EFFECT OF MANAGEMENT DECISIONS ON CORN YIELD PRODUCTIVITY AND STABILITY IN ENVIRONMENTS WITH CONTRASTING WATER AVAILABILITY

Juan Ignacio Di Salvo
University of Kentucky, jdi239@uky.edu
Digital Object Identifier: https://doi.org/10.13023/etd.2020.056

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Recommended Citation
Di Salvo, Juan Ignacio, "EFFECT OF MANAGEMENT DECISIONS ON CORN YIELD PRODUCTIVITY AND STABILITY IN ENVIRONMENTS WITH CONTRASTING WATER AVAILABILITY" (2020). Theses and Dissertations--Plant and Soil Sciences. 126.
https://uknowledge.uky.edu/pss_etds/126

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Juan Ignacio Di Salvo, Student

Dr. Montserrat Salmeron, Major Professor

Dr. Mark Coyne, Director of Graduate Studies
EFFECT OF MANAGEMENT DECISIONS ON CORN YIELD PRODUCTIVITY AND STABILITY IN ENVIRONMENTS WITH CONTRASTING WATER AVAILABILITY

THESIS

A thesis submitted in partial fulfillment of the requirement for the degree of Master of Science in the College of Agriculture, Food and Environment at the University of Kentucky

By

Juan Ignacio Di Salvo

Lexington, Kentucky

Director: Dr. Montserrat Salmerón Cortasa, Grain Crops Assistant Professor

Lexington, Kentucky
2019

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ABSTRACT OF THESIS

EFFECT OF MANAGEMENT DECISIONS ON CORN YIELD PRODUCTIVITY AND STABILITY IN ENVIRONMENTS WITH CONTRASTING WATER AVAILABILITY

Corn (Zea Mays L.) is a grain crop with large productivity, but also elevated evapotranspiration demand, making it highly susceptible to periods of water stress occurring during critical reproductive stages. Environmental conditions in Kentucky make it possible to grow corn under rainfed conditions, but the crop is still likely to experience water stress during some times of the growing season depending on the year and location. There is limited information on the size of the yield gap due to water stress in Kentucky, and the timing and intensity of water deficit. In addition, evaluating the interactive effects of hybrid maturity and planting Population may allow management recommendations that increase corn yield productivity and stability for irrigated and rainfed conditions in Kentucky. This thesis is structured in three chapters that analyze different aspects of this interaction. In Chapter 1 we analyzed data from corn performance tests (2005-2017) in three states with variable number of sites under irrigation (KY, 0% irrigated sites; NE, 62% of irrigated sites; and AR, 100% irrigated sites), to study the yield stability of different hybrid maturities. Results from this analysis showed that later maturities maximized yield under irrigated conditions, but reduced yield stability, meanwhile in rainfed conditions, early hybrids increased stability, with small yield penalties. Thereafter, field experiments were conducted in 2017 and 2018 to quantify the yield response of early and late maturities to irrigation (Chapter 2), and the interactive effect of hybrid maturity and plant population on corn yield and yield components under irrigation (Chapter 3). A preliminary analysis of the expected water deficit during the growing season based on historical water data indicated that 85 to 103 days with cumulative water deficit above 50 mm are expected during the months of May to September in Kentucky. Field experiments showed a 6 to 28 % yield increase under irrigation in 2017, but no effect in 2018 due to higher precipitation. Overall, yield increased with later maturities by 67 to 205 kg ha\(^{-1}\) per unit increase in CRM. Results from Chapter 3 showed that increasing plant population from 7.8 to 10 pl m\(^{-2}\) increased kernel number in early maturities, and kernel weight in later ones. However, there was a compensation of yield components and no effect of plant population on yield. Most of the yield variability was explained by hybrid maturity. Interestingly, higher yields in late maturities was explained by a higher kernel weight in 2017, but by a higher number of kernels in 2018. No differences found in KGR among hybrids in 2018, suggesting that higher KW for later hybrids was associated with an extension in three days of the EFP. Further research should focus on water use of contrasting maturities and populations to develop management recommendations in irrigated cornfields across Kentucky.

KEYWORDS: Corn relative maturity (CRM), Irrigation, Plant population.

Juan Ignacio Di Salvo

October 9\(^{th}\), 2019
EFFECT OF MANAGEMENT DECISIONS ON CORN YIELD PRODUCTIVITY AND STABILITY IN ENVIRONMENTS WITH CONTRASTING WATER AVAILABILITY

By

Juan Ignacio Di Salvo

Montserrat Salmerón Cortasa
Director of Thesis

Mark Coyne
Director of Graduate Studies

October 9th 2019
Date
Acknowledgments

I would like to thank to my major advisor Dr. Montserrat Salmeron Cortasa, for the opportunity to pursue a Master’s degree in Plant and Soil Sciences at University of Kentucky. She continuously supported and encouraged me during the last two years. I would also like to thank to the members of my committee, Dr Hanna Poffenbarger and Dr Chad Lee, for their comments and advice. It is also appreciated the comments and suggestions from Dr. Denis Egli, and the statistical support of Eric Roemmele and Matthew Rutledge.

I would like to thank to the Crop Ecophysiology lab at University of Kentucky, who helped me to conduct my experiments in the field. In particular to Maria Morrogh Bernard, for her assistance during the first year of experiment.

I am thankful, to faculty members and colleagues that encouraged me through the years to foster my education and pursue a master’s degree; Steven McKay, Leandro Perugini, Lucas Borras, Ignacio Ciampitti, Hugo Alvarez and Oscar Sosa.

I would like to acknowledge friends from Kansas State University and Kentucky that made much more easier being far away from home the last three years; Guillermo Balboa, Santiago Tamagno, Paula Silva, Perdro Rossini, Johanie Rivera Zayas, Nicole Guiterrez, Hugo Gonzalez, Nahuel Peralta, Veronica Fumero, Maria Morrogh Bernard, Julia Santoro, Martin Polo, Virginia Verges, Hernan Torres, Ernesto Reboredo, Nicolas Giordano, Facundo Zbinden, and Lucia Garcia Vidal.

I am also thankful to my family; Juan Di Salvo, Patricia Malisani, Marcos Di Salvo, Ivana Gaffuri, Olga Lalla, Luis Sciarresi, and friends Ivan Stamati, Santiago Zurbriggen, Luisina Cuffaro and Martin Bologna that supported me from Argentina.

Finally, I would like to thanks to my partner in life Cintia Sciarresi, for her support, love and understanding. Things would have been definitely much harder without her.
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Chapter 1. Effect of corn hybrid maturity and water availability on yield stability

Abstract

Selection of corn (Zea mays L.) hybrid maturities with a growing cycle that is well adapted to a particular region is key to optimize the use of available resources (water, light, nutrients). Full-season hybrids with a long growing season may have a greater yield potential compared to short-season hybrids. In contrast, short-season hybrids may have reduced water requirements and could provide greater yield stability, in particular under rainfed conditions. To test this hypothesis we analyzed yield data from corn hybrid performance tests conducted between 2005 and 2017 in three states with variable area under irrigation: Arkansas (59 irrigated environments, 100% irrigated), Nebraska (73 environments, 62% irrigated), and Kentucky (73 environments, all rainfed). Within each region, hybrids were grouped in Early (25% of hybrids), middle (50%), and late maturities (25%). Yield stability was analyzed by regressing yields by hybrid maturity against a yield environmental index (average yield at a given environment minus the mean yield by state). Late maturities yielded 3.2, 0.9 and 5.9% more on average than early hybrids in Arkansas, Kentucky and Nebraska, respectively. However, the root mean square error (RMSE) of the regression was greatest with late maturities (1.14 -1.16 Mg ha-1) in all states, indicating a lower yield stability compared to early maturities. This analysis indicates that under rainfed conditions, short-season maturities may provide a higher yield stability with little or no yield penalty compared to full-season maturities. In contrast, full-season maturities would maximize yield in irrigated areas. Hybrid maturity recommendations might need to be reevaluated for producers that transform to irrigation in areas normally under rainfed conditions. In addition, further field research evaluating water use of different corn hybrid maturities under different water management is necessary.

Keywords: Zea Mays L.; Yield potential; Irrigation; CRM
1. Introduction

Corn (*Zea Mays* L.) is the world’s most widely grown crop, with a global production of more than one billion metric tons in 2017 (FAOSTAT, 2019). Due to the high productivity of this crop, total evapotranspiration demand during the growing season is usually higher when compared to other grain crops. For instance, corn seasonal evapotranspiration was 14 -30% higher than grain sorghum (*Sorghum Bicolor* L.) and 8 -25% than soybeans (*Glycine max* L.) in irrigated field experiments (Hattendorf et al., 1988). Corn is most susceptible to water stress during the window around silking, and insufficient water during this period can reduce significantly kernel number and yield (Grant et al., 1989; Harder et al., 1982). Thus, corn can experience high evapotranspiration demands combined with high susceptibility during the critical window around silking. As a result, corn can be very responsive to irrigation in regions where rainfall is scarce or distribution during the growing season is uneven. This has led to the expansion of the corn production area under irrigation in the US during the last decade and contributed to the increase in the water depletion rate from aquifers (Konikow, 2015). Understanding how different management strategies influence corn productivity, yield stability, and the crop water requirements is essential for a sustainable intensification of corn production systems.

Corn hybrid of different relative maturity (CRM) can modify the duration of the corn-growing season and influence the use of available resources (i.e.; water, light, nutrients). Thus, selection of best-adapted corn hybrid maturities for a region could be a low cost management adaptation strategy to increase yield stability in rainfed areas, or increase water productivity under irrigation. Under non-limiting conditions (absence of disease,
pests, water and nutrients stresses), total crop biomass produced during the growing season has a positive linear relationship with the amount of solar radiation intercepted by the canopy (Andrade, 1995; Capristo et al., 2007; Tollenaar and Bruulsema, 1988). As a result, full-season hybrids with a longer growing cycle usually produce greater biomass and higher yields compared to short-season maturities under no water stress (Edwards et al., 2005). In a recent study conducted in Mississippi, irrigated full season corn hybrids (CRM 114 to 118) yielded on average 5% more compared to short season maturities (CRM 103 to 105) (Williams et al., 2018).

Although early-season hybrids may have a lower yield potential compared to full-season, they could provide an advantage in environments that are limited by water availability, or be an adaptation strategy to reduce the need for irrigation. Early-season hybrids have shorter growing cycle that can reduce total evapotranspiration demand and irrigation requirements compared to late-season hybrids (Edwards et al., 2005). Alessi and Power, (1974) conducted research in the Northern Great Plains where they demonstrated that management decisions such as plant populations or maturity choices, were more successful than row spacing, to conserve soil water early in the season for a later use in the grain filling period. Thus, in locations limited by water availability, short-season hybrids may reduce or alleviate late-season water stress and increase yield stability compared to later maturities (Larson and Clegg, 1999). Two out of three early maturing hybrids evaluated under rainfed conditions in Nebraska (CRM 95 to 99) produced similar or higher yields compared to three late maturing hybrids (CRM 114 to 118) (Larson and Clegg, 1999). These results indicate that short-season hybrids may provide an adaptation strategy to water-limited environments by reducing the risk of
water-stress and increasing yield stability. In addition, short-season hybrids with a shorter growing season may be advantageous when precipitation delays planting in the spring or field operations in the fall, and to facilitate rotations with winter cover crops (Howell et al., 1998; Smit et al., 1997).

Yield is a complex quantitative trait influenced by the interaction of Genotype (G), Environment (E) and Management (M). Increasing yield stability may come associated with a reduced yield response under environments that could lead to a higher yield potential (Xavier et al., 2018). However, a large increase in yield stability at the expense of relatively low yield penalties might be desirable to reduce the frequency and severity of years with very low yields and reduce the variability in producer’s net economic returns. Therefore, hybrid choices that provide stable performance from year to year and/or across a wide range of environmental conditions may be preferred as they provide a constant supply of grain for food and other industrial processes (Boyer et al., 2013). Defining the most suitable choice of hybrid maturity for a given environment requires an analysis of yield productivity that is difficult to obtain from field experiments conducted during a limited number of years and environments. In addition, best-adapted hybrid maturities for different U.S. corn growing regions will depend on the environmental conditions and the irrigation management.

The objective of this study was to test the effect of hybrid maturity (early, middle and late) on corn yield productivity and stability with data from Corn Performance Tests from Arkansas, Kentucky and Nebraska, which provide wide range of corn hybrid maturities tested across many site-years. We selected three states that have very different percentage of corn area under irrigation. During 2017, 86% of the corn area harvested in Arkansas
was irrigated, 54% in Nebraska, and only 3% in Kentucky (USDA NASS, 2019). We hypothesized that early maturity hybrids may provide higher yields and/or yield stability in states with low percentage of irrigation, and that late maturity hybrids will have a higher yields in high yielding environments and under irrigation.

2. Material and methods

2.1 Experimental data

Yield data from corn performance tests conducted between 2005 and 2017 in three US states Arkansas (AR), Kentucky (KY) and Nebraska (NE) were used for this study. The information used is publically available in the University of Arkansas variety testing reports (Bond et al., 2011, 2012, 2013, 2014, 2015, 2016, 2017; Dombek et al., 2005, 2006, 2007, 2008, 2009, 2010), University of Kentucky Corn performance tests (Pearce et al., 2006, 2007, 2008, 2009, 2010, 2011, 2012, Kenimer et al., 2013, 2014, 2015, 2016, 2017, 2018), and Seed guides from University of Nebraska – Lincoln (Regassa et al., 2010, 2011, 2013; Regassa and Shapiro, 2014, 2015, 2016). It is common practice in corn performance tests to include hybrids at each environment that encompass the variability of hybrid maturities in that region. Hybrids ranged from 107 to 121 CRM in AR, from 102 to 120 CRM in KY, and from 100 to 117 CRM in NE. A total of 17,218 yield observations were used for this study (Table 1.1).

Yield observations were grouped by hybrid maturity into three categories (early, middle and late) based on the cumulative percentile distribution of CRM values across all hybrids within a state (Figure 1.1). Hybrids in the center of the distribution, between 25 to 75 percentile were considered middle maturities, hybrids were considered early when
below the 25 percentile, and late when higher than 75 (Figure 1.1). Based on the wide range of latitudes involved in the analysis (33 to 45° N latitude) (see Appendix A for details about locations), certain CRM were dominant in one region, meanwhile in other latitudes had minor participation. Grouping CRM into early, middle, and late maturity, allowed us to compare yields by group across states, regardless of CRM.

