ABSTRACT

MORRIS, TRISTAN. Optimizing Soybean Yield and Quality through Planting Date and Maturity Group Selection in North Carolina. (Under the direction of Dr. Rachel A. Vann).

Soybean is an important crop for worldwide food production. As an oilseed crop it is processed into oil and meal that has many desirable end uses, such as animal feed, biodiesel, food products, and industrial products. In North Carolina, soybeans were planted on 635,356 hectares in 2020 establishing it as the largest hectare crop in the state. The majority of soybeans grown in the state are utilized by processors within the state due to the demand created by the significant animal industry. As soybean producers in North Carolina seek to increase yield, there has been increased interest in planting earlier with earlier maturing varieties. Two experiments were conducted to provide producers with information on planting date and maturity group impacts in North Carolina soybean production.

In study one, optimizing soybean yield through planting date and maturity group selection was evaluated. Planting dates (mid-March through mid-July), maturity group (2-8), and seeding rate (185,329 - 432,434 seeds ha^{-1}) on soybean emergence, stand, and yield. The effect of planting date was a linear response with stand, demonstrating that higher stands were achieved as planting date was delayed. The days to emergence were generally fewer as planting was delayed. There were location specific variations in the number of days to emergence due to weather conditions around the time of planting. An evaluation of SoyStage to predict the R1 growth stage in soybeans found that it can be used to accurately predict R1 in North Carolina. Yields tended to be higher when planting during late April through mid-May and mid-late April for the low yielding environments and high yield environment, respectively. Furthermore, planting in late April tended to result in higher yields with a MG 6 and MGs 4 and 5 in the low yield environments and high yield environments, respectively. General observations suggested

that higher yields were achieved by earlier maturing varieties when planting early, whereas yields were similar among maturity groups 4-8 when planting late. The effect of seeding rate tended to be greater in the high yield environments than low yield environments in terms of achieving higher yields. It was found that optimal yields could be reached with a SR of at least 300,000 seeds ha^{-1} in all environments.

In study two, the impacts of planting date and maturity group on soybean seed quality were evaluated. This study was a subset of the first study but only focusing on one seeding rate (247, 105 seeds ha^{-1}). Protein content generally trended towards declining as planting was delayed for the early maturity groups (2-5), but was stable across planting date for the later maturity groups (6-7). It was observed that early maturing varieties (≤ 5) had a lower percent protein than the later maturing varieties (MG 6-7). The oil content tended to be higher in the early maturity groups 2-4 compared to the later maturity groups 5-7, with oil content and protein content generally having an inverse relationship. Seed damage was highest when planting before Late April with early maturity groups (2-4). Soybean planted after Late April typically resulted in low levels of damage regardless of maturity group. There were site-specific variations in the amount of seed damage due to issues with green stem resulting in harvest delays, which further increased seed damage. Similar to seed damage, purple seed stain was lower in maturity groups 5-7 compared to the earlier maturity groups across all planting dates. The greatest amount of purple seed stain was observed with MGs ≤ 4 planted before mid-May.

Optimizing Soybean Yield and Quality through Planting Date and Maturity Group Selection in North Carolina

by
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DEDICATION

This thesis is dedicated in remembrance of my grandparents, Carlton Hammack and Bessie Morris, I wish you were here to experience this. And to my grandparents, Mary Hammack and Bernard F. Morris Jr., for teaching me the value of hard work and instilling in me a love for agriculture. This research is also dedicated to my parents Doug and Cheryl Morris for their continued encouragement and support.

BIOGRAPHY

Tristan C. Morris, son of Doug and Cheryl Morris, was raised in Roanoke Rapids, North Carolina. He was raised on a sixth-generation family diversified row crop farm where he enjoyed working with family and developed a passion for agriculture. Upon graduating from Roanoke Rapids High School in 2015, he attended North Carolina State University. He graduated from North Carolina State University in May of 2019 with a Bachelor of Science degree in Plant and Soil Science with a concentration in Soil Science and a minor in Agricultural Business Management. In May 2019, he started to pursue a Master of Science degree in Crop Science under the direction of Dr. Rachel A. Vann. He plans to continue to serve in the agricultural community in North Carolina.

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Maximizing Soybean Yield by Understanding Planting Date, Maturity Group, and Seeding Rate Interactions in North Carolina

ABSTRACT

Growers across the Southeast USA use a diversity of soybean planting dates and maturity groups for soybean production depending on their rotational needs and crop mixture. Research into the optimal production practices to maximize soybean yield is merited.

Studies were conducted across seven North Carolina locations in 2019 and 2020 to determine the impact of planting date (mid-March through mid-July), maturity group (2-8), and seeding rate (185,329 - 432,434 seeds ha^{-1}) on soybean emergence, stand, and yield.

The effect of planting date was a linear response with stand, demonstrating that higher stands were achieved as planting date was delayed. The days to emergence were generally fewer as planting was delayed. There were location specific variations in the number of days to emergence due to weather conditions around the time of planting. An evaluation of SoyStage to predict the R1 growth stage in soybeans found that it can be used to accurately predict R1 in North Carolina. Yields tended to be higher when planting during late April through mid-May and mid-late April for the low yielding environments and high yield environment, respectively. Furthermore, planting in late April tended to result in higher yields with a MG 6 and MGs 4 and 5 in the low yield environments and high yield environments, respectively (Figure 9). General observations suggested that higher yields were achieved by earlier maturing varieties when planting early, whereas yields were similar among maturity groups 4-8 when planting late. The effect of seeding rate tended to be greater in the high yield environments than low yield environments in terms of achieving higher yields. It was found that optimal yields could be reached with a SR of at least 300,000 seeds ha^{-1} in all environments. Future research is needed in North Carolina to validate these observed interactions in more years.

NOMENCLATURE

Planting date, maturity group, seeding rate, soil moisture, soil temperature, emergence, stand, yield

KEY WORDS

Soybean, *Glycine max* (L.) Merr.; wheat, *Triticum aestivum* L.

INTRODUCTION

Soybean [Glycine max (L.) Merr.] is an important crop for worldwide food production (Zhan et al., 2019). As an oilseed crop it is processed into oil and meal that has many desirable end uses, such as animal feed, biodiesel, food products, and industrial products (SoyStats, 2020). Global demand has increased to the point that soybeans have become one of the dominant crops grown in the USA. In 2019, the USA harvested 96.84 million metric tons, making it the second largest soybean producer in the world (USDA-NASS, 2020b). In North Carolina (NC), soybeans were planted on 635,356 hectares in 2020 establishing it as the largest hectare crop in the state (USDA-NASS, 2020a). Currently, NC is ranked 17th in soybean production in the USA (USDA-NASS, 2019d). The majority of soybeans grown in the state are utilized by processors within the state due to the demand created by the significant animal industry. In 2019, NC ranked second in USA swine production and third in USA total poultry production (USDA-NASS, 2019a; USDA-NASS, 2019b). The demand for soybeans in NC is greater than the state's production creating a grain deficit state (Piggott and Schweizer, 2018) and thereby incentivizing higher yields.

Soybean produced throughout the state across a diversity of soil types and weather conditions. As one of the row crops with the most flexible planting date (PD) for production in the Southeast USA region, soybean are a great fit for diverse rotations. Current production practices include planting that typically takes place between late April and early July with the optimal PD historically defined as May 1 to June 10 (Dunphy, 2017). A wide range of maturity groups (MG) are used depending on PD and rotational complexity ranging from a MG 3 to 7 (Salmeron et al., 2014). The seeding rates (SR) used varied depending on row width and PD but it has been observed that a final stand of 247,105 seeds ha^{-1} is needed to ensure optimal yield potential when planting between late April and early May (Dunphy, 2017, Knott et al., 2019). The great diversity of production practices, PDs, MGs, and soil types across NC result in a range of soybean yields. The state average yield in 2020 was 2488 kg ha^{-1} (USDA-NASS, 2020a). However, entries in the NC Soybean yield contest demonstrate that significantly higher yields can be achieved. In 2020 the highest NC Soybean Yield Contest entries for non-irrigated and irrigated categories was 6,873.0 and 6,624.2 kg ha^{-1}, respectively (Vann, 2021).

A recent analysis of 877 entries into the NC Soybean Yield Contest indicated that PD and MG were the strongest predictors of high soybean yield in the state, with MG $\leq$ 4 providing a yield advantage over later maturing varieties, while PDs earlier than mid-May often lead to yield advantages (Vann et al., in press). Although there has been some soybean research on optimal PD in the Southeast USA, there is a lack of fundamental understanding regarding the optimal MGs and SR to use across diverse soybean PDs.

Planting Date: PD is one of the most important agronomic decisions affecting soybean yields and has been researched for many years (Mooers, 1908). Deciding when to plant is influenced by many factors including but not limited to geographical location, field conditions, crop rotations, equipment availability, and grower preferences (Egli and Cornelius, 2009; Bateman et al., 2020). Depending on when soybean is planted, they can be separated into two main divisions in the Southeast USA: full season and double crop. Full season planting is considered as soybean planted during the optimal planting window, typically before June in the Southeast USA. Double crop is considered as soybean later than the optimal period, usually in mid to late June, following a winter crop harvested for grain, such as wheat (Triticum aestivum L.) (Vann et al., 2018).

It is known that significant yield declines associated with delayed planting are due to the reduction of both the vegetative and reproductive periods (Bateman et al., 2020; Egli and Bruening, 2000; Hu and Wiatrak, 2012; Purcell et al., 2002). The result is plants that are smaller and have fewer nodes and pods leading to reduced yields. Conversely, planting early can result in increased yields (Knott et al., 2019) as planting early allows for longer vegetative and reproductive periods. A longer vegetative stage will allow for a greater number of nodes to form prior to flowering increasing the likelihood of more fruiting sites per plant, and thus, more pods per plant (Bastidas et al., 2008). Additionally, early planting allows for the increased capturing of sunlight given that the soybean reaches full canopy closure earlier in the season (Salmeron et al., 2015). There are also risks with planting early. Concerns with planting early include lower soil temperatures, farm logistics, increased risk of frost damage, and the increased risk of seedling diseases (Egli and TeKrony, 1996). On occasion, these challenges cannot be offset through management and early planting can result in decreased yields (Logan et al., 1998).

A national study conducted by researchers at the University of Wisconsin-Madison to determine the optimal soybean PDs in the USA examined data from 27 states (Mourtzinis et al., 2019). This research illustrated that, on average, across the USA, soybean yield could be increased by 10% if soybean was planted 12 d earlier. It was calculated that planting in the Southeast USA could be moved 30 d earlier than customary, resulting in an average increase of

403.5 kg ha-1. Ultimately, this would result in an increase of 1.09 billion dollars in soybean revenue for NC (Mourtzinis et al., 2019).

In the Mid-south USA there has been a shift in PD and MGs used throughout the region as producers seek to increase yields and reduce production risks (Mengistu and Heatherly, 2006). A study to determine the optimal MG for early and late plantings in the Mid-south found that during early planting the use of MGs 4 and 5 resulted in the highest yields. For late planting, MGs 3 and 4 resulted in the highest yields, and overall MG 4 resulted in the highest yield across PDs (Salmeron, et al. 2014). Additionally, it was found that to maximize yield, the optimum PD varied depending on the location, and ranged from 22 March to 17 May (Salmeron, et al. 2016). In Kentucky, Knott et al. (2019) found that late April to early May PDs maximized soybean yields. As growers across the Southeast USA simplify rotations and consider planting soybean earlier to reap the aforementioned benefits, research into the benefits and potential limitations of early planted soybean in this region, as well as strategies to maximize yield when planting early, is warranted.

Maturity Group: The relative maturity of soybeans is differentiated into MGs. Maturity groups are a way to separate soybean varieties based on their relative flowering date in response to photoperiodism and temperature (Zhang et al., 2007). In order to illustrate where the different MGs are best adapted, a map with MG zones was created by Scott and Aldrich (1970). The map was most recently re-analyzed by Mourtzinis and Conley (2017). Soybeans can be further categorized based on their growth pattern. When soybeans continue to grow vegetatively after flowering it is classified as indeterminate growth. In contrast, determinate growth occurs when soybean cease or nearly cease growing vegetatively after flowering (Wilcox and Guodong, 1997).

A wide range of MGs can be successfully grown in the Southeast USA (Boyer et al., 2015, Norsworthy and Frederick, 2002). The diverse cropping systems of NC allow for the use of several MGs in an effort to optimize yield potential. The MG zone map created by Mourtzinis and Conley (2017) reveals that MGs 5 and 6 are best adapted for NC. However, NC growers are achieving high yields with MGs outside of this range (Vann, 2021).

The plethora of PD research across the USA demonstrates that variations in locations and years make complicate the understanding of the interaction between PD and MG. It has been observed that planting too early with an early maturing variety can result in premature flowering (Board and Hall, 1984; Salmeron et al., 2015) which will lead to reduced vegetative growth and lower yields (Board and Hall, 1984). Alternatively, any MG can be planted too late as there is a clear date beyond which all MGs will likely experience a rapid decline in yield (Egli and Cornelius, 2009).

There has been a greater focus on breeding early MGs (2-4) compared to later MGs (≥5), driven by the extensive use of earlier maturing varieties in the Midwest USA (Boehm et al., 2019; Rincker et al., 2014). This can been seen in the greater improvement in yield over time in early MGs compared to later MGs as MGs 2-4 had an average yield increase over time of 29 kg ha-1 yr-1 (Rincker et al., 2014) while MGs 5-7 had an average yield increase over time of 13.7 kg ha-1 yr-1 (Boehm et al., 2019).

Concerning the difference in disease and nematode resistance of the early maturing versus later maturing varieties, the environment in which the varieties are to be grown has a great impact on the focus of the breeder (Hartman et al., 2005). As breeding is often focused on the major biotic factors limiting yield in the intended growing regions, there are often differences in the disease and nematode resistance packages of different MGs. For instance, a study of 128 soybean plant introductions including three MGs observed a difference in the amount of seed infected by Cercospora kikuchii in the different MGs, as a greater number of seed was infected in the MGs 3 and 4 than the MG 5 (Alloatti et al., 2015). While a diversity of MGs can be produced in the Southeast USA, as growers modify PDs to increase soybean yields and to fit into their rotations, determining optimal MGs to use across a wide range of PDs is merited.

Seeding Rate: Soybean can be successfully planted across a wide range of SRs due to their great plasticity (Cariciochi et al., 2019). Seeding rate has been more thoroughly investigated in recent years as herbicide-resistance weed management has driven a considerable increase in seed price due to technology fees associated with trait packages (Chen and Wiatrak, 2011). De Bruin and Pedersen (2008) suggested that the optimal SR is lower than what is currently used in many locations. In Maryland, Kratochvil et al. (2004) found that a 20% reduction in SR did not statistically differ from the soybean yields achieved with standard SRs (432,300 and 555,800 seeds ha^{-1} in full-season and double-cropping production systems, respectively). Soybean has the flexibility to adjust for low populations by producing more branches and pods (Carpenter and Board, 1997; Board, 2000; Cox et al., 2010). However, a stand loss of up to 35% has been reported for April plantings in Kentucky (Knott et al., 2019).

Additionally, the yield response of MG to varying SRs has been inconsistent over time. Chen & Wiatrak (2011) observed that MGs 4 and 5 had a linear yield response to SR in some years, while in other years, MGs 5 and 8 had a quadratic yield response to SR. However, when precipitation was approximately 30% lower than the 30 year average there was no significant difference in yield due to SR for MGs 5, 7, and 8 (Chen and Wiatrak, 2011). In partial agreement, Edwards and Purcell (2005) investigated a range of MGs (00 to 6) and plant populations in Arkansas and reported that early MGs had a more gradual yield response to increased SR than later MGs. The response of MG 3 and 4 to increased plant population was varied, and was more affected by cultivar and environment than later maturing varieties. Additionally, when planting in late June/early July in Virginia, a MG 3 cultivar required approximately twice the plant population (741,000 plants ha^{-1}) of a MG 5 cultivar (370,500 plants ha^{-1}) to reach maximum yield (Holshouser and Jones, 2003).

Furthermore, when planting is delayed, there have been studies that conclude that greater SRs are needed to maximize yield (Kratochvil et al., 2004; Lee et al., 2008; Siler, 2020). A greater SR was needed to maximize light interception due to smaller plant size often associated with later planting (Egli and Bruening, 2000; Ball et al., 2000). However, other studies such as De Bruin & Pedersen (2008) and Bruns (2011) did not observe a significant interaction between PD and SR for PDs ranging from April to mid-June.

The objective of this research was to provide recommendations for optimizing yield through PD determination and MG selection and adjusting SR accordingly in environments characteristic of the Southeast USA.

MATERIALS AND METHODS

Experimental Sites and Management

Field experiments were conducted over two soybean growing seasons (2019-2020). In 2019, the research sites included four on-farm sites, Sampson County, NC, Currituck County, NC, Union County, NC, and Yadkin County, NC. The soil in Sampson County was a fine-loamy, kaolinitic, thermic Typic Kandiudults. The soil in Currituck County was a fine, mixed, semiactive, thermic Typic Endoaquults. The soil in Union County was a fine, mixed, semiactive, thermic Typic Hapludults. The soil in Yadkin County was a fine, kaolinitic, mesic Typic Kanhapludults.

In 2020 the research sites included three on-farm sites in Rowan County, NC, Robeson County, NC and Beaufort County, NC. The soil in Rowan County was a fine, kaolinitic, thermic Rhodic Kanhapludults. The soil in Robeson County was a fine-loamy, kaolinitic, thermic Typic Kandiudults. The soil in Beaufort County was a fine, mixed, semiactive, thermic Typic Umbraquults.

The combination of year and location will be referred to as an environment (Table 1). These locations were selected to represent a range of geography and growing conditions commonly encountered by soybean producers in NC. Plot size was 7.6m by 1.5m. Individual plots consisted of four treated rows, measuring 762 cm in length with a row width of 38.1 cm.

Treatment Description

The experiment was designed in a split-split plot arrangement with main plot as planting dates (5-8 levels), sub-plot as maturity group (7 levels), and sub-sub plot as seeding rate (5 levels). There were four to five replications per treatment combination depending on space availability at each environment. Planting dates for the 2019 season ranged from March to July and in 2020 they ranged from April to July (Table 2). Maturity groups included 2, 3, 4, 5, 6, 7, and 8 (Table 3). The seeding rates included 185,329, 247,105, 308,881, 370,658, and 432,434 seeds ha^{-1}. The seeding rates for varying MGs were corrected for reported germination to achieve the desired seeding rates.

Data Collection

Soybean stand was measured between soybean growth stage V1-V3 by placing a meter stick randomly beside rows two and three of each subplot and counting the number of plants. Two measurements were taken per subplot and then averaged and converted into a population per hectare.

Soil temperature and soil moisture were captured at planting using a FieldScout TDR 350 soil moisture meter calibrated to measure soil moisture and soil temperature at a 12 cm depth. Average of five soil moisture and five soil temperature measurements were obtained at each main plot across all environments at planting. If equipment for soil temperature was not available at planting, then data from NASA-POWER was used (NASA, 2020). This information is available in Table 2.

After reaching soybean growth stage R8, the plots were harvested using a small-plot combine and yields were adjusted to 13% moisture content (Table 1).

