variability, there is a need to continually update planting recommendations to improve the decision-making process. There is currently a knowledge gap regarding maturity selection when planting is delayed past the optimum planting window. The critical planting date when yield reduction occurs has not adequately been determined for the different sections of Iowa. Furthermore, farmers face a dilemma when determining whether to use a long or short maturing cultivar when planting has been delayed or replanting needs to occur past the optimum planting window.

Our objectives with this study were to:

1) identify the optimum planting date (PD) or planting window for well adapted cultivars to maximize yield potential across seven locations and three years in Iowa;
2) to estimate the risk associated with longer cultivar maturity groups (MG) when planting occurs beyond the optimum PD or planting window; and
3) develop easy to use predictors of grain yield.

To achieve our objectives, we analyzed an experimental dataset from Iowa (n = 1,024), that has soybean PD and MG treatments across 21 site-years, and we quantified the effect of multiple environmental factors on grain yield.

CHAPTER 2

MATERIALS & METHODS

2.1 Experiment sites

Field experiments were conducted over three growing seasons from 2014 to 2016, at seven experimental sites across Iowa. These sites were chosen for their broad representation of Iowa's climate and soil types and were recently described by Baum et al. (2019). All seven sites were located on Iowa State University research farms, with three of the sites located across northern Iowa, three sites across southern Iowa, and one site in central Iowa. Sites will be denoted as Northwest, North Central, Northeast, Central, Southwest, South Central and Southeast based on their respective locations across Iowa. Iowa's Environmental Mesonet weather stations were used to collect weather data for each site (IEM, 2016).

2.2 Experimental design and management

Treatments were replicated four times in a split-plot design with PD and MG as the main and sub-plot factors, respectively. Individual plot size was 4.6 m by 13.7 m and row spacing was 76.2 cm. Soybean were planted following maize (*Zea mays* L.) at 345,800 seeds ha^{-1}. In order to ensure that pests were not a limiting factor to yield, pesticides were applied as needed. Soil fertility for phosphorus, potassium and pH at each site was maintained per Iowa State University recommendations (Mallarino et al., 2013).

2.3 Planting date and maturity

Site-years contained four PD with the target PD of 1 May, 20 May, 10 June, and 1 July. Target dates were not attained every site-year, due to variations in weather (Table 1). This created four categories of actual planting date among site-years, early May, mid-May, early June, and early July. Some of the early May planting dates fell in late April and some of the early July fell into late June.

Six different varieties were planted across site-years; P19T01R, P22T69R, P25751R, 92Y75, P35758R, and P39T67R (DuPont Pioneer, Johnston, IA) with MG ranging from 1.9 to 3.9. Geographically adapted MG were used which resulted in different maturities used in the northern sites as compared to the southern sites. The North Central and Northeast sites used MG 2.2, 2.5 and 2.7, while the Northwest only had MG 2.2 and 2.5. The southern sites used MG 2.5, 3.5 and 3.9. The central site had four MG, 2.2, 2.5, 2.7 and 3.5, in order to capture the range of maturities from both the northern and southern sites.

2.4 Measurements and calculations

Observations of seedling emergence and key reproductive stages beginning flowering (R1), beginning pod (R3), beginning maturity (R7) and full maturity (R8) were recorded (Pedersen & Licht, 2014). Analysis was focused on the phenological durations of non-grain filling (VE-R3) and grain filling (R3-R7). Grain yield was determined by mechanically harvesting the center 4 rows of each plot with a Harvest Master weigh bucket system. All yield data were converted to 130 g/kg grain moisture content. The following formula was used to calculate growing degree days (GDD):

$$[1] \qquad GDD = \frac{\mathrm{Tmax} + \mathrm{Tmin}}{2} - base$$

where Tmax and Tmin were the daily maximum and minimum temperatures, respectively, and a base of 10°C. When daily maximum temperatures exceeded 30°C, 30°C was used for Tmax, and when daily minimum temperatures fell below 10°C, 10°C was used for Tmin

(Archontoulis et al., 2014). The total GDD accumulation was calculated for the non-grain filling (VE-R3) and grain filling (R3-R7) durations.

2.5 Data analysis and statistics

The maximum yield observed in a site-year by MG and PD category was used to calculate relative grain yield for each treatment. An analysis of variance (ANOVA) was used to determine the treatment effects using a linear model of the R statistical software (R Core Team, 2017). The model provided statistical inference for the main effects of PD and MG and their interaction on grain yield. A mixed effects model was used where replication and year were considered a random effect and site, PD, and MG were considered fixed effects. Since site was significant (Table 2) and MG were nested by site, ANOVA's were calculated separately for each site.

A quadratic model was used to explain how PD effected relative grain yield. The *nlme* package in R was used to fit the relative grain yield response to planting date. The following non-linear model was used:

$$[2] \quad y = ax^2 + bx + c$$

where y is yield; x is planting day of year (DOY); and a, b, and c are coefficients specific to each site-year by MG combination. The model was applied separately to each site-year by MG combination (n = 63).

Predicted values derived from equation 2 were used to fit curves to represent yield losses from the observed data points and to determine the mean grain yield over 10-day planting intervals from early May through early July (Table 3).

CHAPTER 3

RESULTS

3.1 Weather conditions and grain yield

Rainfall varied considerably among the site-years (Figure 1). Below average rainfall occurred at Northwest in 2014, Northwest and North Central in 2015 and South Central in 2016. Above average rainfall occurred in North Central, Northeast, Central, Southwest, South Central and Southeast in 2014; Central, Southwest and Southeast in 2015; and Northeast and Southwest in 2016. Precipitation was a particular challenge during the 2014 growing season at the North Central site where some of the plots drowned out late summer before harvest.

Fall frost can also be a yield limiting factor for soybean in Iowa. The typical killing frost (-2.22 °C) date for Iowa falls in mid-October, data not shown. In over 90% of our site-years the fall frost date occurred after the historical average. However, several plots at North Central were damaged by a killing frost in 2014.

3.2 Effects on grain yield and crop phenology

Planting date had the largest effect on grain yield (Table 2, Figure 2). Higher grain yields were achieved when PD occurred in May compared with June and July. Full-season MG had significantly higher grain yields than the short-season MG for the three southern sites, whereas short-season MG had higher grain yields than the full-season MG for the three northern sites. At the Central site, yields were not significantly different among MG.

Delays in PD to early July caused significant delays in flowering and maturity. This, in turn, shortened the vegetative and reproductive intervals (Figure 3). The early May PD had a mean growing season length of 118 days. The growing season length decreased to 113, 94 and 92 days for the late May, early June and early July PD, respectively. From early May to the early July PD, the time from pod-set to maturity decreased from an average of 56 days to 44 days with average relative yield for those PD decreasing from 80% to 55%.

3.3 Optimum planting windows

The observed variability in grain yield response to PD across all the cultivar-specific models from each site-year is illustrated in Figure 2. The non-linear model used to describe the observed grain yields vs day of year performed well (mean $R^2 = 0.80$). The model predicted yields were used to calculate the optimum PD for each combination of site-year and MG. Optimum PD for each site was realized on the DOY that had the highest grain yield for each year-MG combination. Frequency analysis of the optimum PD revealed that the optimum PD window was narrower for the North Central and Southeast sites but was bi-modal for all sites.

Since MG had a minor effect on the yield response to PD, predicted mean values across MG were calculated to estimate the risk of yield loss from different PD. Using model predictions, declines in grain yield change began in mid-June with maximum relative yield most frequently found in mid-May (Table 3). Relative yield of greater than 92% was achieved with PD in late May or earlier while PD before mid-June resulted in greater than 84% relative yield.