For this analysis, each location by year combination was considered as a separate environment. Since the number of hybrids and their range of CRM values used changed from one year to another, and also across locations, only environments that had at least three hybrids within each maturity group were included in this study (Table 1.1). This approach allowed us to avoid bias from introducing hybrids that may not represent accurately the performance of a given CRM. Tests included 12 to 80 hybrids within each maturity group across the three states (Table 1.1). In addition, average group performance was calculated with data from all hybrids within a group.

In Arkansas, fifty-nine irrigated environments were included in the analysis, all of them irrigated. Data from Kentucky included 73 rainfed environments. In Nebraska, a combination of irrigated (n= 45) and rainfed (n=28) environments were included in the analysis (overall 62% irrigated environments) (Table 1.1). Data included in the analysis was based on online availability.

Plot size was four rows wide (0.76 m row spacing) by 4.5 m to 10.5 m long, depending on the environment. Plant populations varied between 4.7 and 9.6 plants m\(^{-2}\) across environments, but were constant across hybrids used at each environment. Planting dates ranged from March 28 to June 2 across environments. Trials were conducted in university research stations as well as in cooperator’s fields, following
common and recommended best management practices for each region. Yield was determined by harvesting the two middle rows within each plot and averaging across 3 (KY) and 4 (AR, NE) replicates. Yield was adjusted to 155 g kg\(^{-1}\) moisture. Information about CRM for each hybrid was obtained from the university reports and/or seed company catalogues.

2.2 Data Analysis

Yield stability can be defined as the ability of a genotype to maintain its productivity in a broad range of environments (Tollenaar and Lee, 2002). Becker and Leon, (1988), explained this source of yield variability as the different response of genotypes to environmental stresses (drought, diseases, etc.). This response can be measured through a regression analysis of the yield for each genotype against an environmental index (EI) as proposed by Finlay, K.W and G. N Wilkinson (1963). The EI for each environment is computed as the difference between the mean yield across all genotypes at that environment and the grand mean across all environments. While some studies have used the slope of this regression as the measure of yield stability (Tollenaar and Lee, 2002), we defined stability as the deviation between the observed yield of each hybrid at each environment and the predicted yield by the regression (Piepho, 1998; Salmeron et al., 2014). We also used cumulative probability functions to quantify the likelihood of each system to fall below a specific yield level.

For this analysis, each location and year combination were considered as a different environment. Yields grouped in early, middle, and late CRM were regressed against the EI by state. Yield data was analyzed through an analysis of covariance (ANCOVA) using
PROC GLIMMIX procedure in SAS v.9.4. (SAS for Windows, v 9.4, SAS Institute, Cary, NC). Maturity group was considered as a fixed effect and EI was the random effect. Significance level was set at P<0.05 and least significant means were used to test the main effects. Normality of yields at each state was tested, and resulted in normal distribution.

The linear regression model used in the analysis of covariance followed Equation 1.

\[ \text{Yield}_i = \beta_0 + \beta_1 x_i + e_i \]  

(1)

Where \( \text{Yield}_i \), is the predicted yield value for model, \( \beta_0 \) is the intercept of the regression and represents the average yield for a maturity group at a given state. \( \beta_1 \) is the slope of the regression indicating the response of a given maturity group to a changes in the environment. \( x_i \) correspond to different values of EI, and the last term \( e_i \) represents the deviation from the regression line. Differences at the intercept and at EI = 10 and 20% below and above the mean, were evaluated with an estimate statement. Comparisons among the estimates of each maturity group at a given EI and state were evaluated with lsmeans. Differences in slope by hybrid maturity were evaluated with an estimate statement that compared the slope of two hybrid maturities in the interaction of maturity group x EI.

To quantify differences in yield variability across hybrids within each maturity group, the root mean square error (RMSE) of data not averaged across hybrids within a group was calculated following Equation 2.
Where $P_i$ is the predicted value, in the regression line and $O_i$ represents individual observations of a given hybrid.

To test whether environments were a main source of variability, the residuals between individual hybrid yield performance and the average yield by maturity group and by environment were regressed against the EI (Figure 1.2). A significant slope of this regression would indicate that yield variability was influenced by the environmental potential.

As a final step, we analyzed the risk of yields falling below certain productivity level at a given environment. Cumulative probability functions were drawn following the procedure described by Piepho (1998). The likelihood of yields falling below the average yield for a given state, calculated with data from the corn performance tests, was plotted with a vertical line. The cumulative probability for a given yield will indicate the likelihood of achieving that yield or lower, within a maturity group (Figure 1.3).

3. Results

3.1 Analysis of yield productivity and stability

Yield averaged across all hybrids by environment (year x location combination) ranged from 9.7 to 16.0 Mg ha$^{-1}$ in Arkansas, 6.0 to 16.5 Mg ha$^{-1}$ in Kentucky, and 9.0 to 17.0 Mg ha$^{-1}$ in Nebraska. The yield stability analysis with an environmental index regression was conducted with an analysis of covariance that allowed testing the hybrid
maturity effect on the intercept and slope of the regression (Table 1.2). The covariance model with hybrid maturity as a fixed factor and the EI as co-variable explained 61.3 %, 75.9 % and 98.2 % of the yield variation in Arkansas, Kentucky and Nebraska, respectively. In Arkansas and Nebraska, all factors in the model were significant (Maturity, EI, EI x Maturity), whereas only Maturity and EI had a significant effect in Kentucky (Table 1.2). Given that there was a significant effect of corn hybrid maturity on either the intercept, the slope of the regression, or both, yield regressions against the EI are shown by hybrid maturity in each state (Figure 1.3). Mean separation of the intercepts, slopes, and RMSE of the regressions by hybrid maturity are provided in Table 1.3. The intercepts (or yield at EI=0) are equivalent to the average yield by maturity group within a state (Table 1.3). The slope of the regression indicates the relative response of a maturity group to environments that are more productive, and is not used in this paper as a measure of yield stability. Thus, a higher slope indicates a relatively better response to environments that have a higher yield potential. The RMSE of the regression was used as a measure of yield stability in this study (Table 1.3). Since the analysis of covariance was performed with yields averaged across hybrids within Maturity (Early, Middle, and Late), the RMSE of yield with data not averaged across hybrids within maturity was calculated with Eq. (2).

In Arkansas, late maturities had the highest yields on average at 13.88 Mg ha\(^{-1}\) (indicated by the intercept of the regression by hybrid maturity in Table 1.3), and average yields were reduced by 1.3% and 3% with middle and late maturities, respectively (Table 1.3 and Figure 1.2.A). Late and middle maturities in Arkansas had a relatively better response to environments with a higher yield potential, as indicated by the greater slope
(1.03 -1.05), compared to the early maturities (0.89). In contrast, yield stability of late hybrids in Arkansas, measured from the RMSE of the regression, was lower in late maturities (1.16 Mg ha\(^{-1}\)) compared to middle and short season hybrids (0.98 -1.01 Mg ha\(^{-1}\)).

In Kentucky, middle maturity hybrids had the highest yield on average (12.27 Mg ha\(^{-1}\)). No differences were detected when comparing the average yield of middle and late maturities, and a reduction of 1.6 % when comparisons were made between middle maturities and early ones (Table 1.3 and Figure 1.2.B). All maturities in Kentucky had a similar yield response to environments with a higher yield potential, indicated by the similar slopes (Table 1.3). However, yield stability of late hybrids (RMSE = 1.14 Mg ha\(^{-1}\)) was significantly lower than for early and middle hybrids (RMSE = 1.00-0.96 Mg ha\(^{-1}\)).

In Nebraska, late maturities had the greatest average yield (13.28 Mg ha\(^{-1}\)), similar to that of middle maturities, and 6% greater than in early maturities (Table 1.3). In addition, late maturities responded better to environments with higher productivity (slope = 1.03) compared to early hybrids (slope = 0.91), while middle maturities had an intermediate response to environments with higher productivity (slope = 0.99) (Table 1.3 and Figure 1.2.C). Finally, yield stability of late maturity group was the lowest on average (RMSE = 1.15 Mg ha\(^{-1}\)) and not different from middle maturities (RMSE = 1.07 Mg ha\(^{-1}\)). Early maturity hybrids in Nebraska had the greatest yield stability with a RMSE of 0.94 Mg ha\(^{-1}\) (Table 1.3).

3.2. Hybrid maturity by environment interaction
Least significant means of yield by maturity group were estimated at different EI values to test if hybrid maturity choices with the highest yields were different depending on the average productivity level at a given environment (Table 1.4). Five productivity levels were defined in each state from environments with average yield 20% below the mean, to environments with yields 20% above the mean (Table 1.4). On average, yields ranged from 10.88 (AR), 9.72 (KY), and 10.09 (NE) Mg ha⁻¹ at environments 20% below the mean productivity level to 16.76 (AR), 14.73 (KY), and 15.94 (NE) Mg ha⁻¹ at environments 20% above (Table 1.4).

Across the three states and all productivity levels, late maturity groups had the greatest yields (or not different from the greatest) in 93% of the comparisons performed, middle maturities has the greatest yields (or not different from the greatest) in 80% of comparisons, and early maturities had similar yields to the highest yielding maturity in 20% of comparisons (Table 1.4). These results indicate an overall yield advantage of late and middle maturities over early season hybrids. However, yield differences by maturity were dependent on the state and productivity level.

In Arkansas, yields by hybrid maturity were similar at the lowest productivity level (-20%), but differed at higher environmental productivity levels (Table 1.4). At the -10% productivity level, late and middle maturities had the highest yields, and early maturities reduced yields by 1.7% compared to late ones. At the mean and +10% productivity level, late maturities had the highest yields, middle maturities reduced yields by 1.3 in both scenarios, and early maturities reduced yields by 3.2-4.3% compared to the late maturities. At the highest yielding environment, late and middle maturities had the highest yields, and early maturities reduced yields by 4.6% (Table 1.4).
In Kentucky, the absence of EI by maturity interaction (Table 1.2) indicates that all hybrids responded with a similar yield increase as the yield productivity level improved. However, lsmeans at different productivity levels were still calculated in Table 1.4. This analysis showed no yield differences among maturities at environments below the yield average (-20 and -10% yield productivity levels; Table 1.4). At the mean and +10% productivity level, middle maturities had the highest yields, followed by late maturities (0.7-0.5% yield reduction), and early maturities (1.6 -1.9% yield reduction). At the highest productivity level (+20%), the late and middle maturities had the highest yields, and early maturities reduced yields by 1.9%.

In Nebraska, yield differences across hybrid maturities were observed in all the environment productivity levels (Table 1.4). At all productivity levels, late and middle hybrids had the highest yields, and early maturity hybrids consistently reduced yields by 5.1 to 5.9%. Middle maturities had similar yields to late maturities in all cases except at environments 10% above the mean, where they yielded 1.2% less than late hybrids.

3.3 Yield probability functions

Yield cumulative probability functions were built to compare the risk of yields falling below a given yield level across hybrid maturities within each state (Figure 1.3). The grand mean yield within each state was selected as reference to calculate the risk of yields falling below a certain yield level that was comparable across states (solid vertical lines in Figure 1.3).
In Arkansas, the probability of yields falling below the average (13.6 Mg ha\(^{-1}\)) was highest with early (p= 0.58), followed by middle (p = 0.56) and late (p = 0.48) maturities (Figure 1.3). Differences across maturities in the probability of yields falling below a certain yield level increased with yields above the average. In consequence, the risk of lower yields increased relatively more in early maturities compared to later maturities under high yielding scenarios.

In Kentucky, the probability of yields falling below average (12.2 Mg ha\(^{-1}\)) was highest with early maturities (p=0.52), followed by middle (p = 0.51) and late (p = 0.48) maturities (Figure 1.3). These small differences in probability across hybrid maturities were consistent across most of the yield range. However, at low yielding environments (10 Mg ha\(^{-1}\) and below), the probability of yields falling below the average, was highest for late maturities.

In Nebraska, early hybrids had a probability of 0.64 of yields falling below the average (12.99 Mg ha\(^{-1}\)); meanwhile middle and late maturity hybrids reduced that chance to 0.49 and 0.39, respectively. The probabilities of yields falling below a certain yield level showed the greatest differences among maturities at medium yielding scenarios, and were lower at very low or high yielding levels (Figure 1.3).

4. Discussion

4.1. Differences in yield stability by hybrid maturity

Our yield data analysis from Corn Performance Tests included a wide range of maturities across 59-73 site-years in AR, KY, and NE, that revealed differences in yield
and yield stability by hybrid maturity. Overall, yield increased with hybrid maturity, whereas yield stability was highest with early maturities. Late maturities in our study (CRM > 118, 116, and 114 in AR, KY, and NE, respectively) had the greatest yields or not different from the highest yielding maturity in 93% of the environment productivity levels. In contrast, early season hybrids had lower yields in 80% of the environment productivity levels, but were more stable than late-maturity hybrids in all cases. Hybrids of intermediate maturity maximized productivity in 83% of the productivity levels, and still provided greater yield stability compared to late hybrids.

The average yield gain of late maturities in this study when comparing with early-season hybrids ranged from 0.9 to 5.8% across the three states and productivity levels and is consistent with previous research. Assefa et al.,(2016) found that full season hybrids maximized yields in a wide range of environments across the US. The shortest maturity group hybrids (CRM = 78-88 days) included in analysis had yield limitations in locations where the environmental conditions allow longer growing cycles, and therefore, higher yields (Assefa et a., 2016). Irrigated full season corn hybrids (CRM 114 to 118) in Mississippi yielded 5% more compared to short season maturities (CRM 103 to 105) (Williams et al., 2018). The yield advantage of late maturities is explained by a greater total crop biomass produced during the growing season as a result of a higher amount of solar radiation intercepted by the canopy (Andrade, 1995; Capristo et al., 2007; Tollenaar and Bruulsema, 1988).

There is less research available documenting differences in yield stability by hybrid maturity. The analysis of yield regression against the EI with the approach proposed by (Finlay and Wilkinson, 1963) was used previously to quantify yield stability in corn
(Tollenaar and Lee, 2002) and soybean (Salmeron et al., 2014). Tollenaar and Lee (2002) used the slope of the regression as a measure of a “dynamic stability” that is relative to the performance of other corn hybrids in the same environments, where b>1 indicates lower stability than the average, and b<1 higher stability than the average. In our study, yield stability was quantified as the RMSE of the regression, and differences in slope across hybrids were used as a measure of the hybrid responsiveness to environments with a higher yield potential. Thus, in our analysis, a hybrid maturity group could have higher and/or lower yield response to the environmental yield potential independently from its yield stability. Our analysis indicated that late and middle maturities had in fact a greater responsiveness to environments of high productivity (as indicated by the greater slope), but a reduced yield stability compared to short-season maturities (as indicated by the lower RMSE). This means that at environments with a higher productivity in our study, partially due to irrigation and/or greater precipitation, middle and late maturities had a relatively greater yield response compared to short-season maturities. This response is consistent with the fact that late maturities have a greater genetic yield potential (Capristo et al., 2007) and thus average yields might be closer to the potential in environments with less water stress.

