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Soybean Maturity Group Tradeoffs: Irrigation, Weed Control, and Nitrogen Fixation

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ABSTRACT

This thesis is divided into four chapters. Chapter I introduces the rationale behind the study and gives a brief overview of the overall study covering weed control, irrigation needs and nitrogen fixation amounts across soybean maturity group. Chapter II will go into further detail outlining the first applied experiment dealing with weed control and irrigation issues. Alternative weed control methods are analyzed in conjunction with irrigation risk analysis across soybean maturity group in response to agricultural issues of glyphosate resistance and declining ground water supply in the Arkansas delta region. Chapter III will jointly examine irrigation application amounts and nitrogen fixation amounts across soybean maturity group to establish tradeoffs of yield impacts from irrigation while trying to address greenhouse gas emissions stemming from agricultural production. Chapter IV offers concluding notes, study limitations and suggests areas of further research.

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DEDICATION

This thesis is dedicated to my wife and best friend, Libby, who has been by my side throughout this entire process and never doubted my abilities. I also want to dedicate this to the rest of my family who have been incredibly supportive and encouraging throughout my graduate studies.

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Chapter 1

Analyses of Soybean Maturity Group effects on Weed Control, Irrigation and Nitrogen Fixation

1.1 Introduction

In an agricultural world where technology and policy are changing more and more every day a producer can get lost in a hurry. Everything from farm payments to planting technologies are things that are evolving at an extremely fast pace. More than ever the need to efficiently communicate new technology and information to our present day producer is crucial. This effective communication line could result in advantages for both the producer and the consumer.

For the case of soybean (*Glycine max* [L.] Merr.), with so many different plant cultivars and maturity groups (MGs) available, a farmer has many options to explore in terms of what to plant. There are many different outcomes that can arise from using these different cultivars and MGs. Crop inputs such as irrigation costs, seeding costs, weed control (WC) methods and even nitrogen (N_2) fixation amounts can differ greatly when switching across the various MGs. These differences mentioned are major production components that must be considered when developing efficient farm management practices.

The purpose of this particular study was to i) examine different weed control strategies involving seeding rate and seed technology to determine yield and irrigation tradeoffs across MG; and ii) to estimate optimal MG selection in terms of irrigation costs and nitrogen fixation amounts.

1.2 Soybean Maturity Groups: Effects on Weed Control and Irrigation Needs

As previously mentioned, the first manuscript included in this thesis which is presented in Chapter 2 deals with varying weed control methods and seeding rates across MG to estimate resulting tradeoffs of yield and irrigation costs. The reason this type of experiment was conducted was to directly address current agricultural issues that producers are facing. The first issue is trying to find alternative weed control methods to battle the ever increasing emergence of new “superweeds.” These “superweeds” are most easily defined as weeds that are now resistant to the herbicide glyphosate. With glyphosate-resistant seed being the most common type of seed planted in today’s production agriculture, these “superweeds” are causing major issues for farmers in terms of hurting yield potential and increasing production costs due to multiple applications of various herbicides or added tillage to control these “superweeds.” By conducting the weed control experiment it was hoped that other potential methods may provide equal or better returns to production compared to using glyphosate-resistant seed.

The other main issue that is addressed in Chapter 2 is the issue of the declining ground water supply in the Arkansas delta region. With the amount of ground water declining at a rapid rate the amount of water available for irrigation is also becoming scarce for many producers. While past research has shown that most crops have a positive correlation between irrigation and yield this possibility of lack of water supply is a major problem. Therefore, this study also looked at different MGs and analyzed the different tradeoffs between yield and irrigation applied. It has been concluded from past research that MGs from a later maturity will typically require more irrigation than MGs from an earlier group. This is due to the fact that the later MGs typically have longer growing seasons and therefore require more water to grow. While this typically leads to greater yields for later MG than earlier MG, earlier MG cultivars can have similar yield potential as later maturing varieties while saving irrigation water.

In this study it was the goal to not only look at weed control but also analyze this tradeoff between irrigation costs and the resulting yields across MG in hopes of finding the most profitable approach.

1.3 Soybean Maturity Groups: Irrigation and Nitrogen Fixation Effects

The second manuscript included in this thesis is Chapter 3. It first examined how varying soybean MGs respond to varying levels of water deficit by controlling irrigation amounts applied and measuring resulting yields. It was the goal to try and find the MG that would have the greatest water use efficiency (WUE) defined as grain yield / water applied (irrigation and rainfall). Economically optimal irrigation amounts for a particular MG soybean could then be estimated where additional costs spent on irrigation would be worth the expenses due to the potential of higher yields.

After analyzing the yield impact of irrigation, the next factor that was considered was nitrogen fixation. Looking at the different N_2 fixation amounts for each MG was deemed important to this study for two main reasons. First, with an increased amount of N_2 fixation that takes place in the crop there is typically more N left in the soil for subsequent crops. This remaining N which is left in the soil provides cost savings for producers when planting succeeding crops as they do not have to purchase and apply as much N fertilizer. Another important aspect of N_2 fixation that was taken into consideration for this study was that any decrease in the amount of N fertilizer directly applied helps reduce greenhouse gas emissions (GHG) and particularly N_2O emissions. It has been found that these soil nitrous oxide (N_2O)

emissions which originate from the application of N have been major contributors to global warming potential or climate change. With growing consumer and policy maker interest in net GHG emissions mitigation in today's society, market based incentives for reducing agriculture's carbon footprint are proposed by trading carbon credits. A producer would get paid for reducing their carbon footprint by modifying current production practices. To do this, changes in net GHG emissions need to be estimated.

After analyzing irrigation application amounts and resulting yields in addition to N_2 fixation amounts across MG, this study's goal was to provide insights about changes in MG on partial returns.

1.4 Hypothesis Statements

Part I – Soybean Maturity Groups: Effects on Weed Control and Irrigation Needs

H_o: Alternative WC methods that satisfy tradeoffs with yield and irrigation needs do not impact producer profitability across a spectrum of MG and WC choices in Arkansas.

H_A: Cost and returns to alternative WC methods alter producer returns, and, therefore, a profit-maximizing MG and WC choice exists.

Part II – Soybean Maturity Groups: Irrigation and Nitrogen Fixation Effects

H_o: WUE, yield potential, harvest index (HI) and N_2 fixation in crop residue do not vary by MG and hence producer returns are not affected by carbon credits, changes in soybean price or fertilizer prices.

H_A: MG differences in water use efficiency, N_2 fixation, yield and HI affect MG choice as profitability varies across MG.

1.5 Summary

With the increasing severity of the previously mentioned agricultural issues alternative production methods to remedy these problems could prove to be essential. With the right alternative production decisions many of these problems can be addressed and aid in increasing producer returns. MG tradeoffs in terms of WUE and higher yields in conjunction with a substantial amount of N_2 fixation within the crop may lead to considerable variation in profit for producers. The details of specific practices are addressed in this study and can outline to what magnitude results can be affected.

This chapter has given a brief overview of the overall study covering WC and irrigation needs across MG in addition to N_2 fixation amounts. Chapter 2 will go into further detail outlining the first applied experiment dealing with WC and irrigation issues. Chapter 3 will jointly examine irrigation application amounts and N_2 fixation. Chapter 4 offers concluding notes, study limitations and suggests areas of further research.

Chapter 2

Economic Implications of Soybean Maturity Group on Weed Control and Irrigation Needs

2.1 Abstract

This study examined different weed control strategies involving seeding rate and seed technology to determine yield and irrigation tradeoffs for soybean [*Glycine max* [L.] *Merr*] maturity groups II through IV. Seeding rate and weed control data from experimental plots at Fayetteville, Keiser, and Pine Tree, Arkansas from 2006 and 2007 were analyzed jointly with an irrigation study conducted at Fayetteville from 2007 to 2010. With a range of observed planting densities, profit-maximizing seeding rates could be calculated. Further, Monte Carlo simulation provided partial return distributions based on empirical observations of yield and irrigation requirements for risk analysis. Results suggested that conventional maturity group IV soybean with no post-emergence herbicide seeded at twice the current recommended rates was preferred when compared to conventional and glyphosate-resistant varieties of the same maturity and earlier maturities, seeded at recommended rates with post-emergence weed control. Sensitivity analysis of soybean price ranging from a ten-year low of \$0.29 kg^{-1} to a high of \$0.43 kg^{-1} did not modify this finding. To simulate the potential effect of declining ground water supply conditions in the region, raising irrigation cost to \$18.64 ha-cm^{-1} (\$0.19 m^{-3}) did result in earlier maturing varieties, requiring less irrigation, to lead to greater returns. This was especially so at relatively low soybean prices when the yield penalty associated with earlier maturity played a lesser role than the irrigation cost savings. Use of high seeding rates to speed canopy closure and thereby obviate the need for post-emergence weed control appears a promising area for further research.

Key words: soybean maturity group, weed control, irrigation, plant density

Abbreviations: PR = partial return to soybean after weed, seed and irrigation cost, MG = maturity group, GM = genetically modified for glyphosate resistance, GR = glyphosate-resistant, PD plant density, WC = weed control

2.2 Introduction

Producers have many options when considering maturity group (MG) in soybean as early maturing varieties are available spanning from MG 000, appropriate for the Northern U.S. and Canada, to late maturing MG X, adapted to growing conditions in tropical regions (Zhang et al., 2007). Typically, the choice of MG and attendant yield is based upon factors such as latitude, planting and harvest scheduling conflicts with competing crops, weed and disease pressure and attendant control options, likelihood of prolonged drought or seasonal rainfall, and irrigation cost. Hence the decision to modify MG is expected to affect yield, returns, and return risk. While in Arkansas, soybean MG IV through VI are well adapted (Ashlock and Purcell, 1997); producers concerned about declining ground water levels, and hence irrigation water availability, may be interested in adopting earlier maturing soybean varieties to avoid summer drought stress and thereby lower irrigation expenses (Edwards and Purcell, 2004). To attain similar yields, however, plant densities need to be significantly higher (Edwards and Purcell, 2004; Popp et al., 2006). For early MGs, added weather risk with a shorter growing season may be an issue, and soybean harvest can coincide with rice and cotton irrigation activities.

Further, the development and rapid adoption of genetically modified (GM) soybean, primarily because of weed control ease without yield penalty, has led to glyphosate-resistant (GR) weed problems in recent years (Norsworthy et al., 2011; Riar et al., 2011). Some refer to these emerging GR weeds as “superweeds” and they include horseweed (*Conyza Canadensis* [L.]), common and giant ragweed (*Ambrosia artemisiifolia* [L.] and *Ambrosia trifida* [L.]), Palmer amaranth (*Amaranthus palmeri* [L.]), Italian ryegrass (*Lolium multiflorum* [L.]), and johnsongrass (*Sorghum halepense* [L.]) (Nandula et al., 2005). In response, some producers have reverted to added tillage, and the application of pre-emergence and non-glyphosate post-emergence herbicides in addition to glyphosate as means to help with weed control. Additional tillage may increase soil erosion and nutrient leaching as well as production cost. In essence, this removes the benefit of GM soybean seed except for protecting against glyphosate drift.

Another strategy, coincident with higher required plant densities and lesser irrigation requirements with earlier MG soybean, is the modification of soybean canopy closure as a means for weed control. In essence, earlier canopy closure with earlier MG soybean or soybean planted at high seeding rates, provide poor growing conditions for weeds (Norsworthy and Oliver, 2001; Nice et al., 2001; Norris et al. 2002; and Norsworthy and Oliveira, 2007).