3.4 Critical vegetative and grain filling thresholds for achieving optimum yields

Regression analysis between yield and key phenological events (Figure 3) revealed important thresholds that can assist with yield predictions and understanding crop physiology. The non-grain filling (emergence to pod-set) duration threshold to achieve the highest relative yield was 54 days for northern sites while no threshold could be determined for the southern sites (Figure 3A & 3C). For the northern sites, yield significantly drops when the threshold is not reached. A cumulative GDD optimum was reached at 689 for the non-grain filling period in the northern sites (Figure 4A). The southern sites reached an optimum cumulative GDD of 709 for the non-grain filling period (Figure 4C). The northern sites reached an optimum duration of 61 days for the grain filling period (pod-set to physiological maturity; Figure 3B). Our data did not reach an optimum but through extrapolation the southern sites would reach an optimum duration of 66 days for the grain filling period (Figure 3D). Neither the northern nor the southern sites reach a threshold during the grain filling period for cumulative GDD (Figure 4B & 4D). With the optimum grain filling duration ranging from 61 to 66 days and the cumulative GDD not reaching a threshold, this illustrates the importance of planting early enough to avoid delays in flowering and grain filling.

High soybean yields were achieved when accumulated radiation during the grain filling period reached 946 and 1074 MJ for the northern and southern sites, respectively (Figure 5). Relative yield gradually declines from the threshold as radiation decreases for both the northern and southern sites (Figure 5). A precipitation accumulation threshold was not reached for the northern sites non-grain filling period (Figure 6A). Precipitation accumulation during grain filling reached a high relative yield threshold at 215 mm for the northern sites. Relative yield declined significantly when that threshold was not reached and a minimum of 179 mm of precipitation was needed to achieve 50% relative yield (Figure 6B). For the southern sites non-grain filling period, an optimum was reached at 321 mm of precipitation, and 195 mm are needed to achieve 50% relative yield (Figure 6C). The southern sites did not reach a threshold for the grain filling period, but relative yield increased as precipitation accumulation increased (Figure 6D). To achieve 50% relative yield, it was found that the grain filling period needed at least 163 mm of precipitation. This shows the importance of both radiation and precipitation during the grain filling period.

There was a strong linear relationship between mean photoperiod and yield during the non-grain filling period ($R^2 = 0.91$, Figure 7A; $R^2 = 0.92$, Figure 7C). The higher mean photoperiod resulted in higher relative yield for the non-grain filling of both the northern and southern sites, but no thresholds were reached (Figure 7A & 7C). The northern sites reached an optimum mean photoperiod for the grain filling period at 14.3 hours day^{-1} (Figure 7B). A photoperiod of 13.5 hours day^{-1} during grain fill period was the optimum for maximizing yields at the southern sites (Figure 7D).

Overall, mean photoperiod is easy to record and is the most important variable for predicting yield during the non-grain filling period with an $R^2 = 0.91$ and 0.92 for the northern and southern sites, respectively. Precipitation and GDD were less reliable variables during the non-grain filling period with GDD having $R^2 = 0.85$ and 0.69 for the northern and southern sites, respectively, and with precipitation having no correlation with relative yield for the northern sites and an $R^2 = 0.77$ for the southern sites. Radiation interception was not measured so there are no results for the non-grain filling period. For the grain filling period, precipitation, radiation, photoperiod and GDD are all important variables. However, GDD is the most important of the four variables for predicting yield for the grain filling with an $R^2 = 0.90$ for the northern sites and $R^2 = 0.96$ for the southern sites. Growing degree days and photoperiod are the most important of the variables since they are known to influence the rate of development in soybean, and photoperiod is constant year after year making it a reliable predictor of grain yield (Pedersen and Licht, 2014; Major et al., 1975). Radiation is also important as it is a driver of photosynthesis, but as the grain fill period is pushed later in the growing season the radiation quantity and quality decreases.

CHAPTER 4

DISCUSSION

Soybean PD recommendations for Iowa have not been updated since 2007 by De Bruin et al. and there is limited research on soybean MG selection based on PD across the Midwestern US. The results of this study show that by planting prior to May 20 farmers can achieve yield potentials greater than 92% and that MG selection is less influential on soybean yield than PD. Additionally, the study can help farmers and modelers forecast yield potential when planting is delayed beyond mid-May.

Soybean yield response to delayed PD has not changed for Iowa and much of the major soybean growing region of the US despite changing climate patterns (Figure 8; Anderson and Vasilas, 1985; Beaver and Johnson, 1981; De Bruin et al., 2007a; De Bruin et al., 2007b; Elmore, 1990; Oplinger and Philbrook, 1992; Pedersen and Lauer, 2003; Wilcox and Frankenberger, 1987). Increased variability in precipitation frequency and quantity and increased temperature have been observed (Hatfield et al., 2018). Water availability will be the greatest weather factor to effect soybean yield in the future. We see later PD due to excess rain in the spring or the need for replanting (Kistner et al., 2018; USDA-NASS, 2018).

While earlier PD have been known to yield more, there is the expectation that too early of a PD increases risk due to killing frost or poor soil conditions (Anderson et al., 1985; De Bruin et al., 2007a; De Bruin et al., 2007b). Our study is focused on a range from average to late planting dates. With increasing climatic variability, frequent delays in planting are observed across Iowa and the Midwestern US (Kistner et al., 2018; Hatfield et al., 2018; Hamlet et al., 2019). We found that in production fields the optimal PD ranged from May 1 to May 20 (DOY 120 to 140) with some sites possibly having earlier optimal PD that were not encompassed within this study.

Our study found a disproportionate yield drop between northern and southern sites when planting was delayed from early June to early July, with northern sites losing an average of 15 kg ha^{-1} day^{-1} and southern sites losing an average of 35 kg ha^{-1} day^{-1}. These observations suggest that early planting is of greater importance for farmers in southern Iowa in order to achieve maximum yields. This could be explained by longer maturing cultivars planted in southern sites, but the same planting dates were used at both the northern and southern sites.

Late planting of soybean has a tremendous impact on grain yield relative to the non-grain filling and grain filling periods. In our study we found that the duration of each of these periods was shortened and in turn, led to a decrease in cumulative radiation, precipitation, GDD, and average photoperiod. When precipitation and GDD accumulation decrease during the grain filling period we see a significant decline in relative yield. A shortened growing season results in reduced biomass accumulation before flower initiation and decreased accumulated dry matter during grain filling (Anderson et al., 1985; Wilcox et al., 1987).

In the past, researchers have found greater grain yield of full-season MG than short-season MG when planted earlier in the growing season; while short-season MG have a grain yield advantage when planted later in the growing season (Nafziger, 2015). The same trend was true for our northwest, southwest, south central, and southeast sites while there was no evidence to support the latter, as there was no significant difference between maturity groups in the later planting dates.

CHAPTER 5

CONCLUSION

Planting soybean earlier in the growing season is a management practice that can be used to increase yield. However, increased climate variability can limit this. Maturity selection within the well adapted range for a given location does not significantly impact grain yield in this study, but it is still important to choose a cultivar maturity appropriate to the growing environment. Grain filling is an important period in determining grain yield potential and is affected by planting date. The grain filling was shown to begin earlier, last longer and accumulate more radiation, precipitation, GDD, and higher mean photoperiod, when planting occurred earlier. An average yield loss of 11 kg ha^{-1} d^{-1} is observed when planting is delayed beyond May 20, this occurs because the non-grain filling and grain filling durations are shortened. With larger climate variability and better cultivars, it is important to continue studying the effect of planting date to optimize soybean management and improve PD recommendations.

