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Physiological and Nutritional Characterization of High Yield Soybean

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Physiological and Nutritional Characterization of High Yield Soybean

Physiological and Nutritional Characterization of High Yield Soybean

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy in Crop, Soil, and Environmental Sciences

By

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ABSTRACT

Soybean [*Glycine max* (L.) Merr.] grain yields greater than three times the national average have been reported in yield contests. Characterization of soybean in a maximum yield environment is necessary to provide empirical data to support those yield claims and to provide an understanding of the physiological processes at that yield level. From 2011 to 2013, research characterized biomass and N accumulation rates, radiation use efficiency (RUE), leaf N dynamics, the rate of harvest index increase (dry matter allocation coefficient, DMAC), seedfill period (SFP), and grain yield components from Mr. Kip Cullers' contest fields and in small plots at the University of Arkansas in Fayetteville. The greatest cultivar mean yield was 7953 kg ha⁻¹, which occurred in 2013 when biomass and N accumulation rates and RUE values as high as 64.3 g m⁻² d⁻¹, 2.08 g N m⁻² d⁻¹, and 1.89 g MJ⁻¹ were observed, respectively. These observed crop growth characteristics were near or above the maximum values previously reported in the literature. The DMAC and SFP values were also abnormally slow and long, respectively. This coupled with the enhanced growth rates provide empirical data and insights into the production of yields >6419 kg ha⁻¹ (100 bushels acre⁻¹).

Additional research in Fayetteville evaluated the yield effects of several of Mr. Cullers' alternative management practices. Management practices evaluated included various seed treatments, intentional herbicide injury, uniform plant spacing and emergence, lodging prevention, and a proprietary foliar-applied product. None of these alternative practices were effective in increasing yields beyond the high input practices utilized within this maximum yield environment.

The feasibility of several of these high input maximum yield management practices in large production fields in eastern Arkansas were evaluated. Enhanced management including

additional inputs of poultry litter, irrigation, supplemental N, and pest control were evaluated on the field scale. Two cultivars had average yields of 6931 and 6986 kg ha⁻¹ at the England location in 2013. Economic analysis suggested that even this scaled down maximum yield management was less profitable than the growers' normal production practices.

Finally, a simple soybean crop model was used to simulate crops grown within maximum yield environments at Fayetteville and Mr. Cullers' contest fields. Sensitivity analyses were also conducted to examine the effects of varying values of RUE, N accumulation, specific leaf N (SLN), and DMAC. The most accurate dataset was for Fayetteville in 2012 and 2013 and the default parameters in the model predicted yields 34.0% less than observed over all cultivars. Modifying the model with the observed parameters for RUE, N accumulation, and SLN resulted in yield predictions that averaged 3.4% greater than the observed for all the cultivars in Fayetteville in 2012 and 2013. Sensitivity analyses indicated that yield could be increased with decreased DMAC values, increased RUE values, increased SLN values when coupled with greater N accumulation rates, and with increasing N accumulation when coupled with increasing RUE values.

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LIST OF ABBREVIATIONS

Biological N₂ fixation (BNF). Biomass accumulation rate (BAR). Days after emergence (DAE).
Dry matter allocation coefficient (DMAC). Day of year (DOY). Fraction of canopy radiation
interception (FRI). Fraction of transpirable soil water (FTSW). Growing degree days (GDD).
Harvest index (HI). Individual seed growth rate (ISGR). Intercepted solar radiation (IR).
Maturity group (MG). Nitrogen use efficiency (NUE). Physiological maturity (PM). Radiation
use efficiency (RUE). Seedfill period (SFD). Specific leaf weight (SLW). Specific leaf N (SLN).
Total biomass production (BM).

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Van Roekel, R.J. and L.C. Purcell. 2014. Soybean biomass and nitrogen accumulation rates and radiation use efficiency in a maximum yield environment. *Crop Sci.* 54:1189-1196.

CHAPTER 1

Introduction

Mr. Kip Cullers of southwest Missouri is globally famous for his high yield soybean [*Glycine max* L. (Merr.)] crops. Mr. Cullers has won the Missouri Soybean Association's annual state soybean yield contest six times since 2006, choosing not to enter the 2009 or 2012 contest due to "unimpressive yields" (Kip Cullers, personal communication, 2012). Not only has Mr. Cullers consistently reported high yields, but his documented yields are more than three times the United States national average. Mr. Cullers first won the Missouri Soybean Association's yield contest with 9339 kg ha⁻¹ in 2006. He went on to break his own record with 10,388 kg ha⁻¹ in 2007. Then, after two years of lower yields, Mr. Cullers again broke his own record with 10,791 kg ha⁻¹ in 2010 (Cubbage, 2010).

Mr. Cullers' route to being called the "Soybean King" is intriguing and somewhat by happenstance. Mr. Cullers is part of a large farming operation consisting largely of non-irrigated corn [*Zea mays* L.] production to feed his very large poultry production operation. Southwest Missouri is not known for its high yields due to challenging soils and limited rainfall. One of the exceptions to this are a few irrigated fields consisting of Newtonia silt loam (fine-silty, mixed, superactive, thermic, Typic Paleudolls) soils. This red soil happens to be a highly productive and was once an upland prairie plateau. As such, the soil is very deep, with a high nutrient and water holding capacity, and is also well drained. Mr. Cullers had been growing green beans (*Phaseolus vulgaris*) on these fields for Allen Canning Company in Siloam Springs, AR. For fun and for a challenge, Mr. Cullers enjoyed growing high yield corn for the National Corn Growers' yield contest. In the pursuit of higher corn yields, in 2006 Mr. Cullers planted soybean at a high density in this yield contest field and was planning to prematurely terminate the crop and use it as a green manure for the following year's corn yield contest location. However, when Mr. Cullers' Pioneer agronomist inspected the soybean crop, they determined that the crop had

tremendous yield potential and decided to take it to yield and enter the Missouri Soybean Association yield contest (Kip Cullers, Scott Dickey, and Larry Purcell, personal communications, 2011).

Mr. Cullers' yields reported in 2006, 2007 and 2010 created quite a controversy in the agricultural community. This was partially due to the fact that no other research has previously reported yields of this magnitude. The highest yields at that time were from Queensland, Australia with reported yields up to 8604 kg ha⁻¹ (Lawn et al., 1984; Cooper, 2003). Since then, yields up to 9200 kg ha⁻¹ were reported in China, although these yields were only based on samples of 14 to 28 individual plants (Isoda et al., 2010). Likewise, no other soybean growers had reported exceptionally high yields since the 1968 winner of the National Soybean Yield Contest with 7310 kg ha⁻¹ (Cooper, 2003). Furthermore, these reported yields were greater than what many believed to be the maximum yield of soybean. Many of these estimates came from crop modeling simulations or yield gap analyses using the currently available data. As such, yields of such magnitude lacked the support of empirical, context-specific data.

To help resolve some of questions surrounding these yields, first we must review the current understandings of the physiological processes involved with soybean grain yield determination. Research should be undertaken to provide unbiased documentation of Mr. Cullers' yield, establish crop growth and nutritional characteristics of his crop, and provide a scientific basis for understanding how and if these yield levels are attainable. These measurements should also be taken and verified in maximum yield research in a small-plot, controlled environment. Furthermore, several management practices utilized by Mr. Cullers need to be evaluated to examine the validity of these practices for elevating yields in a maximum yield environment. An additional question is whether these practices can be scaled up to be used in

normal soybean production as well as considering the costs and net returns of the enhanced management. Finally, we must utilize new physiological and nutritional data to re-evaluate the theoretical maximum yield of soybean by using and modifying an established crop simulation model.

A research program was established and conducted to address these objectives and those studies are described in the ensuing chapters.

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CHAPTER 2

A Review of Soybean Grain Yield Determination

ABSTRACT

The largest reported soybean grain yield is approximately three-fold more than the highest reported U.S. average yield. An understanding of yield determination is needed to identify avenues for increasing yield and for defining the theoretical maximum yield potential of soybean. To illustrate physiological traits important for yield determination, we used a framework that models yield as the product of seed number (seed m^{-2}) and individual seed mass ($\text{mass}_{\text{seed}}$). Developmentally, seed m^{-2} is determined first and is proportional to the biomass accumulation rate (BAR, $\text{g m}^{-2} \text{d}^{-1}$) and the fraction of assimilate allocated to reproductive structures. seed m^{-2} is inversely proportional to the individual seed growth rate (ISGR, $\text{mg seed}^{-1} \text{d}^{-1}$) where the ISGR represents the minimum amount of assimilate necessary to prevent a flower or pod from aborting. Hence, seed m^{-2} can be increased by optimizing conditions for crop growth (e.g., radiation interception, stress-free environment, high soil fertility levels) and having a low ISGR. Determination of $\text{mass}_{\text{seed}}$ occurs later during development than seed m^{-2} and can be expressed as the product of the ISGR and the seedfill period (SFP, d). Variation among genotypes for ISGR is quite large and is generally not affected greatly by the environment. There is also genotypic variation in the SFP, but the SFP is decreased by a variety of biotic and abiotic stresses. Our analysis indicates that maximum soybean yield depends upon high BAR and extending the SFP, and a key factor affecting both of these variables is ensuring non-limiting crop nutrition, especially nitrogen.

INTRODUCTION

Current Yield Levels and Records

United States average soybean [*Glycine max* L. (Merr.)] grain yields have increased from the earliest record of 739 kg ha⁻¹ in 1924 to a high of 2956 kg ha⁻¹ in 2009 (USDA-NASS, 2013). While this increase in soybean yield over time is substantial, both researchers and growers have documented yields much greater than the reported nationwide averages. In New Jersey, Dr. Roy Flannery recorded a soybean yield of 7923 kg ha⁻¹ in 1983 and a 5-yr average irrigated yield of 6921 kg ha⁻¹ (Flannery, 1989). In 1982, Dr. Richard Cooper was able to achieve yields of 6817 kg ha⁻¹ in research in Ohio (Cooper, 2003). In Queensland, Australia yields up to 8604 kg ha⁻¹ were reported (Lawn et al., 1984; Cooper, 2003). The highest reported yield by researchers was in China with yields up to 9200 kg ha⁻¹, although these yields were estimated from samples of 14 to 28 individual plants and are thus questionable (Isoda et al., 2010).

A few soybean growers have also achieved outstanding soybean yields. In 1968, the winner of the United States National Soybean Yield Contest did so with 7310 kg ha⁻¹ (Cooper, 2003). In 1997, a grower achieved yields near 6719 kg ha⁻¹ in the Nebraska irrigated contest category (Specht et al., 1999). In 2008, Mr. Charlie Hinkebein won the Missouri Soybean Association's non-irrigated contest category with 7324 kg ha⁻¹ in southeast Missouri (Steever, 2008). And finally, the highest soybean yields reported from yield contests were submitted by Mr. Kip Cullers of southwest Missouri. Mr. Cullers first entered the Missouri Soybean Association Yield Contest in 2006 with 9339 kg ha⁻¹ and followed this with 10,388 kg ha⁻¹ in 2007 and 10,791 kg ha⁻¹ in 2010 (Cubbage, 2010).

The high yields achieved by Mr. Cullers have created some controversy and skepticism because of the lack of supportive empirical data that would provide a mechanistic explanation for

these high yields. Additional concerns are associated with the uncertainty in what constitutes a theoretical maximum yield potential of soybean. This becomes an issue when attempting to estimate future prospects for yield increases via yield gap analyses using current farmer average yields and the potential yield. To provide an estimate of the maximum yield potential of soybean, it is crucial to first examine the process of soybean grain yield determination.

Theoretical Framework for Seed Number Determination

Soybean grain yield is determined by the seeds m^{-2} and weight or mass of individual seeds ($\text{mass}_{\text{seed}}$; g seed^{-1}):

$$\text{Yield (g m}^{-2}\text{)} = (\text{seeds m}^{-2}\text{)} * (\text{mass}_{\text{seed}}) \quad [1]$$

In soybean grain yield development, seed number determination occurs first, followed by seed weight determination (Board and Kahlon, 2011). Of these two variables, seeds m^{-2} has a greater effect on yield compared with seed weight (Shibles et al., 1975; Kokubun and Watanabe, 1983; Board, 1987; Singer et al., 2004; De Bruin and Pedersen, 2008; Robinson et al., 2009). One theory regarding seeds m^{-2} determination in soybean was described by Egli et al. (1978b) where W.G. Duncan proposed “that the number of seed produced by a soybean community is set at a level such that the sum of their individual growth rates essentially equals the ability of the soybean canopy to support seed growth”. In other words, seeds m^{-2} is a function of the total crop canopy photosynthate production and the rate of photosynthate utilization by the individual seed. Charles-Edwards (1984) theorized that “each growing point on a plant requires a minimum flux of assimilate for growth to continue.” These concepts were applied to the determination of seeds m^{-2} by Charles-Edwards et al. (1986):

$$N_g = \nabla_F * \gamma * A_g^{-1} \quad [2]$$

In Equation [2], N_g represents the number of developing grain, ∇_F represents the daily canopy net photosynthesis, γ represents the partitioning coefficient of daily canopy net photosynthesis to reproductive growth, and A_g is the minimum amount of assimilate required to keep each developing grain from aborting. Equation [2] indicates that the number of grain may be increased by lowering the photosynthate requirement per grain, allowing the total crop photosynthate production to be divided among more reproductive units. Alternative or supplemental avenues to increase the number of grain would be to increase the total amount of crop photosynthate produced during the flowering and podset periods or to increase the proportion of photosynthate partitioned to the seeds.

This model was evaluated by Egli and Zhen-wen (1991) who used seeds m^{-2} as an estimate for N_g and experiments employing shade treatments to vary ∇_F . Net canopy photosynthesis production was estimated as the biomass accumulation rate (BAR; $g\ m^{-2}\ d^{-1}$) during flowering and podset (R1 to R5; Fehr and Caviness, 1977) and the individual seed growth rate (ISGR; $g\ seed^{-1}\ d^{-1}$) was assumed to be a representation of the A_g :

$$\text{seeds } m^{-2} = \text{BAR} * \gamma * \text{ISGR}^{-1} \quad [3]$$

For seeds m^{-2} to be a suitable substitution for N_g , the potential fruit number must be greater than the final seed m^{-2} . If this is not the case, excess photosynthate (∇_F) will not be accounted for after partitioning to the grain sites ($\gamma * A_g^{-1}$). With soybean, estimates indicate that 32 to 87% of flowers and immature pods abort and do not develop into mature pods with fully developed seed (Van Schaik and Probst, 1958; Hansen and Shibles, 1978; Wiebold et al., 1981; Peterson et al., 1986). Highly productive environments favor increased flower production rather than decreased abortion rates (Jiang and Egli, 1993), and the majority of aborted flowers are fertilized, suggesting that failure of fertilization plays a negligible role in flower abortion (Abernathy et al,

1977). As such, it was assumed that the potential number of grain sites in soybean was always greater than the final seeds m^{-2} , and seeds m^{-2} would be an appropriate substitution for N_g (Egli and Zhen-wen, 1991).

Conceptually, total photosynthate production less the amount needed for maintenance and respiration would be used for new vegetative and reproductive biomass. Additionally, in experiments involving cultivars with a range of maturity groups (Egli, 1993) or shade prior to R1, Jiang and Egli (1995) determined that response of seeds m^{-2} to BAR was not affected by total vegetative mass at R1, provided that canopy closure had been achieved. Thus, BAR serves as an appropriate estimate of ∇_F regardless of maturity or cultural practices that affect plant size at flowering.

Lastly, the final seed weight ($mass_{seed}$) is genetically controlled via the ISGR such that cultivars with large seed also have the greatest ISGR, although environmental factors interact with genetics to affect the $mass_{seed}$ (Egli, 1975; Egli et al., 1978b; Guldan and Brun, 1985). Furthermore, within developing pods the seed at the basal position has the slowest growth rate and a lower seed weight compared with seed at the middle or apical position in the pod (Egli et al., 1978b). An additional assumption that is required if ISGR is to be used as a proxy for A_g is that the ISGR must be stable across a range of ∇_F or BAR. Egli and Leggett (1976) documented that the ISGR remained relatively stable despite leaf or pod removal. The ISGR was also stable across changes in the short-term photosynthate supply for soybean (Koller, 1971) and corn [*Zea mays* L.] (Duncan et al., 1965) and with water-deficit stress in soybean (Meckel et al., 1984; Westgate et al., 1989). There were also no consistent differences in ISGR between early and late formed pods (Egli et al., 1978b) and Egli and Zhen-wen (1991) concluded that ISGR would be representative of all the seeds on a plant despite differences in when seeds were first formed.

Although the ISGR is linear throughout most of seedfill, the entire seed growth cycle resembles a sigmoidal function where at the beginning of seedfill, the ISGR increases rapidly to the linear phase and remains constant until near physiological maturity when the rate decreases to 0 (Egli, 1994). For the ISGR to be used as a substitution for A_g , it must be assumed that these periods of non-linear ISGR do not greatly affect the response of seeds m^{-2} . Furthermore, changes in seed composition affect A_g (Sinclair and de Wit, 1975) and the substitution of A_g with ISGR is only appropriate when comparing cultivars or crops with similar seed compositions.

Given these assumptions, Egli and Zhen-wen (1991) evaluated Eq. [3] and found that when BAR increased during flowering and pod set, seeds m^{-2} increased proportionately. The same relationship was described by Ball et al. (2000) with varying plant densities and cultivars to alter BAR and ISGR. Rotundo et al (2012) also found a positive correlation between BAR from R1 to R5 and seeds m^{-2} . Cultivars with high seeds m^{-2} generally had high or intermediate BAR, while cultivars with low seeds m^{-2} tended to have the lowest BAR (Rotundo et al., 2012). Within a cultivar, others have also documented this linear, positive relationship between BAR and seeds m^{-2} (Herbet and Litchfield, 1984; Ramseur et al., 1985; Charles-Edwards et al., 1986; Jiang and Egli, 1995). Shade, defoliation, or stress at any time during flowering and pod set (R1 to R5) increased pod abortion and decreased seeds m^{-2} and yield (Mann and Jaworski, 1970; Schou et al., 1978; Egli and Zhen-wen, 1991; Board and Harville, 1993; Egli, 1993; Jiang and Egli, 1993; Board and Tan, 1995; Andrade and Ferrerio, 1996; Sharma et al., 1996; Egli, 1997). Alternatively, supplemental solar radiation during flowering and pod set increased yield, seeds, nodes, pods and branches $plant^{-1}$, pods $node^{-1}$, and seeds pod^{-1} (Johnston et al., 1969; Schou et al., 1978; Mathew et al., 2000), and supplemental N increased seeds m^{-2} and yield (Brededan et al., 1978). Furthermore, late-developing flowers are more likely to abort than those already

developing at a single node, and the removal of earlier formed flowers and pods can reduce the abortion rates of late-developing flowers (Huff and Dybing, 1980; Brun and Bretts, 1984, Heitholt et al., 1986; Egli and Bruening, 2002). Likewise, depodding can reduce the abortion rates of remaining flowers and pods (Heitholt et al., 1986, McAlister and Krober, 1958; Hicks and Pendleton, 1969). All of these observations support Eq. [2] and [3] whereby seed development depends upon assimilate availability and that additional grain sites can be maintained by increasing photosynthate production or availability.

The effect of the assimilate demand by each developing grain site was also demonstrated by Egli and Zhen-wen (1991), where cultivar ‘Essex’ had a slower ISGR of $4.5 \text{ mg seed}^{-1} \text{ d}^{-1}$ and more seeds m^{-2} than ‘Harper’, which, had a faster ISGR of $6.3 \text{ mg seed}^{-1} \text{ d}^{-1}$. This effect was observed across all BAR levels. Eq. [2] and [3] were further validated in a second experiment involving two additional cultivars of differing ISGR to alter A_g (Egli and Zhen-wen, 1991). Further supporting these models, Hartwig and Edwards (1970) found that lines bred for large seed had fewer seeds and pods plant^{-1} and similar yield to the recurrent parents. Others have also found that a reduction in seed weight resulted in greater pods and seeds m^{-2} (Bruening and Egli, 1999; Pedersen and Lauer, 2004; Woodward and Begg, 1976). Hanson (1986) was able to show that sucrose release into developing seeds was a passive process and concluded that the developing seeds were simply receptacles for assimilate. All of these findings support Eq [3] where at a fixed level of photosynthate production and partitioning ($\text{BAR} * \gamma$), the photosynthate demand is also fixed ($\text{seeds m}^{-2} * \text{ISGR}$). Thus, increases in ISGR will reduce seed m^{-2} . This explains why breeding efforts to increase seed weight have not resulted in increased yield (Hartwig and Edwards, 1970).

Egli and Zhen-wen (1991) and Ball et al. (2000) estimated the partitioning coefficient (γ) from their measurements of BAR, ISGR and seeds m^{-2} . Ball et al. (2000) found γ to remain constant over alterations in BAR across plant densities, irrigation regimes and years. For cultivars from Argentina, Rotundo et al. (2012) found γ was greatest with clusters of cultivars with high seeds m^{-2} and lowest with low seeds m^{-2} . For cultivars from the USA with both high and low seeds m^{-2} had a high γ and there was no relationship between γ and seeds m^{-2} . Although, Vega et al. (2001) found γ decreased slightly with increasing BAR, which was consistent with earlier findings (Egli et al., 1985; Egli and Zhen-wen, 1991), they observed this effect in only a few, very small plants and suggested that this effect with negligible and that γ was a fairly stable trait.

Theoretical Framework of Seed Weight Determination

Individual seed weight ($\text{mass}_{\text{seed}}$, mg seed^{-1}) is simply the product of the seed's ISGR ($\text{mg seed}^{-1} \text{d}^{-1}$) and the duration of seed growth, represented as the seedfill period (SFP, d):

$$\text{mass}_{\text{seed}} = \text{ISGR} * \text{SFP} \quad [4]$$

The ISGR and SFP are independent traits (Egli and Wardlaw, 1980; Egli et al., 1981; 1984; Meckel et al., 1984), suggesting that $\text{mass}_{\text{seed}}$ can be accurately portrayed by Eq. [4]. The length of the SFP ranges from 12 to 57 d (Hanway and Weber, 1971a; Egli and Leggett, 1973; Gay et al., 1980; Egli et al., 1984; Egli et al., 1987; Swank et al., 1987). Drought or high-temperature stress can shorten the SFP, resulting in a corresponding decrease in seed weight (Egli and Wardlaw, 1980; Egli et al., 1984; Meckel et al., 1984). Thomas and Raper (1976) and Gbikpi and Crookston (1981) demonstrated that the ISGR is increased and the SFP decreased by shortening photoperiods. The ISGR also increases as temperature increases from 18/13 to 27/22° C but then

remains stable to 33/28° C (Egli and Wardlaw, 1980). Similarly, Thomas et al. (2010) also found that ISGR was stable from 28/18 to 32/22° C and that the ISGR decreased as temperatures increased to 40/30 and 44/34° C.

Hanway and Weber (1971a) found that differences in yield among a group of eight cultivars were primarily due to SFP and that cultivars had similar ISGR. Likewise, Egli and Leggett (1973) found cultivar differences in ISGR but determined that grain yield differences were more closely associated with SFP. Swank et al. (1987) found examples of variation in $mass_{seed}$ among genotypes that were associated with differences in both ISGR and SFP. When comparing old and new cultivars, the yield advantage of cultivar ‘Williams’ over ‘Lincoln’ was due to a greater $mass_{seed}$ from a longer SFP (Gay et al., 1980). Others have also demonstrated that the SFP in modern cultivars has increased over time of release (Boerma and Ashley, 1988; Kumudini et al., 2001; McBlain and Hume, 1981; Metz et al., 1984; 1985; Pfeiffer and Egli, 1988; Rowntree et al., 2014; Salado-Navarro et al., 1985b; Shiraiwa and Hashikawa, 1995; Smith and Nelson, 1987).

Salado-Navarro et al. (1986a;b; 1993) found that a longer SFP was usually associated with a lower dry matter allocation coefficient (DMAC; d^{-1}). The DMAC was defined as the slope of the linear increase in HI during seedfill (Salado-Navarro et al., 1985a). As such, DMAC is an alternative measure of the ISGR, representative of the whole-plant seed growth rate (Spaeth and Sinclair, 1985).

Crop Nitrogen Dynamics

To sustain high BAR, and potentially increase seed m^{-2} , high rates of N accumulation are required for protein production to support seed growth and high rates of photosynthesis. While

yield is often correlated with biomass accumulation, Sinclair and Jamieson (2006) suggest that N accumulation can explain more yield variation than biomass accumulation, and similar conclusions can be drawn from results of Rotundo et al. (2014). Although Rotundo et al. (2014) did not find differences in total N accumulation among a group of high yielding cultivars, there were differences in their timing of N accumulation. While the majority of N accumulation occurred during R1 to R5, some high yielding cultivars acquired more N prior to flowering while others obtained more N during seedfill. Rotundo et al. (2014) also found differences in apparent N remobilization during seedfilling. Within the high yielding cultivar groups, high seed N demand was met through different combinations of N accumulation during seedfill and the amount of N remobilized.

Genotypes with a short SFP require a more rapid N remobilization from the leaves to support seed protein accumulation when compared with genotypes with a longer SFP (Boon-Long et al., 1983; Egli et al., 1987). A short SFP was also associated with a more rapid rate of decline in CO₂ uptake and earlier leaf abscission (Boon-Long et al., 1983; Gay et al., 1980). Sinclair and de Wit (1976) theorized that the N demand for soybean and other high protein crops could not be met by N accumulation alone and that remobilization and translocation of N and proteins from vegetative tissues must occur to support seed growth. As this pool of N and proteins was depleted (Boote et al., 1978; Borst and Thatcher, 1931; Egli et al., 1978a; Hanway and Weber, 1971b), photosynthetic rates also declined (Boote et al., 1978; Lugg and Sinclair, 1981; Mondal et al., 1978; Sesay and Shibles, 1980; Sinclair, 1980; Wittenbach et al., 1980). Eventually, the photosynthetic apparatus loses functional integrity along with other physiological processes, thereby ending the SFP and limiting final seed yield.

This “self-destruct” hypothesis was supported by Salado-Navarro et al. (1985a) who found differences in leaf senescence rates with cultivars of varying seed protein concentration and seed N demand. Others also observed that N deficiency shortened the SFP and accelerated leaf senescence (Boon-Long et al., 1983; Hayati et al., 1995). The self-destruct hypothesis also explains why a lower DMAC (or ISGR) increased the SFP by slowing the daily demand for C and N remobilization (Salado-Navarro et al., 1986a;b; 1993). Rotundo et al. (2014) documented diversity for N accumulation during seedfill and N remobilization among high yielding elite cultivars and this may provide an avenue for increasing the SFP by delaying senescence.

However, previous efforts to supply N during seedfill did not prevent senescence or N redistribution (Egli et al., 1978a; Hayati et al., 1995; 1996). Likewise, in a comparison of soybean maturity isolines, a maturity group (MG) 6 isoline had 73 to 100% more total N at the beginning of seedfill than the MG 4 isoline but N content in harvested seed was not different (Mastrodomenico and Purcell, 2012), indicating that N supply was not limiting yield. While seed growth is limited by assimilate availability, seeds can still mature normally on a plant with green leaves and an intact photosynthetic apparatus (Egli, 1998). Perhaps seed volume limits, imposed by pod or seed structures, can cause seed maturation despite the presence of available assimilate (Egli 1990; 1998). Regardless of the cause of the termination of the SFP, increases in seed weight and grain yield may be possible by lengthening the SFP and thereby avoiding a compensatory decrease in seeds m^{-2} associated with increasing the ISGR (Swank et al., 1987; Eq. [1], [3] and [4]).

Simplification

Combining Eq [1], Eq [3] and [4], we obtain:

$$\text{Yield (g m}^{-2}\text{)} = (\text{BAR} * \gamma * \text{ISGR}^{-1})(\text{ISGR} * \text{SFP}) \quad [5]$$

Equation [5] can be simplified to:

$$\text{Yield (g m}^{-2}\text{)} = \text{BAR} * \gamma * \text{SFP} \quad [6]$$

One concern with this simplification is that it ignores the factor of time; in Equation [3], BAR is measured from R1 to R5 and the SFP from Equation [4] extends from approximately mid-R5 to R7. In Equations [3] and [4], ISGR is common to both expressions. However, in Equation [3], ISGR is a proxy for the minimum amount of assimilates required per seed (A_g) as opposed to Equation [4] where ISGR is a determinant of $\text{mass}_{\text{seed}}$. Equation [6] will only be appropriate when ISGR and BAR remain relatively constant across the time periods for Equation [3] and [4]. Short-term changes in the source/sink balance in the field do not impact ISGR (Egli and Leggett, 1976; Koller, 1971). Under well-irrigated conditions, BAR was linear in soybean from flowering until near physiological maturity (Mastrondomenico and Purcell, 2012). Likewise, the linear increase in HI during grain filling (Salado-Navarro et al., 1985b) indicates that γ is also linear, at least during the seedfilling period.

An alternative model for grain yield can be expressed as the product of total biomass production (BM; g m^{-2}) and the harvest index (HI):

$$\text{Yield (g m}^{-2}\text{)} = \text{BM} * \text{HI} \quad [7]$$

Where total biomass production is modeled as season long sum of the product of radiation use efficiency (RUE; g MJ^{-1}) and intercepted solar radiation (IR; MJ m^{-2}) from emergence ($i=1$) to physiological maturity ($i=n$):

$$\text{BM} = \sum_{i=1}^n \text{RUE} * \text{IR} \quad [8]$$

The RUE is similar to BAR, as both are measures of crop growth either over time (BAR) or over IR (RUE). Eq. [7] and [8] represent simple models for characterizing soybean yield which are based upon C assimilation.

Maximum Yield Prediction

Yield gap analyses have been used to define future crop yield improvement prospects on both a local and a global scale (Egli and Hatfield, 2014; van Ittersum et al., 2013). One key component of a yield gap analysis is the potential yield with which to compare the current yield and to determine the yield gap. True yield potential, or the theoretical maximum yield of a crop, is the yield possible when the crop is grown in a non-stress environment where nutrients and water availability are non-limiting, all biotic stresses are controlled, and abiotic stresses are minimized (Boyer, 1982; Evans, 1993). Estimates of yield in non-stressed environments can come from farmer yield contests, validated crop simulation models, from intensively managed experiments, or maximum on-farm yields (Lobell et al., 2009). However, aside from crop simulation models, it can be difficult to determine if all stresses were truly eliminated (Evans and Fischer, 1999).

Maximum yield potential is governed by temperature and solar radiation interception and the cultivar's physiological processes. Sinclair (2004) utilized Eq. [7] and [8] to predict a soybean maximum yield potential of 7260 kg ha⁻¹ assuming a harvest index of 0.55, RUE of 1.10 g MJ⁻¹, and cumulative IR of 1200 MJ m⁻². However, Van Roekel and Purcell (2014) reported RUE values up to 1.89 g MJ⁻¹ from a maximum yield contest field, which were 30% more than any other RUE reported measurement and 122% greater than the mean of all RUE values reported in the literature. Additionally, an HI of 0.55 is near the mean for the apparent HI, not

accounting for lost biomass from senesced leaves (Schapaugh and Wilcox, 1980). When using RUE to calculate biomass production, the appropriate HI value to use in this calculation must be the actual HI, the total aboveground biomass produced over the grain produced. The mean actual HI reported by Schapaugh and Wilcox (1980) was 0.45. Using the same cumulative IR value as Sinclair (2004) along with an actual HI value of 0.45 and a RUE of 1.89 g MJ^{-1} , Equations [7] and [8] would indicate a potential yield of $10,206 \text{ kg ha}^{-1}$.

Another simple method used for predicting the yield potential of soybean was by examining the historical grain yield improvement ratio between corn and soybean. Specht et al. (1999) and Egli (2008) found this ratio to range from 2.8- to 3.0-to-1. That is, the rate of corn yield increased 2.8 to 3.0 times faster than soybean yield. Using the 2.8-to-1 ratio, Specht et al. (1999) predicted that the maximum yield potential of soybean was near 8000 kg ha^{-1} based upon observed corn grain yields near $22,500 \text{ kg ha}^{-1}$. More recently, a corn yield of $31,085 \text{ kg ha}^{-1}$ (National Corn Growers Association, 2014) would suggest the maximum yield potential of soybean is near $10,783 \text{ kg ha}^{-1}$.

Management for Maximum Yield

At a location that had previously reported yields up to $10,791 \text{ kg ha}^{-1}$ in yield contests (Cubbage, 2010), Van Roekel and Purcell (2014) reported BAR values up to $64 \text{ g m}^{-2} \text{ d}^{-1}$. That site was noted for an intense fertility regime and large applications of poultry manure (Van Roekel and Purcell, 2014). Similarly, Flannery (1989) reported a maximum yield of 7955 kg ha^{-1} from a management system that included 12 Mg ha^{-1} of dairy manure applications every other year (Table 1). Cooper (2003) also reported high soybean yields, up to 7050 kg ha^{-1} from research with large annual applications of N, P, and K. However, Spaeth et al. (1987) reported

yields of 6490 kg ha⁻¹ with a lower input fertility system. As illustrated by the nutrient uptake and removal data from Flannery (1986), a 6786 kg ha⁻¹ grain yield had a nutrient removal in the grain of 554 kg N ha⁻¹, 55 kg P ha⁻¹, and 392 kg K ha⁻¹. Thus, high soybean yields require large nutrient inputs. These nutrients can be attained via applications of manure (Flannery, 1989; Van Roekel and Purcell, 2014), inorganic fertilizer (Cooper, 2003; Flannery, 1989), and/or from fertile soils (Spaeth et al., 1987). It should also be noted that current fertility recommendations are likely to be inadequate to supply a crop with yields exceeding 5000 kg ha⁻¹, and to achieve yields of this magnitude or greater it may be necessary to supplement N₂ fixation with N fertilizer (Salvagiotti et al. 2008).

Furthermore, with normal soybean water requirements peaking at approximately 7.6 to 7.7 mm d⁻¹ (Benham et al., 1998; Heatherly, 1986; Heatherly and Elmore, 2004), it is evident that soil-moisture management is another critical component for maximizing soybean yields. Sinclair and Rufty (2012) estimate that with a weighted, season-long vapor pressure deficit of 1.5 kPa and a harvest index of 0.40, yields of 6,000 kg ha⁻¹ would require approximately 500 mm of water for transpiration, which ignores any water loss from soil evaporation. Water requirements would increase proportionately as yields increase. Isoda et al. (2010) utilized a drip irrigation system and total water inputs from precipitation and irrigation totaled 465 mm in the highest yielding year of research. Flannery (1989) also employed a drip irrigation system, with precipitation and irrigation amounts totaling 782 mm in the highest yielding year. Flannery (1989) further utilized the irrigation system to deliver approximately 66% of the fertilizer inputs in the growing season. Cooper (2003) used a sprinkler irrigation system to ensure the crop received at least 50 mm water week⁻¹ from precipitation and irrigation. However, Spaeth et al.

(1987) relied solely on rainfall and improved their water management by installing tile drainage to remove excess water from their converted rice paddies.

Pest control was a key factor in eliminating biotic stresses for Flannery (1989), Van Roekel and Purcell (2014), and Cooper (2003). Flannery (1989) utilized seed treatments, soil and foliar insecticides, and fungicides to control pests throughout the season. Cooper (2003) and Van Roekel and Purcell (2014) reported routine fungicide applications and periodic insecticides as needed. Spaeth et al. (1987), however, made no mention of increased pest control practices.

With the exception of Spaeth et al. (1987), these examples of high yield research utilized some form of row widths less than 76 cm (Table 2-1). Narrow rows are an effective method for increasing light interception and BAR (Board et al., 1992; Board and Harville, 1996).

Furthermore, early planting (Bastidas et al., 2008; Salmeron et al., 2014; Wilcox and Frankenberger, 1987) and warmer early spring temperatures (Cooper, 2003) have been cited as ways to induce earlier flowering, lengthen the reproductive period, and increase solar radiation interception and BAR during seedfilling. Additionally, for a particular location, selecting the correct combination of row spacing, planting date, and MG such that the crop has a closed canopy and is beginning to flower close to the summer solstice provides an environment for maximizing BAR and for a relatively long photoperiod, which will extend the reproductive period (Rowntree et al., 2014). As such, these cultural practices illustrate additional factors that can affect the BAR and SFP and increase seeds m^{-2} and $mass_{seed}$.

Increasing Soybean Yield Potential

Maximizing soybean yield requires the integration of light, water and nutrient inputs into a system that optimizes crop growth and limits stresses. The summary of high yield studies

presented in Table 2-1 suggests that yields exceeding 6000 kg ha^{-1} also entail considerably higher nutrient and water inputs than typically recommended. These high input systems likely affect several, if not all, of the previously described physiological, yield-determining factors, and the interactions of these factors must be optimized to generate the seeds m^{-2} and $\text{mass}_{\text{seed}}$ at these yield levels.

As such, yield is considered a quantitative and complex trait (Slafer, 2003). In addition to the physiological processes discussed that determine a cultivar's yield potential, other agronomic traits can affect yield, such as shattering, lodging resistance, and disease resistance. This review focused on the mechanistic framework developed by Charles Edwards (1984) for seed number determination and the importance of BAR from R1 to R5, γ , ISGR, and SFP.

To select for these traits associated with yield determination, diversity must exist with which to develop new populations and higher yielding cultivars (Sneller et al., 1997). Rotundo et al. (2012) and Van Roekel and Purcell (2014) documented that diversity exists among elite cultivars for several of these physiological traits and that different combinations of traits can result in similar yields. Such strategies include increasing the BAR or γ to increase seeds m^{-2} , decreasing the ISGR to increase the seeds m^{-2} but this will decrease $\text{mass}_{\text{seed}}$, and increasing the SFP to increase the $\text{mass}_{\text{seed}}$. Each of these components must be tailored to the end user's growing environment. For example, increasing the SFP may not be beneficial in far northern environments where cooler temperatures will decrease the ISGR (Egli and Wardlaw, 1980) and increase the risk of damaging fall freezes. In southern regions, a high BAR can contribute to excessive plant height which can increase lodging and reduced HI if these cultivars are not planted early to reduce height and induce earlier flowering (Akhter and Sneller, 1996; Bastidas et

al., 2008; Cooper, 2003; Wilcox and Frankenberger, 1987) or not combined with semidwarf plant architecture (Cooper, 1981; 1985).

Rotundo et al. (2014) also documented diversity and alternate strategies among high yielding cultivars for N use efficiency (NUE), N harvest index, seed N and HI. Rotundo et al. (2014) suggested that breeding for increased NUE and HI with the average N accumulation rate (NAR) held promise to increase yield $\sim 500 \text{ kg ha}^{-1}$ in their environment. Van Roekel and Purcell (2014) documented wide ranges in NAR among environments and among cultivars within an environment. This indicates that the combination of increased NAR, NUE, and HI may hold potential for increasing yield even further.

CONCLUSIONS

The theoretical framework of Charles-Edwards (1984) as developed by Egli (1998) for soybean yield determination allows for a mechanistic approach to understand the physiological parameters required to maximize soybean grain yield. The inability to increase soybean yield in previous research by manipulating seed m^{-2} and $\text{mass}_{\text{seed}}$ demonstrate compensatory mechanisms to adjust assimilate supply with seed growth requirements. Extrapolation of measured values of BAR, SFP, and RUE predict yields near the reported maximum of $10,791 \text{ kg ha}^{-1}$ from yield contests (Cubbage, 2010). However, full characterization of crop growth, development, and the environment is needed to accompany these yield reports to provide a clear understanding of the mechanisms and combinations of yield-determining parameters that lead to yields of this magnitude.

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Table 2-1. Summary of location, soil series, maturity group (MG), maximum yield and management comments from peer-reviewed high yield soybean research.

Location	Soil series	MG	Maximum Yield	Management Comments	Reference
Adelphia, NJ	Freehold sandy loam	3	7955 kg ha ⁻¹	Drip fertigation, 156 kg N, 110 kg P, 279 kg K ha ⁻¹ and 12 Mg ha ⁻¹ biennial dairy manure, planted near 1 May in 15 to 36-cm rows	Flannery, 1989
Shihezi, China	nr	nr	9200 kg ha ⁻¹ ‡	Drip irrigation, 240 kg N, 131 kg P, 162 kg K ha ⁻¹ yr ⁻¹ from 15 Mg ha ⁻¹ poultry manure, planted 29 Apr. in alternate 30 and 60-cm rows	Isoda et al., 2006, 2010
Shinjo, Japan	clayey, humic andosol	3	6490 kg ha ⁻¹	Converted rice paddy, rainfed, 25 kg N, 33 kg P, 77 kg K ha ⁻¹ , planted between 18 and 24 May in 75-cm rows	Spaeth et al., 1987
Stark City, MO	Newtonia silt loam	4-5	7953 kg ha ⁻¹	Overhead irrigation, poultry manure, planted 24 Apr. to 30 May in twin rows 24-cm apart, centered on 76 cm.	Van Roekel and Purcell, 2014
Wooster, OH	Wooster silt loam	3	7050 kg ha ⁻¹	Overhead irrigation, 222 kg N, 88 kg P, 334 kg K ha ⁻¹ yr ⁻¹ , 17.5-cm rows	Cooper, 2003

† Not reported.

‡ Yields were based on 14 to 28 plants per plot and are, therefore, questionable.

CHAPTER 3

**Soybean Biomass and Nitrogen Accumulation Rates and Radiation Use Efficiency in a
Maximum Yield Environment**

Van Roekel and Purcell, 2014, Crop Sci. 54:1189-1196

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ABSTRACT

Soybean [*Glycine max* (L.) Merr.] physiological characterization in a maximum yield environment may identify yield-optimization factors, lead to reassessment of fundamental crop model parameters, and provide guidance for management or breeding efforts. From 2011 to 2013, we characterized biomass and N accumulation rates, radiation use efficiency (RUE), and yield for four or five cultivars in a maximum-yield contest field. Grain yield among cultivars ranged from 5290 to 7953 kg ha⁻¹. The highest yields were observed in 2013, when biomass and N accumulation rates ranged from 45.6 to 64.3 g m⁻² d⁻¹ and 1.43 to 2.08 g N m⁻² d⁻¹, respectively and when RUE values ranged from 1.46 to 1.89 g MJ⁻¹. The observed crop growth characteristics in 2013 were near or above the maximum values previously reported in the literature. These empirical measurements provide collateral data documenting a soybean crop with grain yields *ca.* 6719 kg ha⁻¹.

INTRODUCTION

Data obtained from USDA-NASS (2013) indicate that average annual USA soybean grain yields have increased linearly from 739 kg ha⁻¹ in 1924 to 2661 kg ha⁻¹ in 2012 at a rate of 23 kg ha⁻¹ yr⁻¹. Cassman et al. (2003) suggested that continued increases in average crop yield will depend upon decreasing the difference between current and potential yields, which they defined as a so-called “yield gap”. Yield potential is defined as the “yield of a crop cultivar when grown with water and nutrients non-limiting and biotic stress effectively controlled” (van Ittersum et al., 2013).