Given these developments in irrigation and "superweed" pressures, producers may opt for less expensive conventional soybean varieties. This would modify the compendium of seed and weed control costs for soybean and, in comparison to GM soybean, in particular, would add costs of i) applying multiple herbicides at different times in the season which will be more management and labor intensive; ii) a requirement of clean and weedless fields at time of planting to ensure no yield penalty to help soybean plant establishment; and iii) herbicide injury from glyphosate drift.

This study was, therefore, conducted to determine the cost effectiveness of three different soybean MG choices across three different Arkansas locations to address weed control, seed cost and irrigation tradeoffs. The objectives of this research were to determine: i) profit maximizing seeding rates across MG, using methods similar to Poag et al. (2005) and Popp et al. (2010); ii) potential effects of earlier canopy closure with higher plant densities on weed control; and iii) irrigation savings of earlier maturing MG. Results provide producers with information about profitability tradeoffs across MG, seed technology (conventional vs. GM) and irrigation requirements. Further, sensitivity analyses on soybean price, seed costs, and irrigation costs were performed to test the robustness of MG selection. Finally, Monte Carlo simulation was used to evaluate yield vs. irrigation tradeoffs under uncertainty.

2.3 Materials and Methods

2.3.1 Field Plots

Experiment I

Soybean yield results of two separate experimental trials were used to arrive at: i) yield response to plant densities using three weed control management strategies at three locations; and ii) irrigation needs across MG at one location. The first experiment was conducted in 2006 and 2007 at three locations in Arkansas: Fayetteville (36° 5' 42" N, 94° 10' 25" W), Keiser (35° 40' 18" N, 90° 4' 57" W), and Pine Tree (35° 7' 22" N, 90° 55' 35" W). There were relevant empirical data for all locations for the year 2007; however, only Fayetteville trial results were available for 2006. A randomized complete block design was established on plots with main effect of MG (II, III and IV) and sub plots consisted of weed control measures and seeding rates (222,400, 371,700 and 593,100 seeds ha^{-1}). The weed control treatments were: i) GM soybean with glyphosate post-emergence weed control (GM+), considered the current producer practice; ii) conventional seed with pre- and post-emergence, non-glyphosate herbicide application (CONV+); and iii) conventional soybean seeded at the highest rate with pre-emergence weed control but no post-emergence weed control (HICONV-) . All treatment combinations were replicated four times.

Plots consisted of seven drilled rows, 19 cm apart and 6.10 m in length. Observed plant densities at 2 weeks post planting were recorded and allowed yield response calculations per plot. At maturity 4.88 m of the center five rows were harvested, seed moisture measured, and yield expressed at an adjusted moisture content of 13%. The third weed control treatment, HICONV-, only took place in Fayetteville and Keiser in 2007.

Experiment I was designed to test overall effects on cost and yield. Costs and herbicide information are presented in Table 1. Weed control was visually assessed across all treatments and classified from poor to excellent by comparing weed pressure from an untreated control to weed pressure in treated plots.

Soybean cultivars planted were representative of commercial standards within their respective MG and included AG2203 (MG II), S31-V3 (MG III), and AG4801 (MG IV) in 2006. The same cultivars were used in 2006 except that AG2406 replaced AG2203. Planting occurred in mid-May each year. All plots were irrigated to avoid drought stress as determined by the Arkansas irrigation scheduling software such that irrigation was triggered when estimated soil-moisture deficits reached 37mm (Fayetteville and Pine Tree) and 50mm (Keiser). Information on irrigation amounts through growth stage R6 was collected for each treatment as irrigation beyond that growth stage would not materially enhance yield. All other production practices followed current University of Arkansas Extension recommendations at each of the locations and did not differ across treatments. Partial return calculations therefore only considered yield-, seed-, herbicide-, and irrigation-cost differences across treatments to determine economically optimal treatment(s) as all other field operations were the same across treatments and hence would not affect relative profitability.

Experiment II

The second experiment focused on the amount of irrigation applied between emergence and growth stage R6. This experiment was conducted at Fayetteville from 2007 to 2010. Data for 2009 were not analyzed as unusual rainfall during the growing season obviated the need for irrigation which would skew irrigation requirement data for the risk analysis.

The experiment used a line-source irrigation system (Hanks et al., 1976) to vary irrigation amounts across MG II to IV soybean to determine effects of drought stress. A sprinkler irrigation line was constructed through the center of the field. The experimental design was a strip split-plot arrangement of treatments in a randomized complete block with four replications. Maturity groups were whole-plot factors and irrigation treatments were stripped across MG and cultivars. Rain gauges, located throughout the field at the center of each plot, measured varying levels of irrigation applications as a function of distance from the center line source and the front of the field. Interpolation of irrigation data collected across plots thus allowed determination of irrigation amounts applied per plot as a function of distance from the center line source and distance from the end of the field. Irrigation was scheduled as described previously at an estimated moisture deficit of 37 mm. Only the plots receiving within 5% of the irrigation requirements for full yield potential, deemed fully irrigated, were used for this analysis.

Within each MG, there were two cultivars (MG II: AG2406 and AG2802 with AG2909 replacing AG 2802 in 2010; MG III: S31-V3 and S39-A3 with S33-k5 replacing S31-V3 in 2010; MG IV: AG4403 and AG4801 with AG4907 replacing AG4801 in 2010). Soybean was planted at a density of 540,000 (MG II and III) and 310,000 (MG IV) seeds per hectare. The higher seeding rate for the MG II and III cultivars was to ensure that there was adequate light interception to obtain full yield potential (Edwards et al., 2005). Plot dimensions and row spacing were the same as those described for Experiment I.

The purpose of this experiment was, thus, the determination of irrigation requirements from emergence to growth stage R6 across MG over a number of years. Empirically observed irrigation amounts and yields as they varied across MG and production season by plot for 2007, 2008 and 2010 with four replications were used as input for Monte Carlo simulation of uncertain irrigation requirements.

2.3.2 Soybean Price and Input Costs

To determine cost differences across treatments, herbicide prices from the most recent University of Arkansas Cooperative Extension Service (UACES) publication on chemical prices were used (Scott et al., 2011). These prices are summarized in Table 1. A 10-year average soybean price as reported by the National Agricultural Statistics Service for 2001 to 2010 (USDA-NASS, 2012) was also calculated and adjusted for inflation to 2010 dollars using the soybean producer price index (USDL-BLS, 2012). Use of a 10-year average price, \$0.38 kg^{-1}, allowed partial return calculations devoid of effects of unusually high or low soybean prices observed across the experimental years. Using the minimum and maximum of \$0.29 kg^{-1} and \$0.43 kg^{-1}, respectively, as observed across this 10-year period provided the range for sensitivity analysis of output price. Further sensitivity analysis was focused on irrigation needs across MG and was performed using a range of cost estimates using different irrigation methods for irrigation water.

Cost of production estimates for 2010 for direct costs (fuel, irrigation, polypipe, and labor) were \$6.35 ha-cm^{-1} (\$0.06 m^{-3}) for center-pivot and for furrow/flood irrigation \$3.49 ha-cm^{-1} (\$0.03 m^{-3}), (UACES, 2012). Note that fixed costs were excluded as the need for irrigated equipment existed regardless of MG. Finally, sensitivity analysis was also conducted to determine the minimum irrigation cost level needed for the optimal weed control (WC) × MG choice to change to less water-intensive, earlier-maturing varieties using the 10-year average soybean price. This was done to mimic effects of irrigation shortages expected in the study region (USGS, 2008). Seed cost was \$0.93 kg^{-1} for conventional seed and \$1.70 kg^{-1} for GM seed. Again, sensitivity analyses were performed at current irrigation and average soybean price to determine the impact of changing relative cost between conventional and GM seed.

2.3.3 Model Estimation

The following yield response function to plant density was used to determine optimal seeding rates using multivariate regression analysis similar to Poag et al. (2005):

$$(1) \qquad Y= f\,(PD, PD \times MG, PD \times GM, PD \times LOC, PD \times YR)$$

where Y is soybean yield in kg ha^{-1}, PD is the observed number of plants per hectare two weeks post planting and all other variables are zero/one dummy variables that measure deviations from the base case of a conventional variety MG IV soybean, planted at Fayetteville in 2007. As such MG dummy variables were dII = 1 for MG II and 0 otherwise, dIII = 1 for MG III and 0 otherwise. Similarly, seed technology effects (GM) were captured as dGM = 1 for genetically modified and 0 otherwise. Location effects (LOC) were captured as dKeiser = 1 if Keiser and 0 otherwise, dPine Tree = 1 if Pine Tree and 0 otherwise. Finally, year effects (YR) were captured using a dummy variable d06 = 1 for production year 2006 and 0 otherwise. Similar to Popp et al. (2010), Poag et al. (2005), and Popp et al. (2006), plant density (PD) was modeled linearly as well as its square root to allow for non-linear yield response. Further, all two-way interactions allowed for changes in PD coefficients only, as the model was estimated using no constant term (zero yield is expected at zero PD). Three-way interactions were excluded to reduce expected multicollinearity bias (Gujarati, 2007). The model was estimated using linear least squares in EViews version 6.0 (Startz, 2007) and *P*-values for coefficient estimates were calculated using White's heteroskedasticity consistent estimators.

2.3.4 Economic Analysis

Using Eq. 1, per hectare partial returns (PR) to soybean production after seed, irrigation and weed control costs could be estimated for each MG (i), weed control system (j) and production year as a function of plant density as follows:

(2) $$PR_{ij} = Y * p - PD * a_{ij} - b_j - IRR_i * c$$

where p is the price of soybean in \$ kg^{-1}, a_{ij} are seed costs pending seed technology employed in \$ kg^{-1}, varying by MG on the basis of seed count (seeds kg^{-1}) and adjusted for experiment-wide seed survival of 86%, b_j is the cost of the weed control program subject to glyphosate resistance in \$ ha^{-1}, IRR_i are ha-cm (water for one hectare at 1 cm depth or 1 ha-cm amounts to 100 m^3) applied as needed through R6 by MG, and c is the cost of irrigation applied in \$ $ha\text{-}cm^{-1}$.

Substituting Eq. 1 for Y in Eq. 2 and differentiating with respect to PD allowed for solving for the PR-maximizing PD subject to $\frac{\partial Y}{\partial PD} \times p = a_{ij}$, where the yield of an extra plant times its price or marginal revenue per extra plant is equal to its marginal cost on a per hectare basis.[1] Given the non-linear nature of the yield response function (Eq. 1) as well as the use of interaction terms, PR-maximizing PD, PD^*, are thus a function of PD, MG, LOC and YR as well as seed technology- and MG-dependent a_{ij}.

Values of PD^* are then substituted back into equation 2 to determine PR_{ij}^*, the estimated partial returns a profit-maximizing producer would compare across MG and seed technology employed. While comparison of PR_{ij}^* is relatively straight forward -- the highest PR_{ij}^* is the best choice for the profit-maximizing producer -- these values were also subjected to sensitivity

[1] We assume seed survival doesn't vary by seeding rate over the range of seeding rates analyzed.

analysis and Monte Carlo Simulation to determine not only point estimates of return predictions by location but also their distributions. Sensitivity analyses were performed by substituting different p's, a_{ij}'s and c's into equation 2 to assess how robust producer recommendations would be. For Monte Carlo type risk analyses, IRR_i and Y in equation 2 were substituted with their distribution functions (average and standard deviation) from information collected in the weed control and irrigation experiments using Risk Solver Plus, an Add-In to Excel® (RSP v.9.6.3, 2011). Note that IRR_i was only simulated for the Fayetteville location as more detailed data on soybean irrigation requirements were available for that site from the second irrigation experiment described previously. This allowed estimation of PR_{ij} distribution functions for analysis of profitability under risk as 10,000 iterations were performed with values of IRR_i and Y picked independently from their respective distribution functions. Since experiments were fully irrigated, note that IRR was not included as an explanatory variable in the yield response function (Eq. 1) and hence IRR and Y distributions were modeled independently.