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FIGURES & TABLES

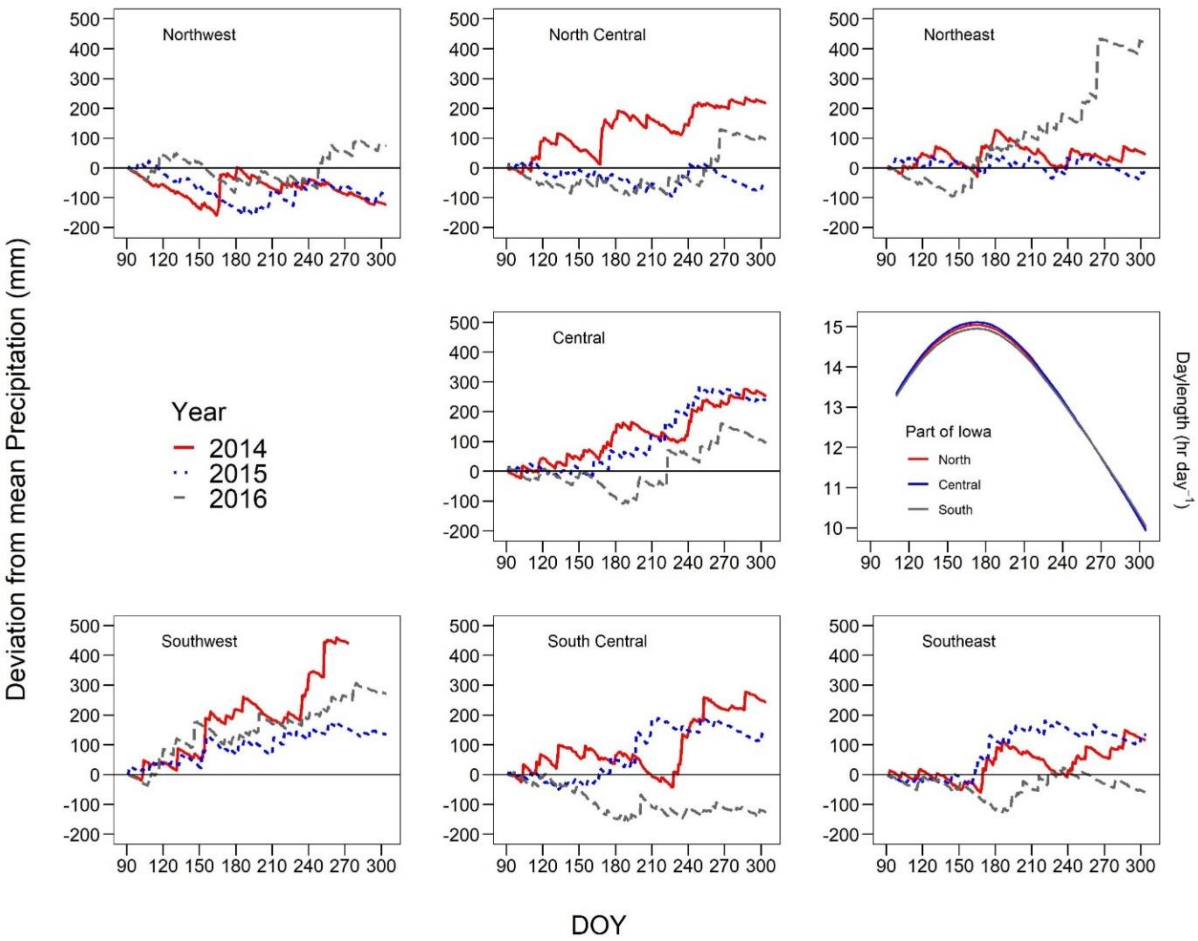

Figure 1. Difference from mean historical precipitation (mm) across the growing season (April 1 to October 31). The horizontal line at y = 0 represents the mean 35-year precipitation for the site. The center right plot shows daylength over the growing season based on geographic location (northern, central, and southern Iowa).

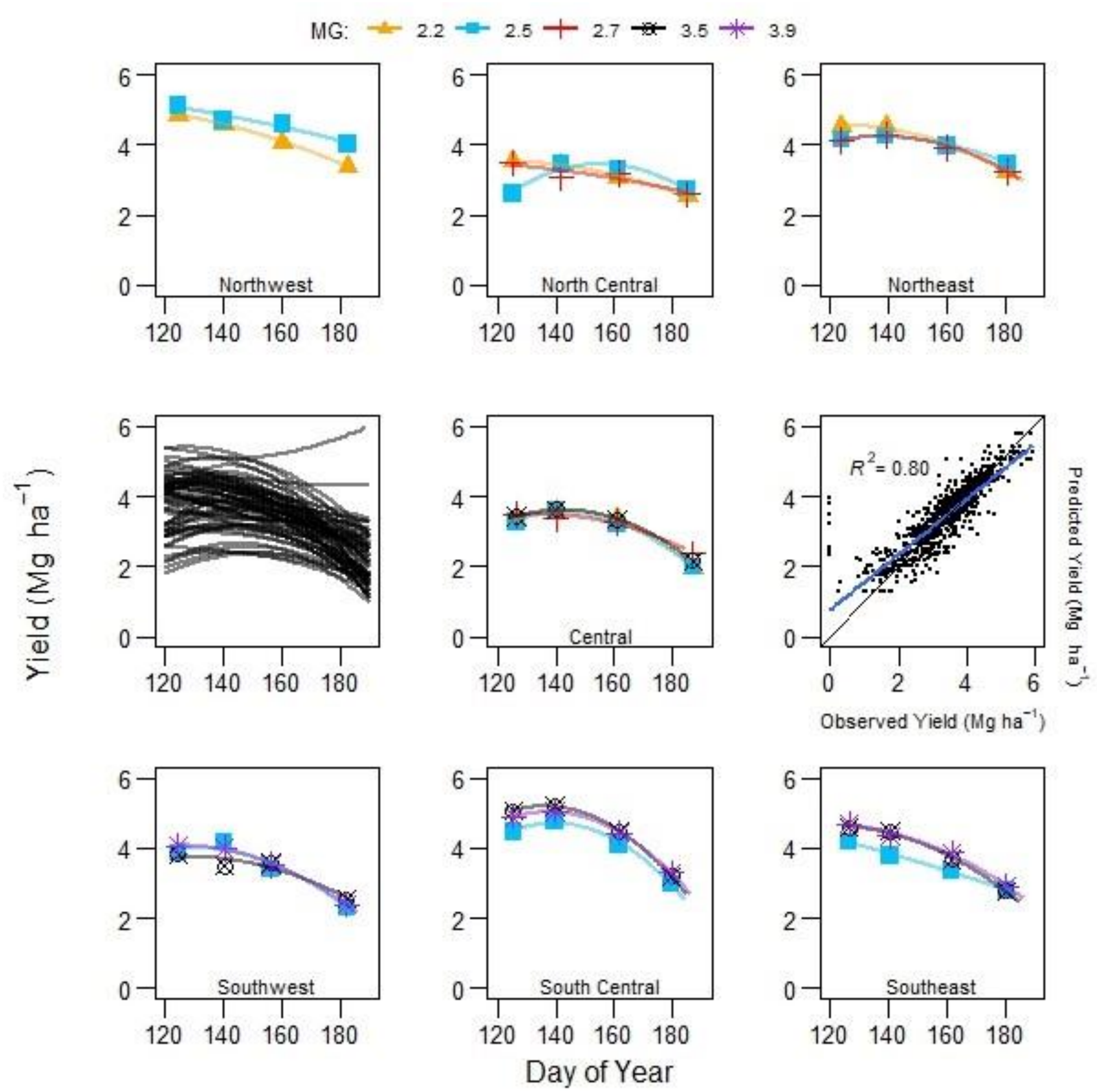

Figure 2. Soybean grain yield response to planting date. Shape and color correspond to individual MG. Lines are predicted values of site-year by MG and points represent actual data. Left center panel illustrates the quadratic response curve variability for each individual MG by site-year (n = 63). Right center panel shows measured versus predicted grain yield for each PD by MG by site-year.