Interestingly, a high yield potential was associated in our study with a lower yield stability. To analyze this response, the effect of maturity on the residuals (deviation between individual hybrid yield and the predicted yield from the regression with EI) was analyzed with an analysis of covariance, with maturity as fixed effect, and the yield EI as an independent variable (data not shown, residuals plotted in Figure 1.2). The analysis of covariance indicated that residuals were not dependent on the hybrid maturity or the yield
EI. Thus, yield stability was not affected by the yield productivity of a given environment or maturity group. This lower yield stability in later maturities could be explained by a greater total water use during vegetative developmental phases, and a higher incidence of water stress during reproductive stages compared to short-season hybrids (Howell et al., 1998; Larson and Clegg, 1999). Howell et al., (1998) reported that water use of early maturities was reduced compared to full season hybrids as a result of lower plant height and smaller leaf area index (LAI) during vegetative developmental stages. Moreover, Larson and Clegg, (1999), found that leaf area development of short season hybrids is one plant characteristic that could help explain reductions in evapotranspiration.

In summary, our results support the potential of adapting corn hybrid maturity to increase yield productivity and stability depending on the environment and water management.

4.2 Hybrid maturity recommendations by state

The hybrid maturity classification in early, middle, and late maturities in this study was based on the range of hybrid maturities used in the Corn Performance Tests. The range of CRM in Nebraska (100-117) and Kentucky (102-120) included earlier hybrid maturities and a wider CRM range compared to Arkansas (107-121). We assume that the data used comprises the range of hybrid maturities available for producers in these areas. However, our hybrid maturity classification does not represent the area planted with different hybrid maturities or the range of commercial hybrid maturities in each region.

Our analysis suggests a greater yield benefit of late maturities depending on the percentage of irrigation. In Arkansas, with 100% of sites in our study under irrigation,
late maturities (CRM > 118) had the highest yields on average. In Nebraska, with 62% of sites under irrigation, middle and late maturities had the highest yields. In Kentucky, with all sites non-irrigated, middle maturities (CRM 111 to 116) provided the highest yields on average, and yield differences with early (CRM<111) and late maturities (CRM>116) were relatively small (1.6 and 0.7% lower yields). Thus, results obtained in Kentucky are in contrast with those from Arkansas and Nebraska, where yield reduction with early maturities ranged from 3.2% to 5.9% depending on the environment. In addition, the yield response to environments with a higher productivity level (slope of the regression with the EI) was similar across hybrids in Kentucky, whereas the higher slope in middle and late maturities in NE and AR indicated that these hybrids had a relatively better response to environments with a higher productivity. This advantage of late maturities in high yielding environments could have important implications for water use for corn grown under irrigation. Management practices to mitigate the effect of water use are very important in states with a higher percentage of crop area under irrigation such as AR (92%) and MS (60%). Management strategies as it is plant populations and row spacing, as a mean to reduce irrigation demand were studied by Edwards et al., (2005) meanwhile Solomon and Zeppa (2017) found a positive yield response of short season hybrids to population increases in favorable conditions. In both studies conclusions supported the need of a population increases for early hybrid maturities to achieve similar yield to later ones (Solomon and Zeppa, 2017), as well as to reduce irrigation requirements (Edwards et al., 2005).

Although only 3% of corn grown in Kentucky was under irrigation in 2017 (USDA NASS, 2019), the estimated yield gap (difference between potential and attainable yields)
ranges from 14 to 24 %, with part of this gap associated to limited water availability (Egli and Hatfield, 2014). Previous studies suggest that in environments where productivity is limited by water, early hybrids may reduce the risk of low yields (Larson and Clegg, 1999). Our results agree with those from Larson and Clegg, (1999), that reported an improvement in yield stability of earlier hybrids in Nebraska when late season drought occurred. Our study indicates that late hybrid maturities with CRM above 116 would not provide any advantage in KY, as they had lower yields than middle maturities, and a lower yield stability compared to other maturity choices. Moreover, no substantial risk reduction was detected among maturities, when the probability of each maturity group falling below certain yield level was assessed. However, for environments of high yield potential in KY and producers that have the ability to irrigate, middle or late maturities would maximize yields.

The percentage of corn area grown under irrigation in the U.S. has increased by 16 % in the last 20 years (USDA-NASS, 2018). Thus, for states with a low percentage of corn area under irrigation, such as it is Tennessee (8.5% USDA-NASS, 2018) or Kentucky (3% USDA-NASS, 2018), producers that adopt irrigation may benefit from adapting to relatively late maturities for KY to maximize yields. Thus, common hybrid maturity recommendations for these areas might need to be redefined depending on the ability of a producer to irrigate.

Current irrigated corn production in Nebraska is 54%. Our results suggest that in NE, the use of middle maturities (CRM= 110 – 113), would maximize both yield and stability providing yield similar to late maturities (CRM > 114), but with a higher stability. Similar recommendations holds for Arkansas with an irrigated corn area of 86%, where
the use of middle maturities (CRM= 114 – 117) reduced yield in 1.3% compared to late ones (CRM > 118), but increased yield stability by 13%. Our results indicate that best hybrid maturity recommendations in these states may need to be based depending on the ability to irrigate for maximizing yield and water productivity, or perhaps the benefits of planting an early cover in the fall, or the possibility to advance harvest and take advantage of better market prices (Lauer et al., 1999).

In the context of climate change, further increase of average temperatures, will lead to higher evapotranspiration rates, increasing the crop water demand. Moreover, temperature increases could accelerate the developmental stages, reducing grain filling duration and grain yield (Hatfield, 2016). Further research on the response of different corn hybrid maturities under these scenarios is critical to mitigate climate effects and maximize productivity, yield stability, and resource use efficiency in the near future.

5. Conclusions

Our results demonstrated that late maturities respond more strongly to environmental conditions than early maturities in irrigated environments (Arkansas and Nebraska). Meanwhile in rainfed areas (Kentucky) middle maturities maximized yield, and no differences were found in the response to EI among maturities. Early maturities showed and overall higher yield stability than later hybrids, suggesting short-season maturities, as a management option to increase yield stability in environments where growing season is limited by low temperatures, drought, or double crop rotation. Risk of yields below the average was higher with early maturities in favorable environments meanwhile in more limited environments, later maturities were riskier. In irrigated environments, risk of
lower yield was lower (10 -25%) when maturity was switched to late hybrids. With temperatures increasing, and rainfall patterns changing, the effect of climate on yield productivity and stability is uncertain. However, selection of maturity choices that can help to mitigate these effects will be important to ensure grain production in the future.

In summary, our results indicate the potential of selecting best-adapted hybrid maturities for different environments and/or irrigation managements to increase yield, yield stability, as well as the use of resources. However, additional research including a diverse range of plant populations, maturities and water availability, is necessary to provide management recommendations that can help to optimize yield, yield stability and water productivity. Further studies should focus on water consumption and water use efficiency of contrasting hybrid maturities to better understand whether short season hybrids could increase water use efficiency meanwhile providing more stable yields. In addition, economic analysis that consider both yield and yield variability or stability are necessary to make informed decisions about whether early middle or late maturities are the best choice for a given environment.
Tables Chapter 1.

**Table 1.1.** Years of data available within each state, number of environments, corn maturity group classification (early, middle, and late), minimum, maximum and average number of hybrids included within each group.

<table>
<thead>
<tr>
<th>State</th>
<th>Years</th>
<th>Number of environments</th>
<th>Maturity (CRM(^a) range)</th>
<th>Number of hybrids within each group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Early (107–113)</td>
<td>Min 31 21</td>
</tr>
<tr>
<td>Arkansas</td>
<td>(2005-2017)</td>
<td>59</td>
<td>Middle (114–117)</td>
<td>Max 70 50</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Late (118–121)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Early (102–111)</td>
<td></td>
</tr>
<tr>
<td>Kentucky</td>
<td>(2005-2017)</td>
<td>73</td>
<td>Middle (112–115)</td>
<td>Min 3 28</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Late (116–120)</td>
<td>Max 41 28</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Early (100–109)</td>
<td></td>
</tr>
<tr>
<td>Nebraska</td>
<td>(2010, 2011, 2013-2016)</td>
<td>73</td>
<td>Middle (110–113)</td>
<td>Min 10 63</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Late (114–117)</td>
<td>Max 81 70</td>
</tr>
</tbody>
</table>

\(^a\) CRM; Corn relative maturity
TABLE 1.2. Analysis of covariance by state for the regression of corn yield averaged across hybrids within each maturity group on the environmental index (EI) as independent variable. Corn hybrid maturity (Early, Middle, and Late) was considered as a fixed factor and allowed to modify the intercept and slope of the model.

<table>
<thead>
<tr>
<th>State</th>
<th>Regression Parameter</th>
<th>Effect</th>
<th>F Value</th>
<th>Pr&gt;F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arkansas</td>
<td>Intercept Slope</td>
<td>Maturity</td>
<td>23.87</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EI</td>
<td>3301</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EI * Maturity</td>
<td>8.38</td>
<td>0.0003</td>
</tr>
<tr>
<td>Kentucky</td>
<td>Intercept Slope</td>
<td>Maturity</td>
<td>4.63</td>
<td>0.0108</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EI</td>
<td>5550</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EI * Maturity</td>
<td>1.09</td>
<td>0.3372</td>
</tr>
<tr>
<td>Nebraska</td>
<td>Intercept Slope</td>
<td>Maturity</td>
<td>65.34</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EI</td>
<td>5980</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EI * Maturity</td>
<td>7.65</td>
<td>0.0007</td>
</tr>
</tbody>
</table>
**Table 1.3.** Estimate of the intercept, slope \((b_i)\) and root mean square (RMSE) obtained from the covariance model of yield regressed with the environmental index (EI) by state and with hybrid maturity allowing to modify the intercept and slope. Different letters indicate significant differences \((p<0.05)\) between maturity groups within a state.

<table>
<thead>
<tr>
<th>State</th>
<th>Number of Environments (% Irrigated)</th>
<th>Maturity (CRM range)</th>
<th>Intercept (Mg ha(^{-1}))</th>
<th>Slope ((b_i))</th>
<th>RMSE* (Mg ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arkansas</td>
<td>59 (100%)</td>
<td>Early (107–113)</td>
<td>13.45 c</td>
<td>0.89 b</td>
<td>0.98 b</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Middle (114–117)</td>
<td>13.70 b</td>
<td>1.03 a</td>
<td>1.01 b</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Late (118–121)</td>
<td>13.88 a</td>
<td>1.05 a</td>
<td>1.16 a</td>
</tr>
<tr>
<td>Kentucky</td>
<td>73 (0%)</td>
<td>Early (102–111)</td>
<td>12.07 b</td>
<td>0.96 ns</td>
<td>1.00 b</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Middle (112–115)</td>
<td>12.27 a</td>
<td>1.01 ns</td>
<td>0.96 b</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Late (116–120)</td>
<td>12.18 ab</td>
<td>1.00 ns</td>
<td>1.14 a</td>
</tr>
<tr>
<td>Nebraska</td>
<td>73 (62%)</td>
<td>Early (100–109)</td>
<td>12.53 b</td>
<td>0.91 b</td>
<td>0.94 b</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Middle (110–113)</td>
<td>13.15 a</td>
<td>0.99 ab</td>
<td>1.07 a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Late (114–117)</td>
<td>13.28 a</td>
<td>1.03 a</td>
<td>1.15 a</td>
</tr>
</tbody>
</table>

*RMSE is the root mean square of the deviation between actual and predicted yields and was calculated with data not averaged across hybrids within a maturity group.*
**TABLE 1.4.** Average yield (Mg ha\(^{-1}\)) by maturity group, at different environment productivity levels at each state. Different letters indicate significant differences (p<0.05) between maturity groups within a state and productivity level.

<table>
<thead>
<tr>
<th>State</th>
<th>Maturity</th>
<th>% Change in the environment productivity level (Mean)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>-20%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mg ha(^{-1})</td>
</tr>
<tr>
<td>Arkansas</td>
<td>Early</td>
<td>11.02 ns</td>
</tr>
<tr>
<td></td>
<td>Middle</td>
<td>10.88 ns</td>
</tr>
<tr>
<td></td>
<td>Late</td>
<td>11.01 ns</td>
</tr>
<tr>
<td>Kentucky</td>
<td>Early</td>
<td>9.72 ns</td>
</tr>
<tr>
<td></td>
<td>Middle</td>
<td>9.75 ns</td>
</tr>
<tr>
<td></td>
<td>Late</td>
<td>9.80 ns</td>
</tr>
<tr>
<td>Nebraska</td>
<td>Early</td>
<td>10.09 b</td>
</tr>
<tr>
<td></td>
<td>Middle</td>
<td>10.60 a</td>
</tr>
<tr>
<td></td>
<td>Late</td>
<td>10.61 a</td>
</tr>
</tbody>
</table>
**Figures Chapter 1.**

**Figure 1.** Histogram of percentile of corn relative maturity (CRM) in the yield datasets obtained from corn performance tests in Arkansas (2005-2017), Kentucky (2005-2017), and Nebraska (2010, 2011, 2013-2016). Within each state, corn hybrids were separated in early (p<25), middle (p=50) and late (p>75) maturity.
FIGURE 1.2. Regression of yield against Environmental Index (EI) by state and hybrid maturity group (Early; square symbol and solid line, Middle; circle and dotted line and Late; triangle and dashed line). Each point represents the mean yield across hybrids within a maturity group at a given environment. The sub-figures show the residuals of individual hybrid yields regressed against the EI for each hybrid maturity. Estimates of the intercept, slope, and root mean square error (RMSE) for each regression are provided in Table 1.3.
Figure 1. Cumulative probability by corn hybrid maturity (Early, middle; dotted line and late; dashed line) of yields falling below a certain yield level. The vertical solid line represents the average yield at each state.
Chapter 2. Irrigation response of different corn hybrid maturities in Kentucky

Abstract

Water stress during early reproductive stages in Corn (*Zea Mays* L.) can severely affect grain yield. There is currently limited quantitative data on the timing and severity of water stress for corn grown in Kentucky, and the expected yield response to irrigation. The objectives of this study were: i) to quantify the expected timing, intensity, and duration of water deficit in four locations in Kentucky based on 30-yr of historical weather data (1988-2018), ii) to quantify the yield response to irrigation in hybrids with a range in corn relative maturity (CRM) from 102 to 120 with experiments conducted in Lexington (2017, 2018), and Princeton, KY (2017), and iii) to quantify the estimated increase in gross economic returns from these experiments for different corn price scenarios, and determine the expected time necessary to pay for irrigation investments. Our analysis of historical weather data showed that western locations (Princeton, Mayfield and Henderson) experience on average 97 to 103 days of water deficit (cumulative deficit > 50 mm) between May and September, whereas this number was reduced to 85 days in Lexington. Field trials showed a positive yield response to irrigation in 2017 (6-28 % yield increase), but no response to irrigation in 2018 in Lexington. The response to irrigation was dependent on the hybrid maturity (p=0.0522). Yields under irrigation increased by 13% with full-season hybrids (CRM>110), but to a lesser extent (8%) with early hybrids (CRM<110). Overall, full-season hybrids were the best option to maximize yield in all conditions, and in particular under irrigated conditions to further increase net economic returns from irrigation. Further research evaluating the response of different corn hybrid maturities to irrigation is necessary to provide more robust recommendations and economic analysis.

