IDENTIFYING OPTIMAL MANAGEMENT DECISIONS BASED ON SOYBEAN PLANTING DATE: SEEDING RATE, SEED TREATMENT, AND MATURITY GROUP SELECTION

By

Thomas Bernard Siler

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

Crop and Soil Sciences - Master of Science

2020

ABSTRACT

IDENTIFYING OPTIMAL MANAGEMENT DECISIONS BASED ON SOYBEAN PLANTING DATE: SEEDING RATE, SEED TREATMENT, AND MATURITY GROUP SELECTION

By

Thomas Bernard Siler

The practice of early-season soybean [Glycine Max (L.) Merr.] planting has been increasing in the northern US. However, a wide range of planting dates (PDs) are still implemented due to poor soil conditions, inclement weather, equipment restrictions, crop rotation, and operation size. Information regarding how soybean management decisions should be adjusted based on PD is lacking in Michigan and other northern US regions. This research was conducted to identify how optimal soybean seeding rate (SR), seed treatment (ST) use, and variety maturity group (MG) selection is determined by PD. Field experiments were conducted at two locations in Michigan during the 2018 and 2019 growing season. In the first experiment, soybean was planted at five SRs, between 123,553 and 518,921 seeds ha^{-1}, with or without a ST, on four PDs (late-April to late-June). In the second experiment, six soybean MGs, between 1.0 and 3.5, were planted on four PDs (late-April to late-June). The use of a ST did not improve yield or net returns in this study. When soybean was planted before mid-May, seed yield and net returns were maximized by planting a late MG (≥3.0) at a SR between 187,660 and 201,451 seeds ha^{-1}. The optimal SR between the mid-May and early-June PDs was between 220,301 and 265,305 seeds ha^{-1} and MG selection had less influence on seed yield compared to earlier PDs. When planting was delayed to late-June, using an early MG (≤ 2.5) resulted in the optimal yield and the optimal SR was >330,000. Results from this study show that soybean yield, quality, and net returns can be improved by adjusting management practices based on PD.

ACKNOWLEDGMENTS

I would first like to thank my advisor, Dr. Maninder Singh for his instruction and guidance during my writing and research. Being a part of the cropping systems agronomy program allowed me to build upon my knowledge in agronomy and develop skills that I can continue to build upon and apply to my future career. I would also like to thank my committee members Dr. Chris DiFonzo and Dr. Dechun Wang for their advice and instruction on my project. Thank you to the Michigan Soybean Promotion Committee for funding and supporting this research.

I would like to thank the programs research technicians Bill Widdicombe and Lori Williams for their guidance and assistance with the field work and technical portions of my project. I am grateful to have had the chance to work with you and I learned a lot from you during my time here. I would also like to thank Mike Particka and John Calogero at the MSU Agronomy Farm and Paul Horny and Dennis Fleischmann at the MSU Saginaw Valley Research and Extension Center for their assistance with field tasks and managment. I thank Joe Paling, Evan Williams, and Andy Chomas for their guidance and suggestions and Randy Laurenz, Rob Stoutenburg, and John Boyse for sharing their technical knowledge about soybean research with me and for assisting with field operations. I am also grateful for the friendship and support of my fellow graduate students; Katlin Fusilier, Kalvin Canfield, and Harkirat Kaur.

Finally, I would like to thank my friends and family for supporting and encouraging me during my time as a graduate student. I am grateful for everything they have done for me. Without them, I would not be where I am today.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

KEY TO ABBREVIATIONS

AOPP	Agronomic optimum plant population
AOSR	Agronomic optimum seeding rate
DOY	Day of year
EOPP	Economic optimum plant population
EOSR	Economic optimum seeding rate
GDD_c	Cumulative growing degree day
LAI	Leaf area index
MG	Maturity group
PAR	Photosynthetically active radiation
PD	Planting date
SR	Seeding rate
ST	Seed treatment

CHAPTER 1

LITERATURE REVIEW

Soybean Planting Date

The effect of planting date on soybean [*Glycine max* (L.) Merr.] yield, composition, and quality has been documented since the early twentieth century (Mooers, 1908). Since then, a number of experiments have been conducted to identify optimal planting dates for US soybean growing regions. The general consensus for these experiments is that delayed planting consistently results in reduced yields while planting earlier than currently practiced has potential for increased soybean yield (Egli & Cornelius, 2009; Hu & Wiatrak, 2012; Mourtzinis, Specht, & Conley, 2019; Rowntree et al., 2013; Zhang, Gao, Herbert, Li, & Hashemi, 2010).

The date that a soybean crop is planted can influence the temperature and water availability during critical developmental stages (Mourtzinis et al., 2015), soil water storage (Popp et al., 2002), and light interception (Board & Harville, 1993), thus, impacting crop development and yield. The impact of planting date is such that it is often the management practice that accounts for a majority of yield variation in many studies (Edreira et al., 2017; Grassini, Torrion, Cassman, Yang, & Specht, 2014; Grassini et al., 2015). In Michigan, soybean producers have responded to this information by planting soybeans about two weeks earlier this decade compared to the 1980s (USDA-NASS, 2019).

The growing conditions during critical soybean developmental stages can influence seed yield. Robinson, Conley, Volenec, & Santini, 2009 found early-season planting resulted in an earlier onset of reproductive growth and overall longer growing period. The longer days and higher light intensity that is present early in the growing season results in increased solar radiation capture and can improve yield (Cooper, 2003). Robinson et al. (2009) also reported that delayed planting resulted in lower yield from reduced intervals between vegetative and reproductive stages, as well as an overall reduction in growing period. This is consistent with the results presented by Bastidas et al. (2008) who found for every day that planting is delayed, the number of days from planting to maturity declined by 0.9 days and 0.5 days in 2003 and 2004, respectively.

The impact that planting date has on soybean composition has been studied extensively but the results of these studies remains inconsistent. Mourtzinis, Gaspar, Naeve, & Conley (2017) found that early planting resulted in increased oil, oleic acid, and sugar, but lower protein and linolenic acid. Robinson et al. (2009) found that oil content decreased with delayed planting while protein content generally increased, but protein content decreased between planting day of year (DOY) 86 and 100. Some studies found protein content either remained consistent across planting dates or decreased with delayed planting (Bajaj et al., 2008; Tremblay, Beausoleil, Filion, & Saulnier, 2006). Bastidas et al. (2008) reported inconsistencies between years with protein content decreasing as planting was delayed in 2003 but increasing in 2004 and oil content decreasing as planting was delayed in 2004 for all planting dates but increasing between the first and second planting date in 2003. Inconsistencies among studies, most likely caused by different environmental factors between studies, makes it difficult to reach a general conclusion on how planting date impacts soybean composition.

Soybean Seeding Rate

Agronomists are constantly seeking to identify management practices that improve soybean production through increasing yield while reducing input costs. Soybean seed accounts for the highest single operating cost for U.S. soybean producers (USDA-ERS, 2019) and soybean seeding rate influences seed yield (Lee, Egli, & TeKrony, 2008; Suhre et al., 2014). These factors make identifying optimal seeding rates of interest for many soybean agronomists.

Soybean seeding rate has a strong influence on plant development. Purcell, Ball, Reaper, & Vories (2002) found that that soybean population density (plants m^{-2}) had a significant impact on light interception, with higher population densities maximizing light interception earlier in the season than lower population densities, resulting in a greater amount of photosynthetically active radiation intercepted. However, for every additional plant m^{-2} they found that radiation use efficiency was decreased by 0.003 to 0.007 g MJ^{-1} depending on year and planting date. Suhre et al. (2014) reported that low seeding rates resulted in an increased number of pods and seeds $plant^{-1}$ which can be attributed to the increased number of pods $node^{-1}$ on the main stem and seeds pod^{-1} on both the main stem and branches. Lower seeding rates also impact soybean branching patterns. A seeding rate of 70,000, 164,000, and 234,000 plants ha^{-1} resulted in a branch dry matter of 14.0, 5.3, and 3.6 g $plant^{-1}$ respectively (Carpenter & Board, 1997). This increase in branch dry matter also resulted in increased branch yield on a per plant basis. Similarly, Norsworthy & Frederick (2002) reported increased branch yield from plants in lower seeding rates, but less yield from the main stem.

Results have varied in experiments to identify optimal seeding rates. In Iowa, De Bruin & Pedersen (2008a) found that a final plant population of 462,200 plants ha^{-1} resulted in the maximum yield but noted that a final plant population of 258,600 plants ha^{-1} resulted in 95% of the maximum yield. Suhre et al. (2014) tested two seeding rates across 116 varieties in Wisconsin, Minnesota, Illinois, and Indiana. They found that a final plant population of 311,000 plants ha^{-1} resulted in higher yield compared to a final plant population of 94,000 plants ha^{-1} across all locations and varieties. In Kentucky, Lee et al. (2008) reported that maximum yield was obtained with a final plant population between 338,000 and 473,000 plants ha^{-1}, however, a range of 108,000 to 282,000 plants ha^{-1} resulted in 95% of the maximum yield depending on year, variety, and planting date. Other studies, testing two to three rates, found that seeding rates have little to no impact on soybean yield (Board, 2000; Norsworthy & Frederick, 2002).

Soybean Seed Treatment

Soybean seed treatment is a general term used to describe a coating that is applied to soybean seed before planting. These coatings can be physical, chemical, or biological and can provide a wide range of benefits. Common seed treatments include insecticides, fungicides, and/or nematicides and are used to reduce or prevent pest damage. These seed treatments are often used to improve crop emergence and yield. As of 2013, it is estimated that 75% of soybean hectares were planted with treated seed (Munkvold, Watrin, Scheller, Zeun, & Olaya, 2014)

There have been numerous experiments quantifying the effect of soybean seed treatments. These experiments have attempted to determine the yield and economic benefits of a soybean seed treatment over different environments and management systems. Mourtzinis, Krupke, et al., 2019 examined yield data from 194 soybean experiments in four soybean growing environments and reported that using a fungicide and insecticide seed treatment improved yields across all regions. They did note however that the increase in yield was small compared to using a fungicide seed treatment alone (40 kg ha^{-1}) or no seed treatment (60 kg ha^{-1}). Cox, Shields, & Cherney (2008) tested two different fungicide and insecticide seed treatments and found that while seeds pod^{-1}, seeds m^{-2}, and seed mass were sometimes impacted from the use of a seed treatment, there was no yield improvement compared to using no seed treatment. Cox et al. (2008) also found that the use of a seed treatment did not improve plant stands where Gaspar, Marburger, Mourtzinis, & Conley (2014) and (2018) both reported that the use of a seed treatment improve plant stands under most growing conditions tested.

Soybean Maturity Group

Soybean is classified as a short day plant which is sensitive to photoperiod (day length) and temperature (Alliprandini et al., 2009; Major, Johnson, Tanner, & Anderson, 1975). There are eight loci, each with two alleles, which control time to flowering and maturity (Cober & Morrison, 2010). Soybean development is controlled by the response of these loci to photoperiod (Cober, Tanner, & Voldeng, 1996).

Soybean varieties are classified into thirteen different maturity groups ranging from an early maturing 000 to a late maturing 10 based on how they respond to photoperiod and temperature under conventional planting practices for a region (Heatherly & Elmore, 2004). Maturity group zones were established in the U.S. to designate the group that is best adapted for a specific area, without implying other maturity groups cannot be grown in that area. Scott & Aldrich (1970) used empirical data to determine maturity group zones and found the maturity groups best adapted for US production range from 00 in the northern US to 8 in the southern US. Recent work using yield data from university variety trials recorded a similar trend in maturity group zones but found the maturity groups best adapted for US production ranged from 0 in the north to 6 in the south (Mourtzinis & Conley, 2017; L. Zhang et al., 2007). Both experiments commented on the adoption of earlier planting dates using early-maturing varieties as a possible reason for the shift in maturity group zones.

LITERATURE CITED

LITERATURE CITED

Alliprandini, L. F., Abatti, C., Bertagnolli, P. F., Cavassim, J. E., Gabe, H. L., Kurek, A., . . . Prado, L. C. (2009). Understanding soybean maturity groups in Brazil: Environment, cultivar classification, and stability. *Crop Science, 49*(3), 801-808.

Bajaj, S., Chen, P., Longer, D., Hou, A., Shi, A., Ishibashi, T., . . . Brye, K. (2008). Planting date and irrigation effects on seed quality of early-maturing soybean in the Mid-South USA. *Journal of New Seeds, 9*(3), 212-233.

Bastidas, A., Setiyono, T., Dobermann, A., Cassman, K. G., Elmore, R. W., Graef, G. L., & Specht, J. E. (2008). Soybean sowing date: The vegetative, reproductive, and agronomic impacts. *Crop Science, 48*(2), 727-740.

Board, J. (2000). Light interception efficiency and light quality affect yield compensation of soybean at low plant populations. *Crop Science, 40*(5), 1285-1294.

Board, J., & Harville, B. (1993). Soybean yield component responses to a light interception gradient during the reproductive period. *Crop Science, 33*(4), 772-777.

Carpenter, A., & Board, J. (1997). Branch yield components controlling soybean yield stability across plant populations. *Crop Science, 37*(3), 885-891.

Cober, E., Tanner, J., & Voldeng, H. (1996). Soybean photoperiod-sensitivity loci respond differentially to light quality. *Crop Science, 36*(3), 606-610.

Cober, E. R., & Morrison, M. J. (2010). Regulation of seed yield and agronomic characters by photoperiod sensitivity and growth habit genes in soybean. *Theoretical and Applied Genetics, 120*(5), 1005-1012.

Cooper, R. L. (2003). A delayed flowering barrier to higher soybean yields. *Field Crops Research, 82*(1), 27-35.

Cox, W. J., Shields, E., & Cherney, J. H. (2008). Planting date and seed treatment effects on soybean in the northeastern United States. *Agronomy Journal, 100*(6), 1662-1665.

De Bruin, J. L., & Pedersen, P. (2008). Effect of row spacing and seeding rate on soybean yield. *Agronomy Journal, 100*(3), 704-710.

Edreira, J. I. R., Mourtzinis, S., Conley, S. P., Roth, A. C., Ciampitti, I. A., Licht, M. A., . . . Mueller, D. S. (2017). Assessing causes of yield gaps in agricultural areas with diversity in climate and soils. *Agricultural and Forest Meteorology, 247*, 170-180.

Egli, D., & Cornelius, P. (2009). A regional analysis of the response of soybean yield to planting date. *Agronomy Journal, 101*(2), 330-335.

Gaspar, A. P., Marburger, D. A., Mourtzinis, S., & Conley, S. P. (2014). Soybean seed yield response to multiple seed treatment components across diverse environments. *Agronomy Journal, 106*(6), 1955-1962.

Grassini, P., Torrion, J. A., Cassman, K. G., Yang, H. S., & Specht, J. E. (2014). Drivers of spatial and temporal variation in soybean yield and irrigation requirements in the western US Corn Belt. *Field Crops Research, 163*, 32-46.

Grassini, P., Torrion, J. A., Yang, H. S., Rees, J., Andersen, D., Cassman, K. G., & Specht, J. E. (2015). Soybean yield gaps and water productivity in the western US Corn Belt. *Field Crops Research, 179*, 150-163.

Heatherly, L. G., & Elmore, R. W. (2004). Managing Inputs for Peak Production. In H. R. Boerma & J. E. Specht (Eds.), *Soybeans: Improvement, Production, and Uses* (pp. 451-536). Madison, WI: American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America.

Hu, M., & Wiatrak, P. (2012). Effect of planting date on soybean growth, yield, and grain quality: Review. *Agronomy Journal, 104*(3), 785-790. doi:10.2134/agronj2011.0382

Lee, C. D., Egli, D. B., & TeKrony, D. M. (2008). Soybean response to plant population at early and late planting dates in the Mid-South. *Agronomy Journal, 100*(4), 971-976.

Major, D., Johnson, D., Tanner, J., & Anderson, I. (1975). Effects of daylength and temperature on soybean development 1. *Crop Science, 15*(2), 174-179.

Mooers, C. A. (1908). Varieties of Soy Beans. University of Tennessee Agricultural Experiment Station and Mooers, Charles A. *Bulletins*. http://trace.tennessee.edu/utk_agbulletin/48

Mourtzinis, S., & Conley, S. P. (2017). Delineating soybean maturity groups across the United States. *Agronomy Journal, 109*(4), 1397-1403.

Mourtzinis, S., Gaspar, A. P., Naeve, S. L., & Conley, S. P. (2017). Planting date, maturity, and temperature effects on soybean seed yield and composition. *Agronomy Journal, 109*(5), 2040-2049.

Mourtzinis, S., Krupke, C. H., Esker, P. D., Varenhorst, A., Arneson, N. J., Bradley, C. A., . . . Herbert, A. (2019). Neonicotinoid seed treatments of soybean provide negligible benefits to US farmers. *Scientific Reports, 9*(1), 1-7.

Mourtzinis, S., Specht, J. E., & Conley, S. P. (2019). Defining Optimal Soybean Sowing Dates across the US. *Scientific Reports, 9*(1), 1-7.

Mourtzinis, S., Specht, J. E., Lindsey, L. E., Wiebold, W. J., Ross, J., Nafziger, E. D., . . . Arriaga, F. J. (2015). Climate-induced reduction in US-wide soybean yields underpinned by region-and in-season-specific responses. *Nature Plants*, *1*(2), 1-4.

Munkvold, G. P., Watrin, C., Scheller, M., Zeun, R., & Olaya, G. (2014). Benefits of chemical seed treatments on crop yield and quality. In *Global perspectives on the health of seeds and plant propagation material* (pp. 89-103): Springer.

Norsworthy, J. K., & Frederick, J. R. (2002). Reduced seeding rate for glyphosate-resistant, drilled soybean on the southeastern Coastal Plain. *Agronomy Journal, 94*(6), 1282-1288.

Popp, M. P., Keisling, T. C., McNew, R. W., Oliver, L. R., Dillon, C. R., & Wallace, D. M. (2002). Planting date, cultivar, and tillage system effects on dryland soybean production. *Agronomy Journal, 94*(1), 81-88.

Purcell, L. C., Ball, R. A., Reaper, J. D., & Vories, E. D. (2002). Radiation use efficiency and biomass production in soybean at different plant population densities. *Crop Science*, *42*(1), 172-177. doi:10.2135/cropsci2002.1720

Robinson, A. P., Conley, S. P., Volenec, J. J., & Santini, J. B. (2009). Analysis of high yielding, early-planted soybean in Indiana. *Agronomy Journal, 101*(1), 131-139.

Rossman, D. R., Byrne, A. M., & Chilvers, M. I. (2018). Profitability and efficacy of soybean seed treatment in Michigan. *Crop Protection, 114*, 44-52.