Weather Data

The NC Climate Retrieval Observations Network Of the Southeast Database (CRONOS) developed by the State Climate office of NC was utilized to acquire weather data. When there were limitations in the CRONOS database, weather data was obtained from the NASA Langley Research Center POWER Project funded through the NASA Earth Science Directorate Applied Science Program (NASA, 2020). The 30-year averages for rainfall and temperature were acquired from NOAA (NOAA, 2021). In an effort to compare conditions in 2019 and 2020 to historical weather conditions in the region, the monthly rainfall totals and the average monthly temperature for each environment from March to November for 2019 and 2020 is available in Figures 1 and 2, respectively.

Flowering

The date of flowering (R1) was visually captured for each PD by MG combination. The observed flowering date for each PD by MG combination is available in Table 4. A PD by MG combination was determined to be flowering when 50% or more of the plants in that plot had at least one flower on the main stem. This data was used to evaluate soybean flowering in proximity to the longest d of the year and to evaluate a soybean phenology prediction tool called SoyStage (https://soystage.uark.edu/) for its applicability for producers in NC.

SoyStage, a program created by researchers at the University of Arkansas, was designed to predict the phenological stages (R1, R5, and R7) of soybeans from a range of soybean maturity groups based on latitude, average daily temperatures, and soybean emergence date (Santos et al., 2019). The average daily temperatures over the past 20 years for each environment were acquired using the nearest CRONOS weather station to use in making phenological predictions. After inputting the necessary data into the program, it generated the number of d after emergence to reach each phenological stage. The d after emergence to reach R1 were used to calculate the predicted flowering date.

To evaluate the accuracy of the SoyStage model prediction for dates of R1, the flowering DOY captured in the field and the flowering DOY predicted by SoyStage for each PD by MG combination were plotted for each environment. There were limitations to using SoyStage to predict R1 for this study due to the MGs that are pre-set in the program on 0.5 MG increments compared to the MGs used in this study (Table 3). The MGs in SoyStage that were the closest to the MGs in this study were MGs 3.7, 4.7, 5.7, and 6.2. Additionally, the logistics of traveling to each environment limited the ability to precisely capture the date of R1 in the field for each PD by MG combination.

Statistical Analysis

Yield and plant stand data were subjected to mixed model analysis of variance using PROC GLIMMIX in SAS Version 9.4 (SAS Institute Inc., Cary, NC). For the yield data analysis, a heterogeneous variance model (covariance parameters varied within each location-year) with lognormal distribution was fitted. For stand data analysis, a mixed model with lognormal distribution was fitted. For both analyses, fixed effects included PD (as d of year), MG, SR, their interactions, and quadratic forms. Random effects included location x year, replication nested within location x year, PD nested within replication x location x year, MG nested within PD x replication x location x year and the overall error term. Degrees of freedom for all analyses were calculated using the Satterthwaite method (Littell et al., 2006).

The predicted and captured flowering dates (as d of year) for each PD by MG combination were graphed by environment. A linear regression was plotted using Sigma plot with the equation of the line and the coefficient of determination shown for each environment.

RESULTS AND DISCUSSION

Soybean Emergence

The d to emergence were captured for each PD averaged across MG for each environment (Table 2). Typically, soybean emerged within 14 d or less of planting in 2019 and within 10 d or less of planting in 2020 regardless of PD (Table 2). The greatest number of d to emergence was observed at the earliest PD (mid-March) in Yadkin-2019 with the soybean requiring 26 d to emerge (Table 2). Planting conditions at early PDs tended to be more adverse due to cooler soil and air temperatures and often abundant soil moisture resulting in delayed seed emergence and greater seedling diseases causing a reduction in stand (Cox et al., 2008). In contrast, as planting was delayed there was generally a decrease in the number of d to emergence with the fewest d to emergence being four d (Table 2), likely a product of higher air temperatures that resulted in warmer soil temperatures at the later planting dates creating a more favorable condition for emergence (Figure 2 and Table 2).

Soybean Flowering

The start of soybean flowering is important as it marks the transition from vegetative to predominantly reproductive growth. The most important time for yield determination in soybean is the period from flowering through seed fill (Nico et al., 2015). It has been reported that a greater amount of solar radiation post flowering has a positive linear correlation with yield (Gaspar and Conley, 2015). Therefore, soybean flowering occurring closer to the longest d of year as possible will maximize the amount of light that a soybean can intercept in reproductive development.

In 2019, it was typically observed that a March planting with all MGs, April through early May planting with MGs 2-4, and a mid-May planting with MGs 2 and 3 resulted in flowering by the longest day of the year (Table 4). It should be noted that there were warmer than average temperatures experienced in May 2019 allowing for accelerated soybean growth (Figure 2A). In 2020, it was generally observed that an early April planting with MGs 2-4 and a late April planting with a MG 2-3 resulted in flowering by the longest day of the year (Table 4). The cooler air temperatures and above average rainfall in 2020 across the state resulted in delayed flowering based on what would be expected based on historical weather data (Figures 1 and 2).

The ability to predict soybean growth stages is beneficial for management decisions. SoyStage has practical applications for soybean growers in NC as a means to identify an approximate date for when soybeans will reach different reproductive growth stages. This would assist with equipment and labor needs throughout the growing season by giving producers an approximate time frame when it would be optimal to scout, make pesticide applications, and to harvest. In order to evaluate the precision of SoyStage for use in NC, a comparison was made between the captured flowering date (R1) for select MGs across a range of PDs and locations and the predicted flowering date (R1) generated by SoyStage.

The SoyStage predictions were closely aligned with observed dates of R1 considering the limitations (Figure 3). Even though the program utilizes an extensive amount of weather data (20-yr average), there are year-to-year weather variations that can result in a difference between the observed and predicted dates. Also, it should be noted that the program assumes adequate soil moisture in its estimates (Santos et al., 2019). , therefore, drought stress could adversely affect growth resulting in a greater difference between the captured and predicted dates.

In Figure 3, the 1:1 trend lines show the optimal situation in which SoyStage predicted the same date that was captured in the field. The 2019 sites tended to be closer to the 1:1 line than the 2020 sites. In 2019, there were warmer temperatures in May 2019 resulting in accelerated growth and development (Figure 2A). Sampson-2019 had the greatest deviation from the 1:1 line due to little to no rainfall during May through July (Figure 1A). In 2020, the temperatures were cooler than 2019 and there was consistently above average rainfall (Figure 2B and 3B) potentially delaying the growth and development of soybean. Furthermore, the predicted dates were typically within 10 d or less of the captured date for PDs mid-May and mid-June. However, when evaluating the effect of the early PDs in 2020 and later PDs in 2019 there was generally a greater difference between the captured and predicted dates ranging from 10 to 28 d. Overall, the strong relationship between the predicted and observed flowering dates indicates that SoyStage can predict R1 with precision in NC.

Soybean Stand

The targeted soybean SRs were 185,329, 247,105, 308,881, 370,658, and 432,434 seeds ha^{-1} across environments. Stand was significantly impacted by PD, MG, and SR across environments but these factors did not interact to impact stand (Table 5). Stand response to PD was linear (Table 5), with higher stands achieved as planting date was delayed as reflected in the combined analysis over environments. Stand response to MG and SR was quadratic (Table 5). Overall, as SR increased there was an increase in the number of plants per hectare achieved across PD and MG in both yield environments as would be expected (Figure 4A).

An analysis by yield environment revealed that for the low yielding environments (LYE) (Table 1), as planting d of the year (PDOY) was delayed there was an increase in the number of plants per hectare achieved across SRs, which was similar to the trend observed in an analysis combined over yield environments (Figure 5A). The response of the LYE was expected as planting conditions were generally more favorable for seed germination in May or later, compared to planting before May (Table 2). In agreement, Oplinger and Philbrook (1992) reported that there was an increase in stand as planting was delayed due to higher soil temperatures. It is important to note that data for the LYE included earlier PDs than the high yielding environments (HYE) (Table 1). At those earliest PD some of the lowest soybean stands were observed. Planting conditions at early PDs can be adverse due to cooler temperatures and abundant moisture resulting in delayed seed emergence and greater incidence of seedling diseases, causing a reduction in stand (Cox et al., 2008). All of the seeds used in this study received a seed treatment (fungicide plus insecticide) in the hopes of minimizing stand reduction due to seedling disease. The greatest number of d to emergence was observed in Yadkin-2019 with a mid-March planting requiring 26 d to emerge (Table 2). In Kentucky, a stand loss of up to 35% was reported for April plantings (Knott et al., 2019). Alternatively, as planting was delayed there was generally a decrease in the number of d to emergence with the fewest d to emergence being four d (Table 2). The higher air temperatures resulted in warmer soil temperatures at the later planting dates (Figure 2 and Table 2). The amount of soil moisture was variable between planting dates (Table 2); however, overall, the planting conditions were more favorable as planting was delayed.

Surprisingly, there was a reduction in stand as planting was delayed in the HYE (Figure 5A). There were periods of adverse planting conditions at two out of the three sites in the HYE at later PDs. In Rowan-2020 there was low soil moisture at the early June planting (Table 2), and in June and July, the precipitation was below the 30-year average (Figure 1B). Additionally, this site experienced cooler temperatures than the other site in that year throughout the growing season. In Beaufort-2020 there was low soil moisture at the late June planting (Table 2) as there was below average rainfall in June at this site (Figure 1B). The trend across yield environments was that soybean stand increased as planting date was delayed (Figure 5B).

Regardless of environment, higher plant stands were achieved across employed PDs and SRs for the later maturing varieties (≥5) (Figure 6). Which could be the result of later MGs being more adapted to the Southeast USA. These MGs (≥5) are bred for production in the Southeast USA and may have lower susceptibility than the early MGs to seedling diseases common to the region. Even though the early MGs (2-4) resulted in lower plant populations than the later maturing varieties (Figure 6), these MGs typically still maintained high yields in the HYE (Figure 7). These early MGs with an indeterminate growth pattern have greater branching plasticity and as a result can compensate for low stands (Yoshihira et al., 2020) as soybean has the flexibility to adjust for low populations by producing more branches and pods (Carpenter and Board, 1997; Board, 2000; Cox et al., 2010).

Yield

PD, MG, and SR interacted to significantly impact soybean yield (Table 6). Due to the complexity of interpreting the three-way interactive graph across all environments (Figure 7), the impact of these factors was evaluated in LYE and HYE as there were clearly trend differences observed between yield environments for the impact of these factors on soybean yield. Planting date and MG interacted to impact soybean yield (P=0.003; Figure 8), indicating that different MGs were optimal for use across different PDs.

Highest Yielding PD by MG Combinations

In the LYE, the highest yield combined over SR and MG was observed with a PD during late April and mid-May (Figure 9). Similar results were observed in other studies demonstrating that planting in late April or early May increased yield compared with later planting (De Bruin and Pedersen, 2008; Knott et al., 2009; Wilcox and Frankenberger, 1987). The yields of PD by MG combinations tended to be higher with MGs 6 and 7 planted during late April in the LYE (Figure 9).

In the HYE, the PD with the highest yield combined over SR and MG was mid to late April (Figure 9). The yields of PD by MG combinations tended to be higher with MGs 3 and 4 when planted during mid-April (Figure 9). Salmeron et al. (2016) reported similar results showing that a MG 4 resulted in maximum yield across latitudes ranging from 30.6°N to 38.9°N.

Early Planting (Mid-April and Earlier)

LYE: When planting early (mid-April and before) in the LYE, yield tended to be highest with MGs 6 and 7 (Figure 9). There were lower yields across all MGs when planting before DOY 110 (April 20) compared to the other PDs. The quadratic yield response suggested that there was a penalty for planting too early with all of the MGs in the LYE (Figure 8). When planting early (March and April), the air and soil temperatures were typically cooler and soil moisture was abundant (Figure 2 and Table 2). These conditions can be adverse for seed germination as they are favorable for the development of seedling disease and delayed seed emergence (Cox et al., 2008). In the LYE, it was observed that the stands at early PDs were much lower than later plantings (Figure 5). However, these stands were still above the number of plants needed per hectare to optimize yield (Dunphy, 2017). Thus, the lower yields observed with all MGs in this environment when planting early were more likely a result of the air temperatures and soil moisture experienced during reproductive stages (Figure 1 and 2). In 2019, there were above-average temperatures and below-average rainfall in May at all locations (Figure 1A and 2A). When planting early many of the PD by MG combinations reached R1 in mid to late May and experienced these adverse conditions during reproductive development.

HYE: In the HYE, it was observed that yield tended to be highest with MGs 3 and 4 as they had similar yields when combined over SR when planting early (mid-April and before) (Figure 9). Planting early has an impact on soybean growth characteristics and offers several advantages such as a longer growing season and canopy closure earlier in the season. A longer growing season can result in the increase in the number of nodes on the main stem, thereby increasing the potential for more pods (Wilcox and Frankenberger, 1987). Reaching full canopy closure earlier in the season will result in the capture of more solar radiation and can improve yield (Cooper, 2003). Furthermore, early planting allowed the reproductive period to start earlier as these PD by MG combinations had reached R1 during mid-June when the days were longer (Table 4) allowing for the capture of more solar radiation during reproduction. The quadratic response was more notable with the later MGs (5-8) and matches previous research that soybean yields may not be optimized when planting too early (Logan et al., 1998; De Bruin and Pendersen, 2008) and will decrease when planted after a certain date (Bastidas et al., 2008; Egli and Cornelius, 2009).

Full Season Planting (Late April to Mid-May)

LYE**:** Currently in NC growers plant the majority of soybean during May, often starting with MGs 4 and 5 and then moving into later MGs as planting is delayed past May (Figure 9). In contrast, when planting full season (late April through May), this study illustrated that higher yields in the LYE tended to be observed with a MG 6 at these PDs. The MG 6 had a later flowering date than the early MGs and had reached R1 during mid-July and early August placing the reproductive period during August when there was acceptable moisture (Figure 1A and 1B). Furthermore, Salmeron et al. (2016) reported that in the Mid-south a MG 6 had an optimal yield when planted between May 11 and 16. Other studies have shown that higher yields were achieved with earlier MGs when planted full season (Knott et al., 2019; Salmeron et al., 2014; Salmeron et al., 2016).

HYE: The highest overall yields in this study were observed when planting full season as yields tended to be higher with MGs 4 and 5 (Figure 9). In agreement, Bateman et al. (2020) observed that the yield of MGs 4 and 5 were maximized by planting on April 20 while Salmeron et al. (2014) observed that a MG 4 yielded the highest when planting between late March and May. When planting full season, the planting conditions were more favorable than earlier in the year, and soybean generally emerged in seven days or less after planting (Table 2) allowing for the soybeans to have a good start. The early maturing varieties started flowering before MGs 4 and 5, potentially resulting in a lower amount of vegetative growth and the reduced inception of solar radiation (Purcell et al., 2002).

Double Crop Planting (June)

LYE: In the LYE, MGs 5-7 tended to have higher yields than the other MGs when planting in June (Figure 9). Overall, yields were lower than the full season planting due to a shorter vegetative period and reduced light captured (Purcell et al., 2002) resulting smaller plants with fewer pods. In contrast, in the Mid-south, Salmeron et al. (2014) observed that a MG 4 was better suited for late planting (mid-June or later) and that a MG 6 resulted in suboptimal yields.

HYE: Yields of MGs 5 and 6 tended to be higher when planting double crop in the HYE (Figure 9). In partial agreement, currently when growers in NC are planting double crop they typically use MGs 6 and 7. Bateman et al. (2020) reported a decrease in plant height when planting after June 2 and a decline in canopy closure of 1% per day when planting after May 27 with MGs 4 and 5. Thus, planting in June can cause reduce vegetative growth resulting in smaller plants with fewer nodes and a decrease in light interception due to incomplete canopy closure (Salmeron et al., 2014).

Late Season Planting (July)

LYE: When planting late (July) yields tended to be similar across most of the MGs (4-8) (Figure 9). The lowest yields in this study were observed during the late planting as late planted soybean plants had reduced vegetative growth (Purcell et al., 2002) and a shortened reproductive period (Egli and Bruening, 2000). These conditions resulted in smaller plants with fewer nodes and a decrease in light interception due to incomplete canopy closure (Salmeron et al., 2014). Additionally, late planted soybean often has greater floral abortion (Heitholt et al., 1986) further reducing yield potential. When planting in July with MGs 4-8, soybean will essentially flower as soon as physiologically possible, often reaching R1 within 10 d of each other (Table 2), which cuses the reproductive period of these MGs to occur during the same time of the year, leading to similar yields.

HYE: In the HYE, yields tended to be higher with MGs 5-7 (Figure 9) when planting in July. When planting late, later MGs were able to have greater vegetative growth before flowering than early MGs due to their photoperiod. Thus, the later MGs were then able to capture more light and produce more yield. Studies have reported significant yield losses due to reduced plant height and incomplete canopy closure when planting late (Bastidas et al., 2008; Salermon et al., 2014; Bateman et al., 2020). Typically, growers in NC do not plant this late due to the significant yield reductions; however, occasionally weather conditions during June will delay planting into July, at which time, growers will often plant a MG 7.

Seeding Rate

Planting date and SR interacted to impact soybean yield (P=<0.001; Table 6), but MG and SR did not interact for yield (Table 6). The quadratic response of SR with yield suggested that yield stabilized at moderate SRs (Table 6), whereas, planting in mid-June and later tended to suggest that higher SRs had a greater impact on yield. These trends align with what has been traditionally recommended in NC as SR should be higher as planting is delayed. As planting is delayed past May, it is recommended that growers increase their SRs (Dunphy, 2017). Similar results were observed by Vossenkemper et al. (2016), who found that there was an interaction between PD and SR in all three years of the study showing that higher SRs resulted in higher yields as PD was delayed. However, other studies reported that there was no interaction between PD by SR with PDs ranging from April to mid-June (Bruns, 2011; De Bruin and Pedersen, 2008).

In the HYE, it was observed that higher SRs had a greater positive effect on yield than was observed in the LYE especially when planting between mid-May and mid-June (Figure 10). This may have been due to the negative correlation between PD and stand observed in the HYE (Figure 5A). Even though the stands were not below optimal across MG and SR, there was an increase in stand as SR increased (Figure 4). Furthermore, it could be reasoned that a HYE could better support a greater number of plants per hectare than a LYE given the more favorable characteristics of that environment such as greater soil water holding capacity and higher CEC. In contrast, Gaspar et al. (2020) concluded that SRs should be higher in LYE and lower in HYE, reporting that the agronomically optimal SR for the LYE was 442,130 seeds ha^{-1} and 348,270 seeds ha^{-1} for the HYE using data primarily from the Midwest and northern Midwest. It is proposed that a greater number of plants are needed in LYE in order to maximize canopy closure.

The LYE included one PD earlier than the HYE and at this PD (late March) there was a minimal difference in yield between SRs (Figure 10). This aligns with Figure 8 illustrating that planting on or before DOY 100 (April 10) resulted in similar yields for LYE MGs 2-7 across SRs. These PD by MG combinations had reached R1 by the end of June. Thus, they were in reproductive stages during July when in 2019 there was below average rainfall (Figure 1 and Table 4). Additionally, there were lower stands at the early PDs as indicated by the positive correlation between PD and stand (Figure 5).