1. Introduction
Water stress in corn (*Zea Mays* L.) can severely affect crop growth and ultimately grain yield, in particular when it occurs during early reproductive stages (Payero et al., 2008). In Kentucky, most corn is grown under rainfed conditions, with approximately 3% of the corn area currently under irrigation (USDA-NASS, 2018). However, the irrigated corn acreage showed a threefold increase during the 1997-2017 period in Kentucky, from 5,400 to 15,500 hectares (USDA-NASS, 2018). This is because despite relatively high precipitation in this region, many corn producers obtain a positive yield response from irrigation depending on the year and location. In an analysis of corn yields by county from 1972 to 2011, it was estimated that corn yields in Kentucky were 14 to 24% below their potential (Egli and Hatfield, 2014). Yield limitations in this study were partially associated with year-to-year variability in precipitation and in the ability of the soil to hold sufficient water (Egli and Hatfield, 2014). Although there is evidence that corn yields are partially limited by water stress in KY, the amount of this yield limitation, and if it could be avoided with irrigation, remains unknown.

Adopting irrigation is an economic investment that also adds fixed management and input cost relative to growing corn without irrigation. The cost of setting up an irrigation system was analyzed previously by other authors, showing a diverse range of prices depending on field size, well depth, energy source, and the type of irrigation system (Boyer et al., 2015; Hogan et al., 2007). The cost of installation varied between $520 ha$^{-1}$ for a furrow system (Hogan et al., 2007) to $3,300$ ha$^{-1}$ for center pivot systems (Boyer et al., 2015). Irrigation management costs will depend on the type of irrigation and the number of irrigations required on any given year, among other factors. Thus, more information on the expected increase in gross economic returns when adopting irrigation
becomes essential to make informed decisions that can have an overall positive impact on the farm net economic returns.

Providing more water than is required to the crop can also have negative effects on corn yields (Kaur et al., 2019; Mukhtar and Baker, 1990). These negative effects of high precipitation and/or irrigation are associated with an increase in soil nitrogen losses through leaching (Gheysari et al., 2009) and a reduction in oxygen supply to roots under waterlogged conditions (Shaw and Meyer, 2015). While some negative effects of excessive water stress are an unavoidable consequence of high and frequent precipitation, excessive irrigation when the crop is not experiencing a deficit should be avoided to properly quantify the potential yield response to irrigation. Research trials evaluating the yield response to irrigation can help quantify the expected yield gain under an optimized water management for environmental conditions in Kentucky.

Some crop management options can have a significant impact on the crop yield potential and the amount and timing of corn water requirements, and thus will influence the crop response to irrigation. One management factor that can influence water use is the choice of corn hybrid maturity. Larson and Clegg (1999) reported that short-season hybrids may provide an adaptation strategy to water-limited environments by reducing the risk of water-stress and increasing yield stability. In contrast, full-season hybrid maturities that have a longer growing cycle could have a greater yield potential and be better adapted to irrigated conditions in Kentucky. Late maturities increased yield over earlier hybrids under irrigation in Mississippi (Williams et al., 2018) and in Arkansas (Edwards and Purcell, 2005). A yield stability analysis of data from corn performance tests showed that later maturities had a greater yield advantage over early maturities in
Arkansas (3.2% greater yields on average), where all sites were irrigated, than in Nebraska (5.9% yield increase), with 62% of sites irrigated (Di Salvo et al. not published). In Kentucky, with all sites under no irrigation, there was no yield advantage of late maturities (CRM>116), but yield stability was reduced when compared to short-season (CRM<111) maturities (-14%) (Di Salvo et al. not published). Based on these results, there is limited benefit from adopting late season hybrids in KY, but this response could be different for producers that adopt irrigation. Hence, testing different maturity hybrids under irrigated conditions in Kentucky could provide information to farmers about the best maturity choice to maximize yield under irrigation and rainfed conditions.

In summary, producers in KY need more information on the timing, severity, and duration of water stress, and the yield gain they can expect when transforming to irrigation. In addition, evaluating this response for a range of corn hybrid maturities well adapted for Kentucky can help identify best management recommendations that maximize productivity under both irrigated and rainfed conditions. The objectives of this experiment were: i) to quantify the expected timing, intensity, and duration of water deficit in four locations in Kentucky based on 30-yr of historical weather data (1988-2018); ii) to quantify the yield response to irrigation in hybrids with a range in corn relative maturity (CRM) from 102 to 120 with experiments conducted in Lexington (2017, 2018), and Princeton, KY (2017); and iii) to quantify the estimated increase in gross economic returns from these experiments for different corn price scenarios, and determine the expected time necessary to pay for irrigation investments. We hypothesized that there will be a yield response to irrigation, but this response will depend on the hybrid maturity, with late maturity hybrids being best adapted to irrigated conditions.
2. Experiment and Analysis

Field experiments were conducted in two locations in 2017, and one location in 2018. In 2017, research plots were planted at the UK North Spindletop Research Farm in Lexington (38.12° N, 84.49° W) and at the UK Research Education Center in Princeton (37.09° N, 87.85° W). During 2018, trials were planted only in Lexington. The experimental design in all the environments was a split-plot with four replications, where the main split factor was irrigation with 3 to 4 hybrids nested within each maturity were randomized in each plot.

Six different corn hybrids were included in 2017 and eight hybrids in 2018, ranging from 102 to 120 CRM. Hybrids were grouped into early maturities when days from emergence to physiological maturity were less than 110, and late when CRM was higher than 110 (Table 2.1).

Corn was planted on May 3rd 2017 and May 9th 2018 in Lexington on a Bluegrass-Maury silt loam soil, and on May 9th 2017 in Princeton on a Crider silt loam. Corn was planted at a seeding rate of 78,000 pl ha\(^{-1}\) using a pneumatic planter. Plots were 9 m in length and had four rows at 0.76 m row spacing. Plots receiving irrigated treatments were drip-tape irrigated in Lexington, and irrigated with a variable rate automatic lateral system (T-L Irrigation CO., Hastings, NE) in Princeton. Irrigation was applied when the cumulative soil water deficit reached 40 mm, estimated based on a daily water balance of precipitation and net evapotranspiration demand. The daily gross evapotranspiration demand was estimated based on Allen et al., (1998). The crop evapotranspiration demand was calculated from the reference evapotranspiration using the dual crop
coefficient approach (Allen et al., 1998) and a visual estimation of the fraction of canopy cover until full canopy. Plots were fertilized with ammonium nitrate in 2017 and urea in 2018 at a rate of 320 kg N ha\textsuperscript{-1} split equally into three applications: at planting, at V6 and at V14 developmental stages (Ritchie and Hanway, 1989). Chemical and manual weed control was performed to keep plots free of weeds.

Grain yield from each plot was obtained by sampling all ears in 4.8 m of the two central rows in 2017, and by harvesting 3.05 m out of the two middle rows with a Wintersteiger quantum combine in 2018. Final yield was calculated after adjusting moisture to 15.5%. A subsample of 15 ears in 2017, and 5 ears in 2018 was taken at physiological maturity (R6; Ritchie and Hanway, 1989) to quantify individual kernel weight (KW, mg kernel\textsuperscript{-1}), and to calculate the total number of kernels on an area basis (KN, kernels m\textsuperscript{-2}). Kernel weight (mg seed\textsuperscript{-1}) was obtained by weighing two samples of 500 kernels in each plot.

2.1 Analysis of weather data and estimated water deficit

Daily weather data containing maximum and minimum temperature and rainfall were obtained from the UK Ag Weather Center website (wwwagwx.ca.uky.edu) for the 1988-2018 period. In addition to our two experimental sites (Lexington, and Princeton, KY), weather data from two additional locations was used to broaden the region of influence of this study: Mayfield (36.7 ° N, 88.6° W) and Henderson (37.8 ° N, 87.6° W).

Potential daily reference evapotranspiration (ET\textsubscript{0}) was estimated using the FAO Penman-Monteith equation (Allen et al., 1998). For this calculation, solar radiation was estimated based on Hargreaves and Samani, (1982) using the latitude and altitude, day of
the year, and the minimum and maximum daily temperature. The cumulative water deficit was calculated from a daily balance of the net reference evapotranspiration demand and effective precipitation. A critical water deficit (CWD, mm) threshold of 50 mm when crops would experience water stress was chosen based on equation (Eq 1), proposed previously by Purcell et al., (2003) to estimate water deficit in corn:

\[ \text{CWD} = D \times \text{ASW} \times f_{\text{ASW}} \times 1000 \]

Eq (1)

where, D is the rooting depth (m) which was set to 0.6 m (Purcell et al., 2003). ASW is the crop available soil water (m$^3$ m$^{-3}$) from the difference between soil water content at field capacity and permanent wilting point. The ASW was set to 0.13 m$^3$ m$^{-3}$ as a representative value from more than 400 soils across the US with contrasting soil textures (Purcell et al., 2003). And, fASW is the fraction of available soil water depleted before a crop will start experiencing water stress. For this analysis, we used a value of fASW = 0.65, as other authors have found that usually symptoms of crop water stress start when less than 65% of the crop soil available water is left in the soil (Ray and Sinclair, 1998).

Using the same equation 1, the estimated total crop available water before reaching permanent wilting point was 78 mm (fASW=1). Thus, cumulative water deficit was allowed to range between zero (field capacity) and 77 mm (permanent wilting point), and the crop was considered to experience water stress when the cumulative water deficit was greater than 50 mm. The number of days within a month with water deficit greater than 50 mm for the period (1988-2018) was calculated for each location.
2.2 Statistical analysis of experimental data

An analysis of variance on yield (Mg ha\(^{-1}\)), kernel number (kernel m\(^{-2}\)), and kernel weight (mg kernel\(^{-1}\)) was performed with the PROC GLIMMIX procedure in SAS v.9.4. (SAS for Windows, v 9.4, SAS Institute, Cary, NC). Location, irrigation, maturity, and hybrid nested within maturity and location were considered fix effects, and block and its interactions with other effects were considered random. Fisher’s least significant difference (LSD) was used to separate means when p<0.05.

The relationship between yield and corn relative maturity under irrigated and non-irrigated conditions was further analyzed through an analysis of covariance (ANCOVA) using the PROC MIXED procedure in SAS v.9.4. (SAS for Windows, v 9.4, SAS Institute, Cary, NC). Irrigation and site were considered as a fixed factors, and CRM was considered as a co-variable allowed to change the response by site and irrigation (CRM*site and CRM*Irrigation interactions). Significance level was set at \(\alpha=0.05\) and least significant means were used to test the main effects.

3. Results and discussion

3.1 Analysis of historical trends in precipitation and water deficit

As a first step in our study, we analyzed the trends in annual and summer (June-September) precipitation for the 30-year period (1988-2018) at the four locations in Kentucky (Figure 2.1). Total annual and summer rainfall regressed over time only showed a significant increase in annual rainfall in Lexington of 13.14 mm per year. However, summer precipitation in Lexington only accounted for 28% of the total annual
rainfall, the remaining 72% distributed among the spring, fall and winter. There was not a significant trend of summer precipitation over time at any location (Figure 2.1). Thus, although annual precipitation could be increasing in recent years in some locations, our data analysis does not show evidence of an increase in summer precipitation when considering data from the last 30 years.

The analysis of cumulative water deficit showed that based on historical weather data we can expect some water stress (water deficit > 50 mm) in Lexington from beginning of July until the end of September (Figure 2.2). Water deficit calculated during our two growing seasons indicate that field experiments conducted in Lexington were subject to a greater water deficit in 2017 than in 2018 (Figure 2.2). Therefore, total irrigation in Lexington during 2017 was 130 mm, applied between July 1st and August 22nd. In contrast, precipitation during 2018 in Lexington was 71% higher than the historical average, and only 87.53 mm of irrigation were applied between July 6 and August 30.

In Princeton, the average water deficit exceeded the 50 mm threshold between June and October, with the highest water deficit values observed in mid-September (Figure 2.2). During 2017 in Princeton, the water deficit exceeded the 50 mm threshold in several occasions, consistent with the total of 140 mm of irrigation water that were applied at this experimental site. Most of the irrigation was applied during the month of July, coincident with corn flowering.

Daily water deficit calculations at Mayfield and Henderson showed similar patterns, with average water deficit exceeding 50 mm from June to early October. While 2018 was a wet year in Lexington with minimal water deficit, this was not the case at western locations in Kentucky. Overall, our results indicate that we can expect a greater water
deficit on average at the western-most locations in our analysis (Princeton, Mayfield, and Henderson) compared to Lexington, KY. However, results also show high variability from year to year and from one location to another.

The effect from water deficit on crop productivity will be more pronounced when water stress occurs over many days. We summed the number of non-consecutive days within a month when cumulative water deficit was above 50 mm based on weather data from the last 30 years (1988-2018) (Figure 2.3). Surprisingly, results showed that the average number of days per month with water deficit above 50 mm ranged from 15 to 25 days from June to October. The number of days with water stress peaked in August at most locations, and ranged from 21 days in Lexington, to 25 days in Henderson. Considering a crop growing season from May to September, the total number of days under water stress during this period were 85, 97, 101, and 103 for Lexington, Mayfield, Princeton, and Henderson, respectively.

Early planting dates that can advance the critical stage of flowering to June, a month with lower average water deficit and number of days with water stress might be helpful to reduce the risk of yield losses under rainfed conditions. However, this might increase the chances of water stress during the seed-filling phase.