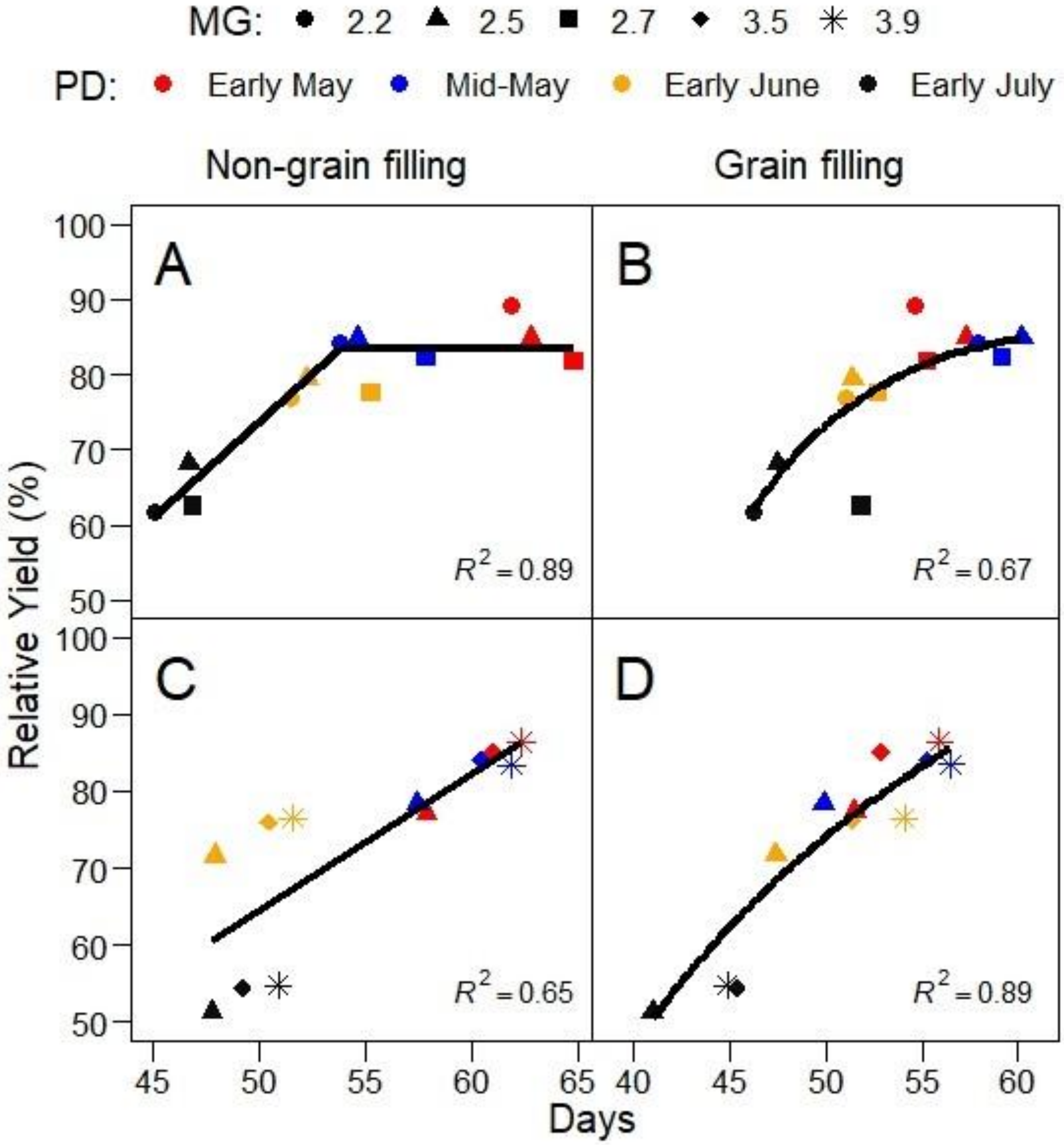

Figure 3. Relative grain yield relationships with the duration (days) of key phenological stages. The top row is the northern sites and the bottom row is the southern sites. The left column represents the non-grain filling period and the right column represents the grain-filling period. Each symbol represents a site-year by maturity group combinations. The interaction between PD and MG is not statistically significant.