Soybean grain yield contests are currently conducted in 14 states in the USA (AL, AR, IL, KS, KY, MI, MO, NC, OH, PA, SC, SD, VA, and WI). The highest soybean yields reported in such contests to date were those submitted by Mr. Kip Cullers to the Missouri Soybean Association. He won their 2006, 2007, and 2010 Yield Contest with grain yields of 9400, 10,390 and 10,790 kg ha⁻¹, respectively (Cubbage, 2010). These are significant outlier yield contest values, given that, with just two exceptions, state soybean yield contest winners from 2000 to 2012 have not submitted yield entries exceeding 6719 kg ha⁻¹ (100 bushels acre⁻¹). The exceptions to this are a 2007 MO contest yield of 7350 kg ha⁻¹ (Steever, 2008) and a 2012 MI contest yield of 6751 kg ha⁻¹ (Reinholt, 2012). These unusually high grain yields have created some controversy and due skepticism (e.g., Sinclair and Cassman, 2004). Some of this skepticism may be based upon the potential uncertainty in what constitutes a theoretical maximum yield potential of soybean, but most skepticism is based on the lack of empirical collateral data that are context-specific and collected during the same growing season. Such data are important in terms of providing evidentiary support of the exceptionally high yield claim.

Prior to 1966, it was commonly believed that the maximum soybean grain yield potential was near 4500 kg ha⁻¹ (Cooper, 2003). Since that time, several yields greater than 6719 kg ha⁻¹ have been reported in contests and scientific research (Cooper, 2003). Potential soybean grain yield estimates based on crop models range from 8290 kg ha⁻¹ in Australia (Muchow and Sinclair, 1986), 5100 kg ha⁻¹ for the 30-yr mean in Japan (Spaeth et al., 1987), and 5400 kg ha⁻¹ in India (Bhatia et al., 2008). Moreover, if one assumes a radiation use efficiency (RUE) of 1.1 g MJ⁻¹, seasonal total interception of 1200 MJ m⁻² of solar radiation, and a harvest index (HI) of 0.55, the inferred maximum yield is about 7300 kg ha⁻¹ (Sinclair, 2004).

Specht et al. (1999) documented a 2.8-to-1 ratio between the rates of on-farm corn (*Zea mays* L.) and soybean grain yield improvement in 25 years of Nebraska's irrigated soybean production systems. Egli (2008a) subsequently documented that the ratio of on-farm corn and soybean yield improvement in Iowa, Illinois and Indiana plateaued at about 2.9 to 3.0 after the early 1970's. Specht et al. (1999) used the 2.8 corn/soybean ratio to postulate that the maximum grain yield potential of soybean might be 8000 kg ha⁻¹ based on the maximum observed corn grain yield from yield contests, near 22,500 kg ha⁻¹ at that time, which was similar to the maximum corn yield potential suggested by de Wit (1967). Using this same logic, recently reported corn yields of 28,530 kg ha⁻¹ (Wojcicki, 2013) would suggest that the maximum soybean yield potential should be adjusted upward to near 10,200 kg ha⁻¹. Regardless, Egli (2008b) concluded that it was not possible to know the true potential of soybean grain yield and that an apparently large amount of yield remained exploitable.

While not used in their yield-gap analyses, Fischer and Edmeades (2010) suggested that contest-winning crops are worthy of further study and may lead to identification of novel management practices, adjustments to the limits for parameters used in simulation models, or

physiological processes to target for breeding efforts. The fundamental building blocks of soybean grain yield are carbohydrates, oil, and protein; thus, the maximum yield potential of soybean will ultimately be limited by C and N accumulation. Obtaining and sustaining high rates of photosynthetic activity requires high rates of N accumulation, and consequently, C and N accumulation are often highly correlated (Sinclair, 2004). Radiation use efficiency (RUE) is an empirically estimable parameter that reflects the crop's ability to use solar energy for production of crop mass, and is typically measured as the ratio of crop biomass accumulated in a given period over energy input (intercepted solar radiation) during the same timeframe (Sinclair and Muchow, 1999). Using these concepts, a relatively simple model of soybean growth was developed and described by Sinclair (1986; Sinclair et al., 2003). In this model, the nominal maximum RUE values and daily N accumulation for soybean are limited to 1.2 g MJ^{-1} and $0.6 \text{ g N m}^{-2} \text{ d}^{-1}$, respectively.

Research was undertaken in Mr. Cullers' contest fields to independently generate replicated yield estimates and to characterize the biomass and N accumulation rates and RUE of the crop. The goals of this work were to provide physiological insight into soybean biomass and N accumulation rates, radiation use efficiency and yield in a maximum yield environment, and to determine potential parameter limits in simulation models.

MATERIALS & METHODS

Measurements were taken from Mr. Cullers' yield contest fields near Stark City, MO ($36^{\circ}51' \text{ N}$, $94^{\circ}11' \text{ W}$) from 2011 to 2013. Five cultivars (Pioneer P94Y81, P94Y82, P94Y91, P94Y92, and P95Y10; DuPont Pioneer, Johnston, IA) in 2011, four cultivars (Pioneer P94Y23, P94Y80, P94Y81, and P94Y82) in 2012 or five cultivars (Pioneer P94B73, P48T53, P49T97,

P50T40 and Asgrow AG5332; Monsanto Co., St. Louis, MO) in 2013 were planted in blocks spanning the contest field. The plant rows aligned in an east-west direction, with the entirety of one cultivar being planted in a block, or strip, several planter-passes wide and consisting of *ca.* 3 ha. Each contest field was *ca.* 13 to 18 ha in total size. All cultivars had an indeterminate stem growth habit, and were glyphosate resistant with relative maturities (RM) of 4.2 to 5.3 RM.

Two contest fields were utilized and the predominant soil type for both fields was a Newtonia silt loam (fine-silty, mixed, superactive, thermic, Typic Paleudolls). The two contest fields were in a corn-soybean rotation such that soybean was grown in field “A” in 2011, field “B” in 2012 and then back to field “A” in 2013. A twin-row planter with Sync-Row® units (Monosem Inc., Edwardsville, KS) was used to achieve a planting pattern in which the center of one twin-row pair (spaced 24 cm apart) was 76 cm from the center of an adjacent twin-row pair. The planting dates were 9 May 2011, 11 Apr. 2012 and 27 May 2013. The emergence (VE; Fehr and Caviness, 1977) dates were 3 to 13 days thereafter, on 16 May 2011, 24 Apr. 2012 and 30 May 2013. Four stand counts were taken soon after emergence from a 1-m length of a single twin-row pair from four locations within each cultivar block. Across cultivars, the mean plant density (\pm standard error) was 31.8 ± 0.6 plants m^{-2} in 2011, 30.6 ± 0.9 plants m^{-2} in 2012 and 25.0 ± 0.7 plants m^{-2} in 2013.

Each year since 2006 or before, poultry litter was applied and incorporated in the fall and again in the spring. Total manure applications, tillage operations and fertilizer amounts were unavailable from the producer. Irrigation was provided through a center pivot system. Irrigation was applied frequently, often daily throughout the midseason, with approximately 1.3 cm of water per irrigation. Supplemental fertilizer was not included with irrigation during the timespan covering this report, in contrast to previous years. Irrigation applications, irrigation input totals,

and soil test analyses were unavailable from the producer. Weeds were controlled with spring tillage coinciding with poultry litter incorporation and with one or more post-emergence applications with glyphosate and other tank mixes as needed. Insects were controlled with multiple aerial applications of various insecticides, and fungal disease pressure was minimized by two or more prophylactic fungicide applications.

Successive aboveground biomass measurements were made in each cultivar block in each year. Samples were collected from four “plots”, which were located *ca.* 1 m from the outside center pivot wheel track and evenly spaced across the cultivar block. In 2011, whole-plant biomass samples were collected from two sets of twin-row pairs at a length corresponding to a sampling area equivalent to 1 m² on 31 May, 15 d after emergence (DAE), when the fraction of canopy radiation interception (FRI) was *ca.* 0.10 and plants were at the V1 stage. A second set of 1-m² samples were collected at V6 on 13 June (28 DAE), when FRI was *ca.* 0.50, and a third set of 0.5-m² samples were collected at R1 on 27 June (42 DAE) when FRI was >0.92. In 2012, a first set of 0.5-m² samples were collected on 24 May at V6 (30 DAE) when FRI reached *ca.* 0.50. Additional sample sets were collected at R1 on 7 June (44 DAE), and at R2 on 19 June (56 DAE), when FRI was >0.93 in both instances. In 2013, the first 0.5-m² samples were collected on 27 June at V7 (28 DAE) when FRI reached *ca.* 0.65. The second sampling occurred on 11 July at R2 (42 DAE) and a third sampling set was taken on 24 July at R3 (55 DAE) when FRI for both dates was >0.95. Biomass samples were dried, weighed, ground to pass a 0.853 mm sieve, and analyzed for N concentration by the Dumas method with a Leco FP-428 Determinator (Leco Corp., St. Joseph, MO). The biomass accumulation rate (g m⁻² d⁻¹) and N accumulation rate (g N m⁻² d⁻¹) were calculated by plot as the respective difference between the total aboveground

biomass and total N content for the last two biomass sampling dates, and divided by the days between those two measurements.

Daily total solar radiation and temperature were measured at the field perimeter with a silicon pyranometer and a shielded 12-bit temperature sensor coupled with a HOBO® Micro Station (Onset Computer Corp., Pocasset, MA). Monthly rainfall data were obtained from NCDC-NOAA (2013a) from the Joplin MO regional airport weather station, *ca.* 40 km from the field. Although rainfall at the field and irrigation applications and amounts were unavailable, it is assumed that the producer's frequent irrigation regime eliminated all water-deficit stress. Each year, canopy radiation interception was measured at least once every 7 d until FRI was >0.92, which occurred on 27 June 2011 (42 DAE), 7 June 2012 (44 DAE) and 4 July 2013 (35 DAE) as determined from digital-image analysis (Purcell, 2000). Linear regression of the weekly FRI measurements for each cultivar on accumulated growing degree days (GDD, using a base temperature of 10°C) generated a regression equation that was used to interpolate FRI values for each day within each of the 7-d intervals. Daily solar radiation measurements were then multiplied by the daily FRI to compute daily intercepted radiation values. Daily intercepted radiation values were successively summed to obtain a total cumulative radiation interception value for the period from VE to the day of the final biomass sample. Radiation use efficiency (g biomass MJ⁻¹) was determined for each plot by regressing the increase in aboveground biomass (g m⁻²) against the cumulative amount of radiation intercepted by the crop (MJ m⁻²) for all three biomass samples.

A few days after the last maturing cultivar reached harvest maturity (R8), 1 m² samples were collected from four bordered locations within each cultivar block near the biomass sample collection locations. These samples were used to determine final grain yield and HI, but no

attempt was made to collect senesced leaves. Whole plant samples were dried, weighed, threshed, and the grain alone was dried overnight to remove any moisture gained, weighed, and adjusted to 130 g kg⁻¹ moisture. Yield data and other variables measured during the season were analyzed using the MEANS procedure of SAS (SAS Institute, Cary, NC) to determine the cultivar means and standard errors (SE) for each variable in each year. Means were separated using a two-tailed t-test and an $\alpha = 0.05$.

RESULTS

Soybean cultivar grain yields measured ranged from 5290 to 7137 kg ha⁻¹ in 2011, 5521 to 6979 kg ha⁻¹ in 2012, and 6158 to 7953 kg ha⁻¹ in 2013 (Table 3-1). In 2011, the difference between the highest yielding cultivar and the third highest (6356 kg ha⁻¹) was not statistically significant ($\alpha = 0.05$). In 2012, the top two cultivars had nearly identical yields, whereas the bottom two also had nearly identical yields, but at a much lower yield level. The highest cultivar yield was observed in 2013 at 7953 kg ha⁻¹, however, greater yield variability was also observed in 2013. In 2013, only the lowest cultivar yield (6158 kg ha⁻¹) was significantly different from the greatest ($\alpha = 0.05$). Harvest index values ranged from 38.1 to 48.8%, with a mean of 43.9% over cultivars and years.

Across both the 2011 and 2012 growing seasons, the average temperatures for the months of June, July and August were 3.8, 5.8, and 2.8°C above the 30-yr mean, respectively (Table 3-2). However, 2013 was markedly cooler than the prior two seasons, and the mean maximum temperature never exceeded $\pm 1.8^\circ\text{C}$ from the 30-yr mean. Mean minimum temperatures were greater in 2011 than in 2012 and 2013 and were $\geq 3.1^\circ\text{C}$ above the 30-yr mean throughout June and July. The mean daily solar radiation levels were near normal with the exception of May

2011, August 2012, and May and August 2013 being $\geq 2.7 \text{ MJ m}^{-2} \text{ d}^{-1}$ below the 30-yr mean. Although rainfall was below normal for periods in all 3 years, frequent and timely irrigation eliminated drought as a confounding effect.

In 2011, biomass accumulation rates were measured between two sample dates when the FRI for the first date was *ca.* 0.50 and was >0.92 for the second date. Under these conditions, biomass accumulation rates among cultivars ranged from 13.6 to 18.2 $\text{g m}^{-2} \text{ d}^{-1}$ (Table 3-1). In 2012 and 2013, biomass accumulation rates were measured between two sample dates when FRI was >0.93 and >0.95 , respectively. Biomass accumulation rates among cultivars ranged from 19.5 to 30.4 $\text{g m}^{-2} \text{ d}^{-1}$ (2012) and from 45.6 to 64.3 $\text{g m}^{-2} \text{ d}^{-1}$ (2013). With the same sampling dates, nitrogen accumulation rates among cultivars ranged from 0.47 to 0.58 $\text{g N m}^{-2} \text{ d}^{-1}$ (2011), 0.83 to 0.90 $\text{g N m}^{-2} \text{ d}^{-1}$ (2012) and 1.43 to 2.08 $\text{g N m}^{-2} \text{ d}^{-1}$ (2013).

Linear regression of the weekly FRI values versus the coincident accumulated GDDs from emergence provided a good fit with r^2 values ≥ 0.90 for all cultivars in all years (data not shown). Radiation use efficiency values were similar between 2011 and 2012 and ranged among cultivars from 0.84 to 1.15 g MJ^{-1} with an average value of 1.01 g MJ^{-1} . In 2013, RUE values among cultivars ranged from 1.46 to 1.89 g MJ^{-1} , with an average over cultivars of 1.77 g MJ^{-1} .

DISCUSSION

Mr. Cullers won the 2011 Missouri Soybean Association yield contest with a yield of 7317 kg ha^{-1} for the Pioneer cultivar P94Y80 (Missouri Soybean Association, 2011), which was managed under a separate irrigation system (drip tape) in the same field but not under the center pivot or within our sampling area. This reported yield was similar to our 2011 yield estimates for the two highest yielding cultivars. Mr. Cullers did not enter the 2012 yield contest due to “low

and inconsistent yields” over the required 1.62 ha harvest area. However, our 2012 1-m² yield estimates indicate that the two highest yielding cultivars were greater than the 6230 kg ha⁻¹ yield that did win (Missouri Soybean Association, 2012). In 2013, Mr. Cullers’ highest cultivar yields were *ca.* 7730 kg ha⁻¹ (Kip Cullers, personal communication, 2013), which were also similar to the best two cultivars from our yield estimates. The foregoing yields are substantively less than the yields of 9,400, 10,390 and 10,790 kg ha⁻¹ that Mr. Cullers submitted as 2006, 2007, and 2010 entries to the MO soybean yield contests.

The reasons for the lower contest yields reported here relative to previous years are not known. Weather conditions in 2011 and 2012 were abnormally warm and dry compared to the 30-yr mean. The mean maximum temperature in July for both years was 37°C, averaging 5.8°C greater than the 30-yr mean (Table 3-2). For comparison, monthly average maximum temperatures near Stark City MO in 2006, 2007 and 2010, were near normal over the growing season and were never >3.1°C of the 30-yr mean and with July maximum temperatures ranging no more than ±1.4°C from the 30-yr mean (data not shown). Gibson and Mullen (1996) demonstrated that increasing day temperatures from 30 to 35°C throughout reproductive growth (R1 to R8) decreased seed growth and photosynthetic rates and ultimately reduced seed yield plant⁻¹ by 27%. Additionally, raising the temperature 2 to 3°C over ambient decreased soybean grain yield from 16 to 40% (Tacarindua et al., 2013). Conversely, other studies have demonstrated photosynthetic rates remained stable over a range of temperatures from 26 to 36°C (Campbell et al., 1990; Jones et al., 1985) and that leaf area, aboveground biomass production, and yield were similar between 31/24 and 36/29°C temperature treatments despite a reduction in the HI with increasing temperatures (Baker et al., 1989).

In 2013, mean maximum temperatures were near normal and were never $>1.8^{\circ}\text{C}$ from the 30-yr mean (Table 3-2). However, due to cool April temperatures and frequent April and May rainfall, planting in 2013 did not occur until 27 May. This may have reduced the yield potential in 2013. De Bruin and Pedersen (2008) found in Iowa that planting in late April compared with early June decreased yield from 12 to 41%, with a mean yield reduction of 25%. The authors also suggested that yield decreases from delayed planting were greater in locations with high-yield potential compared with locations with lower-yield potential. Regardless of why yields of greater magnitude were not observed, the data presented here provide empirical measurements to describe the crop growth characteristics which resulted in yields of 5290 to 7953 kg ha^{-1} over three growing seasons.

Although, the 2011 biomass and N accumulation rates were not representative of the maximum rates attainable for the crop due to sampling dates prior to canopy closure. Biomass accumulation rates in 2012 were near or above the average of the maximum values that we could find reported for soybean in the literature (Supplement 3-1). In Supplement 3-1, we have listed the highest values of soybean biomass and N accumulation rates and RUE from the literature representing 31, 12, and 44 site years of data for these variables, respectively. These maximum rates of biomass accumulation ranged from 8.9 to 55 $\text{g m}^{-2} \text{d}^{-1}$ and averaged 19.8 $\text{g m}^{-2} \text{d}^{-1}$. The 2013 biomass accumulation rates were similar to the maximum rate of 55 $\text{g m}^{-2} \text{d}^{-1}$ previously reported in the literature (Isoda et al., 2010).

As expected, the high biomass accumulation rates observed in our research resulted in high N accumulation rates as well. The N accumulation rates in 2012 were 4 to 13% greater than the highest value reported for soybean in the literature, which ranged from 0.31 to 0.80 $\text{g N m}^{-2} \text{d}^{-1}$, with a mean of 0.45 $\text{g N m}^{-2} \text{d}^{-1}$ (Supplement 3-1). In 2013, the N accumulation rate averaged

over cultivars was $1.79 \text{ g N m}^{-2} \text{ d}^{-1}$ and was more than double that of the previously documented maximum N accumulation rate for soybean. Using a non-nodulating reference cultivar, the fraction of N derived from atmospheric N_2 was determined to range from 0 to 17%, depending on cultivar and sampling date, and averaged 7% over cultivars and sampling dates in 2011 and 2013 (data not shown).

The highest soybean biomass accumulation rates (35 to $55 \text{ g m}^{-2} \text{ d}^{-1}$) were reported by Isoda et al. (2010) and resulted in extremely high yields, up to 9200 kg ha^{-1} . Management by Isoda et al. (2010) also included perennial poultry litter applications ($15 \text{ Mg ha}^{-1} \text{ yr}^{-1}$) and high irrigation inputs similar to what we observed at Mr. Cullers' farm. Egli and Zhen-wen (1991) reported a soybean biomass accumulation rate of $27.0 \text{ g m}^{-2} \text{ d}^{-1}$ for measurements made in China, however, the biomass accumulation rate was accompanied by a relatively small amount of photosynthate being partitioned to seed growth, presumably resulting in a low HI. The reason for the low photosynthate partitioning to seed was not determined but may explain why soybean grain yield in that study ($\leq 3540 \text{ kg ha}^{-1}$) lagged behind the yields observed by Isoda et al. (2010) and in our research. Pal and Saxena (1976) also reported a large N accumulation rate ($0.80 \text{ g N m}^{-2} \text{ d}^{-1}$), but the highest yield reported was 3220 kg ha^{-1} and no indications were provided to explain why higher yields were not observed.

The high rate of N accumulation and high RUE that we found in 2013 did not appear to increase yields compared to 2011 and 2012. We speculate that the biomass and N accumulation rates and RUE values observed in 2013 during vegetative and early reproductive development were likely not maintained throughout reproductive development based upon yield and HI data. If an RUE of this magnitude could be sustained throughout seedfill, grain yields similar to those

reported by Isoda et al. (2010, 9200 kg ha⁻¹) and by Mr. Cullers in 2010 (10,790 kg ha⁻¹) may be possible.

The maximum soybean RUE values reported in the literature for a single treatment or cultivar in each site-yr that we reviewed ranged from 0.5 to 1.36 g MJ⁻¹, with a mean of 0.85 g MJ⁻¹ (Supplement 3-1). The RUE values recorded in this research in 2011 and 2012 were generally above the mean value of 0.85 g MJ⁻¹ (Table 3-1). In 2013, RUE values of all cultivars (1.46 to 1.89 g MJ⁻¹) were greater than the previously reported maximum soybean RUE. For comparison, Nakaseko and Gotoh (1983) reported a soybean RUE of 1.36 g MJ⁻¹, and Kumudini et al. (2008) reported a RUE of 1.26 g MJ⁻¹ from research in 2006-07.

Sinclair et al. (1992) postulated that RUE values would increase with decreasing mean daily radiation because leaf photosynthetic rates become less efficient as radiation levels approach the light saturation level (Monteith, 1977; Sinclair and Horie, 1989). For example, Manrique et al. (1991) documented the RUE for potato (*Solanum tuberosum* L.) decreased 0.15 g MJ⁻¹ for every MJ m⁻² d⁻¹ increase in total solar radiation from 12 to 26 MJ m⁻² d⁻¹. Indeed, a negative trend was found upon reviewing the values for RUE and solar radiation in the soybean literature (Supplement 3-1; Fig. 3-1). Each value cited in Supplement 3-1 was “cherry picked” as the highest value for a single treatment or cultivar within each site-yr of the research; thus, only the highest RUE value from one cultivar in each year of this research was included in Fig. 3-1. Linear regression indicated that RUE values decreased by 0.04 g MJ⁻¹ for every MJ m⁻² d⁻¹ increase in the mean daily solar radiation. The mean RUE value of the data in Fig. 3-1 was 0.80 g MJ⁻¹ at a mean solar radiation level of 19.6 MJ m⁻² d⁻¹. Despite having a relatively high average solar radiation levels during the RUE measurement period (24.3, 23.6 and 22.3 MJ m⁻² d⁻¹ in 2011, 2012 and 2013, respectively), RUE values in 2011 and 2012 were among the highest

values reported in the literature across all solar radiation levels. Averaged across cultivars, the RUE we found in 2013 was 30% greater than the highest RUE previously reported. Based upon the regression equation in Fig. 3-1 and the observed solar radiation, the predicted RUE values were 0.58 (2011), 0.61 (2012) and 0.66 (2013) g MJ^{-1} while the actual RUE values were 78, 90 and 186% greater than these predicted values.

The physiological characteristics presented here represent unique, empirical measurements of a crop grown within a maximum yield environment. Some of these measurements represent new upper limits compared with previous reports in the literature. In the Sinclair soybean model (Sinclair, 1986; Sinclair et al., 2003), N accumulation during vegetative growth is based on the N demand of the expanding leaf area and stem mass, and the maximum N accumulation rate is nominally limited at $0.6 \text{ g N m}^{-2} \text{ d}^{-1}$. While this value of N accumulation is above the mean of maximum values previously reported for soybean (Supplement 3-1), it is about 30% of the maximum N accumulation rate found in our research ($2.08 \text{ g N m}^{-2} \text{ d}^{-1}$). Additionally, the nominal maximal RUE value (1.2 g MJ^{-1}) in the model was 63% of the maximal RUE value found in our research (1.89 g MJ^{-1}). High RUE values are predicted to only be maintained as long as leaf N levels remain high, which depends on high rates of N accumulation. In the Sinclair soybean model, large daily increases in modeled biomass production may result in a dilution of leaf N resulting in decreased RUE if the maximum N accumulation rate is also underestimated. This is one example of how modeling efforts may need to be re-examined or adjusted when predicting soybean yield in maximum yield environments with abundant soil N.

CONCLUSIONS

The physiological characteristics observed in this research provide empirical data describing a soybean crop with *ca.* 6719 kg ha⁻¹ (i.e., 100 bushel acre⁻¹) yield potential. The biomass and N accumulation rates and RUE values observed in 2013 were greater than previously reported values for soybean. These measurements infer how sufficient biomass was produced to support these yields at the observed HI values. While the data collected in this research cannot be used to definitively infer about yields greater than the observed yield range, it does offer physiological insight into the N accumulation rate and RUE necessary for the production and modeling of soybean yields up to 7953 kg ha⁻¹.

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Table 3-1. Biomass and N accumulation rates, radiation use efficiency (RUE), grain yield, and harvest index (HI) means and standard errors (SE) by year and cultivar from Mr. Cullers' contest field.

Year	Cultivar	Accumulation rate				RUE		Yield		HI	
		Biomass		N		Mean	SE	Mean	SE	Mean	SE
		Mean	SE	Mean	SE						
		g m ⁻² d ⁻¹		g m ⁻² d ⁻¹		g MJ ⁻¹		kg ha ⁻¹		%	
2011†	P94Y81	16.3 AB‡	± 0.9	0.58 A	± 0.05	0.90 A	± 0.03	7137 A	± 291	43.0 B	± 0.6
	P94Y82	15.5 AB	± 1.4	0.52 A	± 0.07	0.96 A	± 0.09	7118 A	± 292	48.8 A	± 0.7
	P94Y91	18.2 A	± 1.1	0.55 A	± 0.03	0.97 A	± 0.06	6117 B	± 200	44.0 B	± 0.8
	P94Y92	13.6 B	± 0.4	0.47 A	± 0.03	0.93 A	± 0.03	5290 C	± 211	41.8 B	± 0.3
	P95Y10	16.8 AB	± 2.0	0.58 A	± 0.05	1.03 A	± 0.11	6356 AB	± 298	43.3 B	± 0.8
2012§	P94Y23	30.4 A	± 1.4	0.90 A	± 0.12	1.15 A	± 0.01	6979 A	± 193	48.2 A	± 1.2
	P94Y80	25.6 AB	± 4.2	0.87 A	± 0.12	1.02 AB	± 0.10	6925 A	± 56	46.1 AB	± 0.4
	P94Y81	19.5 B	± 1.1	0.83 A	± 0.04	0.84 B	± 0.02	5555 B	± 61	41.6 B	± 0.5
	P94Y82	25.7 AB	± 3.2	0.88 A	± 0.10	1.01 AB	± 0.07	5521 B	± 119	45.5 AB	± 1.8
2013¶	P94B73	60.6 AB	± 2.5	1.88 AB	± 0.17	1.89 A	± 0.06	7084 AB	± 489	41.4 B	± 1.1
	P48T53	45.6 C	± 2.2	1.43 B	± 0.07	1.46 B	± 0.06	6158 B	± 175	38.1 B	± 2.6
	P49T97	64.3 A	± 1.8	2.08 A	± 0.06	1.89 A	± 0.04	7953 AB	± 731	42.1 B	± 1.0
	P50T40	60.6 AB	± 3.3	2.07 A	± 0.06	1.80 A	± 0.08	6883 AB	± 348	44.9 AB	± 0.3
	AG5332	56.2 B	± 1.0	1.51 B	± 0.17	1.83 A	± 0.04	7482 A	± 381	46.2 A	± 0.8

† RUE determined from three sample dates with corresponding canopy radiation interception of *ca.* 0.10, 0.50 and >0.92 and growth stages V1, V6 and R1. Biomass and N accumulation rates determined from last two sampling dates.

‡ Different letters within a column and year denote that means differed ($\alpha=0.05$) as determined by a two-tailed t-test.

§ RUE determined from three sample dates with corresponding canopy radiation interception of *ca.* 0.50, >0.93 and >0.93 and growth stages V6, R1 and R2. Biomass and N accumulation rates determined from last two sampling dates.

¶ RUE determined from three sample dates with corresponding canopy radiation interception of *ca.* 0.65, >0.95 and >0.95 and growth stages V7, R2 and R3. Biomass and N accumulation rates determined from last two sampling dates.

Table 3-2. Mean monthly high temperature (Tmax), low temperature (Tmin), solar radiation (Rs), from Mr. Cullers' farm and monthly total rainfall (NCDC-NOAA, 2013a) in 2011, 2012 and 2013. Departures from the 30-yr mean (1981-2010; NCDC-NOAA, 2013b) are in parentheses.

Year	Month	Tmax ———— °C —————	Tmin	Rs† MJ m ⁻² d ⁻¹	Rainfall‡ mm
2011	April	21.8 (+1.6)	9.2 (+2.5)	19.6 (-1.5)	162 (+44)
	May	23.3 (-1.1)	12.7 (+0.5)	18.6 (-3.8)	26 (-126)
	June	32.3 (+3.7)	20.6 (+3.7)	24.4 (+1.5)	27 (-114)
	July	36.5 (+5.3)	22.5 (+3.1)	23.7 (+0.8)	38 (-55)
	August	34.6 (+3.0)	20.7 (+2.1)	20.0 (-1.6)	126 (+42)
	September	26.0 (-1.0)	11.6 (-1.9)	16.5 (-2.0)	124 (-6)
2012	April	22.8 (+2.6)	10.9 (+4.2)	19.0 (-2.1)	159 (+41)
	May	28.8 (+4.4)	14.3 (+2.1)	21.7 (-0.7)	105 (-47)
	June	32.4 (+3.8)	17.0 (+0.1)	23.2 (+0.3)	32 (-109)
	July	37.5 (+6.3)	20.5 (+1.1)	22.5 (0.0)	0 (-93)
	August	34.2 (+2.6)	17.4 (-1.2)	18.8 (-2.8)	80 (-4)
	September	27.6 (+0.6)	15.4 (+1.9)	16.2 (-2.3)	183 (+53)
2013	April	18.5 (-1.7)	6.7 (0.0)	19.6 (-1.5)	169 (+51)
	May	23.4 (-1.0)	12.2 (0.0)	19.7 (-2.7)	200 (+48)
	June	29.3 (+0.7)	18.4 (+1.5)	22.2 (-0.7)	137 (-4)
	July	30.8 (-0.4)	18.3 (-1.1)	20.5 (-2.0)	84 (-9)
	August	30.4 (-1.2)	18.2 (-0.4)	18.5 (-3.1)	117 (+33)
	September	28.8 (+1.8)	14.9 (+1.4)	17.2 (-1.3)	35 (-95)

† Solar radiation 30-yr means calculated with 30-yr mean high and low temperatures using a modified Hargreaves and Samani (1982) equation, described by Ball et al. (2004).

‡ Irrigation was applied frequently in an attempt to eliminate all water deficit stress; however total inputs were unavailable from the producer.

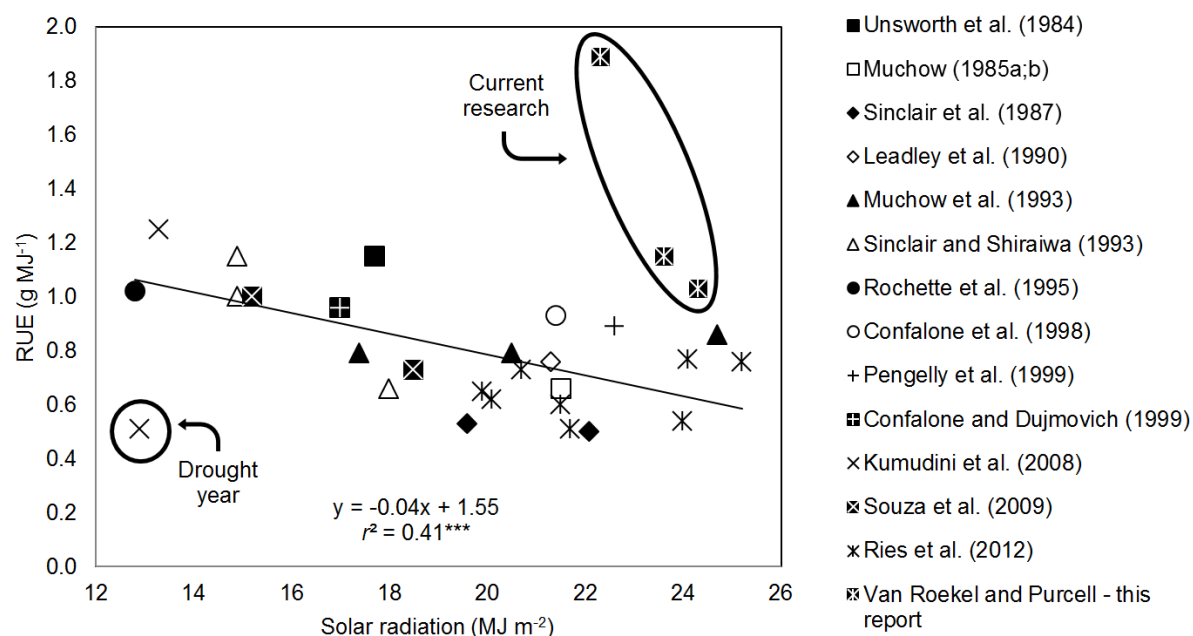


Figure 3-1. Maximum reported radiation use efficiency (RUE) within each site-yr versus mean daily solar radiation during the time of sampling from available literature sources as well as measurements from the current research in 2011, 2012 and 2013. The circled values, from the current research, were not included in the regression nor were the 2005-06 data from Kumudini et al. (2008) due to drought conditions.

Supplement 3-1. Summary of the maximum reported values in the literature from a single treatment or cultivar within each site-yr for the rate of biomass and N accumulation of soybean, radiation use efficiency (RUE), and mean daily solar radiation (Rs) by source, location and year of research.

Source	Location	Year	Accumulation rate		RUE [†] g MJ ⁻¹	Rs MJ m ⁻² d ⁻¹
			Biomass g m ⁻² d ⁻¹	N		
Shibles and Weber (1965)	Ames IA, USA	1962‡	13.0	-	-	-
Shibles and Weber (1966)	Ames IA, USA	1961§	-	-	0.72	-
		1962¶	-	-	0.63	-
Pal and Saxena (1976)	Rampura, India	1972‡	-	0.80	-	-
Nakaseko and Gotoh (1983)	Sapporo, Japan	1972-73§	29.6	-	1.36	-
Unsworth et al. (1984)	Raleigh NC, USA	1982‡	-	-	1.15#	17.7
Muchow (1985a;b)	Kununurra, Australia	1980‡	-	-	0.66	21.5
Sinclair et al. (1987)	Gainesville FL, USA	1985‡	12.3	0.31	0.51††	19.6
		1986‡	-	0.37	0.50	22.1
Leadley et al. (1990)	Raleigh NC, USA	1983¶	-	-	0.80	21.3
Egli and Zhen-wen (1991)	Lexington KY, USA	1987-89‡	17.2	-	-	-
	Taian, China	1987‡	27.0	-	-	-
Sall and Sinclair (1991)	Gainesville FL, USA	1987¶	-	0.42	-	-
Egli (1993)	Lexington KY, USA	1989‡	17.0	-	0.84	-
		1990‡	-	-	0.66	-
Muchow et al. (1993a)	Katherine, Australia	1988§	-	-	0.86	24.7
		1989§	-	-	0.79	20.5
		1990§	-	-	0.79	17.4
Muchow et al. (1993b)	Katherine, Australia	1989§	7.9	0.39	-	-
	Lawes, Australia	1990§	11.0	0.34	-	-
Sinclair and Shiraiwa (1993)	Gainesville FL, USA	1987§	-	-	0.66	18.0
	Azuchi, Japan	1989§	-	-	1.00	14.9
		1991§	-	-	1.15	14.9
Shiraiwa and Hashikawa (1993)	Azuchi, Japan	1989§	-	-	1.21	-
	Kusatsu, Japan	1990§	-	-	1.25	-

Board and Harville (1993)	Baton Rouge LA, USA	1989‡	15.0	-	-	-
		1990‡	18.3	-	-	-
Board et al. (1994)	Baton Rouge LA, USA	1989§	18.0	-	-	-
		1990‡	19.2	-	-	-
		1989-90¶	-	-	0.87	-
Jiang and Egli (1995)	Lexington KY, USA	1991§	14.5‡‡	-	-	-
		1992§	14.7‡‡	-	-	-
Rochette et al. (1995)	Ottawa, Canada	1992‡	-	-	1.02††	12.8
Purcell and King (1996)	Fayetteville AR, USA	1994§	14.8	0.46	-	-
Serraj and Sinclair (1997)	Gainesville FL, USA	1995‡	14.3	0.47	-	-
Confalone et al. (1998)	Viçosa, Brazil	1995-96‡	-	-	0.93	21.4
Pengelly et al. (1999)	Gatton, Australia	1990-91§	-	-	0.89	22.6
Yusuf et al. (1999)	Champaign IL, USA	1993-94‡	18.0	-	-	-
Confalone and Dujmovich (1999)	Azul, Argentina	1997-98‡	-	-	0.96	17.0
		1996‡	-	-	0.90	-
Egli and Bruening (2000)	Lexington KY, USA	1997‡	-	-	0.95	-
		1998‡	-	-	1.00	-
		1996-98‡	19.3	-	-	-
		1998-99‡	-	-	1.05	-
Schöffel and Volpe (2001)	Jaboticabal, Brazil	1998-99‡	-	-	1.05	-
Purcell et al. (2002)	Keiser AR, USA	1997§	-	-	0.73	-
		1998§	-	-	0.67	-
Santos et al. (2003)	de Viçosa, Brazil	2000-01§	-	-	1.26	-
Pedersen and Lauer (2004)	Arlington WI, USA	1998-99‡	13.0	-	-	-
Purcell et al. (2004)	Gainesville FL, USA	1996‡	-	0.52	-	-
Kumudini et al. (2008)	Londrina, Brazil	2005-06¶	-	-	0.51‡‡	12.9
		2006-07¶	-	-	1.25	13.3
Souza et al. (2009)	Paragominas, Brazil	2007§	-	-	0.73	18.5
		2008§	-	-	1.00	15.2
De Bruin and Pedersen (2009)	De Witt IA, USA	2005-06§	14.0	-	-	-
	Nevada IA, USA	2005-06§	12.9	-	-	-
	Whiting IA, USA	2005-06§	18.0	-	-	-

Salvagiotti et al. (2009)	Lincoln NE, USA	2006‡	24.1	-	-	-
		2007‡	17.3	-	-	-
		2006-07¶	-	0.40	-	-
Isoda et al. (2010)	Shihezi, China	2002¶	40	-	-	-
		2003¶	55	-	-	-
		2004¶	50	-	-	-
		2005‡	35	-	-	-
Caviglia et al. (2011)	Balcarce, Argentina	2000-01§	-	-	0.69	-
		2001-02§	-	-	1.17	-
		2000-02‡	13.0	-	-	-
Ries et al. (2012)	Fayetteville AR, USA	2004‡	-	-	0.65	19.9
		2005‡	-	-	0.77	24.1
		2006‡	-	-	0.54	24.0
		2007‡	-	-	0.62	20.1
	Clayton NC, USA	2008‡	-	-	0.73	20.7
		2005‡	-	-	0.51	21.7
		2006‡	-	-	0.60	21.5
		Stuttgart AR, USA	2006‡	-	-	0.76	25.2
Mastrodomenico and Purcell (2012)	Fayetteville AR, USA	2008§	8.9	0.43	-	-
		2009§	11.6	0.51	-	-

† Radiation use efficiency based on total incident solar radiation.

‡ Values determined from samples taken during vegetative and reproductive growth stages prior to seedfill (VE to R5).

§ Values determined from samples taken throughout the growing season (VE to R7).

¶ Values determined from samples taken during the seedfilling growth stages (R5 to R7).

Value cited from only samples taken under ambient air conditions.

†† Values cited from only those determined with aboveground biomass samples.

‡‡ Values cited from only those determined with the control treatments.

CHAPTER 4

Seed Growth and Leaf Nutrient Dynamics of Soybean in a Maximum Yield Environment

ABSTRACT

A soybean [*Glycine max* (L.) Merr.] grain yield of 10,791 kg ha⁻¹ was reported in the 2010 MO Soybean Association Yield Contest. This yield was greater than previous reports, but there were no empirical measurements to support yields of this magnitude. From 2011 to 2013, we characterized the dry matter allocation coefficient (DMAC) as a measure of the seedfilling rate, seedfill period (SFP), grain yield components and constituents, and leaf N dynamics from the contest field where this yield was reported. Grain yields ranged from 5290 to 7953 kg ha⁻¹. The DMAC and SFP averaged 0.0104 and 43.6 d and were slower and longer, respectively, than values typically reported in the literature. This coupled with prolonged retention of leaf N and prior reports of increased crop growth characteristics provide insight into the growth parameters contributing to these elevated yield levels.

INTRODUCTION

The highest average United States soybean yield is 2956 kg ha⁻¹, which occurred in 2009 (USDA-NASS, 2013). The highest soybean yield reported from yield contests is 10,791 kg ha⁻¹, which occurred in 2010 (Cubbage, 2010). This yield by Mr. Kip Cullers of Southwest MO is much higher than other contest entries of 7350 kg ha⁻¹ from MO in 2007 (Steever, 2008) and 6751 kg ha⁻¹ from MI in 2012 (Reinholt, 2012). Furthermore, the theoretical maximum yield potential of soybean was thought to range from 5100 to 8290 kg ha⁻¹ (Muchow and Sinclair, 1986; Spaeth et al., 1987; Specht et al., 1999; Sinclair, 2004; Bhatia et al., 2008). Thus, the reported yields by Mr. Cullers have generated much interest and some skepticism. One source for concern is the lack of empirical data associated with yields of this magnitude.

Since grain yield is the product of seed number and seed weight, growth characteristics effecting the determination of both of these yield components must be examined. Egli and Zhen-wen (1991) validated the concepts of Charles-Edwards et al. (1986) where the determination of seed number is related to the amount of photosynthate partitioned to seeds over the minimum amount of photosynthate needed to keep the seed from aborting. Egli and Zhen-wen used the biomass accumulation rate (BAR) from R1 to R5 as a proxy for net photosynthesis and the individual seed growth rate (ISGR) as a proxy for the amount of assimilate required to prevent abortion. An alternate measure of BAR is the radiation use efficiency (RUE), which is the measure of crop growth over the intercepted solar radiation for a given period of time. Additionally, the slope of the linear increase in harvest index (HI) during seedfill is defined as the dry matter allocation coefficient (DMAC) (Salado-Navarro et al., 1985a) and is a measure of ISGR on a whole plant basis (Spaeth and Sinclair, 1985). This concept and proxies provide an

effective theory for seed number determination in soybean (e.g. Ball et al., 2000; Egli and Zhenwen, 1991; Jiang and Egli, 1995; Matthew et al., 2000).

Large amounts of N are required for protein production to sustain high rates of photosynthesis and crop growth and thus, the N accumulation rate usually correlated with the BAR (Sinclair, 2004). Nitrogen accumulation and remobilization are also important during seedfill to meet the N requirements of high protein soybean seed development (Sinclair and de Wit, 1975) and the pool of N in the vegetative tissues is depleted throughout seed growth (Borst and Thatcher, 1931; Hanway and Weber, 1971b; Boote et al., 1978; Egli et al., 1978a). In the previous chapter, we discussed some of the crop growth parameters measured in Mr. Cullers' field during the vegetative and early reproductive stages. In this chapter, we will discuss several of these other parameters and grain yield components that were measured in the later portions of reproductive development.