3.2 Corn yield response to Irrigation

Yield and yield components depended on the combination of irrigation and location (Table 1.2). Yield under rainfed conditions ranged from 12.36 Mg ha\(^{-1}\) in Princeton 2017 to 17.60 Mg ha\(^{-1}\) in Lexington 2018 (Table 2.3). In 2017, irrigation increased yields by 28% in Princeton, and by 6.2% in Lexington. In contrast, there was not a yield response
to irrigation in 2018 in Lexington. These yield responses to irrigation were consistent with the amount of water deficit estimated at each site during these growing seasons (Figure 2.2), and the amount of days per month when the crop experienced water stress (Figure 2.3). Princeton 2017 experienced 18 days, Lexington 2017 about 23 days and Lexington 2018 about 6 days around flowering during which water deficit was > 50 mm (Figure 2.3). Therefore, our results suggest that the analysis of water deficit based on historical weather data could partially inform producers on the expected yield response to irrigation at their location.

Yield and yield components were affected by the combination of irrigation and maturity (Table 2.2). Irrigation increased late hybrids (CRM>110) average yield in 2 Mg ha\(^{-1}\) whereas the yield increase in early maturities (CRM<110) was 1.2 Mg ha\(^{-1}\) (Table 2.3). Consequently, late hybrids increased yields over early hybrids by 17 % under irrigated conditions, but only 12% under rainfed conditions (Table 2.3). These results partially support previous research by Di Salvo et al. (not published) who found that the yield advantage of late hybrids over early ones was greater in Arkansas (3.2% yield increase), with 100% of sites irrigated in the study, than in Nebraska (5.9% yield increase) with 62% of sites irrigated, and minimal in Kentucky, with all sites non irrigated.

The analysis of yield components can help gain understanding on how irrigation and hybrid maturity influenced yield determination. The yield increase under irrigated conditions observed in Princeton was due to both a 13 % increase in KN, and a 13 % increase in KW, meanwhile in Lexington 2017 only a 6 % increase in KN was
responsible for the higher yield. This response could be explained by the water deficit during the period bracketing flowering, where kernel number is most susceptible to water stress. Recep, (2004) studied the effect of water stress at different developmental stages, on yield and yield components. Results showed that, tasseling and ear development (VT, R1; Ritchie and Hanway, 1989) were the most susceptible stages, producing a reduction of 20% in KN. The same study identified milk stage (R3; Ritchie and Hanway, 1989) as the most susceptible stage for determination of kernel weight (Recep, 2004).

The interaction between location and maturity for yield components indicates that the yield advantage of late maturities over earlier ones was due to 15-17% greater KW in 2017, and due to 11% greater KN in 2018. The increments in kernel number per area basis in later hybrids was thoroughly studied by other authors, suggesting that KN was related with the amount of solar radiation intercepted by a canopy in the period around flowering (Andrade et al., 1993). One interpretation of the results based on this fact is that early and later maturities might have achieved similar canopy closure and light interception by the time of flowering in 2017, but not in 2018 when temperatures were (1.5 °C) higher and flowering occurred relatively earlier in the growing season. Kernel weight is partially determined by the duration of the seed filling period. Caprizzo et al (2007) studied the yield of contrasting hybrid maturities and its components (KW, KN) in Argentina. Results showed that, independently of the maturity class, KW was associated with the duration of the stage between flowering and physiological maturity (R1-R6; (Ritchie and Hanway, 1989). Thus, heavier kernels in late maturities in 2017 could be a result of an extended duration of the seed filling in these hybrids (data not shown). The lack of differences in seed weight in 2018 could be due to competition for assimilates, or
due to kernels weight achieving its maximum capacity. Recent research shows that kernel weight decreases when assimilates per kernel are reduced during seed filling, but is unresponsive to increases in assimilates supply around this time (Ordóñez et al., 2018). Further research is needed to elucidate whether differences in kernel weight in our experiments were a result of a sink or source limitation.

3.3 Effect of corn hybrid maturity on the yield response to irrigation

To further analyze the hybrid effect and the Irrigation * Maturity interaction, an analysis of yield regressed against CRM by irrigation treatment and location was performed (Figure 2.4). An analysis of covariance was used to test if the slope of the yield response by CRM was dependent on the irrigation treatment. Location and Irrigation, were considered fixed effects in the covariance model, and CRM was included as the co-variable. Results from the contrast of slopes (CRM*Irrigation*Location interaction) are presented in Table 2.4. Slope values represent the yield change per unit increase in CRM (kg ha\(^{-1}\) CRM\(^{-1}\)). In addition, the lsmeans at CRM=102 was performed to estimate yield differences between hybrid maturities of this CRM under irrigated or rainfed conditions (Table 2.4). The estimated yield at CRM=102 combined with the slope provided in Table 2.4 allows to quantify the expected yield for any hybrid maturity at any location and irrigation management. For instance, the yield of a 112 day hybrid under irrigation in Lexington 2017 would be 16,709 kg ha\(^{-1}\) (15,239 kg ha\(^{-1}\) + 10 CRM * 147 kg ha\(^{-1}\) CRM\(^{-1}\)).

Results showed a strong linear relationship between yield and CRM, indicating that later maturities increased yields in all locations under both irrigated and rainfed
conditions. The yield increases with later maturities ranged from 143 to 195 kg ha\(^{-1}\) and per unit increase in CRM in Lexington. Based on these results, yield differences from CRM 102 to 112 hybrid at this location could range from 1,430 kg ha\(^{-1}\) to 1,950 kg ha\(^{-1}\). The slope of the regression or yield increase by CRM was not affected by the irrigation treatment during both growing seasons (2017-2018) in Lexington. Only in Princeton 2017, significant differences in the yield response to increase in maturity class were observed (Table 2.4). The interaction between Irrigation * CRM in this location, showed that irrigated treatments had a yield increase of 205 Kg ha\(^{-1}\) by unit increase in CRM, compared to the 67 Kg ha\(^{-1}\) in rainfed treatments (Table 2.4).

Similar conclusion were obtained in an experiment conducted across different environments in Nebraska by Colville et al., (1964), in which they studied the yield response of different hybrid maturities under irrigation. Results showed that under irrigated conditions, later maturities (CRM=120) produced the highest grain yield. However, this experiment also concluded that in order to achieve maximum yield of each hybrid maturity under irrigation, other management practices such as plant population must be considered (Colville et al., 1964).

4. Economic analysis

There was a yield response to irrigation that was dependent on the year and location, ranging from a non-significant increase of 0.44 Mg ha\(^{-1}\) in Lexington 2018, to a 3.52 Mg ha\(^{-1}\) yield increase under irrigation in Princeton 2017. We calculated the gross economic gain from transforming to irrigation under different price scenarios and for a range of yield increases (Figure 2.5). Corn prices for the 2008 to 2018 period averaged $184 Mg\(^{-1}\).
with a minimum of $141 Mg\textsuperscript{-1} (2016), and a maximum of $272 Mg\textsuperscript{-1} (2012) (www.macrotrends.net). We considered a range of price scenarios from $100 to $272 Mg\textsuperscript{-1} in Figure 2.5. If we consider an average corn price of $184 Mg\textsuperscript{-1}, the gross profit related to the yield increase as an effect of turning into irrigation in Princeton (3.48 Mg ha\textsuperscript{-1}) would be of $640 ha\textsuperscript{-1} (Figure 2.7). The cost of setting up irrigation, will depend on field size, well depth, energy source (Boyer et al., 2015), and the type of irrigation system. For example, in Arkansas, the investment for different irrigation systems ranged between $520 ha\textsuperscript{-1} for furrow irrigation to $900 ha\textsuperscript{-1} for a Central pivot system (Hogan et al., 2007). Another publication from Texas, reported average installation costs were $453 ha\textsuperscript{-1} for furrow irrigation, $1,150 ha\textsuperscript{-1} for central pivot and $2,470 ha\textsuperscript{-1} for subsurface drip irrigation (SDI) system (Amosson et al., 2002). In Tennessee, the investment for a central pivot system was calculated in $3,300 ha\textsuperscript{-1} (Boyer et al., 2015).

As noticed, there is a vast difference in costs among systems. We assumed an average cost for a central pivot system of $1,800 ha\textsuperscript{-1}, based on the abovementioned reports. If we consider the investment cost, it will take 3 years to pay the system installation in Princeton, with the yield advantage obtained during 2017, and the average corn price of $184 Mg\textsuperscript{-1} (Table 2.5).

When corn price as well as yield gain due to irrigation was modified, (50\% below and above the yield gain for this study) (Table 2.5) we observed that the cost of irrigation set up, could be paid in a range from 2-8 years, depending on corn price fluctuation and weather conditions. These results indicates that benefits of irrigation should be evident in seasons with severe drought, or when corn price increase substantially. Under the current environmental conditions and corn prices, investing in irrigation systems would be risky.
in some cases if corn prices does not remain stable and annual precipitation keeps increasing, as our results show to be the case for Lexington.

5. Conclusions

If the rainfall pattern observed in Kentucky continues its trend, added to the effects of climate change, it is likely that we will observe a higher contrast in total rainfall among locations. Precipitation in Lexington is increasing on average by 13 mm yr\(^{-1}\), but the distribution of water may still generate periods of water stress during the growing season that could affect corn yields. Overall, our findings show that between 85 and 103 days with water deficit above 50 mm are expected during the months of May to September in Kentucky, depending on the location. This indicates, that depending on the location and the soil type, irrigation could be a valuable management tool to provide more stable yields and economic incomes. Full season hybrids (CRM>110) were the best option to maximize yield in all conditions, and in particular under irrigated conditions to further increase net economic returns from irrigation. Thus, for producers that adopt irrigation, our results show that late hybrid maturities (CRM>110) would have the greatest yield response to irrigation.

Based on the economic analysis performed in this work, the investment in the irrigation system set up could be paid in between 2 to 8 years, depending on corn prices and weather conditions. However, considerations about turning into irrigation requires further research across more years and locations in the state, as well as a more robust irrigation costs assessment including pumping and other management costs.
**Tables Chapter 2.**

**TABLE 2.1.** Corn hybrids used each year, corn relative maturity (CRM) provided by the seed companies, and maturity group classification for this experiment (early or late).

<table>
<thead>
<tr>
<th>Year</th>
<th>Hybrid</th>
<th>Brand</th>
<th>CRM</th>
<th>Maturity</th>
</tr>
</thead>
<tbody>
<tr>
<td>2017</td>
<td>A6267</td>
<td>AgriGold</td>
<td>102</td>
<td>Early</td>
</tr>
<tr>
<td></td>
<td>P0399</td>
<td>Pioneer</td>
<td>103</td>
<td>Early</td>
</tr>
<tr>
<td></td>
<td>D48VC76</td>
<td>DynaGro</td>
<td>108</td>
<td>Early</td>
</tr>
<tr>
<td></td>
<td>DKC68-26</td>
<td>Dekalb</td>
<td>118</td>
<td>Late</td>
</tr>
<tr>
<td></td>
<td>D58VC65</td>
<td>Dynagro</td>
<td>118</td>
<td>Late</td>
</tr>
<tr>
<td></td>
<td>P2089</td>
<td>Pioneer</td>
<td>120</td>
<td>Late</td>
</tr>
<tr>
<td>2018</td>
<td>A6267</td>
<td>AgriGold</td>
<td>102</td>
<td>Early</td>
</tr>
<tr>
<td></td>
<td>A6462</td>
<td>AgriGold</td>
<td>105</td>
<td>Early</td>
</tr>
<tr>
<td></td>
<td>DKC57-97</td>
<td>Dekalb</td>
<td>107</td>
<td>Early</td>
</tr>
<tr>
<td></td>
<td>P0825</td>
<td>Pioneer</td>
<td>108</td>
<td>Early</td>
</tr>
<tr>
<td></td>
<td>P1197AM</td>
<td>Pioneer</td>
<td>111</td>
<td>Late</td>
</tr>
<tr>
<td></td>
<td>DKC64-35RIB</td>
<td>Dekalb</td>
<td>114</td>
<td>Late</td>
</tr>
<tr>
<td></td>
<td>P1870</td>
<td>Pioneer</td>
<td>118</td>
<td>Late</td>
</tr>
<tr>
<td></td>
<td>P2089</td>
<td>Pioneer</td>
<td>120</td>
<td>Late</td>
</tr>
</tbody>
</table>
TABLE 2.2. Analysis of variance for yield, kernel number (kernels m$^{-2}$), and kernel weight (mg kernel$^{-1}$) with Environment, Irrigation, Maturity, hybrid nested within maturity and environment, and their interactions as fixed factors in the model.