Finally, multiple comparisons of different PR_{ij} were summarized using regret calculations. For a particular treatment combination, regret is defined as the economic loss per hectare to which a producer would be subjected had they chosen the non-optimal treatment (e.g., comparing the MG and attendant seed technology with the highest PR with itself (zero regret) to the other treatments (greater than zero regret)). For purposes of this analysis, the regret was calculated for each WC × MG combination per year and location and then averaged across years and locations. As such, the smallest average regret for a particular MG selection with attendant seed technology is optimal. Should the regret ranking not vary across location and years, the selection would also be considered robust.

Finally, the regret analysis also provides information about the cost of choosing a non-optimal MG to meet other constraints. For example, the smallest regret choice may be GM+ × MG IV soybean, but the producer may want to switch to GM+ × MG II for water savings in light of water shortage, for example. The difference between the two average regret values would be the amount a producer pays for water savings.

2.4 Results

2.4.1 Yield response to plant density

Coefficient estimates for independent variables in Eq. 1 are presented in Table 2. The model accounted for approximately 74% of the variation in Y. Consistent with expectations; GM seed did not display different PD effects on yield given good to excellent weed control across most plots (Table 3). The signs of coefficient estimates were also consistent with expectations in the sense that yield response to increasing PD was rapid at low PD and led to yield maxima that were within a reasonable range of PD for most location and year combinations (371- to 618 thousand PD ha^{-1}). Overall, yields in 2007 at Fayetteville were quite high as a result of favorable weather conditions. Estimated MG IV yield maxima were attained at lower PD than their MG III and MG II counterparts across all study locations and years. Similarly, estimated yield potential was highest for MG IV and followed by MG III and II at all study locations and years. Part of the yield differential may have been a function of poorer weed control for earlier maturing varieties (Table 3). Location differences were statistically significant for both locations and reflect changes primarily in weather and soil conditions.

Figure 1 presents yield responses to PD by MG across the three weed control strategies for Fayetteville in 2007. Note that the graphs showcase the maximum observed PD for each treatment, and yields are not expected to diminish at higher PD. Further, also note that the HICONV- yield response functions are based on four observations per MG and location as only one seeding rate treatment was applied. Hence more yield data would certainly add to the reliability of the results reported herein.

2.4.2 Economic Analysis

Using the coefficient estimates from equation 1, profit-maximizing PD^* were calculated and are shown in Table 4 along with estimated attendant Y^* and PR_{ij}^*. Note that the PD^* were curtailed to maximum observed PD as shown in Figure 1 (CONV+ × MGII, HICONV- × MG IV, HICONV- × MG II). Calculated PD^* beyond those maxima have economic meaning as long as yield is increasing at that point but were considered outside the range of results supported by this study. Had higher PD been observed in some of those instances, slight yield improvement may have been possible. Note that at much higher PD (> 1,000,000 plants per hectare), intraspecies competition may also result (Norsworthy and Oliver, 2001).

Within a weed control strategy, MG IV cultivars always showed minimum regret (Table 4). This is a reflection of the higher yield potential observed with MG IV cultivars relative to those of the other MG and is in part a reflection of relatively low irrigation cost.

Comparison of the estimated PR_{ij}^* across years and study locations showed the combination of HICONV- × MG IV to be superior among weed control × MG strategies. This was a function of higher yields (compared to earlier maturing varieties and across weed control method), lower weed control cost (compared to CONV+ and GM+ strategies) and lower total seed cost (compared to GM+). As mentioned earlier, with HICONV-, a producer incurs lower seed cost by avoiding technology fees associated with GM+ while raising seeding rate only marginally compared to CONV+. Cost savings on herbicide play a large role in the comparison between CONV+ and HICONV-. The most striking result, however, is the yield advantage observed with HICONV- which is attributed to higher PD and no post-emergence weed control. These cost savings and yield advantage are summarized in the overall regret numbers in the bottom row of Table 4 under conditions of furrow irrigation and average soybean price.

Table 5 showcases only PR^* and the regret across WC × MG strategy combination for a particular location and year (R_{Year}) but adds information when soybean price and irrigation cost are altered. Similar to Table 4, the HICONV- × MG IV displayed the lowest regret under all soybean prices (0.29 to \$0.43 kg^{-1}) and irrigation cost scenarios (center-pivot and furrow irrigation) and was followed by GM+ × MG IV and then HICONV- × MG III. This sequence of first, second and third best WC × MG choices was the same across all scenarios and the average of R_{All} was used to develop a ranking of WC × MG choices across a set of six different irrigation and soybean price scenarios. Using this methodology a producer could earn approximately \$114 ha^{-1} more by switching from GM+ × MG IV to HICONV- × MG IV and would only sacrifice approx. \$52 ha^{-1} by switching from GM+ × MG IV to HICONV- × MG III, which would save approximately 850 m^3 ha^{-1}.

Further sensitivity analyses results that were conducted on irrigation/seed costs and soybean price are represented in Table 6. The first section of the table highlights the effects of changing irrigation cost on the optimal selection for WC × MG combination. These data show that at the average soybean price, \$0.38 kg^{-1}, and current seed cost, irrigation costs would have to reach \$24.86 ha-cm^{-1} (\$0.25 m^{-3}) (an approximate fivefold increase compared to current average of furrow and center pivot irrigation costs) before any change in selection would occur.

This irrigation cost threshold changes more with changes in soybean price than seed cost differential as discussed in the footnote to Table 6. The second section of Table 6 highlights under what seed cost conditions producers would switch away from HICONV- × MG IV. This analysis suggests seed cost price differential will not play a role as GM seed is likely to continue to demand a premium compared to conventional seed. Thirdly, Table 6 showcases that under current irrigation and seed costs, a producer is not likely to switch from HICONV- × MG IV as irrigation cost savings with lower-yielding MG II would not be sufficient until soybean price were to drop to less than 0.09 \$ kg^{-1}, a price level at which producers would no longer be able to profitably grow soybean.

The Monte Carlo risk simulation revealed no real pattern in the results (Table 4). Yield risk increased in 2007 when switching from MG IV to MG III and then declined again. This trend was not observed in 2006 when a pattern more consistent with expectations was revealed (more yield risk with MG II than higher MG due to shorter growing season and greater likelihood of weather playing a role in yield determination). Variance in irrigation needs was similar across MG and slightly higher for MG IV compared to MG II. This is as expected as a longer irrigation season with MG IV would lead to greater variability. Combining these effects lead to no pattern in σ_{PR}. This suggested that, based on this analysis, that the WC × MG choice would not be significantly affected by risk implications, at least as modeled within.

2.5 Discussion

This experiment summarizes the results of two different soybean MG studies that were conducted at Fayetteville, Keiser, and Pine Tree, AR locations under a variety of factors including seed technology employed, seeding rate, weed control method, and irrigation amounts applied. The results are deemed to be representative of soybean production practices in the southeastern United States at the time of the experiments. The goal of this study was to recommend an optimal WC × MG combination that would provide information about current agricultural issues such as shortages of water for irrigation and the increasing incidence of "superweeds."

After examination of the results, switching from GM+ × MG IV soybean to HICONV- × MG IV soybean was deemed a promising alternative as it improved producer returns by an average of 114 \$ ha^{-1} at Fayetteville and Keiser in 2007. At the same time reducing producer dependence on glyphosate for post-emergence weed control was achieved. Further this strategy was superior across a wide range of input cost and output price scenarios and had no deleterious risk implications. Higher required plant densities are not expected to alter production cost from an equipment perspective as relatively simple equipment and planting practice modifications are envisioned. More troublesome are i) the issue of glyphosate drift with the use of conventional seed which could be combated by using GM+ seed at higher seeding rates and no post-emergence weed control albeit at lesser gain to the producer; and ii) the inclusion of later maturing varieties and more years of observations in this study that would have made this analysis more complete.

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Table 2.1 Weed control program information for 2006 and 2007.

Weed control strategy†	Trade name	Common name	Active ingredient (a.i.) ‡	Application time by vegetative stage (V)	Chemical cost ($ kg^{-1} of a.i.)	Herbicide cost ($ ha^{-1})	Total cost ($ ha^{-1}) §
GM+	Roundup Power Max	glyphosate	0.84	V3 & V6¶	$9.79	$16.45	$41.18
CONV+	Dual Magnum+ Sencor	s- metolachlor+ metribuzin	1.06+ 0.34	pre-emergence #	$31.55+ $47.11	$49.46	$141.83
	Flex star+ Poast Plus+ Crop Oil	fomesafen+ sethoxydim+ agri-dex	0.26+ 0.22+ 0.01	V4††	$140.72+ $126.76+ $317.46	$67.65	
HICONV-	Dual Magnum+ Sencor	s- metolachlor+ metribuzin	1.06+ 0.34	pre-emergence	$31.55+ $47.11	$49.46	$61.82

Notes:

† GM+ is the current most widely adopted practice of using GM soybean with post-emergence, label rate, glyphosate applications, CONV+ is the conventional counterpart to GM+ using non-glyphosate herbicides and HICONV- substitutes post-emergence weed control with early canopy closure supported by high seeding rate using non-GM seed.

‡ Kilograms of active ingredient of herbicide per hectare.

§ Herbicide cost per hectare plus custom application charge per trip. $12.36 per hectare represents the 2007-2011 average custom application charge per application as reported for crop enterprise budgets by the University of Arkansas Cooperative Extension Service.

¶ V3 is the third trifoliate stage and V6 is the sixth trifoliate stage.

Soil application prior to planting requires rain for activation.

†† V4 is the fourth trifoliate stage.

Table 2.2 Regression results of the yield response function (kg ha^{-1}) with a base scenario of conventional MG IV soybean planted with conventional weed control in Fayetteville, 2007.

Dependent Variable	Yield (Y)	
Independent Variables	Coefficients	T-Statistics
PD[†]	- 0.0120***	-6.47
PD × d06[‡]	0.0011	0.51
PD × dII[§]	0.0049**	2.74
PD × dIII[§]	0.0038*	2.13
PD × dKeiser[¶]	0.0042*	2.41
PD × dPine Tree[¶]	0.0019	1.20
PD × dGM+ [#]	- 0.0007	-0.52
PD × dHICONV- [#]	- 0.0002	-0.07
$PD^{.5}$	16.0853***	14.80
$PD^{.5}$ × d06	- 2.4940	-1.90
$PD^{.5}$ × dII	- 4.6931***	-4.43
$PD^{.5}$ × dIII	- 3.3348**	-3.18
$PD^{.5}$ × dKeiser	- 5.8841***	-5.50
$PD^{.5}$ × dPine Tree	- 4.9615***	-5.12
$PD^{.5}$ × dGM+	0.5676	0.69
$PD^{.5}$ × dHICONV-	0.6149	0.26
R-squared (%)	74.36	
Adjusted R-squared (%)	73.05	
S.E. of regression	626.35	
# of observations	310	

Notes: *** p < 0 .0001, ** p < 0.01, * p < 0.05

† PD, plant density in number of plants per hectare.

‡ year effects were deviations from 2007.

§ deviations from MG IV for MG II or III.

¶ location effects were deviations from Fayetteville, AR for Keiser and Pine Tree, AR.

weed control program deviations from using a conventional herbicide program (CONV+) vs. use of GM seed technology (GM+) or higher seeding rate with no post-emergence weed control (HICONV-).

Table 2.3 Average weed control ranking across location, year, maturity group (MG), and weed control method[†] (WC). The rankings of weed control were assigned relative to an untreated control and visually rated as 1=excellent, 2=good, 3=fair, and 4=poor.