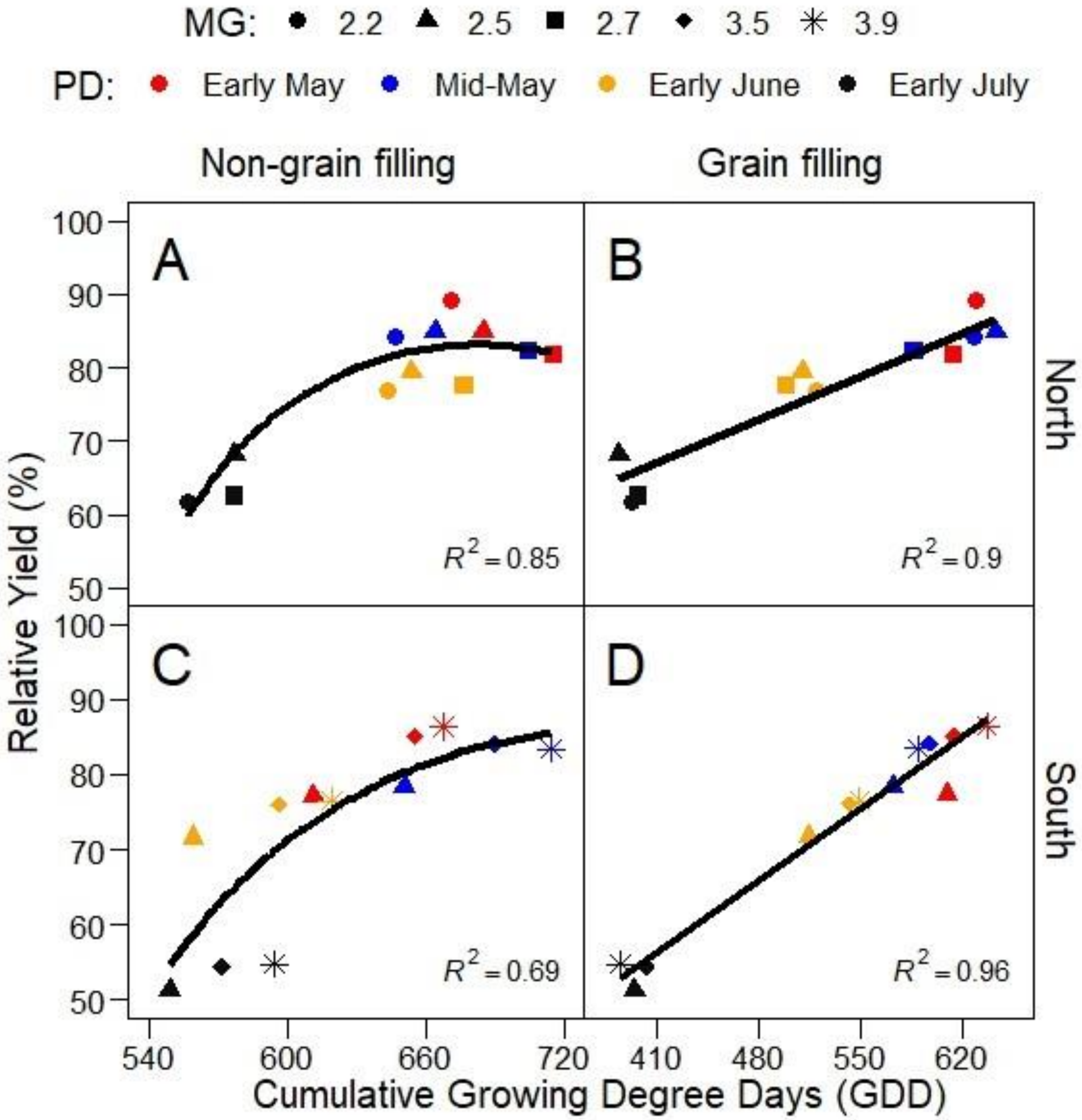

Figure 4. Relative grain yield relationships with the cumulative growing degree days within the non-grain filling and grain filling periods. The top row is the northern sites and the bottom row is the southern sites. The left column represents the non-grain filling period and the right column represents the grain-filling period. Each symbol represents a site-year by maturity group combinations. The interaction between PD and MG is not statistically significant.

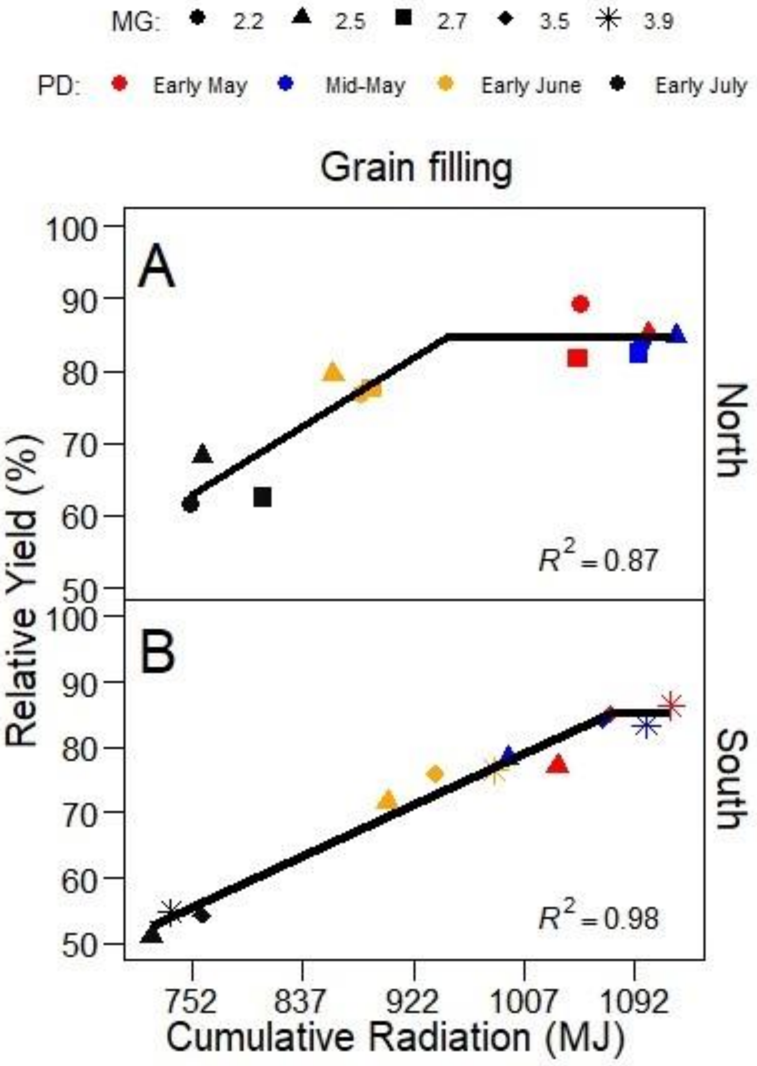

Figure 5. Relative grain yield relationships with the cumulative radiation (MJ) within the grain filling period. The top panel is the northern sites and the bottom panel is the southern sites. Each symbol represents a site-year by maturity group combinations. The interaction between PD and MG is not statistically significant.

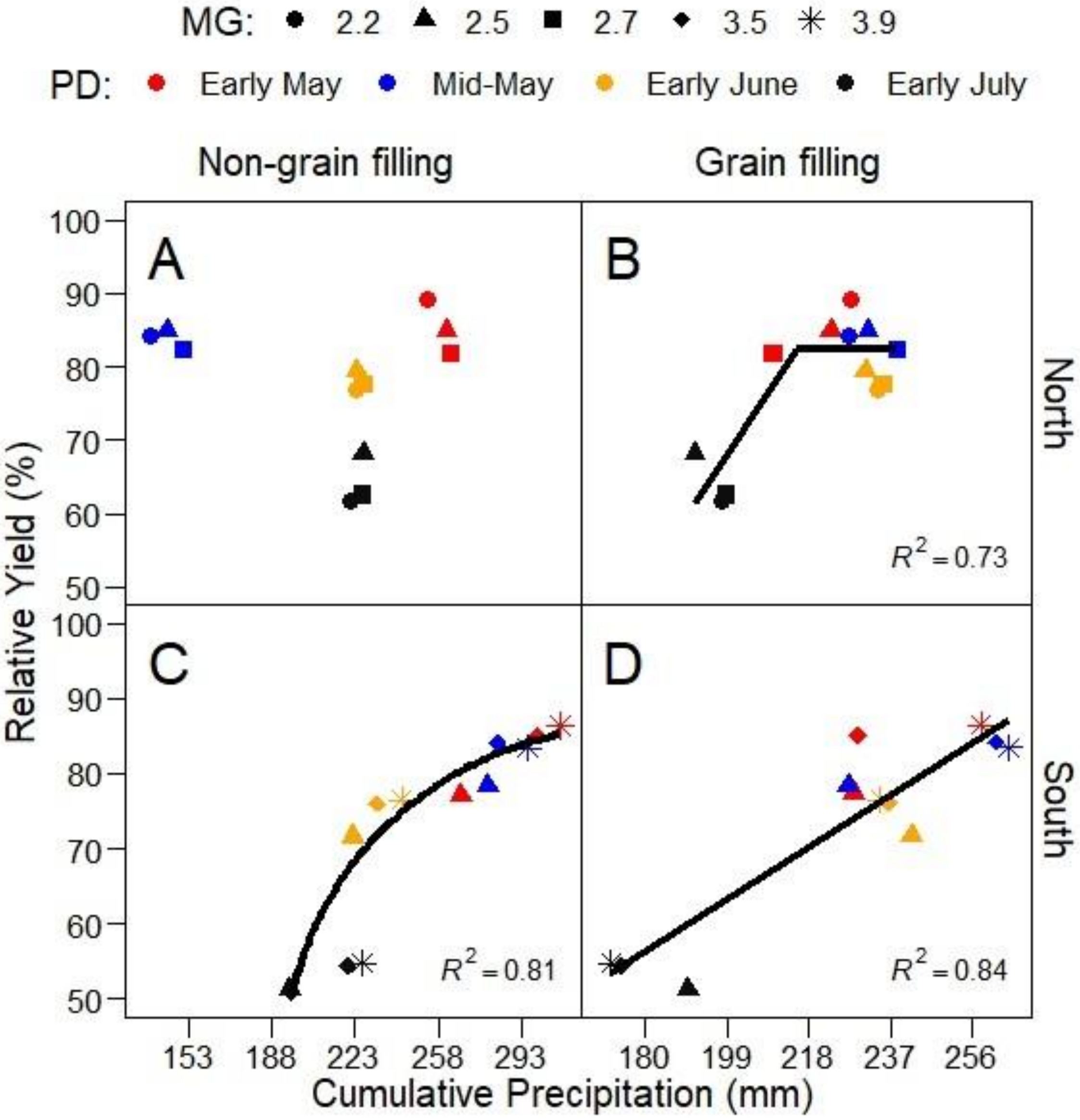

Figure 6. Relative grain yield relationships with the cumulative precipitation (mm) within the non-grain filling and grain filling periods. The top row is the northern sites and the bottom row is the southern sites. The left column represents the non-grain filling period and the right column represents the grain-filling period. Each symbol represents a site-year by maturity group combinations. The interaction between PD and MG is not statistically significant.