<table>
<thead>
<tr>
<th>Effect</th>
<th>Degrees of freedom</th>
<th>Yield</th>
<th>Kernel Number</th>
<th>Kernel Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environment</td>
<td>2</td>
<td>&lt;.0001</td>
<td>0.0032</td>
<td>0.0001</td>
</tr>
<tr>
<td>Irrigation</td>
<td>1</td>
<td>&lt;.0001</td>
<td>0.0110</td>
<td>0.0037</td>
</tr>
<tr>
<td>Environment*Irrigation</td>
<td>2</td>
<td>0.0154</td>
<td>0.0390</td>
<td>0.0041</td>
</tr>
<tr>
<td>Maturity</td>
<td>1</td>
<td>&lt;.0001</td>
<td>0.0228</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Environment*Maturity</td>
<td>2</td>
<td>ns</td>
<td>0.0224</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Irrigation*Maturity</td>
<td>1</td>
<td>0.0522</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>Environment<em>Irrigation</em>Maturity</td>
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<td>ns</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>Hybrid (Environment*Maturity)</td>
<td>14</td>
<td>0.0603</td>
<td>0.0008</td>
<td>0.0015</td>
</tr>
<tr>
<td>Irrigation<em>Hybrid (Environment</em>Maturity)</td>
<td>14</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
</tr>
</tbody>
</table>
**Table 2.3.** Corn grain yield KN and KW by water treatment, maturity (early hybrids CRM<110 and late hybrids CRM>110) and environment. Different letters in Environment*Irigration and Environment*Maturity interactions, means significant different within environment.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Level</th>
<th>Yield (Mg ha⁻¹)</th>
<th>Kernel Number (kernels m⁻²)</th>
<th>Kernel Weight (mg kernel⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environment * Irrigation</td>
<td>Princeton 17’ Irrigated</td>
<td>15.91 a</td>
<td>4203 a</td>
<td>318 a</td>
</tr>
<tr>
<td></td>
<td>Princeton 17’ Rainfed</td>
<td>12.39 b</td>
<td>3711 b</td>
<td>282 b</td>
</tr>
<tr>
<td></td>
<td>Lexington 17’ Irrigated</td>
<td>17.68 a</td>
<td>4408 a</td>
<td>339 a</td>
</tr>
<tr>
<td></td>
<td>Lexington 17’ Rainfed</td>
<td>16.64 b</td>
<td>4165 b</td>
<td>338 a</td>
</tr>
<tr>
<td></td>
<td>Lexington 18’ Irrigated</td>
<td>18.04 a</td>
<td>4578 a</td>
<td>333 a</td>
</tr>
<tr>
<td></td>
<td>Lexington 18’ Rainfed</td>
<td>17.60 a</td>
<td>4566 a</td>
<td>326 a</td>
</tr>
<tr>
<td>Environment * Maturity</td>
<td>Princeton 17’ Early</td>
<td>13.03</td>
<td>3900 a</td>
<td>279 b</td>
</tr>
<tr>
<td></td>
<td>Princeton 17’ Late</td>
<td>15.27</td>
<td>4013 a</td>
<td>320 a</td>
</tr>
<tr>
<td></td>
<td>Lexington 17’ Early</td>
<td>15.94</td>
<td>4319 a</td>
<td>312 b</td>
</tr>
<tr>
<td></td>
<td>Lexington 17’ Late</td>
<td>18.38</td>
<td>4255 a</td>
<td>365 a</td>
</tr>
<tr>
<td></td>
<td>Lexington 18’ Early</td>
<td>16.76</td>
<td>4329 b</td>
<td>327 a</td>
</tr>
<tr>
<td></td>
<td>Lexington 18’ Late</td>
<td>18.87</td>
<td>4815 a</td>
<td>331 a</td>
</tr>
<tr>
<td>Irrigation * Maturity</td>
<td>Irrigated Late</td>
<td>18.54 a</td>
<td>4525</td>
<td>347</td>
</tr>
<tr>
<td></td>
<td>Rainfed Late</td>
<td>16.44 b</td>
<td>4196</td>
<td>331</td>
</tr>
<tr>
<td></td>
<td>Irrigated Early</td>
<td>15.84 a</td>
<td>4267</td>
<td>313</td>
</tr>
<tr>
<td></td>
<td>Rainfed Early</td>
<td>14.65 b</td>
<td>4098</td>
<td>300</td>
</tr>
<tr>
<td>Location</td>
<td>Year</td>
<td>Treatment</td>
<td>Estimated yield for CRM = 102 (kg ha(^{-1}))</td>
<td>Yield change per unit increase in CRM (kg ha(^{-1}) CRM(^{-1}))</td>
</tr>
<tr>
<td>----------</td>
<td>------</td>
<td>-----------</td>
<td>-----------------------------------------------</td>
<td>---------------------------------------------------------------</td>
</tr>
<tr>
<td>Lexington</td>
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<td>15,239 b</td>
<td>147 a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Irrigated</td>
<td>15,897 ab</td>
<td>188 a</td>
</tr>
<tr>
<td></td>
<td>2018</td>
<td>Rainfed</td>
<td>15,920 ab</td>
<td>195 a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Irrigated</td>
<td>16,745 a</td>
<td>143 a</td>
</tr>
<tr>
<td>Princeton</td>
<td>2017</td>
<td>Rainfed</td>
<td>11,717 d</td>
<td>67 b</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Irrigated</td>
<td>13,931c</td>
<td>205 a</td>
</tr>
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</table>
TABLE 2.5. Sensitivity analysis based on low (-50%) medium (average) and high (+50%) response of yield to irrigation, minimum maximum and average historic corn price for the period (2008-2018). Cost of irrigation system installation $1800 ha⁻¹, based on Amosson et al., 2002; Hogan et al., 2007; Boyer et al., 2015.

<table>
<thead>
<tr>
<th>Yield Increase (Mg ha⁻¹)</th>
<th>Low corn price ($141 Mg⁻¹)</th>
<th>Average corn price ($184 Mg⁻¹)</th>
<th>High corn price ($272 Mg⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Increase in gross returns ($ ha⁻¹)</td>
<td>Years to pay the system</td>
<td>Increase in gross returns ($ ha⁻¹)</td>
</tr>
<tr>
<td>1.74</td>
<td>245</td>
<td>8</td>
<td>320</td>
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<tr>
<td>3.48</td>
<td>490</td>
<td>4</td>
<td>640</td>
</tr>
<tr>
<td>5.22</td>
<td>736</td>
<td>3</td>
<td>960</td>
</tr>
</tbody>
</table>
Figures Chapter 2.

**Figure 2.1.** Relationship between average rainfall and year for the period (1988-2018) in Lexington, Princeton, Mayfield and Henderson. Blue circles represents cumulative annual rainfall, while red triangles represent cumulative summer rainfall (June-September)
**Figure 2.2.** Average daily water deficit, calculated from the difference between daily Reference Evapotranspiration (ET$_0$) and Precipitations. Horizontal solid line shows the water deficit threshold when Available soil water is depleted by 65%. Shaded area represents the average daily water deficit for the period 1988-2018. Dashed and solid line represents the average daily water deficit for 2017 and 2018 respectively.
Figure 2.3. Number of days in a month with water stress above a 50 mm deficit at four Kentucky locations. Light red area represents the 30–year average (1988-2018), black dashed line 2017, and solid blue line 2018.
Figure 2.4. Regression analysis of Corn Relative Maturity (CRM) and yield in Lexington 2017-2018, and Princeton 2017. Triangles and full line represents irrigated hybrids and circles and dashed lines represents rainfed hybrids.
Figure 2.5. Gross income due to irrigation by location. Simulation of different corn prices at two environments where irrigation had a significant effect. Average corn price $184 Mg\(^{-1}\). Vertical arrows represent yield grain from irrigation at each environment.
Chapter 3: Population effect on yield of different corn hybrid maturities across irrigated fields in Kentucky

Abstract

The response of corn grain yield to plant population has been widely studied. However, the interaction between hybrid maturity and plant populations could provide additional information to increase not only yields, but also water use efficiency (WUE). The objective of this study was to quantify the yield response of a range of hybrid maturities at different plant populations under irrigated conditions. We hypothesized that increasing plant population in early maturity hybrids will provide similar yield to later maturities at recommended populations. To test our hypothesis, an experiment was conducted under irrigated conditions in three environments across Kentucky (2017-2018). Treatments consisted on a combination of plant population (7.8 and 10 pl m$^2$) and corn hybrid relative maturities (CRM) ranging from 102 to 120. Results indicated a 14% yield increased with later maturities compared to earlier ones. There was no significant effect of plant population on yield under irrigated conditions in our trials, but yield components were affected by the interaction between plant population and hybrid maturity. Increasing plant population increased KN by 11% in early and 3% in late maturities. Meanwhile late maturities increased KW by 11 and 15% compared to early hybrids at 7.8 and 10 pl m$^2$, respectively. No differences were found in KGR among hybrids in 2018, indicating that the greater KW in later hybrids was due to an extended duration of the EFP instead. An increase in plant population decreased individual kernel weight (KW) by 4.5% and reduced kernel number per ear (KNE) by 10%. Our results indicated that under irrigated conditions there was no yield advantage from increasing plant population above 7.8 pl m$^2$. The compensation of yield components observed under the high population requires more research to understand the mechanisms limiting KW during the seed filling phase.
1 Introduction

Corn (*Zea Mays* L.) yield in the United States has increased by 17% in the last decade (USDA NASS 2018). This yield improvement can be partially attributed to an increase in planting populations and in the performance of modern hybrids under these conditions (Duvick et al., 2004). The high dependence of corn yield to plant population relies on its limited capacity to develop new reproductive structures, when there is an increase in the available resources. Therefore, early hybrids, with a reduced overall growing season, biomass (Capristo et al., 2007) and leaf area index (LAI) (Howell et al., 1998) are more dependent on plant population increases to maximize light interception and yield. Moreover, an experiment performed in Arkansas by (Edwards et al., 2005) found that short season hybrids (850 °Cd) required a fourfold increase in planting population to achieve similar yield to later maturities (1050 °Cd) but with a reduction of 45% in irrigation requirements.

Corn grain yield is mostly explained by the number of kernels per unit area, which is highly influenced by the crop growth rate (CGR) during the window around flowering (Andrade et al., 1999). Kernel number per plant has a curvilinear response to crop growth rate (CGR) in non-prolific plants, suggesting that there is a threshold below which there is no grain developed, and a plateau where increases in CGR will not increase number of kernels per plant any further (Andrade et al., 1999). Therefore, a higher amount of resources per plant around the plateau region will provide a reduced overall efficiency in the amount of kernels per plant, and a reduced total number of kernels on an area basis (Andrade et al., 1999). As a result, increasing plant population allows a better efficiency
in kernels produced per resource available per plant, perhaps reducing the number of kernels per ear and yield per plant, but increasing the overall amount of kernels on an area basis and therefore yield (Poneleit and Egli, 1979; Rossini et al., 2011).

The response of kernel number and yield to plant population may be more pronounced in short season hybrids due to smaller crop height (Howell et al., 1998), reduced fraction of intercepted photosynthetic active radiation around flowering (Andrade et al., 2000), and less dry matter produced (Sarlangue et al., 2007) compared to later maturities. The aforementioned plant characteristic of early hybrids indicates that both KN and yield are source limited. As a result, numerous studies have reported a positive yield response to increasing plant populations in short hybrid maturities (Berzensyi and Tokatlidis, 2012; Edwards et al., 2005; Sarlangue et al., 2007). Thus, intensification of plant populations are more required in short season hybrids to increase yield than later hybrids.

Nevertheless, the increase in the number of plants per area, may have other consequences such as a reduction in grain moisture (Widdicombe and Thelen, 2002) or an increase in water demand (Alessi and Power, 1974b). Thus, selection of management practices such as plant population or corn hybrids with a growing cycle (referred as corn hybrid relative maturity, CRM) adapted to a particular environment are important to optimize the available resources and therefore achieve the maximum yield at a given location.

However, it is important to assess which is the optimum planting population for each maturity choice under scenarios with different water availability. Van Averbeke and Marais (1992) conducted an experiment in South Africa, comparing different irrigation
treatments, and plant populations. They reported that optimum planting population for
grain yield, will be affected by the soil available water at a given environment (Van
Averbeke and Marais, 1992). In an irrigated experiment conducted in the Mid-west,
Trooien et al (1999) showed a yield advantage of later maturities over shorter ones of
0.94 Mg ha\(^{-1}\), but with a higher seasonal water use (86 mm). The use of management
decisions that allow increasing productivity meanwhile protecting the water reserves is
crucial to maintain a sustainable production. Selection of early season hybrid maturities
could be a strategy to reduce corn irrigation requirements while achieving similar yield
than with late maturities, and thus increase water use efficiency (WUE).

Hence, understanding, the interaction between hybrid maturities and plant
populations in irrigated environments, can provide substantial information about hybrids
better adapted to irrigated conditions. Therefore, the objectives of this study were to
evaluate the yield and yield components (KN, KW, KNE) of early (CRM<110) and late
(CRM>110) hybrids under irrigation and two planting densities (7.8 and 10 pl m\(^{-2}\)) in
three different environments across Kentucky. We hypothesized that increasing plant
population in early maturity hybrids will provide similar yield to later maturities at
recommended populations.
2. Material and methods

2.1. Description of field experiment

Irrigated field experiments were conducted at the UK North Spindletop Research farm in Lexington, KY in 2017 and 2018, and at the UK Research and Education Center in Princeton, KY in 2017 (Table 3.1). Each year and location combination was treated as a different environment. The experimental design at each site was a split-plot design with four replications. The main split factor was plant population (7.8 and 10 pl m\(^{-2}\)), and hybrids were randomized within each plant population and repetition. Hybrids ranged in corn relative maturity (CRM) from 102 to 120 days, or from 1382 to 1599 Growing Degree Units (GDU) from emergence to physiological maturity (R6; Ritchie and Hanway, 1989) (Table 3.2). The experiments included a total of six corn hybrids in 2017, and eight hybrids in 2018. Most hybrids used in 2017 were replaced in 2018, but by a hybrid of similar maturity. For analysis purposes, hybrids were nested within early and late maturities. Hybrids were grouped in early maturity when CRM was less than 110, and in late maturity when CRM was higher than 110 (Table 3.2). An additional planting population of 4 pl m\(^{-2}\) was added in 2018 to estimate the potential number of kernels per ear with reduced or no competition between plants.

Plots consisted of four rows spaced 0.76 m apart and 9 m long. Corn was seeded on May 3\(^{rd}\) in Lexington and May 19\(^{th}\) in Princeton in 2017 and May 6\(^{th}\) in 2018. Soils in Lexington were classified as Bluegrass-Maury silt loam and as Crider silt loam in Princeton. Plots were fertilized with ammonium nitrate in 2017 and urea in 2018 at a rate of 320 Kg N ha\(^{-1}\) split in three equal applications (at pre-planting, at V6 and V14) to
ensure no nitrogen deficit during the growing season. Weeds were controlled at pre
planting with tillage and 5.0 l ha\(^{-1}\) of Medal II (Atrazine + Metolachlor). Eventual weed
infestation was controlled with hand weeding. In Lexington 2017, 125 ml ha\(^{-1}\) of
Lambda-cyhalothrin (Warrior) was applied to control Japanese beetle (*Popillia
Japonica*).

Experiments were irrigated using a drip-tape system in Lexington, and a lateral
variable rate automatic system in Princeton. Irrigation was based on a daily water balance
and experiments were irrigated when the cumulative soil water deficit reached 40 mm.
The cumulative net evapotranspiration deficit was calculated with a daily balance of crop
evapotranspiration, precipitation and irrigation (Allen et al., 1998). Daily minimum and
maximum temperature and precipitation were obtained from a nearby weather station and
downloaded from the UK Ag Weather Center (http://wwwagwx.ca.uky.edu). The daily
solar radiation for calculation of reference crop evapotranspiration was estimated
according to Hargreaves and Samani (1982). Crop evapotranspiration was calculated
from reference evapotranspiration based on the dual crop coefficient method that
partitions the evaporative demand into soil evaporation and crop transpiration based on
the percentage of light intercepted by the canopy (Allen et al., 1998). The percentage of
canopy cover was estimated from visual observations in treatments seeded at a planting
population of 7.8 pl m\(^{-2}\) until canopy closure, and a constant value of 100% was
considered after that time.
2.2. Crop measurements

In three out of four repetitions, 5 plants per plot were marked to monitor timing of developmental stages (Ritchie and Hanway 1989). Date of emergence (VE), sixth leaf stage (V6), silking (R1) and physiological maturity (R6) were recorded in three repetitions in 2018. Time from planting to flowering (R1), from planting to physiological maturity (R6), and the duration of the reproductive phase (R6 – R1) was calculated for corn in each of these plots.