Weed Control (**WC**)		GM+			CONV+			HICONV-		
MG		II	III	IV	II	III	IV	II	III	IV
Fayetteville	2006	1.58	1.92	1.92	1.25	1.42	1.50		na	
	2007	1.17	1.00	1.25	1.92	1.08	1.25	1.75	1.25	1.50
Keiser	2006	1.50	1.08	1.00	1.92	1.42	1.08		na	
	2007	2.17	1.33	1.17	2.25	1.58	1.67	3.50	2.00	1.50
Pine Tree	2006	2.33	1.58	1.42	3.33	2.83	2.42		na	

Notes:

† GM+ is the current most widely adopted practice of using GM soybean with post-emergence, label rate, glyphosate applications, CONV+ is the conventional counterpart to GM+ using non-glyphosate herbicides and HICONV- substitutes post-emergence weed control with early canopy closure supported by high seeding rate using non-GM seed.

Table 2.4 Yield (Y^*) at profit-maximizing plant density (PD*), observed yield risk (σ_Y), total seed cost (TSC^*), avg. irrigation applied (IRR) and its standard deviation (σ_{IRR}), herbicide cost (H_{WC}), partial return (PR^*), its simulated standard deviation (σ_{PR}) along with annual regret (R_{wc}) within weed control strategy (WC) and across all WC for a location (R_{Year}) using furrow irrigation cost, average soybean price and reported seed cost.

WC		GM+			CONV+			HICONV-		
MG		II	III	IV	II	III	IV	II	III	IV
	Units				Fayetteville,2007					
Y^*	kg ha^{-1}	4,560	4,948	5,449	4,556	4,938	5,390	4,817	5,277	5,701
σ_Y	kg ha^{-1}	476	736	645	476	455	436	485	666	525
$PD^{*†}$	plts	500	475	381	574	546	419	494	566	435
TSC^*	\$ ha^{-1}	126	137	117	79	86	70	68	89	73
IRR	ha-cm	15.5	20.5	29.0	15.5	20.5	29.0	15.5	20.5	29.0
$\sigma_{IRR}^‡$	ha-cm	5.9	6.1	6.9	5.9	6.1	6.9	5.9	6.1	6.9
$H_{WC}^§$	\$ ha^{-1}	-	41	-	-	143		-	62	-
PR^*	\$ ha^{-1}	1,518	1,637	1,818	1,461	1,582	1,741	1,653	1,790	1,938
σ_{PR}	\$ ha^{-1}	182	282	247	183	175	169	187	255	202
$R_{WC}^¶$	\$ ha^{-1}	301	181	-	280	159	-	285	148	-
R_{Year}	\$ ha^{-1}	421	301	120	477	356	197	285	148	-
					Fayetteville,2006					
Y^*	kg ha^{-1}	3,308	3,712	4,302	3,276	3,675	4,227			
σ_Y	kg ha^{-1}	609	550	586	960	703	500			
PD^*	plts	411	397	326	486	462	359			
IRR	ha-cm	30.6	33.1	38.1	30.6	33.1	38.1			
PR^*	\$ ha^{-1}	1,010	1,144	1,366	932	1,070	1,276		na	
σ_{PR}	\$ ha^{-1}	233	211	225	367	269	192			
R_{WC}	\$ ha^{-1}	357	222	-	343	206	-			
R_{Year}	\$ ha^{-1}	357	222	-	434	296	90			

Table 2.4 Continued

		Keiser,2007								
Y^*	kg ha^{-1}	2,498	2,873	3,389	2,396	2,817	3,328	2,765	3,117	3,634
σ_Y	kg ha^{-1}	402	626	345	620	553	654	303	658	318
PD^*	plts	507	461	335	459	471	384	505	459	408
IRR	ha-cm	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PR^*	\$ ha^{-1}	715	822	1,031	639	757	944	854	955	1,138
σ_{PR}	\$ ha^{-1}	153	239	131	236	211	250	116	251	121
R_{WC}	\$ ha^{-1}	316	209	-	305	187	-	284	184	-
R_{Year}	\$ ha^{-1}	423	317	108	500	381	194	284	184	-
		PineTree,2007								
Y^*	kg ha^{-1}	2,044	2,456	3,145	1,966	2,380	3,051			
σ_Y	kg ha^{-1}	343	447	725	235	363	540			
PD^*	plts	282	287	253	330	332	277			
IRR	ha-cm	9.4	14.0	18.8	9.4	14.0	18.8		na	
PR^*	\$ ha^{-1}	585	714	965	528	664	908			
σ_{PR}	\$ ha^{-1}	131	171	277	90	138	206			
R_{WC}	\$ ha^{-1}	380	251	-	380	245	-			
R_{Year}	\$ ha^{-1}	380	251	-	437	302	57			
Avg.PR^*	\$ ha^{-1}	1,116	1,229	1,425	1,050	1,170	1,343	1,254	1,372	1,538
R_{All}#	\$ ha^{-1}	422	309	114	488	368	196	284	166	-

Notes:

† Expressed in thousands of plants per hectare at 2 weeks post planting.

‡ σ_{IRR} is the same for both years at Fayetteville and is estimated from observed irrigation amounts applied for 2007, 2008 and 2010 from the irrigation experiment. Similar data did not exist for Keiser and Pine Tree. σ_{IPR} thus reflects only yield risk at Keiser and Pine Tree.

§ Herbicide cost does not change by location and year but only across WC and are hence only listed once but apply at all location-years.

¶ Regret is the loss in PR^* experienced with a non-optimal seed variety choice either within a particular weed control strategy, R_{WC}, across weed control strategies within a location × year combination, R_{Year} or across weed control strategy averaged across years and locations, R_{All}.

\# Avg. PR^* and R_{ALL} are the average of PR^* and R_{Year} across the location × year combinations where all weed control strategies could be evaluated.

Table 2.5 Irrigation cost and soybean price sensitivity analyses ranked using regret information for Fayetteville and Keiser, AR, 2007 only.

Weed Control (**WC**)			GM+			CONV+			HICONV-		
MG			II	III	IV	II	III	IV	II	III	IV
Irrigation Method	Soybean Price ($ kg^{-1})	Units									
Furrow ($3.49 ha-cm^{-1})	Low 0.29	Avg.PR† ($ ha^{-1})	810	890	1,040	747	832	963	924	1,007	1,132
	Avg. 0.38		1,116	1,229	1,425	1,050	1,170	1,343	1,254	1,372	1,538
	High 0.43		861	949	1,096	815	908	1,039	961	1,054	1,180
Center Pivot ($6.35 ha-cm^{-1})	Low		760	820	951	697	762	874	874	937	1,042
	Avg.		1,066	1,159	1,335	1,000	1,100	1,253	1,204	1,302	1,449
	High		1,241	1,354	1,554	1,172	1,292	1,469	1,392	1,510	1,680
Furrow	Low	R_{All} ‡ ($ ha^{-1})	322	242	92	385	300	169	208	125	0
	Avg.		422	309	114	488	368	196	284	166	0
	High		478	346	126	547	407	211	328	189	0
Center Pivot	Low		283	223	92	345	280	169	169	106	0
	Avg.		383	289	114	449	349	196	245	146	0
	High		439	327	126	508	388	211	288	170	0
		Avg. R_{All}	388	289	110	454	349	192	254	150	0
		Rank§	8	6	2	9	7	4	5	3	1

Notes:

† Avg. PR* are estimated per hectare partial returns to soybean production after accounting for seed, irrigation and weed control costs averaged across locations and years and modified using different soybean and irrigation cost scenarios.

‡ R_{All} is the average per hectare regret across all locations and years a producer would feel by making a non-optimal choice across all weed control and MG comparisons within a location and year.

§ Rank is based on minimum Avg. R_{All}, which in turn is calculated by averaging R_{All} across soybean price and irrigation method scenarios.

Table 2.6 Seed cost and irrigation cost cross breakeven analysis using overall regret based weed control (WC) × maturity group (MG) rankings across all location, year and soybean price scenarios.

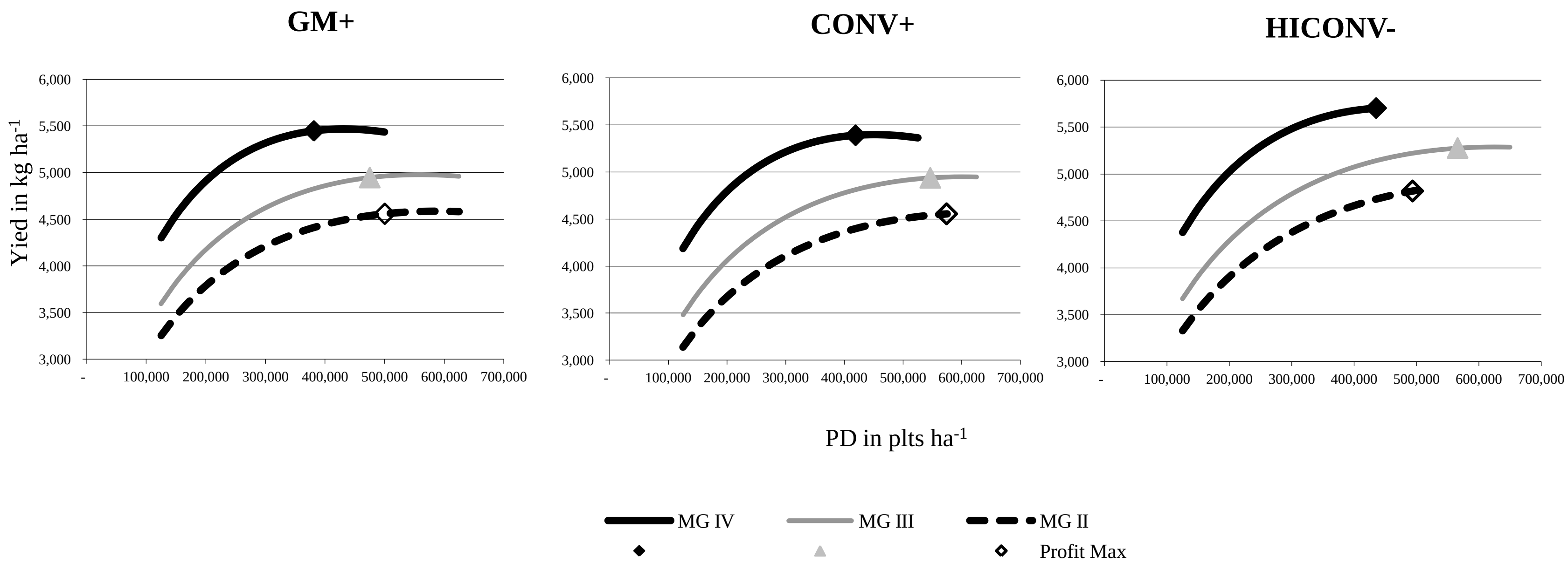
Irrigation Cost ($ ha-cm^{-1} or $ 100 m^{-3})†	Seed Cost ($ kg^{-1}) ‡		Soybean Price ($ kg^{-1})	Optimal Choice	
	Conventional	GM		**WC**	**MG**
18.64 or higher			0.29		
24.19 or higher	0.93	1.70	0.38	HICONV-	II
27.35 or higher			0.43		
Avg. of Center Pivot and Furrow Irrigation Cost	0.93	0.09 or higher	0.38	HICONV-	IV
	0 – 2.51	1.70		HICONV-	IV
	2.52 or higher	1.70		GM+	IV
Avg. of Center Pivot and Furrow Irrigation Cost	0.93	1.70	0.07 or lower	HICONV-	II
			0.08 or higher	HICONV-	IV

Notes:

† With seed cost differential between conventional and GM seed either at no cost difference, optimal MG switches from IV to II at approximately $24.13 ha-cm^{-1} at average soybean price. Hence seed cost differential takes a secondary role in the optimal WC × MG choice compared to irrigation cost. MG III are skipped as cost savings on irrigation outweigh yield revenue losses with the lower yielding but less irrigation intensive MG II compared to the higher yielding more water-intensive MG III.