MATERIALS & METHODS

Measurements were taken from the same cultivars, fields and plot locations as described in Ch. 3. Beginning at the R3 growth stage and continuing on *ca.* 14-d intervals through R7, leaf samples of one of uppermost mature trifoliolates fully exposed to sunlight were taken from three plants at each of the four plots of each cultivar. Leaf samples were dried, ground to pass a 0.853-mm sieve, and analyzed for N concentration with a Leco FP-428 Determinator (Leco Corp., St. Joseph, MO) via the Dumas method. Leaf samples were also ground to pass a 1-mm sieve and were also analyzed for P, K, Ca, Mg, S, Na, Fe, Mn, Zn, Cu, and B concentrations by inductively coupled plasma emission spectroscopy (model D, Spectro Analytical, Fitchburg, MA). Both analyses were measured following wet digestion (Jones and Case, 1990) at the Soil Testing and

Plant Analysis Laboratory at the University of Arkansas. Leaf samples from 10 July 2012 and 15 Aug. 2013, at beginning R5, were measured for leaf area with a LI-3100 area meter (LI-COR, Lincoln, NE), dried, weighed, and analyzed for nutrient concentration to determine the specific leaf weight (SLW, g m^{-2} of leaf area) and specific leaf N (SLN, g N m^{-2} leaf area).

At mid-R5 and again after 14 d, the aboveground portion of 5-8 plants within two adjacent twin-rows of each plot were collected to determine the immature harvest index (HI). In 2011, immature HI samples were collected from one twin-row pair on 25 Aug. (101 days after emergence [DAE]) and a second set was collected on 9 Sept. (116 DAE). In 2012, sample sets were collected on 30 July (97 DAE) and 14 Aug. (112 DAE). In 2013, sample sets were collected on 26 Aug. (88 DAE) and 5 Sept. (98 DAE). The pods were separated from the stems, both the biomass and pods were dried, and the biomass and pods with seed were each weighed. The seeds were removed from the pods, and dry seeds were weighed. The immature HI was calculated as the seed mass divided by the total aboveground biomass, disregarding fallen leaves and petioles.

After the latest maturing cultivar reached the R8 growth stage, 1-m^2 samples were collected from all plots to determine final grain yield and apparent HI. Whole plant samples were dried, weighed, threshed, and the grain was weighed, and sampled for moisture with a Harvest Hand moisture tester (DICKEY-john Corp., Auburn, IL). Grain yield was adjusted to 130 g kg^{-1} moisture. One hundred seed weights were measured and used to estimate seeds m^{-2} by dividing the grain yield sample by individual seed weight. For each plot, the rate of increase in HI between the first two HI measurement dates was defined as the dry matter allocation coefficient (DMAC) (Salado-Navarro et al., 1985a). The seedfill period (SFP) was also calculated for each plot by dividing the final HI by DMAC (Salado-Navarro et al., 1985b). Protein and oil

concentrations were estimated using near-infrared spectroscopy with an Infratec 1241 grain analyser (FOSS, Hillerod, Denmark) and adjusted to 130 g kg⁻¹ moisture.

Data means and standard errors (SE) were calculated with the MEANS procedure of SAS (SAS Institute, Cary, NC), and means were separated with a two-tailed t-test. Individual plot leaf N concentrations were regressed over days before and after beginning R5 growth stage with cultivar as a covariate. Linear and quadratic models with interaction effects were analyzed using the GLM procedure of SAS. Higher order, nonsignificant terms ($\alpha = 0.05$) were removed and the model was reanalyzed until all remaining effects and interactions were significant. Pearson correlation coefficients between variables of interest were determined using the CORR procedure of SAS.

RESULTS & DISCUSSION

Grain Yield

From 2011 to 2013, soybean cultivar grain yields and apparent HI values ranged from 5290 to 7953 kg ha⁻¹ and 38.1 to 48.8%, respectively (Table 3-1). As discussed in Ch. 3, grain yields were lower from 2011 to 2013 than had previously been reported in 2010. Adverse weather conditions in these years may have contributed to lower yields; 2011 and 2012 were noted in Ch. 3 for high temperatures and 2013 for a wet and cool spring delaying planting. Although yields were not >10,000 kg ha⁻¹ as was reported in 2007 and 2010, the seed growth and leaf nutrient dynamics presented here provide empirical measurements pertaining to soybean grain yields ranging from 5290 to 7953 kg ha⁻¹.

Seed Growth Characteristics

Among cultivars, DMAC values ranged from 0.0088 to 0.0111 (2011), 0.0086 to 0.0121 (2012), and 0.0089 to 0.0132 (2013; Table 4-1). The DMAC values averaged slightly lower in 2011 (0.0104) and 2012 (0.0096) compared with 2013 (0.0111). Across four locations in the United States, Salado-Navarro et al. (1993) found a range of cultivar DMAC values from 0.0122 to 0.0156, with a mean of 0.0139. This was higher than the mean of 0.0132 across three tests with different genetic populations presented by Salado-Navarro et al. (1986b). A lower DMAC results in a longer SFP (Salado-Navarro et al., 1986a;b). This occurs because the SFP is calculated as the final HI over the DMAC. Conceptually, a lower DMAC results in a lower daily seed demand for C and N, which can delay the onset of self-destruction via C and N remobilization from the vegetative tissues to the seeds (Sinclair and de Wit, 1975; 1976; Salado-Navarro et al., 1986b).

From the DMAC values and the final HI, SFP among cultivars ranged from 38.9 to 63.0 d (2011), 38.2 to 56.7 d (2012), and 28.8 to 45.8 d (2013; Table 4-1). The mean among cultivars and years in this report was 43.6 d, and the SFP was longer in 2011 (46.6 d) and 2012 (48.8 d) compared with 2013 (36.4 d). For comparison, Salado-Navarro et al. (1993) reported a range of SFP from 33.0 to 44.2 d, with a mean of 38.4 d. Kumudini et al. (2001) reported a range of SFP from 33.8 to 37.2 d, with a mean of 36.0 d, for both new and old cultivars. We suggest that the late planting date in 2013 may have increased the DMAC and reduced the SFP due to shortening photoperiods (Thomas and Raper, 1976; Gbikpi and Crookston, 1981).

Seed Weight and Number

Among cultivars, individual seed weights ranged from 138 to 162 mg seed⁻¹ in 2011, 154 to 163 mg seed⁻¹ in 2012, and 147 to 188 mg seed⁻¹ in 2013 (Table 4-1). In an analysis of 18 public soybean cultivars with maturity groups (MG) from V to VIII, cultivar seed weights ranged from 109 to 146 mg seed⁻¹ (Kahlon et al., 2011). De Bruin and Pedersen (2009) found both old, public-university cultivar and new, private-company cultivar seed weights to range from 134 to 147 mg seed⁻¹. Final seed weight is the product of the individual seed growth rate (ISGR) and the SFP (Eq. [4], Ch. 2). Both of these characteristics are genetically controlled and much diversity exists within the gene pool (Egli et al., 1981; 1984; Guldan and Brun, 1985). Differences in cultivar seed weights have been attributed to differences in ISGR (Egli et al., 1978b; 1981; Guldan and Brun, 1985), SFP (Hanway and Weber, 1971a; Gay et al., 1980) or a combination of the two (Swank et al., 1987).

The majority of the cultivar seed weights in this report were greater than the ranges described by De Bruin and Pedersen (2009) and Kahlon et al. (2011). However, the observed seed weights tended to fall within the range of expected seed weights for these cultivars (DuPont Pioneer, 2014). Regardless, Hartwig and Edwards (1970) determined that seed weight was not an important yield contributing component because yields were similar between small- and large-seeded genotypes due to compensatory changes in seed number. Others have suggested the lengthening the SFP is one avenue to increase seed weight and grain yield without the obligatory decrease in seed number (Smith and Nelson, 1987; Swank et al., 1987). Indeed, a portion of the elevated yield of modern cultivars has been attributed to a lengthened SFP and leaf area duration (Shiraiwa and Hashikawa, 1995; Kumudini et al., 2001; De Bruin and Pedersen, 2009). As

previously discussed, the SFP measured from Mr. Cullers' contest field were longer than in reports by Salado-Navarro et al. (1993) and Kumudini et al. (2001).

Compared with seed weight, seed number is a more important component for determining grain yield (Shibles et al., 1975; Kokubun and Watanabe, 1983; Board, 1987; Singer et al., 2004; De Bruin and Pedersen, 2008; Robinson et al., 2009). Seeds m^{-2} among cultivars ranged from 3286 to 4257 seeds m^{-2} in 2011, 2961 to 3963 seeds m^{-2} in 2012, and 3343 to 4208 seeds m^{-2} in 2013 (Table 4-1). For comparison, the range in seeds m^{-2} reported by Kahlon et al. (2011) and De Bruin and Pedersen (2009) was 1281 to 2948 and 1661 to 2829, respectively; and yields ranged from 1909 to 3978 $kg\ ha^{-1}$ and 2666 to 4384 $kg\ ha^{-1}$, respectively. Grain yields were higher in our research (5521 to 7953 $kg\ ha^{-1}$; Table 3-1) compared with Kahlon et al. (2011) and De Bruin and Pedersen (2009) and were the result of both greater seed number and greater seed weight.

Grain Protein and Oil

Protein concentration among cultivars averaged 36.5% in 2011, 37.9% in 2012, and was 37.3% in 2013 (Table 4-2). Oil concentration among cultivars averaged 21.6% in 2011, 22.3% in 2012, and slightly lower in 2013 at 20.6%. The lower concentration of oil in 2013 was likely due to cooler temperatures in August of 2013, as oil concentration decreases with decreasing temperatures (Bastidas et al., 2008; Kane et al., 1997; Robinson et al., 2009).

Only P94Y81 and P94Y82 were included in more than one year of research. Averaged over 2011 and 2012, protein and oil concentrations averaged 37.5 and 21.4% for P94Y81 and 38.3 and 22.8% for P94Y82, respectively. For both of these cultivars and all other cultivars from single years of research, the observed concentrations were greater than normally expected for

these cultivars (DuPont Pioneer, 2014). Furthermore, protein and oil concentrations were also greater in this research than the United States average protein and oil concentrations, which were 34.9 and 18.1% in 2011 (Naeve et al., 2011), 34.3 and 18.5% in 2012 (Naeve et al., 2013a) and 34.7 and 19.0% in 2013 (Naeve et al., 2013b).

Higher protein concentrations are often associated with decreased yield (Brim and Burton, 1979, Hartwig and Hinson, 1972; Helms and Orf, 1998). Indeed, two analyses document a decrease in seed protein for cultivars over time (Voldeng et al., 1997; Wilcox et al., 1979). The C and N cost of oil and protein synthesis is greater than for carbohydrate synthesis (Penning de Vries et al., 1974) and is often thought to limit soybean yields (Sinclair and de Wit, 1975). However, it appears the soybeans in Mr. Cullers' contests field maintained and even increased protein and oil concentrations compared with national averages. The elevated protein levels may have been the result of an apparent abundance of available N (Gascho, 1991) or increased N acquisition during seedfill (Egli and Bruening, 2007). Since moisture deficit stress can decrease oil concentration (Dornbos and Mullen, 1992; Foroud et al., 1993), perhaps the high irrigation inputs at this location would have contributed to the higher than normal oil concentrations observed.

Leaf N Dynamics

Leaf N concentration among cultivars and years was maximal at 5.5 to 6.0% prior to R5 and decreased throughout the SFP (Fig. 4-1). This was greater than the 4.2% leaf N observed at early podfill by Egli et al. (1978a). Parker and Harris (1977) found that leaf N concentration showed a positive response to N fertilizer with maximum observed leaf N concentrations of 5.6% with 201 kg N ha⁻¹ applied. Thus, the high leaf N concentrations observed in Mr. Cullers'

soybeans provide another indication as to the large abundance of soil N in these growing conditions. The decrease of leaf N during the SFP exhibited a quadratic response in 2011 and 2012; however, cultivars in 2012 had statistically similar intercepts (Fig. 4-1). In 2013, the reduction in leaf N was described by a simple linear function in which all cultivars had similar slopes. Additional leaf nutrient concentration responses to day of year are provided in Appendix 4-1.

At physiological maturity, approximately 50% of the leaves present at R5 remained attached to the plants. The leaf N concentration of those attached green leaves at R7 ranged from 2.5 to 3%. This had also been reported by Egli et al. (1978a) and Hanway and Weber (1971b), where similar leaf N concentrations at R7 were observed when N stress was not a factor. However, yields were greater in this report (5520 to 7953 kg ha⁻¹; Table 3-1) compared with Egli et al. (1978a; 4300 to 5000 kg ha⁻¹).

Specific leaf weight at the beginning of seedfill (R5) averaged 57.4 g m⁻² leaf area in 2012 and 70.3 g m⁻² leaf area in 2013 (Table 4-3). The SLW is a heritable trait for soybean with ranges at R5 being as great as 48.8 to 85.8 g m⁻² leaf area (Lugg and Sinclair, 1979). As such, the SLW values measured in Mr. Cullers' field are not outside the range of previously reported values. Yet, SLW may represent an indirect measurement of leaf apparent photosynthesis (Buttery et al., 1981; Dornhoff and Shibles, 1970; Wiebold et al., 1981), which can sometimes be correlated with yield (Buttery et al., 1981; Ford et al., 1983). Indeed, SLW and SLN both had significant positive correlations ($r=0.41^*$ and $r=0.37^*$, respectively) with yield (Table 4-4).

Specific leaf N at the beginning of seedfill (R5) averaged 2.92 g N m⁻² leaf area in 2012 and 3.47 g N m⁻² leaf area in 2013 (Table 4-3). For comparison, Shiraiwa and Sinclair (1993) found the range of SLN in leaves at the top of canopy at R5 to range from 1.6 to 2.4 g N m⁻² leaf

area. Positive correlations between radiation use efficiency (RUE, g MJ^{-1}) and SLN have been established (Sinclair and Horie, 1989; Sinclair and Shiraiwa, 1993). As such, Shibles and Sundberg (1998) were also able to find positive correlations between SLN and yield. The SLN values observed in this work were greater than in those previous reports and the 2013 measurements were outside of the predicted range by Sinclair and Horie (1989). In combination, the high SLN and RUE values observed in this work (Table 4-3) substantiate the yield levels observed in Mr. Cullers' fields from 2011 to 2013.

Correlations and Interactions

Charles-Edwards et al. (1986) proposed that the determination of seeds m^{-2} was related to the amount of daily net photosynthesis partitioned to seeds over the minimum amount of assimilate required to keep each seed from aborting (Ch. 1, Eq. [2]). Egli and Zhen-wen (1991) used the biomass accumulation rate (BAR) from R1 to R5 as a proxy for canopy net photosynthesis and the ISGR as a proxy for the amount of assimilate required to prevent abortion. This concept is consistent with seed number in soybean under different conditions (e.g., Ball et al., 2000; Egli and Zhen-wen, 1991; Jiang and Egli, 1995; Matthew et al., 2000). However, seed number was not significantly correlated ($r=0.24$ and $r=0.04$, respectively) with either BAR or radiation use efficiency (RUE) values from Ch. 3 (Table 4-4). One possible reason for this nonsignificant relationship is that the growth measurements were taken earlier in the season and not during seed set (R1 to R5).

Based on the model of Charles-Edwards et al. (1986), increases in seed number could also come from reductions in the minimum amount of assimilate required to prevent seed abortion. While Egli and Zhen-wen (1991) used the ISGR, the DMAC measurements represent seed growth on a whole plant basis. Thus, we suggest that a lower DMAC would translate into

slower seed growth rates and reduce the amount of assimilate required per seed on a daily basis. Indeed, greater seed numbers were more often observed with lower DMAC values (e.g., P94Y82 in 2011; P94Y23 and P94Y80 in 2012) but there were exceptions (e.g., P94Y81 in 2012; AG5332 in 2013). Correlation analysis did not reveal a significant correlation ($r=-0.09$) between DMAC and seeds m^{-2} (Table 4-4). Additional correlation analysis results are provided in Appendix 4-2.

Grain yields were also not significantly correlated ($r=0.24$ and $r=-0.06$, respectively) with either the DMAC or SFP (Table 4-4). For example, the highest grain yields were found with P49T97 in 2013 (Table 3-1), which also had the greatest DMAC and shortest SFP (Table 4-1). Even so, we suggest that the elevated yields observed in Mr. Cullers' field can be partially attributed to a lower than average DMAC and a greater than average SFP compared with previously reports in the literature.

Sinclair and de Wit (1975; 1976) and Salado-Navarro et al. (1986b) theorized that a lower DMAC would delay the onset of self-destruction. Boon-long et al. (1983) and Egli et al. (1987) demonstrated that a longer SFP decreased the rate of leaf senescence (leaf N remobilization) rather than delayed the initiation of senescence. In this research, there was no apparent effect of the DMAC or SFP on the rate of leaf N decline between cultivars in this report (e.g., P94Y81 in 2012; Table 4-1, Fig. 4-1). Ignoring cultivar differences, we suggest that the high N accumulation rates (Table 3-1) and lower than average DMAC values (Table 4-1) contributed to delayed senescence, prolonged physiological activity in leaves, and resulted in a relatively long SFP. The retention of a large proportion of leaves through physiological maturity would have provided additional photosynthate to support the yield levels observed in this research.

CONCLUSIONS

The seed growth characteristics and leaf N dynamics presented provide empirical data describing a soybean crop with a yield potential ranging from 5521 to 7953 kg ha⁻¹. The high C and N accumulation rates coupled with a relatively slow DMAC and long SFP contributed to delayed senescence and continued crop growth throughout seedfill. These elevated yields were achieved through a combination of greater seed number and seed weight, while maintaining above normal seed protein and oil concentrations. These and previously described data illustrate how several vegetative and reproductive crop growth characteristics were involved to collectively contribute to these high yield levels in a unique, maximum yield growing environment.

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Table 4-1. Dry matter allocation coefficient (DMAC) and seedfill period (SFP), individual seed weight at 0 g kg⁻¹ moisture, and seeds m⁻² at 0 g kg⁻¹ moisture means and standard errors (SE) by year and cultivar from Mr. Cullers' contest field.

Year	Cultivar	DMAC		SFP		Seed weight		Seeds m ⁻²	
		Mean	SE	Mean	SE	Mean	SE	Mean	SE
				d		mg seed ⁻¹			
2011	P94Y81†	0.0100 AB†	± 0.0011	44.2 AB	± 4.4	159 A	± 2.8	3918 AB	± 210
	P94Y82	0.0088 B	± 0.0003	63.0 A	± 7.3	145 AB	± 2.8	4257 A	± 151
	P94Y91	0.0111 A	± 0.0005	40.0 B	± 1.8	162 A	± 6.1	3286 B	± 124
	P94Y92	0.0108 A	± 0.0003	38.9 B	± 0.9	138 B	± 1.8	3340 B	± 144
	P95Y10	0.0111 AB	± 0.0005	47.1 AB	± 7.5	154 A	± 3.5	3600 B	± 136
2012	P94Y23	0.0086 B	± 0.0004	56.7 A	± 3.4	154 AB	± 4.6	3963 A	± 137
	P94Y80	0.0088 B	± 0.0005	52.3 A	± 2.6	158 B	± 1.6	3815 A	± 84
	P94Y81	0.0087 B	± 0.0006	48.1 AB	± 2.9	154 AB	± 4.4	3217 B	± 39
	P94Y82	0.0121 A	± 0.0007	38.2 B	± 3.7	163 A	± 0.7	2961 C	± 55
2013	P94B73	0.0089 B	± 0.0003	45.8 A	± 1.8	165 B	± 3.2	3740	± 228
	P48T53	0.0105 AB	± 0.0016	31.2 B	± 3.1	147 C	± 5.6	3343	± 237
	P49T97	0.0132 AB	± 0.0026	28.8 B	± 4.5	188 A	± 4.2	3673	± 250
	P50T40	0.0103 AB	± 0.0014	39.8 AB	± 3.9	167 B	± 5.3	3587	± 186
	AG5332	0.0127 A	± 0.0003	36.4 B	± 0.1	155 BC	± 2.7	4208	± 276

† Different letters within a column and year denote that means differed ($\alpha=0.05$) as determined by a two-tailed t-test.

Table 4-2. Protein and oil concentration at 130 g kg⁻¹ moisture means and standard errors (SE) by year and cultivar from Mr. Cullers' contest field.

Year	Cultivar	Protein		Oil	
		Mean	SE	Mean	SE
		%		%	
2011	P94Y81	37.0 A [†]	± 0.3	20.9 C	± 0.2
	P94Y82	37.2 A	± 0.2	22.6 A	± 0.2
	P94Y91	36.2 A	± 0.5	22.0 B	± 0.1
	P94Y92	34.6 B	± 0.3	21.1 C	± 0.1
	P95Y10	37.3 A	± 0.2	21.3 C	± 0.1
2012	P94Y23	36.8 C	± 0.2	22.3 B	± 0.2
	P94Y80	37.5 B	± 0.2	22.2 B	± 0.1
	P94Y81	38.0 B	± 0.4	21.8 B	± 0.1
	P94Y82	39.3 A	± 0.2	23.0 A	± 0.2
2013	P94B73	38.5 A	± 0.3	21.4 A	± 0.2
	P48T53	35.9 B	± 0.4	19.8 C	± 0.2
	P49T97	37.6 A	± 0.1	21.2 A	± 0.1
	P50T40	38.1 A	± 0.2	20.2 BC	± 0.2
	AG5332	36.6 B	± 0.2	20.4 BC	± 0.1

[†] Different letters within a column and year denote that means differed ($\alpha=0.05$) as determined by a two-tailed t-test.

Table 4-3. Specific leaf weight and specific leaf N at beginning R5 means and standard errors (SE) by year and cultivar from Mr. Cullers' contest field.

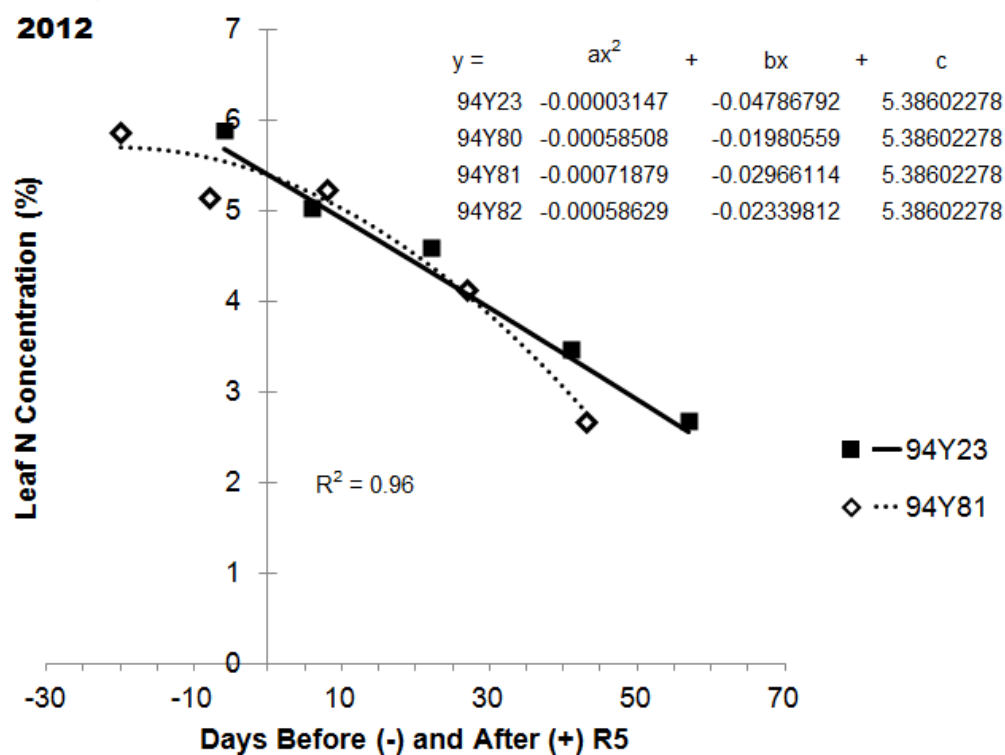
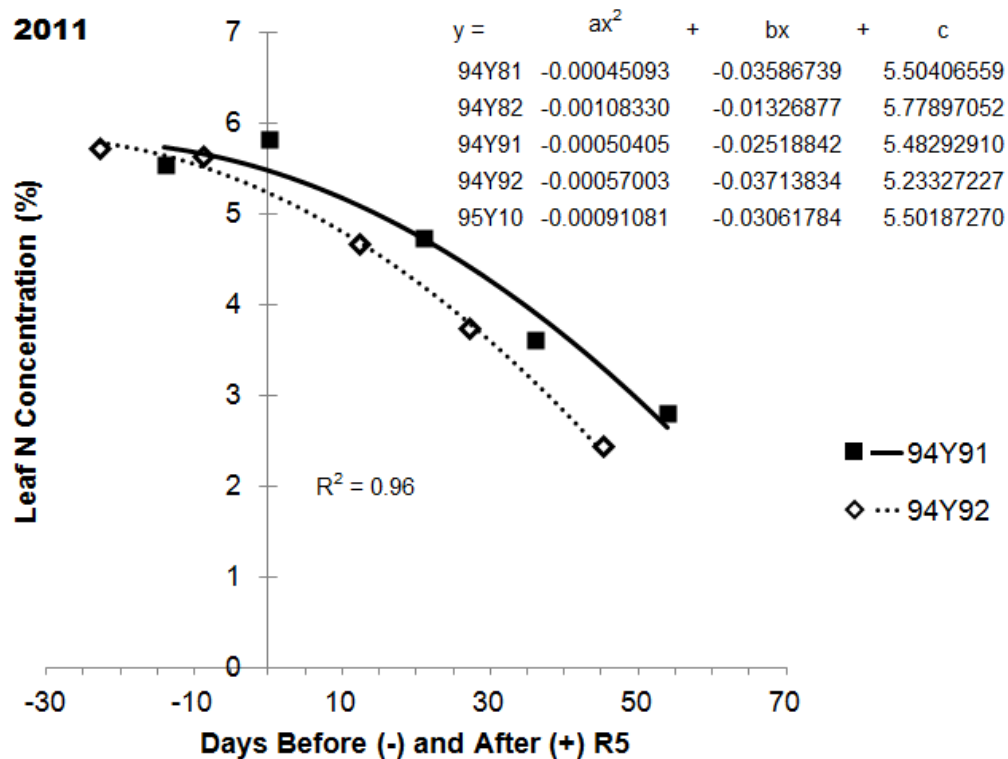
Year	Cultivar	Specific leaf weight		Specific leaf N	
		Mean g m ⁻² leaf area	SE	Mean g N m ⁻² leaf area	SE
2012	P94Y23	58.8 AB†	± 1.1	2.96	± 0.08
	P94Y80	60.8 A	± 1.5	3.01	± 0.07
	P94Y81	55.5 B	± 0.9	2.85	± 0.07
	P94Y82	54.5 B	± 1.5	2.84	± 0.10
2013	P94B73	71.7 A	± 1.0	3.55 B	± 0.08
	P48T53	68.0 B	± 0.7	3.17 BC	± 0.14
	P49T97	72.1 AB	± 2.2	3.55 ABC	± 0.16
	P50T40	69.4 AB	± 1.2	3.84 A	± 0.09
	AG5332	70.3 AB	± 2.3	3.25 C	± 0.06

† Different letters within a column and year denote that means differed ($\alpha=0.05$) as determined by a two-tailed t-test.

Table 4-4. Pearson correlation coefficients and significance levels for biomass accumulation rate (BAR), radiation use efficiency (RUE), specific leaf weight (SLW), specific leaf N (SLN), dry matter allocation coefficient (DMAC), seedfill period (SFP), yield, individual seed weight (Seedwt) and seeds m⁻² from all years and cultivars at Mr. Cullers' contest field.

	RUE	SLW	SLN	DMAC	SFP	Yield	Seedwt	Seeds m ⁻²
BAR	0.99***	0.69***	0.64***	0.28	-0.49**	0.48**	0.51**	0.24
RUE		0.71***	0.61***	0.24	-0.34*	0.35**	0.50***	0.04
SLW			0.84***	0.29	-0.45**	0.41*	0.30	0.22
SLN				0.04	-0.25	0.37*	0.40*	0.21
DMAC					-0.88***	0.24	0.38**	-0.09
SFP						-0.06	-0.35*	0.27
Yield							0.42**	0.82***
Seedwt								-0.10

The symbols, *, **, and *** indicate significance at the $\alpha = 0.05, 0.01,$ and 0.001 levels, respectively.



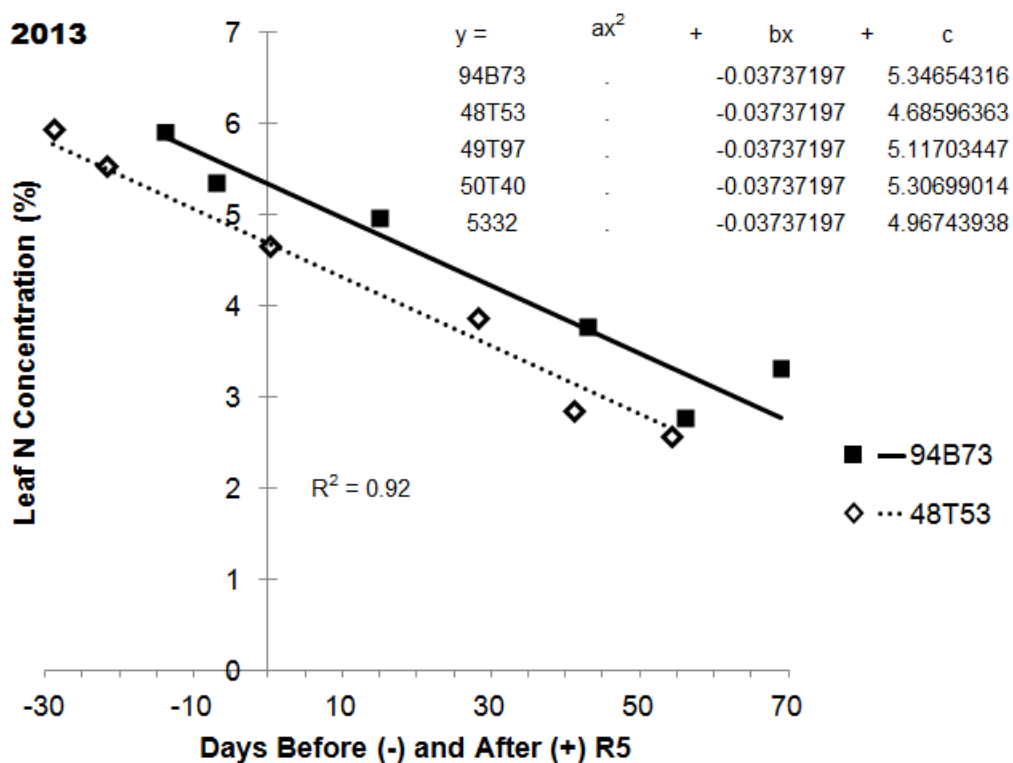


Figure 4-1. Leaf N concentration response to days before and after the R5 growth stage by year and cultivar as illustrated by two cultivars. Data points represent average values (n=4) at given sample dates but covariate analysis was conducted on individual samples. Data were analyzed by covariate analysis using cultivar as a covariate. Regression coefficients for individual cultivars are given in the figure. There was no significant difference in a coefficient among cultivars in those cases in which coefficient values were the same among cultivars.

Chapter 5

Characterization of Soybean Physiological Parameters in a Maximum Yield Environment

ABSTRACT

Soybean [*Glycine max* (L.) Merr.] grain yields $>10,000 \text{ kg ha}^{-1}$ have been reported but lack empirical data to support those yield claims. To compliment research conducted in yield contest fields, small plot research was established at the University of Arkansas. From 2011 to 2013, 12 to 14 elite cultivars were grown in a maximum yield environment and characterized for biomass and N accumulation rates, radiation use efficiency (RUE), leaf N dynamics, the rate of harvest index increase (dry matter allocation coefficient, DMAC), seedfill period (SFP), and grain yield components. Grain yields ranged from 4026 to 7794 kg ha^{-1} , with seed number and seed weights ranging from 1880 to 5576 seeds m^{-2} and 125 to 221 mg seed^{-1} , respectively. Biomass and N accumulation rates and RUE values from R1 to R3 were considerably greater than values typically reported and ranged from 25.4 to 43.2 $\text{g m}^{-2} \text{ d}^{-1}$, 1.08 to 1.52 $\text{g N m}^{-2} \text{ d}^{-1}$, and 1.36 to 1.79 g MJ^{-1} (2013), respectively. The DMAC and SFP values were slow and long, respectively, and suggest another mechanism by which the observed yield and seed numbers were supported. This work highlights and discusses these physiological components and their interactions and contributions to reaching these yield levels as well as cataloging the management practices utilized to achieve grain yields in excess of 6719 kg ha^{-1} (100 bushels acre^{-1}).

INTRODUCTION

United States average soybean yields have increased at a rate of $23.3 \text{ kg ha}^{-1} \text{ yr}^{-1}$ from the earliest record in 1924 to 2012 (USDA-NASS, 2013). This is greater than the Arkansas average soybean yield increase of $20.0 \text{ kg ha}^{-1} \text{ yr}^{-1}$ from 1947 to 2012. Recent contest yield reports up to $10,791 \text{ kg ha}^{-1}$ (Cubbage, 2010) suggest that this rate of increase and current yield levels are substantially less than what may be possible. However, a lack of empirical data from these contest entries raises concerns regarding their credibility (Sinclair and Cassman, 2004).

Soybean grain yields are determined by the seed number and weight. Egli and Zhen-wen (1991) showed that seeds m^{-2} was directly proportional to the biomass accumulation rate (BAR, $\text{g m}^{-2} \text{ d}^{-1}$) and inversely proportional to the individual seed growth rates (ISGR, $\text{mg seed}^{-1} \text{ d}^{-1}$) during the early reproductive growth stages. Sinclair (2004) demonstrated that any increases in C accumulation must be accompanied by an increase in N accumulation to maintain photosynthetic activity. A slower ISGR allows the crop to support more seeds at one time due to decreased daily carbohydrate and N demand per seed (Egli and Zhen-wen, 1991). Likewise, a slower rate of harvest index (HI) increase, or dry matter allocation coefficient (DMAC), over a longer seedfill period (SFP) reduces the rate of leaf N remobilization to the developing seeds (Boon-long et al., 1983; Egli et al., 1987). Increasing N accumulation and slowing the rate of N remobilization could delay or partially prevent the crop from complete self-destruction and allowing the crop to meet the N demand of the seeds (Sinclair and de Wit, 1975; 1976) and lengthen the SFP.

It is likely that not one but all of these crop growth characteristics must be involved if soybean grain yields $>10,000 \text{ kg ha}^{-1}$ are to be achieved. Empirical measurements were made in the contest fields of Mr. Kip Cullers from 2011 to 2013 in an attempt to document and understand soybean yields of this magnitude (Ch. 3 and 4). However, key data from that location

were missing (e.g., N inputs). To address these shortcomings and to verify those measurements, a maximum yield environment was established under defined experimental conditions at the University of Arkansas Main Experiment Station in Fayetteville.

MATERIALS & METHODS

In Fayetteville, AR a small-plot trial was conducted from 2011 to 2013 at the Arkansas Agricultural Research and Extension Center (36°05' N, 94°10' W). The field soil series was a Leaf silt loam (fine, mixed, active, thermic, Typic Albaquults) in 2011 and 2013 and a Captina silt loam (fine-silty, siliceous, active, mesic, Typic Fragiudults) in 2012. The previous crop was corn (*Zea mays* L.) for 2011, for 2012 it was soft red winter wheat (*Triticum aestivum* L.) harvested Jun. 2011, and for 2013 it was a sorghum-sudangrass hybrid (*Sorghum bicolor* L. Moench. X *S. 91udanese*), which was mowed prior to heading twice, killed with the first fall freeze, and incorporated into the soil as a green manure with the fall poultry litter application.

Each fall prior to the growing season, composite soil samples were collected to a depth of 10 cm. Soil samples were dried, ground, and analyzed for pH with a 1:2 soil/water weight ratio, extracted with Mehlich-3 solution and nutrient concentrations measured by inductively coupled plasma spectroscopy by the University of Arkansas Soil Testing and Plant Analysis Laboratory. For the 2012 growing season, additional soil samples for pH were taken on 17 Oct. 2011 in 15 m increments along the length of the field for a subsequent, variable-rate lime application. Poultry litter and fertilizer application dates, amounts and nutrient inputs are specified in Table 5-1. Four subsamples from each poultry litter application were analyzed for total nutrient concentration as described in Ch. 3 with the exception that C and N analysis was performed with a Vario MAX

CN (Elementar, Hanau, Germany). After the fall poultry litter application in each year, the field was deep ripped with a V-Till (Bigham Brothers, Lubbock, TX) to a depth of ≥ 36 cm.

Cultivars were included from Asgrow (Monsanto Co., St. Louis, MO), Pioneer (DuPont Pioneer, Johnston, IA) and NK (Syngenta, Basel, Switzerland) (Table 5-1). All cultivars were of indeterminate stem growth habit, except AG5331. Cultivars were also glyphosate tolerant and had a RM range from 4.2 to 5.5, with the exception of Lee-NN (Hartwig, 1994), a non-nodulating genotype that is a sister line to cultivar Lee, which was sampled only vegetatively to estimate N₂ fixation in 2012 and 2013.

All Asgrow seed came treated with Acceleron (7 mL fluxapyroxad, 24 mL metalaxyl, and 12 mL pyraclostrobin, 59 mL imidacloprid per 45 kg of seed) and all NK seed came treated with CruiserMaxx (20 mL thiamethoxam, 2 mL mefenoxam, and 1 mL fludioxonil per 45 kg of seed). Pioneer seed came untreated in 2011 and 2012 but was treated with Pioneer Premium Seed Treatment (2 mL prothioconazole, 1 mL penflufen, 2 mL metalaxyl and 47 mL imidacloprid per 45 kg of seed) in 2013. In addition, 27 days or less prior to planting, all seeds were over-treated with 59 mL of Bio-Forge (N,N'-diformyl urea; Stoller USA, Houston, TX), 296 mL of Optimize 400 (*Bradyrhizobium japonicum* and lipto-chitooligosaccharide; Novozymes, Bagsvaerd, Denmark) and 89 mL liquid additive, 444 mL of Primo CL (*Bradyrhizobium japonicum*; INTX Microbials, Kentland, IN) and 148 mL rhizobium extension solution (2011 only), 400 g Accolade-(P) (*Azospirillum brasilense*; INTX Microbials), and 227 g Nutriplant SD (4.0% Ca, 2.0% Mg, 4.0% S, 0.001% Co, 0.075% Cu, 1.0% Fe, 0.25% Mn, 0.0005% Mo, 1.0% Zn; Access Business Group Int. LLC., Ada, MI) per 45 kg of seed.

Treatments (cultivars) were arranged in a randomized complete block design with four replications. Plots consisted of four rows, 46 cm apart, and 9 m long. Soybean was flat planted

on 9 May 2011, 11 Apr. 2012, and 15 May 2013. Seeds were planted 2.5 cm deep with a 4-row John Deere 7100 planter (Deere and Co., Moline, IL) topped with Almaco cones (Almaco, Neveda, IA). Soybean emerged on 16 May 2011, 25 Apr. 2012 after rotary hoeing on 19 Apr. 2012, and 21 May 2013. Stand counts were taken 14 days after emergence by counting all plants in four random linear meters within the center two rows of each plot. On average, the mean plant density (\pm standard error) across cultivars was 37.9 ± 0.6 plants m^{-2} in 2011, 34.6 ± 0.9 plants m^{-2} in 2012, and 31.1 ± 0.6 plants m^{-2} in 2013.

Following emergence, an overhead irrigation system was installed and all plots were irrigated when the soil water deficit reached *ca.* 25 mm. Daily moisture deficits were calculated using a 'checkbook' method described by Purcell et al. (2007). In the absence of rainfall with a full canopy, this deficit was reached and irrigation was applied every 3 days. Irrigation continued on all plots until the latest cultivar had reached the R7 growth stage. Irrigation began on 6 June and was terminated on 4 Oct. in 2011, 17 May through 4 Sep. 2012, and 12 June through 17 Sep. 2013. In 2011, irrigation was applied 45 times for a total of 646 mm of irrigation water. In 2012, irrigation totals were 670 mm over 35 applications. In 2013, irrigation totals were 496 mm over 25 applications.

In 2011, supplemental fertilizer was included in the irrigation water beginning on 23 June 2011, near the R1 growth stage (Fehr and Caviness, 1977). Fertilizer inputs were rotated between NH_4SO_4 , KNO_3 , K_2SO_4 , and $Ca(NO_3)_2$. Total fertigation inputs in 2011 were 72 kg N ha^{-1} , 29 kg K ha^{-1} , 38 kg S ha^{-1} , and 31 kg Ca ha^{-1} . Specific irrigation and fertilizer input dates and amounts are specified in Appendix 5-1. Fertigation inputs in 2012 were 32% $CO(NH_2)_2+NH_4NO_3$, NH_4SO_4 , and KNO_3 . Fertigation began on 8 June 2012, at the R2 growth stage, using a rotation of the three fertilizers. Total fertigation inputs in 2012 were 295 kg N ha^{-1} , 22 kg K ha^{-1} , and 39

kg S ha⁻¹. Fertilizer inputs in 2013 were 32% CO(NH₂)₂+NH₄NO₃, NH₄SO₄, and KNO₃ with fertigation beginning on 12 June 2013, near the V4 growth stage. Fertigation inputs were mainly KNO₃ until the beginning of seedfill when inputs shifted to 32% CO(NH₂)₂+NH₄NO₃. Total fertigation inputs in 2013 were 178 kg N ha⁻¹, 33 kg K ha⁻¹, and 11 kg S ha⁻¹. In 2012 and 2013, once 50% of the pods on the latest cultivar had reached mature color, the field was defoliated with 280 g ha⁻¹ paraquat dichloride and 6.7 kg ha⁻¹ sodium chlorate.

Weeds were controlled with preplant, incorporated application of 1.4 kg ha⁻¹ S-metolachlor and 118 g ha⁻¹ imazaquin, one postemergence application of 0.6 kg ha⁻¹ glyphosate alone in 2011 and 2012 or 1.1 kg ha⁻¹ glyphosate with 277 g ha⁻¹ fomesafen in 2013, and hand-weeding as necessary. A prophylactic fungicide application of 217 g ha⁻¹ azoxystrobin and 188 g ha⁻¹ propiconazole was applied at the R3 growth stage in all years. This was followed by 1.9 kg ha⁻¹ of chlorothalonil *ca.* 14 days followed by 217 g ha⁻¹ azoxystrobin and 188 g ha⁻¹ propiconazole *ca.* 14 days later. Despite these applications, minor incidences of cercospora leaf spot, *Cercospora kukuchii*, were observed and are assumed to have had little to no impact on grain yield.

Insecticides were applied frequently to prevent damage from insect pests. In 2011, 36 g ha⁻¹ lambda-cyhalothrin was applied on 22 June, followed by 28 g ha⁻¹ zeta-cypermethrin on 19 July, 560 g ha⁻¹ dimethoate on 4 Aug. and 12 Aug., 13 g ha⁻¹ abamectin on 18 Aug., 112 g ha⁻¹ bifenthrin on 25 Aug., 13 g ha⁻¹ abamectin on 28 Aug., and 560 g ha⁻¹ chlorpyrifos on 30 Aug. Despite these applications, damage from two-spotted spider mite, *Tetranychus urticae* Koch, occurred. In 2012, 36 g ha⁻¹ lambda-cyhalothrin was applied on 29 June, followed by 36 g ha⁻¹ lambda-cyhalothrin on 6 July, 28 g ha⁻¹ zeta-cypermethrin on 11 July, 112 g ha⁻¹ bifenthrin and 124 g ha⁻¹ indoxacarb on 27 July, 112 g ha⁻¹ and bifenthrin on 15 Aug. In 2013, 112 g ha⁻¹

bifenthrin was applied on 16 Jul., followed by 560 g ha⁻¹ chlorpyrifos and 36 g ha⁻¹ lambda-cyhalothrin on 6 Aug., 28 g ha⁻¹ zeta-cypermethrin and 112 g ha⁻¹ bifenthrin on 20 Aug., 13 g ha⁻¹ abamectin on 29 Aug., and 13 g ha⁻¹ abamectin on 6 Sept. Insect control was satisfactory in 2012 and 2013 with no perceivable impact on crop growth or grain yield.