In 2018, one random ear per plot was sampled every 4 days during the grain filling period from the two central rows. Ear samplings started on July 27th and ended on August 9th. Ears were oven-dried at 80 °C for 5 days, and hand threshed. Two 500-kernel samples were weighed. Kernel growth rate (KGR, mg kernel⁻¹ day⁻¹) was obtained from the slope of the regression between kernel dry weight over time. The duration of the effective kernel filling period was calculated by dividing final kernel weight by the KGR.

In 2017, grain yield was determined by hand harvesting all ears in 4.8 m of the two central rows in each plot. In 2018, 3.05 m out of the two middle rows were harvested with a Wintersteiger Quantum plot combine. Final yield was adjusted based on moisture and expressed at a constant moisture of 155 g kg⁻¹. A subsample of 15 ears in 2017, and 5 ears in 2018 were taken at harvest to quantify individual kernel weight (KW, mg kernel⁻¹), kernel number per ear (KNE, kernels ear⁻¹), and to calculate the total number of kernels on an area basis (KN, kernels m⁻²). In 2018, the fraction of maximum number of kernels per ear (F_KNE) was calculated for each treatment as follows:

\[ F_{KNE} = \frac{KNE}{KNE_{MAX}} \]
where $K_{\text{NE}} \text{MAX}$ is the number of kernels for a given hybrid and replicate at the 4 pl m$^{-2}$ plant population treatment.

2.3. Data Analysis

All variables measured were analyzed with an analysis of variance using the PROC GLIMMIX procedure in SAS v.9.4. (SAS for Windows, v 9.4, SAS Institute, Cary, NC). Site (location x year combination), planting population (PP), hybrid maturity, and hybrid nested within maturity and location, and the interactions between these factors were considered fixed factors in the model. Block nested within location, and block nested within location by planting population were considered as random effects. For variables measured only in 2018 (KGR, EFP), site effects were not considered in the analysis. Least significant difference (LSD) was used to separate means (P<0.05). In addition, a contrast analysis was performed between the early maturities at 10 pl m$^{-2}$ and late maturities at 7.8 pl m$^{-2}$ to further test our hypothesis, between maturities and plant population.

3. Results

3.1. Weather data and Irrigation

Precipitation during 2017 and 2018 in Lexington was 29% and 71% higher than the historical average from 1988-2018 of 1571 mm (Figure 3.1A) respectively. In Princeton 2017, annual precipitation was 14% lower than the historical average of 1278 mm (Figure
3.1B). In Lexington, daily cumulative water deficit in 2017 reached values above the 40 mm threshold for irrigation several times during the growing season. As a consequence, total irrigation in 2017 was 130 mm. In 2018, total irrigation applied was 88 mm. In Princeton 2017, total irrigation applied was 140 mm, but this number was approximately 30 mm lower than the irrigation requirements estimated for this site, due to a delay in the set up and start of the irrigation. Average monthly temperatures in Lexington were similar to the 30-year average during the corn growing season in 2017 (Figure 3.2.A dashed line), but above the normal values in 2018 (Figure 3.2.A solid line). Average monthly temperatures in Princeton during the 2017 growing season were similar to the 30-year average (Figure 3.2.B).

### 3.2. Crop phenology

Hybrid maturity and hybrid within maturity affected the number of days from planting to R1, from planting to R6, and from R1 to R6 (Table 3.5). Duration of the vegetative (Planting-R1) and reproductive (R1-R6) phases are summarized in Figure 3.3. The time from planting to flowering was 55 days on average for hybrids of CRM from 102-107, and this number increased up to 5 days in the hybrid with latest maturity (CRM=120) (Figure 3.3). When R6 date was analyzed, the latest hybrid (CRM=120) achieved maturity on average 6 days later than most of the earliest hybrids (CRM =102-107) (Figure 3.3.). Although hybrid P0825 (CRM=108) was classified as early maturity, it had a response similar to hybrids in the late maturity group.

Hybrid with earliest maturity (CRM=102) had the shortest duration of the reproductive stages (66 days) while the latest hybrid (CRM= 120) extended the
reproductive stages by about 2 days. However, hybrids with CRM 111-114 extended reproductive stages by 5 days compared to CRM 102 (Figure 3.3).

3.3. Yield and yield components

Corn yield ranged from 16.07 Mg ha\(^{-1}\) in Princeton 2017 to 18.31 Mg ha\(^{-1}\) in Lexington 2017 and 18.02 Mg ha\(^{-1}\) in 2018. The relatively low yields in Princeton 2017 could be due to the delayed start of irrigation at this site, which could have resulted in some water deficit. Maturity, hybrid within maturity and environment affected yield (Table 3.3). On average, late maturities increased yields by 14% compared to earlier ones (Table 3.4). Yield results from the lsmeans by hybrid and environment are presented in Figure 3.4. In 2017, hybrids with 118 CRM or above had the greatest yields (indicated by Filled symbols) (>19.5 Mg ha\(^{-1}\)), whereas in Lexington 2018 hybrids with CRM higher than 108 had the greatest yields (>18.8 Mg ha\(^{-1}\)) (Figure 3.4).

Hybrid maturity by plant population affected KN (Table 3.3), maturity by environment and hybrid within maturity by environment affected KN. Increasing plant population increased KN to a greater extent in early (+11 %) compared with late (+2.7%) maturities (Table 3.4). As a result, KN was lower in early than later maturities at the normal population, but similar at the high plant population (Table 3.4). The KN was greater with late maturities in Lexington 2018 (+6 %), and similar across maturities in the other two environments (Table 3.4). Hybrid at each environment had variable effect on KN in 2017, whereas late maturities were more likely to increase kernel number in 2018 (Figure 3.5).
Kernel number per ear was affected by planting population, and hybrid nested within maturity and location (Table 3.3). The greater plant population reduced KNE by 9%. There was not a clear trend on the effect of hybrid maturity on KNE in 2017, whereas in 2018 hybrids with greater than CRM 114 maximized KNE (Figure 3.6).

Kernel weight (KW) was affected by most factors in the analysis of variance, except for the highest-level interactions (Table 3.3). The latest maturity at low population produced the greatest KW (Table 3.4). The high population reduced KW by 6% in early maturities, but only by 3% in late ones (Table 3.4). In Lexington, low population produced 3-8% greater KW while in Princeton 2017, population had no effect. In 2017, greater CRM increased KW (Figure 3.7), but in 2018 there was not a clear trend of increases in KW with increasing CRM as observed in 2017, and a hybrid with CRM=111 had the highest KW.

Hybrids did not affect KGR or EFP (Table 3.3), but the analysis excluded A6267 and P2089 because low sample size and outliers within the data. The high plant population, reduced EFP by 4 days, which may explain the 3% reduction of KW. Plant population did not affect KGR.

On average, hybrids at the 7.8 and 10 pl m\textsuperscript{-2} plant population achieved 90% and 82% of their potential ear size, respectively (Figure 3.8). Interestingly, the F\textsubscript{KNE} was relatively large even at the high planting population, indicating that there was little flexibility to increase ear size and number of kernels per ear, when hybrids were planted at a low population.
4. Discussion

Corn yield response to plant population has been thoroughly studied by other authors, finding different optimal rates that maximize yield depending on the year and location, ranging from 7.4 to 13.7 pl m⁻² (Mackey et al., 2016; Sarlangue et al., 2007). For example, in Kentucky, Mackey et al., (2016) found that increasing plant population by 1 pl m⁻² increased yield 381 kg ha⁻¹ under favorable conditions and reduced yield 221 kg ha⁻¹ under rainfed conditions. Surprisingly, there was no significant effect of plant population on yield in our experiment. This lack of response could be partially due to an increase in lodging under the high population. In 2018, the unexceptional rainfall and severe storms experienced in Lexington occasioned the loss of two plots, and lodging (2-27 %) that affected yield performance of the high population treatment.

The yield response of hybrid maturities can be explained by the differences in the cumulative radiation intercepted around flowering. In this sense, differences in hybrid maturity can influence the timing of anthesis, leaf area index, and the amount of radiation intercepted around this stage. Previous research have found that early hybrids have an increased yield response to plant population compared to later maturities (Berzsenyi and Tokatlidis, 2012; Edwards et al., 2005; Sarlangue et al., 2007). Increasing population of early hybrids showed an increased in the cumulative solar interception that compensated
the reduced duration of the growing season for this maturity (Edwards et al., 2005).

However, increases in plant populations enhance plant competition for other resources (water, nutrients). Therefore, the optimum plant population will depend on the available resources of a given environment as well as genotype characteristics.

We hypothesized that early hybrids at higher seeding rate of 10 pl m$^{-2}$, could have similar yields to later maturities at 7.8 pl m$^{-2}$. While the high plant population increased yields of early hybrids by 0.82 Mg ha$^{-1}$, these were still 1.84 Mg ha$^{-1}$ lower compared to late maturities at the normal plant population. We observed an interaction of plant population and maturities for both KN, and KW. Although kernel number increased with higher populations and later maturities, there was a reduction in KW of higher plant populations in both maturities. It is likely that earlier hybrids had a lower reproductive partitioning of assimilates to the ear as their cumulative intercepted radiation around R1 may have been limited by a smaller leaf area index. In this regard, if we assume that early hybrids have experienced a source limitation, further studies should focus in management practices that could enhance plant growth during vegetative stages. One approach could be matching the critical period for yield determination, with environmental conditions with higher solar radiation. This last approach have been used in early soybeans maturities (ESPS) in the mid-south to match critical period with environments of high solar radiation and water availability (Heatherly and Hodges, 1999).

Our analysis under irrigated conditions showed that hybrid maturity explained most of the yield variation, and there was no significant effect of plant populations on yield. Late maturities consistently yielded the greatest. In the two environments analyzed in 2017, hybrids with CRM $\geq$ 118 maximized yield, meanwhile in 2018 hybrids with CRM
greater than 108 showed the greatest yield. These results support previous analysis conducted by Di Salvo et al. (not published) that indicated a yield advantage of late hybrids over shorter maturity hybrids in irrigated conditions in Arkansas and Nebraska (3-6 %). However, in rainfed conditions (Kentucky) yield was maximized with middle maturities (CRM: 112-115) and stability increased by 19% compared to later maturities (CRM>116) (Di Salvo et al.).

The analysis of the yield components in the study, suggest that the number of kernels in area basis, is strongly influenced by the interaction of population and maturity choices. Despite no yield increase for this interaction was observed, Kernel number increased 8% more with early maturities than later ones, at more dense populations. Therefore, one explanation for the absence of yield response to this interaction is that although KN increased (3-11 %), KW was reduced (3-7 %) with higher populations.

KN is highly influenced by the canopy photosynthesis during the critical period for kernel number determination and genetic control (Egli, 1998). Therefore, increasing plant populations in earlier maturities allow a more efficient interception of the solar radiation and enhance crop growth rate. Moreover, KN is known to have a curvilinear response to CGR around flowering, with a threshold below which there are no kernels (barren ear) and a value of CGR at which further increases do not significantly increase KN. Therefore, at high populations, there is an interplant competition for assimilates that reduce assimilate partitioning to the ear, reducing the number of kernels per plant but increase the overall kernel number (Andrade et al., 1999).

Although Plant growth rate (PGR) was not assessed in this study, previous research reported that later maturities and lower populations (Andrade et al., 1999), had a positive
effect in PGR, increasing the number of kernels per plant. While low plant population produced greater KNE, it produced less KN. Plant population had greater effect on late maturities for KNE and early maturities for KN.

Kernel weight is determined by the product of the duration of the grain filling phase and the rate at which these grains accumulate dry weight (KGR). As a result of this relationship, hybrids with longer growing cycles, are likely to experience larger duration of the grain filling phase, and therefore greater kernel weight (Capristo et al., 2007). In 2018, we did not observe differences in KGR. It is likely, that the treatments imposed in our study were not strong enough to either increase or limit the assimilate supply to the seeds during the effective filling period. However, the lower population, extended EFP by 4 days, which was responsible for the greater KW observed.

Yield of the flex-ear hybrid P2089 (CRM 120) was not affected by plant population, even though KW increased by 7.7% at the low population. The use of flex-ear hybrids suggest greater adaptability of the ear size to the available resources in a given environment. Flex hybrids in this study did not show significant differences in yield between the two population rates. Our results agree with those of Thomison and Jordan, (2013) who found small effects of ear growth habit on yield response. These results suggest the consideration of other characteristics, rather than ear growth habit, to take into consideration to determine the optimum seeding rate for each hybrid.

5. Conclusions

In irrigated conditions, the yield of 6 hybrids tested in 2017 and 8 tested in 2018, was not affected when increasing population from 7.8 to 10 pl m$^{-2}$. In 2018, the high plant
population had a 2-27% lodging, which could have partially explained the lack of response to an increase in plant population this year. Hybrid maturity explained most of the yield variability, with greater yields with later maturities due to both an increase in KN and KW.

Yield components were affected by the interaction of plant population and hybrid maturity. The KN was greater with the high plant population and with later maturities. However, KW was reduced with the high plant population.

The limited yield response to high plant population, in particular for early hybrids, was explained by a compensation of yield components and a reduction in KW. In 2018, hybrids did not show differences in KGR, even though hybrids represented different maturities and seed companies. Instead, treatment differences in KW were explained by changes in the duration of the EFP. Interestingly, plant population reduced the EFP. Further studies should focus in understanding the mechanism behind this response and identifying management practices that could enhance plant growth during vegetative and early reproductive stages or increase assimilate supply during the seed filling phase.
### Table 3.1 Locations, planting date and soil type

<table>
<thead>
<tr>
<th>Year</th>
<th>Location</th>
<th>Latitude</th>
<th>Planting date</th>
<th>Soil type</th>
</tr>
</thead>
<tbody>
<tr>
<td>2017</td>
<td>Lexington, KY</td>
<td>38.12 N</td>
<td>May 3\textsuperscript{rd}</td>
<td>Bluegrass-Maury silt loam</td>
</tr>
<tr>
<td>2017</td>
<td>Princeton, KY</td>
<td>37.09 N</td>
<td>May 19\textsuperscript{th}</td>
<td>Crider silt loam</td>
</tr>
<tr>
<td>2018</td>
<td>Lexington, KY</td>
<td>38.12 N</td>
<td>May 9th</td>
<td>Bluegrass-Maury silt loam</td>
</tr>
</tbody>
</table>
Table 3.2 List of corn hybrids included in each experiment, corn relative maturity (CRM), growing degree day (GDU), maturity classification for this study, and ear type (flexible or semi-flexible). This information was collected from data provided for each hybrid by seed companies.