Rowntree, S. C., Suhre, J. J., Weidenbenner, N. H., Wilson, E. W., Davis, V. M., Naeve, S. L., . . Specht, J. E. (2013). Genetic gain× management interactions in soybean: I. Planting date. *Crop Science*, *53*(3), 1128-1138.

Scott, W. O., & Aldrich, S. R. (1970). Modern soybean production. *Modern soybean production.*

Suhre, J. J., Weidenbenner, N. H., Rowntree, S. C., Wilson, E. W., Naeve, S. L., Conley, S. P., . . Specht, J. E. (2014). Soybean yield partitioning changes revealed by genetic gain and seeding rate interactions. *Agronomy Journal, 106*(5), 1631-1642.

Tremblay, G., Beausoleil, J., Filion, P., & Saulnier, M. (2006). Effet de la date de semis sur trois cultivars de soya. *Canadian Journal of Plant Science, 86*(4), 1071-1078.

USDA-ERS. (2019). Soybean production costs and returns per planted acre, excluding Government payments. USDA Economic Research Service. https://www.ers.usda.gov/data-products/commodity-costs-and-returns/commodity-costs-and-returns/#Historical%20Costs%20and%20Returns:%20Soybeans

USDA-NASS. (2019) Soybean, progress, measured in pct planted. USDA National Agriculture Statistics Service. https://quickstats.nass.usda.gov/results/907B0FFD-87B3-3859-BF6A-3429BA70BD43

Zhang, L., Kyei-Boahen, S., Zhang, J., Zhang, M., Freeland, T., Watson, C., & Liu, X. (2007). Modifications of optimum adaptation zones for soybean maturity groups in the USA. *Crop Management, 6*(1), 0-0.

Zhang, Q., Gao, Q., Herbert, S., Li, Y., & Hashemi, A. (2010). Influence of sowing date on phenological stages, seed growth and marketable yield of four vegetable soybean cultivars in North-eastern USA. *African Journal Agricultural Research*, *5*(18), 2556-2562.

CHAPTER 2

IDENTIFYING SOYBEAN SEEDING RATE AND SEED TREATMENT DECISIONS THAT MAXAMIZE YIELD AND PROFITABILITY BASED ON PLANTING DATE

Abstract

The earlier onset of spring and an increase in supporting research has resulted in more early-season planting being conducted by Michigan and other northern US soybean [*Glycine max* (L.) Merr.] growers. However, multiple factors (soil conditions, weather, equipment, etc.) can result in delayed soybean planting and therefore, a wide range of soybean planting dates (PDs) are utilized. There is limited research in Michigan recommending how management practices should be adjusted based on soybean PD. Field experiments were conducted at two locations in Michigan during the 2018 and 2019 growing seasons to determine how seeding rate (SR) and seed treatment (ST) usage impact soybean yield and net returns based on PD. Soybean was planted at five SRs with or without a complete ST (insecticide, fungicide, and nematicide). The use of the ST improved plant stands by 5% at Mason, but did not improve yield regardless of PD at either location. The increased cost associated with the ST and lack of a yield increase resulted in a \$25 ha^{-1} reduction in net returns. The interaction between PD and SR was significant and the effect was not different between the two locations. 99% of the maximum yield potential was achieved with a final plant stand of at least 242,377, 287,823, 307,011, and 383,764 plants ha^{-1} during the late-April, mid-May, early-June, and late-June PDs, respectively. However, the final plant population to achieve 99% of the maximum net return was between 88,871 and 141,387 lower than the plant population that maximized seed yield. Overall, results indicated that ST did not improve net returns across any PD and lower SR were able to achieve maximum yield and net returns during early season planting, but SRs should be increased as planting is delayed.

Introduction

Planting soybean [*Glycine Max* (L.) Merr.] during late-April or early-May in Midwestern US has been shown to improve seed yield (Bastidas et al., 2008; De Bruin & Pedersen, 2008b). Furthermore, soybean planting delayed after May 30 resulted in 0.7% per day yield decline (Egli & Cornelius, 2009). Mourtzinis, Specht, & Conley (2019) speculated that if soybean planting had occurred 5 days earlier between 2007 and 2016, yields may have been 20 kg ha^{-1} higher than what was achieved. While Michigan soybean growers are currently planting approximately two weeks earlier compared to the 1980's (USDA-NASS, 2019), there are still factors such as poor soil condition, inclement weather, equipment restriction, and farm size that result in delayed soybean planting. Therefore, soybean planting in Michigan and other northern US states may occur as early as April and as late as July.

Soybean planting dates (PDs) may become more inconsistent as climatic conditions become more variable. Kim, Kimball, Zhang, & McDonald, 2012 classified daily freeze-thaw status using satellite microwave remote sensing and created a 30-year freeze-thaw record. The northern hemisphere has experienced a strong increasing trend in the mean annual non-frozen season of 0.189 days yr^{-1}. The longer growing season in the northern hemisphere is mostly driven by an earlier onset of spring by 0.149 days yr^{-1} which can provide an opportunity for soybean producers to plant earlier in the season. The Great Lakes Region specifically has experienced a 16-day increase in the number of frost free days between 1951 and 2017 (GLISA, 2017). The benefits of a longer growing season, specifically the earlier onset of spring, could be counteracted by an increase in intense precipitation events. Since 1901, the US has experienced an 4% increase in annual precipitation. Although this increase is mostly attributed to increased fall precipitation, winter and spring daily precipitation totals in the Midwest increased by 0.33

and 0.38 cm, respectively between 1948 and 2015. Heavy precipitation events, defined as the amount of precipitation falling in the heaviest 1% of storms, have increased by 35% between 1951 and 2017 in the Great Lakes Region (GLISA, 2017). Future projections indicate that winter and spring precipitation will continue to increase in the northern US. A seasonal increase in precipitation could result in delayed soybean planting, especially for producers who target early-season planting.

Soybean seeding rate (SR) and the use of a seed treatment (ST) are agronomic decisions that can greatly influence economic returns. The average total operating cost for soybean production in the Northern Crescent was \$428.80 ha^{-1} between 2012 and 2019, with seed costs being the single greatest expense, accounting for \$153.35 ha^{-1} (USDA-ERS, 2019). The high cost of soybean seed makes research focusing on economic returns, rather than yield alone, important when identifying optimal SRs and the benefits of a seed treatment.

Optimal agronomic decisions can vary among regions because of differences in temperature, photoperiod, climate, and growing season length. Therefore, region-specific research in soybean management is necessary to maximize soybean production. The current recommendation in Michigan is to achieve 247,105 plants ha^{-1} at the time of harvest (Michael Staton, personal communication). However, there is evidence that this recommendation could be lower. De Bruin & Pedersen (2008b) found that in Iowa, plant populations as low as 194,000 and 157,300 plants ha^{-1} at harvest acheived 95% of the maximum yield achieved by a harvest plant population of 290,800 and 211,800 plants ha^{-1} on 38 and 76 cm row spacing, respectively. In a separate study by De Bruin & Pedersen (2008a), a plant population of 258,600 plants ha^{-1} at harvest achieved 95% of the maximum yield achieved by 462,200 plants ha^{-1} at harvest. Furthermore, SRs between 185,000 and 556,000 seeds ha^{-1} resulted in similar economic returns.

In contrast, Thompson et al. (2015) found that in the Mid-South US, SR had little influence on seed yield but a SR of 60,000, 63,000, and 354,000 seeds ha^{-1} on 38 cm row spacing and 104,000, 83,000, and 278,000 seeds ha^{-1} on 76 cm row spacing resulted in the optimum economic returns for maturity groups 5.0, 4.0, and 3.0, respectively.

Optimal SR recommendations differ based on soybean PD, and increasing SR is beneficial when soybean planting is delayed. Lee, Egli, & TeKrony (2008) found that optimum plant population for May PDs was between 108,000 and 232,000 plants ha^{-1} but between 238,000 and 282,000 plants ha^{-1} for June PDs. Furthermore, Boquet (1990) found that for a late-June PD, the optimal seeding rate was 38 and 13 plants m^{-2} compared to 51 and 26 plants m^{-2} for an early-July PD at 0.5 and 1.0 m row spacing's, respectively. Other studies such as De Bruin & Pedersen (2008b) and Bruns (2011) did not find a PD by SR interaction between PDs ranging from April to mid-June, but did not test for SR differences when planting is extremely delayed.

Soybean STs consist of a combination of insecticide, fungicide, or nematicide to protect the soybean seed and seedling from pests and pathogens (Munkvold, Watrin, Scheller, Zeun, & Olaya, 2014). The benefits of a ST can include improved emergence, uniform crop growth, and higher soybean yields (Munkvold et al., 2014). Soybean ST has increased in recent years, from 10% of U.S. soybean seed treated with the ST before 2000, to over 75% by 2013 (Munkvold et al., 2014). While widespread blanket use of ST is common, recent research suggests that the ST is not beneficial in all environments. Cox, Shields, & Cherney (2008) found that ST did not impact plant stands or seed yield. In Michigan, using a seed treatment increased plant stands between 1.8 and 8.8% across seven locations, but only increased yield at one site-year compared to the non-treated control (Rossman, Byrne, & Chilvers, 2018). This is similar to the findings of Esker & Conley (2012) who found that using the CruiserMaxx® ST increased plant stands by

3% compared to an untreated control, but using the ApronMaxx® ST did not improve plant stands. Furthermore, the use of the ST impacted yield for four out of seven cultivars tested, but was most likely driven by cultivar differences rather than improvements from the ST (Esker & Conley, 2012). Gaspar, Marburger, Mourtzinis, & Conley (2014) also found that the ST increased stands between 5.5 and 10%, but yield improvements were inconsistent. Mourtzinis, Krupke, et al. (2019) examined the effects of a neonicotinoid seed treatment across 194 field trials from 14 states between 2006 and 2017 and found that the maximum yield benefit from a neonicotinoid plus fungicide ST was 130 kg ha^{-1} and yield responses were environmental specific. Furthermore, the high cost of soybean seed and variable yield improvements from the ST makes improvements in net returns specific to environmental conditions (Bradley, 2008; Cox et al., 2008; Esker & Conley, 2012; Mourtzinis, Krupke, et al., 2019; Rossman et al., 2018).

Soybean PD determines environmental conditions the crop will experience including soil conditions and temperature which in turn influence pest presence and pressure. Early-season soybean planting is often associated with cool, wet soils which can increase the potential for diseases such as sudden death syndrome (SDS; *Fusarium virguliforme*), stem rot (*Sclerotinia sclerotiorum*), seed decay and damping off (*Pythium* and *Phytophthora spp.*), and root rots (*Rhizoctoinia solani* and *Fusairum solani*) (Arias, Munkvold, Ellis, & Leandro, 2013; C. Grau, Oplinger, Adee, Hinkens, & Martinka, 1994; C. R. Grau, Dorrance, Bond, & Russin, 2004; Scherm & Yang, 1996). Furthermore, there is also increased concern of early season damage from bean leaf beetle (*Cerotoma trifurcata*), seedcorn maggot (*Delia platura*), soybean aphid (*Aphis glycines*), and white grubs (Coleoptera: Scarabaeidae) when planting is done early in the season (Hesler, Allen, Luttrell, Sappington, & Papiernik, 2018). The increased risk of pest damage during early-season planting suggests a soybean ST would be more beneficial during early vs late PDs. Mourtzinis, Krupke, et al. (2019) found that a neonicotinoid plus fungicide seed treatment improved yields by 60 and 100 kg ha^{-1} during early- and mid-season PDs, but did not improve soybean yield during late-season planting. Kandel, Wise, Bradley, Tenuta, & Mueller (2016) found that the interaction between PD and ST impacted plant stands and SDS disease index, but the effect was dependent on location. Furthermore, the yield response to the ST was greater for early PDs compared to the late PD, and the yield response to ST for the late PD was more likely to be negative compared to earlier PDs (Kandel et al., 2016). Conversely, Cox et al. (2008) and Vosberg, Marburger, Smith, & Conley (2017) found no PD x ST interaction.

Research in Michigan is lacking regarding optimal soybean PD as well as how other management decisions should be adjusted based on soybean PD to optimize yield, quality, and economic returns. Therefore, this research was conducted to identify the optimal soybean planting window in Michigan, and determine how SR and ST recommendations should be adjusted based on PD. Specific objectives were to:

i. Identify the optimal soybean planting date for Michigan soybean growers.
ii. Quantify the yield and net returns associated with the use of ST and the interaction between PD, SR, and ST.
iii. Determine the SR that maximizes yield and net returns across various soybean PDs.

Methods

Experimental Sites and Design

Field experiments were conducted at Michigan State University (MSU) research stations at the Mason Research Farm in Mason, MI (Mason) and the Saginaw Valley Research and

Extension Center in Frankenmuth, MI (Saginaw) during the 2018 and 2019 growing seasons. The experimental design was a randomized complete block in a split-plot arrangement with four replications. The main-plot factor consisted of four planting dates (PDs) targeted for late-April, mid-May, early-June, and late-June. Specific planting dates for each site-year are listed in Table 2-1. The subplot factor consisted of a maturity group 2.0 soybean cultivar planted at five soybean seeding rates ranging from 123,553 to 518,921 seeds ha^{-1}, in increments of 98,842 seeds, with (treated) or without (control) a complete ST. The seed treatment used was Clariva™ Complete which consists of a nematicide (*Pasteuria nishizawae*), insecticide, and fungicide (Cruiser Maxx®/Vibrance®).

A three point mounted vacuum planter (John Deere, Moline, IL) fitted with a vSet Select multi-hybrid metering system (Precision Planting, Tremont, IL) was used for planting. The vSet Select metering system uses a dual seed hopper which allows for two seed sources to be loaded into one row unit, in this case, seed with or without a ST. Plots were seven rows, spaced 0.38 m apart and 10.6 m in length. Shortly after the final PD reached emergence, plots were trimmed to 9.1 m. The previous year's crop, tillage practices, and soil classification for each site year are reported in Table 2-1. Spring tillage for three site years following corn included cultivation of the entire field in early spring followed by cultivation before each PD. At Saginaw in 2018, the field was cultivated before each PD. Weed management was conducted based on field needs with specific herbicides, rates, and application dates listed in Table 2-1.

Data Collection

Soil samples from each location were collected in a w-shaped pattern at a depth of 0 to 15 cm using a soil probe. Samples were sent to MSU Soil and Plant Nutrient Lab for soil analysis and MSU Diagnostic Services for nematode analysis (Table 2-1). Soil test results for each site year were at or above optimum nutrient levels so no fertilizer was applied. Soil and air temperature at each location was recorded using Thermochron iButton temperature loggers model DS1921G (Maxim Integrated Products, Sunnyvale, California). Soil temperature readings were taken at 5 cm soil depth and air temperature readings were taken at 1.5 m above the soil surface. All iButtons were placed in a 5 x 7.6 cm reclosable plastic bags to reduce the chance of failure from moisture (Roznik & Alford, 2012). The weather station from the MSU Enviro-weather Automated Weather Station Network that was closest to each field was used to report precipitation data.

After third-node appearance (V3), population counts were conducted from two 3.048 m lengths of row in each plot to determine initial plant stand. The area where population counts were taken was marked with field stakes. Insect and disease pressure was monitored weekly. At physiological maturity (R8), population counts were conducted in the same areas as the initial population count to determine final plant stand.

Three harvest dates were implemented to limit seed shatter in early maturing plots and excess seed moisture in late maturing plots (Table 2-1). Harvest was conducted using a Kincaid 8XP (Kincaid Equipment Manufacturing, Haven, KS) plot combine equipped with Harvest MasterTM High Capacity Grain Gauge (Juniper Systems, Logan, UT) to measure seed yield, moisture, and test weight. At harvest, a subsample from each plot was collected and used to determine seed protein and oil content using FOSS NIRS™ DS2500 F (Foss Analytical A/S, Hilleroed, Denmark). Reported seed yield has been adjusted to 13% moisture.

Net returns were calculated using Equation [2-1], which is a variation of the equation used to calculate net returns by Boyer et al. (2015).

$$R = py - C - d \qquad [2\text{-}1]$$

Where R is the net returns (US\$ ha^{-1}); p is the cash price of soybean (US\$ kg^{-1}); y is the yield (kg ha^{-1}); C is production cost (US\$ ha^{-1}); and d is discounts received on delivery (US\$ kg^{-1}). The average soybean cash price for Michigan during September, October, and November for the 2018 and 2019 growing season was \$8.64. C was calculated using a price of \$50 per soybean unit (140,000 seeds) plus an additional \$15 if a complete ST was used. Discounts received on delivery were determined using information from local grain elevators. The seed moisture discount used was \$0.68 kg^{-1} for each 0.5% seed moisture content over 13% at the time of harvest. The test weight discount used was \$0.27 kg^{-1} for each 0.45 kg below 24.5 kg.

Data Analyses

Statistical analysis was conducted with SAS® software version 9.4 (SAS Institute Inc., Cary, NC). Analysis of variance was conducted using the GLIMMIX procedure at a significance level of 0.1. Planting date, SR, ST, location, and their interactions were included as fixed effects. Year, replication, and PD x replication were included as random effects. Degrees of freedom were calculated using the Kenward-Rodger method. Data normality was tested using the UNIVARIATE procedure. Significant effects were compared using lsmeans and the Tukey-Kramer adjustment.

The effect of PD on soybean yield was analyzed using the difference in seed yield among each of the four PDs. Daily decline in seed yield was calculated using the difference in seed yield among each PD divided by the average number of days between PDs.

The response of yield and net returns was modeled as an exponential function of plant population using Equation [2-2] which has been previously used in similar experiments to model the soybean yield response to plant population (De Bruin & Pedersen, 2008b; Edwards & Purcell, 2005).

$$Y = \alpha(1 - e^{-\beta x}) \qquad [2\text{-}2]$$

Where Y is the predicted soybean yield or net returns; α is the predicted maximum yield or net return; and β is the responsiveness of Y as plant population (x) increases. Equation [2-2] forces the intercept through 0 so the model fit (R^2) was calculated using Equation [2-3].

$$R^2 = 1 - (Residual\ SS/Uncorrected\ Total\ SS) \qquad [2\text{-}3]$$

The agronomic optimum plant population (AOPP) is defined here as the final plant population that achieves 99% of the maximum yield potential. The AOPP and 95% of the maximum yield was calculated by substituting Y in Equation [2-2] with (α * 0.99) for the AOPP, or (α * 0.95) for 95% of the maximum yield. Similarly, the economic optimum plant population (EOPP) is defined here as the final plant population that achieves 99% of the maximum net returns and was calculated likewise. To calculate the agronomic optimum SR (AOSR) and the economic optimum SR (EOSR), the AOPP and EOPP was multiplied by the percent plant stand (final plant population / the target SR), achieved for each PD.