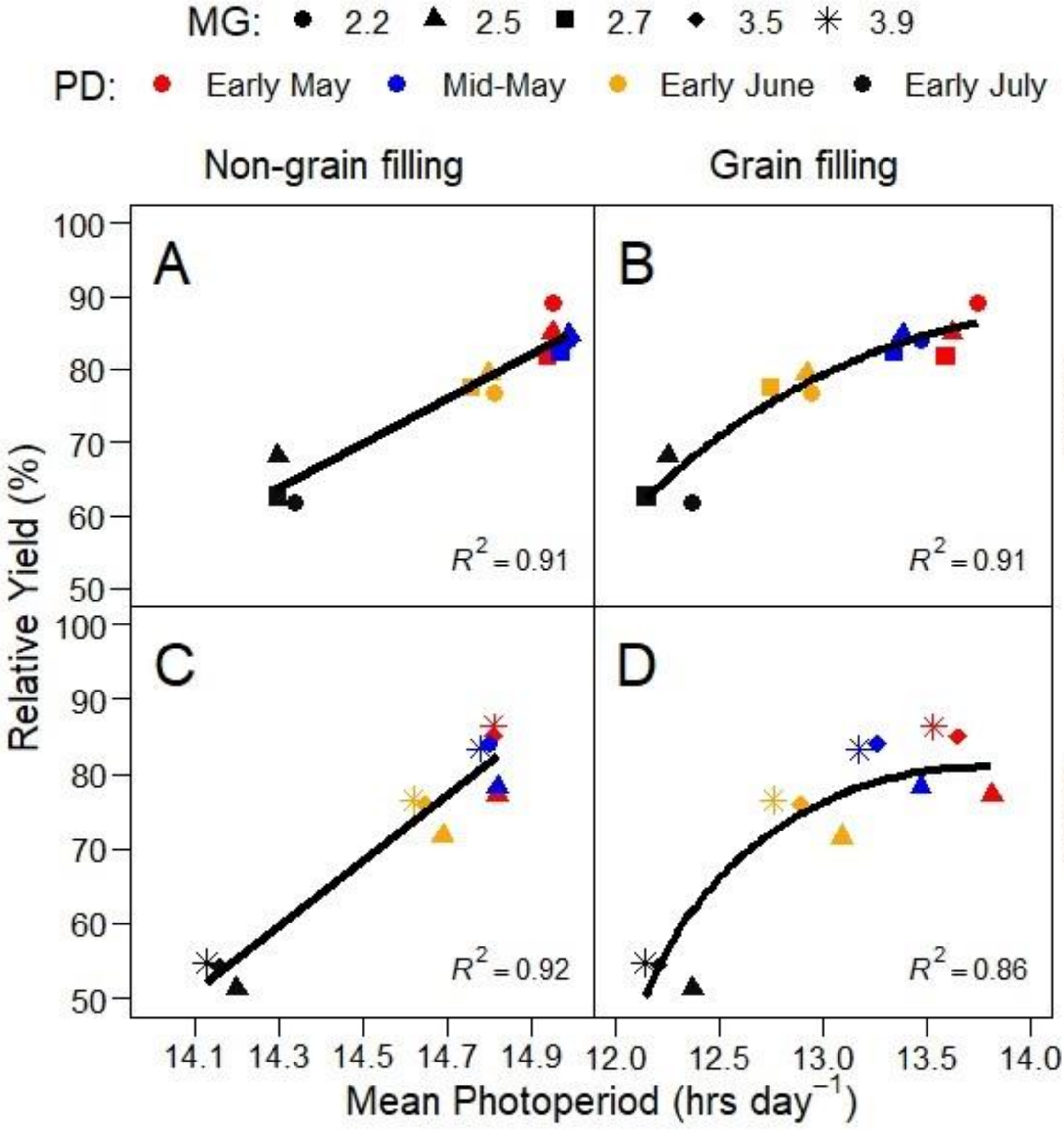

Figure 7. Relative grain yield relationships with the mean photoperiod per day within the non-grain filling and grain filling periods. The top row is the northern sites and the bottom row is the southern sites. The left column represents the non-grain filling period and the right column represents the grain-filling period. Each symbol represents a site-year by maturity group combinations. The interaction between PD and MG is not statistically significant.