Overall, these results confirm that to achieve optimal yield, a SR of at least 300,000 seeds ha^{-1} should be used. In contrast, others have observed that a final stand of 247,105 seeds ha^{-1} is needed to ensure optimal yield potential (Dunphy, 2017; Knott et al., 2019).

The economic implications of SR are often considered by producers as seed cost has increased considerably due to technology fees associated with herbicide-resistance trait packages (Chen and Wiatrak, 2011). Usually the economically optimal SR is lower than the agronomically optimal SR (Chen and Wiatrak, 2011; Gaspar et al., 2020; Norsworthy and Oliver, 2001). Therefore, it is important to understand the impact of SR on yield and how that corresponds to revenue. This is not a clear analysis as the cost of seed and the market price of soybean changes from year to year. Chen and Wiatrak (2011) reported that for a MG 8, the economically optimum SR was 20% less than the SR needed to achieve maximum yield. Even though it was observed in this study that higher yields were often obtained with higher SRs up to a point, those higher SRs may not translate to an increase in revenue due to the increased seed cost.

CONCLUSIONS

The results from this study demonstrate that the interaction between PD and MG significantly impacted the yield of soybean grown in the Southeast USA. The impact of these factors was evaluated in LYE and HYE as there were clear trend differences observed between yield environments for the impact of these factors on soybean yield. Yield tended to be higher when planting during late April and mid-May and mid to late April for the LYE and HYE, respectively. Furthermore, the PD by MG combinations that tended to result in higher yields were a MG 6 and MGs 4 and 5 planted during late April for the LYE and HYE, respectively (Figure 9). Overall, optimal yields resulted from maturing varieties when planting early, while there were similar yields across MGs 4-8 when planting late. It was found that optimal yields could be reached with a SR of at least 300,000 seeds ha^{-1}. As growers in the Southeast USA consider shifting their production systems to using earlier maturing varieties (MG<5) planted early (before mid-May), the impact of yield environment and MG should be considered. Future agronomic studies are necessary to understand if the observed interactions continue to occur in subsequent years.

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Table 1. Environment, latitude, soil type, tillage system, row spacing, planting equipment, and harvest equipment.

Environment	Latitude (°N)	Soil Type	Tillage System	Row Spacing (cm)	Planting Equipment	Harvest Equipment	Average Soybean Yield (kg ha^{-1})	Yield Environment
Currituck-2019	36.4	Roanoke fine sandy loam	Conventional	38.1	Wintersteiger Plotseed XXL	Wintersteiger Quantum	4244	HYE
Sampson-2019	35.2	Norfolk loamy sand	No-till	38.1	Wintersteiger Plotseed XXL	Wintersteiger Quantum	2925	LYE
Union-2019	35.2	Badin channery silt loam	No-till	38.1	Wintersteiger Plotseed XXL	Wintersteiger Quantum	3887	LYE
Yadkin-2019	36.2	Clifford sandy clay loam	No-till	38.1	Wintersteiger Plotseed XXL	Wintersteiger Quantum	2764	LYE
Beaufort-2020	35.6	Cape Fear fine sandy loam	Conventional	38.1	Wintersteiger Dynamic Disc	Wintersteiger Quantum	4391	HYE
Robeson-2020	34.7	Norfolk loamy sand	Conventional	38.1	Wintersteiger Dynamic Disc	Wintersteiger Quantum	3975	LYE
Rowan-2020	35.7	Lloyd clay loam	No-till	38.1	Wintersteiger Dynamic Disc	Wintersteiger Quantum	4015	HYE

Table 2. Environment, planting date, soil moisture, soil temperature, and days to emergence.

Environment	Planting Date	Soil Moisture (%)	Soil Temperature (C)	Days to Emergence
Currituck-2019	5/2/2019	17.9	27.4	7
	5/14/2019	19.2	23.6	7
	5/29/2019	15.5	113.3	9
	6/25/2019	-	28.0	10
	7/16/2019	19.6	35.2	9
	7/31/2019	14.4	37.8	8
Sampson-2019	3/13/2019	20.3	11.7	19
	3/29/2019	20.1	20.4	10
	4/11/2019	18.7	26.3	7
	5/13/2019	10.6	32.4	7
	5/28/2019	12.8	41.7	9
	6/18/2019	-	27.3	4
	7/17/2019	12	35.9	5
	7/29/2019	-	32.3	8
Union-2019	3/29/2019	24.5	21.7	13
	4/18/2019	16.3	20.9	12
	5/3/2019	16.7	27.4	7
	5/17/2019	20.9	23.4	5
	6/17/2019	24.3	38.3	10
	7/18/2019	17.5	33.3	4
	7/30/2019	21.9	36.4	13
Yadkin-2019	3/14/2019	29.9	10.9	26
	3/28/2019	18.4	15.3	14
	4/18/2019	23.3	26.2	12
	5/16/2019	22.5	33.8	13
	6/27/2019	24.4	38.4	12
	7/30/2019	16	34.4	6
Beaufort-2020	4/6/2020	47.7	18.2	9
	4/29/2020	28.4	21.4	7
	5/26/2020	32.1	22.7	7
	6/24/2020	15.5	27.8	6

Table 2 (continued)

	7/14/2020	41.8	29.7	8
Robeson-2020	4/7/2020	40.1	18.9	6
	4/29/2020	16.5	24.5	8
	6/4/2020	16.7	29.5	5
	6/23/2020	-	29.8	7
	7/14/2020	26.5	34.6	6
Rowan-2020	4/7/2020	51.4	23.1	9
	4/28/2020	40.3	26.1	8
	6/3/2020	12.1	34.3	5
	6/26/2020	41.6	32.8	10
	7/13/2020	58.1	34.2	8

†Missing data due to soil moisture equipment not being available

Table 3. Year and maturity group.

Year	Maturity Group						
	2	3	4	5	6	7	8
2019	AG26X8	AG36X6	AG49X6	AG56X8	AG64X8	AG72X7	AG79X9
2020	AG26X8	AG36X6	AG47X9	AG56X8	AG64X8	AG72X7	AG79X9

†Abbreviations: AG: Asgrow

Table 4. Observed flowering date (R1) for each planting date by maturity group combination at each environment.

Environment	Planting Date	Maturity Group 2	3	4	5	6	7	8
Currituck-2019	5/2/2019	6/25/2019	6/10/2019	6/10/2019	7/11/2019	7/16/2019	7/11/2019	7/24/2019
	5/14/2019	6/25/2019	6/25/2019	6/25/2019	7/16/2019	7/24/2019	7/24/2019	7/24/2019
	5/29/2019	7/11/2019	7/11/2019	7/11/2019	7/31/2019	8/8/2019	8/8/2019	8/8/2019
	6/25/2019	7/24/2019	7/31/2019	8/8/2019	8/22/2019	8/22/2019	8/22/2019	8/22/2019
	7/16/2019	-	-	-	-	-	-	-
	7/31/2019	8/27/2019	9/17/2019	9/17/2019	9/17/2019	9/17/2019	9/17/2019	9/17/2019
Sampson-2019	3/13/2019	5/13/2019	5/13/2019	5/28/2019	5/28/2019	5/28/2019	5/28/2019	5/28/2019
	3/29/2019	5/13/2019	5/28/2019	5/28/2019	5/28/2019	6/12/2019	6/12/2019	6/12/2019
	4/11/2019	5/28/2019	5/28/2019	5/28/2019	6/18/2019	6/18/2019	6/12/2019	6/26/2019
	5/13/2019	6/18/2019	6/18/2019	6/26/2019	7/10/2019	7/17/2019	7/17/2019	7/29/2019
	5/28/2019	7/10/2019	7/10/2019	7/10/2019	7/29/2019	8/6/2019	8/6/2019	8/6/2019
	6/18/2019	7/17/2019	7/29/2019	7/29/2019	8/30/2019	8/30/2019	8/30/2019	8/30/2019
	7/17/2019	8/30/2019	8/30/2019	8/30/2019	8/30/2019	8/30/2019	8/30/2019	8/30/2019
	7/29/2019	8/30/2019	8/30/2019	8/30/2019	9/19/2019	9/3/2019	9/19/2019	9/19/2019
Union-2019	3/29/2019	5/17/2019	5/17/2019	5/17/2019	6/11/2019	6/11/2019	6/11/2019	6/11/2019
	4/18/2019	6/3/2019	6/3/2019	6/11/2019	6/27/2019	6/27/2019	6/27/2019	6/27/2019
	5/3/2019	6/11/2019	6/11/2019	6/17/2019	7/9/2019	7/9/2019	7/9/2019	7/9/2019
	5/17/2019	6/17/2019	6/17/2019	6/27/2019	7/18/2019	7/18/2019	7/18/2019	7/22/2019
	6/17/2019	7/18/2019	7/18/2019	7/22/2019	8/12/2019	8/12/2019	8/12/2019	8/12/2019
	7/18/2019	8/20/2019	8/20/2019	8/20/2019	8/29/2019	8/29/2019	8/29/2019	8/29/2019
	7/30/2019	8/29/2019	8/29/2019	8/29/2019	9/20/2019	9/20/2019	9/20/2019	9/20/2019
Yadkin-2019	3/14/2019	5/16/2019	6/3/2019	6/3/2019	6/27/2019	6/27/2019	6/27/2019	6/27/2019
	3/28/2019	6/3/2019	6/3/2019	6/3/2019	6/27/2019	6/27/2019	6/27/2019	6/27/2019
	4/18/2019	6/11/2019	6/11/2019	6/11/2019	7/9/2019	7/9/2019	7/9/2019	7/9/2019
	5/16/2019	6/27/2019	6/27/2019	7/9/2019	7/18/2019	7/26/2019	7/26/2019	8/5/2019
	6/27/2019	7/30/2019	8/5/2019	8/5/2019	8/19/2019	8/19/2019	8/29/2019	8/29/2019
	7/30/2019	9/10/2019	9/10/2019	9/10/2019	9/20/2019	9/10/2019	9/10/2019	9/10/2019
Beaufort-2020	4/6/2020	6/2/2020	6/9/2020	6/9/2020	6/30/2020	7/7/2020	7/7/2020	7/14/2020
	4/29/2020	6/18/2020	6/18/2020	6/24/2020	7/14/2020	7/22/2020	7/29/2020	7/29/2020
	5/26/2020	6/30/2020	7/7/2020	7/7/2020	7/29/2020	8/6/2020	8/6/202	8/6/202

Table 4 (continued)

	6/24/2020	7/29/2020	7/29/2020	8/6/2020	8/17/2020	8/17/2020	8/17/2020	8/17/2020
	7/14/2020	8/17/2020	8/17/2020	8/17/2020	8/24/2020	9/2/2020	9/2/2020	9/2/2020
Robeson-2020	4/7/2020	6/4/2020	6/4/2020	6/4/2020	6/23/2020	6/30/2020	6/30/2020	6/30/2020
	4/29/2020	6/18/2020	6/18/2020	6/23/2020	7/7/2020	7/14/2020	7/14/2020	7/20/2020
	6/4/2020	7/7/2020	7/14/2020	7/14/2020	7/27/2020	8/6/2020	8/6/2020	8/6/2020
	6/23/2020	7/27/2020	7/27/2020	7/27/2020	8/6/2020	8/11/2020	8/11/2020	8/11/2020
	7/14/2020	8/18/2020	8/18/2020	8/25/2020	9/1/2020	9/1/2020	8/25/2020	9/1/2020
Rowan-2020	4/7/2020	6/8/2020	6/8/2020	6/19/2020	7/6/2020	7/13/2020	7/13/2020	7/13/2020
	4/28/2020	6/19/2020	6/19/2020	6/26/2020	7/13/2020	7/21/2020	7/21/2020	7/28/2020
	6/3/2020	7/6/2020	7/13/2020	7/13/2020	8/5/2020	8/5/2020	8/5/2020	8/10/2020
	6/26/2020	-	-	-	-	-	-	-
	7/13/2020	8/19/2020	8/19/2020	8/19/2020	8/26/2020	8/26/2020	8/26/2020	8/26/2020

†Missing data due to planting dates being dropped as a result of poor emergence

Table 5. Summarized ANOVA results for the effects of planting date (PD), maturity group (MG), seeding rate (SR), and the relevant interactions on stand in a combined analysis across environments.

Dependent Variable	Num DF	Den DF	F Value	P > F
PD	1	682.5	4.38	0.0366
MG	1	4941	4.20	0.0404
PD *MG	1	4673	0.18	0.6726
SR	1	5266	264.86	<.0001
PD*SR	1	5266	0.00	0.9937
MG*SR	1	5266	0.03	0.8639
PD*MG*SR	1	5267	0.00	0.9893
PD*PD	1	493	3.14	0.0769
MG*MG	1	5279	12.90	0.0003
SR*SR	1	5266	218.52	<.0001

†Abbreviations: PD: planting date; MG: maturity group; SR: seeding rate; NDF: numerator degrees of freedom; DDF: denominator degrees of freedom

Table 6. Summarized ANOVA results for the effects of planting date (PD), maturity group (MG), seeding rate (SR), and the relevant interactions on yield in a combined analysis across environments.

Dependent Variable	NDF	DDF	F Value	P > F
PD	1	303.8	159.13	<.0001
MG	1	1736	70.80	<.0001
PD*MG	1	1582	8.91	0.0029
SR	1	4061	0.24	0.6273
PD*SR	1	4076	15.05	0.0001
MG*SR	1	4064	1.31	0.2517
PD*MG*SR	1	4071	3.88	0.0490
PD*PD	1	160.1	337.20	<.0001
MG*MG	1	4231	750.47	<.0001
SR*SR	1	4038	8.75	0.0031

†Abbreviations: PD: planting date; MG: maturity group; SR: seeding rate; NDF: numerator degrees of freedom; DDF: denominator degrees of freedom

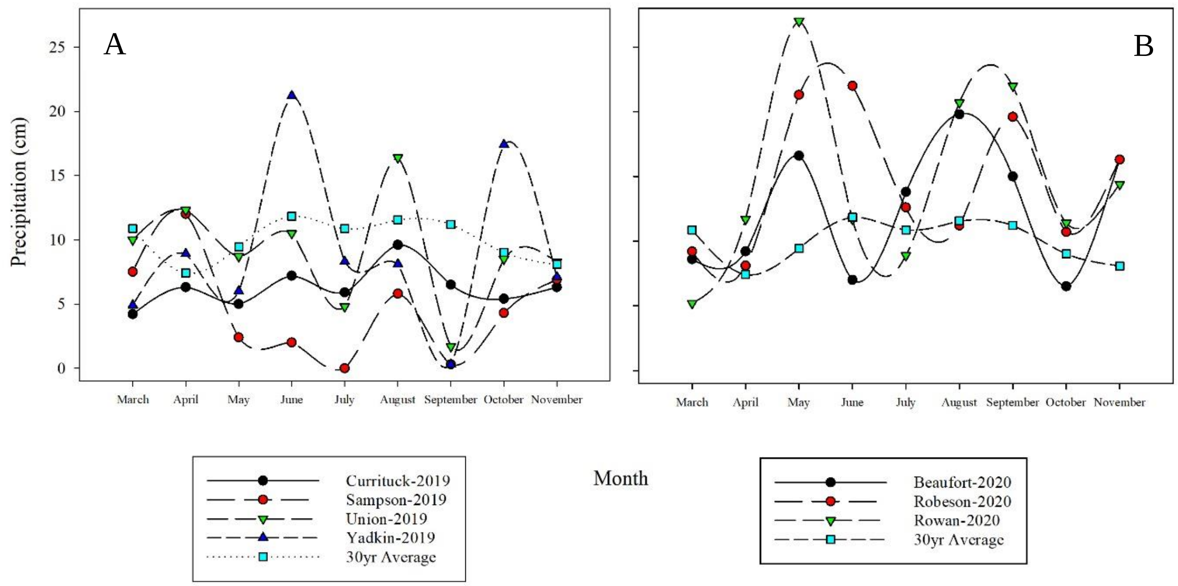

Figure 1. Monthly rainfall totals for environments in 2019 and 2020 compared to the 30 year average. A-2019 B-2020.

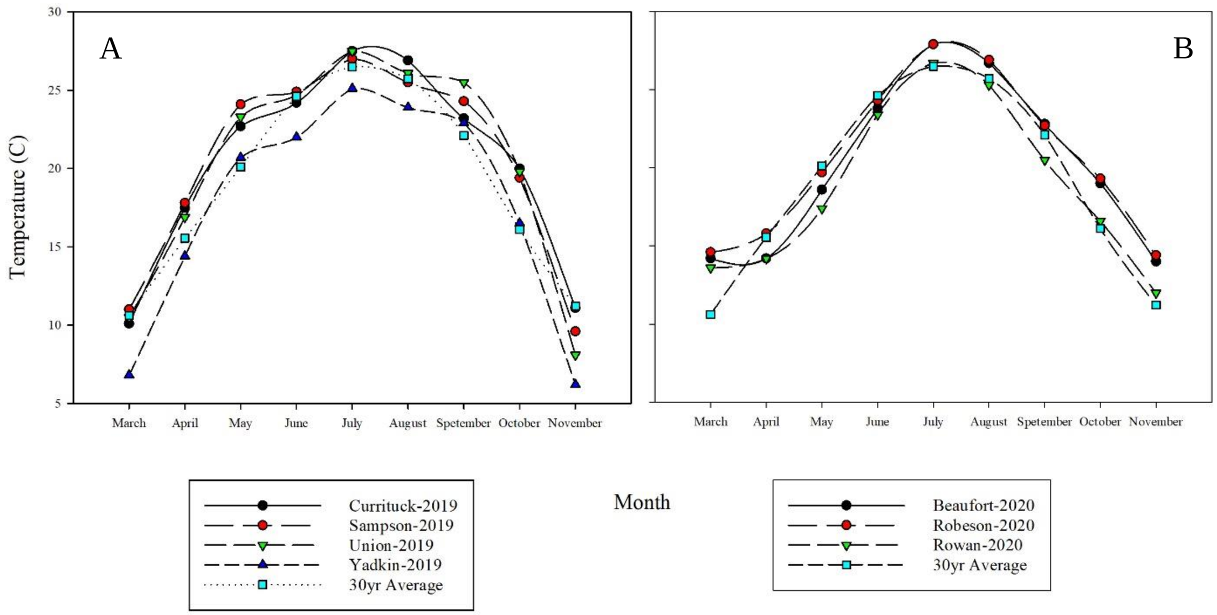

Figure 2. Monthly average temperature for the environments in 2019 and 2020 compared to the 30 year average. A- 2019 B- 2020.