Results

Weather and Growing Conditions

The late-April soybean PD occurred within the median last freeze date for each site year (Table 2-2). Average soil temperature during the first 24h after the late-April PD was 12.4° and 8.2° C during the 2018 growing season and 12.6° and 8.0° C during the 2019 growing season at Mason and Saginaw, respectively. Soil temperature was above 10° C for all other PDs. Cold, saturated soil conditions typical in April and May resulted in delayed soybean emergence in the late-April PD at all site years (data not shown) compared to later PDs. Days between planting and emergence ranged from 16 to 25 days, 5 to 18 days, 6 to 11 days, and 4 to 6 days for the late-April, mid-May, early-June, and late-June PDs, respectively. Final plant populations averaged 79% of the target SR across all site-years, and were equal to or above 70% of the target SR for all site-years except for the late-June PD at Saginaw 2018 (61%).

Total precipitation between April and October was similar to the 30-year average for both growing seasons at Mason (Table 2-3). At Saginaw, precipitation totals were 15% lower than the 30-year average during the 2018 growing season, and were lower than average for every month in 2018 except August. Total precipitation at Saginaw during the 2019 growing season was 15% higher than the 30-year average, mostly driven by high precipitation in October. The month of June was dry during the 2018 growing season at both locations (< 45% of the 30-year average). July precipitation was below average for all site years and extremely low during the 2018 growing season at both locations. During August, precipitation was deficient (< 35% of the 30-year average) at both locations during the 2019 growing season.

Mean air temperatures between the months of June and October were within 20% of the 30-year average for all site years (Table 2-3). Air temperatures were 53% and 49% lower than the 30-year average during April, but 20% and 40% higher than the 30-year average during May at Mason and Saginaw, respectively, during the 2018 growing season. Air temperature during April and May during the 2019 growing season was similar to the 30-year average.

Planting Date

The effect of PD on seed yield varied across locations (Table 2-4) but the trend for both locations was similar. Soybean yield was different between the late-April and mid-May PD for one site-year, Saginaw 2018, where yield was 657 kg ha^{-1} lower for the early-April PD compared to the mid-May PD (data not shown). Seed yield was reduced between the mid-May and early-June PDs and further reduced between the early-June and late-June PDs (Table 2-5). The yield reduction between the mid-May and early-June PD was 12.9 and 24.5 kg ha^{-1} d^{-1} at Mason and Saginaw, respectively. The daily decline in yield was even greater between the early-June and late-June PDs, at 30.3 and 62.8 kg ha^{-1} d^{-1} at Mason and Saginaw, respectively.

Seed Treatment

The population density for soybean cyst, lesion, spiral, and stunt nematode was low for every site year (Table 2-1). The effect of the ST on percent plant stand, seed yield, and net returns was not different across PDs or SRs (Table 2-4). However, the main effect of the ST on percent plant stand was significant at one location (Table 2-4), increasing percent plant stand by 6.7% at Mason (Table 2-6). This improvement in plant stand did not increase seed yield or net returns. The additional cost of the ST without a yield increase resulted in a \$26 ha^{-1} reduction in net returns across all site-years (\$796 and \$822 ha^{-1} from treated vs control, respectively).

Seeding Rate

Soybean seed yields and net returns were affected by SR, but the effect differed among PDs (Table 2-4). The predicted seed yield for the late-April PD increased rapidly with increased plant population (Figure 2-1). This increase in seed yield by adding extra plants (at lower plant stand) became more gradual as planting was delayed. For the late-April PD, the maximum predicted yield was 3304 kg ha^{-1} (Table 2-7) and plant population required to achieve 99% and 95% of the maximum predicted yield was 242,377 and 157,670 plants ha^{-1}, respectively. As planting was delayed, the required plant population to achieve 99% and 95% of the maximum predicted yield increased (Table 2-7). The maximum predicted yield for the late-June PD was the lowest across all PDs (2579 kg ha^{-1}), but required the highest plant population to achieve 99% (383,764 plants ha^{-1}) and 95% (249,644 plants ha^{-1}) of the maximum yield (Table 2-7).

The plant population required to achieve 99% of the maximum predicted net returns was lower than that to achieve 99% of the maximum predicted yield across all PDs (Table 2-8). The trend for net returns was similar to yield in that as planting was delayed, a higher plant populations were required to achieve 99% of the maximum predicted net return. The maximum net return for the late-April PD was $882 ha^{-1}, and a plant population of 153,506 plants ha^{-1} achieved 99% of the maximum net returns (Table 2-8). However, when planting was delayed to mid-May or early-June, a plant population of 191,882 and 209,326 plants ha^{-1} was required to achieve 99% of the maximum net returns. The maximum net returns for the late-June PD was $588, requiring a plant population of 242,377 to achieve 99% of the maximum (Table 2-8).

The interaction between PD and SR impacted percent plant stand, but the effect was different across locations (Table 2-4). At Mason, there was no differences in percent target stand achieved across PD and SR (P = 0.70). At Saginaw, the only difference between SRs in percent target stand was between the late-April and late-June PDs. However, these differences were minimal (data not shown). Therefore, the average percent target stand for each PD was used to calculate the SR necessary to achieve 95% and 99% of the maximum yield and net returns for each location separately (Table 2-9). At both locations, the mid-May PD achieved the highest percent target stand, and planting in late-April or late-June resulted in lower percent target stands (Table 2-9).

At both locations, the AOSR for the first three PDs ranged from 318,000 to 389,000 seeds ha^{-1}, but was <300,000 seeds ha^{-1} to achieve 95% of the maximum yield (Table 2-9). The

AOSR increased for both locations as planting was delayed (Table 2-9). When planting was delayed to late-June, the AOSR was >500,000 seeds ha^{-1} for both locations. The same trends were observed for the EOSR. The EOSR increased as planting was delayed at both locations, but the EOSR was always lower than the AOSR (Table 2-9). At both locations, the 99% EOSR was similar to the 95% AOSR.

Discussion

Identifying the optimal soybean planting window for Michigan growers is critical in maximizing yield and profitability. Previous studies suggested that planting earlier can improve soybean yields, and the optimal planting window in other Midwestern states is between late-April and early-May (Bastidas et al., 2008; De Bruin & Pedersen, 2008b; Mourtzinis, Specht, et al., 2019). Results from this study are in general agreement with previous studies in that planting in mid-May resulted in the greatest seed yield, although this increase was not different from seed yield in the late-April PD for three of four site years. When planting was delayed, soybean yield decreased by an average of 131 kg ha^{-1} wk^{-1} between the mid-May and early-June PDs and by 326 kg ha^{-1} between the early-June and late-June PD. This is similar to De Bruin & Pedersen (2008b) who found that the weekly yield decline between the early-May and late-May PD was 130 kg ha^{-1} and 404 kg ha^{-1} between the late-May and early-June PD. The trend at both locations was similar and showed that optimal soybean PD in Michigan is between late-April and mid-May. However, there was no apparent benefit to planting before mid-May in this study. If optimal planting is not possible, it is still critical to plant soybean as soon as possible because the rate of yield decline increases as planting is delayed.

Early-season soybean planting brings concerns of stand losses due to cool and wet soils, pest damage, and late spring freeze. Soybean stands were lower for the late-April PD compared to the mid-May PD (Table 2-9), but ~75% of the target population was still achieved during the late-April PD. Furthermore, soybean emergence was delayed during the late-April PD compared to later PDs, with emergence taking as much as 25 days after planting for the late-April PD. This extended period of time the seed and seedling spends in cool and wet soil may increase the chance of pest damage, suggesting the ST would be beneficial during early-season soybean planting. However, the lack of interaction between PD and ST at any site years indicates that there is not a greater benefit from the ST during early-season compared to later PD. The benefits of a ST were limited to plant stand improvement at Mason. Furthermore, the use of the ST did not significantly improve seed yield, and thus, reduced net return by \$26 ha^{-1}. For the ST to be beneficial (increase yield and net returns), there must be insect and/or disease pressure early in the growing season. In this experiment, there was minimal pest pressure which most likely explains the lack of improvement in yield and net returns from the ST. This is similar to Rossman et al. (2018) who found that the use of the ST improved plant stands by 1.8 to 8.8%, but did not consistently improve yield or net returns. Furthermore, ST responsiveness was dependent on environment, which is similar to the findings in other studies (Bradley, 2008; Dorrance et al., 2009). Additionally, other studies evaluating the effect of the ST on soybean seed yield did not see an interaction between PD and ST (Cox et al., 2008; Vosberg et al., 2017). The results from this and other studies agree that there is a high level of variability in the effectiveness of a ST, indicating that decisions regarding the use of a ST need to be made with environmental conditions in mind.

Across all PDs, the EOSR was similar to the SR that achieved 95% of the maximum yield. The SR that optimizes net return may not always result in maximized seed yield. Furthermore, the average increase in SR from 95% of the maximum yield to the AOSR was

107,359, 119,005, 130,594, and 188,053 seeds ha^{-1} for the late-April, mid-May, early-June, and late-June PDs, respectively (Table 2-9). The additional seed required to achieve the AOSR increases yield by 4%, but increase net returns by < 1%. Furthermore, if the 4% increase in yield is not achieved from the increased SR, net returns are reduced. The results from this study suggest that current MSU final plant stand recommendations for soybean may be higher than what is necessary to achieve maximum net returns. The EOPP for the late-April, mid-May, early-June, and late-June was 93,599, 55,223, 37,779, and 4,728 plants ha^{-1} lower than the current MSU recommendation of 247,105 plant ha^{-1} respectively. This is similar to the findings of De Bruin & Pedersen (2008b) who found that in Iowa, SRs range between 370,000 and 494,200 seeds ha^{-1}, but net return did not improve above 185,300 seeds ha^{-1}.

The variability in yield among the PDs can explain why the AOPP and EOPP are lower for early-season planting and increase as planting is delayed (Table 2-7 and 2-8). The higher yield potential from planting early in the season may require fewer plants to achieve maximum yield and net return, while the low yield environment from delayed planting requires more plants to maximize yield. Furthermore, the maximum predicted yield and net returns (α) were higher for early-season planting, and required fewer plants compared to delayed planting. This is in agreement with Corassa et al. (2018) who found that a SR of 290,000 seeds ha^{-1} was necessary to achieve the maximum predicted yield in low yield environments, but only 262,000 and 245,000 seeds ha^{-1} were needed in medium and high yield environments.

In summary, the results from this research show that the optimal time for soybean planting in Michigan is between late-April and mid-May. Furthermore, the benefits of the ST were limited to stand improvements at one location but resulted in a decrease in net returns. Although there is a potential benefit from use of the ST during early-season planting, no interaction between PD and ST was observed in this study, suggesting that the use of the ST may not be necessary to achieve maximum yield and net returns for Michigan soybean growers. However, there are various factors that could impact the effectiveness of a ST such as weather, soil condition, plant phenology, and varietal pest resistance traits. The AOSR and EOSR was lowest during late-April planting and increased as planting was delayed. However, the cool, wet soil conditions often experienced during early season planting can result in stand loss and therefore, may require higher SRs and/or a use of ST to achieve maximum net returns in other environments. Soybean seed yield and net returns were greatly reduced as planting was delayed and required the highest SR compared to earlier PDs to achieve optimal seed yield and net returns. Future research should be conducted to build a systems approach to soybean management based on PD. Overall, adjusting SR based on PD can improve both yield and net returns for Michigan soybean growers. Research exploring how other soybean management practices such as cultivar maturity group, row spacing, seed inoculation, and fertilizer application should be adjusted based on PD will benefit growers by maximizing the benefits of early-season soybean planting while mitigating losses from delayed planting.

APPENDICES

APPENDIX A:

Chapter 2 Tables and Figures

Table 2-1. Agronomic details for each site year at two locations in Michigan during the 2018 and 2019 growing seasons.

Year	Location	Planting Dates	Previous Crop	Fall Tillage	Spring Tillage	Soil Class	Soil pH	P	K	Mg	Ca	CEC	Nematode	Weed Control‡	Harvest Dates
								g kg^{-1}				meq 100g^{-1}	100 cm^3		
2018	Mason	April 29 May 25 June 8 June 29	Corn	Chisel Plow	Field Cultivator x2	Conover Loam	6.8	52	104	238	1617	10.3	Cyst: 120 Lesion: 44 Spiral: 2 Stunt: 72	May 28 glyphosate July 01 glyphosate	Oct. 17 Nov. 8 Nov. 19
	Saginaw†	April 30 May 17 June 9 June 26	Wheat	None (oat cover)	Field Cultivator	Tappan-Londo Loam	7.9	52	124	303	2451	15.1	Cyst: 140 Lesion: 8 Spiral: 348 Stunt: 40 Pin: 4	May 29 glyphosate July 24 glyphosate	Oct. 23 Oct. 30 Nov. 20
2019	Mason	April 26 May 15 June 4 June 27	Corn	Chisel Plow	Field Cultivator x2	Conover Loam	6.2	37	101	132	1139	8.3	Cyst: 0 Lesion: 20 Stunt: 54	May 30 glyphosate June 19 glyphosate July 17 ssb + asi	Oct. 10 Oct. 25 Nov. 23
	Saginaw	April 27 May 14 June 8 June 26	Corn	Chisel Plow	Field Cultivator x2	Tappan-Londo Loam	7.6	35	167	424	2541	16.7	Cyst: 0 Lesion: 4 Spiral: 386	May 16 glyphosate June 19 glyphosate	Oct. 11 Oct. 25 Nov. 24

†An application of monoammonium phosphate (MAP) was applied at a rate of 62 kg ha^{-1} to supply nutrients to an oat (*Avena sativa*) cover crop in the fall.
‡Glyphosate was applied at a rate of 1.68 kg a.i. ha^{-1}, sodium salt of bentazon (ssb) was applied at a rate of 1.35 kg a.i. ha^{-1}, ammonium salt of imazamox (asi) was applied at a rate of 0.45 kg a.i. ha^{-1}

Table 2-2. Climatological date of the last spring freeze (≤ -2.22° C) for each location.

Location	Last (Spring) Freeze†		
	Percentile		
	10th	50th	90th
Mason	Apr 1 - 10	Apr 21 - 30	May 1 - 10
Saginaw	Apr 1 - 10	Apr 21 - 30	May 1 - 10

† Freeze data collected from Midwestern Regional Climate Center Vegetation Impact Program (https://mrcc.illinois.edu) for years 1980-81 to 2009-2010.

Table 2-3. Monthly† and 30-year mean‡ precipitation and temperature for each site year.

Location	Year	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Total
		Precipitation cm							
Mason	2018	6.0	12.6	3.7	2.7	11.7	10.3	10.5	57.5
	2019	7.2	8.5	11.5	5.8	1.8	9.3	13.0	57.1
	30-yr.	**7.3**	**8.5**	**8.9**	**8.3**	**8.4**	**9.2**	**7.0**	**57.6**
Saginaw	2018	7.2	5.4	3.7	5.0	20.1	4.9	5.9	52.2
	2019	5.8	12.8	17.7	6.0	2.7	9.6	16.0	70.6
	30-yr.	**7.5**	**8.7**	**10.0**	**9.3**	**8.6**	**9.8**	**7.4**	**61.3**
		Temperature °C							
Mason	2018	4.1	17.6	20.0	21.9	21.8	18.0	9.6	
	2019	8.0	14.3	20.0	24.2	21.4	19.1	10.5	
	30-yr.	**8.7**	**14.7**	**20.0**	**22.1**	**21.3**	**16.9**	**10.4**	
Saginaw	2018	3.6	18.3	20.8	23.3	22.2	18.3	9.8	
	2019§	7.4	12.7	18.3	22.7	19.9	17.8	9.7	
	30-yr.	**7.0**	**13.1**	**18.6**	**20.5**	**19.5**	**15.7**	**9.2**	

†Monthly air temperatures between May and October were collected from iButton installed 1.5m above the soil surface. Monthly precipitation data and monthly temperature data during April was collected from the nearest weather station in the MSU Enviro-weather
‡30-year mean temperature and precipitation data collected from the National Oceanic and Atmosphere Administration (https://www.ncdc.noaa.gov/cdo-web/datatools/normals)
§Monthly air temperature collected from MSU Enviro-weather.

Table 2-4. Soybean percent plant stand, seed yield (kg ha^{-1}) and net return (\$ ha^{-1}) analysis of variance for planting date (PD), seeding rate (SR), seed treatment (ST), and location (loc) across the 2018 and 2019 growing seasons at a significance level of 0.1.

Source	df	Percent plant stand	Seed yield	Net return
		Pr > F		
PD	3	<0.001	<0.001	<0.001
SR	4	0.006	<0.001	0.018
ST	1	0.002	0.633	0.068
Loc	1	<0.001	<0.001	<0.001
PD*SR	12	0.006	0.024	0.043
PD*ST	3	0.462	0.954	0.965
SR*ST	4	0.837	0.580	0.306
PD*SR*ST	12	0.795	0.959	0.972
PD*Loc	3	<0.001	<0.001	<0.001
SR*Loc	4	0.320	0.932	0.946
ST*Loc	1	0.006	0.433	0.396
PD*SR*Loc	12	0.037	0.569	0.612
PD*ST*Loc	3	0.319	0.885	0.892
SR*ST*Loc	4	0.696	0.907	0.892
PD*SR*ST*Loc	12	0.429	0.858	0.876

Table 2-5. Seed yield reduction between the late-April and mid-May, mid-May and early-June, and early-June and late-June planting dates at Mason and Saginaw across the 2018 and 2019 growing seasons.

Location	Late-April to Mid-May	Mid-May to Early-June	Early-June to Late-June
		kg ha^{-1}	
Mason	-178.0c†	219.6b	666.6a
Saginaw	-468.6c	588.3b	1098.1a

† Values followed by the same letter within a location are not different at *P*<0.1

Table 2-6. Percent of target plant population achieved between treated seed and the non-treated control at Mason and Saginaw.

Location	Percent plant stand
Mason	%
Treated	80.0a†
Control	75.0b
Saginaw	
Treated	81.3a
Control	81.0a

† Values followed by the same letter within a location are not different at P<0.1

Table 2-7. Coefficient estimates (α, β), model siginifiance level (Pr>F), and model fit (R^2) for the equation $Y = \alpha(1 - e^{-\beta x})$ and the agronomic optimum plant population (AOPP) necessary to achieve 95% and 99% of the maximum soybean seed yield for each planting date across both locations (Mason and Saginaw) during the 2018 and 2019 growing seasons.

Planting date	Regression coefficients $Y = \alpha(1 - e^{-\beta x})$		Pr>F	R^2	Agronomic optimum plant population	
	α	β			95%	99%
					plants ha^{-1}	
Late-April	3304.3	0.000019	<0.001	0.946	157,670	242,377
Mid-May	3699.8	0.000016	<0.001	0.946	187,233	287,823
Early-June	3328.5	0.000015	<0.001	0.949	199,716	307,011
Late-June	2577.8	0.000012	<0.001	0.948	249,644	383,764

Table 2-8. Coefficient estimates (α, β), model siginifiance level (Pr>F), and model fit (R^2) for the equation $Y = \alpha(1 - e^{-\beta x})$ and the economic optimum plant population (EOPP) necessary to achieve 99% of the maximum soybean seed yield for each planting date across both locations (Mason and Saginaw) during the 2018 and 2019 growing seasons.