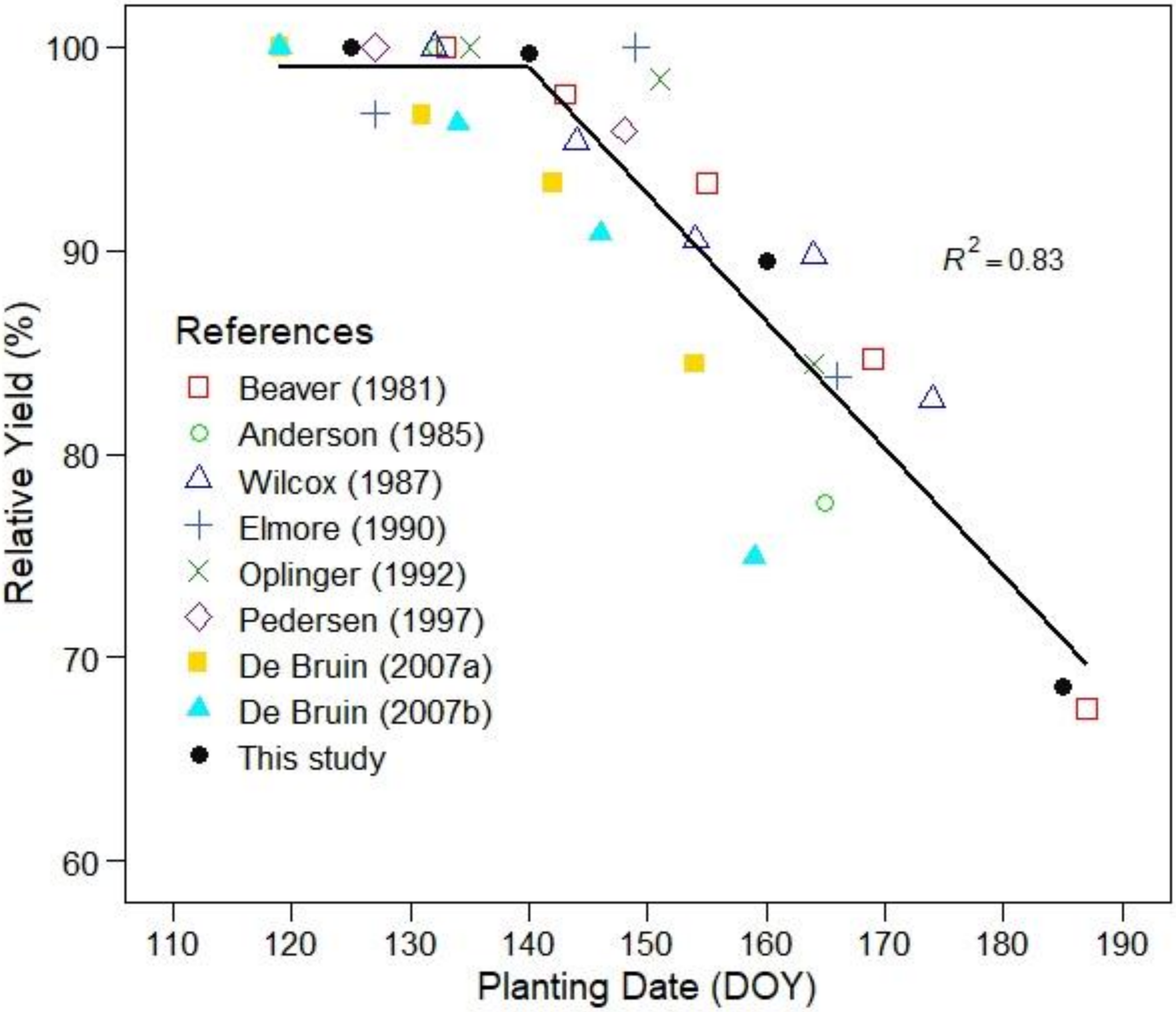

Figure 8. Summary of 8 experiments conducted in the Midwest, US from 1977 to 2006 with an average of all PD and MG from this study for comparison.

Table 1. Actual planting date for each experimental site-year

Year	Northwest	North Central	Northeast	Central	Southwest	South Central	Southeast
2014	5-May	7-May	5-May	6-May	5-May	6-May	5-May
	20-May	20-May	19-May	20-May	19-May	20-May	19-May
	11-Jun	10-Jun	9-Jun	10-Jun	3-Jun	12-Jun	12-Jun
	3-Jul	9-Jul	28-Jun	8-Jul	3-Jul	26-Jun	27-Jun
2015	30-Apr	1-May	1-May	6-May	1-May	30-Apr	4-May
	19-May	23-May	19-May	20-May	21-May	19-May	19-May
	9-Jun	10-Jun	9-Jun	10-Jun	2-Jun	10-Jun	10-Jun
	30-Jun	1-Jul	30-Jun	8-Jul	1-Jul	30-Jun	1-Jul
2016	7-May	6-May	4-May	6-May	6-May	9-May	9-May
	20-May	21-May	18-May	19-May	20-May	19-May	22-May
	7-Jun	10-Jun	8-Jun	9-Jun	10-Jun	9-Jun	9-Jun
	1-Jul	1-Jul	30-Jun	1-Jul	29-Jun	29-Jun	29-Jun

Table 2. Site means and standard deviation (sd) across planting date (PD) and maturity group (MG). Including an analysis of variance for each treatment means effect on grain yield. Dash mark represent no data since MG was nested within site and not all sites had all MG.

PD	MG	Northwest	North Central	Northeast	Central	Southwest	South Central	Southeast
		Mg ha^{-1}	Mg ha^{-1}	Mg ha^{-1}	Mg ha^{-1}	Mg ha^{-1}	Mg ha^{-1}	Mg ha^{-1}
Early May	-	4.64a	3.28a	3.98a	3.16a	3.65a	4.47a	4.18a
Mid-May	-	4.35ab	3.19a	4.06a	3.37a	3.74b	4.66a	3.91b
Early June	-	4.04b	2.97a	3.69b	3.12a	3.25b	4.03b	3.38c
Early July	-	3.45c	2.44b	3.10c	1.98b	2.24c	2.93c	2.63d
sd		0.82	0.92	0.40	0.71	0.92	0.66	0.45
	2.2	4.30	2.99	3.79	2.92	-	-	-
	2.5	3.94	2.98	3.70	2.87	3.19	3.79	3.28
	2.7	-	2.93	3.63	2.91	-	-	-
	3.5	-	-	-	2.92	3.22	4.17	3.61
	3.9	-	-	-	-	3.25	4.11	3.68
	sd	0.91	0.98	0.55	0.90	1.09	0.93	0.73
ANOVA								
Planting date (PD)		***	**	***	***	***	***	***
Maturity Group (MG)		*	ns†	ns	ns	ns	*	***
PD x MG		ns	ns	ns	ns	ns	ns	ns

* < 0.05.

** < 0.01.

*** < 0.001.

† ns, not significant.

Table 3. Predicted means of grain yield changes per 10-day planting interval in response to planting delays across maturity group and year for each site.

	Northwest	North Central	Northeast	Central	Southwest	South Central	Southeast
	change in mean grain yield, kg ha^{-1} d^{-1}						
Early May	-10	-1	7	24	11	20	-8
Mid-May	-13	-4	0	11	0	3	-14
Late May	-15	-7	-8	-2	-11	-14	-20
Early June	-18	-11	-16	-15	-22	-30	-26
Mid-June	-20	-14	-24	-28	-32	-47	-32
Late June	-22	-18	-32	-40	-43	-64	-38
Early July	-25	-22	-41	-54	-55	-83	-45

APPENDIX

SUPPLEMENTARY MATERIAL

Table S1. Location and soil summary for each experimental site-year.

Year	Site	Latitude degrees N	Longitude degrees W	Soil Series	Soil Classification
2014/2016	Northwest	42.928315	95.538114	Galva	Fine-silty, mixed, superactive, mesic Typic Hapludolls
	North Central	42.914867	93.790702	Canisteo	Fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls
	Northeast	42.940226	92.568560	Kenyon	Fine-loamy, mixed, superactive, mesic Typic Hapludolls
				Readlyn	Fine-loamy, mixed, superactive, mesic Aquic Hapludolls
	Central	42.010602	93.742283	Nicollet	Fine-loamy, mixed, superactive, mesic Aquic Hapludolls
				Clarion	Fine-loamy, mixed, superactive, mesic Typic Hapludolls
	Southwest	41.309837	95.183666	Marshall	Fine-silty, mixed, superactive, mesic Typic Hapludolls
	South Central	40.974864	93.420158	Grundy	Fine, smectitic, mesic Aquertic Argiudolls
	Southeast	41.191977	91.480351	Taintor	Fine, smectitic, mesic Vertic Argiaquolls
2015	Northwest	42.927926	95.538799	Primghar	Fine-Silty, mixed mesic, Aquic Hapludolls
	North Central	42.914641	93.789808	Canisteo	Fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls
	Northeast	42.942328	92.567735	Kenyon	Fine-loamy, mixed, superactive, mesic Typic Hapludolls
	Central	42.012814	93.743343	Nicollet	Fine-loamy, mixed, superactive, mesic Aquic Hapludolls
				Clarion	Fine-loamy, mixed, superactive, mesic Typic Hapludolls
	Southwest	41.327887	95.180568	Marshall	Fine-silty, mixed, superactive, mesic Typic Hapludolls
	South Central	40.971814	93.420158	Haig	Fine, smectitic, mesic Vertic Argiaquolls
	Southeast	41.203000	91.492431	Mahaska	Fine, smectitic, mesic Aquertic Argiudolls

Table S2. Statistical analysis of the date of the crop phenological stage. Dash mark represent no data since MG was nested within site and not all sites had all MG.