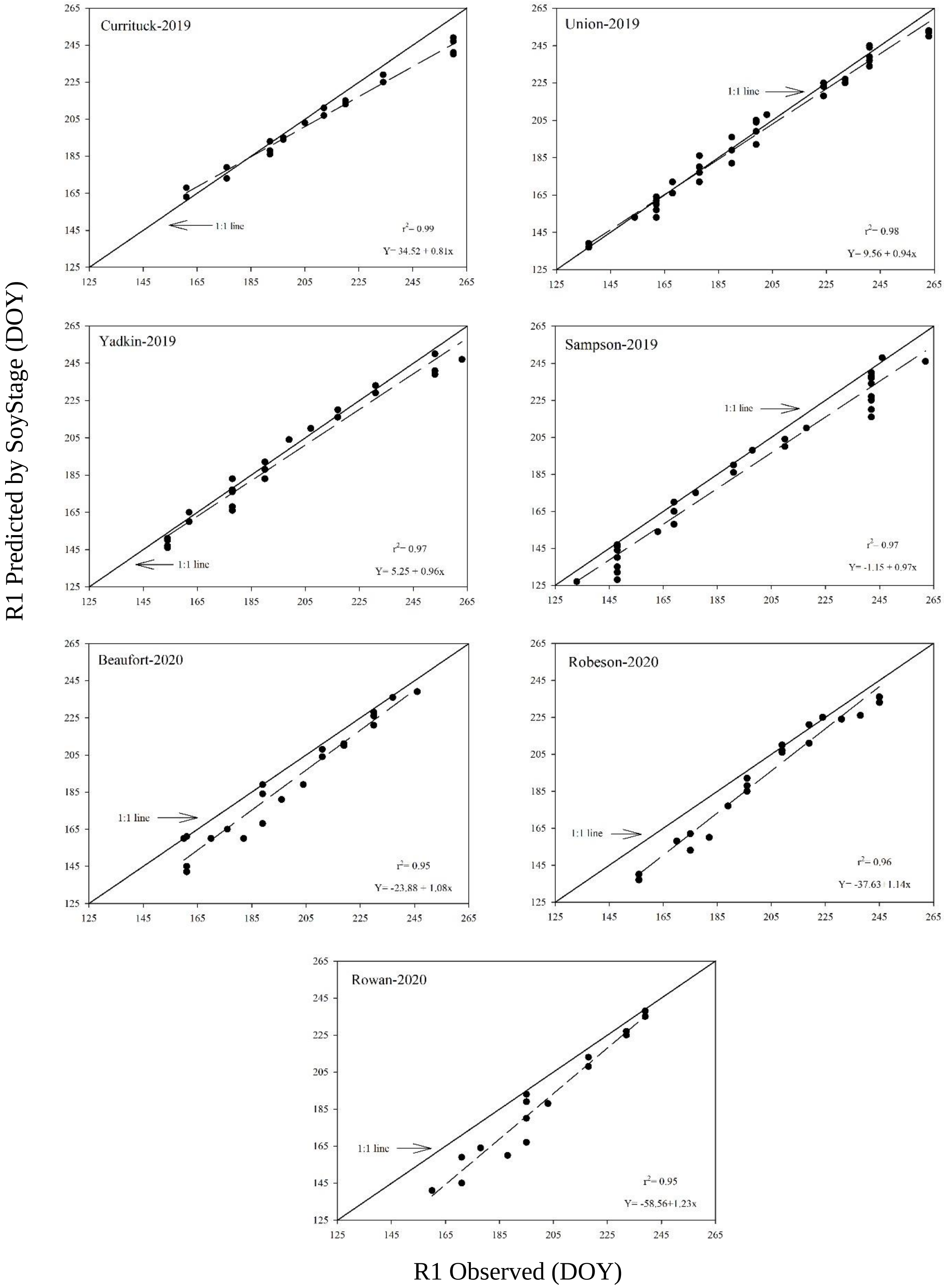

Figure 3. Relationship between SoyStage predictions and observed dates for R1 for seven locations. DOY, day of year.

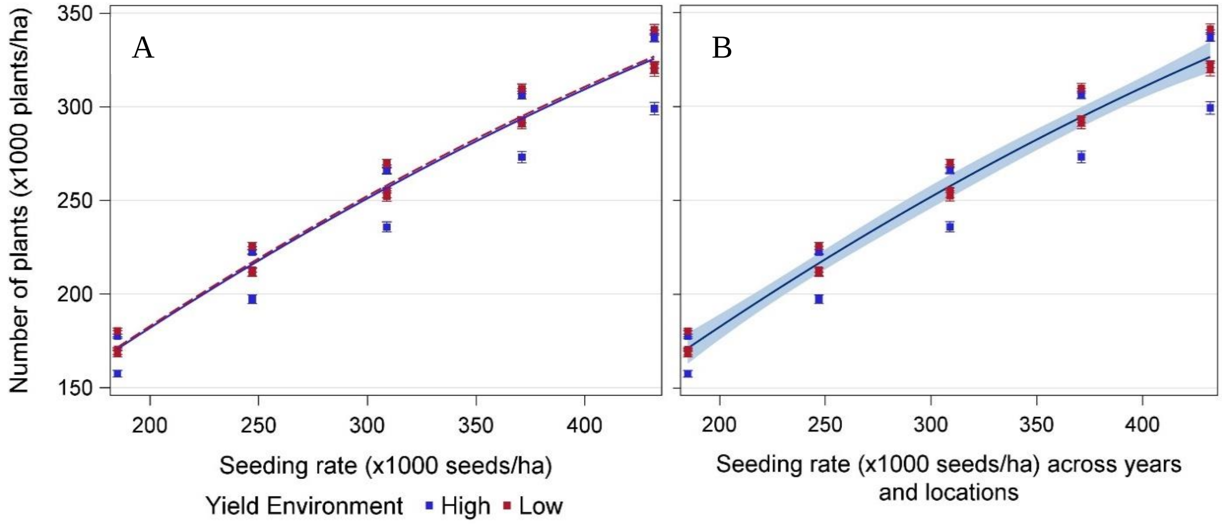

Figure 4. Effect of seeding rate on stand combined over planting date and maturity group. Mean stand values by environment with standard error bars.

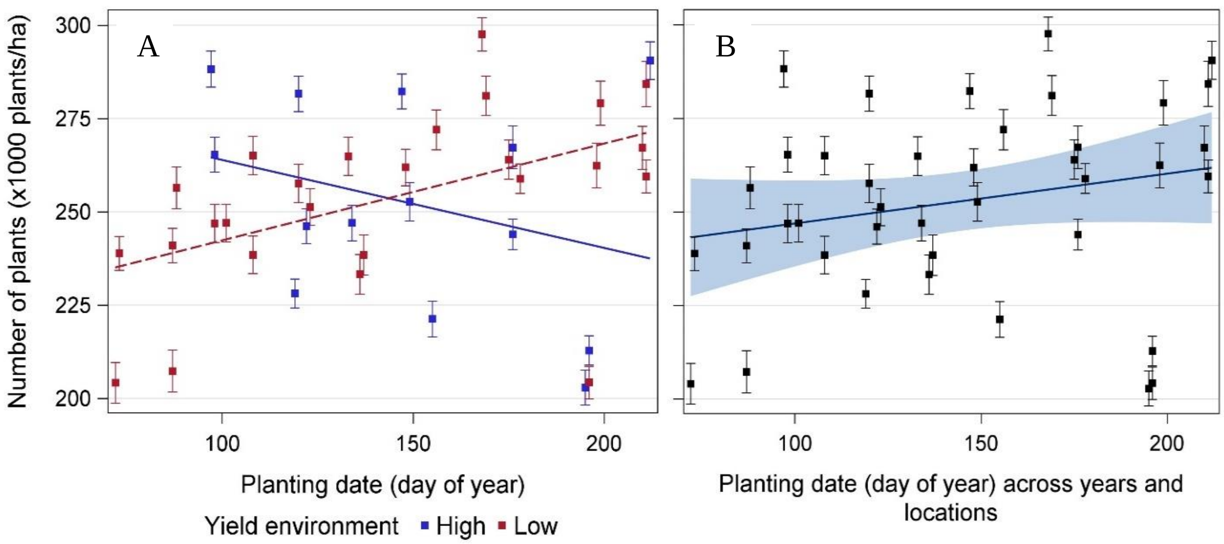

Figure 5. Effect of planting day of the year on stand combined over seeding rate and maturity group. Mean stand values by environment with standard error bars.

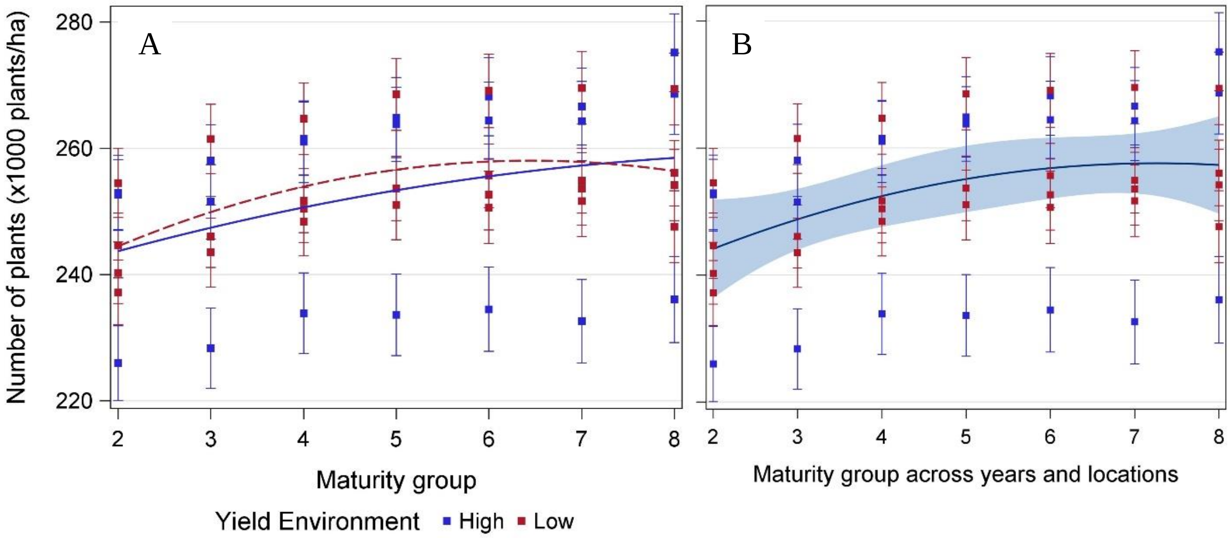

Figure 6. Effect of maturity group on stand combined over planting date and seeding rate. Mean stand values by environment with standard error bars.

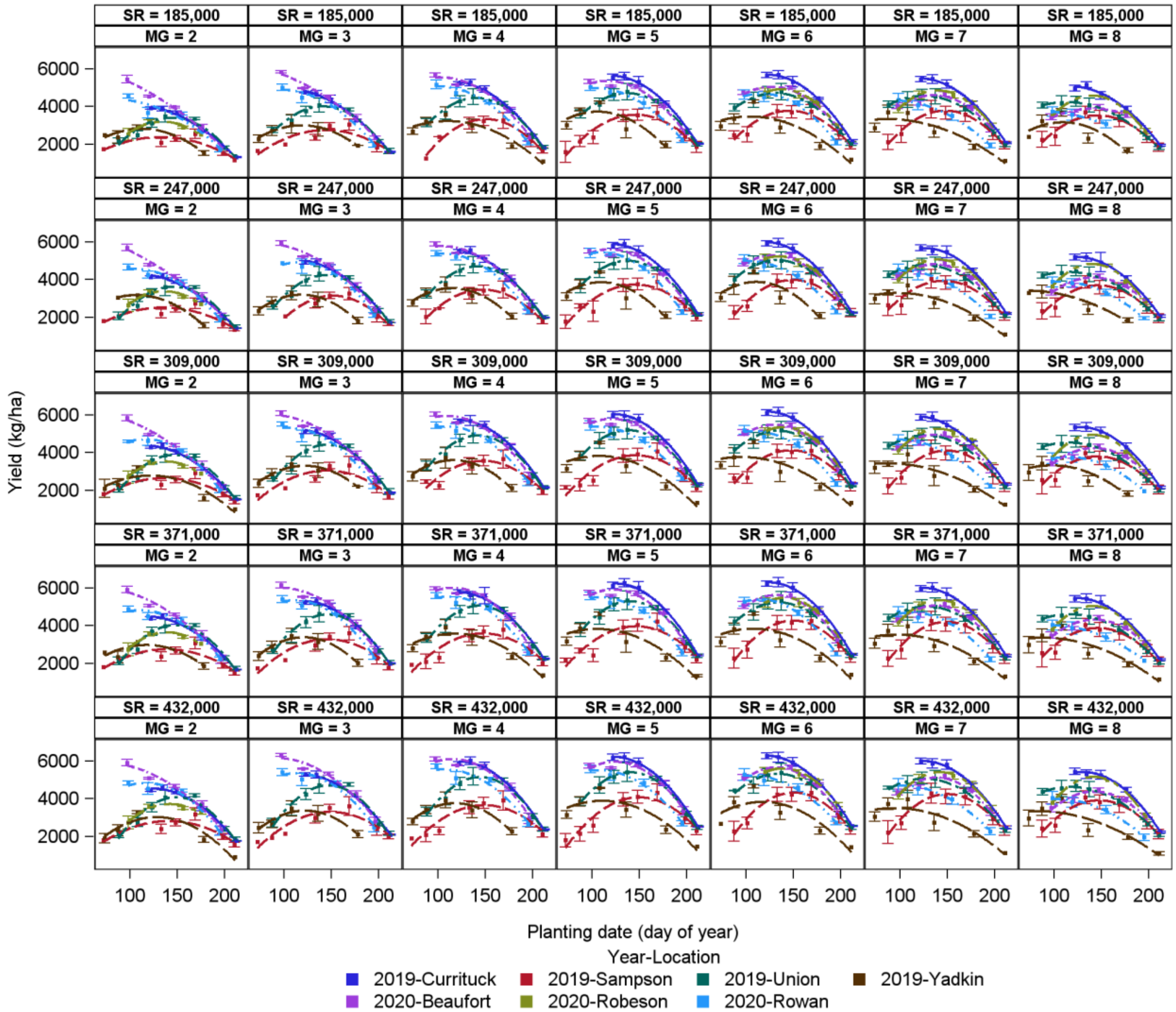

Figure 7. Effect of planting day of the year and maturity group (MG) on yield. Mean yield values by environment with standard error bars.

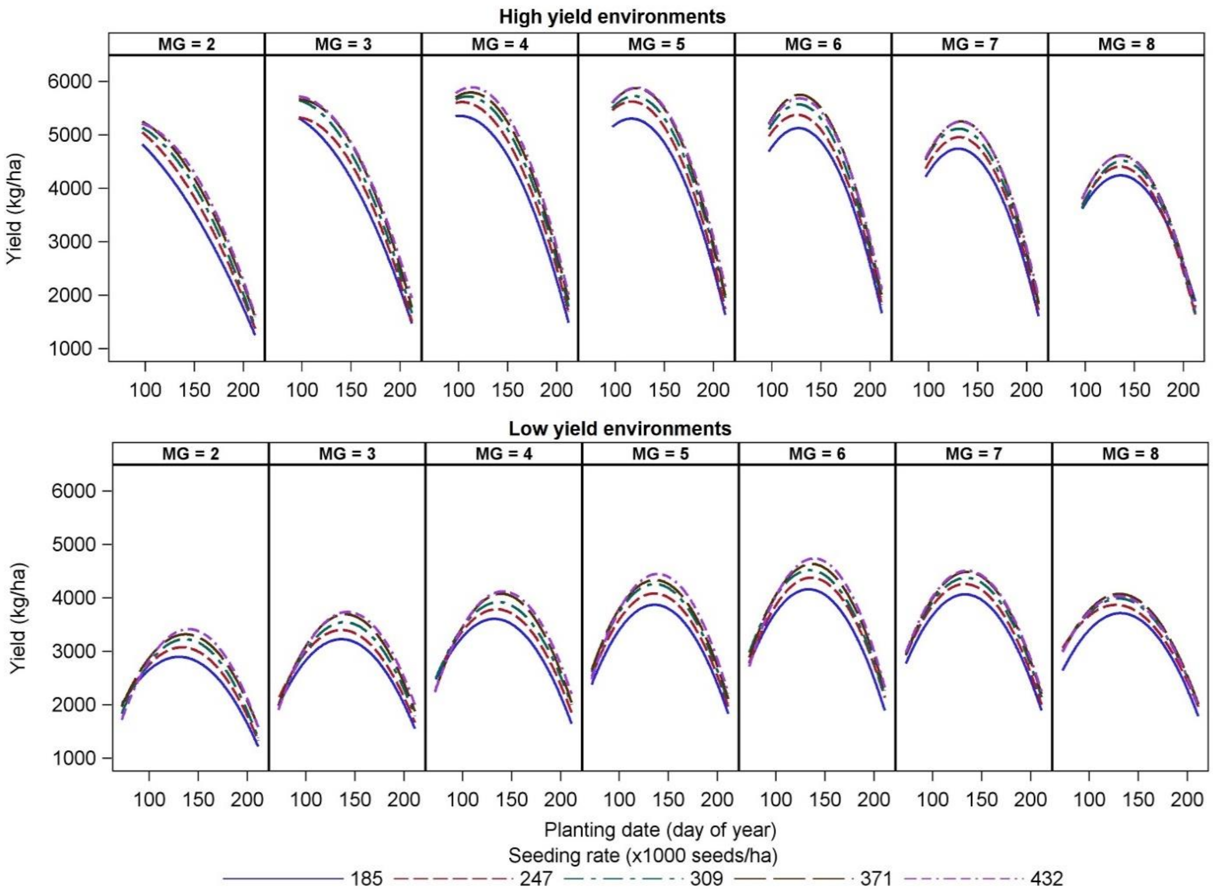

Figure 8. Effect of planting day of the year, seeding rate, and maturity group (MG) on yield. Mean yield values by environment.

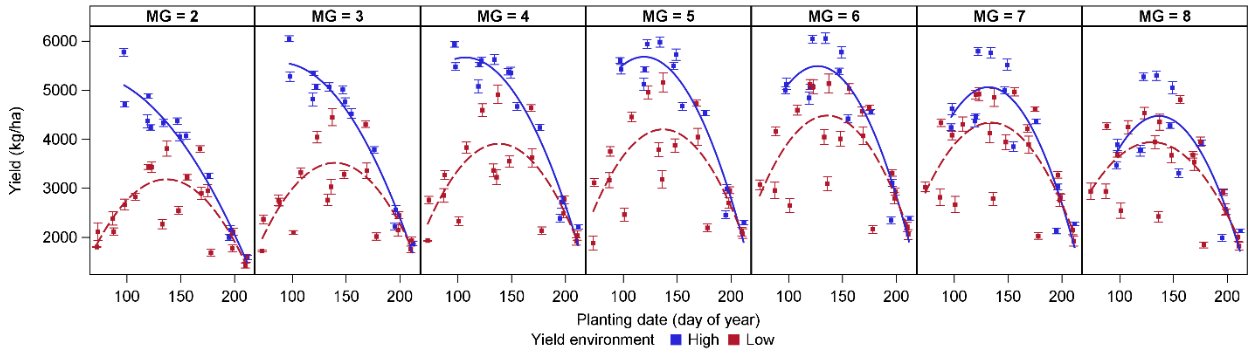

Figure 9. Effect of planting day of the year and maturity group (MG) on yield averaged over seeding rate. Mean yield values by environment with standard error bars.