The fraction of canopy radiation intercepted (FRI) was measured bi-weekly using the same method as was previously described (Ch. 3). Successive aboveground biomass measurements were made in each plot from the center two rows. In 2011, whole-plant biomass samples were collected from 0.5 m² on 13 June, 28 days after emergence (DAE), when the FRI was *ca.* 0.50 and plants were at the V5 stage. A second set of 0.5-m² samples were collected at R2 on 28 June (43 DAE), when FRI was >0.91. In 2012, a first set of 0.5-m² samples were collected on 11 June at R2 (47 DAE) when FRI reached *ca.* 0.90. An additional sample set was collected at R3 on 25 June (61 DAE) when FRI was >0.95. In 2013, a first set of 0.5-m² samples were collected on 28 June at R1 (38 DAE) and an additional sample set was collected at R3 on 12 July (52 DAE) and at R5 on 1 Aug (72 DAE), all occurring when FRI was >0.95. Biomass samples were processed and analyzed for nutrient concentration, and the biomass and nutrient accumulation rate and radiation use efficiency were calculated as previously described in Ch. 3. Temperature data were collected from a weather-station within 1 km of the field, and solar radiation was estimated using the methods of Ball et al. (2004). The fraction of N derived from the atmospheric N₂ in 2012 and 2013 was determined using Lee-NN as a reference crop for the ¹⁵N natural abundance method (Peoples et al., 2009). Biomass of Lee-NN was sampled along with the other cultivars, and the final two biomass samples from all cultivars were analyzed for ¹⁵N and ¹⁴N at the University of California Stable Isotope Facility (Davis, CA).

Leaf samples were collected and analyzed for nutrient concentration as previously described in Ch. 4. Leaf samples from 17 July 2012 and 9 Aug. 2013 were used to determine the specific leaf weight (SLW, g m⁻² of leaf area) and specific leaf N (SLN, g N m⁻² leaf area) as described in Ch. 4. Samples for immature and final HI data were collected from one of the center two rows of each plot and processed, analyzed, and DMAC and SFP were calculated as previously described in Ch. 4. Grain yield was determined by harvesting 6 m of the center two rows of each plot with a plot combine. Machine harvest samples were cleaned, weighed and measured for grain moisture. One hundred seeds were weighed from the grain sample, and seed number, protein, and oil were determined as previously described in Ch. 4. Data were analyzed using the GLM procedure of SAS (SAS Institute, Cary, NC). Each year was analyzed separately. Mean comparisons were made using Fisher's protected LSD test ($\alpha = 0.05$) when the effect of cultivar was significant at $\alpha = 0.05$. Leaf N concentrations were regressed over days before or after R5 as described in Ch. 4. The CORR procedure of SAS was utilized to provide Pearson correlation coefficients over all cultivars and years.

RESULTS

Growing Conditions

The temperature and rainfall in Fayetteville were numerically similar to the weather at Mr. Cullers' fields (Table 3-2), which was *ca.* 100 km to the north. As such, mean monthly high temperatures in June, July, and August 2011 and 2012 were ≥ 3.1 °C above the 30-yr mean (Table 5-2). However, the 2013 season was near normal throughout the summer with June, July, and August temperatures ranging from -1.4 to $+0.9$ °C from the 30-yr mean. Monthly mean minimum temperatures were greatest in 2011 and were ≥ 2.9 °C above the 30-yr mean in June,

July, and August. Mean monthly minimum temperatures in 2012 were always above the 30-yr mean. April and May 2012 maximum and minimum temperatures were +2.5 to +3.9 °C above the 30-yr mean, which allowed for an earlier planting date. During the remainder of 2012, minimum temperatures ranged from +0.7 to +2.0 °C above the 30-yr mean. Like maximum temperatures, minimum temperatures in 2013 were near normal and ranged from -1.0 to +1.8 °C from the 30-yr mean. Solar radiation was near normal with the exception of May 2013, which was -2.6 MJ m⁻² d⁻¹ from the 30-yr mean. Rainfall amounts were >50 mm above the 30-yr mean in April and May 2011 and April, May and August 2013. Rainfall amounts <50 mm from the 30-yr mean were observed in June and July 2011, April, May, June and September 2012, and June 2013.

Grain Yield and Yield Components

Cultivar grain yields ranged from 4026 to 5697 kg ha⁻¹ in 2011, 5765 to 7690 kg ha⁻¹ in 2012, and 4977 to 7794 kg ha⁻¹ in 2013 (Table 5-3). Grain yields were higher in 2012 and 2013 compared with 2011. In 2011, the highest yielding cultivar was P94Y91 (5697 kg ha⁻¹), which was ranked fourth highest and 420 kg ha⁻¹ greater in Mr. Cullers' field (Table 3-1). The two greatest yielding cultivars at Mr. Cullers' field had average yields in Fayetteville, while the lowest yielding cultivar was consistent between locations (Table 3-1; 5-3). The cultivar with the highest yield in 2012 was P94Y23 (7690 kg ha⁻¹) and was also the highest yielding cultivar in Mr. Cullers' field (6979 kg ha⁻¹). In 2012, the lowest yielding cultivar was S49-A5 (5765 kg ha⁻¹), which was the second lowest in cultivar ranking in 2011 (4066 kg ha⁻¹). The highest yielding cultivar in 2013 was S46-G9 (7794 kg ha⁻¹), which was new to the research. The lowest yielding 2013 cultivar was P94Y82 (4977 kg ha⁻¹) which had been statistically similar to the lowest

yielding cultivar in prior years in Fayetteville but was one of the highest yielding cultivars in Mr. Cullers' field in 2011. The only cultivar grown in both Fayetteville and Mr. Cullers' contest field in 2013 was AG5332, which had a higher numerical cultivar ranking and yield in Mr. Cullers' field.

Harvest index values among cultivars ranged from 39.2 to 51.2% in 2011, 43.2 to 50.9% in 2012, and 45.5 to 57.9% in 2013 (Table 5-3). In 2011, the highest yielding cultivar had a HI statistically similar to the lowest HI, while the greatest yielding cultivars in 2012 and 2013 also had the greatest HI values. Over cultivars and years, HI was positively correlated ($r=0.41^{***}$) with grain yield (Table 5-4). Harvest index values were generally greater in Fayetteville compared with Mr. Cullers' contest field (Table 3-1). This is likely due to differences in defoliation practices, where a combination of herbicides and sodium chlorate was used to completely defoliate the crop in Fayetteville and samples were taken after defoliation as opposed to Mr. Cullers' field where less effective defoliant were used and HI samples were taken prior to complete canopy defoliation.

Seed numbers ranged from 1880 to 2749 seeds m^{-2} in 2011, 3625 to 5576 seeds m^{-2} in 2012, and 2380 to 4131 seeds m^{-2} in 2013 (Table 5-3). Individual seed weights ranged from 157 to 221 mg seed $^{-1}$ in 2011, 125 to 184 mg seed $^{-1}$ in 2012, and 156 to 200 mg seed $^{-1}$ in 2013. Across all cultivars, yields were similar in 2012 and 2013 but seed numbers were greater in 2012 and seed weights were greater in 2013. Expected seed weights were only available for P94Y23, P46T21, P47T36, P94Y80, P94Y81, P94Y82, and P95Y10. Of these, seed weight in 2011 was greater than expected for P94Y80, P94Y81, and P94Y82. P94Y81 had lower than expected seed weight in 2012. P94Y23, P46T21, P94Y80 and P94Y82 had greater than expected seed weights in 2013 (DuPont Pioneer, 2014). In 2011, the greatest yielding cultivar (P94Y91) had a seed

number statistically similar to the greatest seeds m^{-2} and a seed weight statistically similar to the lowest seed weight. In 2012, the greatest yielding cultivar (P94Y23) had a seed weight statistically similar to the greatest seed weight and an average seed number. The greatest yielding cultivar in 2013 (S46-G9) had the greatest seeds m^{-2} and a seed weight statistically similar to the lowest seed weight. These data reveal that many combinations of seed number and seed weight are capable of achieving grain yields $>6719 \text{ kg ha}^{-1}$ ($100 \text{ bushels acre}^{-1}$). However, grain yield was only significantly correlated ($r=0.85^{***}$) with seed number (Table 5-4).

Over all cultivars, grain protein and oil concentrations were similar among years (Table 5-3). Protein concentration ranged from 36.3 to 42.0% in 2011, 37.6 to 40.6% in 2012, and 38.6 to 42.8% in 2013. In all years, the greatest yielding cultivar had a protein concentration less than the mean of all cultivars. However, low protein concentrations did not guarantee greater yields (e.g., AG5503 in 2011, S49-A5 in 2012, P94Y81 in 2013) and neither protein nor oil were significantly correlated ($r=0.08$, $r=0.05$, respectively) with yield (Table 5-4). Oil concentration ranged from 20.0 to 23.0% in 2011, 20.6 to 23.0% in 2012, and 21.8 to 24.4% in 2013. Protein concentration was inversely related ($r=-0.54^{***}$) to oil concentrations (e.g., AG4531 in 2011, P94Y23 in 2012, S44-K7 in 2013) as expected (Wilson, 2004) (Table 5-4).

Six cultivars were common for all years of research. Over years, protein and oil for these cultivars averaged 41.4 and 21.1% (AG4531), 37.6 and 22.8% (AG5503), 40.8 and 22.2% (P94Y80), 39.6 and 22.1% (P94Y81), 41.2 and 22.8% (P94Y82), and 41.7 and 21.2% (S44-K7). These concentrations are greater than the United States average protein and oil concentrations of 34.6 and 18.5% from 2011 to 2013 (Naeve et al 2012; 2013a; 2013b). Furthermore, the protein and oil concentration of the Pioneer cultivars was greater than what is normally expected for these cultivars (DuPont Pioneer, 2014).

Physiological Parameters

The samples for biomass and N accumulation in 2011 were collected prior to complete canopy closure and therefore underestimate the rates after canopy closure. When biomass and N accumulation rates were measured with a FRI *ca.* 0.50 for the first sample and >0.91 for the second sample, rates among cultivars ranged from 13.5 to 20.3 g m⁻² d⁻¹ and 0.51 to 0.73 g N m⁻² d⁻¹, respectively (Table 5-5). In 2012, when the FRI was *ca.* 0.90 for the first sample and >0.95 for the second sample, biomass and N accumulation rates ranged from 23.0 to 33.7 g m⁻² d⁻¹ and 0.88 to 1.19 g N m⁻² d⁻¹, respectively. The cultivar with the highest biomass accumulation rate was P94Y80 (33.7 g m⁻² d⁻¹) and seven of the eleven remaining cultivars had statistically similar values. A relatively small range of values among cultivars and variability within cultivar measurements likely contributed to the lack of significance of the rest of the parameters and years. In 2013, when the FRI was *ca.* >0.95 for the first two sample dates, biomass and N accumulation rates ranged from 25.4 to 43.2 g m⁻² d⁻¹ and 1.08 to 1.52 g N m⁻² d⁻¹, respectively. These values were slightly less than measured at Mr. Cullers' field in 2013 (Table 3-1), however, the N accumulation rates remain greater than had ever been reported prior to this work (Supplement 3-1). A third set of biomass samples were collected in 2013 to determine the biomass and N accumulation rates throughout seed set (R1 to R5). When analyzed over this timeframe, biomass and N accumulation rates ranged from 17.3 to 27.9 g m⁻² d⁻¹ and 0.47 to 0.88 g N m⁻² d⁻¹, respectively. This indicates that the abnormally large accumulation rates observed from R1 to R3 were not maintained throughout the remainder of reproductive growth.

Radiation use efficiency values among cultivars ranged from 0.83 to 1.28 g MJ⁻¹ (2011), 1.14 to 1.51 g MJ⁻¹ (2012), 1.36 to 1.79 g MJ⁻¹ (R1 to R3, 2013) or 0.76 to 1.25 g MJ⁻¹ (R1 to R5, 2013). Solar radiation during the measurement period averaged 21.1 MJ m⁻² d⁻¹ (2011), 23.1

MJ m⁻² d⁻¹ (2012), and 23.9 MJ m⁻² d⁻¹ (R1 to R3, 2013) or 22.2 MJ m⁻² d⁻¹ (R1 to R5, 2013). The highest yielding cultivar in 2012 also had the highest N accumulation rate, with the biomass accumulation rate and RUE value also being near the greatest among cultivars. However, these early-season growth parameters did not appear to relate well with yield. For example, the highest yielding cultivar in 2013 (S46-G9) also had the lowest R1 to R3 biomass accumulation rate. However, S46-G9 had the greatest biomass accumulation rate from R1 to R5, indicating that growth rates over this timeframe were a better indicator for yield potential. Additionally, the higher biomass and N accumulation rates and RUE values observed from R1 to R3 in 2013 compared with 2012 did not translate into higher yields, and the R1 to R5 measurements demonstrate that growth rates were not maintained throughout grain fill as was suspected and discussed for Mr. Cullers' field in 2013 (Ch. 3). Of all the crop growth variables, only RUE had a significant positive correlation ($r=0.25^*$) with yield (Table 5-4).

From the biomass samplings of Lee-NN, the estimated proportion of N in the biomass from biological N₂ fixation among cultivars ranged from 0 to 4.8% in 2012 and 0 to 9.8% in 2013. Leaf N concentrations were 5.5 to 6% at the beginning of the R5 growth stage (Fig. 5-1) and were similar to the measurements made from Mr. Cullers' fields. Both the proportion of N from N₂ fixation and the leaf N concentrations were indicative of the large amount of available N applied. Leaf N declined in a quadratic manner in all years; however, the quadratic coefficient was not significantly different among cultivars in 2011 or 2013. Additional leaf nutrient dynamics are provided in Appendix 5-3. Similar to Ch. 4, green leaves remained attached at physiological maturity and a desiccant was applied to facilitate harvest.

At the beginning of seedfill, SLW averaged 55.1 g m⁻² leaf area in 2012 and 57.2 g m⁻² leaf area in 2013 over all cultivars (Table 5-6) but there were no significant differences among

cultivars. The SLW is a heritable trait and with ranges as large as 48.8 to 85.8 g m⁻² leaf area (Lugg and Sinclair, 1979). Among these elite cultivars, the range in SLW in 2012 was 49.4 to 61.1 g m⁻² leaf area and 50.6 to 62.3 g m⁻² leaf area in 2013. For a given cultivar, the SLW was fairly consistent between years (e.g., AG4531 and S44-K7).

Among all cultivars, SLN averaged 2.88 g N m⁻² leaf area, with a range from 2.45 to 3.22 g N m⁻² leaf area in 2012 and was significantly affected by cultivar. In 2013, the average SLN was 3.01 g N m⁻² leaf area, with a range from 2.71 to 3.17 g N m⁻² leaf area. These values are greater than was reported by Shiraiwa and Sinclair (1993) where SLN ranged from 1.6 to 2.4 g N m⁻² leaf area. The SLN values from Fayetteville in 2013 were slightly less than those observed at Mr. Cullers, as were the RUE values (Table 3-1), as expected since RUE and SLN are positively correlated (Sinclair and Horie, 1989). However, SLW and SLN were not correlated with RUE or yield in this dataset (Appendix 5-4).

The dry matter allocation coefficient (DMAC) among cultivars ranged from 0.0080 to 0.0123 (2011), 0.0035 to 0.0101 (2012), and 0.0083 to 0.0138 (2013). Calculations with this value and the final HI resulted in seedfill periods (SFP) ranging from 37.9 to 55.1 d (2011), 47.5 to 128.6 d (2012), and 37.0 to 58.7 d (2013). Several of the 2012 values for DMAC and SFP are unfeasibly low and long, respectively. The reason for these errors is unknown but it is possible that the first immature HI sample occurred prior to the period of linear seedfill. The DMAC and SFP values measured in 2011 and 2013 were comparable to those measurements taken from Mr. Cullers' contest field (Table 4-1). As such, DMAC values were also slower than the mean of 0.0139 and SFP longer than the mean of 38.4 d reported by Salado-Navarro et al. (1993). In 2011, DMAC values appeared to be positively correlated with yield (e.g., AG5331 and P94Y91). However, in 2012 and 2013, there did not appear to be any relationship between DMAC and SFP

with yield (e.g., P94Y23 and S49-A5 in 2012, P94Y23 and P46T21 in 2013). Over all cultivars and years, DMAC was not correlated ($r=-0.08$) with yield but the SFP did have a significant and positive correlation ($r=0.23^*$) with yield (Table 5-4).

DISCUSSION

Evidence of genetic by environment interactions for grain yield and some physiological measurements exists between the Fayetteville and Mr. Cullers' field locations and also within Fayetteville between years. A severe spider mite outbreak in Fayetteville in 2011 introduced additional biotic interactions within the 2011 environment. We suggest the higher yields in Fayetteville in 2012 compared with 2011 were partially due to the earlier planting date, increased fertility from poultry litter and N fertigation, and a refined pest management program. Compared to mid-April planting dates, mid-May planting are detrimental to grain yields by increasing the DMAC and reducing the SFP (Thomas and Raper, 1976; Gbikpi and Crookston, 1981), reducing node production and increasing plant height (Akhter and Sneller, 1996; Bastidas et al., 2008; Wilcox and Frankenberger, 1987), increasing flower abortion (Heitholt et al., 1986), and resulting in fewer seeds or pods m^{-2} (Beatty et al., 1982; Bruns 2011; Pedersen and Lauer, 2004; Robinson et al., 2009). In accordance with the prior discussion of seed number determination in soybean, we suggest that the decline in seed number with late planting can be attributed to a combination of decreased photosynthate production during seed set and higher seed growth rates. In addition, the increased poultry litter and fertigation inputs in 2012 would have helped provide adequate N and K availability to meeting the demands of the high yielding crop (Flannery 1986; 1989). Uncontrolled insect outbreaks resulting in 100% defoliation of an irrigated soybean crop at the R4 growth stage can decrease yield by 57% (Caviness and Thomas, 1980). Therefore, the

refined pest management practices were crucial to prevent another insect outbreak and would have helped minimize yield losses due to those pests.

Yields in 2013 also benefited from the increased fertility program and refined pest management as well as near normal weather conditions without excessive heat stress. High temperatures like in 2011 and 2012 increase flower and pod abortion (Mann and Jaworski, 1970) and again, we suggest this is due to reduced photosynthetic rates during seed set (Ferris et al., 1998; Gibson and Mullen, 1996; Paulsen, 1994). Additional yield losses with excessive temperatures are the result of a shortened SFP and accelerated senescence (Dornbos and Mullen, 1991; Egli and Wardlaw, 1980). However, grain yield in 2013 was not significantly affected by cultivar ($P = 0.12$, Appendix 5-2). This may have been from increased yield variability caused by early lodging, which was more severe in 2011 and 2013. We suggest that the delayed mid-May planting date in 2011 and 2013 resulted in excessive early growth, or alternatively the mid-April planting dates in 2012 reduced plant height, although this trait was not quantified. Delayed planting in 2011 and 2013 resulted in warmer growing conditions without significantly hampering the growing season length and may have led to higher early-season biomass accumulation rates and longer internode lengths resulting in detrimentally tall plant heights and increased early lodging (Akhter and Sneller, 1996; Bastidas et al., 2008; Wilcox and Frankenberger, 1987). This early lodging may have contributed to the reduced growth rates after R3 in 2013 (Table 5-5). Lodging during the reproductive stages decreases yields by 21 to 23% (Cooper, 1971) and is primarily due to a reduction in seeds or pods plant^{-1} (Noor and Caviness, 1980; Woods and Swearingin, 1977), likely stemming from reduced photosynthate production. While the 2013 biomass accumulation rates and RUE values from R1 to R3 are among or above

the greatest values ever reported (Supplement 3-1), we propose that these growth rates must be maintained throughout seedfill if yields in excess of 10,000 kg ha⁻¹ are to be achieved.

The yield levels achieved in this research were attained through different combinations of seed number and seed weights. Egli and Zhen-wen (1991) demonstrated that increased biomass accumulation rates could increase seed number. The biomass accumulation rates presented here are greater than the mean of all previous reports (Supplement 3-1) and similar to those observed at Mr. Cullers' field (Table 3-1). This, in combination with the high N accumulation rates, results in a high RUE and subsequently high yield and seed number. Indeed, correlation analysis indicated that the biomass and N accumulation rates and RUE values had significant positive correlation ($r=0.41^{**}$, $r=0.43^{***}$, and $r=0.41^{***}$, respectively) with seed number (Table 5-4).

Egli and Zhen-wen (1991) also demonstrated an inverse effect of the ISGR on seed number determination. Likewise, the DMAC values measured in this work had significant negative correlation ($r=-0.32^{***}$) with seed number (Table 5-4). The lower DMAC values were also negatively correlated ($r=-0.84^{***}$) with the SFP (Table 5-4). A longer SFP slows N remobilization from the vegetative biomass to the developing seeds (Boon-Long et al., 1983; Egli et al., 1987) and can delay or partially prevent photosynthetic canopy self destruction (Boon-long et al., 1983; Egli et al., 1987; Salado-Navarro et al., 1986a; 1986b; 1993; Sinclair and de Wit, 1975; 1976).

Some have suggested that lowering the protein or oil concentration of soybean grain would increase total grain output because of the high energy requirement of those constituents compared with starch (Brim and Burton, 1979, Hartwig and Hinson, 1972; Helms and Orf, 1998; Penning de Vries et al., 1974). Conversely, the protein and oil concentrations found in this high yield research were greater than the U.S. national average (Naeve et al 2012; 2013a; 2013b). One

explanation of the high protein is that an abundance of available N and increased N accumulation rates increase seed protein (Gascho, 1991; Egli and Bruening, 2007). Certainly, the amount of N applied in this research may have contributed to these high protein levels observed as would the high N accumulation rates (Table 5-5). High temperatures during R5 to R6 increase soybean oil concentration (Dornbos and Mullen, 1992) which may explain the high oil concentrations. Soil moisture deficits can also reduce seed oil concentration (Dornbos and Mullen, 1992; Foroud et al., 1993). While hot high temperatures $\geq 3.3^{\circ}\text{C}$ above the 30-yr mean were observed in July and August of 2011 and July 2012, mean high temperatures in 2013 peaked at 31.3°C in July, -0.4°C below the 30-yr mean for July. Alternatively, or in conjunction with hot temperatures, the irrigation practices in this research would have eliminated any soil moisture deficits and also allowed oil concentrations to rise above the national average.

CONCLUSIONS

The management practices outlined in this research created a maximum yield environment with the goal of meeting all nutrient and water requirements while controlling all biotic stresses. Several of the physiological characteristics measured represent unique growth patterns resulting in grain yields much greater than normally observed. Overall, the mean and range of yield levels and physiological characterizations were generally similar between Fayetteville and Mr. Cullers' contest fields in 2012 and 2013. As such, the goals of duplicating the yields and physiology of Mr. Cullers' contests in a controlled environment were met. However, we suggest that certain biotic and abiotic stresses remained influential on final crop yield and prevented the crop from reaching full potential. Regardless, this work highlights the many physiological components that contributed to these yield levels and provides additional

insight into the inputs and management necessary to achieve grain yields in excess of 6719 kg ha⁻¹.

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Table 5-1. Summary of the date, amount, and form used for nutrient inputs, and the cultivars used in each year of research at Fayetteville. Fertility inputs from fertigation are specified in Appendix 5-1.

Year	Nutrient Inputs			
	Date	Amount	Form	Cultivars
2011	10 Dec. 2010	263 kg N, 110 kg P, 134 K, 324 kg Ca ha ⁻¹	8.4 Mg ha ⁻¹ dry poultry litter	AG4303, AG4531, AG4907, AG5331,
	8 Apr. 2011	87 kg N, 39 kg P, 61 K, 103 kg Ca ha ⁻¹	3.3 Mg ha ⁻¹ dry poultry litter	AG5503, P94Y80, P94Y81, P94Y82, P94Y91, P94Y92, P95Y10, S44-K7, S46-U6, S49-A5
2012	17 Nov. 2011	24 kg N, 191 K, 106 kg S, 31 kg Mg, 32 kg Zn ha ⁻¹	280 kg KCl, 280 kg K ₂ Mg(SO ₄) ₂ , 90 kg ZnSO ₄ , 112 kg NH ₄ SO ₄ ha ⁻¹	AG4303, AG4531, AG4907, AG5332, AG5503, P94Y23, P94Y80, P94Y81, P94Y82, S44-K7,
	17 Nov. 2011	390 kg N, 142 kg P, 188 K, 366 kg Ca ha ⁻¹	10.1 Mg ha ⁻¹ dry poultry litter	S46-U6, S49-A5, Lee-NN
	16 Mar. 2012	191 kg N, 62 kg P, 88 K, 134 kg Ca ha ⁻¹	5.3 Mg ha ⁻¹ dry poultry litter	
2013	7 June 2012	199 kg N, 71 kg P, 111 K, 196 kg Ca ha ⁻¹	5.6 Mg ha ⁻¹ dry poultry litter	AG4531, AG4632, AG4933, AG5332, AG5503, P94Y23,
	8 Nov. 2012	87 kg N, 71 kg P, 56 K, 173 kg Ca ha ⁻¹	5.5 Mg ha ⁻¹ dry poultry litter	P46T21, P47T36, P94Y80, P94Y81,
	8 Mar. 2013	24 kg N, 247 K, 90 kg S, 31 kg Mg ha ⁻¹	392 kg KCl, 280 kg K ₂ Mg(SO ₄) ₂ , 112 kg NH ₄ SO ₄ ha ⁻¹	P94Y82, S44-K7, S46-G9, S49-F8, Lee-NN
	8 Mar. 2013	471 kg N, 163 kg P, 220 K, 332 kg Ca ha ⁻¹	11.4 Mg ha ⁻¹ dry poultry litter	

Table 5-2. Mean monthly high temperature (Tmax), low temperature (Tmin), solar radiation (Rs), monthly total rainfall, and irrigation from Fayetteville in 2011, 2012 and 2013. Departures from the 30-yr mean (1981-2010; NCDC-NOAA, 2013) are in parentheses.

Year	Month	Tmax	Tmin	Rs [†]	Rainfall	Irrigation
		°C		MJ m ⁻² d ⁻¹	mm	
2011	April	22.1 (+1.8)	9.7 (+1.8)	19.7 (-0.6)	330 (+220)	0
	May	23.3 (-1.0)	13.0 (+0.2)	20.2 (-1.7)	189 (+60)	0
	June	32.3 (+3.6)	21.6 (+3.9)	21.7 (-0.6)	26 (-108)	109
	July	36.5 (+4.8)	23.6 (+3.3)	23.4 (+1.2)	11 (-69)	229
	August	34.9 (+3.3)	22.2 (+2.9)	21.2 (+0.2)	86 (+10)	179
	September	25.5 (-1.6)	12.6 (-2.5)	17.8 (+0.4)	122 (-1)	119
2012	April	22.8 (+2.5)	11.8 (+3.9)	18.8 (-1.5)	48 (-62)	0
	May	27.7 (+3.4)	16.1 (+3.3)	21.7 (-0.2)	37 (-92)	52
	June	31.8 (+3.1)	19.0 (+1.3)	23.8 (+1.5)	65 (-69)	175
	July	35.6 (+3.9)	22.3 (+2.0)	23.7 (+1.5)	55 (-25)	227
	August	32.4 (+0.8)	20.0 (+0.7)	20.6 (-0.4)	84 (+8)	205
	September	28.1 (+1.0)	17.1 (+2.0)	16.5 (-0.9)	56 (-67)	12
2013	April	19.6 (-0.7)	6.9 (-1.0)	20.1 (-0.2)	165 (+55)	0
	May	22.8 (-1.5)	13.3 (+0.5)	19.3 (-2.6)	220 (+91)	0
	June	29.6 (+0.9)	19.5 (+1.8)	21.1 (-1.2)	27 (-107)	98
	July	31.3 (-0.4)	19.8 (-0.5)	22.1 (-0.1)	62 (-18)	199
	August	30.2 (-1.4)	19.5 (+0.2)	19.4 (-1.6)	138 (+62)	121
	September	29.4 (+2.3)	16.5 (+1.4)	17.9 (+0.5)	92 (-31)	78

[†] Solar radiation 30-yr means calculated with 30-yr mean high and low temperatures using a modified Hargreaves and Samani (1982) equation, described by Ball et al. (2004).

Table 5-3. Grain yield at 130 g kg⁻¹ moisture, harvest index (HI), seeds m⁻² at 0 g kg⁻¹ moisture, individual seed weight at 0 g kg⁻¹ moisture, and protein and oil concentration at 130 g kg⁻¹ moisture means by year and cultivar from Fayetteville.

Year	Cultivar	Yield kg ha ⁻¹	HI %	Seeds m ⁻²	Seed weight mg seed ⁻¹	Protein %	Oil %
2011	AG4303	4777 ABCD†	51.2 A	1880 D	221 A	41.6 AB	21.7 BC
	AG4531	5377 AB	48.1 AB	2580 AB	183 BC	41.3 AB	20.0 F
	AG4907	5355 AB	44.0 BCDE	2749 A	157 D	38.8 EF	21.7 BC
	AG5331	4270 D	42.8 BCDE	1911 D	195 B	39.3 DEF	21.1 DE
	AG5503	4125 D	40.4 CDE	2112 CD	169 CD	36.3 H	22.9 A
	P94Y80	4902 ABCD	48.4 AB	2356 BC	182 BC	40.8 BC	21.7 BC
	P94Y81	4518 BCD	43.3 BCDE	2140 CD	183 BC	39.5 DEF	21.5 BCD
	P94Y82	4412 CD	48.6 AB	2129 CD	180 BCD	41.5 AB	22.0 B
	P94Y91	5697 A	44.7 BCDE	2365 ABC	164 CD	39.6 DE	22.0 B
	P94Y92	4026 D	46.6 ABC	1936 D	166 CD	38.6 F	21.6 BCD
	P95Y10	5243 ABC	40.1 DE	2545 AB	179 BCD	40.1 CD	21.2 CDE
	S44-K7	4615 BCD	45.4 ABCD	2337 ABC	164 CD	42.0 A	20.6 EF
	S46-U6	4848 ABCD	39.2 E	2360 BC	178 BCD	39.9 CD	21.9 B
	S49-A5	4066 D	44.1 BCDE	2262 BCD	157 D	37.6 G	23.0 A
2012	AG4303	6618 BC	49.4 AB	3625 E	184 A	39.9 A	22.6 AB
	AG4531	6473 BC	47.8 ABC	4259 D	152 BCD	40.0 A	21.2 E
	AG4907	6977 ABC	44.3 CD	5576 A	125 G	38.9 B	21.5 DE
	AG5332	7171 AB	45.8 BCD	4907 BC	146 CDE	40.3 A	20.6 F
	AG5503	6517 BC	45.6 CD	4652 BCD	140 DEFG	37.9 C	21.2 C
	P94Y23	7690 A	50.9 A	4485 BCD	170 AB	38.4 BC	22.8 A

	P94Y80	7144 ABC	47.4 ABC	4365 CD	163 BC	40.1 A	22.0 C
	P94Y81	7057 ABC	46.0 BCD	5130 AB	140 DEFG	39.0 B	21.9 CD
	P94Y82	6411 CD	50.3 A	4305 D	149 CDE	39.9 A	23.0 A
	S44-K7	6399 CD	49.4 AB	4867 BC	132 FG	40.5 A	21.1 E
	S46-U6	6730 BC	43.2 D	4915 BC	137 DEFG	40.6 A	21.2 E
	S49-A5	5765 D	44.0 CD	4280 D	135 EFG	37.6 C	22.3 BC
2013	AG4531	7071	51.9 ABC	3160 BCD	200 A	42.8 A	22.0 JK
	AG4632	7047	51.7 ABC	3415 ABCD	180 BCD	41.3 BCDE	22.3 HIJ
	AG4933	7599	47.4 BC	3685 ABC	178 CDE	41.2 CDEF	22.1 JK
	AG5332	6237	45.5 C	2927 DE	169 EF	42.1 AB	22.9 CDE
	AG5503	6062	45.7 C	3000 CDE	176 CDEF	38.6 G	24.4 A
	P94Y23	6760	52.1 ABC	3087 BCDE	190 AB	40.6 DEF	23.2 BC
	P46T21	6502	48.7 BC	3056 CDE	187 ABC	41.7 BC	22.6 FGH
	P47T36	6636	51.4 ABC	3246 BCD	178 CDE	41.0 CDEF	23.2 BCD
	P94Y80	5792	49.2 BC	2740 DE	183 BC	41.6 BC	22.8 EFG
	P94Y81	6118	46.1 BC	3104 BCDE	171 DEF	40.4 EF	22.9 CDE
	P94Y82	4977	53.4 AB	2380 E	181 BCD	42.2 AB	23.4 B
	P95Y10	6779	51.1 ABC	3210 BCD	183 BC	41.5 BC	22.9 DEF
	S44-K7	5767	53.2 AB	3363 ABCD	167 EFG	42.6 A	21.8 K
	S46-G9	7794	57.9 A	4131 A	165 FG	40.3 F	22.5 GHI
	S49-F8	6794	52.7 AB	3777 AB	156 G	41.4 BCD	22.2 IJ

† Means followed by different letters within a column and year denote that means differed ($\alpha=0.05$) as determined Fisher's protected LSD.

Table 5-4. Pearson correlation coefficients for biomass accumulation rate (BAR), radiation use efficiency (RUE), nitrogen accumulation rate (NAR), specific leaf weight (SLW), specific leaf nitrogen (SLN), harvest index (HI), dry matter allocation coefficient (DMAC), seedfill period (SFP), yield, individual seed weight (Seedwt), seeds m⁻² (Seed#), protein and oil concentrations for all cultivars and years from Fayetteville.

	RUE	NAR	HI	DMAC	SFP	Yield	Seedwt	Seed#	Protein	Oil
BAR	0.99***	0.90***	-0.08	0.45	0.32**	0.19	-0.40***	0.41***	-0.05	-0.05
RUE		0.91***	-0.01	0.16	0.37***	0.25**	-0.35***	0.41***	-0.50	0.06
NAR			-0.17	0.23	0.49***	0.08	-0.54***	0.43***	-0.10	-0.07
HI				0.27	-0.03	0.41***	0.12	0.26**	0.25**	0.04
DMAC					-0.84***	-0.08	0.42***	-0.32***	0.11	-0.06
SFP						0.23*	-0.40***	0.42***	-0.04	0.10
Yield							-0.11	0.85***	0.08	0.05
Seedwt								-0.60***	0.29***	-0.09
Seed#									-0.06	0.05
Protein										-0.54***

The symbols, *, **, and *** indicate significance at the $\alpha = 0.05, 0.01,$ and 0.001 levels, respectively

Table 5-5. Biomass and N accumulation rates, radiation use efficiency (RUE) means from sampling during the R1 to R3 and R1 to R5 growth stages by year and cultivar from Fayetteville.

Year	Cultivar	Accumulation rate R1 to R3			Accumulation rate R1 to R5		
		Biomass	N	RUE	Biomass	N	RUE
		g m ⁻² d ⁻¹		g MJ ⁻¹	g m ⁻² d ⁻¹		g MJ ⁻¹
2011†	AG4303	20.3	0.71	1.28	.	.	.
	AG4531	18.9	0.66	0.96	.	.	.
	AG4907	14.7	0.57	1.06	.	.	.
	AG5331	15.1	0.55	0.91	.	.	.
	AG5503	13.9	0.47	0.94	.	.	.
	P94Y80	14.5	0.57	0.86	.	.	.
	P94Y81	14.9	0.58	0.97	.	.	.
	P94Y82	16.1	0.59	0.92	.	.	.
	P94Y91	18.1	0.73	1.09	.	.	.
	P94Y92	13.5	0.56	0.83	.	.	.
	P95Y10	14.1	0.51	0.88	.	.	.
	S44-K7	15.9	0.59	0.98	.	.	.
	S46-U6	15.8	0.56	1.06	.	.	.
	S49-A5	19.1	0.62	1.19	.	.	.
2012‡	AG4303	27.4 ABC§	1.05	1.23	.	.	.
	AG4531	28.2 ABC	0.94	1.16	.	.	.
	AG4907	29.0 ABC	0.96	1.42	.	.	.
	AG5332	26.2 BC	1.02	1.18	.	.	.
	AG5503	23.0 C	0.97	1.18	.	.	.
	P94Y23	32.0 AB	1.19	1.46	.	.	.
	P94Y80	33.7 A	1.26	1.51	.	.	.
	P94Y81	23.9 C	0.88	1.14	.	.	.
	P94Y82	29.5 ABC	1.11	1.34	.	.	.

	S44-K7	32.8 AB	1.10	1.45	.	.	.
	S46-U6	23.1 C	1.06	1.27	.	.	.
	S49-A5	28.4 ABC	0.98	1.28	.	.	.
2013¶¶	AG4531	41.3	1.52	1.71	††23.0 ABC	††0.62 CDE	††1.01 ABC
	AG4632	32.9	1.08	1.36	23.4 AB	0.64 BCDE	1.04 AB
	AG4933	33.4	1.17	1.38	17.4 D	0.47 E	0.77 CD
	AG5332	36.9	1.35	1.53	21.1 BCD	0.72 ABCD	0.93 BCD
	AG5503	37.9	1.28	1.57	17.3 D	0.50 E	0.76 D
	P94Y23	43.2	1.43	1.79	20.8 BCD	0.57 CDE	0.91 BCD
	P46T21	40.3	1.09	1.67	20.1 BCD	0.51 DE	0.89 BCD
	P47T36	40.2	1.45	1.67	23.6 AB	0.78 ABC	1.05 AB
	P94Y80	38.4	1.48	1.59	23.4 AB	0.65 ABCDE	1.04 AB
	P94Y81	33.4	1.26	1.39	23.8 AB	0.62 CDE	1.06 AB
	P94Y82	35.5	1.31	1.47	17.8 CD	0.53 DE	0.78 CD
	P95Y10	37.2	1.15	1.55	21.7 BCD	0.55 DE	0.96 BCD
	S44-K7	38.4	1.31	1.59	20.1 BCD	0.58 CDE	0.89 BCD
	S46-G9	25.4	1.39	1.47	24.9 AB	0.88 A	1.11 AB
	S49-F8	40.6	1.43	1.72	27.9 A	0.86 AB	1.25 A

† From two sample dates with corresponding canopy radiation interception of *ca.* 0.50 and >0.91 and growth stages V5 and R2.

‡ From two sample dates with corresponding canopy radiation interception of *ca.* 0.90 and >0.95 and growth stages R2 and R3.

§ Means followed by different letters within a column and year denote that means differed ($\alpha=0.05$) as determined Fisher's protected LSD.

¶ From two sample dates with corresponding canopy radiation interception of *ca.* >0.95 and growth stages R1 and R3.

†† From three sample dates with corresponding canopy radiation interception of *ca.* >0.95 and growth stages R1, R3 and R5.

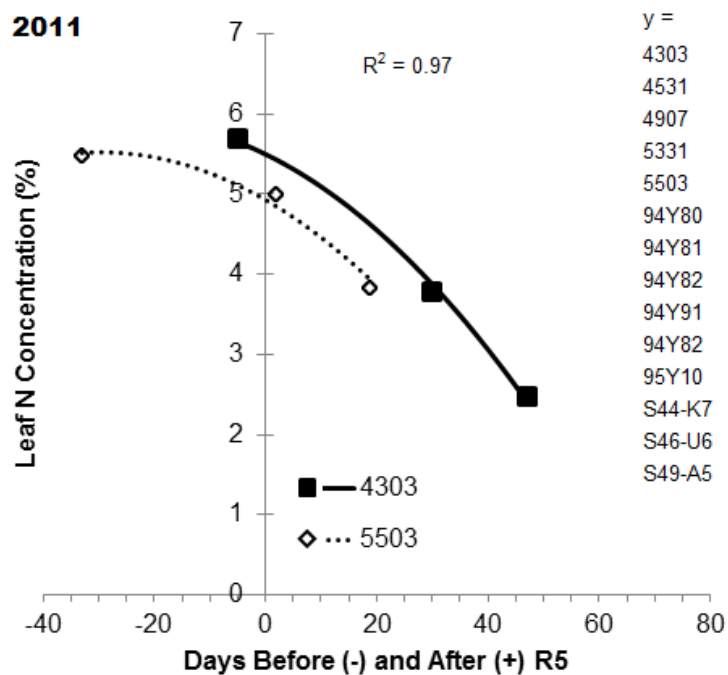
Table 5-6. Proportion of N from biological N₂ fixation (BNF), specific leaf weight, specific leaf N, dry matter accumulation coefficient (DMAC) and seedfill period (SFP) means by year and cultivar from Fayetteville.