<table>
<thead>
<tr>
<th>Year</th>
<th>Location</th>
<th>Brand</th>
<th>Hybrid</th>
<th>CRM</th>
<th>GDU to R6 (°dC)</th>
<th>Maturity Type</th>
<th>Flexibility in ear size†</th>
</tr>
</thead>
<tbody>
<tr>
<td>2017</td>
<td>Lexington</td>
<td>AgriGold</td>
<td>A6267</td>
<td>102</td>
<td>1382</td>
<td>Early</td>
<td>Semi</td>
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<tr>
<td></td>
<td>Princeton</td>
<td>Pioneer</td>
<td>P0339AM</td>
<td>103</td>
<td>1326</td>
<td>Early</td>
<td>Semi (5)</td>
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<tr>
<td></td>
<td>December</td>
<td>Dynagro</td>
<td>D48VC76RIB</td>
<td>108</td>
<td>1443</td>
<td>Early</td>
<td>Semi</td>
</tr>
<tr>
<td></td>
<td>Princeton</td>
<td>Dekalb</td>
<td>DKC68-26RIB</td>
<td>118</td>
<td>1621</td>
<td>Late</td>
<td>Flex</td>
</tr>
<tr>
<td></td>
<td>November</td>
<td>Dynagro</td>
<td>D58VC65</td>
<td>118</td>
<td>1549</td>
<td>Late</td>
<td>Flex</td>
</tr>
<tr>
<td></td>
<td>December</td>
<td>Pioneer</td>
<td>P2089AM</td>
<td>120</td>
<td>1599</td>
<td>Late</td>
<td>Flex (8)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>Location</th>
<th>Brand</th>
<th>Hybrid</th>
<th>CRM</th>
<th>GDU to R6 (°dC)</th>
<th>Maturity Type</th>
<th>Flexibility in ear size†</th>
</tr>
</thead>
<tbody>
<tr>
<td>2018</td>
<td>Lexington</td>
<td>Pioneer</td>
<td>P0825AM</td>
<td>108</td>
<td>1471</td>
<td>Early</td>
<td>Semi (6)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pioneer</td>
<td>P1197AM</td>
<td>111</td>
<td>1499</td>
<td>Late</td>
<td>Semi (6)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dekalb</td>
<td>DKC64-35RIB</td>
<td>114</td>
<td>1565</td>
<td>Late</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pioneer</td>
<td>P1870AM</td>
<td>118</td>
<td>1571</td>
<td>Late</td>
<td>Semi (6)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pioneer</td>
<td>P2089 AM</td>
<td>120</td>
<td>1599</td>
<td>Late</td>
<td>Flex (8)</td>
</tr>
</tbody>
</table>

†Flexibility in ear size was provided by seed companies using a ranking from 0 to 10 is included in parenthesis.
### Table 3.3. Analysis of variance for Yield, kernel number (KN, kernels m$^{-2}$), kernel number per ear (KNE, kernels ear$^{-1}$), kernel weight (KW, mg kernel$^{-1}$), kernel growth rate (KGR, mg day$^{-1}$), and effective filling period (EFP, days). Environment (location x year combination), planting population (PP), maturity (CRM<110 and CRM>110), and hybrid nested within maturity and location were considered as fixed factors in the model.

<table>
<thead>
<tr>
<th>Effect</th>
<th>DF</th>
<th>Yield</th>
<th>KN</th>
<th>KNE</th>
<th>KW</th>
<th>KGR†</th>
<th>EFP†</th>
<th>F_{KNE}†</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environment (Env)</td>
<td>2</td>
<td>0.0007</td>
<td>0.0009</td>
<td>&lt;.0001</td>
<td>ns</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Planting population (PP)</td>
<td>1</td>
<td>ns</td>
<td>0.0023</td>
<td>0.0082</td>
<td>&lt;.0001</td>
<td>ns</td>
<td>0.090</td>
<td>0.0002</td>
</tr>
<tr>
<td>Maturity (M)</td>
<td>1</td>
<td>&lt;.0001</td>
<td>ns</td>
<td>0.0342</td>
<td>&lt;.0001</td>
<td>ns</td>
<td>ns</td>
<td>0.0678</td>
</tr>
<tr>
<td>PP*M</td>
<td>1</td>
<td>ns</td>
<td>0.0021</td>
<td>0.109</td>
<td>0.0495</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>Env*PP</td>
<td>2</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>0.0093</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Env*M</td>
<td>2</td>
<td>ns</td>
<td>0.0065</td>
<td>0.093</td>
<td>&lt;.0001</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Env<em>PP</em>M</td>
<td>2</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Hybrid (M*Env)</td>
<td>6-14</td>
<td>0.018</td>
<td>&lt;.0001</td>
<td>&lt;.0001</td>
<td>&lt;.0001</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>PP<em>Hybrid(M</em>Env)</td>
<td>6-14</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
</tr>
</tbody>
</table>

†KGR, EFP, and F_{KNE} were measured only in Lexington 2018. Thus, the environment effect and its interactions with other factors is not considered in the analysis of variance model for these variables. Hybrids are nested only within maturity in this case, instead of within maturity and environment.
TABLE 3.4. Corn yield (Mg ha\(^{-1}\)), kernel number (KN, kernels m\(^{-2}\)), kernels per ear (KNE, kernels ear\(^{-1}\)), and kernel weight (KW, mg kernel\(^{-1}\)) by treatment for significant factors according to the analysis of variance. Hybrid with CRM < 110, were considered Early hybrids and CRM>110 late. Means followed by different letters indicate different means within an effect and location.

<table>
<thead>
<tr>
<th>Effect</th>
<th>Treatment</th>
<th>Yield (Mg ha(^{-1}))</th>
<th>KN (kernels m(^{-2}))</th>
<th>KNE (kernels ear(^{-1}))</th>
<th>KW (mg kernel(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maturity</td>
<td>Early</td>
<td>16.27 b</td>
<td>4551</td>
<td>544 b</td>
<td>303 b</td>
</tr>
<tr>
<td></td>
<td>Late</td>
<td>18.66 a</td>
<td>4623</td>
<td>571 a</td>
<td>342 a</td>
</tr>
<tr>
<td>PP * Maturity</td>
<td>7.8 pl m(^2) *Early</td>
<td>15.86</td>
<td>4308 c</td>
<td>558</td>
<td>313 c</td>
</tr>
<tr>
<td></td>
<td>7.8 pl m(^2) *Late</td>
<td>18.52</td>
<td>4561 b</td>
<td>608</td>
<td>347 a</td>
</tr>
<tr>
<td></td>
<td>10 pl m(^2) *Early</td>
<td>16.68</td>
<td>4793 a</td>
<td>529</td>
<td>293 d</td>
</tr>
<tr>
<td></td>
<td>10 pl m(^2) *Late</td>
<td>18.87</td>
<td>4685 a</td>
<td>534</td>
<td>337 b</td>
</tr>
<tr>
<td>Environment*PP</td>
<td>Lexington 17*7.8 pl m(^2)</td>
<td>17.68</td>
<td>4506</td>
<td>611</td>
<td>337 a</td>
</tr>
<tr>
<td></td>
<td>Lexington 17*10 pl m(^2)</td>
<td>19.10</td>
<td>4861</td>
<td>537</td>
<td>326 b</td>
</tr>
<tr>
<td></td>
<td>Lexington 18*7.8 pl m(^2)</td>
<td>18.02</td>
<td>4583</td>
<td>646</td>
<td>332 a</td>
</tr>
<tr>
<td></td>
<td>Lexington 18*10 pl m(^2)</td>
<td>18.01</td>
<td>4955</td>
<td>590</td>
<td>307 b</td>
</tr>
<tr>
<td></td>
<td>Princeton 17*7.8 pl m(^2)</td>
<td>15.91</td>
<td>4216</td>
<td>553</td>
<td>319 a</td>
</tr>
<tr>
<td></td>
<td>Princeton 17*10 pl m(^2)</td>
<td>16.22</td>
<td>4402</td>
<td>475</td>
<td>312 a</td>
</tr>
<tr>
<td>Environment* Maturity</td>
<td>Lexington 17*Early</td>
<td>16.97</td>
<td>4795 a</td>
<td>577</td>
<td>302 b</td>
</tr>
<tr>
<td></td>
<td>Lexington 17*Late</td>
<td>19.82</td>
<td>4607 a</td>
<td>573</td>
<td>361 a</td>
</tr>
<tr>
<td></td>
<td>Lexington 18*Early</td>
<td>17.09</td>
<td>4624 b</td>
<td>586</td>
<td>313 b</td>
</tr>
<tr>
<td></td>
<td>Lexington 18*Late</td>
<td>18.94</td>
<td>4913 a</td>
<td>650</td>
<td>327 a</td>
</tr>
<tr>
<td></td>
<td>Princeton 17*Early</td>
<td>14.76</td>
<td>4268 a</td>
<td>468</td>
<td>294 b</td>
</tr>
<tr>
<td></td>
<td>Princeton 17*Late</td>
<td>17.37</td>
<td>4349 a</td>
<td>491</td>
<td>337 a</td>
</tr>
</tbody>
</table>
Table 3.5. Analysis of variance for Lexington 2018 on days from planting to R1 (Silking), from planting to R6 (physiological maturity), and from R1 to R6. Planting population (PP), maturity (CRM<110 and CRM>110), and hybrid nested within maturity were considered as fixed factors in the model.

<table>
<thead>
<tr>
<th>Effect</th>
<th>DF</th>
<th>Planting-R1</th>
<th>Planting- R6</th>
<th>R1-R6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planting population (PP)</td>
<td>1</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>Maturity</td>
<td>1</td>
<td>&lt;.0001</td>
<td>&lt;.0001</td>
<td>0.0517</td>
</tr>
<tr>
<td>PP*Maturity</td>
<td>1</td>
<td>0.0513</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>Hybrid(Maturity)</td>
<td>6</td>
<td>0.0001</td>
<td>0.0208</td>
<td>0.0199</td>
</tr>
<tr>
<td>PP*Hybrid(Maturity)</td>
<td>6</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
</tr>
</tbody>
</table>
Figures Chapter 3.

**Figure 3.1.** Monthly precipitation in Lexington (a) and Princeton (b) during 2017 and 2018 (dashed and solid lines, respectively), and historical averaged from 1988-2018 (bars).
Figure 3.2. Average monthly temperature in Lexington (A) and Princeton (B) during 2017 and 2018 (dashed and solid lines, respectively), and historical averaged for 1988-2018 (dotted line).
Figure 3.3. Duration of A) vegetative (gray bars) and B) reproductive (blue bars) phases by hybrid in Lexington 2018. Different letters mean significant differences (α<0.05).
FIGURE 3.4. Yield (kg ha⁻¹) by corn relative maturity (CRM) and by environment. Filled symbols indicate the highest yield within an environment, or not significantly different from the highest yield. Error bars represent +/- standard deviation.
**Figure 3.5.** Kernel number (KN, kernels m\(^{-2}\)) by corn relative maturity (CRM) and by environment. Filled symbols indicate highest value within an environment, or not significantly different from the highest value (P<0.05). Error bars indicate +/- standard deviation.
Figure 3.6. Kernel number per Ear (KNE, kernels ear\(^{-1}\)), by corn relative maturity (CRM) at each experimental site. Filled symbols indicate the highest KNE within an environment, or not significantly different from the highest KNE. Error bars indicate +/- standard deviation.
**Figure 3.7.** Kernel weight (KW, mg kernel\(^{-1}\)) by corn relative maturity (CRM) at each experimental site. Filled symbols indicate the highest KW within an environment, or not significantly different from the highest KW. Error bars indicate standard deviation.
Figure 3.6. Fraction of maximum kernel number per ear (F\textsubscript{KNE}) by relative maturity and plant population. Filled symbols indicate the maximum number of kernels per ear within a plant population, or not significantly different from the highest F\textsubscript{KNE}. Error bars indicate standard deviation.
GENERAL CONCLUSIONS

Chapter 1, analyzed data from corn performance tests (2005-2017) in three states with variable number of sites under irrigation to study the yield stability of different hybrid maturities. Results showed that in Arkansas and Nebraska (100 and 75% of irrigated sites, respectively), later maturities achieved greater yields (3-6 %) than earlier ones, but with reduction on yield stability (-18-22 %). In Kentucky (100% rainfed sites), middle maturity hybrids maximized yield and increased stability by 19% compared to later maturities. The risk of yields falling below the average within a region was greater with early maturities in favorable environments, meanwhile in less productive environments, later maturities were more risky.

In chapter 2, we quantified that between 85-103 days of water deficit can be expected during the corn growing season in Kentucky. Thus, irrigation is likely to increase yield productivity and stability of corn grown in this region. Field experiments conducted across 3 site-years showed an average yield increase due to irrigation of 3.5 Mg ha\(^{-1}\), but the response was variable dependent on the site and weather conditions each year. Yield was increased with later maturities in all site-years, but the size of the response was greater under irrigated conditions or conditions of high precipitation (143-205 kg ha\(^{-1}\) CRM\(^{-1}\)), and lower in rainfed conditions that experienced water stress (67 kg ha\(^{-1}\) CRM\(^{-1}\)). Further research evaluating the response of different corn hybrid maturities to irrigation is necessary to provide more robust recommendations and economic analysis.

Chapter 3 studied the interaction between hybrid maturity and plant population under irrigation. Results showed a positive yield response to later hybrid maturities, but
not an effect of plant population on yield. The KN was increased at the high plant populations, but this did not result in greater yields due to a decrease in KW. The compensation of yield components observed under the high population requires more research to understand the mechanisms limiting KW during the seed filling phase.

Our results indicate that best management practices (maturity choices, plant population, etc) will need to be reconsidered to maximize economic returns for Kentucky producers that decide to invest in irrigation equipment. Similarly, our results indicate that management recommendations can be tailored to improve productivity and yield stability depending on the location. Further experiments could explore hybrids responses to changes in assimilates supply during the seed filling phase, to detect the mechanism limiting KW at high populations and different hybrid maturities. In addition, an assessment of water use of contrasting maturities at different populations is needed to make provide informed management practices recommendations.
References


https://doi.org/10.2135/cropsci1999.0011183X0039000200026x


https://doi.org/10.2135/cropsci2016.04.0215


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037X.1998.tb00526.x


VITA

Juan Ignacio Di Salvo received a B.S. in Agronomy at University of Rosario in Argentina. In 2017, he decided to attend to the University of Kentucky to pursue a Master’s of Science degree in Integrated Plant and Soil Sciences. Once graduated, he will start to work for a Soybean breeding company in his hometown of Rosario, Argentina.