‡ GM seed cost has no impact on the optimal WC × MG choice as a price drop to 0.08 $ kg^{-1} for GM seed was necessary to switch to GM+ MGIV. The price thresholds for conventional seed in $ kg^{-1} changes from $2.51 to $2.25 and $2.67 with $0.29 and $0.43 kg^{-1} soybean, respectively, and continues to switch to GM+ MG IV.

Figure 2.1 Modeled yield effects of plant density (PD) by maturity (MG) and weed control (WC) strategy in Fayetteville, AR, 2007. GM+, CONV+ and HICONV- represent GM seed with glyphosate post-emergence weed control, conventional seed with conventional herbicide post-emergence weed control and conventional seed at highest seeding rate only with no post-emergence weed control, respectively. Note that profit maximizing PD* vary directly with soybean prices (\$0.38 kg^{-1}) and indirectly with seed cost (\$0.93 kg^{-1} for conventional and \$1.70 kg^{-1} for GM). Also, note that estimated yield response curves are terminated at maximum observed PD.



Chapter 3

Economic Implications of Soybean Maturity Group on Irrigation Needs and Nitrogen Fixation

3.1 Abstract

This study analyzed different production tradeoffs across soybean (*Glycine max* [L.] Merr.) maturity groups (MG), I through V, by using experimental data on irrigation applied through growth stage R6, harvest index (HI), yield, and nitrogen (N) fixed in crop residue. An irrigation study was conducted on experimental plots at Fayetteville, AR from 2007 to 2010 and at Keiser, AR from 2008 to 2010 for MG I to MG V. A separate N study was conducted at Fayetteville in 2008 and 2009 using MG IV to MG VI to assess N amounts left in soybean stubble after harvest. Water use efficiency (WUE) defined as grain yield / water applied (irrigation and rainfall) was estimated using data from the irrigation experiment. A N_2 fixation prediction equation using yield and harvest index from the N study allowed analysis of tradeoffs between irrigation use and N_2 fixation as a result of MG under both irrigated and non-irrigated conditions. Analysis of partial returns by year and location revealed no consistent optimal MG choice under irrigated conditions. Irrigated soybean always outperformed non-irrigated production, however, and MG V soybean had higher yields than earlier MG for six of the seven study conditions. Further, WUE, averaged across location and study years, was highest for MGs II and III with no loss in yield potential compared to MG IV and V with MG III. N_2 fixation was inversely related to HI and positively correlated with Y. Later maturing cultivars, typically lower in HI and higher yielding than earlier maturing cultivars, thus displayed multifold increases in N_2 fixation regardless of irrigation. Adding N value to partial returns did not modify optimal MG choice. Economic impacts of net GHG emissions associated with irrigation water use and N_2 fixation also did not modify MG choice.

Key words: soybean maturity group, irrigation applied, harvest index, nitrogen fixation, net greenhouse gas emissions

Abbreviations: MG = maturity group, N = nitrogen, WUE = water use efficiency

3.2 Introduction

When a producer changes relative maturity group (MG) in soybean (*Glycine max* [L.] Merr.), several production attributes can change. Economic and environmental tradeoffs across these changes, such as irrigation requirements and the amount of nitrogen (N_2) fixation that takes place during the production year, for example, are affected by MG selection. Given declining irrigation water resources and recent interest in climate change and/or mitigation of net greenhouse gas (GHG) emissions (lowering agriculture's carbon footprint), these production tradeoffs are important to analyze. Simply speaking, producers, commodity groups and policy makers need to be informed of changes in profitability and environmental impact when changing soybean production practices.

Similar analyses, as proposed here, have analyzed soybean MG effects related to weed control, seeding, and irrigation costs (Wegerer et al., 2012); seeding rate and replanting thresholds (Poag et al., 2005); and biomass, nitrogen fixation, and yield effects (Mastrodomenico and Purcell, 2011). However, an economic analysis linking the effect of N_2 fixation to MG and associated irrigation has not been performed and is critical for helping resolve what MG to choose when input costs change or lesser irrigation-intensive production practices are needed. For example, the expectation of higher synthetic fertilizer N cost, perhaps as a function of climate change policy given the link of N fertilizer and N_20 emissions may affect the choice of MG. Even though soybean is not typically fertilized with N, MG differential levels of N_2 fixation in above ground biomass that remain and are reintegrated into the soil across MG, affect the level of N fertilizer needed for subsequent crops when soybean MG is changed.

When examining the relationship between MG choice and level of irrigation, an array of past research findings suggests significant weather effects. For example, Edwards et al. (2003) found that non-irrigated soybean had similar yields as those under irrigation and no statistically significant yield effects across MGs I, II, III and IV as observed in the southeastern United States. By the same token, Wegerer et al. (2012) identified irrigated MG IV to have superior yield, weed control and irrigation attributes compared to irrigated MGs II and III. Similar findings were reported by Popp et al. (2004) suggesting an optimal MG (among MG I through MG VI) under irrigated conditions and significant positive effects of irrigation on yield. Doss, Pearson and Rogers (1974) also reported positive yield effects from irrigation. In their study, soybean yields increased by as much as 55% when irrigated in comparison to soybeans where water was limited throughout the growing season.

Since soybean is an N_2 fixing crop, its ability to support its own growth in terms of N needs plays an important role in its relative carbon footprint compared to other crops. Further, MG differences lead to changes in the length of growing season as well as physical growth characteristics that affect harvest index (HI) and thereby the amount of N-containing, above ground residue left in the field (Mastrodomenico and Purcell, 2011). The process of N_2 fixation not only benefits the overall crop in terms of increased seed protein concentration, but also the producer in terms of fertilizer cost savings in current and subsequent crops. If N_2 fixation is successful within a cropping system the potential to produce up to 45 kg of N ha^{-1} has been reported (Lindemann and Glover, 2003). It has also been estimated in previous studies, that up to 90% of the N contained by soybean can come from the N_2 fixation process (Mastrodomenico and Purcell, 2011).

While N fertilizer cost savings may vary by MG, reducing N needs of subsequent crops also reduces environmental greenhouse gas emissions (GHG) and specifically N_2O emissions. Popp et al. (2011), for example, used a carbon equivalent[2] (CE) emissions level of 1.30 kg CE kg^{-1} N applied as a result of upstream GHG emissions in the production of fertilizer (Lal, 2004) and an additional average of 1.27 kg CE kg^{-1} N applied as a result of N_2O emissions that results when N fertilizer is applied in the field (IPCC, 2007). Hence, if part of N requirement for crops following soybean can be met by excess N fixed in soybean crop residue, a GHG emissions total of 2.57 kg C kg^{-1} N_2 fixed can be avoided. Therefore, amounts of N_2 fixed can be valued by both their savings on N fertilizer as well as the reduction in N emissions at varying CE price levels for trading of GHG emissions.

The goal of this particular study was to evaluate soybean MG effects as they relate to: i) yield effects associated with varying levels of irrigation; ii) N_2 fixation levels impacted by HI and yield; and iii) partial return analysis considering fertilizer cost savings and GHG credits due to excess N_2 fixed while accounting for irrigation cost. Optimal MG selection on the basis of highest partial return was further subjected to sensitivity analyses by varying irrigation cost, fertilizer and CE price levels.

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2 Carbon equivalence is a process where various GHG -- principally nitrous oxide, methane and carbon dioxide -- are converted to their CE given their different global warming potential.

3.3 Materials and Methods

3.3.1 Field Plots

Soybean yield, HI, irrigation requirement rates and N_2 fixation results of two separate experimental trials were used to arrive at: i) yield response to water by MG; and ii) analysis of fixed N_2 by MG.

3.3.2 Irrigation Experiment

The first experiment was focused on studying yield effects of both rainfall and irrigation to growth stage R6 and was conducted at two locations in Arkansas: Fayetteville (36° 5’ 42” N, 94° 10’ 25” W) and Keiser (35° 40’ 18” N, 90° 4’ 57” W). The experiment was conducted at Fayetteville from 2007 to 2010. At Keiser, the study was conducted from 2008 to 2010. The experimental design involved a single sprinkler irrigation sprinkler line erected through the middle of plots that were randomly assigned to different MG soybean. A strip split-plot arrangement of treatments using a randomized complete block with four replications was used. The whole plot factors of MG and irrigation treatments were stripped across MG and cultivars. Rain gauges, centered in each plot, were located throughout the field to measure actual amounts of rainfall and irrigation applied as a function of distance from the center line source and the front of the field. Collected irrigation and rainfall data was interpolated across plots to determine irrigation amounts applied using distance from the center line source and distance from the end of the field. A soybean irrigation scheduling program (Purcell, Edwards and Brye, 2007) was used to determine irrigation frequency and amounts applied using a soil moisture deficit trigger of 37 mm. The data were used to determine yield effects of applied water ranging from rainfed or nearly non-irrigated conditions in plots furthest from the sprinkler system to fully irrigated levels located closer to the sprinkler system. Note that rainfall events that led to runoff were not recorded at full rainfall amount but only that level which would saturate the ground. Within each MG, the cultivars summarized in Table 1 were used and field tasks performed were commensurate with production practices and recommendations commensurate with local practices and field conditions. For additional details on the experimental design, please look to Hanks, Rasmussen and Wilson (1976).

3.3.3 N_2 Fixation Experiment

The second experiment focused on measuring the amount of N_2 fixed in the crop residue remaining in the field as a function of the soybean's relative MG. The experiment was conducted in Fayetteville (36° 5' 42" N, 94° 10' 25" W) in 2008 and 2009 and used five different genotypes. Three of the genotypes were near isolines of one another for maturity and representing MG IV, MG V, and MG VI (Mastrodomenico and Purcell, 2011). A fourth genotype was a non-nodulating sisterline of 'Lee' (Hartwig, 1994) which is a MG VI. The fifth genotype was R01-46F which represents a modern, high yielding, MG V genotype (Chen et al., 2007). Subtracting amounts of N contained in the above ground biomass of nodulating cultivars from non-nodulating Lee-NN, allowed calculation of amounts of N_2 fixation as a function of yield and HI. The more newly released genotype, R01-46F, was included to capture effects of modified yield potential and potentially different HI characteristics compared to the older lines used for comparing with Lee-NN.

All plots used in this experiment received full irrigation through growth stage R6. An overhead sprinkler system was used when soil-water deficit reached 37 mm (Purcell et al., 2007). Genotypes were replicated four times within each irrigation block in a randomized complete design (Mastrodomenico and Purcell, 2011). Before the experiment took place and soybean was planted, rye (*Secale cereale* [L.]) was sown and removed after heading to remove residual N in the soil. P and K fertilizer were applied to recommended levels based on soil tests. Nitrogen fixation was estimated using the N-difference method (Weber, 1965) in which the N content of Lee-NN was subtracted from the nodulating genotypes.

Planting took place on 12 June 2008 and 4 June 2009. All plots were drilled in seven 19-cm rows and were approximately 9.14 m long. The seeding rate used for the experiment was approximately 30 seeds m^{-2}. The experimental soil type was a Captina silt loam. For additional information on experimental design see Mastrodomenico and Purcell (2011).

3.3.4 Soybean Price and Input Costs

A 10 year-average soybean price as reported by the National Agricultural Statistics Service for 2001 to 2010 (USDA-NASS, 2012) was calculated and adjusted for inflation to 2010 dollars using the soybean producer price index (USDL-BLS, 2012). Using this 10 year-average, 0.38 \$ kg^{-1}, soybean revenue was calculated without effects of unusually high or low pricing that may result had only a single or experimental year prices been used.