Year	Cultivar	Specific leaf			DMAC	SFP
		BNF %	weight g m ⁻² leaf area	Specific leaf N g N m ⁻² leaf area		
2011	AG4303	.	.	.	.	.
	AG4531	.	.	.	0.0095	51.6
	AG4907	.	.	.	0.0101	46.6
	AG5331	.	.	.	0.0080	55.1
	AG5503	.	.	.	0.0107	37.9
	P94Y80	.	.	.	0.0091	53.0
	P94Y81	.	.	.	0.0091	49.0
	P94Y82	.	.	.	0.0107	44.9
	P94Y91	.	.	.	0.0123	39.5
	P94Y92	.	.	.	0.0092	44.0
	P95Y10	.	.	.	0.0085	49.0
	S44-K7	.	.	.	0.0101	45.8
	S46-U6	.	.	.	0.0101	44.2
S49-A5	.	.	.	.	.
2012	AG4303	4.8	53.9	2.70 BC	0.0048 CD†	108.6 ABCD
	AG4531	0.0	54.5	2.85 B	0.0082 AB	59.9 D
	AG4907	0.0	51.9	2.77 BC	0.0063 BC	73.3 CD
	AG5332	0.0	54.8	2.85 B	0.0035 D	128.6 A
	AG5503	0.0	56.8	2.90 AB	0.0061 BC	77.6 BCD

	P94Y23	0.0	58.2	2.98 AB	0.0059 C	85.9 BCD
	P94Y80	0.7	54.7	2.81 BC	0.0101 A	47.5 D
	P94Y81	0.0	55.4	3.00 AB	0.0053 CD	91.1 ABCD
	P94Y82	0.0	54.2	3.04 AB	0.0046 CD	122.9 AB
	S44-K7	1.7	61.1	3.22 A	0.0088 A	57.3 D
	S46-U6	0.0	55.9	2.93 AB	0.0046 CD	91.6 ABCD
	S49-A5	0.0	49.4	2.45 C	0.0056 C	83.9 BCD
2013	AG4531	2.4	56.6	2.97	0.0121	43.4 CDEF
	AG4632	0.0	62.4	3.17	0.0113	38.4 EF
	AG4933	0.0	58.8	3.05	0.0129	36.9 F
	AG5332	4.9	56.7	3.01	0.0097	41.3 CDEF
	AG5503	9.8	53.6	2.85	0.0089	54.0 ABC
	P94Y23	3.5	58.4	3.11	0.0138	37.0 F
	P46T21	3.1	56.5	2.91	0.0083	58.7 A
	P47T36	0.0	59.6	3.15	0.0114	45.2 CDEF
	P94Y80	0.0	62.3	3.16	0.0110	46.4 BCDEF
	P94Y81	0.0	58.7	3.12	0.0116	39.3 DEF
	P94Y82	2.5	58.4	3.20	0.0122	38.9 EF
	P95Y10	0.0	52.2	2.71	0.0100	51.3 ABCD
	S44-K7	3.3	58.9	3.08	0.0096	57.1 AB
	S46-G9	0.0	50.6	2.78	0.0122	49.4 ABCDE
	S49-F8	0.0	54.0	2.92	0.0106	50.3 ABCDE

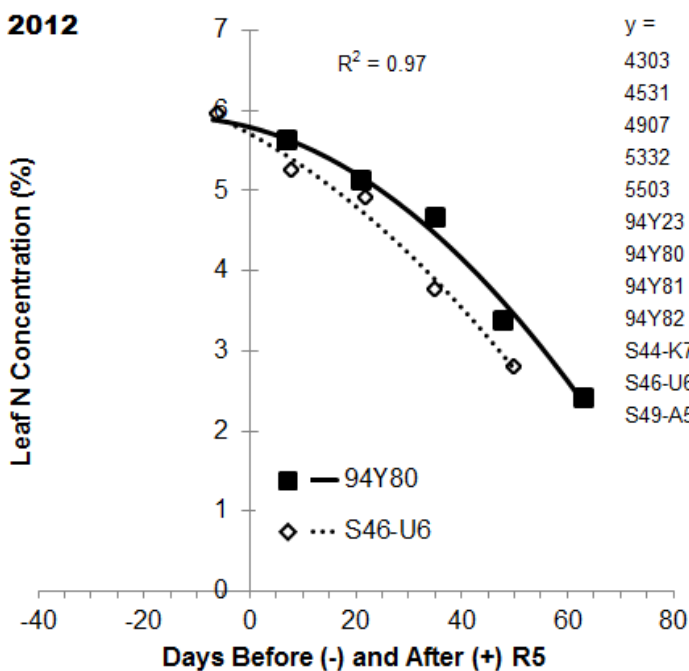
† Means followed by different letters within a column and year denote that means differed ($\alpha=0.05$) as determined Fisher's protected LSD.

2011



y =	ax^2	+	bx	+	c
4303	-0.00067838	-0.03382867	5.50006456		
4531	-0.00067838	-0.02689703	5.62855638		
4907	-0.00067838	-0.04463882	5.21214426		
5331	-0.00067838	-0.03629929	4.79093536		
5503	-0.00067838	-0.04016302	4.93005073		
94Y80	-0.00067838	-0.03142141	5.29098003		
94Y81	-0.00067838	-0.03820606	5.22667425		
94Y82	-0.00067838	-0.03454030	5.40520126		
94Y91	-0.00067838	-0.04174551	5.15572440		
94Y82	-0.00067838	-0.04163633	4.96746017		
95Y10	-0.00067838	-0.03887875	5.08729281		
S44-K7	-0.00067838	-0.03632255	5.33546605		
S46-U6	-0.00067838	-0.02309749	5.46692805		
S49-A5	-0.00067838	-0.03562517	5.00217379		

2012



y =	ax^2	+	bx	+	c
4303	0.00002748	-0.05446840	6.18067489		
4531	-0.00033194	-0.02784536	5.97582093		
4907	-0.00085032	-0.01851396	5.70321869		
5332	-0.00055661	-0.02704231	5.49191197		
5503	-0.00103511	-0.00419206	5.48350720		
94Y23	-0.00029284	-0.03492043	5.85550135		
94Y80	-0.00059263	-0.01724946	5.79424903		
94Y81	-0.00092570	-0.01424774	5.72698690		
94Y82	-0.00111143	0.01593635	5.60133658		
S44-K7	-0.00050703	-0.03471290	5.51830151		
S46-U6	-0.00045196	-0.03622766	5.71201515		
S49-A5	-0.00060635	-0.03402502	5.12865548		

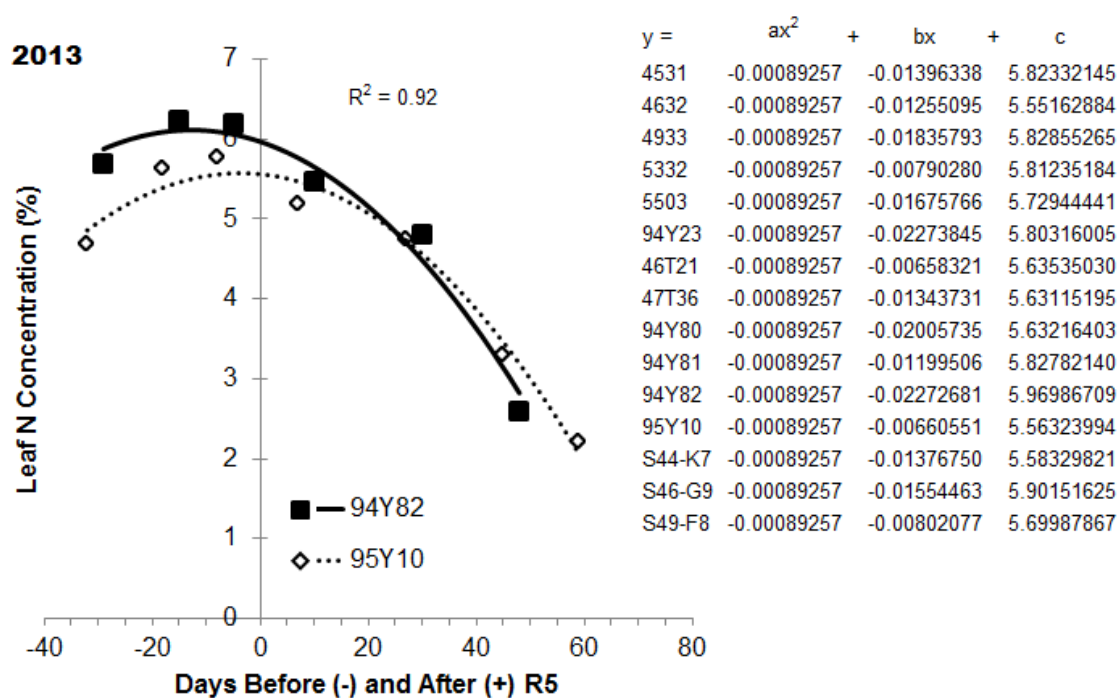


Figure 5-1. Leaf N concentration over days before and after the R5 growth stage by year and cultivar from Fayetteville. For clarity, only responses of two cultivars are shown for each year. At given sample dates, average values (n=4) are represented by data points. Individual samples were used to conduct covariate analysis, using cultivar as a covariate. For cultivars, regression coefficients are given in the figure with significantly different regressions represented by different coefficient values.

CHAPTER 6

Evaluation of Management Factors for Increasing Soybean Yield in a Maximum Yield

Environment

ABSTRACT

In 2006, 2007, and 2010, Mr. Kip Cullers of southwest Missouri submitted soybean yields of 9339 kg ha⁻¹, 10,388 kg ha⁻¹ and 10,791 kg ha⁻¹ to the Missouri Soybean Association Yield Contest, respectively. These extraordinary yields spurred great interest in elevating soybean yields. As such, several of Mr. Cullers' alternative management practices were employed by farmers throughout the United States without unbiased data supporting their efficacy. In concurrent maximum yield research at the University of Arkansas from 2011 to 2013, we examined the yield effect of various seed treatments, intentional herbicide injury, uniform plant spacing and emergence, lodging prevention, and a proprietary foliar-applied product. Grain yields over all treatments and years ranged from 6038 to 6726 kg ha⁻¹, with no significant differences among treatments. In 2011, yields ranged from 4916 to 6082 kg ha⁻¹ with lactofen herbicide plus crop-oil application being the only treatment with significantly greater yield than the control. In 2012, yields ranged from 6387 to 7248 kg ha⁻¹, with no treatments significantly greater than the control. In 2013, there was a significant cultivar by treatment interaction with yields ranging from 4862 to 8687 kg ha⁻¹ but again, no treatments were significantly greater than the control for either cultivar evaluated. It was concluded that none of these alternative practices likely contributed to the yields reported by Mr. Cullers beyond the intense fertility, irrigation and pest control practices utilized within this maximum yield environment.

INTRODUCTION

The greatest United States mean soybean yield was 2956 kg ha⁻¹ in 2009 (USDA-NASS, 2013). Although there is not currently a national soybean yield contest, several states conduct annual yield contests for their respective soybean growers. Over all of these contests, the greatest yields belong to Mr. Kip Cullers of southwest Missouri. Mr. Cullers entered and won the Missouri Soybean Association Yield Contest in 2006, 2007 and 2010 with yields of 9339 kg ha⁻¹, 10,388 kg ha⁻¹ and 10,791 kg ha⁻¹, respectively (Cubbage, 2010). The only other grower in a Missouri contest to break 6719 kg ha⁻¹ (100 bushels acre⁻¹) was Mr. Charlie Hinkebein with a yield of 7324 kg ha⁻¹ in 2008 (Steever, 2008). Despite the requirement for unbiased judges and strict oversight during harvest of the contest (Missouri Soybean Association, 2013), the magnitude of Mr. Cullers yield levels were brought into question and were higher than many had previously thought possible for soybean. As such, research was undertaken to provide empirical data from those contest fields as well as in defined experimental conditions at the University of Arkansas (Ch. 3, 4, and 5) in an attempt to document and understand soybean yields of this magnitude.

Another byproduct of the extraordinary yields reported by Mr. Cullers was the interest generated in several of the unusual management practices made popular via the press and advertisements. The press has widely publicized Mr. Cullers use of irrigation, daily scouting, Optimize 400 (Novozymes, Bagsvaerd, Denmark) and Bio-Forge (Stoller USA, Houston, TX), seed treatments, Headline (BASF, Ludwigshafen, Germany) foliar fungicide, Asana XL and Steward EC (DuPont, Wilmington, DE) insecticides, intentional injury with lactofen herbicide (Cobra, Valent, Libertyville, IL), sugar applications, and several other alternative practices (e.g. Ball, 2011). Many of these practices were tried by farmers throughout the U.S. in efforts to

recreate those yields reported by Mr. Cullers. In some cases, scientists set out to examine such practices. For example, Furseth et al. (2011) determined that foliar sugar applications had no effect on grain yield. This should not be a surprise given that 3.36 kg sucrose ha⁻¹ would only offset *ca.* 18 minutes of canopy photosynthesis, assuming a typical crop growth rate of 16 g m⁻² d⁻¹. Other practices including seed treatments, intentional herbicide injury, and uniform plant spacing have not been systematically evaluated. Research was undertaken to examine the yield effects of these other practices that have been popularized by Mr. Cullers in a similar maximum yield environment.

MATERIALS & METHODS

Within the same field and management system described previously at the University of Arkansas Agricultural Research and Extension Center (Ch. 5), two cultivars, AG4907 (2011-2012) or AG4632 (2013) and P94Y81 (2011-2012) or P47T36 (2013) were evaluated for nine (2011), fourteen (2012) or seventeen (2013) treatments. Plots were planted in four rows, 46-cm apart, and 6 m in length. Plots were arranged in a randomized complete block design with four replications.

All of the following treatments are summarized in Table 6-1. To elaborate: Asgrow seed was treated with Acceleron (7 mL fluxapyroxad, 24 mL metalaxyl, and 12 mL pyraclostrobin, 59 mL imidacloprid per 45 kg of seed). Pioneer seed was untreated by the seed company in 2011 and 2012 but was treated with Pioneer Premium Seed Treatment (2 mL prothioconazole, 1 mL penflufen, 2 mL metalaxyl and 47 mL imidacloprid per 45 kg of seed) in 2013. All seed treatment trials included these seed treatments and the “Untreated” did not receive any additional seed treatments. The “Optimize” treatment included the addition of Optimize 400

(*Bradyrhizobium japonicum* and lipto-chitooligosaccharide; Novozymes, Bagsvaerd, Denmark) at a rate of 296 mL of Optimize 400 and 89 mL liquid additive per 45 kg seed. “Accolade” included the addition of Accolade-(P) (*Azospirillum brasilense*; INTX Microbials, Kentland, IN) at 400 g per 45 kg seed. “Bio-Forge” included the addition of Bio-Forge (N,N’-diformyl urea; Stoller USA, Houston, TX) at 59 mL per 45 kg seed. “Bio-Forge+Optimize” (2013 only) included the addition of Optimize 400 and Bio-Forge, both at the previously described rate. Lastly, the “Treated control” contained all of the seed treatments used in Ch. 5, which were Bio-Forge, Optimize 400, Accolade-(P), 89 mL liquid additive, 444 mL of Primo CL (*Bradyrhizobium japonicum*; INTX Microbials, Kentland, IN) and 148 mL rhizobium extension solution (2011 only), and 227 g Nutriplant SD (4.0% Ca, 2.0% Mg, 4.0% S, 0.001% Co, 0.075% Cu, 1.0% Fe, 0.25% Mn, 0.0005% Mo, 1.0% Zn; Access Business Group Int. LLC., Ada, MI). All of the following additional treatments evaluated were planted with seed that included all of the seed treatments used for the “Treated control”.

The evaluation of purposeful herbicide injury treatments included a *ca.* V3 growth-stage application of 219 g ha⁻¹ lactofen for the “Cobra” treatment, 219 g ha⁻¹ lactofen and 2% v/v crop oil concentrate for “Cobra+CO”. In 2012 and 2013, a “Cadet” and “Aim” treatment were added with a V3 growth stage application of 7 g ha⁻¹ fluthiacet-methyl or 9 g ha⁻¹ carfentrazone-ethyl, respectively. In 2013, the “Cobra+Aim+CO” included 219 g ha⁻¹ lactofen, 9 g ha⁻¹ carfentrazone-ethyl, and 2% v/v crop oil concentrate applied at *ca.* the V3 growth stage. All plots had all the same seed treatments as the “Treated control”.

Additionally, the effect of uniform within-row plant spacing and uniform emergence were evaluated. The “Even spacing” treatment consisted of over seeding at a high population and hand thinning to the same plant density as the “Treated control” prior to the V1 growth stage

with emphasis on creating even within-row seedling spacing (perfect picket fence spacing). In 2012 and 2013, an “Even height” treatment was added where plots were again over seeded and thinned to the same plant density as the “Treated control” but with emphasis on removing abnormally large or small seedlings, leaving a stand of uniformly sized seedlings to simulate a perfectly emerged crop. All plots had all the same seed treatments as the “Treated control”. Another treatment included “No lodging”, where fence posts were placed at the outside corners of plots and outside the first and last row in the middle of the plots. String was laced between posts to prevent plants from lodging. Grids were strung at *ca.* 0.75 m and 1.25 m above the ground and the plants grew through the string grid. Lastly, in 2013, a “Foliar” treatment consisted of a foliar application of a proprietary product developed by Mr. Cullers (www.kipcullers.com) at a rate of 1.4 L ha⁻¹ at the V6 and R3 growth stages.

Stand counts were determined soon after emergence as previously described (Ch. 5). Grain was harvested from 4.5 m of the center two rows. Grain yield, seed weight and seed number were calculated as previously described. Data for each year were analyzed using the GLM procedure of SAS (SAS Institute, Cary, NC). Mean comparisons were separated using Fisher’s protected LSD test ($\alpha = 0.05$). In addition, treatments that were included in all three years of research were analyzed using the MIXED procedure of SAS. Only treatment was considered a fixed effect, with cultivar, year, block (nested within year) and all interactions being considered random effects.

RESULTS & DISCUSSION

Growing conditions were discussed in Ch. 5 (Table 5-2). Briefly, 2011 and 2012 were characterized by abnormally hot temperatures from June to August and the months of April and

May in 2011 and 2013 were abnormally wet compared to the 30-yr mean. Despite these challenges, grain yields averaged 6726 kg ha⁻¹ for the Treated control treatment over 3 years and two cultivars (Table 6-2).

Analysis of variance over 3 years and two cultivars indicates that none of the treatments had a significant effect on yield ($P = 0.81$), seeds m⁻² ($P = 0.80$) or seed weight ($P = 0.44$) (Table 6-2). However, when examining the data by year, cultivar had a significant effect on seeds m⁻² in 2011 and 2012 and seed weight in all years (Appendix 6-1). Over all treatments in 2011, cultivar AG4907 had significantly more seed (3090 seeds m⁻²) and significantly lower seed weight (152 mg seed⁻¹) than P94Y81 (2557 seeds m⁻² and 177 mg seed⁻¹). This trend continued in 2012 between AG4907 (4460 seeds m⁻² and 136 mg seed⁻¹) and P94Y81 (4040 seeds m⁻² and 152 mg seed⁻¹). In 2013, seed weights were greater for P47T36 (183 mg seed⁻¹) compared with AG4632 (177 mg seed⁻¹). Additionally, treatments significantly affected yield in all years (Appendix 6-1) and a cultivar by treatment interaction existed in 2013 for yield and seeds m⁻². These results are further examined and discussed below.

Supplemental Seed Treatments

Of all the supplemental seed treatments evaluated in 2011 (Optimize, Accolade, Bio-Forge), no treatment statistically increased yield over the Untreated treatment (Table 6-3). The only statistical yield difference was where the Bio-Forge treatment significantly increased yield 757 kg ha⁻¹ over the Treated control. In 2012, the Accolade treatment (6387 kg ha⁻¹) had significantly lower yield than the Untreated (7248 kg ha⁻¹), Optimize (7309 kg ha⁻¹) and Treated control (7065 kg ha⁻¹), while all other treatments had statistically similar yields. However in 2013, a significant cultivar by treatment interaction revealed an alternative response to the

Optimize treatment (Appendix 6-1). Cultivar AG4632 had a 1261 kg ha⁻¹ yield increase with the Optimize treatment compared with the AG4632 Untreated, while P47T36 had a 1634 kg ha⁻¹ yield decrease compared with the P47T36 Untreated (Table 6-4). The Treated control also had significantly higher yield than the Untreated, Accolade and Optimize treatment with P47T36. With AG4632, only the Bio-Forge+Optimize treatment had significantly lower yield compared to the Optimize treatment. The reasons for these responses are unknown but may be due to the random effects of early season lodging that was observed in 2013.

De Bruin et al. (2010) demonstrated that across 73 experiments, only 10 had a significant yield response to *Bradyrhizobia japonicum* inoculant products when nodulating soybeans had previously been grown at those locations. Thus, the Accolade-(P) and Optimize 400 inoculants would be unlikely to significantly affect soybean yields when native *Bradyrhizobia* are present for nodulation and N₂ fixation. Additionally, in the presence of large amounts of mineral N, N₂ fixation would be greatly decreased (Salvagiotti et al., 2008).

Stoller's Bio-Forge is classified as an antioxidant and is claimed to improve growth by preventing excessive ethylene production and increasing stress tolerance and root growth via up-regulation of several different genes. While Stoller has reported several University studies documenting yield increases with various Bio-Forge applications (Stoller USA, 2014), no yield responses were observed in the present work despite heat stresses in 2011 and 2012 (Table 6-3). It is possible that the seed treatment application did not supply sufficient amounts of the product to benefit the crop later in the year when the hot high temperatures occurred (Table 5-2). In summary, these results indicate that there were no synergistic effects among these additional seed treatments and no statistically significant yield response is expected when fungicide and insecticide seed treatments are utilized within a maximum yield environment.

Intentional Herbicide Injury

When examining these herbicide treatments by year (Cobra, Cobra+CO, Cadet, Aim, Cobra+Aim+CO), a significant yield increase was observed in 2011 with Cobro+CO (6082 kg ha⁻¹) compared with the Cobra (5210 kg ha⁻¹) and Treated control (5003 kg ha⁻¹) (Table 6-3). However in 2012, there was no significant effect on yield with the Cobra+CO (7128 kg ha⁻¹), Cobra (6717 kg ha⁻¹), Cadet (6533 kg ha⁻¹) or Aim (6651 kg ha⁻¹) treatments compared to the Treated control (7065 kg ha⁻¹). A significant cultivar by treatment interaction existed in 2013 (Table 6-4, Appendix 6-1). For P47T36, the Aim only treatment (7265 kg ha⁻¹) had a similar yield to the Treated control (8687 kg ha⁻¹) but all other herbicide injury treatments had significantly lower yield (6250 to 6962 kg ha⁻¹). For AG4632, all treatments had similar yield (6146 to 6587 kg ha⁻¹) to the Treated control (6841 kg ha⁻¹) except the Cobra+Aim+CO treatment, which had significantly lower yield (4865 kg ha⁻¹).

The intended goal of these herbicide injury treatments was to limit growth from the apical meristem and induce branching to reduce plant height and lodging. This effect was only achieved in 2013 with the Cobra+Aim+CO treatment (Fig. 6-1). While a reduction in plant height and increased branching was observed, grain yields were 2437 and 1976 kg ha⁻¹ lower than the Treated control for P47T36 and AG4632, respectively (Table 6-4). This yield loss was associated with a reduction in seed number for P47T36 and a combination of seed number and weight for AG4632. An alternative option for decreasing plant height in a high fertility situation in the mid-southern US to decrease plant height and positively affect yield may be to plant soybean earlier during the month of April. Early planting can result in more node production for indeterminate cultivars but with shorter internode lengths due to the cooler temperatures compared with later planting dates (Akhter and Sneller, 1996; Bastidas et al., 2008; Wilcox and Frankenberger,

1987). While the application of Cobra herbicide has occasionally shown yield benefits by helping to suppress white mold (Oplinger et al., 1999; Nelson et al., 2002), most other research results suggest yield reductions are more likely to occur (Dann et al., 1999; Kyle, 2013).

Plant Spacing and Emergence Timing

In 2011, the Even spacing treatment (5298 kg ha⁻¹) did not affect yield compared with the Treated control (5003 kg ha⁻¹, Table 6-3, Appendix 6-1). In 2012, neither the Even spacing (7123 kg ha⁻¹) nor the Even height (7129 kg ha⁻¹) treatment affected yield compared with the Treated control (7065 kg ha⁻¹). In 2013, there was a significant cultivar by treatment interaction for yield (Table 6-4, Appendix 6-1). For P47T36, the Even spacing and Even height treatments had 2795 kg ha⁻¹ and 1978 kg ha⁻¹ lower yield than the Treated control, respectively (Table 6-4). However, for AG4632, the Even spacing and Even height treatments had similar yield to the Treated control. With P47T36, the yield differences were due to significantly fewer seeds.

For comparison, the cultivar by treatment interaction was nonsignificant in 2011 and 2012 (Appendix 6-1). Although these opposing cultivar responses in 2011 and 2012 compared with 2013 may be artifacts of small plot research, recent research indicates that newer cultivars have a greater ability to increase grain yield on branches compared with older cultivars (Suhre et al., 2014). As such, it is possible that differences exist among cultivars for their ability to compensate for non-uniformity of within-row spacing or emergence. This is an area that may warrant future investigation.

With corn [*Zea mays* L.] production, increasing plant spacing variation can significantly reduce yield (Krall et al., 1977; Nielsen, 1997; Vanderlip et al., 1988) but not always (Erbach et al., 1972; Johnson and Mulvaney, 1980; Lauer and Rankin, 2004; Muldoon and Daynard, 1981;

Nielsen, 1995). Holshouser et al. (2006) determined that in late-planted, double-crop soybean, both 19-cm rows and uniform spacing were required to increase yield over a uniform stand in 38-cm rows or a non-uniform stand in 19-cm rows. However, with normal planting dates, others have determined that within-row distribution had no effect on soybean yield (Ess et al., 2005; Naeve et al., 2001), in agreement with this study.

We suspect that the effects of these treatments are related to the response of soybean to plant density. Edwards et al. (2005) demonstrated that 605 MJ m^{-2} of intercepted solar radiation was required to obtain 90% of the asymptotic yield, while 90% of asymptotic biomass required 1175 MJ m^{-2} . With increasing plant densities and intercepted solar radiation $>605 \text{ MJ m}^{-2}$, a decrease in the harvest index offset the yield benefit of the increased biomass production (Edwards et al., 2005). Likewise, we suggest that increasing the stand uniformity may act to increase solar radiation interception and a similar decline in the yield response occurs after sufficient radiation is intercepted. However, interactions with maturity group may affect the minimum plant density or degree of uniformity required to achieve such radiation interception levels to maintain full yield potential (Edwards et al., 2005). Beyond the effect of radiation interception and utilization, increasing plant (and root) spacing uniformity may allow the crop to better scavenge nutrient and water resources and act to reduce stresses on the plants. These effects have been documented for corn production in narrow rows (Sharratt and McWillimas, 2005). However, the likelihood of uniformity affecting resource utilization would presumably decrease under conditions of high fertility and irrigation as in the present research.

Lodging Prevention

In 2011, limited lodging was observed and yields were similar between the No lodging and Treated control treatments (Table 6-3). Increased lodging was observed in 2012; however, the No lodging treatment did not affect yield compared with the Treated control. Lodging was also evident in 2013, but there were opposing responses to the No lodging treatment between cultivars. Cultivar P47T36 had a significant 2306 kg ha⁻¹ yield reduction for the No lodging treatment but there was no effect of the treatment for AG4632 compared with the Treated control. Yield reductions for P47T36 were due to fewer seeds m⁻².

Lodging during the reproductive stages decreases yields by 21 to 23% (Cooper, 1971), with the greatest decreases occurring when lodged at the R5 growth stage (Woods and Swearingin, 1977). We suggest that the yield decrease with this No lodging treatment in P47T36 in 2013 was due to the supports used to hold plants upright. The sting grids were triangles with each side approximately 0.5 m long. As such, the grids allowed plants to lean but not completely lodge. Several of the plants leaned together into the corners of the triangle grids and likely shaded themselves more so than if the whole plot had been allowed to lean to one direction.

Foliar Product

In 2013, the foliar product supplied by Mr. Cullers did not significantly affect yield, seeds m⁻² or seed weight (Table 6-4). As farmers apply herbicides or late-season fungicides, many consider the addition of foliar fertilizer products since the application costs will have already been incurred (Binford et al., 2004; Nelson et al., 2010). Mr. Cullers recommended applying his product with a postemergence glyphosate application and again with a fungicide application during reproductive growth. Similar to these results, the results of foliar fertilization

research have often been variable for yield and economic responses (Binford et al., 2004; Mallarino et al., 2001; Nelson and Motavalli, 2007; Nelson et al., 2010). Additionally, the response to foliar fertilization is suggested to decrease with adequate fertility (Mallarino et al., 2001) as existed in the present research. At this time, it is undetermined whether Mr. Cullers will release this product for sale in the U.S. or what the exact contents and formulations were.

CONCLUSIONS

Over three years of research, none of the seed treatments, herbicide treatments, or additional management practices significantly or consistently increased yield above the prescribed maximum yield management with the standard seed treatment provided by the seed companies. One practice that may be worthy of further research is the idea of uniform versus nonuniform within-row plant spacing and/or emergence with the interaction of cultivar. While not conclusive, our results indicate that cultivars may respond differently to changes in plant spacing and/or emergence variability. While some of these alternative management practices gain publicity because of their utilization by Mr. Cullers as a component of his maximum yield contest entries, we could not confirm their utility as part of a high yield management program. We conclude that the management practices detailed in Ch. 5 will have a greater impact on soybean grain yield than the additional management practices examined in this chapter.

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Table 6-1. Summary of treatments evaluated with two cultivars in three years of research at Fayetteville.

Treatment	Treatment No.	Year		
		2011	2012	2013
Untreated	1	Asgrow seed: fluxapyroxad, metalaxyl, pyraclostrobin + imidacloprid. Pioneer seed: no trt.	Asgrow seed: fluxapyroxad, metalaxyl, pyraclostrobin + imidacloprid. Pioneer seed: no trt.	Asgrow seed: fluxapyroxad, metalaxyl, pyraclostrobin + imidacloprid. Pioneer seed: trifloxystrobin, metalaxyl and imidacloprid.
Optimize	2	Trt 1 + Optimize 400 on seed	Trt 1 + Optimize 400 on seed	Trt 1 + Optimize 400 on seed
Accolade	3	Trt 1 + Accolade P on seed	Trt 1 + Accolade P on seed	Trt 1 + Accolade P on seed
Bio-Forge	4	Trt 1 + Bio-Forge on seed	Trt 1 + Bio-Forge on seed	Trt 1 + Bio-Forge on seed
Bio-Forge+Optimize	5	Trt 1 + 2 + 4	Trt 1 + 2 + 4	Trt 1 + 2 + 4
Treated control	6	Trt 1 + 2 + 3 + 4 + Primo Cl + Nutriplant SD on seed	Trt 1 + 2 + 3 + 4 + Primo Cl + Nutriplant SD on seed	Trt 1 + 2 + 3 + 4 + Primo Cl + Nutriplant SD on seed
Cobra	7	Trt 6 + Cobra at V3	Trt 6 + Cobra at V3	Trt 6 + Cobra at V3
Cobra+CO	8	Trt 7 + 2% crop oil at V3	Trt 7 + 2% crop oil at V3	Trt 7 + 2% crop oil at V3
Cadet	9	-	Trt 6 + Cadet at V3	Trt 6 + Cadet at V3
Aim	10	-	Trt 6 + Aim at V3	Trt 6 + Aim at V3
Cobra+Aim+CO	11	-	-	Trt 8 + 10
Even Spacing	12	Trt 6 + thinning to even intra-row spacing	Trt 6 + even intra-row spacing	Trt 6 + even intra-row spacing
Even height	13	-	Trt 6 + thinning to even height at emergence	Trt 6 + thinning to even height at emergence
No Lodging	13	Trt 6 + grid to prevent lodging	Trt 6 + grid to prevent lodging	Trt 6 + grid to prevent lodging
Foliar	14	-	-	Trt 6 + Foliar application at V6 and R3

Table 6-2. Grain yield, seeds m⁻², and seed weight for treatments across three years of research and two cultivars at Fayetteville.

Treatment	Grain yield kg ha ⁻¹	Seeds m ⁻²	Seed Weight mg seed ⁻¹
Treated control	6726†	3608	170
Untreated	6365	3464	167
Optimize	6337	3441	166
Accolade	6174	3295	167
Bio-Forge	6490	3583	164
Cobra	6129	3352	168
Cobra+CO	6337	3370	168
Even Spacing	6367	3420	167
No Lodging	6038	3342	162

† Treatments did not affect grain yield ($P = 0.81$), seeds m⁻² ($P = 0.80$) or seed weight ($P = 0.44$).

Table 6-3. Grain yield, seeds m⁻² and seed weight means by year, cultivar, and treatment over two cultivars from Fayetteville in 2011 and 2012. The cultivar by treatment interaction was not significant for these variables in either year.

Year	Cultivar	Treatment	Yield kg ha ⁻¹	Seeds m ⁻²	Seed weight mg seed ⁻¹
2011	AG4907	Avg.	5451	3090 A†	152 B
	P94Y81	Avg.	5228	2557 B	177 A
	Avg.	Treated control	5003 C	2708	163
	Avg.	Untreated	5350 BC	2960	164
	Avg.	Optimize	5244 BC	2837	163
	Avg.	Accolade	5192 BC	2783	163
	Avg.	Bio-Forge	5762 AB	2996	166
	Avg.	Cobra	5210 BC	2686	170
	Avg.	Cobra+CO	6082 A	2954	168
	Avg.	Even spacing	5298 BC	2813	165
	Avg.	No lodging	4916 C	2670	161
2012	AG4907	Avg.	6802	4460 A	136 B
	P94Y81	Avg.	6974	4040 B	152 A
	Avg.	Treated control	7065 ABCD	4988	143
	Avg.	Untreated	7248 AB	5042	145
	Avg.	Optimize	7309 A	5002	146
	Avg.	Accolade	6387 E	4568	141
	Avg.	Bio-Forge	6902 ABCDE	4863	142
	Avg.	Cobra	6717 BCDE	4823	144
	Avg.	Cobra+CO	7128 ABC	4852	147

Avg.	Cadet	6533 DE	4556	145
Avg.	Aim	6651 CDE	4521	148
Avg.	Even spacing	7123 ABC	4833	148
Avg.	Even height	7129 AB	4927	145
Avg.	No lodging	6528 DE	4758	138

† Different letters within a column and year denote that means differed ($\alpha=0.05$) as determined Fisher's protected LSD.

Table 6-4. Grain yield, seeds m⁻² and seed weight for each treatment by cultivar from Fayetteville in 2013.

Treatment	Yield		Seeds m ⁻²		Seed weight	
	AG4632	P47T36	AG4632	P47T36	AG4632	P47T36
	———— kg ha ⁻¹ ————				— mg seed ⁻¹ —	
Treated control	6841 BCD†	8687 A	3276 BCDEFG	4021 A	192	188
Untreated	6426 CD	6496 BCD	3212 BCDEFG	3065 CDEFGHI	174	184
Optimize	7687 ABC	4862 E	3692ABCD	2426 I	181	176
Accolade	6427 CD	7009 BCD	3099 BCDEFGHI	3250 BCDEFG	178	187
Bio-Forge	6676 BCD	7047 ABCD	3414 ABCDEFG	3476 ABCDEFG	176	171
Bio-Forge+Optimize	6020 ED	7495 ABC	3288 BCDEFG	3551 ABCDEF	177	183
Cobra	6399 CDE	6517 BCD	3158 BCDEFGH	3123 BCDEFGHI	176	181
Cobra+CO	6146 CDE	6588 BCD	3124 BCDEFGHI	3069 CDEFGHI	171	187
Cadet	6587 BCD	6962 BCD	3230 BCDEFG	3390 ABCDEFG	178	179
Aim	6307 CDE	7265 ABCD	2899 EFGHI	3309 ABCDEFG	188	188
Cobra+Aim+CO	4865 E	6250 CDE	2512 HI	2892 FGHI	170	188
Even spacing	7805 ABC	5892 ED	3893 AB	2845 GHI	177	180
Even height	7136 ABCD	6709 BCD	3480 ABCDEFG	3276 BCDEFG	179	187
No lodging	6794 BCD	6381 CDE	3591 ABCDEF	3008 DEFGHI	169	184
Foliar	7391 ABCD	7901 AB	3614 ABCDE	3731 ABC	179	184
Avg.	6608	6862	3291	3274	177 B‡	183 A

† Different letters within a variable column denote that means differed ($\alpha=0.05$) as determined Fisher's protected LSD.

‡ Different letters within the Seed weight column and Avg. treatment row denote that means differed ($\alpha=0.05$) as determined Fisher's protected LSD.

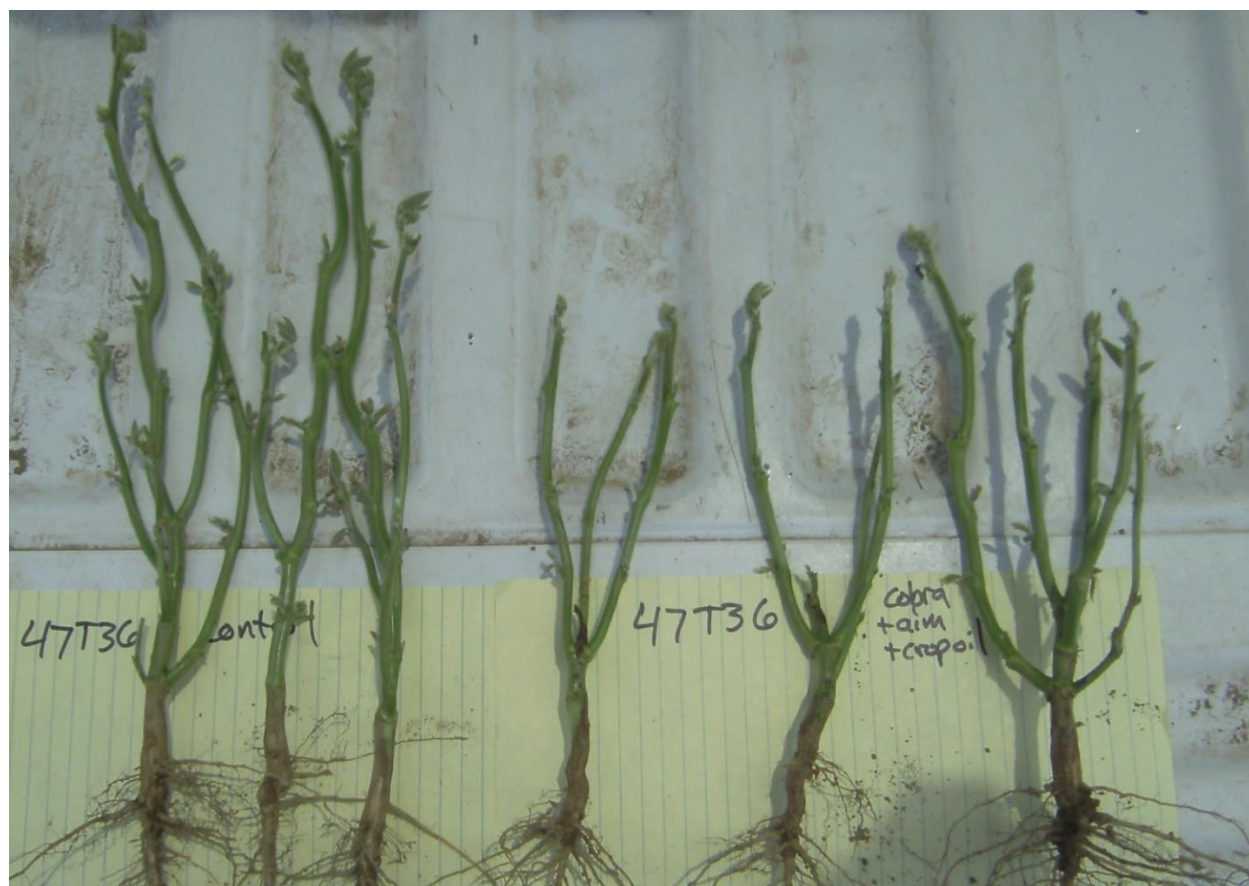


Figure 6-1. A sampling of representative plants with leaves removed to illustrate the effects of terminating the shoot apical meristem with the Cobra+Aim+CO treatment compared with the Treated control for P47T36 in 2013 from Fayetteville.

CHAPTER 7

High-input Management and Soybean Yield Response at the Field Level

ABSTRACT

In 2007, the Arkansas Soybean Association created a prize to award the first Arkansas producer to produce 6719 kg ha⁻¹ (100 bushel acre⁻¹) soybean. In 2011, research was initiated to evaluate the effects of several high yield practices in large-scale production fields. These practices included frequent irrigation and fertility inputs (including supplemental N), early planting, narrow rows, and strict pest control. Several of these practices were observed and utilized at Mr. Cullers' contest fields and in maximum yield experiments in Fayetteville, where yields greater than 6719 kg ha⁻¹ were routinely achieved. However, the intensity of these practices was restrained in order to remain practical for large-scale soybean production. Over cultivars and locations, grain yields averaged 5067 kg ha⁻¹ in 2011, 5906 kg ha⁻¹ in 2012, and 6254 kg ha⁻¹ in 2013. At England, AR in 2013, cultivars P46T21 and P48T53 averaged 6931 and 6986 kg ha⁻¹, respectively. The difference in yield for these two cultivars was mainly due to greater seeds m⁻². Grain yield was positively correlated with final plant height but not main-stem nodes. Favorable weather conditions were observed throughout Arkansas in 2013 and three Arkansas growers had yields exceeding 6719 kg ha⁻¹ in the yield contest. However, a rudimentary economic analysis indicated that these high input production practices were less profitable than the growers' normal production practices, despite the increased grain yields. While 6719 kg ha⁻¹ yields were documented, the production practices necessary for reaching these yields do not appear suitable for widespread adoption.

INTRODUCTION

An annual soybean yield challenge has been conducted by the Arkansas Soybean Association since 1998 (Arkansas Soybean Association, 2006). Several Arkansas growers have submitted contest yields greater than 6000 kg ha⁻¹ but prior to 2013 none of the entries had yields over 6719 kg ha⁻¹ (100 bushels acre⁻¹). In 2007, the Arkansas Soybean Association announced a one-time prize of \$50,000 for the first Arkansas grower to break 6719 kg ha⁻¹, calling this the “Race for 100 Bu/A Soybean Yield Contest” (Arkansas Soybean Association, 2013). One contributing factor which spurred this initiative were the yields reported by Mr. Cullers in 2006 and 2007 (Cubbage, 2010). Arkansas soybean farmers were left contemplating why they could not match the yields reported by Mr. Cullers in the neighboring state of Missouri. Another goal of this contest was to reignite interest in soybean production and encourage farmers to re-examine their production practices and yield goals.

In 2011, research began in Mr. Cullers’ contest field and in Fayetteville to document and understand the crop physiology behind yields greater than 6719 kg ha⁻¹. From this work, several key production practices were identified as major contributing factors for high yield soybean. These practices included cultivar selection, frequent irrigation, intensive fertilization, early planting, narrow rows, strict pest control and supplemental N. These practices were examined for their feasibility for application within traditional Arkansas soybean production systems.

Cultivar selection is a practice that can be utilized wherever soybean are grown. Within a maximum yield environment, the range in yield between cultivars in small plot research in Fayetteville was 1631, 1925 and 2817 kg ha⁻¹ in 2011, 2012 and 2013 (Table 5-2). From that research, it was determined that yields greater than 6719 kg ha⁻¹ could be achieved with several combinations of seed number and weight with a range of elite cultivars with maturity groups

ranges from 4.2 to 5.5. These results highlight the importance of choosing a cultivar that can excel within a specific production system.

Approximately 1,081,000 ha of soybean in Arkansas were grown with some form of irrigation in 2013 (USDA-NASS, 2014). From 2009 to 2013, soybean was grown with irrigation on 77.7% of the hectares, on average. Over this same time period, mean irrigated soybean yields were 2888 kg ha⁻¹, compared with 1783 kg ha⁻¹ for non-irrigated production. While not all of this yield discrepancy can be attributed to irrigation, we can conclude that irrigation is a key practice in Arkansas soybean production and is a practice necessary when attempting to increase yield.

In addition to irrigation, fertility programs are essential for increasing yield. In high yield, irrigated research, Flannery (1986; 1989) documented that a 6786 kg ha⁻¹ soybean crop had a total N and K uptake of 553 and 369 kg ha⁻¹, while the grain removed 361 and 96.5 kg ha⁻¹, respectively. These two nutrients are taken up and removed in greater amounts than any of the other nutrients. In fact, Sinclair and de Wit (1975) found that soybean had the greatest requirement for N out of 24 other plant species. Normally, N is supplied from the soil and through a symbiotic biological N₂ fixation (BNF) relationship with *Bradyrhizobium japonicum*. This relationship generally accounts for 25 to 75% of the total N accumulation by soybean (Varco, 1999). For soils low in organic matter, which are typical in the mid-South, BNF can provide up to 90% of the seed N needs (Mastrodomenico and Purcell, 2012).