	Regression coefficients $Y = \alpha(1 - e^{-\beta x})$				Economic optimum plant population
Planting date	α	β	Pr>F	R^2	99%
					plants ha^{-1}
Late-April	882.0	0.000030	<0.001	0.926	153,506
Mid-May	993.4	0.000024	<0.001	0.927	191,882
Early-June	859.3	0.000022	<0.001	0.934	209,326
Late-June	588.2	0.000019	<0.001	0.931	242,377

Table 2-9. Percent plant stand achieved for each planting date averaged across treatments, and the agronomic optimum seeding rate (AOSR) and economic optimum seeding rate (EOSR) necessary to achieve 95% and 99% of the maximum yield and 99% of the maximum net returns at Mason and Saginaw during the 2018 and 2019 growing seasons.

Location	Planting date	Plant Stand	Agronomic optimum seeding rate		Economic optimum seeding rate
			99%	95%	99%
Mason		%	seeds ha^{-1}		
	Late-April	76.2bc†	318,080	206,916	201,451
	Mid-May	82.1a	350,576	228,055	233,717
	Early-June	78.9ab	389,114	253,125	265,305
	Late-June	72.8c	527,148	342,918	332,935
Saginaw					
	Late-April	81.8b	296,304	192,751	187,660
	Mid-May	87.1a	330,451	214,963	220,301
	Early-June	85.7ab	358,239	233,041	244,254
	Late-June	69.9c	549,019	357,144	346,748

† Values followed by the same letter within a location are not different at $P<0.1$.

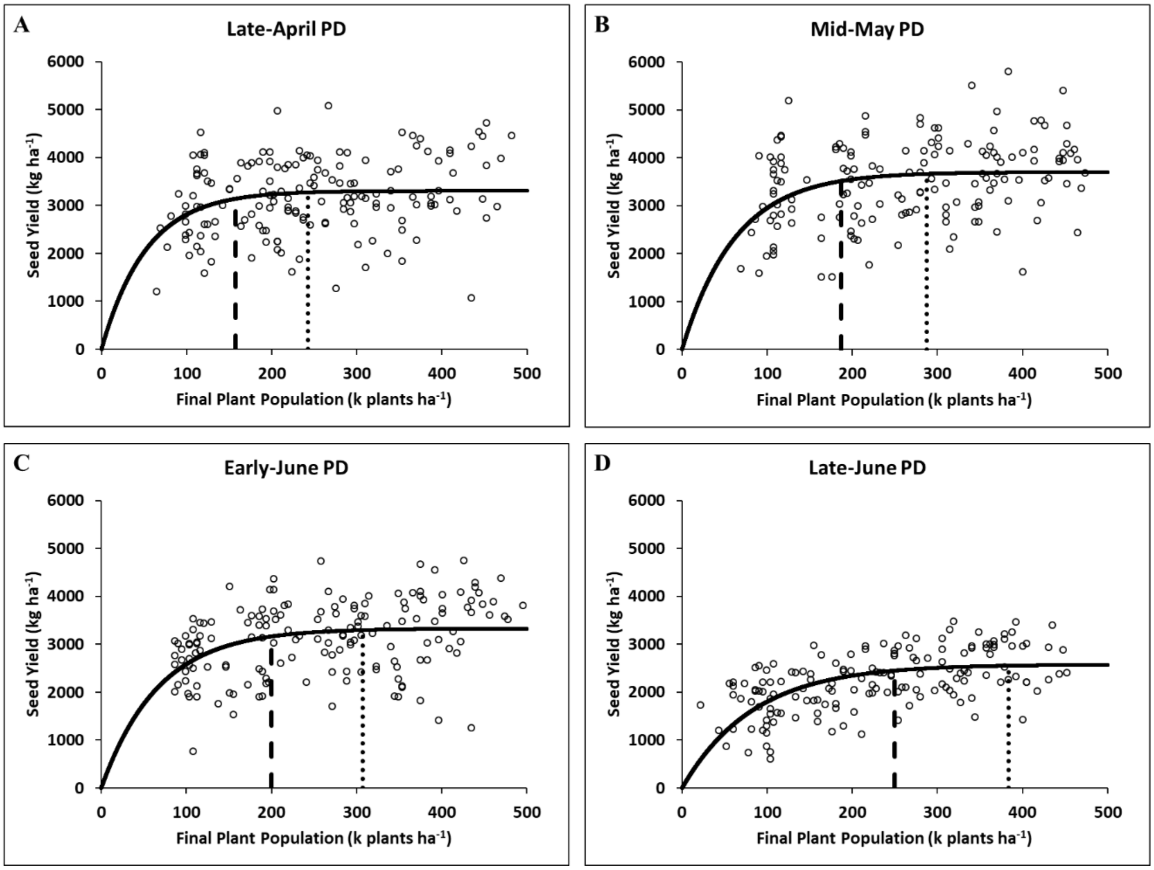

Figure 2-1. Response of soybean yield to plant population during late-April (A), mid-May (B), early-June (C), and late-June (D) planting dates (PD) across both locations and years. Lines indicate the final plant population that achieves 99% (dotted line) and 95% (dashed line) of the maximum predicted yield.

APPENDIX B:

Chapter 2 Additional Data

After final harvest, pods that remained on soybean stubble were removed from 1.5 m length in each of the middle three rows in a subset of plots. The pods were then threshed by hand and the seeds were counted to determine harvest loss. In addition, five representative plants from two rows were measured to determine plant height, height of the lowest pod on the plant, and the number of reproductive branches for each plant.

Table 2-10. Soybean plant height (cm), height of the lowest pod (cm), and number of reproductive branches analysis of variance for planting date (PD), seeding rate (SR), and location across the 2018 and 2019 growing seasons.

Effect	Plant height	Low pod height	Branches
		Pr>F	
PD	<0.001	<0.001	0.026
SR	0.126	<0.001	<0.001
Location	0.885	0.001	0.539
PD*SR	0.619	0.161	0.076
PD*Location	0.003	<0.001	<0.001
SR*Location	0.469	0.007	0.034
PD*SR*Location	0.707	0.008	0.020

Table 2-11. Effect of the interaction between planting date (PD) and location, sliced by location, on soybean plant height for Mason 2018 (*P*<0.001) and Saginaw 2019 (*P*<0.001).

Location	Planting date	Plant height†
Mason		cm
	Late-April	68.1b
	Mid-May	70.0ab
	Early-June	73.9a
	Late-June	57.3c
Saginaw		
	Late-April	65.7a
	Mid-May	67.1a
	Early-June	62.2a
	Late-June	56.5b

† Values followed by the same letter within a location are not different at *P*<0.1.

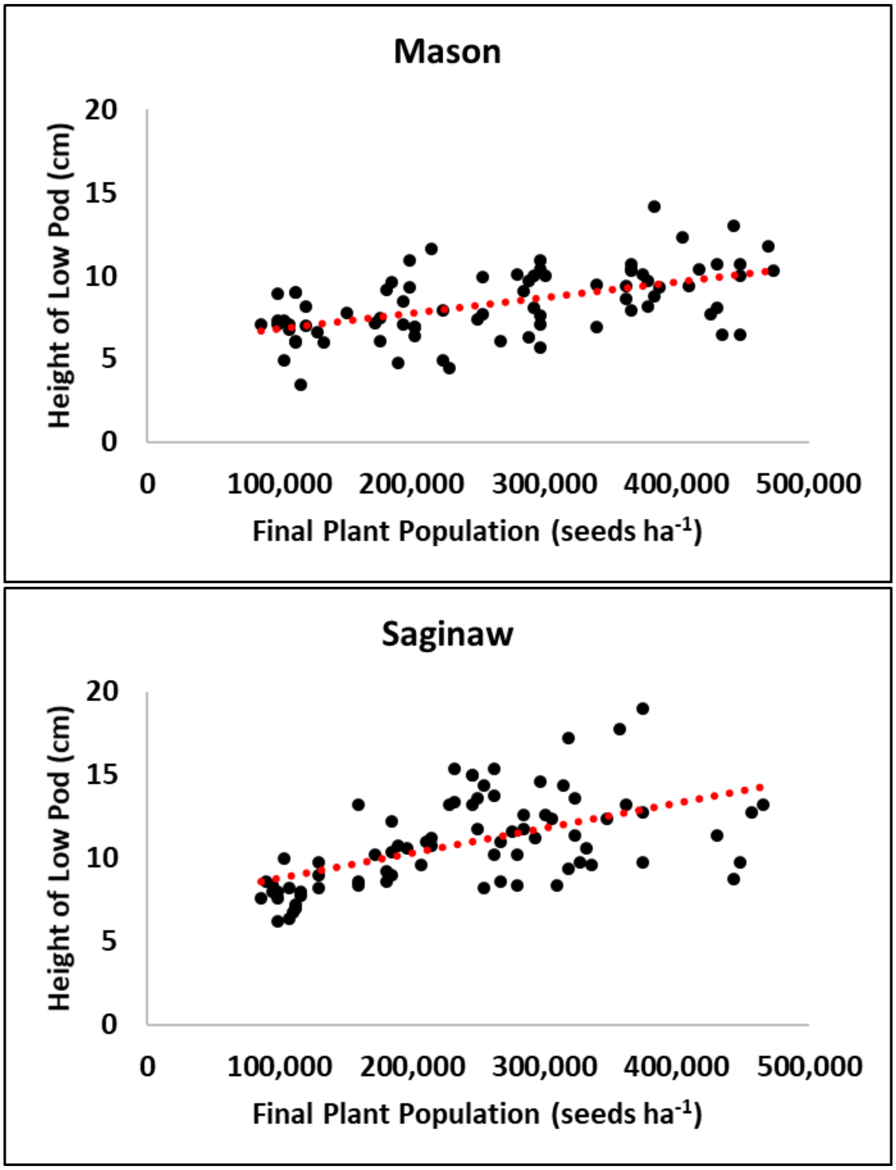

Figure 2-2. Relationship between final plant population and the height of the lowest pod on the plant from the soil surface at Mason 2018 (R^2=0.28; *P*<0.001) and Saginaw 2019 (R^2= 0.30; *P*<0.001)

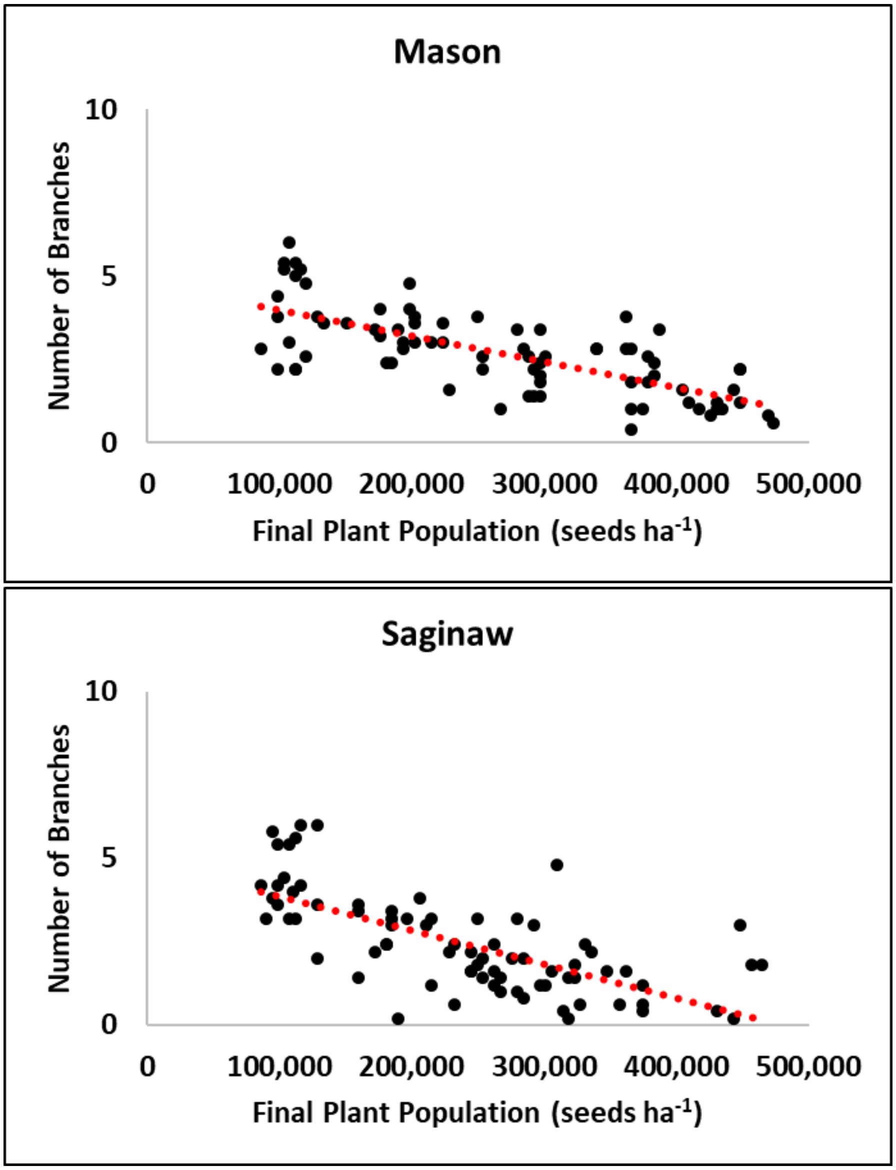

Figure 2-3. Relationship between final plant population and the number of reproductive branches on each plant at Mason 2018 (R^2=0.50; P<0.001) and Saginaw 2019 (R^2= 0.47; P<0.001)

LITERATURE CITED

LITERATURE CITED

Arias, M. D., Munkvold, G., Ellis, M., & Leandro, L. (2013). Distribution and frequency of Fusarium species associated with soybean roots in Iowa. *Plant Disease, 97*(12), 1557-1562.

Bastidas, A., Setiyono, T., Dobermann, A., Cassman, K. G., Elmore, R. W., Graef, G. L., & Specht, J. E. (2008). Soybean sowing date: The vegetative, reproductive, and agronomic impacts. *Crop Science, 48*(2), 727-740.

Boquet, D. (1990). Plant population density and row spacing effects on soybean at post-optimal planting dates. *Agronomy Journal, 82*(1), 59-64.

Boyer, C. N., Stefanini, M., Larson, J. A., Smith, S. A., Mengistu, A., & Bellaloui, N. (2015). Profitability and risk analysis of soybean planting date by maturity group. *Agronomy Journal, 107*(6), 2253-2262.

Bradley, C. (2008). Effect of fungicide seed treatments on stand establishment, seedling disease, and yield of soybean in North Dakota. *Plant Disease, 92*(1), 120-125.

Bruns, H. A. (2011). Planting date, rate, and twin-row vs. single-row soybean in the Mid-South. *Agronomy Journal, 103*(5), 1308-1313.

Corassa, G. M., Amado, T. J., Strieder, M. L., Schwalbert, R., Pires, J. L., Carter, P. R., & Ciampitti, I. A. (2018). Optimum soybean seeding rates by yield environment in southern Brazil. *Agronomy Journal, 110*(6), 2430-2438.

Cox, W. J., Shields, E., & Cherney, J. H. (2008). Planting date and seed treatment effects on soybean in the northeastern United States. *Agronomy Journal, 100*(6), 1662-1665.

De Bruin, J. L., & Pedersen, P. (2008a). Effect of row spacing and seeding rate on soybean yield. *Agronomy Journal, 100*(3), 704-710.

De Bruin, J. L., & Pedersen, P. (2008b). Soybean seed yield response to planting date and seeding rate in the Upper Midwest. *Agronomy Journal, 100*(3), 696-703.

Dorrance, A., Robertson, A., Cianzo, S., Giesler, L., Grau, C., Draper, M., . . . Anderson, T. (2009). Integrated management strategies for *Phytophthora sojae* combining host resistance and seed treatments. *Plant Disease, 93*(9), 875-882.

Edwards, J. T., & Purcell, L. C. (2005). Soybean yield and biomass responses to increasing plant population among diverse maturity groups. *Crop Science, 45*(5), 1770-1777.

Egli, D., & Cornelius, P. (2009). A regional analysis of the response of soybean yield to planting date. *Agronomy Journal, 101*(2), 330-335.

Esker, P. D., & Conley, S. P. (2012). Probability of yield response and breaking even for soybean seed treatments. *Crop Science*, *52*(1), 351-359.

Gaspar, A. P., Marburger, D. A., Mourtzinis, S., & Conley, S. P. (2014). Soybean seed yield response to multiple seed treatment components across diverse environments. *Agronomy Journal, 106*(6), 1955-1962.

GLISA. (2017). Climate change in the great lakes region. http://glisa.umich.edu/gl-climate-factsheet-refs. (accessed 05 Febuary 2019)

Grau, C., Oplinger, E., Adee, E., Hinkens, E., & Martinka, M. (1994). Planting date and row width effect on severity of brown stem rot and soybean productivity. *Journal of Production Agriculture, 7*(3), 347-351.

Grau, C. R., Dorrance, A. E., Bond, J., & Russin, J. S. (2004). Fungal Diseases. In H. R. Boerma & J. E. Specht (Eds.), *Soybeans: Improvement, Production, and Uses* (pp. 679-763). Madison, WI: American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America.

Hesler, L. S., Allen, K. C., Luttrell, R. G., Sappington, T. W., & Papiernik, S. K. (2018). Early-season pests of soybean in the United States and factors that affect their risk of infestation. *Journal of Integrated Pest Management, 9*(1), 19.

Kandel, Y. R., Wise, K. A., Bradley, C. A., Tenuta, A. U., & Mueller, D. S. (2016). Effect of planting date, seed treatment, and cultivar on plant population, sudden death syndrome, and yield of soybean. *Plant Disease*, *100*(8), 1735-1743.

Kim, Y., Kimball, J. S., Zhang, K., & McDonald, K. C. (2012). Satellite detection of increasing Northern Hemisphere non-frozen seasons from 1979 to 2008: Implications for regional vegetation growth. *Remote Sensing of Environment*, *121*, 472-487.

Lee, C. D., Egli, D. B., & TeKrony, D. M. (2008). Soybean response to plant population at early and late planting dates in the Mid-South. *Agronomy Journal, 100*(4), 971-976.

Mourtzinis, S., Krupke, C. H., Esker, P. D., Varenhorst, A., Arneson, N. J., Bradley, C. A., . . . Herbert, A. (2019). Neonicotinoid seed treatments of soybean provide negligible benefits to US farmers. *Scientific Reports, 9*(1), 1-7.