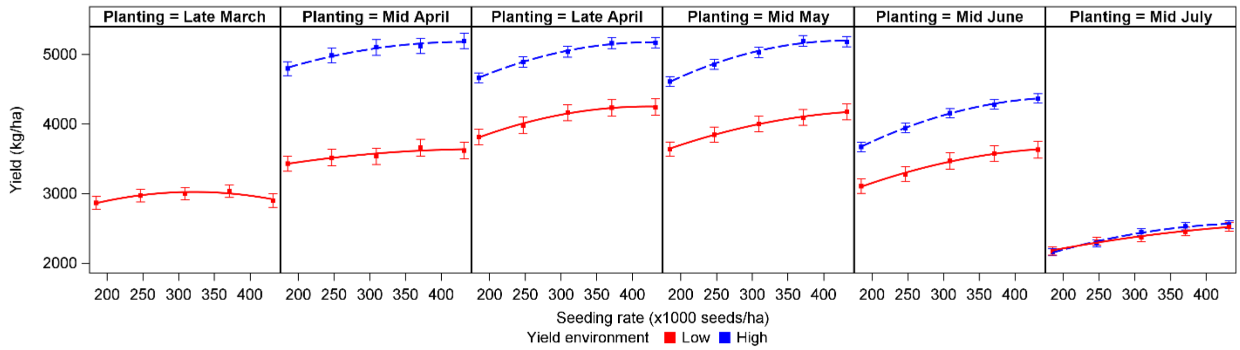

Figure 10. Effect of planting and seeding rate on yield averaged over maturity group. Mean yield values by environment with standard error bars.

CHAPTER 2

Planting Date and Maturity Group Impacts on Soybean Seed Quality in North Carolina

ABSTRACT

As growers in the Southeast USA increasingly plant earlier maturing varieties at earlier than historical-planting dates, the impact of shifting these production practices on soybean seed quality are not well understood. The objective of this study was to determine the impacts of diverse planting dates with diverse maturity groups on soybean protein content, oil content, seed damage, and purple seed stain.

Studies were installed across seven North Carolina locations in 2019 and 2020 to determine the impact of planting date (mid-March through mid-July) and maturity group (2-7) on seed quality.

Protein content generally trended towards declining as planting was delayed for the early maturity groups (2-5), but was stable across planting date for the later maturity groups (6-7). It was observed that early maturing varieties (≤ 5) had a lower percent protein than the later maturing varieties (MG 6-7). The oil content tended to be higher in the early maturity groups 2-4 compared to the later maturity groups 5-7, with oil content and protein content generally having an inverse relationship. Seed damage was highest when planting before Late April with early maturity groups (2-4). Soybean planted after Late April typically resulted in low levels of damage regardless of maturity group. There were site-specific variations in the amount of seed damage due to issues with green stem resulting in harvest delays, which further increased seed damage. Similar to seed damage, purple seed stain was lower in maturity groups 5-7 compared to the earlier maturity groups across all planting dates. The greatest amount of purple seed stain was observed with MGs ≤ 4 planted before mid-May. Further research is needed to understand how to minimize seed damage and purple seed stain as producers consider shifting to an earlier production system in North Carolina and across the Southeast USA.

NOMECLATURE

Soybean, *Glycine max* (L.) Merr.; Purple seed stain, Cercospora kikuchii

KEY WORDS

Maturity group, planting date

INTRODUCTION

Soybean [*Glycine max* (L.) Merr.] is an important legume crop in North Carolina (NC) as is the largest hectarage crop in the state with 635,356 hectares planted in 2020 (USDA-NASS, 2020). The soybean has many uses and is a vital feed source for the animal industry (Hedrick, 2020). In recent years, the decline in wheat acreage has led to an increase in full season soybean planting in NC (USDA-NASS, 2020). Historically, MGs 5-7 soybeans have been produced in NC and planted from mid-May through early July (Vann, personal communication). However, growers have been considering planting soybeans earlier and using earlier maturing varieties for the associated yield benefits (Salmeron, 2016). Additionally, some growers are seeking to reduce the risk of hurricane damage by planting earlier maturing varieties and subsequently harvesting their soybeans prior to later-season hurricanes. However, as a result of warm temperatures and higher humidity when earlier maturing varieties approach physiological maturity, there have been more issues with soybean seed quality (damage and purple seed stain) at harvest than historically encountered in the region (Vann, 2020).

The increased interest in earlier planting dates (PD) and maturity groups (MG) in NC has been greatly influenced by the shift in production practices seen in the Mid-South USA (Salmeron, 2015; Salmeron, 2014; Heatherly et al., 2002). Growers throughout the Mid-South have observed yield increases and reduced production risks by shifting their soybean planting earlier in the season (Mengistu and Heatherly, 2006). A study to determine the optimal MG for early and late plantings in the Mid-South found that during early planting the use of MGs 4 and 5 resulted in the highest yields (Salmeron et al., 2014). A similar study by Salmeron, et al. (2016) observed that MG 4 cultivars resulted in maximum yield across latitudes ranging from 30.6°N to 38.9°N when planted in early May. Additionally, it was found that to maximize yield the optimum PD varied depending on the location and MG and ranged from 22 March to 17 May (Salmeron, et al. 2016). In Kentucky, Knott et al. (2019) found that late April to early May PDs maximized soybean yields.

A recent analysis of 877 entries into the NC Soybean Yield Contest indicated that PD and MG were the largest predictors of high soybean yield in the state, with MG $\leq$ 4 providing a yield advantage over later maturing varieties and PDs earlier than mid-May often leading to yield advantages over later PDs (Vann et al., in press). Although there has been extensive soybean research in the Southeast USA, there is a lack of knowledge about how earlier than mid-May PDs and earlier MGs (MG $\leq$ 4) impact soybean seed quality.

Soybean seed composition is an important part of determining the economic value of soybeans for marketing (Brumm and Hurburgh, 2006). As an oilseed crop, soybeans consist of approximately 20% oil and 80% meal (Uses of Soybeans, n.d.). The meal is a great source of protein and is used for animal feed due to its relatively low cost and high protein content (Grieshop and Fahey, 2001). Currently, the animal industry is the largest consumer of soybeans with 97% of US soybean meal being used to feed livestock and poultry (Hedrick, 2020). Soybean oil is also of importance as it makes up 28% of the world vegetable oil consumption and 55% of the US vegetable oil consumption (Soystats, 2019). The oil has many uses including but not limited to cooking oil, food additives, plastics, biodiesel, and motor oil (Raghuvanshi and Bisht, 2010).

In 2019, the national average for protein and oil concentration was 34.1% and 19.0%, respectively (Naeve and Miller-Garvin, 2019). Soybean seed composition is known to vary due to environment, genetics, and management (Assefa et al., 2019; Bellaloui et al., 2015; Yaklich et al., 2002). The influence of PD on seed composition has shown varied responses. Assefa et al. (2019) found that delaying planting resulted in a decrease in oil content and that the protein content was negatively affected only at northern latitudes with delayed planting. In partial agreement, Kane et al. (1997) observed that delaying planting resulted in higher seed protein content and lower oil content. In contrast, Robinson et al. (2009) found that in one year, the protein and oil content varied by PD. Then, in the next year, protein content increased as planting was delayed. On the other hand, in Wisconsin and Minnesota, Mourtzinis et al. (2017) saw that early planting with a MG 2 resulted in the highest oil content. However, Pedersen and Lauer (2003) reported that PD did not have a significant effect on the protein content.

Oil and protein content can also vary depending on MG (Yaklich et al., 2002) and cultivar (Bastidas et al., 2008). However, environmental conditions tend to have the greatest effect on seed composition (Grieshop and Fahey, 2001). Studies analyzing seed composition often separate the data by regions (Bellaloui et al., 2015; Rotundo, 2016; Assefa et al., 2019). Assefa et al. (2019) observed that in the southern region (latitude 30–35°N), there was a reduction in oil content and an increase in protein content with later MGs (MG 6-7). Rotundo et al. (2016) found that Southern USA states have a higher protein content than the Corn Belt with similar regional patterns demonstrated by others (Breene et al., 1988; Yaklich et al., 2002). Assefa et al. (2019) observed that at mid (35–40°N) and southern latitudes (30–35°N) mean oil content declined significantly as planting was delayed. Additionally, at northern latitudes (40–45°N), there was a greater decline in mean oil content as PD was delayed. The impact of wide ranging PD and MG combinations on soybean seed composition tested with recent soybean genetics in NC remains unknown.

Greater concerns for seed quality (damage and purple seed stain) in NC have developed as interest in earlier soybean PDs and MGs has increased in recent years. At the earlier PDs, growers are often using earlier MGs, resulting in a portion of NC soybeans reaching physiological maturity at an earlier time in the year (mid-August to mid-September) than historical for soybean production in the state (early October to mid-November). The weather conditions at this earlier time of the year are hot and humid, allowing for the growth and spread of fungus and disease that can cause seed damage (Gillen et al., 2012, Wrather et al., 1996). Soybeans are susceptible to many different diseases that can have a significant economic impact on the crop. Bandara et al. (2020) reported that on average, the annual economic loss due to soybean diseases in the U.S. was approximately 4.55 billion dollars with the northern and southern regions at 3.85 and 0.69 billion dollars, respectively. A plethora of soybean diseases can cause reduced seed quality (Joyce and Thiessen, 2020).

A common fungus seen in soybean production in the Southern USA is *Cercospora kikuchii* (Turner et al., 2020). This fungus is known for being the causal agent for Purple Seed Stain (PSS). PSS causes discoloration of the soybean seed coat resulting in purple spots covering parts or the entire surface of the seed coat (Hartman et al., 2015). Turner et al. (2020) reported delayed seed germination when 50% or more of the seeds were stained by PSS but that the oil and protein content were not significantly affected. Therefore, PSS does not generally affect the market price if the seed will be crushed for meal and is not being produced for seed. Using the USDA grading process, PSS is quantified separately from damage by visual observation.

Phomopsis seed decay (PSD) is present in every soybean growing region (Sinclair, 1993). Symptoms include seed that is severely shriveled, elongated, cracked, and may also be moldy, resulting in lower germination and quality for processing (Hartman, 2015). In Missouri, Wrather (1996) observed that PSD occurred more in early planting (mid-April) than the traditional planting (mid-May) with MGs 3 and 4.

Anthracnose is a disease caused primarily by the fungus *Colletotrichum truncatum* that can impact soybean seed quality (Hartman, 2015). It usually infects the stem but can also spread to the entire plant. Additionally, Anthracnose often causes significant yield reduction in the Southern USA (Wrather and Koenning, 2006). Infected seed may develop brown staining or small, irregularly-shaped, gray areas with black specks (Hartman, 2015).

Fusarium solani is primarily associated with causing root rot but can also cause seed rot. When present on seeds, it may be moldy, chalky, and/or light brown to reddish in color, resulting in reduced or delayed germination and lower seed vigor (Hartman, 2015).

There are many causes of soybean seed damage; however, it is important to understand what qualifies as “damaged” for grading purposes. A soybean is graded as damaged when the seed is clearly recognized as damaged for commercial purposes. There are many different types of damage, including but not limited to weather-damage, heat-damage, mold-covered, insect-bored, stinkbug-stung, immature, frost-damaged, and sprout-damaged (USDA-AMS, 2020). When the seeds are damaged, their protein and oil content are often reduced, causing a decline in the quality. Therefore, it is critical to ensure that soybean seed quality is maintained in an effort to continue to meet the demands of the end users and to reduce dockage for producers at the elevator.

The objective of this study was to determine the impacts of PD and MG on soybean seed quality (protein, oil, damage, PSS) in the Southeast USA.

MATERIALS AND METHODS

Experimental Sites and Management

Field experiments were conducted over two soybean growing seasons (2019-2020). In 2019, the research sites included five on-farm sites: Sampson County, NC, Currituck County, NC, Hyde County, NC, Union County, NC, and Yadkin County, NC. The soil in Sampson County was a fine-loamy, kaolinitic, thermic Typic Kandiudults. The soil in Currituck County was a fine, mixed, semiactive, thermic Typic Endoaquults. The soil in Hyde County was a fine-silty, mixed, active, acid, thermic Cumulic Humaquepts. The soil in Union County was a fine, mixed, semiactive, thermic Typic Hapludults. The soil in Yadkin County was a fine, kaolinitic, mesic Typic Kanhapludults.

In 2020 the research sites included Rowan County, NC, and an on-farm site in Beaufort County, NC. The soil in Rowan County was a fine, kaolinitic, thermic Rhodic Kanhapludults. The soil in Beaufort County was a fine, mixed, semiactive, thermic Typic Umbraquults.

These locations were selected to represent a range of growing conditions experienced by soybean producers in NC. The combination of year and location will be referred to as an environment (Table 1). Plot size was 7.6m by 1.5m planted on 38.1 cm rows.

Treatment Description

The experiment was designed in a split-plot design with the main plot as planting date (5-8 levels) and sub-plot as maturity group (7 levels). There were four to five replications per treatment combination. Maturity groups included 2. 3, 4, 5, 6, 7E and 7L (Table 2). All plots were seeded at 247,105 seeds ha^{-1}.

Data Collection

Grain subsamples (~100 g) were collected from each plot using a small-plot combine (Table 1). The subsamples were analyzed for seed damage, PSS, protein and oil content. In order to quantify damage and PSS, the entire subsample was first weighed to give a total weight. Soybeans that were considered damaged using USDA grading guidelines were removed from the subsample and weighed (USDA-AMS, 2020). Then soybeans with PSS were removed from the same subsample and weighed separately (Figure 1). This was repeated for each subsample. The methods for determining damage used in this study were the same grading standard used at the grain elevators as defined by the USDA (USDA-AMS, 2020). However, PSS was quantified differently from the USDA in that it was quantified on a mass basis versus using an Interpretive Line Print (USDA-AMS, 2020). After the damaged seed and PSS were removed, the subsamples were analyzed for protein and oil content using a Pertan DA7520 Near Infrared spectrometer (NIR) analyzer (Hagersten, Sweden).

Weather Data

The NC climate retrieval observations network of the Southeast USA database (CRONOS) developed by the State Climate office of NC was utilized to acquire weather data. When there were limitations in the available CRONOS data, weather data was obtained from the NASA Langley Research Center POWER Project funded through the NASA Earth Science Directorate Applied Science Program (NASA, 2020). Weekly rainfall and temperature for each environment from July 22 to November 24, 2019 and July 20 to November 22, 2020 is available in Figures 2 and 3.

Statistical Analysis

Analysis of variance was conducted using PROC MIXED in SAS 9.4 (SAS Institute Cary, NC). PD and MG were considered fixed factors and replication and environment were considered random factors. A combined analysis across environments was performed and is the focus of this manuscript because of the typically small variance component for the independent-by-environment interaction relative to the main effect of the independent variable and to make broad conclusions about PD and MG impact on seed quality in the region (Table 3), however data from individual environments are also presented.

RESULTS AND DISCUSSION

Seed Composition

Seed Composition for this study will be defined as the protein and oil content of the soybean seed. It is important to note that protein and oil content reflects the analysis of seed samples after removing PSS and damaged seed for this study (Figure 1D).

Protein

The PD by MG interaction trended towards significance for the combined analysis (P = 0.0957) (Table 3). As planting was delayed there was typically a decline in the protein content with the earlier maturing varieties (MG ≤5), however protein content was relatively consistent across PDs with the later maturing varieties (Figure 4). These results are in contrast to some previous studies that reported that as planting was delayed there was an increase in the protein content (Kane et al., 1997; Mourtzinis et al., 2017; Robinson et al., 2009). However, Pedersen and Lauer (2003) reported that PD did not have a significant effect on the protein content.

When comparing the later MGs to the early MGs, it was observed that the later MGs (≥6) resulted in a greater protein content than the average across all MGs regardless of PD (Figure 4E-G). In agreement, Assefa et al. (2019) observed that at lower latitudes (30–35°N) there was an increase in protein content with later MGs (6 and 7). Breeding efforts can partially explain the differences in protein observed between MGs as breeders in the Midwest have aggressively focused on increasing yield in the earlier MGs and inadvertently there has been a decrease in protein concentration due to the inverse relationship between yield and seed protein (Rincker et al., 2014; Piper and Boote, 1999). Additionally, there is a greater focus on breeding early MGs (2-4) compared to later MGs (≥5), driven by the greater volume of their use in the Midwest USA (Boehm et al., 2019; Rincker et al., 2014). Boehm et al. (2019) observed that there was no change in the seed protein content for MGs 5 and 7; however there was a reduction for MG 6. Therefore, the genetic background of these cultivars may be driving the observed protein content differences. Furthermore, the impact of environmental differences potentially influenced protein content. The environmental conditions during seed development is the most critical part for determining seed composition (Rotundo and Westgate, 2009). Therefore, as the flowering of the later MGs occurs during a later time of the year compared to early MGs planted at the same time, seed development is delayed to a later time during the year where conditions may be more favorable for protecting seed quality.

While our primary goal was to understand the broad impact of PD and MG on protein across the region, the impact of PD and MG on protein was also explored within the individual environments. The mean protein content ranges for each environment across all MGs and PDs were Currituck-2019 32.7-37.0%, Union-2019 33.1-37.1%, Hyde-2019 35.5-38%, Sampson-2019 32.6-36.4%, Yadkin-2019 32.7-36.5%, Rowan-2020 32.6-38.2%, and Beaufort-2020 33.7-41.3%. Across most environments, tends were similar to those observed for the combined analysis with higher levels of protein being observed with the later maturing varieties and more stable protein contents observed across PDs with the later maturing varieties (Figure 4 and 5). Beaufort-2020 tended to have a higher protein content (33.7-41.3%) for most of the PD by MG combinations than other environments (Figure 5). At this site, protein content also tended to be more stable across PDs. This site had good soil moisture due to timely rainfall and is characterized by a soil type with high water holding capacity (Table 1). Additionally, the warmer temperatures in the later part of the growing season at this site may account for the observed increases in protein as has been reported in the literature. Studies have illustrated that higher temperatures during R1-R8 growth stage correlated with greater protein content (Gibson and Mullen, 1996; Piper and Boote, 1999). Yadkin-2019 had the lowest protein content (32.7-35.8%) for PDs mid-May and beyond with MGs 5-7 compared to the other environments. This site experienced lower than average temperatures during most of the growing season (Figure 2).

Generally, there was a higher protein content across MGs in 2020 versus 2019 (Figure 5). This is likely due to the difference in temperature and rainfall experienced in 2019 compared to

2020 (Figure 2 and 3). In 2019, there was very little rainfall between the weeks of 36 and 40 (September 2 to October 6, 2019) (Figure 3A) while during most of that time the temperatures were above average (Figure 2A). However in 2020, rainfall was more consistent throughout the growing season and the total amount of rain was greater than in 2019 (Figure 3). Additionally, there were more weeks at or above the average temperature with less variation from the average temperature than observed in 2019 (Figure 2).

Oil

A combined analysis across environments showed that the PD by MG interaction was significant for oil content (Table 3). It was observed that the highest oil content (20.8%) was achieved with the combination of the late March planting and MG 2 (Figure 6). This is consistent with Mourtzinis et al. (2017), who reported that the highest oil content in Wisconsin and Minnesota was achieved with a MG 2 planted early. The percent oil of MGs 2-4 across all PDs (16.8-20.8%) was greater than the average of all of the MGs (Figure 6). The genetic background of these cultivars can in part explain the observed higher oil content in the early MGs. As breeders have focused on increasing yield, there has been an increase in the oil content due to the positive correlation between oil and yield (Rincker et al., 2014; Piper and Boote 1999). On the other hand, there is usually a decrease in the protein content due to a negative correlation between oil and protein (Burton, 1985; Ray et al., 2006) as was observed with protein content for these earlier maturing varieties planted early in these studies. Therefore, it is important to understand the tradeoff between protein and oil content as soybean yields continue to increase.