Despite the large N requirement, the response of soybean to supplemental N has been inconsistent. A comprehensive review by Salvagiotti et al. (2008) revealed that the difference between total soybean crop N accumulation and the amount of N supplied by BNF increased with increasing seed yield. On average, BNF was able to supply 50-60% of the soybean N demand across all studies. Biological N₂ fixation displayed a negative exponential response to N

fertilization. In the absence of N fertilization, Salvagiotti et al. (2008) predicted that 337 kg ha⁻¹ of N would be fixed. With 100 and 300 kg ha⁻¹ fertilizer-N applied, the predicted amount of N₂ fixed decreased to 129 and 17 kg N ha⁻¹, respectively. The review by Salvagiotti et al. (2009) concluded that a soybean yield response to N fertilization would be more likely to occur at yield levels >4500 kg ha⁻¹ and that deep placement of controlled release fertilizer-N may increase the yield response to supplemental N by not suppressing BNF as greatly as with surface N applications. In the case of K, soybean is often responsive to supplemental K application, especially when soil tests results indicate low levels of soil K (Slaton et al., 2010).

Delayed planting of soybean decreases yield via reductions in seed number and seed weight (Anderson and Vasilas, 1985; Beatty et al., 1982; Bruns, 2011; De Bruin and Pedersen, 2008a; Pedersen and Lauer, 2004; Raymer and Bernard, 1988; Robinson et al., 2009). Alternatively, early planting of indeterminate soybean can result in earlier flowering coinciding with longer daylengths near the summer solstice which can increase seed set (Cooper, 2003; Robinson et al., 2009; Specht, 2010). Along with early flowering, the seedfill period can be extended, which could potentially increase seed weight (Ch. 2, Eq. [4]; Bastidas et al., 2008; Wilcox and Frankenberger, 1987). Narrowing the row width can increase the fraction of radiation interception and reduce the time required to intercept >90% radiation interception (Ball et al., 2000). As a result, grain yield and dry matter production are greater in narrow rows than in wider rows (Ball et al., 2000; Bowers et al., 2000; Bruns, 2011; De Bruin and Pedersen, 2008b; Edwards et al., 2005; Weber et al., 1966).

Protecting a crop through proper pest management is key to maintaining the full yield potential of any crop. Fungicides may increase soybean yield by as much as 15% in high yield environments (Cooper, 1989) and can be an important component in pest management. Failure to

control weeds, like Palmer amaranth (*Amaranthus palmeri*) can reduce yield up to 68% at 10 Palmer amaranth m^{-1} of row (Klingaman and Oliver, 1994). Furthermore, uncontrolled insect outbreaks resulting in 100% defoliation of an irrigated soybean crop at the R4 growth stage decreased yield by 57% (Caviness and Thomas, 1980). Earlier in the season, when the crop is still in the vegetative growth stages, much of this damage can be overcome, and 100% defoliation at the V5 growth stage only reduced yields by 15% (Caviness and Thomas, 1980). Preventing yield losses from all insects, weeds, and diseases is a complex but critical component necessary to realize the true yield potential of soybean.

A project was initiated to evaluate the effects of these high yield soybean production strategies together in large-scale experiments in production fields in the Mississippi Delta region of Arkansas. The goals were to evaluate high-yield production practices while minimizing the additional costs of production, and to demonstrate the yield potential of these practices in unison for Arkansas soybean production.

MATERIALS & METHODS

Two farmers in the Delta region of Arkansas agreed to participate in this research and demonstration project from 2011 to 2013, and a third farmer was added in 2012 and 2013. Weeds were controlled at all locations through standard combinations of pre-plant and post-emergence herbicides. All fields were irrigated with irrigation scheduling performed by the checkbook method with some adjustments made via visual observations. All fields were periodically soil sampled and fertilized at each grower's discretion. Complete soil tests and fertilizer applications were unavailable for every site-yr and it was assumed that there were no major underlying pH or nutritional limitations.

In 2011, cultivars included Pioneer (DuPont Pioneer, Johnston, IA) cultivars P94Y40, P94Y61, P94Y70, P94Y81, and P95Y10 and were treated with trifloxystrobin (Trilex, Bayer CropScience, Monheim, Germany), metalaxyl (Allegiance, Bayer CropScience), molybdenum, and *Bradyrhizobium japonicum* with lipto-chitooligosaccharide (Optimize 400, Novozymes, Bagsvaerd, Denmark). In 2012, cultivars included Pioneer cultivars P94Y40, P94Y50, P94Y70, P94Y81, and P95Y10 and were treated with thiamethoxam, mefenoxam and fludioxonil (Cruiser Maxx, Syngenta, Basel, Switzerland), molybdenum, *Bradyrhizobium japonicum* (Launcher Pro, Precision Laboratories, Waukegan, IL), and N,N'-diformyl urea (Bio-Forge ST, Stoller USA, Houston, TX). In 2013, cultivars included Pioneer P94Y23 (Newport only), P94Y40, P46T21R, P94Y70, P48T53R, and P95Y10 and were treated with metalaxyl (Allegiance), imidacloprid (Gaucho, Bayer CropScience), and *Bradyrhizobium japonicum* (PPST 120+, DuPont Pioneer). The cultivars were randomized and planted in five (England and Helena, 2012; England and Newport, 2013) or six (England and Helena, 2011; Newport, 2012; Helena, 2013) replications across the length of the field.

Supplemental fertility was provided with poultry litter and urea and elevated pest control measures included two prophylactic fungicide applications and insecticides as needed. A summary of the cultural practices and inputs utilized in this research are cataloged in Table 7-1 by location and year. Just prior to harvest in all locations and years, final plant height was measured from the soil surface to the top of the main-stem from three plants in each plot and the main-stem nodes were counted beginning with the cotyledonary node. The crop was harvested with each growers' combine. The outside edges of the field were first harvested to create a straight edge on both ends of the plots. Plot length was measured with a measuring wheel or a laser range finder. One plot was harvested at a time and weighed with a calibrated weigh wagon.

Moisture was measured with a hand held moisture meter on a subsample of the grain taken from the weigh wagon. Grain subsamples were taken from each plot at harvest and were again moisture tested at the lab and subsampled to weigh 100 seeds. Seed yield at 130 g kg⁻¹ moisture (g m⁻²) was divided by average seed weight (g seed⁻¹) to estimate seeds m⁻². Protein and oil concentrations were also estimated with near-infrared spectroscopy (Infratec 1241 grain analyser, FOSS, Hillerod, Denmark) and adjusted to 130 g kg⁻¹ moisture.

Weather data was taken from NWS weather stations near Keo, Helena, and Newport AR, which was approximately 10 km from the fields near England, 6 km from the fields near Helena, and 6 km from the fields near Newport, respectively. Solar radiation was calculated using mean monthly temperature data and the methods of Ball et al. (2004). Each year and location of data were analyzed separately with the GLM procedure of SAS (SAS Institute, Cary, NC). When the effect of cultivar was significant at $\alpha = 0.05$, Fisher's protected LSD test ($\alpha = 0.05$) was used to make mean comparisons. Pearson correlation coefficients were determined using the CORR procedure of SAS over cultivars and years.

RESULTS & DISCUSSION

Growing Conditions

Mean high temperatures from April to September ranged from 4.6 °C below to 3.9 °C above the 30-yr mean from 2011 to 2013 (Table 7-2). Precipitation variation from the long-term mean was 110 and 238 mm above the 30-yr mean in April for England and Helena, respectively. Maximum temperatures in Helena during June, July, and August 2011 were 2.0 to 3.9 °C above the 30-yr mean, while England ranged from 2.1 °C below to 0.8 °C above the 30-yr mean during the same time period. Seasonal solar radiation averaged 2.3 MJ m⁻² d⁻¹ below the 30-yr mean for

England and $0.7 \text{ MJ m}^{-2} \text{ d}^{-1}$ above the 30-yr mean for Helena. A heavy rainfall event occurred at England shortly after V1 and washed away a portion of one of the twin rows across the whole field; however, an adequate stand remained. Heavy rainfall and hail events also occurred at Helena in 2011 but again an adequate stand survived. In 2012, April maximum temperatures ranged from 0.0 to $2.3 \text{ }^\circ\text{C}$ above the 30-yr mean. England maximum temperatures averaged $1.4 \text{ }^\circ\text{C}$ below the 30-yr mean, while Helena and Newport maximum temperatures averaged $1.5 \text{ }^\circ\text{C}$ above the 30-yr mean for all months. Likewise, solar radiation was $2.0 \text{ MJ m}^{-2} \text{ d}^{-1}$ below the 30-yr mean for England and $0.7 \text{ MJ m}^{-2} \text{ d}^{-1}$ above the 30-yr mean for Helena and Newport. Rainfall throughout 2012 averaged 54 mm below normal from April through July across all locations. At England in 2012, the three earliest cultivars reached physiological maturity near 15 Aug. and the rest by 30 Aug. but the presence of green leaves and stems on the crop delayed harvest and resulted in very poor grain quality. In 2012 at Helena, severe charcoal rot (*Macrophomina phaseolina*) infestations were documented in all cultivars, which may have resulted in premature senescence.

Maximum temperatures in April and May of 2013 were 1.3 to $4.1 \text{ }^\circ\text{C}$ below the 30-yr mean for all locations. Cooler temperatures persisted throughout the year with July averaging $2.6 \text{ }^\circ\text{C}$ below the 30-yr mean across locations. Rainfall in May was much above normal for Helena and Newport, averaging 124 mm above the 30-yr mean. Solar radiation in 2013 were 2.9 $0.7 \text{ MJ m}^{-2} \text{ d}^{-1}$ below the 30-yr mean for England overall and $0.2 \text{ MJ m}^{-2} \text{ d}^{-1}$ above the 30-yr mean for Helena and Newport.

Grain Yields

In 2011, grain yields at England averaged 4735 kg ha⁻¹ with a range from 4595 to 4979 kg ha⁻¹ but were not significantly affected by cultivar (Table 7-3, Appendix 7-1). Yields at Helena averaged 5399 kg ha⁻¹ with a range from 5150 to 5557 kg ha⁻¹ and were significantly affected by cultivar (Table 7-3, Appendix 7-1). Cultivars P94Y40, P94Y61 and P94Y70 had significantly greater yield than P94Y81 and P95Y10 at Helena.

In 2012, grain yields were significantly affected by cultivar at all locations (Table 7-3, Appendix 7-1). At England yield averaged 5825 kg ha⁻¹ with a range from 5720 to 6011 kg ha⁻¹. Cultivar P94Y40 had significantly greater yield than P94Y50 and P94Y81, but all other cultivars had similar yields. Yields at Helena averaged 5819 kg ha⁻¹ with a range from 5612 to 6004 kg ha⁻¹. The greatest yield was achieved with P94Y40, which had similar yield to P94Y50, and the lowest yields were with P94Y81 and P95Y10. Yields at Newport averaged 6073 kg ha⁻¹ with a range from 5892 to 6363 kg ha⁻¹. Cultivar P95Y10 had significantly greater yield than the other cultivars and the lowest yields were with P94Y40 and P94Y81.

Grain yields were again significantly affected by cultivar at all locations in 2013 (Table 7-3, Appendix 7-1). Grain yields at England averaged 6681 kg ha⁻¹ with a range from 6149 to 6986 kg ha⁻¹. Cultivars P46T21 and P48T53 had the greatest yields with P95Y10 having the lowest yield. Yields at Helena averaged 5763 kg ha⁻¹ with a range from 5292 to 6064 kg ha⁻¹. The highest yields were with P46T21, P48T53 and P95Y10 and the lowest yield was with P94Y40. Yields at Newport averaged 6308 kg ha⁻¹ with a range from 5989 to 6608 kg ha⁻¹. The greatest yields were again with cultivars P46T21 and P48T53 and the lowest yield was with P95Y10.

Yield Components

Over all three years, grain yield was significantly correlated ($r=0.60^{***}$ and $r=0.42^{***}$) with both seed weight and seeds m^{-2} , respectively (Table 7-4). Seeds m^{-2} and seed weight were significantly affected by cultivar at every location in each year with the only exception being seeds m^{-2} at England in 2012 (Table 7-3, Appendix 7-1). Additionally, seeds m^{-2} was inversely correlated ($r=-0.44^{***}$) with seed weight. This inverse relationship agrees with the Charles-Edwards et al. (1986) and Egli and Zhen-wen (1991) concepts for soybean grain yield determination where a greater seed weight requires more photosynthate to sustain growth, thereby limiting the number of seeds m^{-2} that can be supported.

Within a location and year, the highest yields were obtained with several different combinations of seeds m^{-2} and seed weight. At Helena in 2011, P94Y40, P94Y61 and P95Y10 has the highest yields but only P94Y40 and P94Y61 had the greatest seeds m^{-2} and these three cultivars had average to low seeds weights. All cultivars at both locations in 2011 had seed weights that were lower than expected for each individual cultivar (DuPont Pioneer, 2014). In 2012, the highest yields at England were obtained with similar seeds m^{-2} and both high and low seed weights. At Helena in 2012, the highest yields were also obtained with the highest seeds m^{-2} and both high and low seeds weights. The highest yield at Newport in 2012 was with the highest seeds m^{-2} and lowest seed weight. In 2012, seed weights were below expected for all cultivars in Helena but within the expected range for all other cultivars at England and Newport (DuPont Pioneer, 2014). In 2013 at England, the highest yields were with average to high seeds m^{-2} and average to low seed weights. The highest yields at Helena were with the highest seeds m^{-2} and similar seed weights. At Newport in 2013, the highest yields were with the highest seeds m^{-2} and average to low seed weights. In 2013, seed weights were again below expected for all cultivars in

Helena but within the expected range for all other cultivars at England and Newport with the exception of P46T21 and P95Y10 being below expected in England (DuPont Pioneer, 2014).

Final Plant Height and Main-Stem Nodes

Final plant height and main-stem nodes were significantly affected by cultivar in every location and year with the only exception being main-stem nodes at Newport in 2013 (Table 7-3, Appendix 7-1). Caution should be taken when comparing main-stem nodes and final plant height between locations due to variance in plant density (Ball et al., 2001; Boquet, 1990; Egli, 2013; Parvez et al., 1989). Final plant height and main-stem nodes were significantly correlated with cultivar maturity group, as expected (Boerma, 1979; Curtis et al., 2000; Egli, 2013; Egli et al., 1985; Egli and Bruening, 2000; Jiang and Egli, 1993; Wilcox et al., 1995; Wilcox and Sediyaama, 1981) and main-stem nodes were positively correlated ($r=0.43^{***}$) with plant height (Table 7-4). Final plant height at England and Helena in 2011 averaged 66.7 cm and 85.8 cm, respectively, and was greatest for P94Y81 and P95Y10 at both locations (Table 7-3). Final plant height in 2012 averaged 88.6, 103.9, and 80.2 cm at England, Helena, and Newport, respectively. Cultivar P95Y10 again had the greatest plant height, with P94Y81 having similar height at Newport. In 2013, final plant height at England, Helena, and Newport averaged 113.0, 86.0, and 107.3 cm, respectively. For unknown reasons, P94Y70 was the tallest cultivar at England, while P95Y10 was again tallest at Helena, and both P94Y70 and P95Y10 had the greatest plant height in Newport.

Final main-stem nodes at England and Helena in 2011 averaged 19.8 and 20.7, respectively, with P94Y81 having the most main-stem nodes at both locations (Table 7-3). In 2012, final main-stem nodes averaged 18.2, 19.3, and 17.9 at England, Helena, and Newport,

respectively. Both P94Y81 and P95Y10 had the most main-stem nodes at all locations. In 2013, final main-stem nodes at England, Helena, and Newport averaged 20.2, 19.5, and 21.9, respectively. At England, only P94Y40 had fewer main-stem nodes than the other cultivars, while P95Y10 had significantly more main-stem nodes at Helena, and there were no significant differences in main-stem node production at Newport.

Bastidas et al. (2008) found that delayed planting dates increased internode lengths of soybean due to warmer temperatures during internode elongation; however, final plant height was shorter due to fewer main-stem nodes produced. Bastidas et al (2008) demonstrated that in one year of research, due to cooler temperatures after emergence, the early May planting date had a lower plant height than the mid-May planting date. We hypothesize that this effect continues as planting dates advance into April and may partially account for differences in plant height between locations in this research. For example, in 2011, England was planted 10 days before Helena and the average plant height was 19 cm shorter. We suggest that the warmer growing conditions after emergence with the 18 Apr. planting date at Helena would have increased internode elongation and contributed to greater plant height compared with the 8 Apr. planting date at England. Similarly, the earlier planting dates in 2012 for all locations (29 Mar. to 10 Apr.) likely contributed to the reduced plant height in 2012, averaging 90.9 cm and 18.5 main-stem nodes compared with 2013 (22 to 25 Apr.), averaging 102.1 cm and 20.5 main-stem nodes. These data also suggest that extremely early planting dates, like in 2012, can reduce main-stem node production.

Grain yield was positively correlated ($r=0.68^{***}$) with plant height, as were seed weight ($r=0.26^{***}$) and seeds m^{-2} ($r=0.46^{***}$) (Table 7-4). However, grain yield was not correlated ($r=0.04$) with final main-stem nodes, seed weight was negatively correlated ($r=-0.23^{***}$) with

main-stem nodes, and seeds m^{-2} was positively correlated ($r=0.24^{***}$) to main-stem nodes. Previous research suggests that grain yield and nodes m^{-2} often have positive relationships (Ball et al., 2001; Board and Modali, 2005; Carter and Boerma, 1979; Kahlon et al., 2011) as do pods or seeds m^{-2} and nodes m^{-2} (Egli and Bruening, 2000; Kahlon et al., 2011; Parvez et al., 1989). However, with a wide range in cultivar maturity groups and plant densities, Egli (2013) demonstrated that pods m^{-2} were maximized at a critical level near 70% of the maximum nodes m^{-2} produced. Also with a wide range in cultivar maturity groups and plant densities, Edwards et al. (2005) documented asymptotic grain yield and biomass levels after intercepted solar radiation reached 605 MJ m^{-2} and 1175 MJ m^{-2} , respectively. Egli (2013) suggested that these findings were in agreement with the proposed concept that seed numbers in soybean are related to assimilate supply (Charles-Edwards et al., 1986; Egli and Zhen-wen, 1991) such that after some critical level, increasing nodes m^{-2} does not increase assimilate supply and seeds or pods m^{-2} remain the same. It may be possible that nodes m^{-2} in this research was greater than this critical level needed to maximum assimilate supply; however, only main-stem nodes were tallied in this work. This idea of a critical level of nodes m^{-2} required to maximize yield may be an area worthy of future investigations.

Protein and Oil

Protein concentrations were significantly affected by cultivar at all locations and years except England in 2012 and Helena in 2013, while oil concentrations were always significantly affected by cultivar (Table 7-3, Appendix 7-1). Across locations, cultivar mean protein and oil ranged from 36.5 to 38.7% and 20.1 to 22.4% in 2011, 38.1 to 40.7% and 22.2 to 24.1% in 2012, and 38.2 to 42.6% and 21.8 to 25.6% in 2013, respectively. Cultivars P94Y40, P94Y70 and

P95Y10 were present in all years and locations of this research and the respective average protein and oil concentrations were 39.1% and 23.6% (P94Y40), 38.6% and 23.0% (P94Y70), and 39.5% and 22.6% (P95Y10). For all cultivars and years, the observed protein and oil concentration was greater than would normally be expected for these cultivars (DuPont Pioneer, 2014) and greater than the national average for each year (Naeve et al., 2012; 2013a; 2013b). Increasing soil N availability and plant accumulation increases protein concentration (Gascho, 1991; Egli and Bruening, 2007). It is possible that the addition of poultry litter and late season N applications may have contributed to these elevated seed protein levels. Additionally, protein concentrations increase with high temperatures ≥ 27 °C during seedfill (Dornbos and Mullen, 1992). While oil concentrations have a positive correlation with temperature (Howell and Cartter, 1953), Dornbos and Mullen (1992) found oil concentrations decreased when temperature was increased from 27 to 33 °C or from 29 to 35 °C. Mean maximum temperatures were ≥ 31.3 °C during August of all years, while September maximum temperatures ranged from 28.2 to 30.6 °C (Table 7-2). Another possible explanation for the elevated oil concentration is that the irrigation management practices may have prevented water deficit stress, and increased seed oil concentration because moisture deficit stress decreases seed oil concentration (Dornbos and Mullen, 1992; Foroud et al., 1993).

Documented 6719 kg ha⁻¹ (100 bushels acre⁻¹) yields in Arkansas

At England in 2013, two cultivars averaged grain yields greater than 6719 kg ha⁻¹ across all replications over the width of the field. In addition, three other growers in Arkansas submitted grain yields over 6719 kg ha⁻¹ in the Race for 100 (bushels acre⁻¹) Yield Contest in 2013 (Arkansas Soybean Association, 2013). Nelson Crow was the first grower to reach this yield

level. Mr. Crow submitted 6771 kg ha^{-1} to the contest from near Dumas, AR. Mr. Crow planted Pioneer 93Y92, treated with Cruiser Maxx, on 24 Apr. and harvested on 29 Aug. 2013. The field consisted mainly of Rilla silt loam and was planted in 76 cm rows with $35.8 \text{ seeds m}^{-2}$. The crop was furrow irrigated six times, weeds were completely controlled and the crop also received an insecticide (FasTac, BASF, Ludwigshafen, Germany), fungicide (Priaxor, BASF) with 1.12 kg ha^{-1} table sugar as a surfactant and 112 kg N ha^{-1} at R2. This was followed by another fungicide (Priaxor) application with 3.8 L of a foliar slow-release N fertilizer (N-Pact, Loveland, Loveland, CO) at R4 and another insecticide (acephate) application at R6 (Arkansas Soybean Association, 2013; Bennett, 2013a).

Matt Miles was the second grower to reach 6719 kg ha^{-1} . Mr. Miles submitted 7232 kg ha^{-1} to the contest from near McGehee, AR. Mr. Miles planted Asgrow (Monsanto, St. Louis, MO) AG4632, treated with Cruiser Maxx, on 23 Apr. and harvested on 13 Sep. 2013. The field consisted of a silt loam and was planted in 97 cm rows with 42 seeds m^{-2} . The crop was furrow irrigated weekly nine times, weeds completely controlled, a fungicide (Priaxor) and insecticide (acephate) were used, and 3360 kg ha^{-1} of poultry litter was applied (Arkansas Soybean Association, 2013; Bennett, 2013b).

The third grower was Eddie Tackett, who submitted 7044 kg ha^{-1} from near Atkins, AR. Mr. Tackett planted Pioneer P94Y70 on 13 May and harvested on 27 Sep. 2013. The field consisted of a silt loam and was planted in 76 cm rows with 37 seeds m^{-2} . The crop was furrow irrigated seven times, with each application supplying approximately 5 cm of water. An insecticide was applied, as was a fungicide (Stratego YLD, Bayer, Leverkusen, Germany) at R4, and 4480 kg ha^{-1} of poultry litter was applied (Arkansas Soybean Association, 2013).

All three growers were quick to mention the weather as contributing factors in their yields (Bennett, 2014). Certainly, 2013 did not have the July heat stress that was experienced in 2011 and 2012 (Table 7-2). Other practices in common between these growers and the aforementioned research included planting dates prior to mid-May, indeterminate cultivars, irrigation, additional fertility, and strict pest control practices. All fields received at least one fungicide application and weeds and insects were fully controlled. All fields were irrigated and eliminating water deficit stress was another critical component to achieving high yield levels. Most fields also consisted of a silt loam soil texture (Table 7-1), which typically have good internal drainage characteristics and can limit yield losses associated with excessive water stresses. Lastly, all fields received supplemental fertility in the form of preplant applied poultry litter and/or late season N applications. Elevated fertility levels were noted as critical components in the maximum yield research from Mr. Cullers' contest fields and in Fayetteville. The additional N and K applied was likely one of the contributing factors for these yield contest entries to break the 6719 kg ha⁻¹ mark.

Break-even Analysis

While achieving yields greater than 6719 kg ha⁻¹ was substantial, it is important to examine the economic feasibility of the practices utilized to reach this goal. Since the management system was being continually refined, a break-even analysis was conducted only for the 2013 growing season. The average costs of the practices beyond the growers' normal practices were tallied. These costs included the application and incorporation of 4480 kg ha⁻¹ poultry litter (\$198 ha⁻¹), two applications of 123 kg ha⁻¹ of urea (\$185 ha⁻¹), the second

fungicide application ($\$49 \text{ ha}^{-1}$), and a defoliant application ($\$37 \text{ ha}^{-1}$). Thus, the additional cost of this high yield management system was $\$469 \text{ ha}^{-1}$ ($\$190 \text{ acre}^{-1}$).

Although this research was not designed to observe the individual effects of these management practices, nearby fields planted on the same day with one of the same cultivars were compared to the cultivar yields across replications in the research field. Two of these situations indicated that the growers' normal practices yielded 571 kg ha^{-1} ($8.5 \text{ bushels acre}^{-1}$) less. With the extra costs incurred, the soybean grain price required to break even would be $\$0.82 \text{ kg}^{-1}$ ($\$22 \text{ bushel}^{-1}$). Given the current grain prices at the time of this publication, the practices utilized to reach these yields were less profitable than the growers' normal production practices and normal yields. Granted, these growers were already utilizing fairly intensive irrigation and management practices and producing grain yields greater than the statewide average. While this is not a true economic analysis, it certainly indicates that one should carefully examine the economic feasibility, as well as the ecological and sustainability impacts of these high yield management practices prior to implementing them across their whole farm.

CONCLUSIONS

The management systems outlined in this research resulted in grain yields greater than 6000 kg ha^{-1} within each location in 2012 and 2013. One location in 2013 was able to reach the goal of 6719 kg ha^{-1} ($100 \text{ bushel acre}^{-1}$) large-scale, replicated, mean yields for two cultivars. The greater yield of these two cultivars was mainly due to greater seeds m^{-2} and all cultivars maintained greater than normal protein and oil concentrations in each site-yr. Grain yields were positively associated with final plant height but not main-stem nodes. Weather conditions in 2013 favored high soybean yields and three other Arkansas soybean growers were also able to

achieve yields of 6771, 7044, and 7232 kg ha⁻¹. However, the management practices utilized to reach the yields in this research do not appear to be economically favorable. While achieving 6719 kg ha⁻¹ (100 bushel acre⁻¹) soybean yields are a prestigious achievement, it is important to account for the long-term economic and ecological sustainability of the practices necessary to achieve this goal. At this time, it appears that the extra inputs required to reach these yields are not practical for widespread adoption in soybean production.

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Table 7-1. Summary for each location cataloging the cultural practices and inputs utilized in each year of research in the Delta region of Arkansas.

Year	Location	Cultural Practices	Inputs
2011	Dow Brantley near England, AR, 34.492° N, 91.847° W, Caspiana silt loam, previous crop was corn	Planted 8 Apr. 2011 in twin rows centered on beds 97-cm apart and with twin rows 20 cm apart, 26.8 plants m ⁻² , furrow irrigation, harvested 15 Sept. 2011 with plots averaging 3300 m ²	4700 kg poultry litter ha ⁻¹ applied and incorporated on 18 Mar. 2011, 112 kg (NH ₄) ₂ PO ₄ ha ⁻¹ of at R3, azoxystrobin at R3 and R5, bifenthrin at R6
	Michael Taylor, Jr. near Helena, AR, 34.483° N, 90.633° W, Commerce silt loam, previous crop was soybean	Cereal rye winter cover crop, flat planted on 18 Apr. 2011 in 76-cm rows, 28.2 plants m ⁻² , furrow irrigation, harvested 15 Sept. 2011 and 23 Sept. 2011 with plots averaging 3700 m ²	4600 kg poultry litter ha ⁻¹ applied and incorporated on 20 Mar. 2011, 0.2 kg N ha ⁻¹ , 0.1 kg P ha ⁻¹ , 0.5 kg K ha ⁻¹ , 1.0 kg S ha ⁻¹ , 0.08 kg Mn ha ⁻¹ , 0.28 kg Zn ha ⁻¹ , 0.002 kg B ha ⁻¹ , 0.03 kg Cu ha ⁻¹ , 0.04 kg Fe ha ⁻¹ , 0.13 kg Mn ha ⁻¹ at planting, 168 kg (NH ₄)SO ₄ ha ⁻¹ at V1, azoxystrobin and bifenthrin at R3 and R5, 112 kg (NH ₄)SO ₄ ha ⁻¹ at R5.5
2012	Dow Brantley near England, AR, 34.577° N, 91.924° W, Rilla silt loam, previous crop was cotton	Planted 5 Apr. 2012 in twin rows centered on beds 97-cm apart and with twin rows 20 cm apart, 36.6 plants m ⁻² , furrow irrigation, paraquat applied on 11 Sept. 2012 for defoliation, harvested 13 Sept. 2012 with plots averaging 4250 m ²	5600 kg poultry litter ha ⁻¹ applied and incorporated on 15 Mar. 2012, 146 kg urea ha ⁻¹ of at R1 and R5, prothioconazole and trifloxystrobin at R3 and R5, bifenthrin at R5
	Michael Taylor, Jr. near Helena, AR, 34.486° N, 90.656° W, Tunica silty clay, previous crop was corn	Flat planted on 10 Apr. 2012 in 76-cm rows, 32.6 plants m ⁻² , center pivot irrigation, harvested 6 Sept. 2012 with plots averaging 2040 m ²	0.2 kg N ha ⁻¹ , 0.1 kg P ha ⁻¹ , and 0.5 kg K ha ⁻¹ , 0.002 kg B ha ⁻¹ , 0.03 kg Cu ha ⁻¹ , 0.04 kg Fe ha ⁻¹ , 0.13 kg Mn ha ⁻¹ , 0.2 kg Zn ha ⁻¹ at planting, azoxystrobin at R3 and R5, 235 kg N ha ⁻¹ with irrigation from R3 to R6,
	Stan Haigwood near	Planted 29 Mar. 2012 in three, 19-cm rows	3400 kg poultry litter ha ⁻¹ applied and incorporated

	Newport, AR, 35.612° N, 91.237° W, Bosket fine sandy loam, previous crop was cotton	atop a single bed centered on 97 cm, 36.6 plants m ⁻² , furrow irrigation, paraquat and NaClO ₃ applied on 4 Sept. 2012 for defoliation, harvested on 12 Sept. 2012 with plots averaging 3260 m ²	on 15 Nov. 2011, 112 kg (NH ₄)SO ₄ ha ⁻¹ at R1, 112 kg KCl ha ⁻¹ of at R3, azoxystrobin at R3 and R5, 140 kg urea ha ⁻¹ of at R3, R5, and R6
2013	Dow Brantley near England, AR, 34.571° N, 91.972° W, Caspiana silt loam, previous crop was corn	Planted 25 Apr. 2013 in twin rows centered on beds 97-cm apart and with twin rows 20 cm apart, 37.7 plants m ⁻² , furrow irrigation, carfentrazone-ethyl and NaClO ₃ , for defoliation, harvested on 19 Sept. 2013 with plots averaging 3300 m ²	4500 kg poultry litter ha ⁻¹ applied and incorporated on 28 Mar. 2013, prothioconazole, trifloxystrobin, bifenthrin, and chlorantraniliprole at R3, prothioconazole, trifloxystrobin, and bifenthrin at R5, 123 kg urea ha ⁻¹ of at R3 and R5,
	Michael Taylor, Jr. near Helena, AR, 34.467° N, 90.651° W, Commerce silt loam, previous crop was corn	Cereal rye and tillage radish winter cover crop, flat planted on 22 Apr. 2013 in 76-cm rows, 29.4 plants m ⁻² , furrow irrigation, harvested on 18 Sept. 2013 with plots averaging 2900 m ²	560 kg pelletized poultry litter ha ⁻¹ (equivalent of 5600 kg normal poultry litter ha ⁻¹) applied and incorporated on 27 Mar. 2013, tetraconazole and bifenthrin at R3, azoxystrobin, propiconazole and acephate at R5, 112 kg urea ha ⁻¹ of at R3 and R5
	Stan Haigwood near Newport, AR, 35.625° N, 91.224° W, Dundee silt loam, previous crop was cotton	Planted 23 Apr. 2013 in three, 19-cm rows atop a single bed centered on 97 cm, 33.3 plants m ⁻² , furrow irrigation, harvested on 24 Sept. 2013 with plots averaging 2350 m ²	9000 kg poultry litter ha ⁻¹ applied and incorporated on 15 Mar. 2013, prothioconazole, trifloxystrobin, and lambda-cyhalothrin at R4, prothioconazole, trifloxystrobin, and bifenthrin at R5.5, 123 kg urea ha ⁻¹ of at R4 and R5,

Table 7-2. Mean monthly high temperature (Tmax), low temperature (Tmin), solar radiation (Rs), monthly total rainfall, and irrigation from NWS weather stations near England, Helena, and Newport in 2011, 2012 and 2013. Departures from the 30-yr mean (1981-2010; NCDC-NOAA, 2013) are in parentheses.

Year	Month	Tmax ———— °C —————	Tmin	Rs† MJ m ⁻² d ⁻¹	Rainfall mm
2011					
England	April	24.4 (-0.4)	11.1 (+1.8)	21.0 (-1.7)	236 (+110)
	May	25.8 (-3.6)	14.4 (+0.0)	21.6 (-3.2)	223 (+91)
	June	34.3 (+0.8)	22.2 (+3.2)	23.1 (-2.2)	39 (-53)
	July	33.7 (-1.4)	22.9 (+1.8)	21.4 (-3.0)	41 (-60)
	August	32.7 (-2.1)	21.7 (+1.3)	19.8 (-2.9)	160 (+90)
	September	27.8 (-3.5)	13.6 (-2.5)	19.2 (-0.7)	33 (-26)
Helena	April	24.9 (+1.8)	12.7 (+1.2)	20.1 (+0.4)	370 (+238)
	May	26.6 (-0.5)	15.6 (-1.0)	21.3 (+0.5)	135 (+17)
	June	34.7 (+3.9)	22.6 (+1.9)	23.1 (+2.0)	71 (-21)
	July	35.0 (+2.7)	24.4 (+2.1)	21.2 (+0.0)	42 (-50)
	August	34.1 (+2.0)	23.2 (+1.6)	19.7 (+0.6)	61 (+10)
	September	28.1 (-0.6)	16.4 (-0.9)	17.4 (+0.3)	46 (-33)
2012					
England	April	24.8 (+0.0)	11.9 (+2.6)	20.7 (-2.0)	52 (-74)
	May	29.3 (-0.1)	17.1 (-0.1)	22.4 (-2.4)	77 (-55)

	June	30.9 (-2.6)	17.9 (-1.1)	24.0 (-1.3)	38 (-54)
	July	34.0 (-1.1)	22.6 (+1.5)	22.0 (-2.4)	33 (-68)
	August	32.7 (-2.1)	20.1 (-0.3)	21.2 (-1.5)	162 (+92)
	September	28.7 (-2.6)	17.2 (+1.1)	17.3 (-2.6)	135 (+76)
Helena	April	25.0 (+1.9)	13.2 (+1.7)	19.8 (+0.1)	48 (-83)
	May	30.3 (+3.2)	17.8 (+1.2)	22.7 (+1.9)	53 (-64)
	June	32.8 (+2.0)	20.1 (-0.6)	23.7 (+2.6)	51 (-41)
	July	34.3 (+2.0)	24.3 (+2.0)	20.6 (+0.0)	89 (-3)
	August	33.1 (+1.0)	21.9 (+0.3)	20.0 (+0.6)	31 (-21)
	September	30.2 (+1.5)	18.4 (+1.1)	17.5 (+0.3)	93 (+14)
Newport	April	23.5 (+2.3)	12.0 (+1.6)	19.5 (+0.6)	45 (-78)
	May	29.5 (+3.6)	19.2 (+3.5)	20.6 (+0.0)	86 (-40)
	June	30.7 (+0.2)	18.8 (-1.5)	23.0 (+1.7)	41 (-48)
	July	34.0 (+1.7)	23.3 (+1.0)	21.3 (+0.7)	56 (-42)
	August	31.8 (-0.4)	19.9 (-1.4)	20.5 (+0.8)	56 (-11)
	September	27.2 (-1.1)	16.7 (+0.1)	16.3 (-0.9)	175 (+97)
2013					
England	April	20.7 (-4.1)	8.3 (-1.0)	20.3 (-2.4)	139 (+13)
	May	25.4 (-4.0)	14.8 (+0.4)	20.9 (-3.9)	132 (+0)
	June	30.7 (-2.8)	20.4 (+1.4)	21.3 (-4.0)	90 (-1)

	July	30.5 (-4.6)	19.7 (-1.4)	21.4 (-3.0)	28 (-73)
	August	31.3 (-3.5)	20.1 (-0.3)	20.0 (-2.7)	72 (+2)
	September	30.8 (-0.5)	17.4 (+1.3)	18.6 (-1.3)	84 (+25)
Helena	April	21.8 (-1.3)	9.8 (-1.7)	20.0 (+0.3)	199 (+68)
	May	25.8 (-1.3)	15.3 (-1.3)	20.8 (+0.0)	250 (+133)
	June	31.9 (+1.1)	21.6 (+0.9)	21.3 (+0.2)	41 (-51)
	July	31.1 (-1.2)	21.0 (-1.3)	20.7 (+0.1)	92 (+0)
	August	33.4 (+1.3)	22.2 (+0.6)	20.0 (+0.6)	5 (-46)
	September	32.2 (+3.5)	17.6 (+0.3)	19.5 (+2.3)	76 (-2)
Newport	April	19.2 (-2.0)	8.4 (-2.0)	18.9 (+0.0)	109 (-14)
	May	24.3 (-1.6)	14.2 (-1.5)	20.4 (-0.2)	242 (+116)
	June	30.3 (-0.2)	20.2 (-0.1)	21.2 (-0.1)	57 (-32)
	July	30.3 (-2.0)	19.6 (-2.7)	21.3 (+0.7)	86 (-12)
	August	29.4 (-2.8)	20.2 (-1.1)	18.1 (-1.6)	115 (+48)
	September	29.5 (+1.2)	17.3 (+0.7)	17.6 (+0.4)	40 (-38)

† Solar radiation 30-yr means calculated with 30-yr mean high and low temperatures using a modified Hargreaves and Samani (1982) equation, described by Ball et al. (2004).

Table 7-3. Grain yield, seeds m⁻², seed weight, final plant height, number of main-stem nodes produced, and grain protein and oil concentration means for cultivars by year and location.

Year	Location	Cultivar	Yield kg ha ⁻¹	Seeds m ⁻²	Seed weight mg seed ⁻¹	Height cm	Main-stem nodes	Protein %	Oil %
2011	England	P94Y40	4602	3382 ABC†	118 BC	62.7 B	19.4 B	37.7 B	22.2 A
		P94Y61	4595	3553 A	113 C	64.1 B	19.7 B	37.8 B	20.9 C
		P94Y70	4631	3195 C	126 A	62.9 B	18.8 B	36.5 D	22.4 A
		P94Y81	4868	3313 BC	128 A	69.4 A	21.4 A	37.2 C	21.4 B
		P95Y10	4979	3518 AB	123 AB	73.8 A	19.6 B	38.7 A	20.9 C
	Helena	P94Y40	5557 A	3498 A	138 B	77.8 C	19.7 C	37.5 C	22.4 A
		P94Y61	5517 A	3619 A	133 C	85.5 B	20.3 BC	38.5 A	20.1 E
		P94Y70	5610 A	3301 B	148 A	84.9 B	19.8 C	36.7 D	21.6 B
		P94Y81	5150 B	3264 B	137 B	88.0 AB	22.7 A	37.6 C	21.1 C
		P95Y10	5161 B	3325 B	135 BC	92.6 A	21.1 B	38.2 B	20.6 D
2012	England	P94Y40	6011 A	3029	175 A	80.2 D	17.0 B	40.5	24.1 A
		P94Y50	5685 B	3026	163 AB	85.9 C	17.7 B	39.9	23.6 B
		P94Y70	5856 AB	2905	175 A	87.8 C	17.9 B	39.8	23.5 B
		P94Y81	5720 B	3094	161 B	92.3 B	19.5 A	39.2	23.4 B
		P95Y10	5853 AB	3292	155 B	97.0 A	19.1 A	39.3	23.6 B
	Helena	P94Y40	6004 A	3813 ABC	140 A	91.7 C	17.9 C	38.9 A	23.5 A
		P94Y50	5938 AB	3864 AB	137 A	102.4 B	18.5 BC	38.3 B	22.7 B
		P94Y70	5873 B	3722 BC	141 A	103.5 B	18.7 B	38.1 B	22.7 B
		P94Y81	5612 C	3636 C	138 A	105.7 B	20.7 A	38.7 A	22.3 C

		P95Y10	5670 C	3962 A	127 B	116.3 A	20.6 A	38.8 A	22.2 C
	Newport	P94Y40	5962 CD	3042 C	173 A	75.6 B	17.2 B	40.7 A	24.0 A
		P94Y50	6129 B	3250 B	167 AB	77.7 B	17.6 B	40.2 AB	23.1 B
		P94Y70	6017 C	3122 BC	170 A	75.1 B	17.9 B	39.9 BC	23.1 B
		P94Y81	5892 D	3192 B	163 BC	86.8 A	18.9 A	39.4 C	22.7 C
		P95Y10	6363 A	3555 A	158 C	85.9 A	18.1 AB	39.6 C	22.7 C
2013	England	P94Y40	6716 B	3839 C	157 A	103.5 C	19.4 B	38.9 A	23.3 A
		P46T21	6931 A	4361 A	143 C	113.1 B	20.8 A	38.2 B	21.8 D
		P94Y70	6622 B	3826 C	156 AB	121.7 A	20.1 AB	38.9 A	22.3 C
		P48T53	6986 A	4132 B	152 B	113.3 B	20.3 A	38.4 B	22.7 B
		P95Y10	6149 C	3844 C	144 C	113.3 B	20.4 A	38.8 A	22.5 BC
	Helena	P94Y40	5292 C	3086 C	144	79.2 D	18.4 C	38.9	25.6 A
		P46T21	5930 A	3746 A	136	88.3 B	19.7 B	39.0	24.6 BC
		P94Y70	5661 B	3366 BC	142	86.2 BC	19.5 B	37.9	25.0 AB
		P48T53	5869 AB	3547 AB	139	83.8 C	19.4 B	39.0	25.0 AB
		P95Y10	6064 A	3640 AB	142	92.6 A	20.7 A	39.9	24.2 C
	Newport	P94Y23	6424 B	3502 B	160 AB	101.9 C	21.8	39.4 C	23.7 B
		P94Y40	6149 C	3270 C	164 A	105.3 BC	21.5	40.9 B	24.1 A
		P46T21	6555 AB	3669 AB	153 BC	107.1 B	22.4	41.2 B	23.2 D
		P94Y70	6121 CD	3273 C	162 A	112.3 A	22.0	40.8 B	23.4 BC
		P48T53	6608 A	3775 A	150 C	104.2 BC	21.3	40.6 B	23.3 CD
		P95Y10	5989 D	3169 C	160 AB	112.7 A	22.1	42.6 A	23.9 A

† Different letters within a location and year denote that means differed ($\alpha=0.05$) as determined Fisher's protected LSD.

Table 7-4. Pearson correlation coefficients and significance levels for cultivar maturity group (MG), yield, individual seed weight (Seedwt), seeds m⁻², final plant height (Height) and main-stem nodes (Nodes), protein and oil from all locations, years and cultivars.

	Yield	Seedwt	Seeds m ⁻²	Height	Nodes	Protein	Oil
MG	-0.07	-0.17*	0.10	0.21**	0.23***	0.08	-0.44***
Yield		0.60***	0.42***	0.68***	0.04	-0.17*	-0.01
Seedwt			-0.44***	0.26***	-0.23***	0.04	0.20**
Seeds m ⁻²				0.46***	0.24***	-0.19**	-0.26***
Height					0.43***	-0.12	-0.27***
Nodes						0.01	-0.44***
Protein							-0.24***

The symbols, *, **, and *** indicate significance at the $\alpha = 0.05$, 0.01, and 0.001 levels, respectively.