Mourtzinis, S., Specht, J. E., & Conley, S. P. (2019). Defining optimal soybean sowing dates across the US. *Scientific Reports, 9*(1), 1-7.

Munkvold, G. P., Watrin, C., Scheller, M., Zeun, R., & Olaya, G. (2014). Benefits of chemical seed treatments on crop yield and quality. In *Global perspectives on the health of seeds and plant propagation material* (pp. 89-103): Springer.

Rossman, D. R., Byrne, A. M., & Chilvers, M. I. (2018). Profitability and efficacy of soybean seed treatment in Michigan. *Crop Protection, 114,* 44-52.

Scherm, H., & Yang, X. (1996). Development of sudden death syndrome of soybean in relation to soil temperature and soil water matric potential. *Phytopathology, 86*(6), 642-649.

Thompson, N. M., Larson, J. A., Lambert, D. M., Roberts, R. K., Mengistu, A., Bellaloui, N., & Walker, E. R. (2015). Mid-South soybean yield and net return as affected by plant population and row spacing. *Agronomy Journal, 107*(3), 979-989.

USDA-ERS. (2019). Soybean production costs and returns per planted acre, excluding Government payments. USDA Economic Research Service. https://www.ers.usda.gov/data-products/commodity-costs-and-returns/commodity-costs-and-returns/#Historical%20Costs%20and%20Returns:%20Soybeans (accessed 23 February 2019)

USDA-NASS. (2019) Soybean, progress, measured in pct planted. USDA National Agriculture Statistics Service. https://quickstats.nass.usda.gov/results/907B0FFD-87B3-3859-BF6A-3429BA70BD43 (accessed 23 February 2019)

Vosberg, S. K., Marburger, D. A., Smith, D. L., & Conley, S. P. (2017). Planting date and fluopyram seed treatment effect on soybean sudden death syndrome and seed yield. *Agronomy Journal, 109*(6), 2570-2578.

CHAPTER 3

OPTIMAL SOYBEAN CULTIVAR MATURITY SELECTION IS INFLUENCED BY PLANTING DATE

Abstract

Changing climate conditions has resulted in a shift towards longer growing seasons in Michigan and other northern US states, providing soybean growers with an opportunity to achieve early planting dates (PDs). However, increasingly variable spring precipitation may result in planting being delayed. Current soybean maturity group (MG) recommendations are based only on optimal PD and may not fully utilize the available growing season. To determine how MG selection should be adjusted based on PD, six MGs ranging from MG 1 to 3.5 were planted on four PDs (from late-April to late-June) during the 2018 and 2019 growing season at two locations in Michigan. Predicted seed yield increased by an average of 286, 171, and 73.0 kg ha^{-1} for each 0.5 increase in MG when planting was conducted on day of year (DOY) 120, 140, and 160, respectively. When planting was delayed to DOY 180, there was a yield reduction of 51.4 kg ha^{-1} for each 0.5 increase in MG. The increase in yield from using a late MG in early-planting was correlated with an increase in seeds m^{-2} which was mainly driven by an increase in cumulative growing degree days (GDD_c) during pod and seed set. Results generated from this study indicate that Michigan and northern US soybean growers can increase seed yield and eventual profitability by adjusting MG selection based on PD such that the maximum available growing season is utilized.

Introduction

Soybean [*Glycine max* (L.) Merr.] production is greatly influenced by environmental conditions including photoperiod (Kumudini, Pallikonda, & Steele, 2007; Nico, Miralles, & Kantolic, 2019), temperature (Bellaloui, Reddy, & Gillen, 2011; Mourtzinis, Gaspar, Naeve, & Conley, 2017; Wolf, Cavins, Kleiman, & Black, 1982), and precipitation (Chen & Wiatrak, 2010; Egli & Bruening, 1992) which in turn affect the duration of vegetative and reproductive growth, yield components, seed quality, and seed yield. Soybean planting date (PD) and maturity group (MG) selection are two critical management decisions that have a strong influence on the environmental conditions a soybean crop will experience. Selecting the optimum MG based on PD is especially critical in the northern soybean production regions (such as Michigan and other northern US states) due to the relatively short growing season. Planting soybean too early in the season has the potential risk of chilling injury from cool soils and damage from a late-spring frost. Furthermore, if planting is delayed and/or a late-maturing soybean cultivar is planted, there is an increased chance of late-season damage from a fall-frost. The ideal combination of PD and MG selection would utilize the entire growing season while avoiding damage from both late-spring and early-fall frosts.

Previous research found various benefits from adjusting MG selection based on soybean PD. In Iowa, Kessler, Archontoulis, & Licht (2019) found that the interaction between PD and MG did not impact yield or phenological development, but planting before May 20 increase yield and the duration of growth stages. This is in agreement with Boyer et al (2015) who found that the profit-maximizing PD was not different for MGs 2.0 through 5.0 in Tennessee. In Wisconsin, planting a later-maturing soybean cultivar (late MG) compared to earlier-maturing cultivars (early MG) maximized yield and oil content, but reduced protein content during early-season planting (Mourtzinis et al., 2017). Furthermore, when planting was delayed, there was little difference in yield between early and late MGs (Mourtzinis et al., 2017). This is in agreement with Salmeron et al. (2014) who found using MG 4.0 and 5.0 maximized yield during early-season planting, while using MG 3.0 and 4.0 maximized yields during late-season planting in the U.S. Mid-south. In a separate study, Salmerón et al. (2016) found that the yield for early MGs showed a quadratic response to PD while late MGs showed a more linear response, suggesting early-season planting was more appropriate for late MGs. Weeks et al. (2016) tested MG 3.0 through 6.0 across four soybean PDs and found that early-season planting using either a MG 3.0 or 4.0 improved profits in the U.S. Mid-south compared to later PDs, and higher oil and protein content compared to other PDxMG combinations. Furthermore, implementing multiple PDxMG combinations reduced the risk of profit loss compared to selecting one profit-maximizing PDxMG (Weeks et al., 2016). Overall, previous research indicates that there are benefits from adjusting MG selection based on PD, but the interaction between PD and MG is variable across environments. However, there is a lack of regional research on this aspect especially in northern soybean production environments where growers can maximize the utilization of relatively-short growing season by matching optimal MG with PD.

Soybean planted early in the growing season can accumulate more days in vegetative and reproductive growth (Chen & Wiatrak, 2010), increase light interception (Gaspar & Conley, 2015), and avoid damaging temperatures and drought stress often associated with late-season planting during critical growth stages including beginning flowering (R1), beginning seed set (R3), beginning seed fill (R5), and seed fill duration (R5-R7) (Desclaux & Roumet, 1996; Frederick, Camp, & Bauer, 2001). As a result, soybean planted early consistently produces more nodes per plant (Bastidas et al., 2008), pods m^{-2} and seeds m^{-2} (De Bruin & Pedersen, 2008;

Pedersen & Lauer, 2004). Mourtzinis, Specht, and Conley (2019) defined optimal soybean PDs in the U.S. and found that yields would have been 10% greater if growers had planted 12 days earlier than the average PD between 2007 and 2016. While Michigan soybean growers are currently planting approximately two weeks earlier in the growing season compared to the 1980s (USDA-NASS, 2019), there are often uncontrollable factors that cause delayed planting such as poor soil conditions (e.g. cool temperatures and high moisture), inclement weather, and equipment restrictions. These factors result in a wide range of soybean PDs being utilized throughout Michigan, similar to other northern US maize belt states.

There is a complex interaction between soybean PD and MG selection and the effect they have on soybean yield, quality, and phenology (Green, Pinnell, Cavanah, & Williams, 1965). Generalized areas where a particular soybean variety is best adapted, based on its MG classification, are designated by soybean MG zones (Berglund, Helmes, Jensen, & Bothun, 1998). Optimum soybean MG zones have been defined in the US by Scott & Aldrich (1970), Zhang et al. (2007), and most recently by Mourtzinis & Conley (2017) using data from state variety trials. However, these trials are restricted to one PD and do not evaluate the interaction between soybean PD and MG selection. Therefore, it is often unknown in many regions how MG selection should be adjusted based on PD. Mourtzinis & Conley (2017) recommended the use of multi-location trials using varieties of different MG grown across several PD to test PD effects on location-specific MG selection. Region-specific research evaluating MG selection based on PD will benefit growers in optimizing soybean variety maturity selection decisions. To address this need, research was conducted to determine how MG selection could be adjusted based on planting time for Michigan and other northern US states. Specific objectives were to:

i. Identify optimal soybean MG selection based on PD to maximize yield and quality while avoiding fall frost damage across Michigan environments.
ii. Determine how phenological development and yield components are impacted by PD and MG selection.
iii. Correlate differences in soybean yield with phenological development and yield components.

Methods

Experimental Sites and Design

Field experiments were conducted at Michigan State University (MSU) research stations, Mason Research Farm in Mason, MI (Mason) and Saginaw Valley Research and Extension Center in Frankenmuth, MI (Saginaw) during the 2018 and 2019 growing seasons. These sites were selected to represent two different optimal MG zones (Mourtzinis & Conley, 2017) in high soybean producing areas in Michigan (Figure 3-1). Experimental design was a randomized complete block in a split-plot arrangement with four replications at both locations. The main-plot factor consisted of four PDs and the split-plot factor consisted of six soybean varieties. The targeted PDs were late-April (~DOY 120), mid-May (~DOY 140), early-June (~DOY 160), and late-June PD (~DOY 180), specific planting dates for each site-year are reported in Table 3-1. Six soybean varieties, each separated by ~0.5 MG, were selected to represent MG 1.0, 2.0, and 3.0 (MGs 1.0, 1.4, 2.0, 2.5, 3.0, 3.5). The same six varieties were used across all site years and PDs. All varieties were glyphosate- and dicamba-tolerant.

Plots were seven rows spaced 0.38 m apart and 10.6 m in length, planted with a three-point mounted vacuum planter (John Deere, Moline, IL) fitted with vSet Select multi-hybrid metering system. The vSet Select metering system used a dual seed hopper which allowed for two seed sources to be loaded into one row unit. The variety planted into a specific plot was then controlled using a planting prescription created in SMS^{TM} (Ag Leader Technology, Inc., Ames, IA). To maneuver through the field after changing varieties, a 10.6 m alley was used between ranges. Shortly after plants in the final PD emerged, plots were trimmed to 9.1 m. The previous year's crop, tillage practices, and soil classification for each site year are presented in Table 3-1. Spring tillage for the three site years following maize (*Zea mays*) included cultivation of the entire field in early spring followed by cultivation before each PD, while spring tillage for Saginaw 2018 consisted of only cultivation before each PD. Weed management was conducted based on field needs with specific herbicides, rates, and application dates as listed in Table 3-1.

Data Collection

Soil samples from each location were collected in a w-shaped pattern at a depth of 0 to 15 cm using a soil probe and sent to MSU Soil and Plant Nutrient Lab for soil analysis (Table 3-1). Soil test results for each site-year following maize were at or above optimum nutrient levels, so no fertilizer was applied. Soil and air temperature at each location were recorded using Thermochron iButton temperature loggers' model DS1921G (Maxim Integrated Products, Sunnyvale, California). Soil temperature readings were taken at 5 cm soil depth and air temperature readings were taken at 1.5 m above the soil surface. All iButtons were placed in a 5 x 7.6 cm reclosable plastic bag to reduce the chance of failure from moisture (Roznik & Alford, 2012). The weather station closest to each field (within 7 km) in the MSU Enviro-weather Automated Weather Station Network (MAWN) was used to report precipitation data.

The whole-plant phenology staging system as described by Fehr & Caviness (1977) was used to determine soybean phenology approximately twice per week starting at emergence (VE). The timing of growth stages that were not physically recorded was estimated. Growing degree days (GDD) were calculated using a minimum temperature of 10° C, maximum temperature of 30° C, and a base temperature of 10° C. Daily minimum and maximum air temperature were collected from iButtons in each field (an iButton failed at Saginaw 2019, so the daily minimum and maximum air temperature from the nearest MAWN weather station was used). The sum of GDD accumulation for each day between growth stages was then used to calculate cumulative GDD (GDDc). After third-node appearance (V3), population counts were conducted from 3.048 m lengths of two middle rows in each plot to determine the initial plant stand. The area where population counts were taken was marked with field stakes.

At physiological maturity (R8), population counts were conducted in the same areas as the initial population count to determine the final plant stand and stand loss during the growing season. Before harvest, five representative plants from each plot were sampled by hand. The overall height, number of reproductive branches, number of nodes with pods on the main stem, and total number of nodes with pods for each plant was recorded in the field. The pods from each of the five plants were then removed from each plant and counted. Seeds were removed from pods by hand. The seed samples were cleaned using Agriculex CB-2A: Large Column Blower (Agriculex Inc., Guelph, Ontario, Canada). The seed from the five plants were then counted and weighed to determine seeds m^{-2} and seed weight.

The number of PD and MG combinations made it necessary to have three harvest dates for each site year. Harvest dates were timed to minimize seed shatter in early maturing plots and excess seed moisture in late-maturing plots. Specific harvest dates for each site year are listed in Table 3-1. All plots remaining after the second harvest date were harvested on the third harvest date. Harvest was conducted using a Kincaid 8XP (Kincaid Equipment Manufacturing, Haven, KS) plot combine equipped with Harvest Master$_{TM}$ High Capacity Grain Gauge (Juniper

Systems, Logan, UT) to measure plot weight, moisture, and test weight. Reported seed yield has been adjusted to 13% moisture.

Data Analyses

Statistical analysis was conducted with SAS® software version 9.4 (SAS Institute Inc., Cary, NC). Analysis of variance was conducted using the GLIMMIX procedure at a significance level of α=0.1. Location, PD, MG, and their interactions were included as fixed effects. Year, replication, and PD x replication were included as random effects. Degrees of freedom were calculated using the Kenward-Rodger method. Data normality was tested using the UNIVARIATE procedure. Significant effects were compared using lsmeans and the Tukey-Kramer adjustment at a significance level of α=0.1. When the interaction between PD and MG was significant, the SLICE statement was used to slice the interaction by PD. Regression analysis was conducted using the REG procedure. The correlation between yield, yield components, and phenology was analyzed using the CORR statement.

Response surface methodology was conducted using the GLIMMIX procedure to examine the effects of PD, as day of year (DOY), MG, and their interaction on seed yield. Fixed effects were considered continuous variables in the model and included the linear and quadratic terms of DOY and MG, as well as their interaction. Replication and the interaction between PD and replication were included as random effects. Response surface methodology was used to account for the limited number of varieties representing each MG in this experiment. The relationship between PD and MG is easily visualized from the response surfaces generated and is less restrictive compared to analysis of variance.

Results

Weather and Growing Conditions

Total precipitation between April and October was similar to the 30-year average for both growing seasons at Mason (Table 3-2). At Saginaw, precipitation was lower than average for every month except during August. Total precipitation at Saginaw during the 2019 growing season was 15% higher than the 30-year average, mostly driven by high precipitation during the month of October. Furthermore, the frequency of precipitation events was greater during the 2019 growing season (392 h) compared to the 2018 growing season (326 h). The month of June was dry during the 2018 growing season at both locations (< 45% of the 30-year average). July precipitation was below average for all site years and extremely low during the 2018 growing season at both locations. During August, precipitation was deficient (< 35% of the 30-year average) at both locations during the 2019 growing season.

Mean air temperatures between the months of June and October were within 20% of the 30-year average for all site years (Table 3-2). Air temperatures were 53% and 49% lower than the 30-year average during April, but 20% and 40% higher than the 30-year average during May at Mason and Saginaw, respectively, during the 2018 growing season. Air temperature during April and May during the 2019 growing season was similar to the 30-year average.

Average soil temperature during the first 24h after the late-April PD was 12.4° and 8.2° C during the 2018 growing season and 12.6° and 8.0° C during the 2019 growing season at Mason and Saginaw, respectively. Soil temperature was above 10° C at the time of planting for all other PDs. Final plant populations averaged 81% of the target population across the entire study and were above 70% of the target population for all site-years except for the late-April PD at Mason 2019 (69%) and the late-June PD at Saginaw 2018 (58%)

The first fall frost (≤ 0° C) was October 16 and 15 at Mason and October 18 and 26 at Saginaw during the 2018 and 2019 growing season, respectively. Some frost damage occurred on the leaves of the late MGs (MG 3.0 and 3.5) planted during late-June at Mason in 2018. However, because it was not a killing freeze (≤ -2.2° C), no damage to the seeds or pods occurred. All PD and MG combinations were able to reach beginning maturity before a killing freeze occurred.

Seed Yield

The interaction between PD and MG had a significant effect on soybean yield at both Mason (P=0.011) and Saginaw (P<0.001). Slicing the interaction by PD showed that the interaction between PD and MG was significant during the first two PDs (late-April and mid-May) at both locations (Table 3-4). Furthermore, the interaction was significant at Mason during the early-June PD, but was not significant at Saginaw. MG selection during late-June planting did not have a significant effect on yield at either location. However, there was a trend of decreasing yield as a longer MG was planted in late-June PD (Figure 3-2 and 3-3).

All model terms had a significant effect on yield except of the quadratic effect of MG (Table 3-5). During early-season planting, using a late MG consistently resulted in higher predicted yields (Figure 3-2 and 3-3). The predicted seed yield on DOY 120 was 3487 and 3845 kg ha^{-1} at Mason and Saginaw, respectively, when the optimal MG (Figure 3-1) for each location was used (Table 3-6). Using a full MG later than optimal (+1.0 MG) on DOY 120 increased yields by 502 and 539 kg ha^{-1} at Mason and Saginaw, respectively. Furthermore, using a full MG earlier than optimal (-1.0 MG) reduced yield by 566 and 611 kg ha^{-1} at Mason and Saginaw, respectively. Across all site years, predicted yield increased by 286 kg ha^{-1} for each 0.5 increase in MG during the late-April PDs (R^2=0.31, P <0.001). This trend was similar when planting was conducted on DOY 140 and 160, but the yield benefit of using a late MG during these planting dates was progressively reduced as planting was delayed (Table 3-6). Using a full MG later than optimal increase yield by an average of 297 kg ha^{-1} when planting on DOY 140 and 72.6 kg ha^{-1} when planting on DOY 160. Across all site years, soybean yield increased by 171 and 73.0 kg ha^{-1} for each 0.5 increase in MG during mid-May (R^2=0.15, P<0.001) and early-June (R^2=0.05, P=0.03) PDs, respectively. When planting was delayed to DOY 180, using a full MG earlier than optimal resulted in a 46.4 and 121 kg ha^{-1} yield increase at Mason and Saginaw, respectively, and using a full MG later than optimal resulted in a 111 and 192 kg ha^{-1} reduction in yield at Mason and Saginaw, respectively. Across all site years, there was a 51.4 kg ha^{-1} reduction in yield for each 0.5 increase in MG during the late-June PD (R^2=0.03, P=0.09).