It was observed that there was a greater rate of decline in the oil content for the early MGs (2-4) as planting was delayed relative to the later MGs. Others have reported results that are consistent with these observations (Kane et al., 1997; Mourtzinis et al., 2017). Upon further investigation, a by environment analysis revealed that Yadkin-2019 resulted in a higher oil content for MG 2 at the early PDs (late March and mid-April) than the other environments. This environment encounter cooler temperatures throughout the growing season and more rainfall than the other environments in June when these PD by MG combinations were in early reproductive stages (Figure 3, data not shown). A correlation analysis revealed that there was a negative correlation between oil and protein content (Table 4). The observed inverse relationship between protein and oil further supports the well documented negative correlation between protein and oil content (Gibson and Mullen, 1996; Piper and Boote, 1999; Weiss et al., 1952).

The oil content of MGs 6-7 was below the average of all MGs and was largely unaffected by PD (Figure 6). These findings aligned with Assefa et al. (2019), who observed a reduction in the oil content in the southern region (30–35°N) with the use of later MGs (6 and 7). Conversely, these same MGs had a greater protein content than the average across all MGs regardless of PD (Figure 4E-G). This clear inverse relationship was also clear in specific environments. At Beaufort-2020, the lower oil content observed with a MG 7L at all PDs (Figure 7G) coincided with a higher protein content for this MG (Figure 5G). Likewise, at Union-2019, there was a corresponding increase in protein as oil decreased in the MG 3 (Figure 5B and 7B). Similar results were generally observed across individual environments as protein and oil content was correlated at every environment except Yadkin-2019 (Figure 5 and 7; Table 4).

The mean oil content ranges for each environment across all MGs and PDs were Currituck-2019 16.3-18.6%, Union-2019 16.4-20.6%, Hyde-2019 15.4-19.1%, Sampson-2019 15.8-19.5%, Yadkin-2019 15-22.5%, Rowan-2020 14.4-21.3%, and Beaufort-2020 13.3-20.1%.

Seed Quality

Seed quality for this study is defined as the percent of damaged seed in a sample based on mass with damage determined by USDA grading standards. Purple seed stain (PSS) will be addressed separately as it is quantified separately than damaged seed at most grain elevators.

Damage

In a combined analysis, the PD by MG interaction significantly affected the percent damage (Table 3). The highest amount of damage (9.5-42%) was observed at early PDs (late April and before) with MGs 2-4. These PD by MG combinations were in the reproductive stages between June to September when there were warmer temperatures and higher humidity. As planting was delayed beyond late April there was a rapid decline in the amount of damage for the earlier maturing varieties (MGs 2-5) (Figure 8). The significant change in the amount of damage as planting was delayed demonstrates the influence of weather on soybean seed damage during the reproductive stages. Warm temperatures in combination with high humidity increase the chances for fungal infection and growth (Gillen et al., 2012; Mayhew and Caviness, 1994; Wrather et al., 2003). Therefore, when these early MGs are planted early, they start flowering and transition to seed development earlier in the year when the conditions are favorable for fungal growth, likely resulting in greater potential for seed damage. Conversely, as planting was delayed, the reproductive stages were progressively moved to a later time in the year when the temperatures are cooler, lowering the risk for damage as was observed in this study. The amount of damage remained consistently low for MGs 6-7 across all PDs (2.8-5.5%) likely due to the reproductive stages occurring at a later time in the year when temperatures are lower, limiting the growth of fungal diseases (Mayhew and Caviness, 1994), and also possibly due to superior diseases resistant packages for production in Southeast USA environments.

When a by environment analysis was conducted, PD by MG had a significant impact at most environments (Table 3). The mean damage ranges for each environment across all MGs and PDs were Currituck-2019 1.8-21.5%, Union-2019 2.2-62.7%, Hyde-2019 1.5-47.6%, Sampson-2019 0-100%, Yadkin-2019 0-24.4%, Rowan-2020 0.9-15.4%, and Beaufort-2020 0-60.4%. In general, trends were similar across individual environments with the highest levels of damage occurring when using earlier maturing varieties (MG 2-4) at earlier PDs (late April and before) (Figure 9). However, there were environments where higher levels of damage (high of 32.2%) persisted into even mid-May PDs. In these environments there were issues with green stem in MGs 3, 4, and 5s that resulted in harvest delays and had subsequent seed quality ramifications.

In 2020, there was increased stinkbug pressure and greater issues with green stem in Eastern NC, specifically in the MG 4 (Table 2), resulting in harvest delays. The soybean seed in many cases had reached physiological maturity and were ideal for harvest; however, the stems were still at a high moisture content (Hill et al., 2006). Out of concern for damaging the combine, the decision was made to delay harvest in the hopes that the stems would further dry over additional time. Therefore, the seeds were exposed to the weather longer and this is illustrated by the increased damage seen at Beaufort-2020 with PDs mid-May and before in the MG 4 (32.2 - 60.4%) (Figure 9). Additionally, this was observed in Union-2019 with the MG 5 for the earliest PDs (late April and before) (Figure 9D). These two instances of higher damage clearly impacted the combined analysis as these same PD by MG combinations resulted in an increased amount of damage (Figure 9). Specifically, PDs mid-late April with a MG 4 in Figure 10C had elevated levels of damage due to Union-2019 and Beaufort-2020. These results underscore the importance of timely harvest to protect soybean seed quality when producing earlier maturing varieties at earlier PDs and also demonstrate the impact of delayed harvest due to persistent green stem on soybean seed quality.

Depending on the year and weather conditions, growers across the USA experience challenges with soybean seed quality. However, as growers in the Mid-South USA shift to early planting and early MGs there has been an increased potential for seed damage compared to what was historically encountered in the region (ESPS Handbook, 1998). As demonstrated from this study, the earliest PD (late March) of the MG 2 at Sampson-2019 had 100% damage, demonstrating this phenomenon can also be problematic in Southeast USA environments. This also suggest that there is the possibility of having a complete loss due to adverse weather conditions and early planting of early maturing varieties if harvest is delayed.

Purple Seed Stain

In a combined analysis, PD and MG interacted to significantly affect PSS (Table 3). The highest percentage of PSS (4-18.4%) was observed when planting occurred at mid-May or prior with MGs 2-4 (Figure 10). These PD by MG combinations were flowering during June and July when the air temperatures were at their highest (Figure 2). Conversely, at later PDs (after mid-May) the same MGs had lower levels of PSS (3-9.7%). Warm temperatures coupled with high humidity favor the infection and growth of *Cercospora kikuchii*, the causal agent of PSS (Gillen et al., 2012; Mayhew and Caviness, 1994; Wrather et al., 2003). Therefore, when these early MGs planted early reach R1 and transition to seed development earlier in the year, conditions are more favorable for fungal growth and there will be greater potential for PSS. Conversely, as planting is delayed the time of reproductive stages are shifted to a later time in the year when the temperatures are cooler lowering the risk of PSS, as was observed in this study.

There was minimal impact of PD on the percent PSS for MGs 5-7 combined across locations (Figure 10). These MGs resulted in a relatively low level of PSS (0.3-6.4%) when planted at the early PDs (late April or prior) with a slight variation between environments as planting was delayed. This can be partially explained by the reproductive stages taking place later in the year when temperatures are lower. The genetic background of these cultivars is also a contributing factor. It should be noted that breeding of early MGs is typically conducted in the Midwest USA where the fungal pressure of *C. kikuchii* is much lower than that experienced in the Southeast USA resulting in cultivars that are potentially more susceptible to PSS bred in that region (Alloatti et al., 2015). A study of 128 soybean plant introductions reported a greater number of seeds infected with *C. kikuchii* in MGs 3 and 4 than MG 5 (Alloatti et al., 2015). The genetic background of the cultivars in this study may also be influencing the observed trend in PSS across MGs.

There was a rapid decrease in the amount of PSS as planting was delayed from late April to mid-May for MGs 3 and 4 and from mid-May to mid-June for MG 2 (Figure 10). These PD by MG combinations correspond to a shift in flowering from June to July. A by environment analysis revealed that the decline was largely influenced by the MGs 2-4 at Rowan-2020 (Figure 11A-C). These PD by MG combinations at this environment had a greater amount of PSS (27.5-42.8%) than the other environments. It is important to note that there was visually greater *Cercospora* pressure at this site. The increase in PSS may potentially be due to the longer duration of leaf wetness in August and September caused by the shorter time periods between rainfall and cooler temperatures experienced at Rowan-2020 than other environments (Figure 2 and 3) (Schuh, 1993). It has been reported that seed infected by *Cercospora kikuchii* has reduced germination (Turner et al., 2020; Wilcox, 1973). Consequently, there are important implications for the end use of seed with greater amounts of PSS as this can impact seed quality for planting. However, those seeds can typically be used for crushing without quality impact as their composition has not been compromised.

There was a positive correlation between PSS and damage at every environment except Hyde-2019 and Sampson-2019 (Table 4). As both are caused by fungus it would be reasonable to assume that as damage increased there should be an increase in PSS. Generally the amount of damage was slightly higher than the amount of PSS. There was variations in the amounts of damage and PSS by environment possibly due to the differences in fungal spread and weather.

The mean percent PSS ranges for each environment across all MGs and PDs were Currituck-2019 0.1-22.5%, Union-2019 0.1-22.5%, Hyde-2019 0-22.7%, Sampson-2019 0-12%, Yadkin-2019 0.1-19.2%, Rowan-2020 0-42.8%, and Beaufort-2020 0.4-18%.

CONCLUSIONS

Results from this study indicate that the interaction between PD and MG significantly impacted the protein content, oil content, seed damage, and PSS of soybeans grown in the Southeast USA. The later MGs (6-7) produced a higher percent protein than MGs ≤ 5 grown in the same environments and typically had minimal seed damage or PSS regardless of planting date. As planting was delayed, the protein content tended to decline in the earlier maturing varieties but was stable across planting dates in the later maturing varieties (MG 6-7). Oil content and protein content were typically inversely related and early MGs 2-4 tended to have a higher oil concentration than the later MGs 5-7. There was a greater amount of seed damage with planting dates before mid-April and with early MGs (≤ 4). Typically, damage was relatively low across all MGs when soybeans were planted mid-May or later. A by environment analysis showed the site specific issues with green stem observed at one location in 2019 with a MG 5 and at another location in 2020 with a MG 4 resulted in harvest delays and subsequently the highest levels of seed damage. Furthermore, PSS was the highest with MGs ≤ 4 planted before mid-May. The percentage of PSS in MGs 5-7 was low across all PDs illustrating the influence of both the genetic background of the cultivars and the environmental conditions encountered when entering physiological maturity. As growers in the Southeast USA consider shifting their production systems to the utilization of earlier maturing varieties (MG < 5) planted early (before mid-May), the impact on seed quality must be considered. However, currently producers are not getting paid for protein content, so even if protein content declines on average for earlier maturing varieties planting before mid-May, much interest remains due to the associated yield potential. Future management studies are necessary to understand how to minimize seed damage and PSS encountered with using these production scenarios across the Southeast USA.

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Table 1. Environment, latitude, soil type, tillage system, row spacing, planting equipment, and harvest equipment.

Environment	Latitude (°N)	Soil Type	Tillage System	Row Spacing (cm)	Planting Equipment	Harvest Equipment
Currituck-2019	36.4	Roanoke fine sandy loam	Conventional	38.1	Wintersteiger Plotseed XXL	Wintersteiger Quantum
Sampson-2019	35.2	Norfolk loamy sand	No-till	38.1	Wintersteiger Plotseed XXL	Wintersteiger Quantum
Union-2019	35.2	Badin channery silt loam	No-till	38.1	Wintersteiger Plotseed XXL	Wintersteiger Quantum
Yadkin-2019	36.2	Clifford sandy clay loam	No-till	38.1	Wintersteiger Plotseed XXL	Wintersteiger Quantum
Beaufort-2020	35.6	Cape Fear fine sandy loam	Conventional	38.1	Wintersteiger Dynamic Disc	Wintersteiger Quantum
Robeson-2020	34.7	Norfolk loamy sand	Conventional	38.1	Wintersteiger Dynamic Disc	Wintersteiger Quantum
Rowan-2020	35.7	Lloyd clay loam	No-till	38.1	Wintersteiger Dynamic Disc	Wintersteiger Quantum

Table 2. Year and maturity group.

Year	Maturity Group						
	2	3	4	5	6	7	8
2019	AG26X8	AG36X6	AG49X6	AG56X8	AG64X8	AG72X7	AG79X9
2020	AG26X8	AG36X6	AG47X9	AG56X8	AG64X8	AG72X7	AG79X9

†Abbreviations: AG: Asgrow

Table 3. Summarized ANOVA results for the effects of planting date (PD), maturity group (MG), environment (E), and the relevant interactions on damage, oil, protein, and purple seed stain (PSS) for combined analysis and by individual environment.

Dependent Variable	Source	Mean Square Combined	Combined	Currituck-2019	Hyde-2019	Sampson-2019	Union-2019	Yadkin-2019	Beaufort-2020	Rowan-2020
			P > F							
Damage	PD	1498.7	0.0007	0.0004	0.0969	0.0352	0.0019	0.5226	<.0001	0.3540
	MG	1664.9	0.006	0.0014	0.0002	<.0001	<.0001	0.0027	<.0001	0.0028
	E	1133.9	0.0658	-	-	-	-	-	-	-
	PDxMG	411.2	0.0053	<.0001	0.0018	<.0001	<.0001	0.1794	<.0001	0.0924
	PDxE	244.7	0.439	-	-	-	-	-	-	-
	MGxE	495.9	0.0004	-	-	-	-	-	-	-
	PDxMGxE	223.3	<.0001	-	-	-	-	-	-	-
Oil	PD	16.9	0.0007	0.0203	0.6787	0.0016	0.0196	0.0522	<.0001	<.0001
	MG	66.3	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
	E	11.7	0.0228	-	-	-	-	-	-	-
	PDxMG	1.7	<.0001	0.0001	0.7347	0.0004	<.0001	<.0001	0.0114	<.0001
	PDxE	2.9	<.0001	-	-	-	-	-	-	-
	MGxE	2.5	<.0001	-	-	-	-	-	-	-
	PDxMGxE	0.7	<.0001	-	-	-	-	-	-	-

Table 3. (continued)

Protein	PD	12.8	0.0063	0.0986	0.00029	0.0034	<.0001	0.0164	0.0031	0.0610
	MG	24.5	<.0001	<.0001	<.0001	<.0001	<.0001	0.0028	<.0001	<.0001
	E	98.0	<.0001	-	-	-	-	-	-	-
	PDxMG	2.0	0.0957	<.0001	0.0028	<.0001	<.0001	0.0008	0.2403	<.0001
	PDxE	3.3	0.0456	-	-	-	-	-	-	-
	MGxE	3.9	<.0001	-	-	-	-	-	-	-
	PDxMGxE	1.6	<.0001	-	-	-	-	-	-	-
PSS	PD	167.2	0.1238	0.0013	0.3251	0.0467	0.0114	0.0279	0.3913	0.0262
	MG	1269.4	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
	E	870.3	0.0007	-	-	-	-	-	-	-
	PDxMG	132.2	0.0001	<.0001	0.4764	<.0001	<.0001	<.0001	0.0074	<.0001
	PDxE	94.0	0.0941	-	-	-	-	-	-	-
	MGxE	128.2	0.0001	-	-	-	-	-	-	-
	PDxMGxE	54.1	<.0001	-	-	-	-	-	-	-

† Abbreviations: E, environment; MG, maturity group; PD, planting date; PSS, Purple seed stain

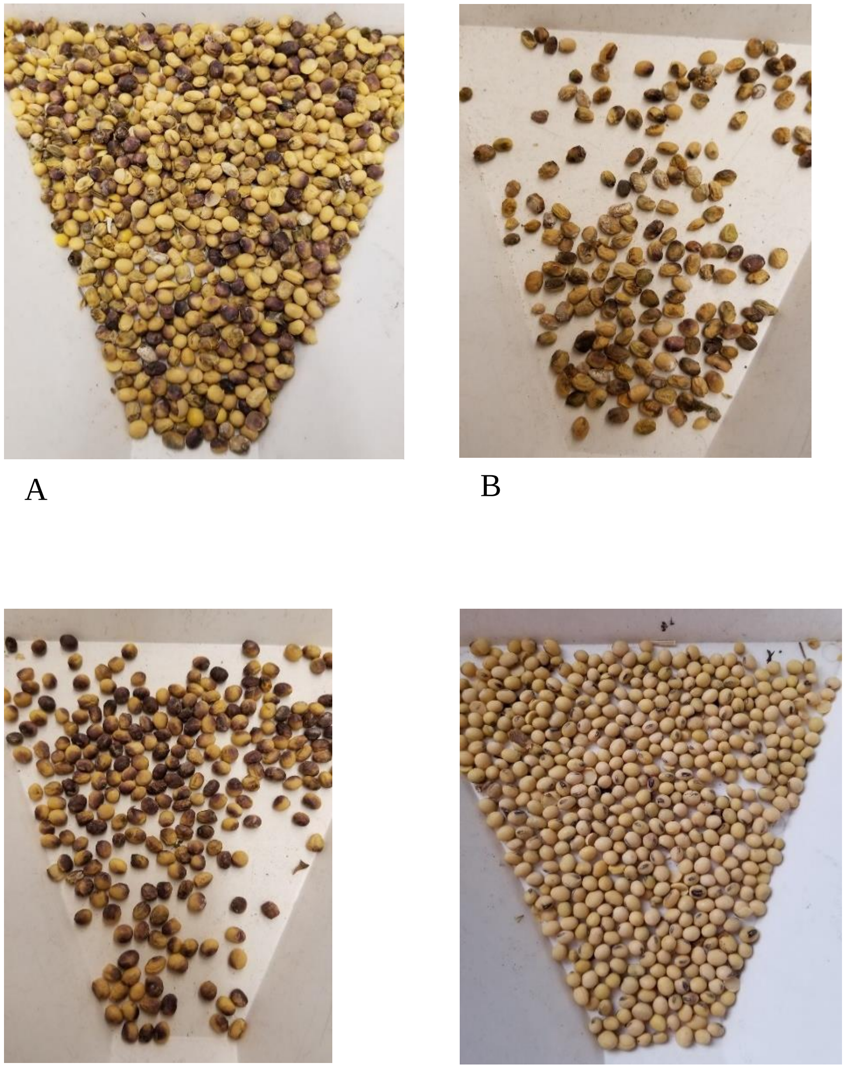
Table 4. Pearson correlations among data collection variables by individual environments.