The production costs for irrigation were obtained from the Crop Enterprise Budgets provided by University of Arkansas Division of Agriculture Research & Extension. Specific furrow irrigation costs that were included were fixed costs (capital recovery on equipment and irrigation supplies considered fixed since plastic tubing would be laid regardless of the amount applied in a season) as well as variable costs (labor, fuel and repair and maintenance). The 2008 to 2011 average of fixed costs was 70.65 \$ ha^{-1}, whereas a similar average for variable costs was

0.30 \$ ha-mm^{-1} or 2.99 ¢ m^{-3}. Again, multiple year averages of costs were used to eliminate unusually high or low irrigation costs that could have occurred in any one particular year.

Fertilizer value for N_2 fixed, \$1.13 kg^{-1}, was also based on multi-year averages of N prices reported for Arkansas producers from the Crop Enterprise Budgets for 2008 through 2011. Finally, a CE price level of \$0.03 kg^{-1} was the mid-point of hypothetical carbon prices used by Popp et al., 2011. In a carbon market, producers would get a payment for lowering their carbon footprint from a base level. For this analysis, irrigated MG V was chosen as the base level since that reflects the current, most common MG choice of producers in Arkansas.

Partial returns (PR) to soybean production were thus defined as yield times soybean price less irrigation costs plus fertilizer savings from excess N_2 fixed plus potential carbon credits. Carbon credits are a function of differential fuel emissions resulting from MG dependent irrigation requirements (none for non-irrigated production) and differences in GHG emissions associated with excess N supplied for subsequent crops. The reader is thus advised that the partial returns in this analysis do not represent returns to producers. Rather, differences in PR across MG are analyzed to choose profit-maximizing MG given no change in other production costs with changing MG.

3.3.5 Model Estimation

The following yield response function to irrigation amounts applied was estimated to calculate optimal irrigation using multivariate regression analysis:

(1) $$Y = f\ (IRR, MG, YR, LOC)$$

where Y is soybean yield in kg ha^{-1} adjusted to 13% moisture, IRR is the amount of irrigation applied and rainfall observed in mm ha^{-1} and all other variables are zero/one dummy variables that measure deviations from the base case of MG V soybean, planted at Fayetteville in 2010.

As such MG dummy variables were dI = 1 for MG I and 0 otherwise, dII = 1 for MG II and 0 otherwise, dIII = 1 for MG III and 0 otherwise and dIV = 1 for MG IV and 0 otherwise. Similarly, production year effects (YR) were captured as d07 = 1 for production year 2007 and 0 otherwise, d08 = 1 for production year 2008 and 0 otherwise and d09 = 1 for production year 2009 and 0 otherwise. Finally, location effects (LOC) were captured using a dummy variable, dloc =1 for Keiser and 0 otherwise. All two, three and four way interactions with IRR were included to estimate effects on yield. Other two way and three way interactions were excluded to minimize multicollinearity bias (Gujarati, 2005). Finally, non-linear yield response to IRR was tested with superior fit judged on the basis of overall F-statistic, adj. R^2 and Ramsey Reset test available in Eviews v 6.0 (Startz, 2007). Coefficient estimates and associated p-values were calculated using the White's heteroskedasticity consistent estimator option available in Eviews v 6.0.

The second response function was used to estimate N_2 fixation as a function of HI, Y and production year as follows:

(2) $N = f\,(HI, Y, d09)$

where N is nitrogen fixation in kg ha^{-1}, HI is the harvest index (ratio of seed weight to total above ground weight of the plant) and other variables are as defined above. Using Y and HI as explanatory variables for N_2 fixation rather than above ground biomass allowed the use of coefficient estimates of eq. 2 with estimated yields and irrigation requirements from eq.1 since HI information was also available for the irrigation experiment. Hence, the tradeoff between irrigation and N_2 fixation could be estimated for 2008 and 2009 in Fayetteville as both experiments were conducted at that location with Y and HI information available. Different specifications of eq. 2 were tested using similar non-linear functional forms and procedures as reported for eq. 1 above. Further, variables with absolute t-statistics less than 1 were removed to avoid misspecification bias (Gujarati, 2005).

3.3.6 Economic Analysis

Using coefficient estimates of Eqs. 1 and 2, partial returns (PR) to soybean production for each MG (i) were calculated as follows:

(3) $$PR_i = Y_i \cdot p - (IRR_i \cdot vc_{IRR}) - fc_{IRR} + N_i \cdot vc_N$$

where p is the price of soybean in \$ kg^{-1}, IRR_i is the average measured rainfall and applied irrigation in ha-mm^{-1} at fully irrigated level across MG, vc_{IRR} is the variable cost of irrigation in \$ ha-mm^{-1} or \$ 10 m^{-3}, fc_{IRR} is the fixed cost of irrigation, N_i is the amount of N_2 fixed by MG and vc_N is the cost of nitrogen fertilizer in \$ kg^{-1}. Using Eq. 3 to estimate PR under irrigated and non-irrigated conditions as well as with and without fertilizer credits was possible by setting vc_{IRR} and fc_{IRR} as well as vc_N to zero as needed.

Adding a hypothetical carbon market to Eq. 3 allowed analysis of the effects of a carbon market as described above and resulted in the following revenue potential compared to a baseline of MG V production:

(4) $$CC_i = p_{CE} \cdot [(N_i - N_{MG\ V}) \cdot 2.57\ kg\ N^{-1} + (IRR_{MG\ V} - IRR_i) \cdot 0.31\ kg\ ha\text{-}mm^{-1}]$$

where CC_i was a carbon credit (positive or negative) and relative to MG V production, p_{CE} is the price of carbon in a carbon market in \$ kg^{-1}, N fertilizer CE were calculated using 2.57 kg CE per kg of N fixed and irrigation fuel emission differences were valued using 0.84 kg CE l^{-1} of diesel fuel (Lal, 2004) and 0.37 l ha-mm^{-1} or 0.037 l m^{-3} fuel use for pumping irrigation water.

3.3.7 Sensitivity Analysis

MG rankings on the basis of PR_i could be developed for each location and production year under irrigated and non-irrigated conditions, with and without credits for N_2 fixation and carbon credits using Eqs. 1 through 4. Profit-maximizing MG would be those with highest PR. Varying the variable cost of irrigation, the price of fertilizer and CE or the value of carbon credits allowed for sensitivity analyses that would indicate under what conditions MG choice would change from that obtained under current average price conditions.

3.4 Results

3.4.1 Yield response to irrigation by MG

Coefficient estimates for independent variables in Eq. 1 are presented in Table 2. The model accounted for approximately 64% of the variation in yield according to the adjusted R^2. A linear yield response to IRR provided the best fit, was significantly positive and varied with MG, location and year as reflected in the statistically significant IRR coefficient ($p < 0.0001$) and the many statistically significant coefficient estimates with IRR interactions. Estimated irrigated soybean yield across production year and location was always higher under irrigated than rainfed conditions as shown in Table 3 and supports findings of Doss, Pearson and Rogers (1974). Note the great range in yield differences across irrigated and non-irrigated conditions, MG, location and years. For example, MG III, IV and V soybean have nearly the same non-irrigated yield in 2009 at Fayetteville while MG effects are quite strong in 2010 at the same location under similar non-irrigated but lesser rainfall. Picking a consistent PR leader for irrigated conditions was thus not possible and representative of earlier findings listed in the introduction. Under non-irrigated conditions, MG V, offered higher yields in six of the seven study-location-by-year combinations.

Estimated water use efficiency (WUE), calculated by adding coefficient estimates from Table 2 for IRR and IRR interaction variables as appropriate, revealed a pattern of greater soybean yield per ha-mm applied for soybean in the middle of the MG spectrum when averaged across years and location (Table 4). With expected limitations in irrigation resources or declining ground water tables in the study region, this suggests that MG II or III return more yield per ha-mm applied than earlier or later maturing varieties on average. This is also reflected in the steeper yield response slope to irrigation and rainfall depicted in Figure 1. Earlier maturing varieties (MGs I to III) with shorter growing seasons experienced less rainfall to growth stage R6. Mid- to late-maturing varieties (MG III to V) had similar yield potential under full irrigation with earlier MG using significantly less irrigation albeit at a yield penalty for MG I and II. These findings are similar to Edwards et al. (2003).

3.4.2 Nitrogen fixation response

Table 5 presents the regression results of N_2 fixation as a function of HI and Y. The final model specification provided good fit as shown in adj. R^2 statistic and the overall F-statistic with all coefficient estimates of dependent variables statistically significant at $p< 0.01$ and of expected sign. Harvest index revealed a negative, non-linear relationship with N_2 fixation which was expected due to previous research (Mastrodomenico and Purcell, 2011). Cultivars with higher HI imply greater seed yield in relation to total above ground biomass or less crop residue, and hence less N_2 fixation, than for soybean cultivars with lower HI. Higher yield led to more N_2 fixation as higher yield would also lead to greater biomass *ceteris paribus*. The findings were subject to production year since 2009, with more rainfall than 2008, which led to more N_2 fixation. This result was primarily due to lower HI in 2009 as yields were also slightly lower compared to 2008. Given the range in observed HI (0.32 to 0.63) and associated yields (241 to 661 g m^{-2}) this experiment proved useful for providing estimates of N_2 fixation for yields and HI observed in the irrigation experiment at the same location and years.

3.4.3 Economic Analysis

Using coefficient estimates from Table 5, observed yields and HI in the irrigation experiment for those plots at fully irrigated and non-irrigated irrigation levels could be matched with predictions of N_2 fixation and are reported for 2008 and 2009 with their average in Table 6. As expected, irrigation resulted in higher yields and hence more biomass which also increased the amount of N_2 fixed. Further, later maturing cultivars typically had lower HI and hence more crop residue containing N which allowed for greater benefit for subsequent crops under both irrigated and non-irrigated conditions as expected. Multifold increases in N_2 fixation were apparent between the latest maturing MG V compared to earlier varieties but its fertilizer value was insufficient to affect MG rankings as estimated for 2008-09 average conditions in Table 7. Adding relative change in carbon footprint valued at \$0.03 kg^{-1} or roughly 300 times the current U.S. trade price on the Chicago climate exchange, did not affect PR rankings either (Table 8).

3.4.4 Sensitivity Analysis

Using the results reported in Table 4, or PRs averaged across experiment year and location, a breakeven price for soybean could be calculated at which point irrigation made economic sense. These B/E prices are reported in the right hand column of Table 4 and suggest that soybean prices would have to drop dramatically before a soybean producer that has irrigation capacity would switch to non-irrigated production. It should further be noted that a producer would stop growing soybean altogether at those price levels as they are insufficient to cover cash operating expenses that are not reported in this study.

Table 9 provides further insights about soybean and N fertilizer price levels that would need to be reached before optimal choice of MG would change based on the average performance for soybean grown in Fayetteville in 2008 and 2009, the location- year combination for which pertinent information was available to estimate PR including economic repercussions of N fertilizer value and irrigation response. Similar to findings presented for the decision to irrigate or not, soybean and fertilizer price levels did not play a role in MG selection as soybean prices would need to drop below levels that would be considered feasible for soybean production and fertilizer prices would need to increase approximately three to ten-fold before MG selection would change.

3.5 Discussion

This study merged the results of two different soybean MG experiments to analyze irrigation and N_2 fixation tradeoffs for producers interested in selecting optimal MG under irrigated and non-irrigated conditions. While significant production year effects precluded reporting of a profit-maximizing MG under irrigated conditions, the results included a wide range of yield and harvest index data that may be applicable for other locations and years. As such, use of soybean yield and harvest index information proved useful in developing estimates for N_2 fixation.