CHAPTER 8

Physiological Limitations to Maximum Soybean Yield – A Simulations Approach

ABSTRACT

Crop models can be used to test hypotheses and can also help identify potential constraints to crop growth and yield. A relatively simple soybean model consisting of a daily C, N, and water budget was used to simulate crops grown within maximum yield environments at the University of Arkansas in Fayetteville and on Mr. Cullers' contest fields in SW Missouri from 2011 to 2013. Certain crop growth processes such as the radiation use efficiency (RUE), N accumulation rate, and specific leaf N (SLN) are simulated as upper limits for leaf and seed growth, and the seed growth rate is represented as the dry matter accumulation coefficient (DMAC). Simulations with the default parameter limitations for RUE, N accumulation rate, and SLN under-predicted yields at both locations. In Fayetteville, where observed yields ranged from 4125 to 7144 kg ha⁻¹, simulated yields averaged 14.2% below the observed yields using default values of the parameters for each cultivar. Using observed parameters in a modified model, predicted yields were 7.3% above observed. Default parameter simulations for Mr. Cullers' field were 28.2% below observed yield and were 19.4% below observed yield when using measured parameters. Sensitivity analyses indicated that lower DMAC values increased yields due to slower seedfill rates allowing for additional N accumulation and a slower decline in leaf area to translocate N to the growing seeds. Increasing the SLN and RUE only increased yield in 2012 and 2013 when N accumulation rates were great enough to supply the required N for the new biomass. Alternatively, increasing N accumulation rates increased yield up to a plateau when all N requirements were met. These results illustrate the importance and interconnectivity of the crop growth processes relating to C and N accumulation and utilization.

INTRODUCTION

Crop modeling was defined by Sinclair and Seligman (1996) as the “dynamic simulation of crop growth by numerical integration of constituent processes with the aid of computers.” Crop models simulate growth and development and allow for hypotheses to be tested via simulation. Other uses of crop models relate to the simulated growth processes which can be examined to help identify potential constraints to crop growth and yield. One of the earliest models involved estimating maximum crop productivity based on available solar radiation for photosynthesis (Loomis and Williams, 1963). Eventually, exceptionally complex models were developed that characterized plant development, leaf photosynthesis and other biochemical processes (e.g., GOSSYM, Whisler et al., 1986; SOYGRO, Wilkerson et al., 1985).

Despite their complexity, some of the more recent models fell short of accurately explaining many of the processes within the crops and were occasionally outperformed by simplistic models. For example, GOSSYM was inferior to a simple water balance model in predicting crop water stress and field water balance (Asare et al., 1992), and SOYGRO was also outperformed in predicting soybean yield by a simple sample average (Colson et al., 1995). No model is universal among crops or environments and often requires calibration to a new set of cultivars or location. However, even with significant calibration efforts, models can have deficiencies when trying to be adopted elsewhere (Porter et al., 1993).

Boote et al. (2001) suggested that crop models are capable of partially reproducing genotype by environment interactions, which can help breeders target physiological traits for cultivar improvement within specific environments. Crop models have also been used in the prediction of the theoretical maximum yield of crops in non-limiting environments. For an Australian environment, the maximum yield potential of soybean was simulated to be 8290 kg

ha⁻¹ when simulating large portions of soil N and N₂ fixation rates (Muchow and Sinclair, 1986). Long-term simulation of soybean yield in Japan suggested a maximum yield potential of 5100 kg ha⁻¹ (Spaeth et al., 1987) and 5400 kg ha⁻¹ in India (Bhatia et al., 2008).

Models can serve efficiently as teaching aids through the understanding of the model components and crop growth processes and identification of faulty reasoning or important, but poorly understood components of the model (Sinclair and Seligman, 1996). Most models include a crop growth, or C accumulation, component in the simulation. This can be measured experimentally through the biomass accumulation rate (g m⁻² d⁻¹) or the radiation use efficiency (RUE, g MJ⁻¹), where crop growth is measured per unit of intercepted solar radiation. Other model components can include nutrient uptake and translocation components. Soybean has a large N requirement, and is capable of accumulating N from both the soil and symbiotic N₂ fixation. Some or all of those physiological processes can also be measured and simulated.

The model of focus in this chapter was developed and originally described by Sinclair (1986) and Sinclair et al. (2003). This is a relatively simple model consisting of a C, N, and water budget for biomass and grain production. Several of the parameters within this model represent physiological measurements, such as the radiation use efficiency (RUE; g MJ⁻¹ intercepted). This model was used to simulate soybean yield within a maximum yield environment to identify parameter limitations and to provide additional insights into key physiological processes for maximizing soybean yields.

MATERIALS & METHODS

Model Description

The Sinclair-Soybean model (Sinclair, 1986; Sinclair et al., 2003) utilizes a C, N, and water budget for soybean from emergence to maturity to estimate biomass and grain production on a daily basis. Leaf growth is modeled through both estimation of the leaf emergence rate and then by determining the leaf area of the emerged leaves. The model requires an input of the date of V1, when the first trifoliolate leaves have unrolled (Pedersen, 2009). This is when the plastochron index equals zero (Hofstra et al., 1977; Vendeland et al., 1982) and a linear increase of the plastochron index begins, based on the mean daily temperature minus the base temperature for growth (Sinclair, 1984). The plastochron index is used to calculate the maximum potential leaf area based on the exponential relationship defined by Sinclair (1984), which is multiplied by plant density to determine the leaf area index and solar radiation interception assuming an extinction coefficient of 0.6 (Sinclair, 1986).

Leaf growth is retarded by water stress and begins to rapidly decline as the fraction of transpirable soil water (FTSW) reaches 0.20 and ceases at a FTSW value of 0.05. A shortage of available N can also limit leaf growth. The N budget of the model was modified in 2003 to eliminate the need for calibration for environment due to the previous N accumulation functions being empirical (Sinclair et al., 2003). The new approach simulates N accumulation based upon demand from stem growth and developing leaf area. The model calculates daily N requirements during vegetative growth based on a specific leaf N content of 2.5 g N m^{-2} and a maximum stem N content of 20 mg N g^{-1} . Nitrogen accumulation is assumed to be supplied by both soil and symbiotic N_2 fixation and is calculated from the demand by the new leaf area only, up to a maximum daily uptake of $0.6 \text{ g N m}^{-2} \text{ d}^{-1}$. Nitrogen accumulation rates are modeled to decrease

at a FTSW value of 0.50 (Sinclair, 1986). Too much water can also limit N accumulation and N accumulation is set to zero any day that the soil is flooded. When insufficient N is accumulated, stem N content decreases until 8 mg N g^{-1} , where it is maintained, and low N accumulation rates inhibit leaf area development. If leaf area development decreases to zero, additional N can be translocated from senesced leaves to the growing leaves. It was assumed that the senesced leaves contained 0.8 g N m^{-2} , which results in 1.7 g N m^{-2} of translocated N because of the 2.5 g N m^{-2} specific leaf N limitation (Sinclair et al., 2003). This process continues until the day of year when leaf growth ceases and seed growth begins, which are both inputs for the model.

The model uses daily solar radiation values intercepted by the crop to estimate daily C inputs, which is calculated as an exponential function of the fraction of radiation interception and the maximum potential radiation use efficiency (RUE) of 0.9 g MJ^{-1} . However, if leaf N is considered limiting, the RUE is decreased proportionally reaching a RUE value of 0 at 1 g N m^{-2} in accordance with the relationship described by Lugg and Sinclair (1981). The C input is also reduced by water stress. This is represented by another logistic function describing the reduction in the RUE, represented by the relative transpiration rate, as FTSW decreases (Sinclair and Ludlow, 1986).

The total transpirable soil water is a function of the effective depth of water extraction and the volumetric fraction of extractable soil water, assumed to be 0.13 (Ratliff et al., 1983). It is also assumed that the soil can hold 10 mm of water over the total transpirable soil water potential, and any excess is lost as runoff. The soil is considered flooded, for N accumulation purposes, any day that the amount of soil water is greater than the total transpirable soil water. Soil water inputs are calculated every day from rainfall and irrigation amounts. Transpired water is derived from multiplying the C input by the average vapor pressure deficit, estimated by the

daily maximum and minimum temperatures, divided by the water-use efficiency coefficient of 5 Pa (Tanner and Sinclair, 1983). Soil water evaporation is also accounted for using a two-stage model by Ritchie (1972).

Seed growth rates are calculated through a linear increase in the harvest index (HI) over time (Salado-Navarro et al., 1985a; Spaeth and Sinclair, 1985) on an hourly basis. The slope of this linear increase in HI, or dry matter allocation coefficient (DMAC), is an input in the model as well as the date when linear HI increases begin. Nitrogen demand is calculated based on the daily linear increase in seed mass at a N concentration of 65 mg N g⁻¹ (406 mg protein g⁻¹). Once N accumulation of the seeds exceeds N accumulation from the soil and N₂ fixation, N is provided to the seeds from the stems and then the leaves, to a minimum N content of 8 mg N g⁻¹ and 0.8 g N m⁻² of the senesced tissue, respectively (Sinclair et al., 2003). When N is remobilized from the leaves to the seed, the leaf area is decreased proportionately and continues until the leaf area index reaches 0.1, at which time the simulation ends (Sinclair, 1986).

Model validations revealed close agreement with observed crop biomass accumulation for the 1981 growing season in Lawes, Queensland, Australia. Sensitivity analysis demonstrated that the variables related to radiation interception and biomass accumulation had the greatest effects on simulated seed yields (Sinclair, 1986). Further model analysis and association with field experiments revealed good agreement and provided meaningful insights for deciphering yield reductions (Muchow and Sinclair, 1986). This model was also compared with high yield soybean research in Japan and resulted in close agreement with observed yields, which ranged from 5060 to 6490 kg ha⁻¹ (Spaeth et al., 1987).

After the N budget was modified (Sinclair et al., 2003), the model was analyzed in comparison to two years of research in Brazil. The rate of increase in leaf area was more rapid

than observed and the model was again modified by decreasing the leaf appearance coefficient from 0.018 to 0.014 and the base temperature from 10 to 8°C, which resulted in good agreement between the simulated and observed leaf area increases (Sinclair et al., 2003). The revised model agreed well with a tillage experiment for N accumulation (Sinclair et al., 2003). The revised model also agreed well with an irrigation experiment in eight of nine seasons, but simulated yield was 37% less than observed yield in one season due to the simulated irrigation causing flooded conditions and decreased N₂ fixation in the model. Additionally, removing the empiricism from the model allowed for prediction without direct calibration for each environment; however, the accuracy of yield prediction may have been slightly compromised (Sinclair et al., 2003).

Model Simulations

The Sinclair-soybean model (Sinclair et al., 2003) was utilized to simulate soybean yield and development from observed research data taken in maximum yield trials at the University of Arkansas in Fayetteville (Ch. 5) and Mr. Kip Cullers' soybean yield contest fields in SW Missouri (Ch. 3 and 4). At Fayetteville, daily temperature, rainfall, and irrigation amounts were measured at the field. Solar radiation was calculated from temperature data using the methods of Ball et al. (2004). At Mr. Cullers' fields, daily temperature and solar radiation were measured at the field. Rainfall and irrigation amounts were not measured on site. Instead, monthly rainfall data were obtained from the Joplin MO regional airport weather station (NCDC-NOAA, 2013a) and the irrigation option of the model was used to simulate 20 mm of irrigation whenever the fraction of total soil water was predicted to be less than 0.50.

The day of year (DOY) when cultivars first entered the R5 growth stage was used for the input of the DOY when leaf growth was terminated. It was assumed that 10 days following the

beginning of R5 was the DOY when the linear increase in HI began. The mean DMAC from Ch. 4 and 5 were used as inputs in the simulations. The mean plant density and DOY of growth stage V1 for all cultivars in each site-yr was used for each simulation. Given these inputs, default simulations were conducted for cultivars AG4531, AG5503, P94Y80, P94Y81, P94Y82, and S44-K7 at Fayetteville from 2011 to 2013 and cultivars P94Y81, P94Y82, P94Y91, P94Y92, and P95Y10 in 2011, P94Y23, P94Y80, P94Y81, and P94Y82 in 2012, and P94B73, P48T53, P49T97, P50T40 and AG5332 in 2013 at Mr. Cullers' field. These were referred to as default simulations because the simulated upper limits for specific leaf N, radiation use efficiency (RUE), and N accumulation rates were left as 2.5 g N m^{-2} leaf area, 0.9 g MJ^{-1} , and $0.6 \text{ g N m}^{-2} \text{ d}^{-1}$, respectively (Sinclair, 1986; Sinclair et al., 2003). All simulations were then modified to include the maximum observed values for specific leaf N, RUE, and N accumulation rate (Table 3-1, 4-1, 4-3, 5-3, 5-5, and 5-6) and simulations were again conducted for all cultivars and site-yr. For Fayetteville in 2013, the modified simulations were conducted with the observed values from growth stages R1 to R3.

Finally, a sensitivity analysis was conducted for cultivars AG5503 and S44-K7 in all years at Fayetteville. Using the simulations modified with the observed specific leaf N and R1 to R3 parameters of RUE, and N accumulation rate, DMAC values were simulated from 0.004 to 0.014, in 0.002 increments, while holding all other parameters constant. Individual sensitivity simulations were also conducted for the specific leaf N from 2.5 to 3.3 g N m^{-2} leaf area, in 0.2 g N m^{-2} leaf area increments, RUE from 0.9 g MJ^{-1} , in 0.2 g MJ^{-1} increments, and N accumulation rates from $0.6 \text{ g N m}^{-2} \text{ d}^{-1}$, in $0.2 \text{ g N m}^{-2} \text{ d}^{-1}$ increments. A second sensitivity analysis was conducted with observed parameters for AG5503 from Fayetteville in 2013 and

varying both the RUE from 0.9 to 1.9 g MJ⁻¹, in 0.2 g MJ⁻¹ increments, and N accumulation rates from 0.6 to 1.6 g N m⁻² d⁻¹, in 0.2 g N m⁻² d⁻¹ increments.

RESULTS

Simulations

Default simulations for Fayetteville using only the observed DOY for leaf growth termination and linear HI increase and DMAC (Table 8-1) resulted in the over-prediction of grain yield, PM, and HI compared with the observed values in 2011 (Table 8-2). This is contrary to subsequent simulations in 2012 and 2013 and can be partially attributed to a severe spider mite infestation in 2011 that likely reduced yield and hastened PM in all cultivars. When all biological pests were fully controlled, default simulations in 2012 and 2013 underestimated the grain yield of all cultivars by 34.0% on average (Table 8-2). The default setting tended to over-predict the date of PM. In 2012, the average observed DOY of PM was 241 compared with 250 for the default simulation, and in 2013, the average observed was 262 compared with 278. The default simulation under-predicted HI for all cultivars in 2012 and 2013. However, the observed HI measurements were taken after the crop was defoliated to facilitate harvest. This resulted in an erroneous measurement for the HI at the DOY when the crop reached PM, as provided by the model.

In 2011, the modified simulations only included the addition of observed values for the RUE and the N accumulation rate. Additionally, the N accumulation rates were measured prior to complete canopy closure and were not representative of the true potential of the crop. For all cultivars, except AG4531, the observed N accumulation rate was less than the default model limit of 0.6 g N m⁻² d⁻¹, ranging from 0.47 to 0.66 g N m⁻² d⁻¹, but the model was edited with

those values regardless (Table 8-1). As such, the modified simulations in 2011 reflect only increases with the RUE, which were only slightly greater than the default RUE of 0.6 g MJ^{-1} and ranged from 0.86 to 0.98 g MJ^{-1} (Table 8-1). Modified simulations resulted in both over- and under-prediction of grain yield compared with default simulations but were still greater than observed for all cultivars due to pest damage.

In 2012 and 2013, modified simulations included changes to the specific leaf N, RUE, and N accumulation rate, all of which were measured to estimate the maximum potential of each value for the crop (Table 8-1). Modified simulations using the observed parameters increased grain yield compared with default simulations for all cultivars in both 2012 and 2013 (Table 8-2; Figure 8-1). Compared with observed grain yields, modified simulations both over- and under-predicted grain yields for a given cultivar but were closer to the observed yields than the default simulations (Figure 8-1). On average, observed grain yield across cultivars for 2012 was 6667 kg ha^{-1} , compared with 4871 and 6689 kg ha^{-1} for the default and modified simulations, respectively. The prediction of PM was also much closer to the observed DOY with the modified simulations in 2012 and 2013 than with the default settings. Harvest index values were generally less for modified simulations compared with the default simulations.

Using the observed inputs from Mr. Cullers' contest field (Table 8-3), observed values of grain yield for each cultivar were underestimated by the default simulations in all years except for P94Y92 in 2011 (Table 8-4). In 2011, measurements for the N accumulation rate were again not representative of the true maximum potential N accumulation by the crop and were below the maximum default value of $0.6 \text{ g N m}^{-2} \text{ d}^{-1}$ for all cultivars (Table 8-3). As a result, modified simulated grain yields were less than with default simulations, and both simulations were less than the observed grain yields for all cultivars (Table 8-4). In 2012 and 2013, simulations using

default parameters under-predicted yield by 37.6%, and modified simulations predicted greater yields than default simulations. However, on average, modified simulations still predicted yields 17.6% less than the observed values across cultivars for 2012 and 2013 (Figure 8-2).

The yield predictions with the modified model in Fayetteville were more accurate than at Mr. Cullers' field. One discrepancy between the two locations was the lack of irrigation totals from Mr. Cullers' field, and it may be that the simulated irrigations may not have accurately simulated the management practices at this location. Altering the model to simulate irrigation when the fraction of total soil water was predicted below 0.60 did not increase simulated yields, however. Changing the simulated depth of water extraction from 1.5 m to 2 m resulted in a 10% increase in simulated yields (data not shown). This indicates that the amount of total transpirable soil water may not have been accurately estimated. Perhaps alternative combinations of the fraction of total soil water level used to trigger irrigation and/or the irrigation amount would be able to overcome this water budget shortfall at that location.

Prediction of the DOY of PM was over- and under-predicted by both the default and modified simulations depending on cultivar and year (Table 8-4). This may have resulted from inaccuracies in the growth stage notes taken from Mr. Cullers' field due to field visits and staging notes only occurring about every 10 days. Harvest index values were over-predicted by the default model and under-predicted by the modified model in 2011 (Table 8-4). Harvest index samples were taken prior to complete defoliation at this location and better represent the apparent HI of the crop with the remaining leaves and petioles on the plants at PM. In 2012, HI values were slightly under-predicted by both simulations, while the 2013 default simulation of HI was accurate, averaging 0.428 compared with 0.425 for the observed HI over all cultivars. However, the modified simulation greatly under-predicted HI, averaging 0.289.

Sensitivity Analysis

The modified simulations were used to conduct sensitivity analyses of DMAC, specific leaf N, RUE, and the N accumulation rates. Using inputs for S44-K7 and AG5503 provided a range in the timing of leaf growth termination, the beginning of linear harvest index increases, and the predicted PM, yet both cultivars responded similarly in all simulations (Table 8-5). Predicted yields decreased as DMAC values increased. This effect was greatest with low DMAC values. For example, as DMAC increased from 0.004 to 0.006, yield decreased 1384 kg ha⁻¹ compared with a 330 kg ha⁻¹ yield decrease as DMAC increased from 0.012 to 0.014. A similar effect was observed with the predicted PM and at the lowest simulated values of DMAC, PM was unrealistically delayed by ≥ 37 days compared with observed dates of PM.

When photosynthetic rates are high and seedfill rates and seed N demands are low, an excess of current photosynthate can allow for additional N accumulation (Sinclair et al., 2003). Thus, the low DMAC values also allow for N accumulation to continue longer into seedfill. Once the seed N demand is greater than N accumulation, the stems and leaves provide the N to the seed in accordance with the self-destruct proposal (Sinclair and de Wit, 1976). Thus, the lower DMAC values and lower daily seed N requirements resulted in minimal reductions in the leaf area index to supply N to the growing seeds and a lengthened seedfill period. This greatly delayed the simulated DOY of PM (Table 8-5), which is simulated once the leaf area index reaches 0.1 (Sinclair et al., 2003). Yet, the HI tended to be unaffected by changes in DMAC (Table 8-5). Apparently the longer retention of leaf area and increased photosynthate production with lower DMAC values was simulated to produce both greater biomass and seed yield.

Simulated yields increased with increasing SLN, with the exception of 2011 (Table 8-5). In 2011, simulated yields were relatively unresponsive to increases in SLN and were likely due

to the low N accumulation rates measured in 2011. Increasing the SLN increases the N requirement to create new leaves (Sinclair et al., 2003). When the observed N accumulation rates measured prior to canopy closure and were therefore low, increases in the SLN in 2011 did not increase yield due to the greater N requirement to develop new biomass. However in 2012 and 2013, when observed N accumulation rates were much higher (Table 8-1), increases in the SLN increased yields because the N requirement of new biomass was fulfilled through greater N accumulation. This also provided a larger pool of N to be available to support seedfill and increased yields without increasing the HI and total biomass production or significantly delaying PM. This response is similar to the sensitivity analysis of this variable reported by Sinclair et al. (2003), where the limit imposed by the N accumulation rates prevented a further increase in the SLN.

The sensitivity analysis of the RUE gave mixed results (Table 8-5). In 2011, increases in RUE decreased yield. In 2012, increasing RUE increased yield until a plateau was reached at 1.5 g MJ⁻¹. In 2013, increasing RUE increased yield for all values. Since the development of new leaf area and stem mass are used to calculate the amount of N accumulation, this response to RUE is likely affected by the N accumulation rate within each year. Since the N accumulation rates in 2011 were underestimated, simulating greater RUE resulted in a limited pool of N to be distributed to greater leaf area and stem mass and unavailable for seed growth. As a result, the simulated yield, HI and PM decreased. In 2012, N accumulation rates were greater, and the increase in RUE resulted in a yield increase up until the greater amount of biomass limited the N available to increase seed growth and yield. Finally, N accumulation rates in 2013 were the greatest of all years studied and as a result, a yield increase was simulated for each increase in RUE.

In all years, simulating increased N accumulation rates increased yield up until a certain plateau (Table 8-5). This occurred where the RUE was not great enough to generate a daily N demand greater than the limit imposed by the daily N accumulation rate and thus, the simulated yields were identical. As such, increasing the N accumulation in the N budget will not increase final grain yield without a subsequent increase the RUE in the C budget. This is further demonstrated with a sensitivity analysis for both RUE and N accumulation rates (Table 8-6). Using observed parameters from AG5503 in 2013 at Fayetteville, it becomes evident that increases in yield depend on the increase of both the RUE and the N accumulation rate in tandem.

DISCUSSION

As a whole, datasets for Fayetteville 2012 and 2013 represent the most accurate and complete datasets examined in these modeling simulations. Simulations of these site-years with default parameters under-predicted yields by 34.0% while simulations where the model was modified to reflect the observed parameters over-predicted yields by 3.4%. With all Fayetteville simulations, irrigation amounts were recorded and included in the model as rainfall. Since most of the 2012 and 2013 simulated yields were within 15% of the observed yields (Figure 8-1), it is assumed that the irrigation inputs within these simulations were appropriate.

With regards to the N budget, the latest iteration of this model (Sinclair et al., 2003) simulates N accumulation from both the soil and supplemented by N₂ fixation. Thus, the model does not simulate the soil N budget and assumes that N₂ fixation can provide any additional N required beyond what exists in the soil, provided a water deficiency does not limit N₂ fixation. In the maximum yield environments simulated in this Chapter, there was an abundance of soil N

provided through manure and fertilizer applications and we assume that the crop was never lacking access to available soil N, in accordance with the model's assumptions.

The model also allows for additional N accumulation via N₂ fixation provided that excess photosynthate is available. Given the low DMAC values, it is likely that photosynthate was simulated to be available for relatively long time and N accumulation would continue into reproductive development. This agrees well with other work illustrating that N₂ fixation and N accumulation can continue late into seedfill (Hanway and Weber, 1971; Nelson and Weaver, 1980; Spaeth and Sinclair, 1983; Zapata et al., 1987; Leffel et al., 1992; Mastrodomenico and Purcell, 2012). It is likely that all of this contributed to the modified model being able to reasonably simulate grain yields in this maximum yield environment.

CONCLUSIONS

Empirical measurements from maximum yield research at the University of Arkansas (Ch. 5, Table 8-1) and from Mr. Cullers' contest fields (Ch. 3 and 4, Table 8-3) revealed that several soybean growth characteristics can be greater in a maximum yield environment than previously measured. As a result, simulations using default parameters under-predicted observed yields. When the observed measurements were incorporated into C and N budget simulations, a classical crop growth model did predict yield levels similar to the observed grain yields at Fayetteville, ranging from 4125 to 7114 kg ha⁻¹. Grain yields up to 7953 kg ha⁻¹ were observed in Mr. Cullers' contest fields but the model was unable to predict yields of this magnitude, possibly due to a lack of irrigation data and inaccuracies surrounding simulated irrigations and the model's water budget. As these modeling simulations have reaffirmed, C and N accumulation rates are key factors for providing resources for the development of high grain

yields. In addition, all of the contributing factors influencing the C, N, and water budgets are dynamic and interconnected. This and the results from the sensitivity analyses suggest that not one, but all of these processes must be optimized in concert in order to maximize soybean grain yields.

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Table 8-1. Model inputs for the day of year (DOY) of the termination of leaf growth (DOYTLG), DOY of beginning linear harvest index increase (DOYBLHI), and dry matter allocation coefficient used in all simulations as well as the specific leaf N (SLN), radiation use efficiency (RUE), and N accumulation rate (NAR) used in modified simulations by year and cultivar from Fayetteville.

Year	Cultivar	DOYTLG	DOYBLHI	DMAC	SLN	RUE	NAR
		—— DOY ——			g N m ⁻² leaf area	g MJ ⁻¹	g N m ⁻² d ⁻¹
2011	AG4531	212	222	0.0095	.	0.96	0.66
	AG5503	236	246	0.0107	.	0.94	0.47
	P94Y80	215	225	0.0091	.	0.86	0.57
	P94Y81	220	230	0.0091	.	0.97	0.58
	P94Y82	214	224	0.0107	.	0.92	0.59
	S44-K7	215	225	0.0101	.	0.98	0.59
2012	AG4531	178	188	0.0082	2.85	1.16	0.94
	AG5503	198	208	0.0061	2.89	1.18	0.97
	P94Y80	178	188	0.0101	2.81	1.51	1.26
	P94Y81	192	202	0.0053	3.00	1.14	0.88
	P94Y82	181	191	0.0046	3.04	1.34	1.11
	S44-K7	191	201	0.0088	3.22	1.45	1.10
2013	AG4531	211	221	0.0121	2.97	1.71	1.52
	AG5503	220	230	0.0089	2.85	1.57	1.28
	P94Y80	214	224	0.0110	3.16	1.59	1.48
	P94Y81	214	224	0.0116	3.12	1.39	1.26
	P94Y82	211	221	0.0122	3.20	1.47	1.31
	S44-K7	211	221	0.0096	3.08	1.59	1.31

Table 8-2. Grain yield, day of year (DOY) of physiological maturity, and harvest index as observed or from default and modified simulations by year and cultivar from Fayetteville.

Year	Cultivar	Yield (kg ha ⁻¹)			Physiological Maturity (DOY)			Harvest Index (%)		
		Observed	Default	Modified	Observed	Default	Modified	Observed	Default	Modified
2011	AG4531	5377	5470	6048	259	272	274	48.1	47.7	49.6
	AG5503	4125	6748	4596	276	316	276	40.4	75.1	33.0
	P94Y80	4902	5797	5448	263	278	277	48.4	49.1	48.1
	P94Y81	4518	6016	5581	263	287	275	43.4	52.3	41.1
	P94Y82	4412	5243	5177	259	269	267	48.6	48.5	46.4
	S44-K7	4615	5412	5275	259	272	266	45.4	48.3	41.6
	Avg.	4658	5781	5354	263	282	273	45.7	53.5	43.3
2012	AG4531	6473	4202	5081	239	232	228	47.8	36.5	33.2
	AG5503	6517	5655	7868	250	269	267	45.6	37.5	36.5
	P94Y80	7144	3732	5973	239	224	219	47.4	37.0	32.1
	P94Y81	7057	5748	7551	244	269	267	46.0	35.9	34.9
	P94Y82	6411	5211	6051	239	260	228	50.3	32.3	33.1
	S44-K7	6399	4677	7611	234	244	240	49.4	38.3	34.5
	Avg.	6667	4871	6689	241	250	242	47.8	36.3	34.1
2013	AG4531	7071	3249	6403	259	252	248	51.9	38.0	32.8
	AG5503	6062	4138	6864	270	271	265	45.7	37.4	31.9
	P94Y80	5792	3408	6454	262	257	254	49.2	37.0	33.3
	P94Y81	6118	3391	5853	262	256	255	46.1	37.6	36.1
	P94Y82	4977	3241	5565	259	252	249	53.4	38.0	34.4
	S44-K7	5767	3386	6620	259	258	255	53.2	35.7	33.1
	Avg.	5965	3469	6293	262	258	254	49.9	37.3	33.3

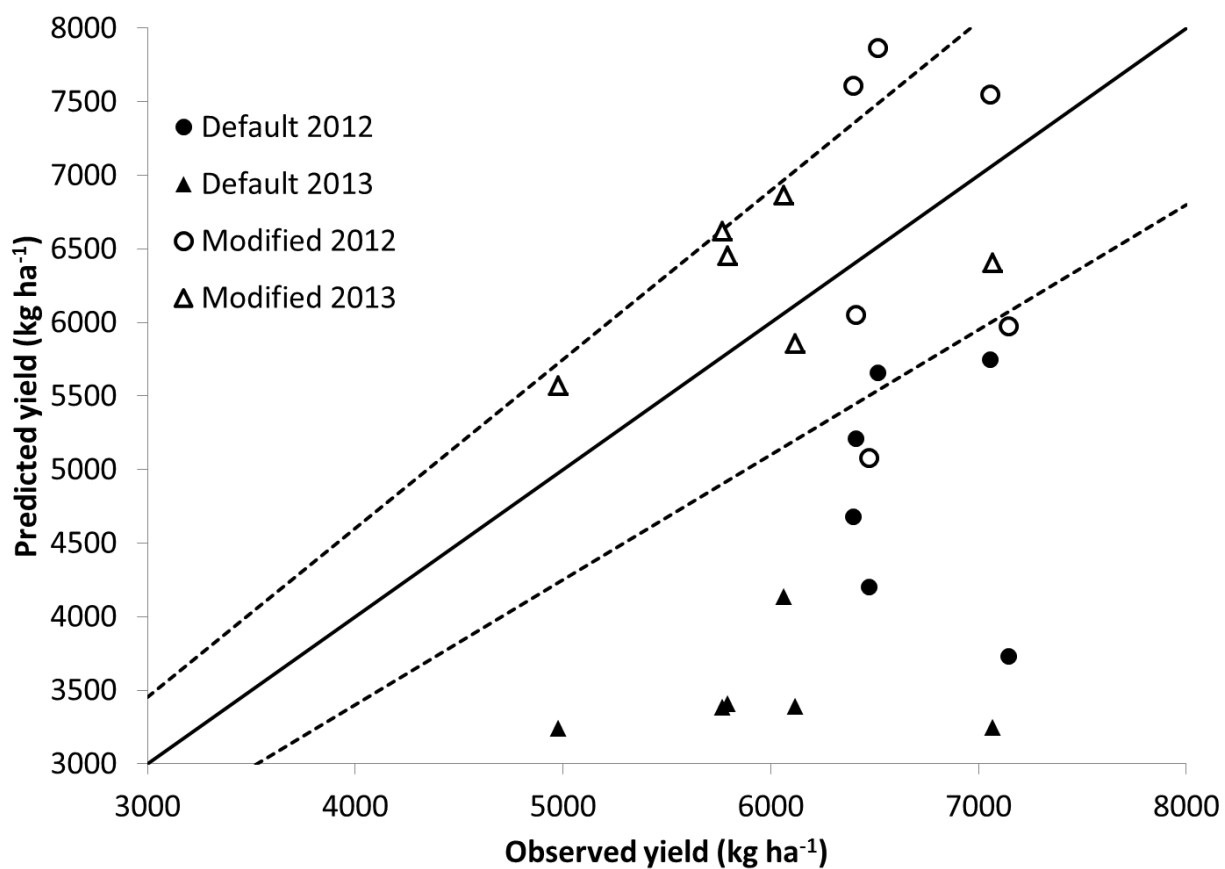


Figure 8-1. Predicted cultivar grain yield over observed cultivar grain yield for default and modified model simulations from Fayetteville in 2012 and 2013. Dashed lines represent $\pm 15\%$ of the observed 1:1 solid line.

Table 8-3. Model inputs for the day of year (DOY) of the termination of leaf growth (DOYTLG), DOY of beginning linear harvest index increase (DOYBLHI), and dry matter allocation coefficient used in all simulations as well as the specific leaf N (SLN), radiation use efficiency (RUE), and N accumulation rate (NAR) used in modified simulations by year and cultivar from Mr. Cullers' contest field.

Year	Cultivar	DOYTLG	DOYBLHI	DMAC	SLN	RUE	NAR
		—— DOY ——			g N m ⁻² leaf area	g MJ ⁻¹	g N m ⁻² d ⁻¹
2011	P94Y81	218	228	0.0100	.	0.90	0.58
	P94Y82	214	224	0.0088	.	0.96	0.52
	P94Y91	216	226	0.0111	.	0.97	0.55
	P94Y92	220	230	0.0108	.	0.93	0.47
	P95Y10	226	236	0.0111	.	1.03	0.58
2012	P94Y23	180	190	0.0086	2.96	1.15	0.90
	P94Y80	192	202	0.0088	3.01	1.02	0.87
	P94Y81	200	210	0.0087	2.85	0.84	0.83
	P94Y82	186	196	0.0121	2.84	1.01	0.88
2013	P94B73	212	222	0.0089	3.55	1.89	1.88
	P48T53	227	237	0.0105	3.17	1.46	1.43
	P49T97	222	232	0.0132	3.55	1.89	2.08
	P50T40	219	229	0.0103	3.84	1.80	2.07
	AG5332	219	229	0.0127	3.25	1.83	1.51

Table 8-4. Grain yield, day of year (DOY) of physiological maturity, and harvest index as observed or from default and modified simulations by year and cultivar from Mr. Cullers' contest field.

Year	Cultivar	Yield (kg ha ⁻¹)			Physiological Maturity (DOY)			Harvest Index (%)		
		Observed	Default	Modified	Observed	Default	Modified	Observed	Default	Modified
2011	P94Y81	7137	5569	5383	265	283	279	43.0	55.4	51.9
	P94Y82	7118	5351	4580	263	281	265	48.8	50.7	36.4
	P94Y91	6117	5155	4712	265	272	262	44.0	51.7	40.6
	P94Y92	5290	5692	4173	267	283	261	41.8	57.7	34.2
	P95Y10	6356	6243	5813	270	298	277	43.3	69.8	45.7
	Avg.	6404	5602	4932	266	283	269	44.2	57.1	41.8
2012	P94Y23	6979	4139	5102	229	234	230	48.2	38.3	35.3
	P94Y80	6925	4868	5865	233	249	249	46.1	41.9	42.0
	P94Y81	5555	5226	6013	236	259	269	41.6	43.2	51.8
	P94Y82	5521	3845	4504	236	229	229	45.5	40.7	40.3
	Avg.	6245	4520	5371	234	243	244	45.4	41.0	42.4
2013	P94B73	7084	3430	5275	268	265	251	41.4	38.6	26.6
	P48T53	6158	4222	5773	268	278	268	38.1	43.9	32.9
	P49T97	7953	3771	5651	274	266	253	42.1	45.3	27.8
	P50T40	6883	3799	5869	274	269	257	44.9	42.0	29.2
	AG5332	7482	3618	5188	276	263	251	46.2	44.0	28.0
	Avg.	7112	3768	5551	272	268	256	42.5	42.8	28.9

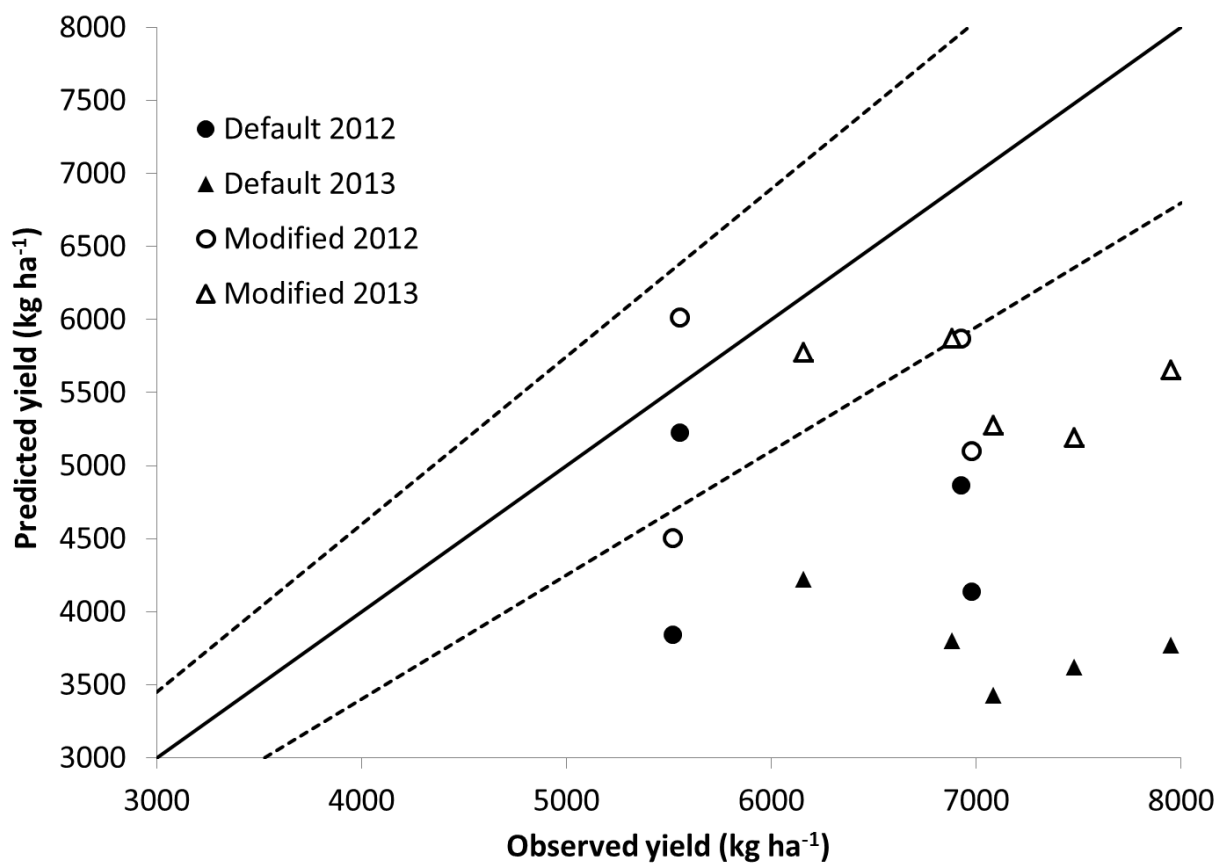


Figure 8-2. Predicted cultivar grain yield over observed cultivar grain yield for default and modified model simulations from Mr. Cullers' contest field in 2012 and 2013. Dashed lines represent $\pm 15\%$ of the observed 1:1 solid line.

Table 8-5. Simulated grain yield, day of year (DOY) of physiological maturity (PM), and harvest index from sensitivity analyses by varying the dry matter allocation coefficient (DMAC), specific leaf N (SLN, g N m⁻² leaf area), radiation use efficiency (RUE, g MJ⁻¹), and the N accumulation rate (N_{acc}, g N m⁻² d⁻¹) with data from two cultivars in all years at Fayetteville.

Year	DMAC	Yield (kg ha ⁻¹)		PM (DOY)		Harvest Index (%)	
		AG5503	S44-K7	AG5503	S44-K7	AG5503	S44-K7
2011	0.004	6355	7675	326	326	32.3	40.8
	0.006	5458	6369	299	295	32.0	42.4
	0.008	4976	6056	286	278	32.3	42.5
	0.010	4763	5367	279	266	33.4	42.0
	0.012	4583	4935	273	259	33.6	42.0
	0.014	4613	4684	270	255	35.0	42.8
	<u>SLN</u>						
	2.5	4596	5275	276	266	33.0	41.6
	2.7	4657	5113	276	264	32.8	39.5
	2.9	4591	5014	275	262	31.5	37.8
	3.1	4396	4979	273	261	29.7	37.1
	3.3	4355	4926	273	260	29.2	36.4
	<u>RUE</u>						
	0.9	4634	5311	279	271	35.9	47.2
	1.1	4015	5041	267	259	22.8	34.5
	1.3	3705	4982	261	252	16.9	27.6
	1.5	3324	4770	257	247	12.8	22.7
	1.7	3032	4623	255	243	10.2	19.2
	1.9	2577	3921	253	239	07.9	15.0
	<u>N_{acc}</u>						
	0.6	6600	5419	305	267	63.8	43.0
	0.8	7891	7104	339	286	100.0	62.6
	1.0	7974	7392	339	289	100.0	65.2
	1.2	7974	7392	339	289	100.0	65.2
	1.4	7974	7392	339	289	100.0	65.2
	1.6	7974	7392	339	289	100.0	65.2

Year	DMAC	Yield (kg ha ⁻¹)		PM (DOY)		Harvest Index (%)	
		AG5503	S44-K7	AG5503	S44-K7	AG5503	S44-K7
2012	0.004	9515	10,623	301	283	37.7	32.9
	0.006	8070	9081	269	257	36.9	33.9
	0.008	7129	7856	254	243	37.5	34.1
	0.010	6622	7252	246	235	38.5	34.8
	0.012	6251	6619	240	229	39.2	34.6
	0.014	5788	6101	235	225	38.9	34.2
<u>SLN</u>							
	2.5	7449	7108	265	238	35.0	32.7
	2.7	7697	7254	266	238	35.9	33.2
	2.9	7868	7376	267	239	36.5	33.6
	3.1	8109	7539	269	239	37.3	34.2
	3.3	8405	7686	270	240	38.3	34.7
<u>RUE</u>							
	0.9	6554	5610	276	250	41.8	43.7
	1.1	7533	6231	269	244	37.8	38.7
	1.3	8902	7323	267	242	36.1	36.8
	1.5	9426	8036	262	240	33.2	34.6
	1.7	9174	7740	256	235	29.5	30.7
	1.9	9307	8361	252	234	27.1	29.2
<u>N_{acc}</u>							
	0.6	6162	4916	255	228	29.3	23.9
	0.8	7445	6589	265	235	34.9	30.8
	1.0	7891	7419	267	239	36.6	33.9
	1.2	7896	7691	267	240	36.6	34.7
	1.4	7896	7691	267	240	36.6	34.7
	1.6	7896	7691	267	240	36.6	34.7

Year	DMAC	Yield (kg ha ⁻¹)		PM (DOY)		Harvest Index (%)	
		AG5503	S44-K7	AG5503	S44-K7	AG5503	S44-K7
2013	0.004	9578	10,213	307	303	31.2	33.3
	0.006	8008	8336	282	275	31.4	33.0
	0.008	7236	7440	269	263	32.0	33.8
	0.010	6630	6520	262	254	32.1	33.2
	0.012	6027	5972	256	248	31.5	33.3
	0.014	5574	5616	252	244	31.0	33.3
<u>SLN</u>							
	2.5	6611	6212	264	253	31.0	31.6
	2.7	6730	6337	265	254	31.4	32.1
	2.9	6909	6511	265	255	32.1	32.7
	3.1	7201	6638	267	255	33.0	33.2
	3.3	7457	6848	268	256	33.9	34.0
<u>RUE</u>							
	0.9	4625	4088	275	263	41.0	40.9
	1.1	5058	4622	270	259	35.8	36.7
	1.3	5965	5504	268	257	34.7	35.4
	1.5	6842	5968	267	254	33.2	32.5
	1.7	8002	7322	266	255	32.9	33.6
	1.9	8660	7842	265	254	31.6	32.0
<u>N_{acc}</u>							
	0.6	5683	4983	260	248	26.9	26.7
	0.8	6453	6070	264	253	30.4	31.2
	1.0	6864	6615	265	255	31.9	33.1
	1.2	6864	6620	265	255	31.9	33.1
	1.4	6864	6620	265	255	31.9	33.1
	1.6	6864	6620	265	255	31.9	33.1

Table 8-6. Simulated grain yield (kg ha^{-1}) from sensitivity analyses by varying the radiation use efficiency (RUE, g MJ^{-1}) and the N accumulation rate (N_{acc} , $\text{g N m}^{-2} \text{d}^{-1}$) with data from AG5503 in 2013 at Fayetteville.