Phenology and Yield Components

The interaction between PD and MG had a significant effect on the duration (number of days) of and GDD_c during vegetative growth (emergence to beginning flower; VE to R1), pod and seed set (beginning flower to beginning seed; R1 to R5), and seed fill (beginning seed to beginning maturity; R5 to R7) at P<0.1. The duration of vegetative growth was greatest when a MG 3.0 or 3.5 was used across all PDs (Table 3-7). Furthermore, the duration of vegetative growth was the greatest for all MGs during the late-April PD. Averaged across all MGs, each day delay in planting after DOY 116 resulted in a 0.17 d (R^2=0.34, P<0.001) reduction in vegetative growth. However, this did not always translate to a reduction in GDD_c. Accumulation of GDD_c during vegetative growth for MGs 1.0, 1.4, and 2.0 was not impacted by PD, while maximum vegetative GDD_c was achieved when planting occurred in early-June for MGs 2.5, 3.0, and 3.5 (Table 3-7). Across all PDs, GDD_c during vegetative growth was higher when a later

MG was planted (Table 3-7). During late-April and mid-May planting, vegetative GDD_c was highest when a MG 3.0 or 3.5 was planted. Maximum vegetative GDD_c was achieved when a MG 3.5 was planted during early-June and when a 2.5, 3.0, or 3.5 was planted during late-June.

The effect of the PDxMG interaction on the duration of pod and seed set was similar to the effect on GDD_c during pod and seed set, but the effect of MG was different based on PD (Tables 3-7 and 3-8). During the late-April PD, the duration of pod and seed set was extended as a later MG was used (Table 3-7). This resulted in greater GDD_c for the later MGs (Table 3-8). This trend was similar when planting occurred in mid-May, but the effect was less pronounced compared to the late-April PD. When planting was delayed to early-June, GDD_c was greatest using a MG 1.4 or 2.0 and reduced when a MG 1.0, 3.0, or 3.5 was planted. There was no impact on GDD_c or duration of pod and seed set during the late-June PD. A longer duration in pod and seed set typically resulted in greater GDD_c, but was not always the case. The duration of pod and seed set was not impacted by PD for MG 1.0 (Table 3-7). However, GDD_c during pod and seed set was greater for MG 1.0 when planting occurred earlier in the season (Table 3-8). Furthermore, the duration of pod and seed set was greatest for MG 1.4 during the mid-May PD, but GDD_c was maximized during the early-June PD. GDD_c was highest during the late-April PD for MGs 2.5, 3.0, and 3.5 and was not different from the highest for MGs 1.0, 1.4, and 2.0.

Similar to GDD_c during pod and seed set, the effect of MG selection on the duration of seed fill and GDD_c during seed fill was different across PDs (Table 3-7 and 3-8). During the late-April PD, the duration of seed fill typically increased with the use of a later MG (Table 3-7). However, MG selection did not impact GDD_c during seed fill for the late-April PD (Table 3-8). The same trend was observed for the mid-May and early-June PDs. During the mid-May PD, MG 3.0 and 3.5 had the greatest duration of seed fill, but the 1.0 MG accumulated 51 more

GDD_c during seed fill than the 3.5 MG. Furthermore, no other differences were observed between MGs for GDD_c. The duration of seed fill during the early-June PD was extended with the use of a late MG, but did not increase GDD_c accumulation. When planting was delayed to late-June, the duration of seed fill was greatest for MG 2.0 and above. However, MGs 1.4, 3.0, and 3.5 accumulated the fewest GDD_c. While the duration of seed fill was variable across MGs based on PD, GDD_c during seed fill was greatest during the late-April PD for all MGs, but was not different from the mid-May and early-June PD for MG 1.0 and not different from the mid-May PD for MG 2.5.

There was a positive correlation between yield and all examined yield components except the number of nodes plant^{-1} (Table 3-9). Furthermore, there was a positive correlation between yield and GDD_c during vegetative growth, pod and seed set, and seed fill. There was a stronger correlation between yield and seeds m^{-2} (r=0.43) compared to other yield components (r<0.25). The number of seeds m^{-2} was positively correlated with GDD_c during seed fill (r=0.25) which also had the strongest correlation with yield (r=0.41) compared to other growth phases. The correlation between GDD_c during seed fill was strongly correlated with seed weight (r=0.52) and with seed yield (r=0.36). However, the correlation between seed yield and seed weight was weaker when compared to seeds m^{-2} (r=0.24).

Using a late MG resulted in an overall increase in the number of seeds m^{-2} (Figure 3-4). There was a greater increase in seeds m^{-2} when a late MG was used before ~DOY 160, with the maximum number of seeds m^{-2} achieved from using a late MG on ~DOY 140 (Figure 3-4). However, using a late MG resulted in an overall reduction in seed weight (Figure 3-5). Using a late MG after DOY 140 resulted in a greater reduction in seed weight compared to when planting was conducted earlier in the season. This suggests that the increase in yield from using a longer

MG during late-April, mid-May, and early-June is mainly driven by the increase in the number of seeds m^{-2} rather than an increase in seed weight.

Harvest Quality

The last harvest at each location was postponed as late as possible to give the late MGs planted late in the season the maximum amount of time to dry. Adjusting MG selection during the late-June PD had implications on soybean quality at the time of harvest. Across all site years, soybean seed moisture at the time of harvest was the highest when a late MG was planted later in the season (Figure 3-6). Seed moisture was lower when soybean were planted earlier in the season, or when an early MG was planted late.

Discussion

The overall goal of this study was to evaluate the effect of adjusting MG selection based on soybean PD in the northern US production regions, where early and late-season freeze damage is more of a concern compared to southern states. The relatively-short growing season makes soybean PD and MG selection especially important in northern regions so the entire available growing season can be utilized. Failure to properly adjust MG based on PD can result in either "under-utilization" of the growing season or can lead to frost damage in the fall. Results from this study show that the complex interaction between soybean PD and MG selection determines yield potential, phenological development, and growing season utilization for a soybean crop.

Planting a late MG early in the season increased the duration of vegetative growth and pod and seed set compared to planting early MGs, which also resulted in greater GDD_c accumulation (Table 3-7). However, the longer duration spent in seed fill did not result in greater

GDD_c during seed fill. This is similar to the findings of Chen & Wiatrak (2010) who found that as soybean planting was delayed, the length of the growing season shortened. Depending on MG selection, the duration of vegetative growth decreased by 0.39 to 1.64 days, while the duration of reproductive growth was reduced by 0.88 to 1.99 for each day planting was delayed (Chen & Wiatrak, 2010). Therefore, using a full MG later than what is considered optimal increased yield by an average of 521 kg ha^{-1} during early-season planting (DOY 120), which is in agreement with other studies that found using a late MG during early-season planting results in a yield increase (Mourtzinis et al., 2017; Salmeron et al., 2014; Weeks et al., 2016; Wood et al., 2019). The stronger correlation between seeds m^{-2} and seed yield compared to seed weight and seed yield suggests that the yield increase from using a late MG during early-season planting was mainly driven by an increase in the number of seeds m^{-2} (Table 3-9).

The yield benefits from using a late MG were reduced as soybean planting was delayed (Figures 3-2 and 3-3). However, soybean growers who do not intend to plant early in the season can still benefit from adjusting MG selection. The effect of MG selection on seed yield during the mid-May PD was significant at both locations, but only significant at Mason during the early-June PD (Table 3-4). Furthermore, the yield benefit from using a late MG was less during the mid-May and early-June PDs compared to the late-April PD. This is in agreement with Mourtzinis et al. (2017) and Salmerón et al. (2016) who found that there was a greater yield benefit from using a late MG during early-season planting compared to later PDs. Furthermore, using a late MG during the mid-May and early-June PDs increased the duration and GDD_c during vegetative growth, but there was little difference in GDD_c during pod and seed set and seed fill for the mid-May and early-June PDs (Table 3-8). This suggests that growers have the opportunity to select a wide range of MGs during mid-season planting without losing soybean yield. Selecting an early MG during mid-season planting can result in earlier soybean harvest. This has the potential to benefit soybean growers who include fall-planted crops in their rotation such as wheat (*Triticum aestivum* L.). The earlier soybean harvest would provide a greater opportunity for wheat planting to be conducted at an optimum planting date, which has been shown to improve wheat yields (Dahlke, Oplinger, Gaska, & Martinka, 1993), without any soybean yield penalty as shown in this study.

When soybean planting was delayed to late-June, soybean yield was not impacted by MG selection. However, there was a trend of decreasing yield when a later MG was planted during the late-June PD (Figures 3-2 and 3-3). Using a late MG during the late-June PD resulted in increased duration and GDD_c accumulation for vegetative growth (Table 3-8 and 3-9). However, the duration and GDD_c for pod and seed set was not impacted by MG selection during the late-June PD. Using a longer MG resulted in a longer duration of seed fill for the late-June PD, but did not increase GDD_c during seed fill (Table 3-8). This is in agreement with Chen & Wiatrak (2010) who found the duration of vegetative and reproductive growth shortened when planting was delayed using a late MG.

While adjusting MG selection based on PD has benefits, especially during early-season planting, improper MG selection can have repercussions. Using a late MG consistently resulted in increased yield during early-season planting. This trend was also similar during mid-season planting. However, using a late MG during late planting may make it difficult to achieve optimal harvest quality. Delayed planting results in a reduction in the available growing season and GDD accumulation. If planting is delayed and a late MG is used, problems may occur during harvest due to high seed moisture (Figure 3-6). This would likely increase production cost from seed drying or reduced net returns due to discounts applied during sale. When planting is delayed, an early MG should be planted. This provided adequate time for seed to dry to harvest moisture in the field and did not impact yield in this study.

The increase in weather variability during the soybean planting season makes optimizing MG selection based on PD a difficult task. The actual soybean PD is often unknown until shortly before planting occurs. Furthermore, MG selection is often done months before soybean planting. Therefore, it is unlikely that quick adjustments in MGs can be achieved once the PD is known. Instead, growers should plan ahead to predict the optimal MG selection based on their targeted PDs, equipment availability, farm size, crop rotation, and location. Large soybean operations, which work with various field conditions, can benefit from implementing a wide range of MGs. This would allow late MGs to be planted on fields that can be prepared earlier in the season (e.g. light textured soil, tile drainage) and early MGs on fields that require more time before planting can occur (e.g. heavy textured soils, low topography). Growers who target early-season soybean planting can increase yield by using a late MG. If conditions cause planting to be slightly delayed, a yield benefit can still be achieved when a late MG is used compared to an early MG. If planting is delayed to late-season, there is no yield benefit to using a late MG and issues with high seed moisture at harvest may cause production complications. If this occurs, the grower may consider changing to an early MG.

Overall, the results of this study show that soybean growers can benefit from adjusting MG selection based on PD. Growers should target the PD and MG combination that utilizes the entire available growing season, while avoiding damage from fall and spring freezes, to maximize yield and profits. Improper MG selection based on PD can result in under-utilization of the growing season and reduce soybean yield. This is in agreement with similar studies such as Mourtzinis, Gaspar, Naeve, & Conley (2017), Salmeron et al. (2014), Weeks et al. (2016), and

Wood et al. (2019). These studies find that adjusting MG selection based on PD is successful in achieving higher yields, improved quality, and higher profits. Information from this research can be used to make specific MG recommendations based on soybean PD in Michigan and other northern US soybean growing regions. Identifying how MG selection should be adjusted based on PD is just one part in developing a complete recommendation for how soybean should be managed based on PD. Future research should be conducted to determine how other management practices (e.g. fertility, row spacing, seeding rate) should be adjusted based on PD and MG selection to create recommendations that soybean growers can use to maximize yield, quality, and profitability.

APPENDICES

APPENDIX A:

Chapter 3 Tables and Figures

Table 3-1. Agronomic details for each site year at two locations in Michigan during the 2018 and 2019 growing seasons.

Year	Location	Planting Dates	Previous Crop	Fall Tillage	Spring Tillage	Soil Class	Soil pH	P	K	Mg	Ca	CEC	Weed Control‡	Harvest Dates
								g kg^{-1}				meq 100g^{-1}		
2018	Mason	April 29 May 25 June 8 June 29	Corn	Chisel Plow	Field Cultivator x2	Conover Loam	6.8	52	104	238	1617	10.3	May 28 glyphosate July 01 glyphosate	Oct. 17 Nov. 8 Nov. 19
	Saginaw†	April 30 May 17 June 9 June 26	Wheat	None (oat cover)	Field Cultivator	Tappan-Londo Loam	7.9	52	124	303	2451	15.1	May 29 glyphosate July 24 glyphosate	Oct. 23 Oct. 30 Nov. 20
2019	Mason	April 26 May 15 June 4 June 27	Corn	Chisel Plow	Field Cultivator x2	Conover Loam	6.2	37	101	132	1139	8.3	May 30 glyphosate June 19 glyphosate July 17 ssb + asi	Oct. 10 Oct. 25 Nov. 23
	Saginaw	April 27 May 14 June 8 June 26	Corn	Chisel Plow	Field Cultivator x2	Tappan-Londo Loam	7.6	35	167	424	2541	16.7	May 16 glyphosate June 19 glyphosate	Oct. 11 Oct. 25 Nov. 24

†An application of (MAP) was applied at a rate of 62 kg ha^{-1} to supply nutrients to an oat (*Avena sativa*) cover crop in the fall.

‡Glyphosate was applied at a rate of 1.68 kg a.i. ha^{-1}, sodium salt of bentazon (ssb) was applied at a rate of 1.35 kg a.i. ha^{-1}, ammonium salt of imazamox (asi) was applied at a rate of 0.45 kg a.i. ha^{-1}

Table 3-2. Monthly† and 30-year mean‡ precipitation and temperature for each site year.

Location	Year	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Total
		Precipitation cm							
Mason	2018	6.0	12.6	3.7	2.7	11.7	10.3	10.5	57.5
	2019	7.2	8.5	11.5	5.8	1.8	9.3	13.0	57.1
	30-yr.	**7.3**	**8.5**	**8.9**	**8.3**	**8.4**	**9.2**	**7.0**	**57.6**
Saginaw	2018	7.2	5.4	3.7	5.0	20.1	4.9	5.9	52.2
	2019	5.8	12.8	17.7	6.0	2.7	9.6	16.0	70.6
	30-yr.	**7.5**	**8.7**	**10.0**	**9.3**	**8.6**	**9.8**	**7.4**	**61.3**
		Temperature °C							
Mason	2018	4.1	17.6	20.0	21.9	21.8	18.0	9.6	
	2019	8.0	14.3	20.0	24.2	21.4	19.1	10.5	
	30-yr.	**8.7**	**14.7**	**20.0**	**22.1**	**21.3**	**16.9**	**10.4**	
Saginaw	2018	3.6	18.3	20.8	23.3	22.2	18.3	9.8	
	2019*	7.4	12.7	18.3	22.7	19.9	17.8	9.7	
	30-yr.	**7.0**	**13.1**	**18.6**	**20.5**	**19.5**	**15.7**	**9.2**	

†Monthly air temperatures between May and October were collected from iButton installed 1.5m above the soil surface. Monthly precipitation data and monthly temperature data during April was collected from the nearest weather station in the MSU Enviro-weather

‡30-year mean temperature and precipitation data collected from the National Oceanic and Atmosphere Administration (https://www.ncdc.noaa.gov/cdo-web/datatools/normals)

§Monthly air temperature collected from MSU Enviro-weather.

Table 3-3. Climatological date of the first fall freeze for each location.

Location	First (Fall) Freeze†		
	Percentile		
	10th	50th	90th
Mason	Oct 1 - 10	Oct 11 - 20	Nov 1 - 10
Saginaw	Sep 21 - 30	Oct 11 - 20	Oct 21 - 31

† Freeze data collected from Midwestern Regional Climate Center Vegetation Impact Program (https://mrcc.illinois.edu) for years 1980-81 to 2009-2010.

Table 3-4. Interaction between planting date (PD) and maturity group (MG), sliced by PD, on soybean seed yield at Mason and Saginaw.

Location	Pr > F
Mason	
Late-April PD	<0.001
Mid-May PD	0.005
Early-June PD	0.007
Late-June PD	0.359
Saginaw	
Late-April PD	<0.001
Mid-May PD	0.021
Early-June PD	0.745
Late-June PD	0.152

Table 3-5. The linear and quadratic effects of planting date (DOY) and maturity group (MG), and the interaction between DOY and MG on soybean seed yield. DOY and MG are treated as continuous variables.

Location	Estimate	Pr > F
Mason		
Intercept	-12967	-
DOY	203.05	<0.001
DOY*DOY	-0.6546	<0.001
MG	1866.18	<0.001
MG*MG	-37.7311	0.573
DOY*MG	-9.7063	<0.001
Saginaw		
Intercept	-12364	-
DOY	203.89	<0.001
DOY*DOY	-0.6632	<0.001
MG	2180.63	<0.001
MG*MG	-35.6666	0.547
DOY*MG	-12.1919	<0.001

Table 3-6 . Estimated seed yield for the optimal maturity group (MG) for each location compared to ±1.0 MG of the optimal MG on four planting dates (DOY).

Location	DOY	-1.0 MG	Optimal MG	+1.0 MG
			kg ha^{-1}	
Mason				
	120	2921	3487	3989
	140	3309	3670	3968
	160	3160	3317	3411
	180	2474	2428	2317
Saginaw				
	120	3235	3845	4385
	140	3620	3987	4282
	160	3475	3598	3649
	180	2799	2678	2486

Table 3-7. Duration (days) of vegetative growth, pod and seed set, and seed fill by planting date, for soybean varieties in six maturity groups (MG).

	Vegetative				Pod and Seed Set				Seed Fill			
MG	Late-April	Mid-May	Early-June	Late-June	Late-April	Mid-May	Early-June	Late-June	Late-April	Mid-May	Early-June	Late-June
	days											
1.0	40 aC†	34 bD	32 cC	30 cC	25 aC	26 aC	23 aA	23 aA	40 aD	42 aB	39 aC	40 aB
1.4	41 aC	35 bCD	32 cC	32 cC	25 bC	31 aABC	24 bA	22 bA	43 aBCD	39 bB	39 bC	38 bB
2.0	42 aC	37 bC	34 cC	32 cC	29 abBC	31 aAB	26 bcA	24 cA	44 aBC	40 bB	41 abBC	45 aA
2.5	46 aB	43 bB	40 cB	37 dAB	32 aAB	29 abABC	27 bA	21 cA	43 bCD	42 bB	42 bBC	47 aA
3.0	50 aA	46 bAB	40 cB	37 dB	32 aAB	27 bBC	27 bA	22 cA	47 aAB	48 aA	45 aAB	48 aA
3.5	50 aA	48 aA	44 bA	40 cA	34 aA	32 aA	27 bA	24 bA	51 aA	48 abA	47 bA	48 abA

† Within a growth stage, treatment means followed by a different lowercase letter represent a planting date difference at $P < 0.1$ within a given maturity group (MG); and means followed a different uppercase letter represent a MG difference difference at $P < 0.1$ within a given planting date.