The results of the study showed differences in water use efficiency across soybean MG and found cultivars of mid-level maturity to provide the greatest soybean yield response. Given declining water supplies in the study region in conjunction with similar yield potential of MG III compared to later maturing MG V, this result merits attention, especially since non-irrigated production always led to lower returns compared to irrigated production across all study years and locations.

Adding fertilizer value to partial returns as a function of differentials in N_2 fixation across MG did not materially affect return rankings in this study. Nonetheless, multifold declines in N_2 fixation can be expected should producers switch from later maturing cultivars, currently common in the region. MG choice including fertilizer value was invariant to changes in soybean and fertilizer prices. Adding consequences of net GHG emissions trading in the form of a carbon market that would reward a producer for lowering their carbon footprint did not modify MG rankings presented in this paper. Adding additional locations and years of observations would add to the accuracy and generalizability of the results found.   Finally, adding information on N_2 fixed in the root system, while deemed minor given low root-shoot ratios and little information on differences across MG, may be beneficial to analyze.

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Table 3.1 Summary of soybean cultivars used by MG, year and location for determining yield response to irrigation by distance from centered sprinkler irrigation at Fayetteville and Keiser, AR, 2007 to 2010.

		Year			
Location	MG†	2007	2008	2009	2010
		Varieties Used			
Fayetteville	I	S19-V2	S17-A1; S19-V2	S17-A1; S19-L7	S17-B5; S19-A6
	II	AG2406; AG2802	AG2406; AG2802	AG2406; AG2802	AG2909; AG2406
	III	S31-V3; S39-A3	S31-V3; S39-A3	S39-A3; S32-E2	S33-K5; S39-A3
	IV	AG4403; AG4801	AG4403; AG4801	AG4907; AG4403	AG4907; AG4403
	V	P95m80; Arm53k3	P95m80; Arm53k3	95Y70; Arm53Z5	Arm53Z5; 95Y40
Keiser	I		S17-A1; S19-V2	S17-A1; S19-L7	S17-B5; S19-A6
	II		AG2406; AG2802	AG2406; AG2802	AG2909; AG2406
	III	na	S31-V3; S39-A3	S39-A3; S32-E2	S33K5; S39-A3
	IV		AG4403; AG4801	AG4907; AG4403	AG4907; AG4403
	V		P95m80; Arm53k3	95Y70; Arm53Z5	Arm53Z5; 95Y40

Notes:

† MG is the soybean maturity group. The plots consisted of 7 drilled rows that were approximately 19 cm apart and approximately 6 m long. The middle of May was the planting date for all years and locations. Seeding rates in seeds per hectare for MG I, II, and III = 540,000, and were = 310,000 for MG IV and V.

Table 3.2 Regression results of yield effects (kg ha^{-1}) associated with irrigation and rainfall by location, maturity group (MG) and production year with a base line of MG V in Fayetteville, 2010**.**

Effect	Dependent Variable	Yield (Y)	
	Independent Variables†	Coefficients	T-Statistics
	Constant	1,343.72***	6.02
Maturity Group	dI	-892.36***	-4.19
	dII	-939.71***	-4.16
	dIII	-710.88**	-2.93
	dIV	-197.91	-0.74
Year	d07	-377.39	-1.54
	d08	2,143.73***	11.66
	d09	885.65**	2.67
Location	dloc	-8.05	-0.04
Rainfall and Irrigation Applied	IRR	5.62***	10.81
	IRR × dI	3.08***	4.74
	IRR × dII	3.83***	5.15
	IRR × dIII	3.73***	4.94
	IRR × dIV	0.71	1.01
	IRR × d07	1.09	1.69
	IRR × d08	-3.73***	-6.28
	IRR × d09	-3.32***	-4.26
	IRR × dloc	1.92**	3.77

Table 3.2 continued

IRR × dI × d07	-1.41*	-2.37
IRR × dI × d08	0.56	1.14
IRR × dI × d09	-0.58	-1.10
IRR × dII × d07	-0.16	-0.28
IRR × dII × d08	0.77	1.39
IRR × dII × d09	-0.10	-0.18
IRR × dIII × d07	1.11	1.91
IRR × dIII × d08	0.66	1.23
IRR × dIII × d09	0.51	0.91
IRR × dIV × d07	0.28	0.58
IRR × dIV × d08	1.82**	3.74
IRR × dIV × d09	0.27	0.58
IRR × dI × dloc	1.02*	2.06
IRR × dII × dloc	1.17	1.62
IRR × dIII × dloc	-0.15	-0.29
IRR × dIV × dloc	-0.52	-1.33
IRR × dI × dloc × d08	-5.57***	-10.88
IRR × dI × dloc × d09	-6.84***	-9.81
IRR × dII × dloc × d08	-4.92***	-6.44
IRR × dII × dloc × d09	-6.78***	-8.18
IRR × dIII × dloc × d08	-2.78***	-4.27
IRR × dIII × dloc × d09	-4.46***	-5.53
IRR × dIV × dloc × d08	-3.78***	-7.83
IRR × dIV × dloc × d09	-0.47	-0.84
R^2	64.82	
Adj. R^2	63.72	
F-statistic	58.92***	
# of observations	1,353	

Notes: *** $p < 0$ .0001, ** $p < 0.01$, * $p < 0.05$.

† Y is soybean yield at 13% moisture in kg ha^{-1}. IRR is the amount of rainfall and irrigation measured per plot in mm. All remaining variables are zero/one dummy variables set to zero except for dI =1 for MG 1, dII = 1 for MG 2, dIII = 1 for MG 3, dIV = 1 for MG 4, dloc = 1 for Keiser, d07 = 1 for 2007, d08 = 1 for 2008 and d09 = 1 for 2009. Note that the irrigation experiment was not conducted at Keiser in 2007.

Table 3.3 Summary of predicted soybean yields, average rainfall and irrigation amounts applied as well as partial returns for Fayetteville and Keiser, 2007-2010 excluding fertilizer and carbon credits.

						Est. Y†		Partial Returns‡	
Location	Year	MG	WUE §	Irr. (applied)	Rain	Non-Irr.	Full-Irr.	Non-Irr.	Full-Irr.
			kg ha-mm^{-1}	mm ha^{-1}		kg ha^{-1}		\$ ha^{-1}	
Fayetteville	2007	I	8.4	177	112	1,013	2,495	386	828
		II	10.4	212	115	1,215	3,415	464	1,169
		III	11.6	247	129	1,745	4,594	666	1,608
		IV	7.7	290	147	1,901	4,134	725	1,419
		V	6.7	329	189	2,235	4,445	852	1,526
	2008	I	5.5	156	140	3,369	4,233	1,285	1,497
		II	6.5	156	140	3,458	4,471	1,319	1,588
		III	6.3	181	158	3,765	4,898	1,436	1,743
		IV	4.4	190	188	4,122	4,961	1,572	1,765
		V	1.9	189	208	3,881	4,239	1,480	1,490
	2009	I	4.8	182	194	2,268	3,142	865	1,073
		II	6.0	182	194	2,462	3,560	939	1,233
		III	6.5	182	206	2,862	4,052	1,092	1,420
		IV	3.3	182	267	2,908	3,507	1,109	1,212
		V	2.3	182	295	2,909	3,328	1,109	1,144
	2010	I	8.7	250	135	1,626	3,803	620	1,305
		II	9.5	267	135	1,681	4,208	641	1,454
		III	9.4	301	135	1,895	4,704	723	1,633
		IV	6.3	331	188	2,334	4,430	890	1,520
		V	5.6	325	216	2,558	4,383	976	1,504

Table 3.3 continued

Keiser	2008	I	2.9	191	165	3,064	3,614	1,169	1,251
		II	4.7	203	191	3,432	4,381	1,309	1,539
		III	5.3	203	238	4,018	5,087	1,532	1,809
		IV	2.1	203	277	3,847	4,263	1,467	1,494
		V	3.8	203	297	4,612	5,386	1,759	1,923
	2009	I	0.9	83	418	1,703	1,777	649	582
		II	2.4	83	418	2,263	2,457	863	842
		III	3.8	83	418	3,116	3,433	1,188	1,214
		IV	4.2	108	455	3,939	4,394	1,502	1,573
		V	4.2	108	474	4,222	4,678	1,610	1,681
	2010	I	11.6	279	99	1,595	4,842	608	1,693
		II	12.6	279	99	1,638	5,139	625	1,806
		III	11.1	305	99	1,725	5,115	658	1,789
		IV	7.7	330	124	2,097	4,649	800	1,604
		V	7.5	330	127	2,293	4,782	875	1,655

† Estimated yields using Eq. 1 and associated location, year and MG coefficient estimates from Table 2.

‡ Partial returns are calculated using Eq. 3 without credit for N fixed or carbon credits. Comparisons across MG and irrigation level are appropriate but are not producer returns to soybean production.

§ Water use efficiency is expressed in yield response kg ha^{-1} per added mm of water or the sum of location, year and MG-specific IRR coefficients from Table 2.

Table 3.4 Average marginal value of water, irrigation costs and partial returns for irrigated and non-irrigated soybeans for Fayetteville, AR (2007-10) and Keiser, AR (2008-10) by MG (excluding N_2 fixation and carbon credits).

MG	MVP of Irr.†	Irr. Fixed Cost	Irr. Variable Cost	Partial Returns Non-Irr.	Partial Returns Full-Irr.	B/E Soybean Price for Irr.‡
	$ ha-mm^{-1}	$ ha^{-1}	$ ha-mm^{-1}	$ ha^{-1}		$ kg^{-1}
I	2.33			798	1,176	0.10
II	2.83			880	1,376	0.08
III	2.94	70.65	0.30	1,042	1,602	0.07
IV	1.95			1,152	1,512	0.11
V	1.75			1,237	1,560	0.12

Notes:

† Marginal value product or the value of soybean produced per added mm of rainfall and irrigation applied per hectare. This is calculated by multiplying the average water use efficiency across location, year and MG reported in Table 3 by the soybean price.

‡ Breakeven soybean price at which irrigation cost savings are equal to the value of yield losses associated with non-irrigated production. Hence, at soybean prices below the B/E price, non-irrigated production is more profitable and irrigated production is more profitable above the B/E price.

Table 3.5 Regression results of nitrogen fixation (N_2) as a function of harvest index (HI) and yield (Y) at Fayetteville, AR with a baseline of 2008.

Effect[†]	Dependent Variable	N	
	Independent Variables	Coefficients	T-Statistics
	Constant	28.642***	8.44
Non-linear Harvest Index	HI	-97.258***	-7.30
	HI^2	75.654***	5.73
Yield	Y	0.008***	8.07
Year Interactions[‡]	HI × d09[†]	-16.377**	-3.67
	HI^2 × d09	22.339**	3.37
	Y × d09	0.006**	3.01
	R^2 in %	83.55%	
	Adj. R^2 in %	82.42%	
	F-statistic	73.66***	
	# of observations	94	

Notes: *** $p < 0.0001$, ** $p < 0.01$, * $p < 0.05$

† N is nitrogen fixation in g m^{-2}. HI is the harvest index or ratio of grain to total above ground weight of the plant. Y is soybean yield at 13% moisture in g m^{-2}. All remaining variables are zero/one variables set to zero except for d09 = 1 for 2009.

‡ Note that production year was initially introduced as an intercept shifter but was not statistically significant and hence removed. Also note that yield effects were initially introduced both in linear and non-linear fashion.

Table 3.6 Amount of predicted N_2 fixed for each year and MG combination at Fayetteville, AR, 2008 and 2009.