Environment	Variable	P>F	Regression Coefficient
Combined	Protein vs Oil	<.0001	-0.6936
	Protein vs Damage	<.0001	0.34587
	Protein vs PSS	0.002	0.11383
	Oil vs Damage	0.3508	0.03449
	Oil vs PSS	<.0001	0.27759
	Damage vs PSS	<.0001	0.23701
Currituck-2019	Protein vs Oil	<.0001	-0.76994
	Protein vs Damage	0.0004	0.35743
	Protein vs PSS	0.3381	0.10044
	Oil vs Damage	0.3329	-0.10152
	Oil vs PSS	0.0018	0.31881
	Damage vs PSS	<.0001	0.58438
Hyde-2019	Protein vs Oil	<.0001	-0.63986
	Protein vs Damage	0.0006	0.47993
	Protein vs PSS	0.0357	0.30402
	Oil vs Damage	0.7965	0.03821
	Oil vs PSS	0.0662	0.26732
	Damage vs PSS	0.0571	0.26301
Sampson-2019	Protein vs Oil	<.0001	-0.66796
	Protein vs Damage	0.0001	0.32592
	Protein vs PSS	0.4572	0.06427
	Oil vs Damage	0.1333	-0.12940
	Oil vs PSS	0.0030	0.25246
	Damage vs PSS	0.8942	-0.01095
Union-2019	Protein vs Oil	<.0001	-0.76270
	Protein vs Damage	<.0001	0.38098
	Protein vs PSS	0.0292	0.19359
	Oil vs Damage	0.5010	0.06025
	Oil vs PSS	0.4108	0.07362
	Damage vs PSS	0.0008	0.27090
Yadkin-2019	Protein vs Oil	0.0630	-0.20254
	Protein vs Damage	0.011	0.27438
	Protein vs PSS	<.0001	0.46185
	Oil vs Damage	<.0001	0.44858
	Oil vs PSS	0.7236	0.03892
	Damage vs PSS	0.0001	0.37526

Table 4. (continued)

Beaufort-2020	Protein vs Oil	<.0001	-0.84306
	Protein vs Damage	0.8607	0.01454
	Protein vs PSS	<.0001	-0.34457
	Oil vs Damage	0.0016	0.25681
	Oil vs PSS	<.0001	0.45231
	Damage vs PSS	<.0001	0.34382
Rowan-2020	Protein vs Oil	<.0001	-0.73447
	Protein vs Damage	0.6425	0.04772
	Protein vs PSS	0.0097	-0.26149
	Oil vs Damage	0.5783	0.05714
	Oil vs PSS	<.0001	0.66271
	Damage vs PSS	0.0003	0.35211

† Abbreviations: PSS, Purple seed stain



A B C D

Figure 1. Damage quantification process using USDA grading standards. A- Whole sample B- Damaged seed C- Purple seed stain D- Sample after the damaged seed and purple seed stain have been removed.

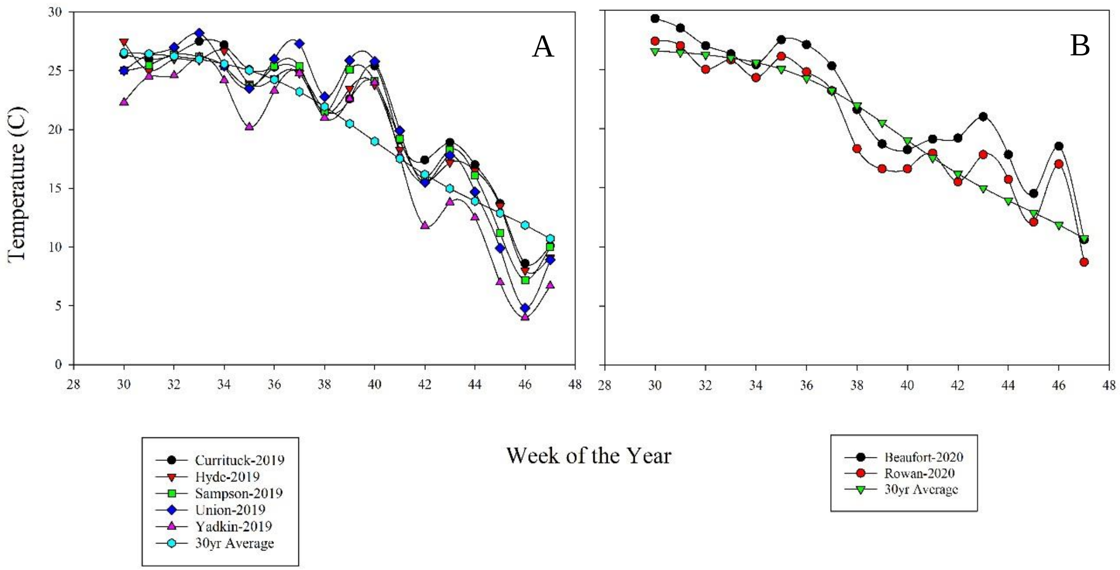


Figure 2. Weekly average temperature for the environments in 2019 and 2020 compared to the 30 year average. A-2019 B-2020.

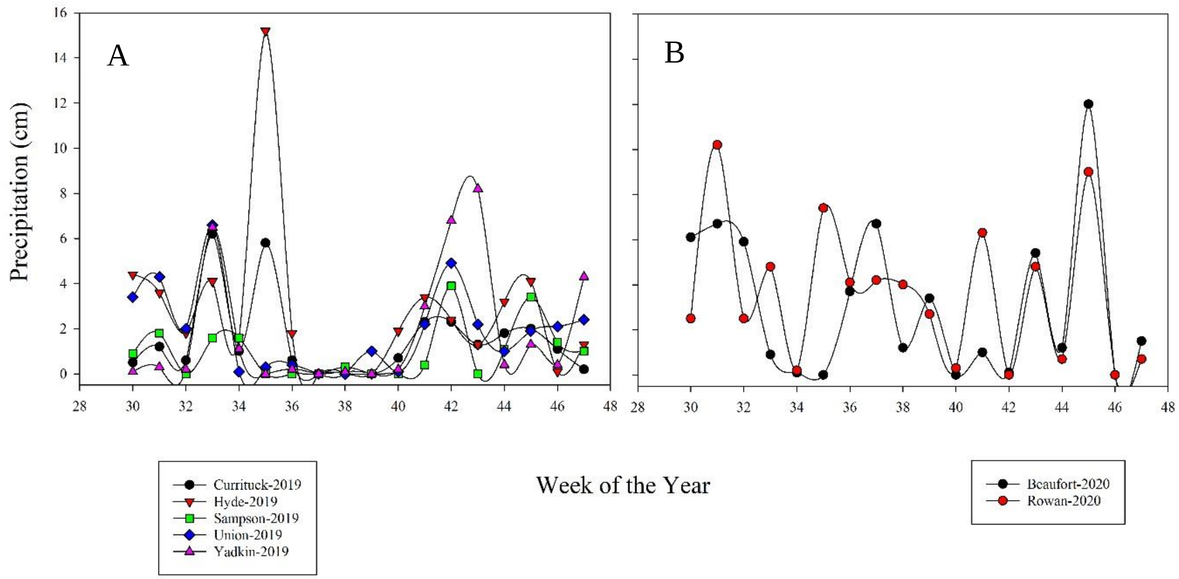


Figure 3. Weekly rainfall totals for environments in 2019 and 2020. A-2019 B-2020.

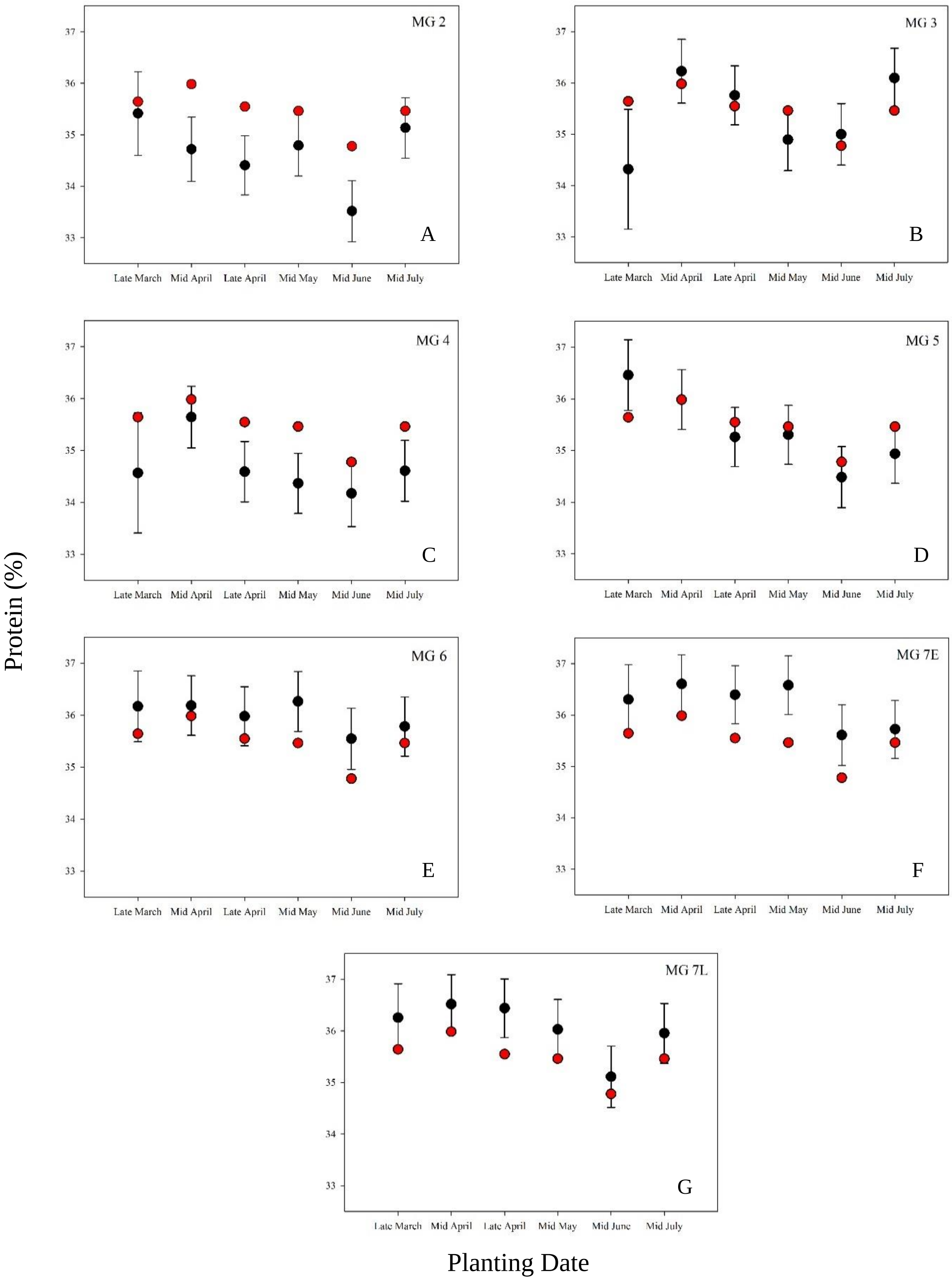


Figure 4. Effect of planting date and maturity group (MG) on the percent protein of soybean seed. Mean percent protein values across seven environments with standard error bars. Red points are the average percent protein across all maturity groups.

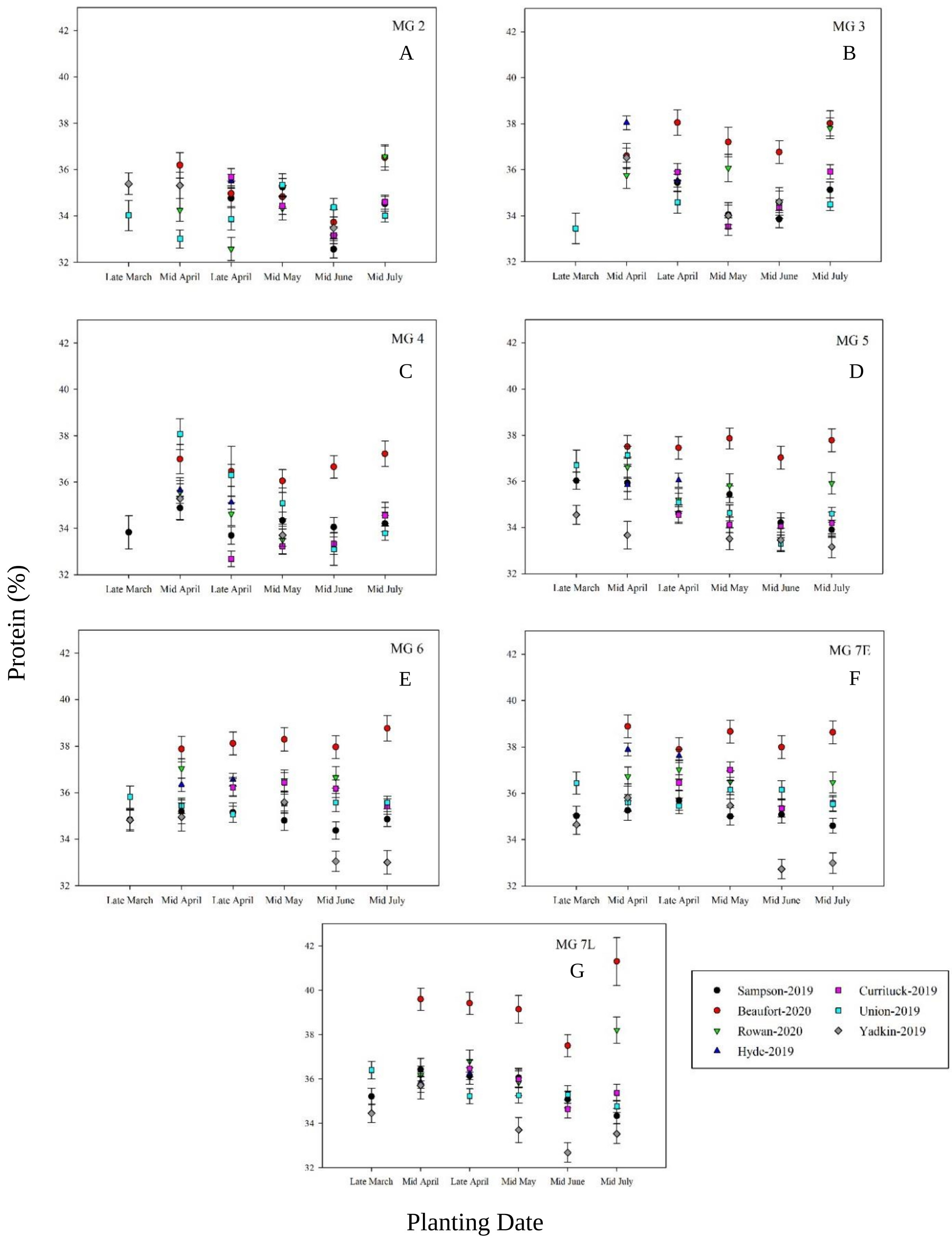


Figure 5. Effect of planting date and maturity group on percent protein of soybean seed. Mean percent of protein values by environment with standard error bars.

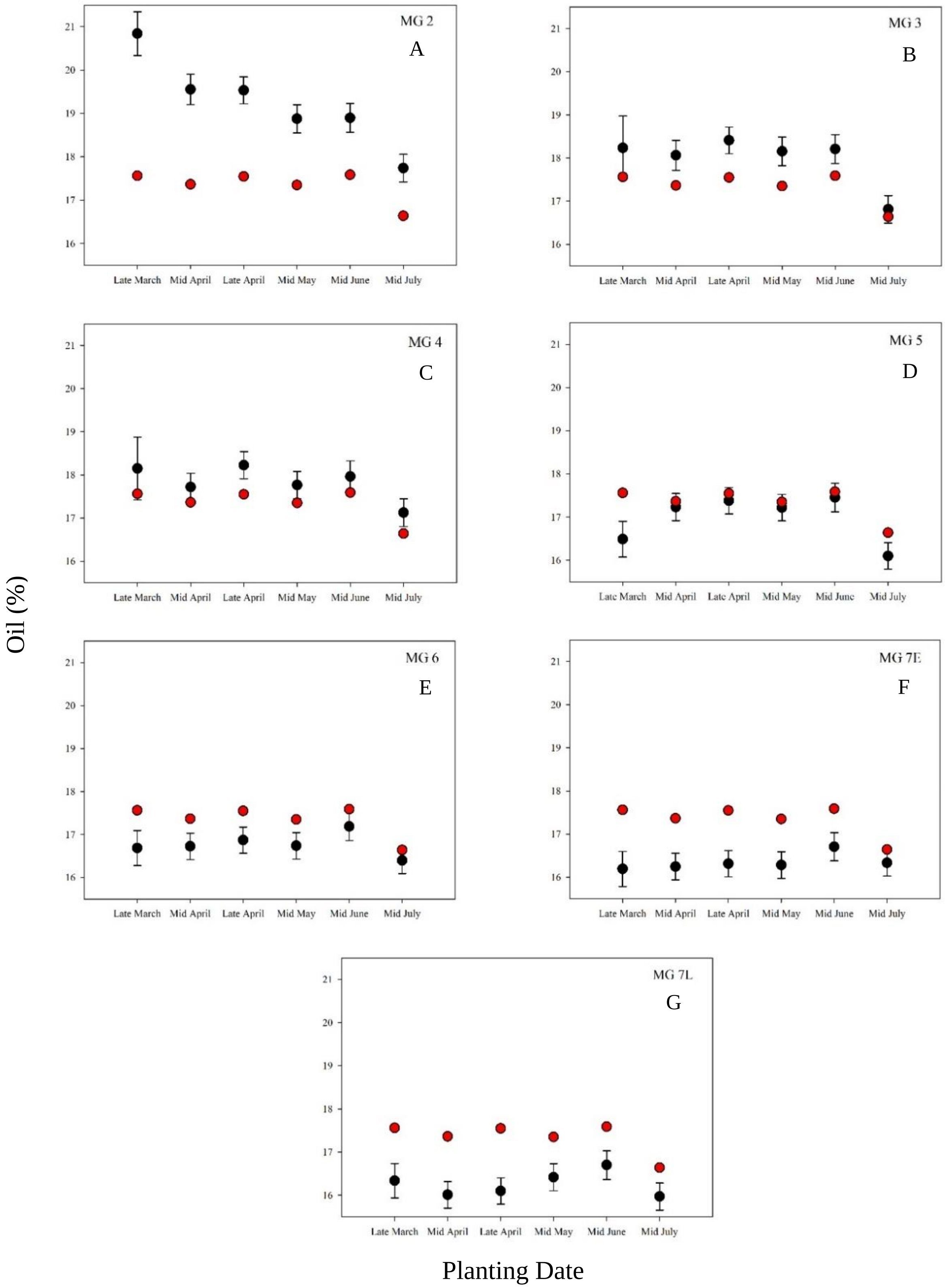


Figure 6. Effect of planting date and maturity group (MG) on percent oil of soybean seed. Mean percent oil values across seven environments with standard error bars. Red points are the average percent oil across all maturity groups.