Table 3-8. Cumulative growing degree day (GDD_c) accumulation during vegetative growth, pod and seed set, and seed fill by planting date, for soybean varieties in six maturity groups (MG).

	Vegetative				Pod and Seed Set				Seed Fill			
MG	Late-April	Mid-May	Early-June	Late-June	Late-April	Mid-May	Early-June	Late-June	Late-April	Mid-May	Early-June	Late-June
	GDD_c											
1.0	385 aC†	392 aD	406 aC	401 aB	331 aC	305 abB	284 bcB	241 cA	463 aA	442 aA	432 aA	350 bA
1.4	401 aC	411 aCD	404 aC	428 aB	329 abC	305 bB	361 aA	238 cA	496 aA	430 bAB	403 bA	337 cAB
2.0	419 aC	440 aC	417 aC	426 aB	365 aBC	315 bAB	361 abA	257 cA	490 aA	438 bAB	413 bA	354 cA
2.5	464 bB	488 bB	522 aB	489 bA	396 aAB	328 bAB	320 bAB	229 cA	459 aA	417 abAB	403 bA	345 cA
3.0	511 abA	519 aAB	534 aB	484 bA	388 aAB	329 bAB	297 bcB	251 cA	497 aA	440 bAB	429 bA	327 cAB
3.5	522 bcA	555 abA	578 aA	520 cA	420 aA	360 bA	298 cB	260 cA	495 aA	391 bB	402 bA	290 cB

† Within a growth stage, treatment means followed by a different lowercase letter represent a planting date difference at $P < 0.1$ within a given maturity group (MG); and means followed a different uppercase letter represent a MG difference difference at $P < 0.1$ within a given planting date.

Table 3-9. Pearson correlation coefficients for soybean yield, yield components, and GDD_c during main growth phases.

	Yield	Nodes plant^{-1}†	Pods node^{-1}	Seeds pod^{-1}	Pods m^{-2}	Seeds m^{-2}	Seed weight	GDD_c VE-R1	GDD_c R1-R5	GDD_c R5-R7
Yield	1.00	-0.03	0.24***	0.14**	0.23***	0.43***	0.24***	0.21***	0.41***	0.36***
Nodes plant^{-1}		1.00	-0.51***	-0.14**	0.29***	0.26***	-0.36***	0.11*	-0.09	-0.16**
Pods node^{-1}			1.00	0.24***	0.36***	0.42***	0.26***	0.16**	0.18***	0.14**
Seeds pod^{-1}				1.00	-0.04	0.25***	-0.01	0.25***	0.05	-0.14**
Pods m^{-2}					1.00	0.77***	0.05	0.12*	0.11*	0.17***
Seeds m^{-2}						1.00	0.01	0.16**	0.25***	0.18***
Seed weight							1.00	0.02	0.18***	0.52***
GDD_c VE-R1								1.00	-0.11*	0.05
GDD_c R1-R5									1.00	0.25***
GDD_c R5-R7										1.00

*, **, *** Significant correlations at α=0.05, 0.01, and 0.001, respectively.
† The number of reproductive nodes on each plant.

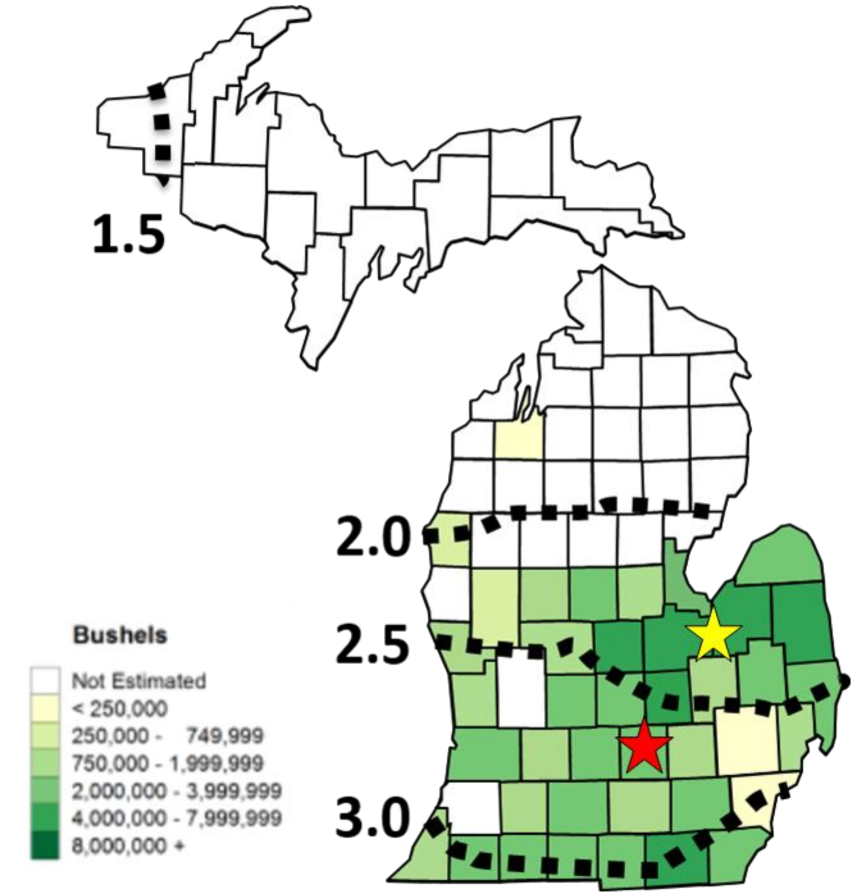

Figure 3-1. Soybean maturity groups best adapted to each region (i.e. optimal) in Michigan as described by Mourtzinis & Conley (2017). Trials locations (Mason- red star; Saginaw- yellow star) represents two major zones of soybean production in Michigan. Shade of green color in counties signify soybean production based on 2018 USDA-NASS estimates.

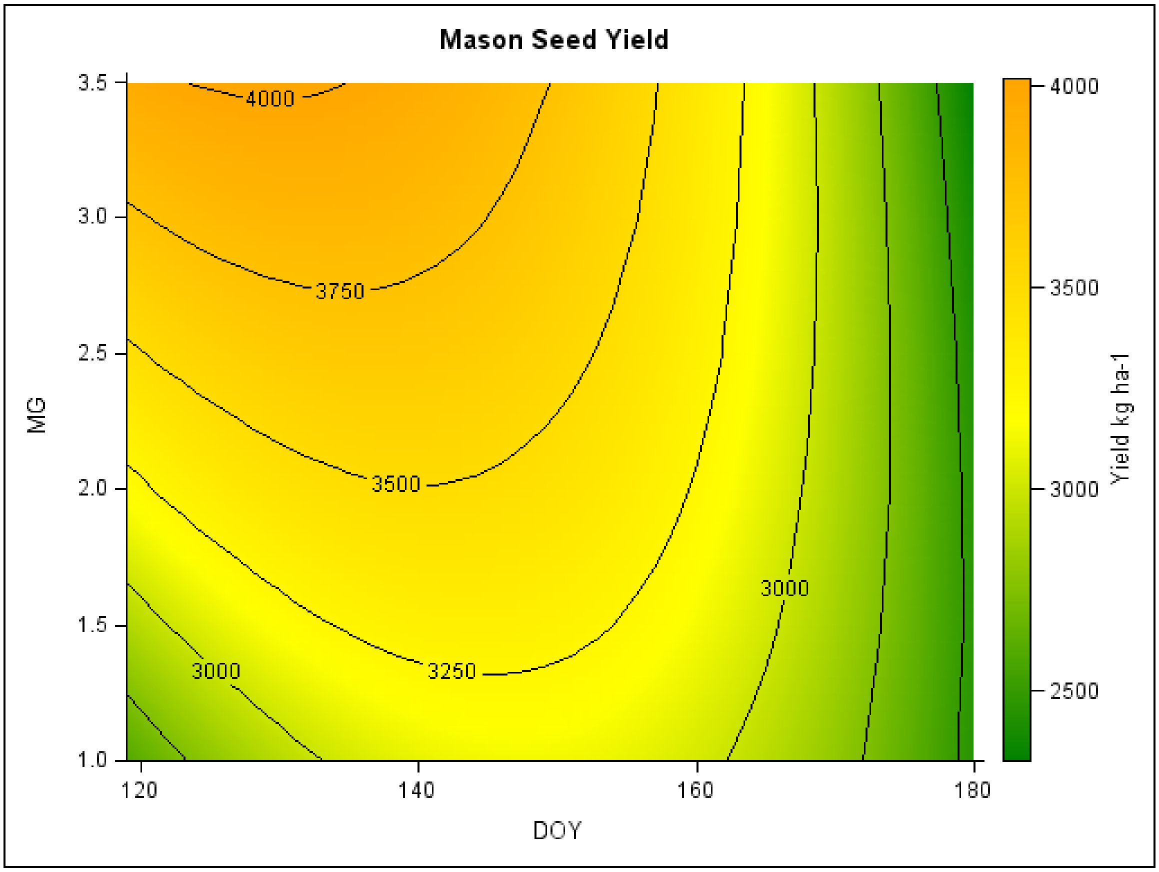

Figure 3-2. The effect of planting date (DOY) and maturity group (MG) selection on soybean seed yield at Mason during the 2018 and 2019 growing season.

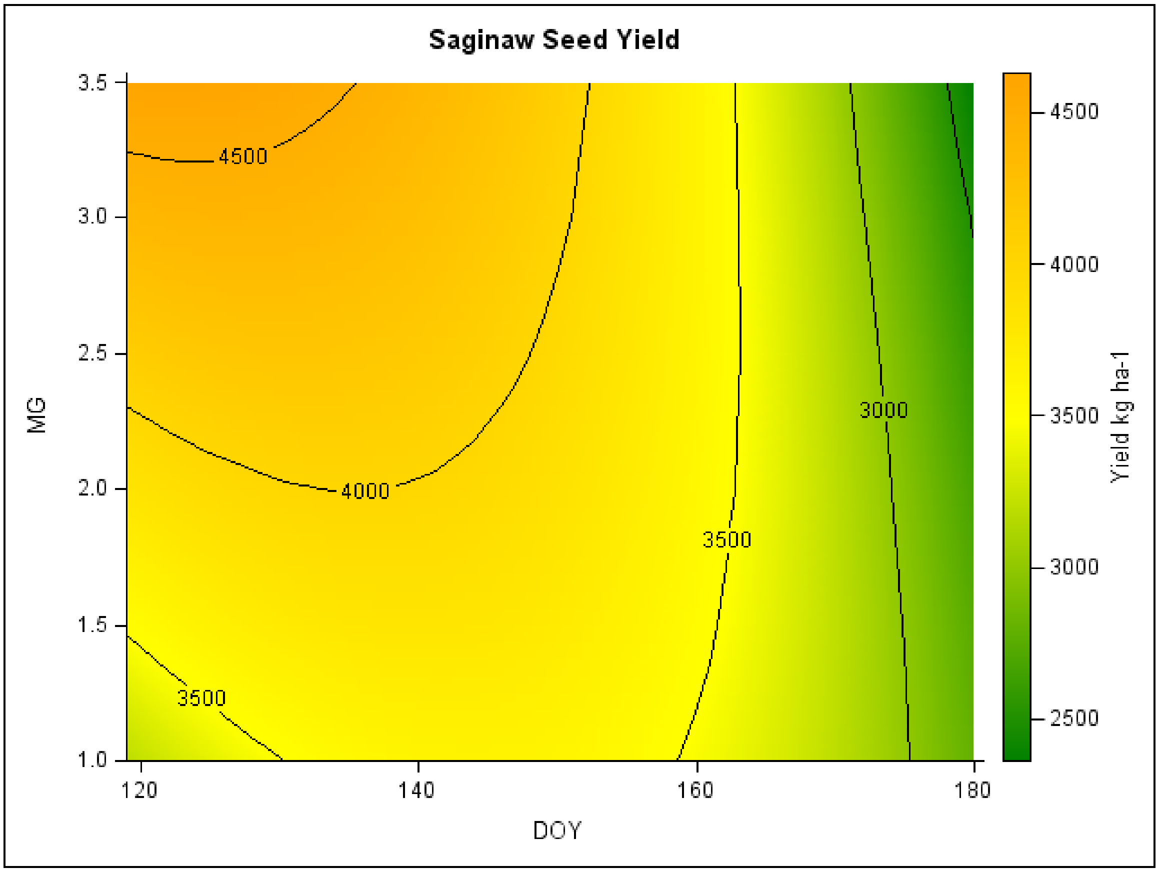

Figure 3-3. The effect of planting date (DOY) and maturity group (MG) selection on soybean seed yield at Saginaw during the 2018 and 2019 growing season.

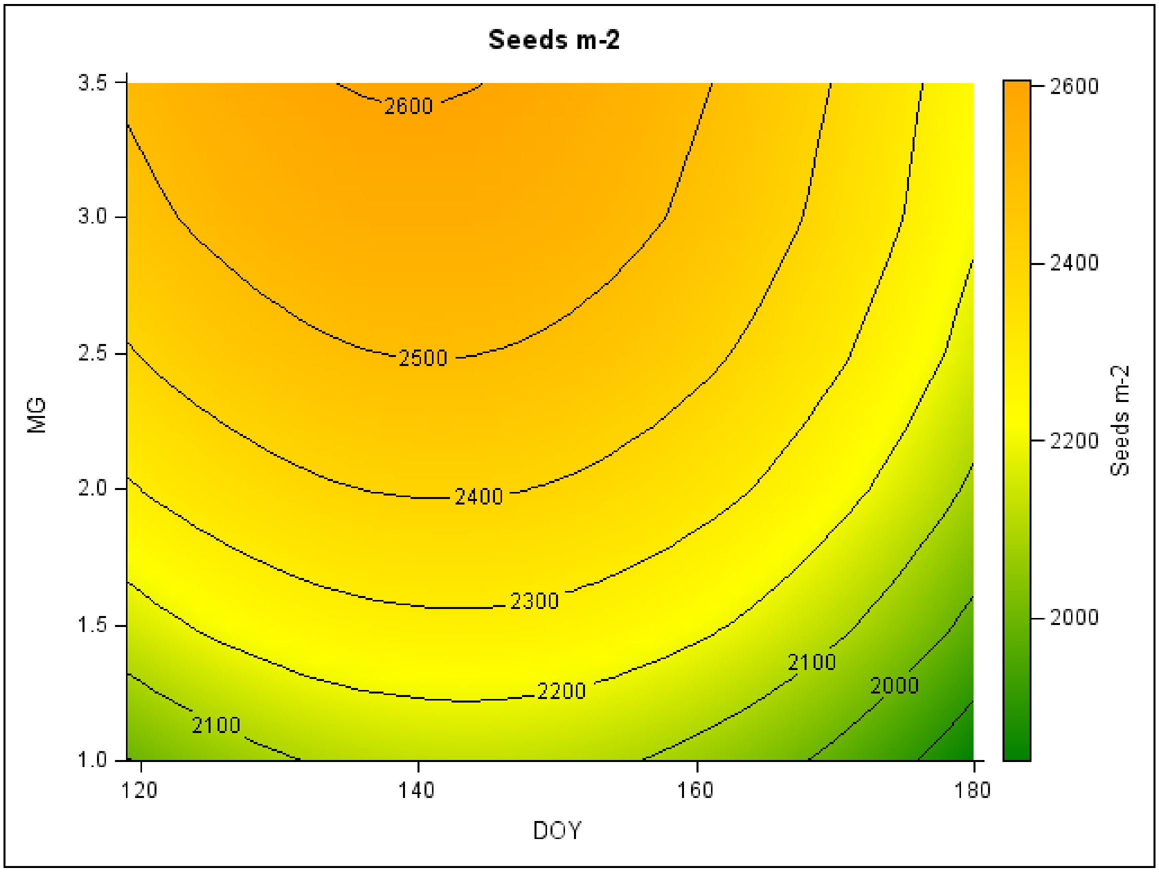

Figure 3-4. The effect of planting date (DOY) and maturity group (MG) selection on soybean seeds m^{-2} across both locations during the 2018 and 2019 growing season.

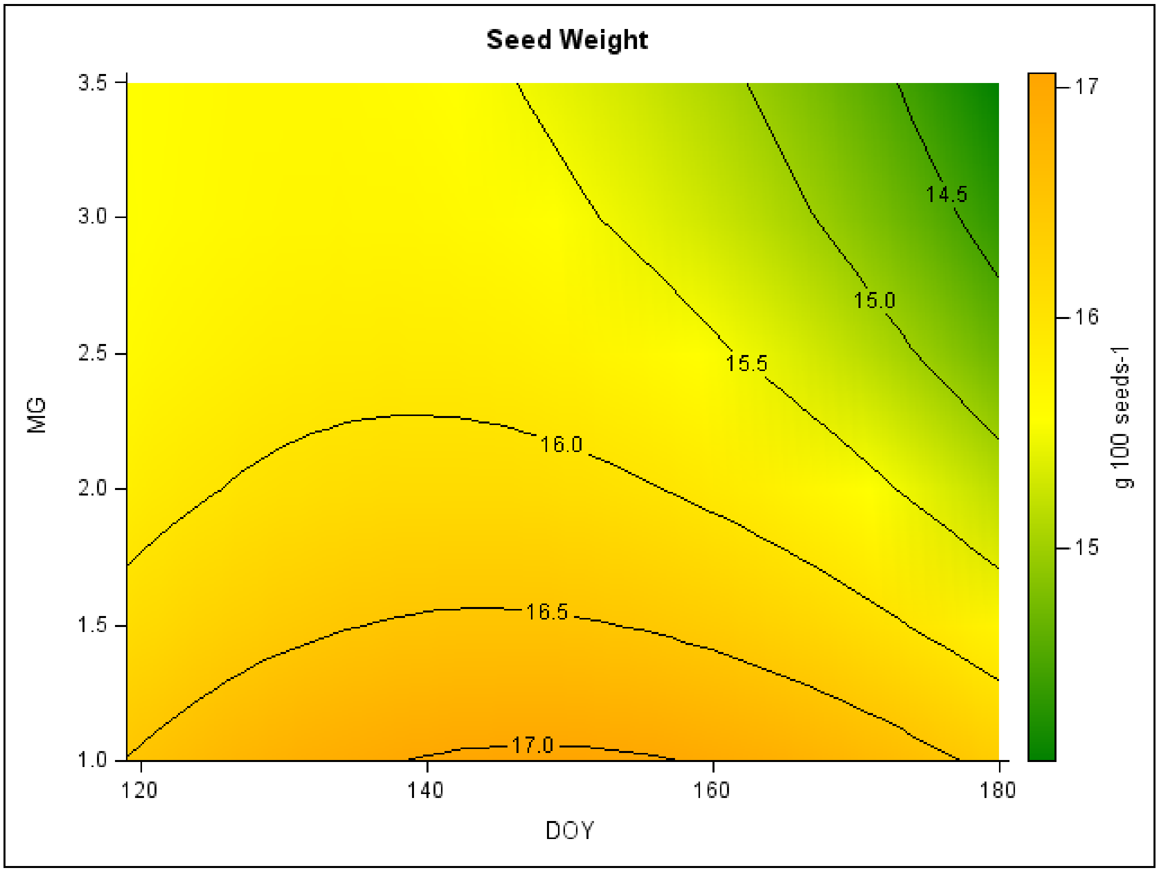

Figure 3-5. The effect of planting date (DOY) and maturity group (MG) selection on soybean seed weight across both locations during the 2018 and 2019 growing season.