		Emergence DOY							Flowering DOY							Physiological Maturity DOY						
PD	MG	Northwest	North Central	Northeast	Central	Southwest	South Central	Southeast	Northwest	North Central	Northeast	Central	Southwest	South Central	Southeast	Northwest	North Central	Northeast	Central	Southwest	South Central	Southeast
		DOY	DOY	DOY	DOY	DOY	DOY	DOY	DOY	DOY	DOY	DOY	DOY	DOY	DOY	DOY	DOY	DOY	DOY	DOY	DOY	DOY
Early May		136	135	139	136	137	138	141	178	186	178	183	185	179	183	256	257	253	251	258	244	254
Mid-May		149	151	147	148	149	147	148	187	190	183	188	192	188	187	265	264	256	262	265	260	259
Early June		167	167	166	167	167	168	169	204	209	202	205	209	205	204	270	273	269	269	271	267	269
Early July		187	190	186	191	188	186	187	221	224	216	223	225	224	225	280	280	283	276	281	282	279
sd		2.39	3.54	1.08	2.60	2.80	3.52	2.34	3.08	6.24	3.30	6.62	4.45	9.44	3.33	4.08	2.19	2.63	3.32	4.58	6.22	5.88
	2.2	160	161	160	161	-	-	-	197	202	192	200	-	-	-	266	267	262	265	-	-	-
	2.5	160	161	160	161	160	160	162	198	203	195	200	201	199	198	269	266	266	265	264	260	258
	2.7	-	161	160	161	-	-	-	-	204	197	200	-	-	-	-	267	269	265	-	-	-
	3.5	-	-	-	161	160	160	162	-	-	-	200	203	199	201	-	-	-	265	269	260	268
	3.9	-	-	-	-	160	160	162	-	-	-	-	205	199	201	-	-	-	-	274	262	270
	sd	19.55	20.84	18.15	20.87	19.81	19.05	18.64	17.06	16.58	15.07	17.19	15.90	19.55	16.88	9.53	7.26	12.06	9.72	8.52	14.03	10.28
ANOVA																						
Planting date (PD)		***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***
Relative Maturity (RM)		ns	ns	ns	ns	ns	ns	ns	ns	ns	***	ns	***	ns	***	**	ns	***	ns	***	ns	***
PD x RM		ns	ns	ns	ns	ns	ns	ns	ns	ns	***	ns	ns	ns	ns	ns	ns	***	ns	***	ns	*

* < 0.05.
** < 0.01.
*** < 0.001
† ns, not significant.

Table S3. Model parameters and goodness of fit of the quadratic model used to create the 63 lines in Figure 2.

			Coefficients			
Site	Year	MG	a	b	c	R^2
Northwest	2014	2.2	-0.0005842	0.1413688	-4.3299639	0.98
Northwest	2014	2.5	-0.0006443	0.1594257	-5.5018148	0.98
Northwest	2015	2.2	-0.0000833	0.0043778	5.2122754	0.98
Northwest	2015	2.5	-0.0000099	-0.0160605	6.7939283	0.89
Northwest	2016	2.2	0.0001801	-0.0659961	10.3428018	0.51
Northwest	2016	2.5	0.0003431	-0.0939130	11.4568757	0.22
North Central	2014	2.2	-0.000137	0.030214	0.891671	0.08
North Central	2014	2.5	-0.0005588	0.1653214	-9.6652421	0.10
North Central	2014	2.7	-0.000386	0.1055999	-4.8178546	0.14
North Central	2015	2.2	0.0001376	-0.0654142	10.0783702	0.80
North Central	2015	2.5	-0.0000902	0.00031015	3.7536208	0.11
North Central	2015	2.7	0.0001356	-0.0468136	7.3003030	0.20
North Central	2016	2.2	-0.0002984	0.0726128	-0.6105779	0.67
North Central	2016	2.5	-0.0006116	0.1798195	-9.5437414	0.37
North Central	2016	2.7	-0.0000329	-0.0239006	6.0586022	0.09
Northeast	2014	2.2	-0.0007095	0.1844056	-7.3336338	0.97
Northeast	2014	2.5	-0.0008717	0.2475086	-13.0599602	0.82
Northeast	2014	2.7	-0.0006593	0.1710126	-6.5849953	0.91
Northeast	2015	2.2	-0.0001202	0.0195009	3.6683254	0.94
Northeast	2015	2.5	-0.0000639	0.0075859	4.161151	0.80
Northeast	2015	2.7	-0.0001597	0.0406704	1.3027812	0.53
Northeast	2016	2.2	-0.0003759	0.0975263	-2.4459106	0.80
Northeast	2016	2.5	-0.000253	0.072538	-1.857088	0.40
Northeast	2016	2.7	-0.0007344	0.2167585	-12.396932	0.65
Central	2014	2.2	-0.0008368	0.2353306	-13.3176873	0.88
Central	2014	2.5	-0.0007359	0.2167022	-12.7850951	0.56
Central	2014	2.7	-0.0004598	0.1243663	-5.2661802	0.60
Central	2014	3.5	-0.00037	0.0964455	-3.2382030	0.53
Central	2015	2.2	-0.0005385	0.1463671	-7.0785566	0.37
Central	2015	2.5	-0.0007583	0.2242169	-13.4091329	0.58
Central	2015	2.7	-0.0005108	0.1421176	-6.8018301	0.64
Central	2015	3.5	-0.0004023	0.1083880	-4.3541737	0.63
Central	2016	2.2	-0.001133	0.340938	-21.559602	0.36
Central	2016	2.5	-0.001288	0.358763	-22.512016	0.74
Central	2016	2.7	-7.663831	0.0148966	2.8872733	0.03
Central	2016	3.5	-0.00143	0.42271	-26.98550	0.36
Southwest	2014	2.5	-0.001308	0.3862970	-24.790325	0.35
Southwest	2014	3.5	-0.0006383	0.159967	-5.6321012	0.97
Southwest	2014	3.9	-0.0005979	0.1374835	-3.0192311	0.94
Southwest	2015	2.5	-0.0004751	0.1095568	-1.5373344	0.86
Southwest	2015	3.5	-0.0003321	0.0796052	-0.4825898	0.81
Southwest	2015	3.9	-0.0001326	0.0129678	4.8355477	0.92
Southwest	2016	2.5	-0.0008184	0.2369878	-14.4917458	0.31
Southwest	2016	3.5	-0.0005537	0.1681524	-10.3902526	0.07
Southwest	2016	3.9	-0.0005472	0.1623354	-9.6305417	0.10
South Central	2014	2.5	-0.001042	0.2836564	-14.758606	0.72
South Central	2014	3.5	-0.001531	0.4336901	-25.8270756	0.85
South Central	2014	3.9	-0.00139	0.3921928	-22.969138	0.89
South Central	2015	2.5	-0.001273	0.3693886	-23.1149295	0.59
South Central	2015	3.5	-0.0006399	0.1641731	-6.1473983	0.73
South Central	2015	3.9	-0.0006669	0..1752365	-7.2075453	0.82
South Central	2016	2.5	-0.0004204	0.0949954	0.0085862	0.89
South Central	2016	3.5	-0.000705	0.1787722	-5.9312766	0.74
South Central	2016	3.9	-0.0008006	0.220567	-10.0736265	0.62
Southeast	2014	2.5	-0.0002071	0.0404199	2.2183926	0.64
Southeast	2014	3.5	-0.000679	0.1717935	-6.3720412	0.93
Southeast	2014	3.9	-0.0006036	0.1522541	-4.9846550	0.82
Southeast	2015	2.5	0.0003035	-0.1081444	12.4768478	0.39
Southeast	2015	3.5	-0.0000813	-0.0426957	8.0534465	0.49
Southeast	2015	3.9	0.0001088	-0.0533307	8.9326497	0.78
Southeast	2016	2.5	-0.0002788	0.0528562	1.7011576	0.84
Southeast	2016	3.5	-0.0009308	0.2430072	-11.4554725	0.97
Southeast	2016	3.9	-0.0007769	0.2022070	-8.7560598	0.90