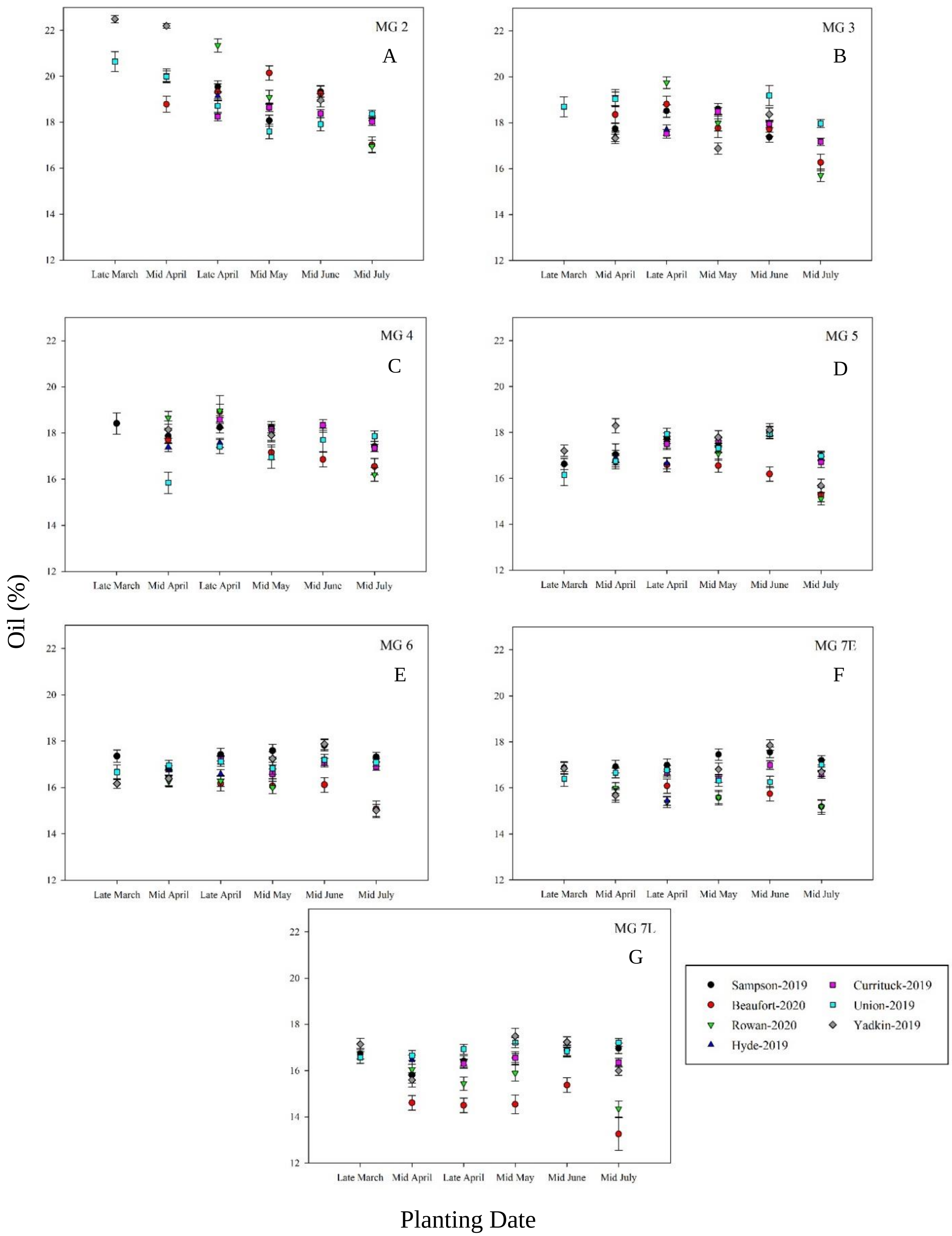


Figure 7. Effect of planting date and maturity group on percent oil of soybean seed. Mean Percent of oil values by environment with standard error bars.

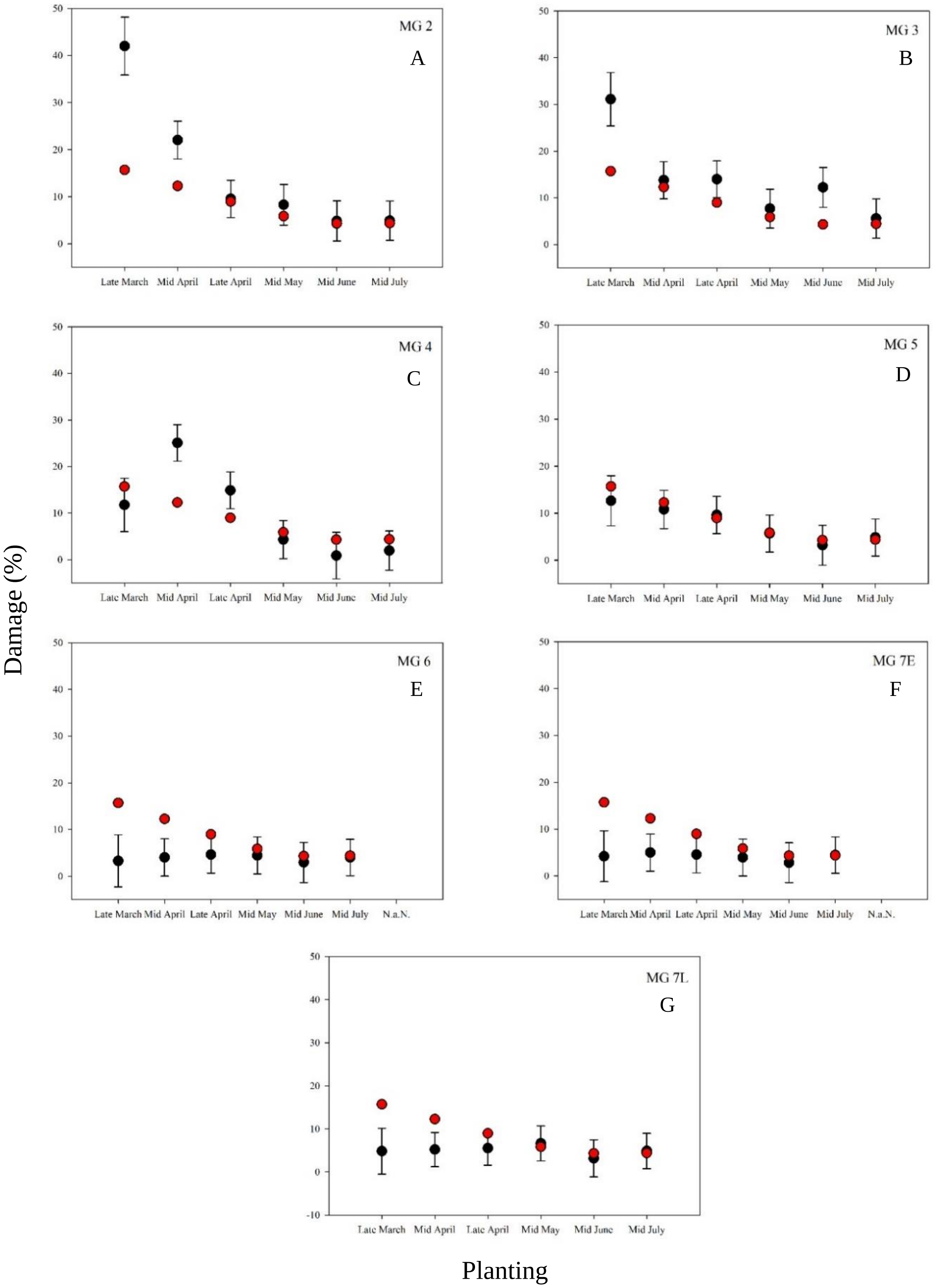


Figure 8. Effect of planting date and maturity group (MG) on percent damage of soybean seed. Mean percent damage values across seven environments with standard error bars. Red points are the average percent damage across all maturity groups.

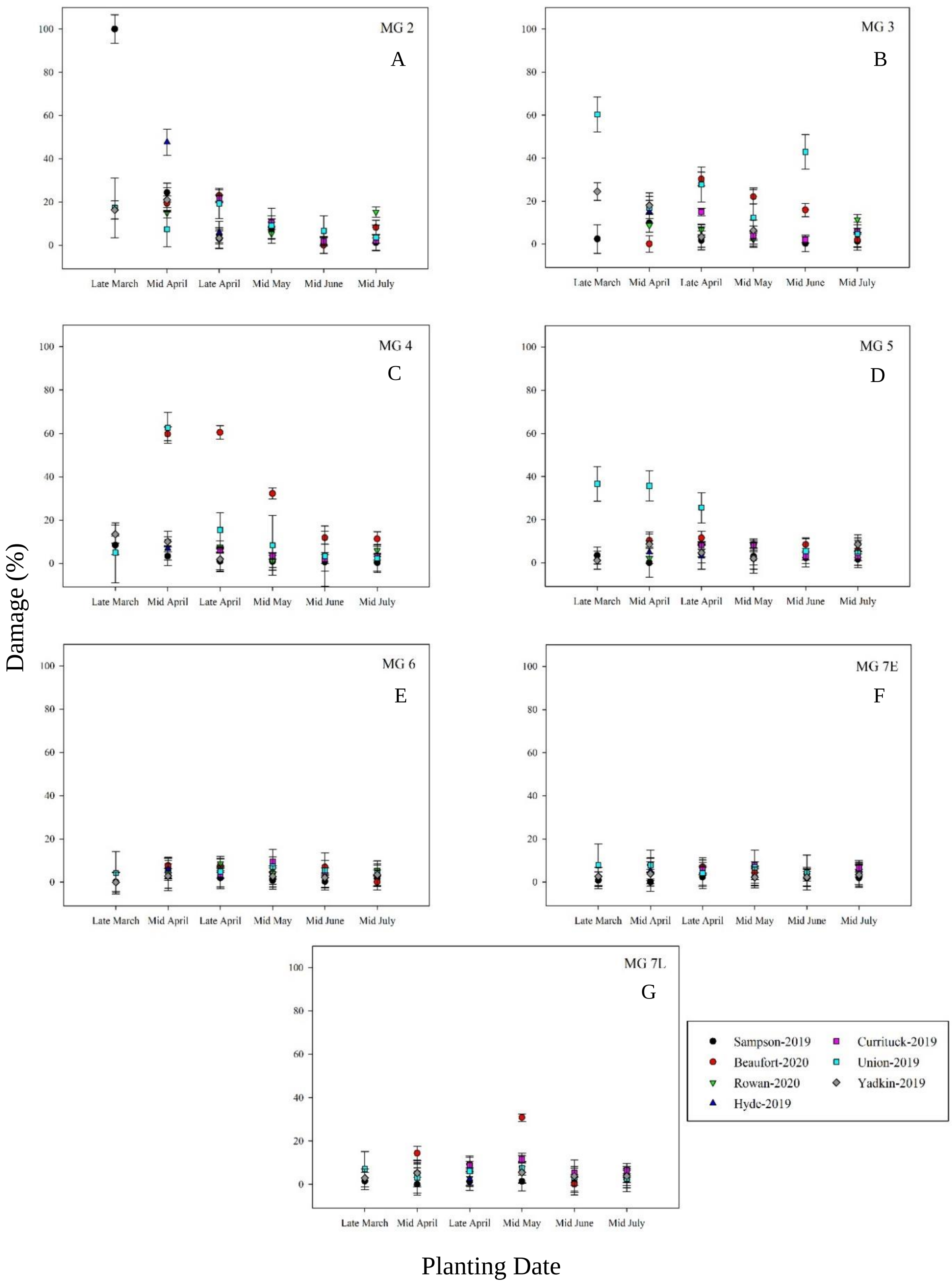


Figure 9. Effect of planting date and maturity group on percent damage of soybean seed. Mean percent of damage values by environment with standard error bars.

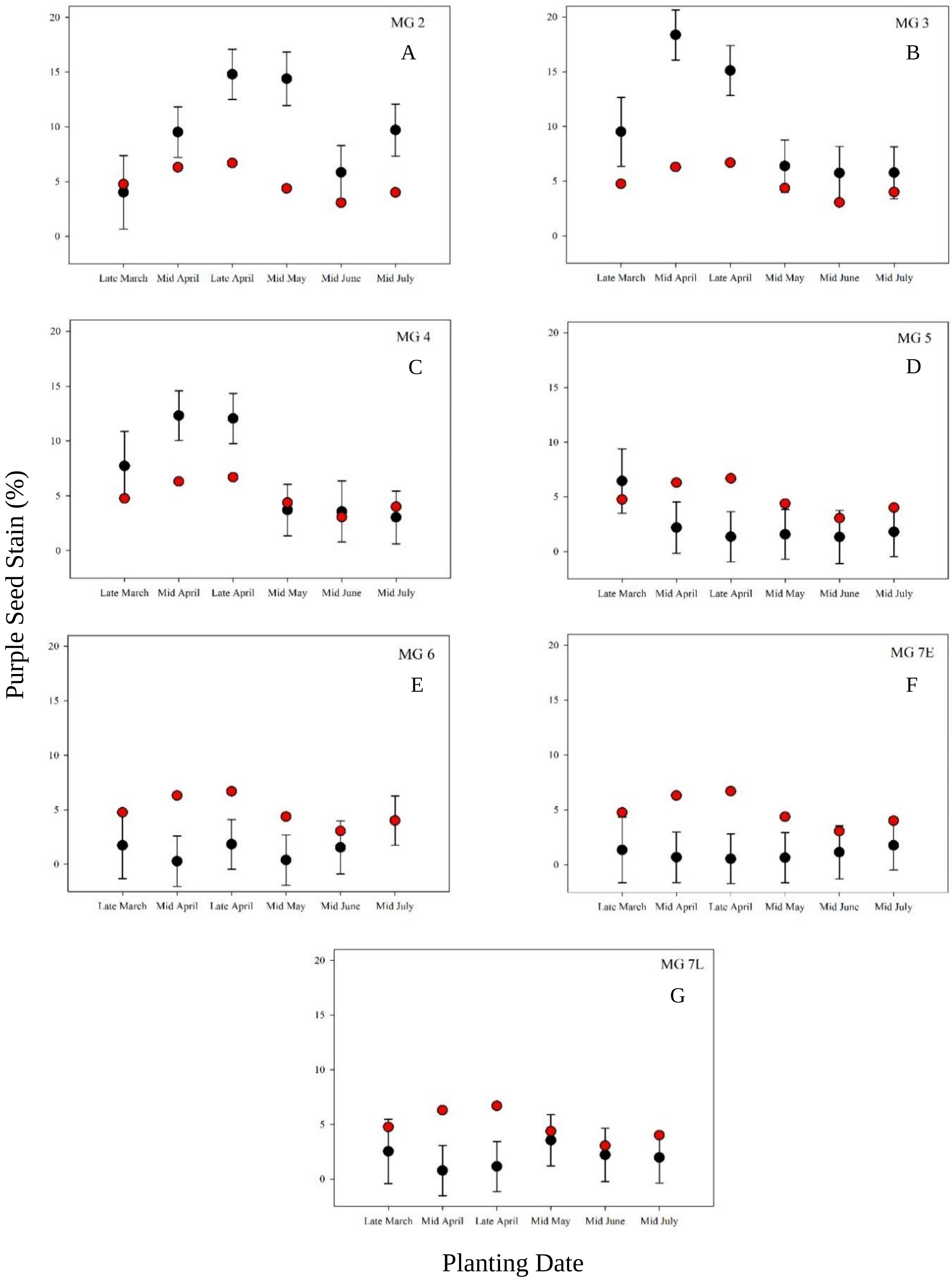


Figure 10. Effect of planting date and maturity group (MG) on percent purple seed stain of soybean seed. Mean percent of purple seed stain values across seven environments with standard error bars. Red points are the average purple seed stain across all maturity groups.

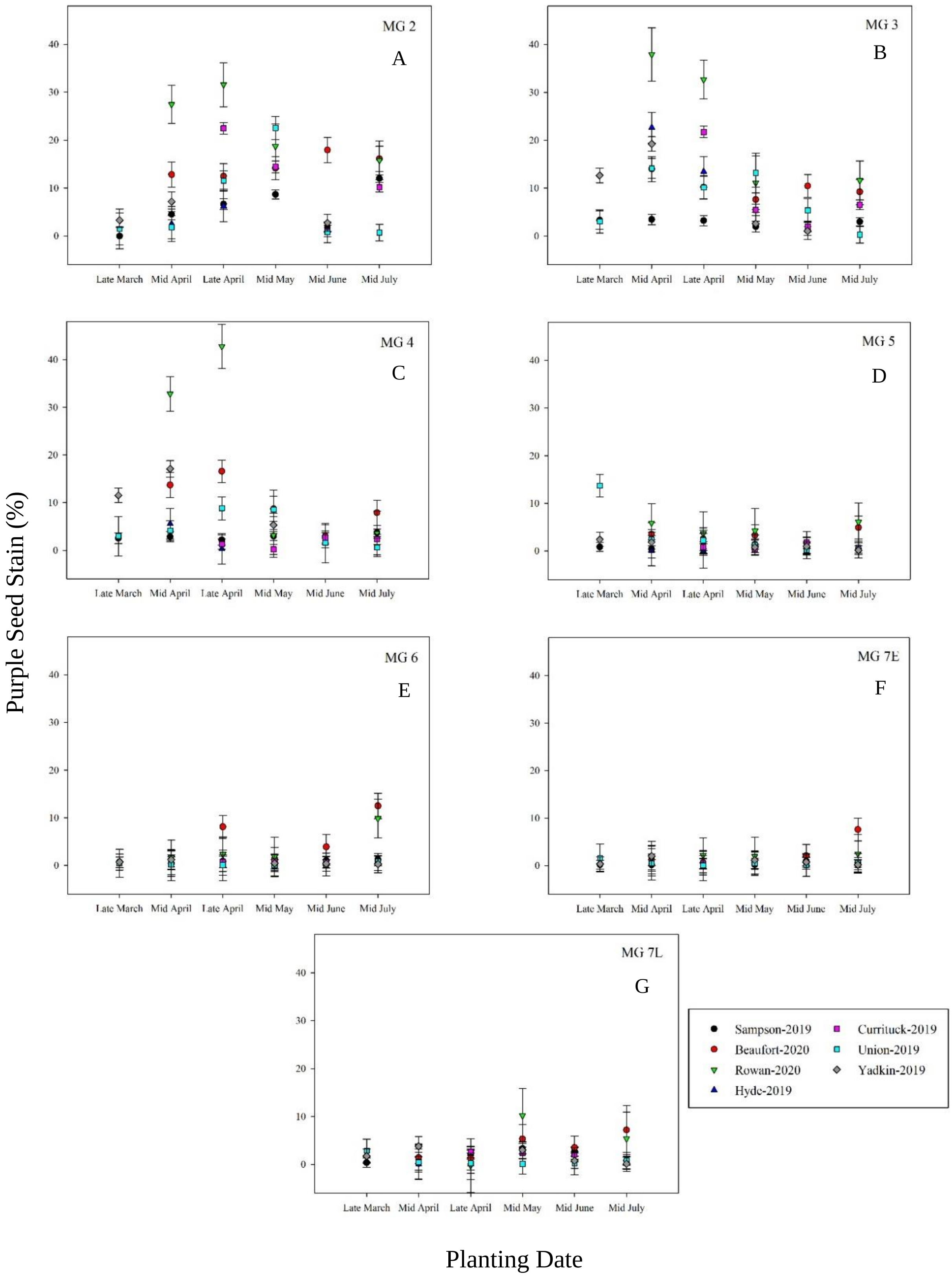


Figure 11. Effect of planting date and maturity group on percent purple seed stain of soybean seed. Mean percent of purple seed stain values by environment with standard error bars.