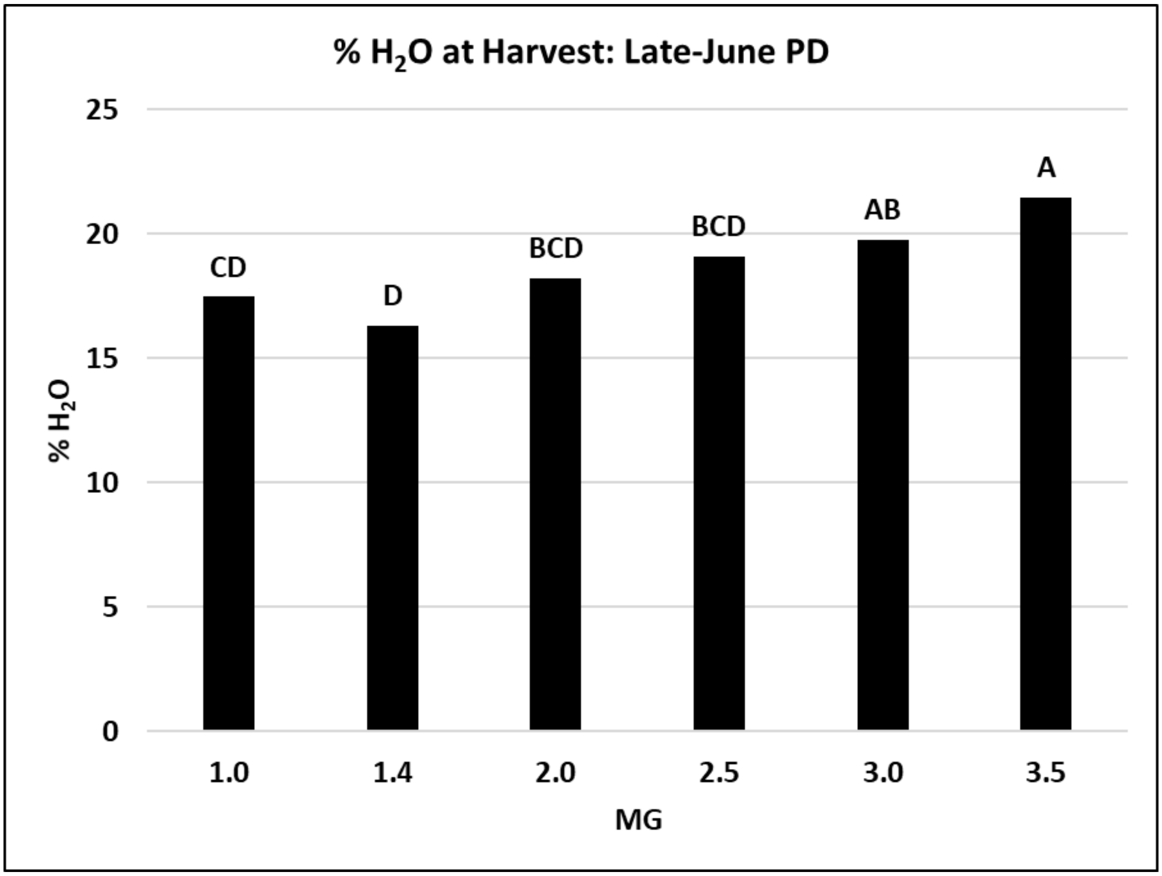

Figure 3-6. Effect of maturity group (MG) selection on percent seed moisture at the time of harvest for the late-June planting date (PD) across all site years. Bars with the same letter are not different at $P<0.1$.

APPENDIX B:

Chapter 3 Additional Data

Leaf area index (LAI) was recorded throughout the growing season using Delta-T SunScan Canopy Analysis System type SS1 radio version (Sunscan) with a BF5 Sunshine sensor (Delta-T Devices Ltd, Cambridge, UK) mounted on a tripod. Sunscan readings were taken at 2.5 cm above the soil surface at four locations within each plot. The 1 m long probe was positioned at a 45° angle so that the three center rows of each plot were covering the sensor.Photosynthetically active radition (PAR) was measured above and below the canopy using this system. Percent canopy cover was calculated using Equation [3-1]:

$$C = \left[1\left(\frac{PARbelow}{PARabove}\right)\right]100 \qquad [3\text{-}1]$$

Where *C* is the percent canopy cover, *PARbelow* is the PAR below the canopy (µmol m^{-2} s^{-1}) and *PARabove* is the PAR above the canopy (µmol m^{-2} s^{-1}).

The Canopeo smartphone app (Oklahoma State University, Stillwater, OK) was used to take percent canopy cover estimations from each plot on the same days that LAI was recorded, by holding camera at 1.5m above the canopy. The Trimble® Greenseeker® handheld crop sensor (Trimble Inc., Sunnyvale, California) was used to record NDVI. A constant height above the canopy was achieved using a weight affixed to a string which was then attached to the sensor. All canopy readings were taken within the same 3.048 m length of row used for initial population counts.

$$C = \left[1\left(\frac{PARbelow}{PARabove}\right)\right]100$$

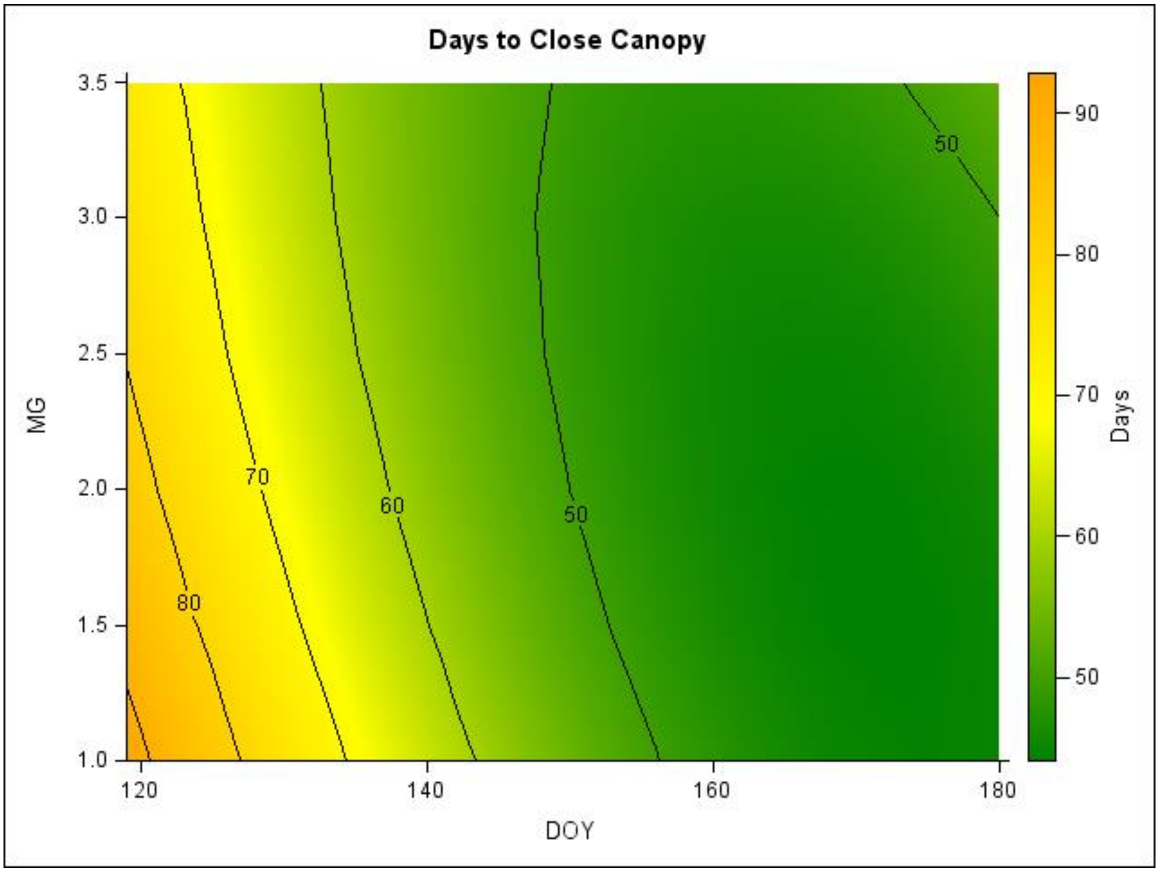

Figure 3-7. Effect of planting date (DOY) and maturity group (MG) selection on the number of days to reach canopy closure (LAI = 4) measured with the Sunscan system at Mason 2018.

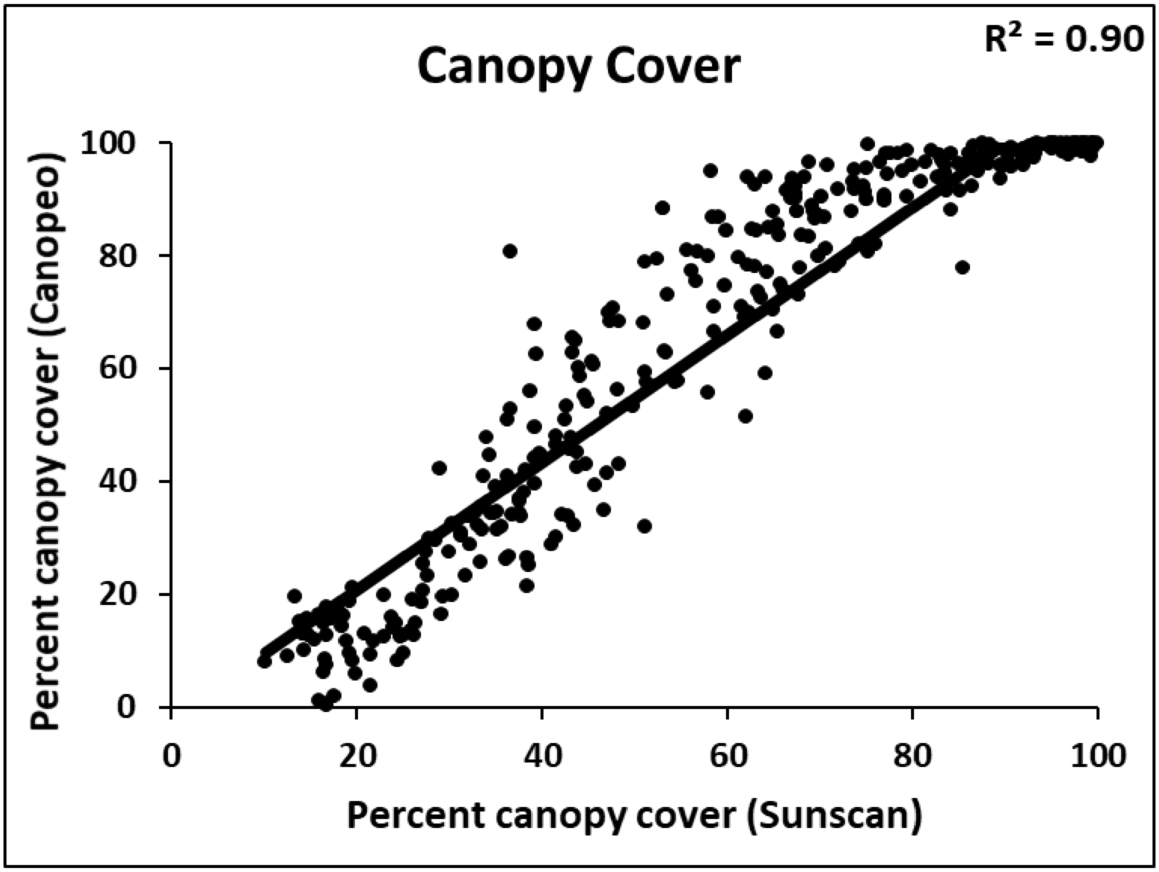

Figure 3-8. Relationship between percent canopy cover based on measurements using the Canopeo app and the Sunscan system (P<0.001).

LITERATURE CITED

LITERATURE CITED

Bastidas, A., Setiyono, T., Dobermann, A., Cassman, K. G., Elmore, R. W., Graef, G. L., & Specht, J. E. (2008). Soybean sowing date: The vegetative, reproductive, and agronomic impacts. *Crop Science, 48*(2), 727-740.

Bellaloui, N., Reddy, K. N., & Gillen, A. M. (2011). Influence of planting date on seed protein, oil, sugars, minerals, and nitrogen metabolism in soybean under irrigated and non-irrigated environments. *American Journal of Plant Sciences,* 2, 702-715.

Berglund, D. R., Helmes, T. C., Jensen, L., & Bothun, R. (1998). Soybean production. *North Dakota State University Extension.* A-250.

Boyer, C. N., Stefanini, M., Larson, J. A., Smith, S. A., Mengistu, A., & Bellaloui, N. (2015). Profitability and risk analysis of soybean planting date by maturity group. *Agronomy Journal, 107*(6), 2253-2262.

Chen, G., & Wiatrak, P. (2010). Soybean development and yield are influenced by planting date and environmental conditions in the southeastern coastal plain, United States. *Agronomy Journal, 102*(6), 1731-1737.

Dahlke, B., Oplinger, E., Gaska, J., & Martinka, M. (1993). Influence of planting date and seeding rate on winter wheat grain yield and yield components. *Journal of Production Agriculture, 6*(3), 408-414.

De Bruin, J. L., & Pedersen, P. (2008). Soybean seed yield response to planting date and seeding rate in the Upper Midwest. *Agronomy Journal, 100*(3), 696-703.

Desclaux, D., & Roumet, P. (1996). Impact of drought stress on the phenology of two soybean (*Glycine max* L. Merr) cultivars. *Field Crops Research, 46*(1-3), 61-70.

Egli, D., & Bruening, W. (1992). Planting date and soybean yield: evaluation of environmental effects with a crop simulation model: SOYGRO. *Agricultural and Forest Meteorology, 62*(1-2), 19-29.

Fehr, W. R., & Caviness, C. E. (1977). Stages of soybean development. *Special Report.* 87.

Frederick, J. R., Camp, C. R., & Bauer, P. J. (2001). Drought-stress effects on branch and mainstem seed yield and yield components of determinate soybean. *Crop Science, 41*(3), 759-763.

Gaspar, A. P., & Conley, S. P. (2015). Responses of canopy reflectance, light interception, and soybean seed yield to replanting suboptimal stands. *Crop Science, 55*(1), 377-385.

Green, D., Pinnell, E., Cavanah, L., & Williams, L. (1965). Effect of planting date and maturity date on soybean seed quality 1. *Agronomy Journal, 57*(2), 165-168.

Kessler, A., Archontoulis, S., & Licht, M. (2019). Soybean yield and crop stage response to planting date and cultivar maturity in Iowa, USA. *Agronomy Journal*.

Kumudini, S. V., Pallikonda, P. K., & Steele, C. (2007). Photoperiod and E-genes influence the duration of the reproductive phase in soybean. *Crop Science, 47*(4), 1510-1517.

Mourtzinis, S., & Conley, S. P. (2017). Delineating soybean maturity groups across the United States. *Agronomy Journal, 109*(4), 1397-1403.

Mourtzinis, S., Gaspar, A. P., Naeve, S. L., & Conley, S. P. (2017). Planting date, maturity, and temperature effects on soybean seed yield and composition. *Agronomy Journal, 109*(5), 2040-2049.

Mourtzinis, S., Specht, J. E., & Conley, S. P. (2019). Defining optimal soybean sowing dates across the US. *Scientific Reports, 9*(1), 1-7.

Nico, M., Miralles, D. J., & Kantolic, A. G. (2019). Natural post-flowering photoperiod and photoperiod sensitivity: Roles in yield-determining processes in soybean. *Field Crops Research, 231*, 141-152.

Pedersen, P., & Lauer, J. G. (2004). Response of soybean yield components to management system and planting date. *Agronomy Journal, 96*(5), 1372-1381.

Roznik, E. A., & Alford, R. A. (2012). Does waterproofing Thermochron iButton dataloggers influence temperature readings? *Journal of Thermal Biology, 37*(4), 260-264.

Salmeron, M., Gbur, E. E., Bourland, F. M., Buehring, N. W., Earnest, L., Fritschi, F. B., . . . Miller, T. D. (2014). Soybean maturity group choices for early and late plantings in the Midsouth. *Agronomy Journal, 106*(5), 1893-1901.

Salmerón, M., Gbur, E. E., Bourland, F. M., Buehring, N. W., Earnest, L., Fritschi, F. B., . . . McClure, A. T. (2016). Yield response to planting date among soybean maturity groups for irrigated production in the US Midsouth. *Crop Science, 56*(2), 747-759.

Scott, W. O., & Aldrich, S. R. (1970). Modern soybean production. *Modern Soybean Production*. 192.

Weeks, W., Popp, M. P., Salmeron, M., Purcell, L. C., Gbur, E. E., Bourland, F. M., . . . Golden, B. R. (2016). Diversifying soybean production risk using maturity group and planting date choices. *Agronomy Journal, 108*(5), 1917-1929.

Wolf, R., Cavins, J., Kleiman, R., & Black, L. (1982). Effect of temperature on soybean seed constituents: oil, protein, moisture, fatty acids, amino acids and sugars. *Journal of the American Oil Chemists' Society, 59*(5), 230-232.

Wood, C., Krutz, L., Falconer, L., Pringle, H., Henry, W., Irby, T., . . . Boykin, D. (2019). Soybean Planting Date and Maturity Group Selection as a Method to Optimize Net Returns above Total Specified Costs and Irrigation Water Use Efficiency. *Crop, Forage & Turfgrass Management*, *5*(1).

Zhang, L., Kyei-Boahen, S., Zhang, J., Zhang, M., Freeland, T., Watson, C., & Liu, X. (2007). Modifications of optimum adaptation zones for soybean maturity groups in the USA. *Crop Management, 6*(1), 0-0.