		Observed Data						Predicted			
		Irrigation†		Yield		HI		N_2 Fixed‡		Value of N§	
Year	MG	Low-Irr.	Full Irr.	Low-Irr.	Full Irr.	Low-Irr.	Full Irr.	Low-Irr.	Full Irr.	Low-Irr.	Full Irr.
		ha-mm		$kg\ ha^{-1}$		kg seed / kg plant mass		$g\ m^{-2}$		$\$\ ha^{-1}$	
2008	I	49	156	3,385	4,161	0.48	0.48	2.16	2.81	24.41	31.76
	II	49	156	3,530	4,381	0.51	0.49	1.70	2.71	19.18	30.67
	III	55	181	3,836	4,696	0.46	0.48	3.14	3.30	35.52	37.31
	IV	57	190	4,259	4,761	0.44	0.44	4.11	4.46	46.39	50.37
	V	57	189	4,268	4,922	0.40	0.35	5.29	7.83	59.80	88.48
2009	I	58	182	2,607	2,887	0.51	0.53	-0.01	0.11	-0.06	1.28
	II	58	182	3,009	3,327	0.51	0.52	0.42	0.76	4.79	8.57
	III	58	182	3,207	4,089	0.52	0.54	0.53	1.62	5.95	18.26
	IV	58	182	3,363	3,354	0.49	0.49	1.34	1.26	15.09	14.26
	V	59	182	3,023	2,668	0.42	0.41	2.83	2.28	31.95	25.74
Average	I	54	169	2,996	3,524	0.50	0.50	1.08	1.46	12.17	16.52
	II	54	169	3,670	3,854	0.51	0.50	1.06	1.74	11.99	19.62
	III	57	182	3,522	4,393	0.49	0.51	1.84	2.46	20.74	27.78
	IV	58	186	3,811	4,058	0.46	0.46	2.72	2.86	30.74	32.32
	V	58	186	3,646	3,795	0.41	0.38	4.06	5.05	45.87	57.11

Notes:

† Irrigation amounts are defined as two treatments: low and full irrigation. Low irrigation consists of applied irrigation in plots furthest from the center line sprinkler system whereas full irrigation to attain yield potential was achieved closer to the water source.

‡ The amount of predicted N_2 fixed across year and MG under both the non-irrigated and fully irrigated scenarios in $g\ m^{-2}$.

§ The value of N_2 fixed is determined by taking the quantity of N_2 fixed per year and MG multiplied by the average value of N fertilizer as experienced over the years 2008-2011, which was $\$1.13 kg^{-1}$. The value of N_2 fixed is reported in $\$\ ha^{-1}$.

Table 3.7 Average partial returns ($\$ ha^{-1}$) with and without N_2 fixation for low and fully irrigated soybean at Fayetteville, AR, 2008 and 2009.

		Non-Irr.			Full Irr.		
Year	MG	PR[†]	PR Rank[‡]	PR_N[§]	PR	PR Rank	PR_N
Avg. of 2008 and 2009	I	1,075	5	1,087	1,285	5	1,302
	II	1,129	4	1,141	1,410	3	1,430
	III	1,264	3	1,284	1,582	1	1,610
	IV	1,341	1	1,371	1,489	2	1,521
	V	1,295	2	1,341	1,317	4	1,374

Notes:

† Partial returns to soybean production net of irrigation cost without assigning a value for N_2 fixation.

‡ Partial return rank is based on 1 = highest PR and 5 = lowest PR. Rankings apply to columns to either side as they did not change when fertilizer value from N_2 fixation was added.

§ Partial returns to soybean production net of irrigation cost with value added from N_2 fixation.

Table 3.8 Average net greenhouse gas emissions in carbon equivalents valued at a carbon price of \$0.03 kg^{-1} and resultant carbon credits (payments) in \$ ha^{-1} for deviating from MG V at Fayetteville, AR, 2008-2009.

		Value of Net GHG Emissions†		Carbon Credit‡	
Year	MG	Non-Irr.	Full-Irr.	Non-Irr.	Full-Irr.
Avg. of 2008 and 2009	I	0.79	-0.67	(2.18)	(2.17)
	II	0.78	-0.56	(2.20)	(2.05)
	III	1.34	-0.19	(1.63)	(1.68)
	IV	1.99	-0.07	(0.98)	(1.56)
	V	2.97	1.50	base	base

Notes:

† Net GHG emissions are calculated based on N fertilizer emission savings at 2.57 kg CE kg N_2^{-1} fixed minus emissions associated with burning of diesel fuel for irrigation at 0.31 kg CE ha-mm^{-1} of irrigation applied.

‡ A negative carbon credit as indicated by parenthetic enclosure implies that, principally due to lower N_2 fixation compared to MG V, a producer would have to pay to move to earlier maturing cultivars.

Table 3.9 Sensitivity analyses on soybean price and cost of N for soybean production in Fayetteville, AR, 2008 and 2009. PR values included soybean production returns and fertilizer value as per Eq. 3.

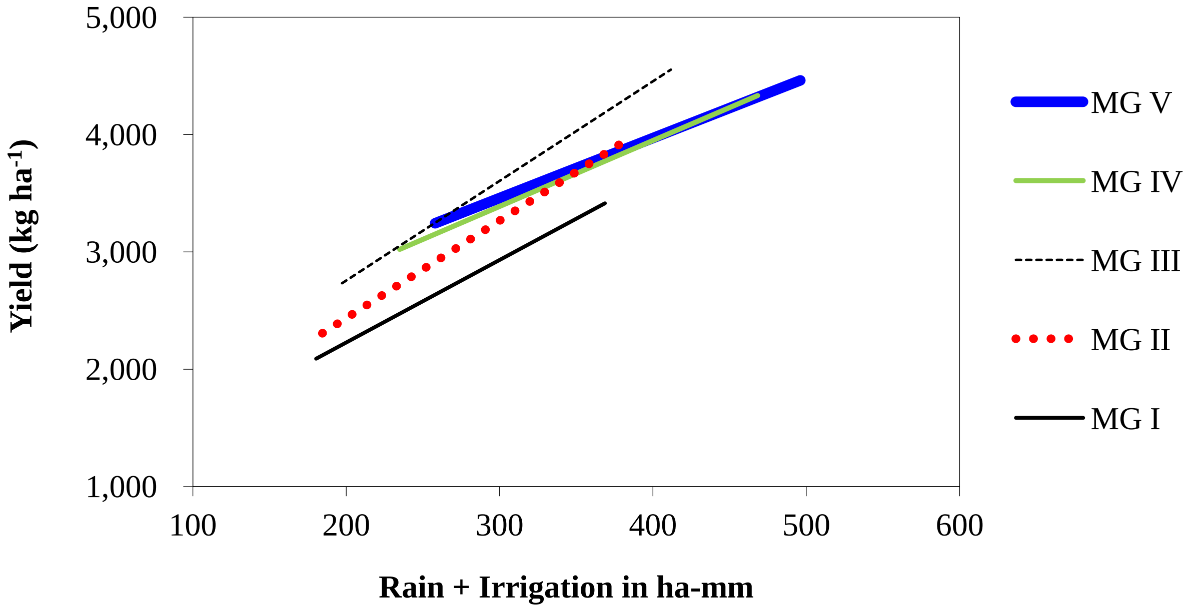
Scenario	Soybean Price[†]	N Cost[‡]	Optimal MG
	(\$kg^{-1})	(\$ kg^{-1})	
Non-Irr.	0.12 and lower		V
	0.13 and higher	1.13	IV
Full-Irr.	0.04 and lower		V
	0.05 and higher	1.13	III
		3.41 or lower	IV
Non-Irr.	0.38	3.42 or higher	V
		10.20 and lower	III
Full-Irr.	0.38	10.21 and higher	V

Notes:

† When holding N to average cost level, \$1.13 kg^{-1}, soybean price must decrease to \$0.12 kg^{-1} before changing from previous optimal MV IV to new optimal V under non-irrigated conditions. Soybean price must decrease to \$0.04 kg^{-1} before changing from previous optimal MG III to new optimal MG V under irrigated conditions.

‡ When holding soybean to average price, \$0.38 kg^{-1}, cost of N fertilizer must increase to \$3.41 kg^{-1} before switching from previous optimal MG IV to new optimal MG V under non-irrigated conditions. Cost of N fertilizer must increase to \$10.20 kg^{-1} before changing from previous optimal MG III to new optimal MG V under fully irrigated conditions.

Figure 3.1 Average linear yield response by MG from rainfall and irrigation applied at Fayetteville, AR and Keiser, AR, from 2007 to 2010.



Chapter 4

Producer Soybean MG Recommendations

4.1 Introduction

This study has examined i) alternative weed control methods incorporating seed technology and seeding rate by MG in conjunction with irrigation requirements as well as ii) nitrogen fixation effects by MG taking irrigation requirements into account. Chapter 1 provided a brief overview of the study while providing some background information on the current agricultural issues this study was performed to address.

Two null hypothesis and alternative hypothesis were formulated:

Part I – Soybean Maturity Groups: Effects on Weed Control and Irrigation Needs

H_o: Alternative weed control methods that satisfy tradeoffs with yield and irrigation needs do not impact producer profitability when compared against standard weed control methods in Arkansas such as the planting of genetically modified (GM) seed.

H_A: Cost and returns to alternative weed control methods alter producer returns and an optimal MG and weed control choice exists that is different from the current practice of GM seed and MG V.

Part II – Soybean Maturity Groups: Irrigation and Nitrogen Fixation Effects

H_o: Water use efficiency, yield potential, harvest index and N_2 fixation in crop residue do not vary by MG and hence producer returns are not affected by carbon credits, changes in soybean price or fertilizer prices.

H_A: MG differences in water use efficiency, N fixation, yield and harvest index affect MG choice.

Chapter 2 presented the detailed findings of alternative weed control methods including varying seed type and seed technology across MG with respect to irrigation applied. Chapter 3 analyzed the different amounts of nitrogen fixation that took place across MG while also looking at irrigation application rates and their resulting yields. This Chapter summarizes the findings and limitations of this thesis. In addition, recommendations are made for possible future studies that may be conducted in these same areas of research.

4.2 Summary of Major Findings

After much analysis, the resulting studies found later maturing varieties to be optimal in multiple ways. The results from Chapter 2 demonstrated that by seeding at twice the recommended rates (HICONV-) and using a later maturing variety (MG IV) optimal yields and WC could be established. Despite the heightened irrigation cost that was experienced with the later maturity it was outweighed by higher yields of the MG IV and less fertilizer expenses due to the HICONV- WC method. Sensitivity analysis found that this MG choice was robust to changes in soybean price and seed cost. Further study of using higher seeding rates and earlier canopy closure as a mode for weed control are thus deemed fruitful.

Chapter 3 results also suggested a mid-range maturing variety (MG III) to provide optimal WUE at similar yield potential compared to MG IV and V while using less irrigation water. When looking at N_2 fixation amounts to save on fertilizer and GHG emissions, the carbon equivalent credit amount given was minor relative to fertilizer savings. Second changes in fertilizer and soybean prices did not affect optimal MG choice.

Overall, when combining the results from the two different experiments it could be recommended that a MG III or IV soybean would be the most ideal producer choice when facing issues of glyphosate resistant weeds, declining water supply and increasing N_2 fixation in order to decrease fertilizer costs and address current GHG emissions issues.

4.3 Study Limitations/Suggestions for Further Research

Study limitations were presented for each experiment. When examining the WC experiment presented in Chapter 2, additional years and the use of more MGs could have provided useful information and possibly more accurate results. Also, the HICONV- WC treatment was only conducted at Fayetteville and Keiser in 2007, and therefore more replications of this treatment may provide further insights. The addition of years and locations would also allow further generalizations beyond study conditions observed in Chapter 3.