N_{acc} ($\text{g N m}^{-2} \text{d}^{-1}$)	RUE (g m^{-2})					
	0.9	1.1	1.3	1.5	1.7	1.9
	Simulated grain yield (kg ha^{-1})					
0.6	4651	5238	5336	5630	5875	5426
0.8	4622	5050	5658	6525	7315	7407
1.0	4622	5058	5965	6842	7999	8579
1.2	4622	5058	5965	6842	8002	8660
1.4	4622	5058	5965	6842	8002	8660
1.6	4622	5058	5965	6842	8002	8660

CHAPTER 9

Conclusion

A theoretical discussion of soybean yield determination provides a mechanistic understanding of seed number and seed weight determination with physiological processes that can be readily measured and understood. Physiological characterization of the yield determining physiological processes in maximum yield environments revealed that many of these determinants were near or above the greatest values previously reported for soybean. On average, the yields and growth parameters were similar between research in Mr. Kip Cullers' contest fields and in small-plot research in Fayetteville. Additionally, several of Mr. Cullers' alternative management practices that were evaluated in Fayetteville did not significantly affect yield. Thus, we conclude that the management practices utilized within research at Fayetteville were able to create a maximum yield environment similar to that of Mr. Cullers' fields. When a scaled-down, high-yield management system was employed in large-scale research in eastern Arkansas, yields $>6719 \text{ kg ha}^{-1}$ ($100 \text{ bushels acre}^{-1}$) were obtained. However, economic analysis suggested that even these scaled-down, high-yield practices were not suitable for widespread adoption. Finally, crop modelling procedures further emphasized the importance of maximizing the yield determining physiological processes for generating high soybean yields.

From this research and modeling efforts, it is evident that C and N accumulation rates are key factors for maximizing soybean yield. High C accumulation rates must be maintained throughout the reproductive stages as well, as demonstrated in 2013 when biomass and N accumulation rates were decreased from R3 to R5 and grain yields were not truly maximized. Radiation use efficiency was also much greater than normally observed under high amounts of solar radiation. The water and N management systems likely help allow for this by eliminating all water deficit and excess stresses and providing ample amounts of available N for uptake and utilization. Furthermore, striving for complete pest control practices ensured there were no biotic

competitors for light, water, or nutrients, which eliminated additional stresses to the plants throughout the growing season. Earlier planting induced flowering prior to the summer solstice and may have helped decrease the rate of harvest index increase. This and the N management system may have helped delay N remobilization and lengthened the seedfill period. From this maximum yield work, it appears that the best avenue for increasing final grain yield is to maximize C and N accumulation while lowering the seed growth rates and extending the seedfill period.

Of all the management practices employed in this research, several hold great promise for increasing soybean yields on a broad scale. First, meticulous scouting practices and economically controlling all pests, including weeds, insects, and diseases, remains a key component for maintaining the yield potential of the crop. Second, when irrigation is available and is utilized, it is important to properly manage irrigation timings and amounts to capitalize on the benefits of supplemental water inputs. Third, ensuring that adequate amounts of nutrients are available is required to reach the desired yield goal. It is not likely that supplemental N will be profitable or sustainable for soybean production. Rather, one should focus on maintaining the proper soil pH, correcting any nutrient deficiencies, and supplementing additional K fertility for the most likely benefits to soybean yield. Fourth, early planting is an important cultural practice that may increase soybean yield via earlier and longer flowering and by potentially reducing plant height and lodging in high fertility environments. Fifth, narrow row widths can increase soybean yield by allowing the crop to reach full light interception earlier in the growing season to potentially increase radiation use efficiency. Finally, selecting the best cultivar can have a large impact of final grain yield. No clear trends could be distinguished from this work with regard to which cultivar would return the greatest yield. Yield rankings tended to be similar for cultivars between

years but not locations. This suggests that evaluating cultivars in one's specific growing environment is the best way to determine which cultivar may provide the greatest yield.

In conclusion, attaining yields $>6719 \text{ kg ha}^{-1}$ ($100 \text{ bushel acre}^{-1}$) are not without significant challenges. Large inputs of nutrients and water along with excellent pest control measures are required to achieve the growth rates necessary to generate these yields. These practices do not occur without economic and environmental costs. This research served to highlight the key physiological processes involved in maximizing soybean yield and catalog the management practices utilized to achieve these yields. One goal is that other soybean producers may take away portions of these management practices and profitably and sustainably implement them to increase yields on their farm. Another goal is for other researchers to utilize this physiological and nutritional framework of high yield soybean to develop improved cultivars and further refine management systems to increase soybean yields. Hopefully, these goals can be met through the publication of dissertation along with past and future extension and outreach efforts to share the knowledge gained from this research.

APPENDIX

Appendix 4-1. Leaf nutrient concentration response to day of year from covariate analysis by year and cultivar from Mr. Cullers' contest field.

Year	Cultivar	N†			P†			K†		
		ax ²	bx	c	ax ²	bx	c	ax ²	bx	c
2011	P94Y81	-0.0004509	0.1607379	-8.1068208	.	-0.00374364	1.22287683	0.0003289	-0.1689688	22.8900829
	P94Y82	-0.0010833	0.4503827	-40.9922197	.	-0.00374364	1.22287683	0.0003289	-0.1674283	22.4280731
	P94Y91	-0.0005040	0.1925594	-12.5931390	.	-0.00374364	1.22287683	0.0003289	-0.1716359	23.7224326
	P94Y92	-0.0005700	0.2193755	-15.2684039	.	-0.00374364	1.22287683	0.0003289	-0.1701908	23.3982482
	P95Y10	-0.0009108	0.3865336	-35.2504830	.	-0.00374364	1.22287683	0.0003289	-0.1624177	21.5649479
2012	P94Y23	-0.0000315	-0.0361608	13.3309787	0.00001707	-0.00994496	1.60097971	0.0004462	-0.1931906	17.0437879
	P94Y80	-0.0005851	0.2048661	-12.4615010	0.00001707	-0.00994496	1.61197971	0.0004199	-0.1874025	17.0437879
	P94Y81	-0.0007188	0.2578530	-17.4679629	0.00001707	-0.00994496	1.61697971	0.0000852	-0.0518661	17.0437879
	P94Y82	-0.0005863	0.2017370	-11.7482803	0.00001707	-0.00994496	1.59847971	0.0002597	-0.1186440	17.0437879
2013	P48T53	.	-0.0373720	13.1694006	0.00001370	-0.00844985	1.53065737	0.0002574	-0.1298638	17.1317767
	P49T97	.	-0.0373720	13.4883555	0.00001370	-0.00844985	1.55276724	0.0002574	-0.1285857	17.1317767
	P50T40	.	-0.0373720	13.6035672	0.00001370	-0.00844985	1.59065737	0.0002574	-0.1249858	17.1317767
	AG5332	.	-0.0373720	13.1519006	0.00001370	-0.00844985	1.54232403	0.0002574	-0.1250996	17.1317767
	P94B73	.	-0.0373720	13.2694066	0.00001370	-0.00844985	1.54732403	0.0002574	-0.1285162	17.1317767

† Based upon concentration expressed as a percentage.

‡ Based upon concentration expressed as mg kg⁻¹.

Appendix 4-1 cont.

Year	Cultivar	Ca†			Mg†			S†		
		ax ²	bx	c	ax ²	bx	c	ax ²	bx	c
2011	P94Y81	-0.0002607	0.1495932	-18.3010602	.	-0.00393016	1.17115850	-0.00000781	0.00096196	0.47273984
	P94Y82	-0.0005688	0.2915058	-34.4075622	.	-0.00393016	1.19616266	-0.00007051	0.02960382	-2.75517833
	P94Y91	-0.0004827	0.2493080	-29.5962775	.	-0.00393016	1.13365850	-0.00003273	0.01291979	-0.93905953
	P94Y92	-0.0000864	-0.0066596	-0.9388289	.	-0.00393016	1.16765850	-0.00001301	0.00327563	0.22673544
	P95Y10	-0.0000430	0.0421027	-5.4201319	.	-0.00393016	1.19765850	-0.00003257	0.01301535	-0.96444376
2012	P94Y23	0.00025273	-0.07700480	7.18690852	.	-0.00156874	0.51143448	-0.00000705	0.00161695	0.22485591
	P94Y80	0.00025273	-0.07700480	6.70240852	.	-0.00156874	0.56143448	-0.00002657	0.00975246	-0.60880272
	P94Y81	0.00025273	-0.07700480	6.55340852	.	-0.00156874	0.54143448	-0.00003430	0.01278185	-0.90057147
	P94Y82	0.00025273	-0.07700480	6.63440852	.	-0.00156874	0.54293448	-0.00000814	0.00207508	0.18797274
2013	P48T53	.	0.02801077	-4.38145060	.	-0.00209474	0.67189404	-0.00000506	0.00103191	0.28604781
	P49T97	.	0.02801077	-4.38145060	.	-0.00161001	0.61737232	0.00001940	-0.01039615	1.61811587
	P50T40	.	0.02801077	-4.38145060	.	-0.00194967	0.66638894	0.00001559	-0.00850109	1.40317475
	AG5332	.	0.02801077	-4.38145060	.	-0.00274221	0.84788857	0.00001359	-0.00748969	1.23729351
	P94B73	.	0.02801077	-4.38145060	.	-0.00145370	0.57868367	0.00002344	-0.01211957	1.79437193

† Based upon concentration expressed as a percentage.

‡ Based upon concentration expressed as mg kg⁻¹.

Appendix 4-1 cont.

Year	Cultivar	Na‡			Fe‡			Mn‡		
		ax ²	bx	c	ax ²	bx	c	ax ²	bx	c
2011	P94Y81	-0.000610	0.20297	-0.931410	0.00013	-0.77604	270.57514	-0.04289	20.90379	-2397.59411
	P94Y82	0.027100	-12.62175	1483.931520	-0.00115	-0.24322	219.52951	-0.04289	20.90379	-2362.60635
	P94Y91	0.003880	-2.11148	299.883560	0.01792	-9.39627	1311.62083	-0.04289	20.90379	-2367.45411
	P94Y92	0.000030	-0.12632	45.968040	-0.00813	3.09828	-178.14912	-0.04289	20.90379	-2359.98911
	P95Y10	0.000310	-0.13016	27.643800	-0.01271	5.34068	-443.49190	-0.04289	20.90379	-2404.44411
2012	P94Y23	0.005291	-2.285238	254.094436	.	-0.329466	148.939038	-0.012766	6.638711	-597.33332
	P94Y80	-0.000279	0.085611	5.825044	.	-0.329466	148.939038	-0.012766	6.629148	-597.33332
	P94Y81	0.004173	-1.794450	201.642861	.	-0.329466	148.939038	-0.012766	5.632985	-597.33332
	P94Y82	-0.009905	4.067027	-396.373327	.	-0.329466	148.939038	-0.012766	5.567952	-597.33332
2013	P48T53	-0.007789	3.722018	-418.145559	.	-0.263394	150.180425	-0.01460	9.55921	-1267.81006
	P49T97	0.009737	-4.472301	515.226647	.	0.093685	67.656076	-0.01460	8.05098	-944.99292
	P50T40	0.009520	-4.353470	503.012280	.	-0.477118	218.956269	-0.01460	8.24244	-990.29972
	AG5332	0.003460	-1.442318	156.457199	.	-0.094133	104.897788	-0.01460	10.52008	-1424.44743
	P94B73	0.000104	0.075859	-13.425067	.	-0.449683	185.445149	-0.01460	7.86181	-907.74440

† Based upon concentration expressed as a percentage.

‡ Based upon concentration expressed as mg kg⁻¹.

Appendix 4-1 cont.

Year	Cultivar	Zn [†]			Cu [‡]			B [‡]		
		ax ²	bx	c	ax ²	bx	c	ax ²	bx	c
2011	P94Y81	.	0.615503	-118.080121	.	.	12.9652500	0.008381	-4.508711	638.644917
	P94Y82	.	2.579730	-118.080121	.	.	12.9652500	0.005987	-3.272956	474.292317
	P94Y91	.	1.449260	-118.080121	.	.	12.9652500	0.014601	-7.300042	950.900177
	P94Y92	.	1.166718	-118.080121	.	.	12.9652500	-0.000990	0.025881	102.349999
	P95Y10	.	0.909617	-118.080121	.	.	12.9652500	0.006734	-3.604637	512.435938
2012	P94Y23	-0.011856	4.856587	-446.519766	-0.0002478	.	16.5726679	0.007065	-2.957175	355.851157
	P94Y80	-0.011856	4.856587	-426.574766	-0.0002478	.	16.8976679	-0.005202	2.033305	-151.832533
	P94Y81	-0.011856	4.856587	-451.604766	-0.0002478	.	16.9076679	-0.017418	7.320182	-700.306153
	P94Y82	-0.011856	4.856587	-449.334766	-0.0002478	.	18.1276679	-0.007263	3.084017	-279.185879
2013	P48T53	.	1.417259	-179.608149	0.0001946	-0.1428626	29.4337585	0.005179	-2.597271	363.334386
	P49T97	.	2.260711	-382.363227	0.0010613	-0.5800024	83.6417165	0.005179	-2.597271	358.491124
	P50T40	.	0.848802	-103.113625	0.0005230	-0.3031838	47.2468026	0.005179	-2.597271	357.638552
	AG5332	.	2.398451	-409.596425	-0.0005384	0.2029750	-11.0477652	0.005179	-2.597271	354.234386
	P94B73	.	0.781808	82.806388	0.0005503	-0.3275867	51.1956419	0.005179	-2.597271	361.396886

[†] Based upon concentration expressed as a percentage.

[‡] Based upon concentration expressed as mg kg⁻¹.

Appendix 4-2. Pearson correlation coefficients for biomass accumulation rate (BAR), radiation use efficiency (RUE), nitrogen accumulation rate (NAR), specific leaf weight (SLW), specific leaf nitrogen (SLN), harvest index (HI), dry matter allocation coefficient (DMAC), seedfill period (SFP), yield, individual seed weight (Seedwt), and seeds m⁻² (Seed#) for all cultivars and years from Mr. Cullers' contest field.

		BAR	RUE	NAR	SLW	SLN	HI	DMAC	SFP	Yield	Seedwt	Seed#	Protein	Oil
BAR	Pearson	1.000	0.987	0.941	0.693	0.638	-0.149	0.277	-0.490	0.484	0.508	0.236	0.638	-0.186
	Prob		<0.0001	<0.0001	<0.0001	<0.0001	0.3723	0.1183	0.0052	0.0037	0.0011	0.1722	<0.0001	0.2636
	n=	38	37	38	37	37	38	33	31	34	38	35	38	38
RUE	Pearson		1.000	0.904	0.705	0.614	-0.137	0.239	-0.340	0.354	0.501	0.043	0.607	-0.237
	Prob			<0.0001	<0.0001	<0.0001	0.3078	0.0886	0.0156	0.0092	<0.0001	0.7564	<0.0001	0.0754
	n=		57	37	36	36	57	52	50	53	57	54	57	57
NAR	Pearson			1.000	0.664	0.677	-0.244	0.292	-0.510	0.391	0.518	0.092	0.661	-0.165
	Prob				<0.0001	<0.0001	0.1300	0.0886	0.0024	0.0183	0.0006	0.5872	<0.0001	0.3079
	n=			40	39	39	40	35	33	36	40	37	40	40
SLW	Pearson				1.000	0.836	-0.055	0.293	-0.451	0.409	0.300	0.222	0.304	-0.180
	Prob					<0.0001	0.7404	0.0927	0.0096	0.0147	0.0637	0.1930	0.0598	0.2718
	n=				39	39	39	34	32	35	39	36	39	39
SLN	Pearson					1.000	0.051	0.039	-0.245	0.372	0.398	0.214	0.421	-0.052
	Prob						0.7591	0.8258	0.1768	0.0280	0.0121	0.2102	0.0076	0.7520
	n=					39	39	34	32	35	39	36	39	39
HI	Pearson						1.000	-0.067	0.385	0.370	0.048	0.513	-0.139	0.477
	Prob							0.6289	0.0044	0.0050	0.7153	<0.0001	0.2901	0.0001
	n=						60	55	53	56	60	57	60	60
DMAC	Pearson							1.000	-0.881	0.241	0.384	-0.087	0.111	-0.044
	Prob								<0.0001	0.0880	0.0038	0.5398	0.4179	0.7511
	n=							55	52	51	55	52	55	55
SFP	Pearson								1.000	-0.055	-0.350	0.268	-0.150	0.318
	Prob									0.7081	0.0102	0.0597	0.2845	0.0203
	n=								53	49	53	50	53	53
Yield	Pearson									1.000	0.424	0.818	0.293	0.105
	Prob										0.0011	<0.0001	0.0286	0.4429

	n=		56	56	56	56	56
Seedwt	Pearson			1.000	-0.100	0.581	0.125
	Prob				0.4606	<0.0001	0.3405
	n=			60	57	60	60
Seed#	Pearson				1.000	-0.040	0.159
	Prob					0.7677	0.238
	n=				57	57	57
Protein	Pearson					1.000	0.029
	Prob						0.8238
	n=					60	60
Oil	Pearson						1.000
	Prob						
	n=						60

Appendix 5-1. Summary of the date and amount of irrigation and the amount of NH_4SO_4 , KNO_3 , K_2SO_4 , CaNO_3 , or 32% $\text{CO}(\text{NH}_2)_2 + \text{NH}_4\text{NO}_3$ (UAN) fertilizer used for fertigation nutrient inputs in each year of research at Fayetteville.

Irrigation and Nutrient Inputs			
Year	Date	Amount	Form
2011	6 June	10 mm H_2O	
	13 June	9 mm H_2O	
	19 June	10 mm H_2O	
	21 June	15 mm H_2O	
	23 June	20 mm H_2O , 3.1 kg N, 3.6 kg S ha^{-1}	NH_4SO_4
	23 June	23 mm H_2O , 0.9 kg N, 2.5 kg K ha^{-1}	KNO_3
	30 June	22 mm H_2O , 1.7 kg K, 0.7 kg S ha^{-1}	K_2SO_4
	3 July	21 mm H_2O , 3.1 kg N, 3.8 kg Ca ha^{-1}	CaNO_3
	6 July	24 mm H_2O , 3.0 kg N, 3.5 kg S ha^{-1}	NH_4SO_4
	9 July	30 mm H_2O , 1.0 kg N, 2.8 kg K ha^{-1}	KNO_3
	11 July	18 mm H_2O , 1.6 kg K, 0.7 kg S ha^{-1}	K_2SO_4
	15 July	22 mm H_2O , 4.3 kg N, 5.2 kg Ca ha^{-1}	CaNO_3
	18 July	18 mm H_2O , 0.9 kg N, 2.6 kg K ha^{-1}	KNO_3
	21 July	23 mm H_2O , 3.0 kg N, 3.5 kg S ha^{-1}	NH_4SO_4
	24 July	24 mm H_2O , 0.9 kg N, 2.6 kg K ha^{-1}	KNO_3
	27 July	25 mm H_2O , 3.0 kg N, 3.5 kg S ha^{-1}	NH_4SO_4
	30 July	24 mm H_2O , 0.9 kg N, 2.6 kg K ha^{-1}	KNO_3
	2 Aug.	17 mm H_2O , 3.0 kg N, 3.5 kg S ha^{-1}	NH_4SO_4
	3 Aug.	8 mm H_2O	
	4 Aug.	2 mm H_2O	
	5 Aug.	19 mm H_2O	
	8 Aug.	19 mm H_2O , 3.0 kg N, 3.5 kg S ha^{-1}	NH_4SO_4
	12 Aug.	6 mm H_2O	
	13 Aug.	4 mm H_2O	
	14 Aug.	8 mm H_2O	
	15 Aug.	6 mm H_2O	
	17 Aug.	13 mm H_2O , 3.1 kg N, 3.8 kg Ca ha^{-1}	CaNO_3
	20 Aug.	13 mm H_2O , 0.9 kg N, 2.6 kg K ha^{-1}	KNO_3
	22 Aug.	13 mm H_2O , 3.0 kg N, 3.5 kg S ha^{-1}	NH_4SO_4
	24 Aug.	13 mm H_2O , 0.9 kg N, 2.6 kg K ha^{-1}	KNO_3
	26 Aug.	9 mm H_2O , 2.4 kg N, 2.8 kg Ca ha^{-1}	CaNO_3
	27 Aug.	9 mm H_2O , 0.9 kg N, 2.6 kg K ha^{-1}	KNO_3
	28 Aug.	9 mm H_2O , 3.0 kg N, 3.5 kg S ha^{-1}	NH_4SO_4
	30 Aug.	10 mm H_2O , 0.9 kg N, 2.6 kg K ha^{-1}	KNO_3
1 Sep.	12 mm H_2O , 3.0 kg N, 3.5 kg S ha^{-1}	NH_4SO_4	

	2 Sep.	9 mm H ₂ O	
	4 Sep.	8 mm H ₂ O	
	7 Sep.	12 mm H ₂ O, 4.3 kg N, 5.3 kg Ca ha ⁻¹	CaNO ₃
	8 Sep.	13 mm H ₂ O, 0.9 kg N, 2.6 kg K ha ⁻¹	KNO ₃
	11 Sep.	12 mm H ₂ O, 3.0 kg N, 3.5 kg S ha ⁻¹	NH ₄ SO ₄
	13 Sep.	13 mm H ₂ O, 4.3 kg N, 5.3 kg Ca ha ⁻¹	CaNO ₃
	21 Sep.	12 mm H ₂ O, 2.0 kg N, 2.2 kg S ha ⁻¹	NH ₄ SO ₄
	27 Sep.	15 mm H ₂ O, 4.3 kg N, 5.3 kg Ca ha ⁻¹	CaNO ₃
	29 Sep.	13 mm H ₂ O, 0.9 kg N, 2.6 kg K ha ⁻¹	KNO ₃
	4 Oct.	10 mm H ₂ O	
2012	17 May	14 mm H ₂ O	
	22 May	12 mm H ₂ O	
	25 May	23 mm H ₂ O	
	29 May	3 mm H ₂ O	
	8 June	24 mm H ₂ O, 1.6 kg N, 4.3 kg K ha ⁻¹	KNO ₃
	13 June	24 mm H ₂ O, 23.0 kg N ha ⁻¹	UAN
	15 June	24 mm H ₂ O, 4.8 kg N, 5.6 kg S ha ⁻¹	NH ₄ SO ₄
	19 June	18 mm H ₂ O, 23.0 kg N ha ⁻¹	UAN
	20 June	10 mm H ₂ O, 1.6 kg N, 4.3 kg K ha ⁻¹	KNO ₃
	23 June	24 mm H ₂ O, 19.7 kg N ha ⁻¹	UAN
	26 June	24 mm H ₂ O, 4.1 kg N, 4.7 kg S ha ⁻¹	NH ₄ SO ₄
	28 June	3 mm H ₂ O	
	29 June	24 mm H ₂ O, 16.9 kg N ha ⁻¹	UAN
	2 July	6 mm H ₂ O	
	3 July	16 mm H ₂ O, 18.4 kg N ha ⁻¹	UAN
	5 July	24 mm H ₂ O, 1.2 kg N, 3.4 kg K ha ⁻¹	KNO ₃
	6 July	5 mm H ₂ O	
	7 July	16 mm H ₂ O	
	12 July	24 mm H ₂ O, 4.1 kg N, 4.7 kg S ha ⁻¹	NH ₄ SO ₄
	14 July	16 mm H ₂ O, 14.9 kg N ha ⁻¹	UAN
	17 July	24 mm H ₂ O, 1.2 kg N, 3.4 kg K ha ⁻¹	KNO ₃
	20 July	24 mm H ₂ O, 4.1 kg N, 4.7 kg S ha ⁻¹	NH ₄ SO ₄
	23 July	24 mm H ₂ O, 23.0 kg N ha ⁻¹	UAN
	26 July	24 mm H ₂ O, 1.2 kg N, 3.4 kg K ha ⁻¹	KNO ₃
	29 July	24 mm H ₂ O, 23.0 kg N ha ⁻¹	UAN
	1 Aug.	24 mm H ₂ O, 4.1 kg N, 4.7 kg S ha ⁻¹	NH ₄ SO ₄
	4 Aug.	24 mm H ₂ O, 4.1 kg N, 4.7 kg S ha ⁻¹	NH ₄ SO ₄
	5 Aug.	24 mm H ₂ O	

	7 Aug.	24 mm H ₂ O, 1.2 kg N, 3.4 kg K ha ⁻¹	KNO ₃
	10 Aug.	24 mm H ₂ O, 4.1 kg N, 4.7 kg S ha ⁻¹	NH ₄ SO ₄
	13 Aug.	24 mm H ₂ O, 23.0 kg N ha ⁻¹	UAN
	16 Aug.	24 mm H ₂ O, 23.0 kg N ha ⁻¹	UAN
	21 Aug.	24 mm H ₂ O, 23.0 kg N ha ⁻¹	UAN
	23 Aug.	12 mm H ₂ O, 4.1 kg N, 4.7 kg S ha ⁻¹	NH ₄ SO ₄
	4 Sep.	12 mm H ₂ O, 23.0 kg N ha ⁻¹	UAN
2013	12 June	8 mm H ₂ O, 1.1 kg N, 3.2 kg K ha ⁻¹	KNO ₃
	14 June	12 mm H ₂ O, 1.1 kg N, 3.2 kg K ha ⁻¹	KNO ₃
	21 June	20 mm H ₂ O, 2.6 kg N, 2.9 kg S ha ⁻¹	NH ₄ SO ₄
	25 June	20 mm H ₂ O, 1.1 kg N, 3.2 kg K ha ⁻¹	KNO ₃
	27 June	30 mm H ₂ O, 1.1 kg N, 3.2 kg K ha ⁻¹	KNO ₃
	28 June	8 mm H ₂ O, 1.1 kg N, 3.2 kg K ha ⁻¹	KNO ₃
	2 July	24 mm H ₂ O, 1.1 kg N, 3.2 kg K ha ⁻¹	KNO ₃
	6 July	24 mm H ₂ O, 1.1 kg N, 3.2 kg K ha ⁻¹	KNO ₃
	9 July	24 mm H ₂ O, 1.1 kg N, 3.2 kg K ha ⁻¹	KNO ₃
	11 July	24 mm H ₂ O, 1.1 kg N, 3.2 kg K ha ⁻¹	KNO ₃
	13 July	24 mm H ₂ O, 1.1 kg N, 3.2 kg K ha ⁻¹	KNO ₃
	16 July	10 mm H ₂ O, 0.6 kg N, 1.6 kg K ha ⁻¹	KNO ₃
	19 July	24 mm H ₂ O, 3.7 kg N, 4.3 kg S ha ⁻¹	NH ₄ SO ₄
	22 July	24 mm H ₂ O, 3.7 kg N, 4.3 kg S ha ⁻¹	NH ₄ SO ₄
	31 July	20 mm H ₂ O, 17.4 kg N ha ⁻¹	UAN
	7 Aug.	24 mm H ₂ O, 17.4 kg N ha ⁻¹	UAN
	18 Aug.	24 mm H ₂ O, 17.4 kg N ha ⁻¹	UAN
	22 Aug.	24 mm H ₂ O, 17.4 kg N ha ⁻¹	UAN
	26 Aug.	24 mm H ₂ O, 17.4 kg N ha ⁻¹	UAN
	30 Aug.	24 mm H ₂ O, 17.4 kg N ha ⁻¹	UAN
	3 Sep.	10 mm H ₂ O, 17.4 kg N ha ⁻¹	UAN
	5 Sep.	24 mm H ₂ O, 17.4 kg N ha ⁻¹	UAN
	9 Sep.	10 mm H ₂ O, 17.4 kg N ha ⁻¹	UAN
	11 Sep.	24 mm H ₂ O, 17.4 kg N ha ⁻¹	UAN
	17 Sep.	10 mm H ₂ O	

Appendix 5-2. Significance of *F*-values for the cultivar source of variation from statistical analyses for dependent variables biomass accumulation rate (BAR), nitrogen accumulation rate (NAR), and radiation use efficiency (RUE) at different sampling intervals, specific leaf N (SLN), specific leaf weight (SLW), dry matter allocation coefficient (DMAC), seedfill period (SFP), grain yield, harvest index (HI), seeds m⁻², seed weight, and oil and protein concentrations within each year of study at Fayetteville.

Dependent variable	Cultivar		
	2011	2012	2013
	<i>P</i> > <i>F</i>		
BAR, V5-R2	0.1918	.	.
NAR, V5-R2	0.5271	.	.
RUE, V5-R2	0.0798	.	.
BAR, R1-R3	.	0.0385	0.6579
NAR, R1-R3	.	0.5484	0.7866
RUE, R1-R3	.	0.3645	0.6351
BAR, R1-R5	.	.	0.0137
NAR, R1-R5	.	.	0.0104
RUE, R1-R5	.	.	0.0136
SLN	.	0.0332	0.8995
SLW	.	0.3184	0.1203
DMAC	0.8315	<0.0001	0.2428
SFP	0.5132	0.0041	0.0026
Yield	0.0138	0.0098	0.1221
HI	0.0046	0.0019	0.0453
Seeds m ⁻²	0.0006	<0.0001	0.0152
Seed weight	0.0004	<0.0001	0.0006
Oil	<0.0001	<0.0001	<0.0001
Protein	<0.0001	<0.0001	<0.0001

Appendix 5-3. Leaf nutrient concentration response to day of year from covariate analysis by year and cultivar from Fayetteville.

Year	Cultivar	N†			P†			K†		
		ax ²	bx	c	ax ²	bx	c	ax ²	bx	c
2011	AG4303	-0.0006784	0.2483757	-16.8128222	0.00005122	-0.02770214	3.96422797	0.0005035	-0.2520067	32.4814057
	AG4531	-0.0006784	0.2607343	-19.1581937	0.00005122	-0.02739986	3.87659994	0.0005035	-0.2520067	32.6314057
	AG4907	-0.0006784	0.2606303	-19.0868948	0.00005122	-0.02766658	3.93431094	0.0005035	-0.2520067	32.4097390
	AG5331	-0.0006784	0.2743968	-22.4712312	0.00005122	-0.02650192	3.64827846	0.0005035	-0.2520067	32.7564057
	AG5503	-0.0006784	0.2800303	-23.3742946	0.00005122	-0.02701757	3.78624195	0.0005035	-0.2520067	32.6705723
	P94Y80	-0.0006784	0.2602802	-19.3113367	0.00005122	-0.02768613	3.94218197	0.0005035	-0.2520067	32.4805723
	P94Y81	-0.0006784	0.2602793	-19.2013804	0.00005122	-0.02779993	3.96691644	0.0005035	-0.2520067	32.5339057
	P94Y82	-0.0006784	0.2558045	-18.2700715	0.00005122	-0.02838848	4.10595983	0.0005035	-0.2520067	32.4155723
	P94Y91	-0.0006784	0.2635236	-19.7943104	0.00005122	-0.02802753	4.03638539	0.0005035	-0.2520067	32.5547390
	P94Y92	-0.0006784	0.2636328	-20.0071390	0.00005122	-0.02862497	4.16165803	0.0005035	-0.2520067	32.6355723
	P95Y10	-0.0006784	0.2677471	-20.7748305	0.00005122	-0.02783016	3.97642925	0.0005035	-0.2520067	32.6697390
	S44-K7	-0.0006784	0.2553790	-18.2131060	0.00005122	-0.02859118	4.15132019	0.0005035	-0.2520067	32.6722390
	S46-U6	-0.0006784	0.2658906	-20.3905374	0.00005122	-0.02781949	3.97728747	0.0005035	-0.2520067	32.5739057
	S49-A5	-0.0006784	0.2669304	-20.7883611	0.00005122	-0.02733407	3.84883678	0.0005035	-0.2520067	32.4780723
2012	AG4303	0.0000275	-0.0640851	16.5541072	0.00004201	-0.01944208	2.48131254	0.0002074	-0.1055385	14.0171407
	AG4531	-0.0003319	0.0903241	0.4152103	0.00003838	-0.01832128	2.41258078	0.0002074	-0.1055385	14.1603002
	AG4907	-0.0008503	0.3080072	-22.0881301	-0.00000852	0.00113922	0.40303764	0.0002074	-0.1055385	14.0882152
	AG5332	-0.0005566	0.1855841	-9.6488334	0.00001433	-0.00810036	1.32266396	0.0002074	-0.1055385	14.1628152
	AG5503	-0.0010351	0.4057129	-34.2670524	0.00004338	-0.02003304	2.54136590	0.0002074	-0.1055385	14.3088567
	P94Y23	-0.0002928	0.0710876	2.5823726	0.00003303	-0.01586795	2.12042941	0.0002074	-0.1055385	14.1877987
	P94Y80	-0.0005926	0.193726	-9.9121619	-0.00001498	0.00416020	0.05327147	0.0002074	-0.1055385	14.0907392
	P94Y81	-0.0009257	0.3412213	-25.6624753	-0.00000448	-0.00010521	0.49083525	0.0002074	-0.1055385	14.1464322

	P94Y82	-0.0011114	0.4182755	-33.6948325	0.00000531	-0.00501266	1.09272931	0.0002074	-0.1055385	14.1093117
	S44-K7	-0.0005070	0.1589734	-6.3485739	0.00001176	-0.00748731	1.31059305	0.0002074	-0.1055385	14.1698517
	S46-U6	-0.0004520	0.1364224	-3.8565788	0.00001643	-0.00901789	1.44000604	0.0002074	-0.1055385	14.1019137
	S49-A5	-0.0006064	0.2085151	-12.3203573	0.00004625	-0.02162372	2.74138030	0.0002074	-0.1055385	14.2393267
2013	AG4531	-0.0008926	0.3627023	-30.9686315	-0.00003795	0.01460339	-1.04888567	0.0001617	-0.0832860	11.8548488
	AG4632	-0.0008926	0.3658998	-31.9033537	-0.00003922	0.01460339	-0.98945830	0.0001617	-0.0826446	11.8548488
	AG4933	-0.0008926	0.3583077	-30.0361517	-0.00003893	0.01460339	-1.00258409	0.0001617	-0.0834324	11.8548488
	AG5332	-0.0008926	0.3741183	-33.3727063	-0.00003718	0.01460339	-1.07527853	0.0001617	-0.0839580	11.8548488
	AG5503	-0.0008926	0.3759743	-33.7843857	-0.00003734	0.01460339	-1.06149567	0.0001617	-0.0874498	11.8548488
	P94Y23	-0.0008926	0.3557124	-29.4920741	-0.00003953	0.01460339	-0.97087818	0.0001617	-0.0813890	11.8548488
	P46T21	-0.0008926	0.3700824	-32.7138198	-0.00003796	0.01460339	-1.04770592	0.0001617	-0.0806650	11.8548488
	P47T36	-0.0008926	0.3632284	-31.2718033	-0.00003885	0.01460339	-1.01347705	0.0001617	-0.0807235	11.8548488
	P94Y80	-0.0008926	0.3583934	-30.2314620	-0.00003865	0.01460339	-1.02053949	0.0001617	-0.0848096	11.8548488
	P94Y81	-0.0008926	0.3664557	-31.7450114	-0.00003891	0.01460339	-0.98803694	0.0001617	-0.0843732	11.8548488
	P94Y82	-0.0008926	0.3539388	-28.9730019	-0.00003923	0.01460339	-0.97688251	0.0001617	-0.0826534	11.8548488
	P95Y10	-0.0008926	0.3754156	-33.8994385	-0.00003670	0.01460339	-1.10984379	0.0001617	-0.0797323	11.8548488
	S44-K7	-0.0008926	0.3628982	-31.2499861	-0.00003876	0.01460339	-1.00838788	0.0001617	-0.0794082	11.8548488
	S46-G9	-0.0008926	0.3611210	-30.5567928	-0.00003840	0.01460339	-1.02458420	0.0001617	-0.0853801	11.8548488
	S49-F8	-0.0008926	0.3686449	-32.3459665	-0.00003800	0.01460339	-1.04439008	0.0001617	-0.0834706	11.8548488

† Based upon concentration expressed as a percentage.

‡ Based upon concentration expressed as mg kg⁻¹.

Appendix 5-3 cont.

Year	Cultivar	Ca†			Mg†			S†		
		ax ²	bx	c	ax ²	bx	c	ax ²	bx	c
2011	AG4303	0.0006237	-0.2431757	25.2462214	0.00009739	-0.04826486	6.23910714	0.00002955	-0.01697962	2.59490900
	AG4531	0.0006237	-0.2650213	29.3960816	0.00009739	-0.04826486	6.13827381	0.00002955	-0.01648531	2.49522905
	AG4907	0.0006237	-0.2574271	28.0558848	0.00009739	-0.04826486	6.16827381	0.00002955	-0.01635373	2.47053607
	AG5331	0.0006237	-0.2609513	28.8034950	0.00009739	-0.04826486	6.08494048	0.00002955	-0.01579719	2.33391801
	AG5503	0.0006237	-0.2773008	32.0707627	0.00009739	-0.04826486	6.19410714	0.00002955	-0.01583809	2.34757258
	P94Y80	0.0006237	-0.2566536	27.9131062	0.00009739	-0.04826486	6.20410714	0.00002955	-0.01632173	2.44811075
	P94Y81	0.0006237	-0.2513816	26.7299910	0.00009739	-0.04826486	6.15994048	0.00002955	-0.01639463	2.46669065
	P94Y82	0.0006237	-0.2540007	27.3409630	0.00009739	-0.04826486	6.17660714	0.00002955	-0.01685693	2.57894527
	P94Y91	0.0006237	-0.2535740	27.1152921	0.00009739	-0.04826486	6.15577381	0.00002955	-0.01588076	2.35413968
	P94Y92	0.0006237	-0.2586077	28.1706299	0.00009739	-0.04826486	6.14494048	0.00002955	-0.01643553	2.47784522
	P95Y10	0.0006237	-0.2651387	29.5566411	0.00009739	-0.04826486	6.12660714	0.00002955	-0.01615637	2.41807993
	S44-K7	0.0006237	-0.2571906	27.7960199	0.00009739	-0.04826486	6.09327381	0.00002955	-0.01671291	2.53719800
	S46-U6	0.0006237	-0.2553787	27.5956643	0.00009739	-0.04826486	6.12077381	0.00002955	-0.01628083	2.44445618
	S49-A5	0.0006237	-0.2527169	27.3289585	0.00009739	-0.04826486	6.16327381	0.00002955	-0.01602123	2.37756191
2012	AG4303	-0.0001784	0.1206157	-14.7195178	0.00004616	-0.01857139	2.22938944	-0.00001327	0.00385264	0.05641011
	AG4531	-0.0000819	0.0809545	-10.8722349	0.00004616	-0.02002731	2.50152185	-0.00001327	0.00385264	0.08490961
	AG4907	0.0009320	-0.3467051	33.5967038	0.00004616	-0.01799451	2.07097224	-0.00001327	0.00385264	0.08262211
	AG5332	0.0006853	-0.2467243	23.6346174	0.00004616	-0.02018972	2.46995581	-0.00001327	0.00385264	0.06368361
	AG5503	0.0009348	-0.3528428	34.5513596	0.00004616	-0.01754365	1.98303636	-0.00001327	0.00385264	0.08372061
	P94Y23	0.0001349	-0.0186970	0.5821954	0.00004616	-0.02074585	2.59095873	-0.00001327	0.00385264	0.06360061
	P94Y80	0.0004069	-0.1164755	8.9034575	0.00004616	-0.01789244	2.05664472	-0.00001327	0.00385264	0.06118211
	P94Y81	0.0009031	-0.3317647	31.9987849	0.00004616	-0.01785785	2.06651303	-0.00001327	0.00385264	0.08033261

	P94Y82	0.0008315	-0.3002022	28.5011423	0.00004616	-0.01900045	2.2663906	-0.00001327	0.00385264	0.08820711
	S44-K7	0.0001986	-0.0298582	0.1180504	0.00004616	-0.01819329	2.07427217	-0.00001327	0.00385264	0.06947111
	S46-U6	0.0004701	-0.1444717	12.0341296	0.00004616	-0.01714033	1.92330596	-0.00001327	0.00385264	0.06843811
	S49-A5	0.0009228	-0.3437563	33.5168422	0.00004616	-0.01833283	2.11957041	-0.00001327	0.00385264	0.06628261
2013	AG4531	0.0007910	-0.3152157	32.4927132	0.00006100	-0.02770047	3.41884434	-0.00001785	0.00661729	-0.30290146
	AG4632	0.0006791	-0.2661286	27.2237435	0.00004579	-0.02103878	2.64033461	-0.00001785	0.00661367	-0.31461371
	AG4933	0.0007237	-0.2833828	28.8896252	0.00003153	-0.01489257	1.98055317	-0.00001785	0.00645280	-0.26587412
	AG5332	0.0003786	-0.1391813	13.829699	-0.00000099	-0.00112546	0.53129479	-0.00001785	0.00708154	-0.40265900
	AG5503	0.0005563	-0.2201636	22.8732289	0.00002264	-0.01039684	1.46299714	-0.00001785	0.00683379	-0.34982718
	P94Y23	0.0006011	-0.2314013	23.4763238	0.00000774	-0.00551770	1.03826144	-0.00001785	0.00614796	-0.19957115
	P46T21	0.0005388	-0.2063914	21.0131759	0.00001197	-0.00564272	0.93454382	-0.00001785	0.00691730	-0.37315409
	P47T36	0.0006276	-0.2465609	25.4555566	0.00001320	-0.00810262	1.36445496	-0.00001785	0.00643197	-0.27842784
	P94Y80	0.0008488	-0.3362050	34.4640551	0.00006546	-0.02898726	3.45597919	-0.00001785	0.00636708	-0.25056384
	P94Y81	0.0006119	-0.2361920	23.8537717	0.00003654	-0.01745596	2.31701417	-0.00001785	0.00651316	-0.27733675
	P94Y82	0.0009090	-0.3650340	37.7395476	0.00003200	-0.01539843	2.10288851	-0.00001785	0.00644193	-0.24934418
	P95Y10	0.0006495	-0.2597103	27.0526348	0.00004059	-0.01948929	2.5370802	-0.00001785	0.00699602	-0.39337943
	S44-K7	0.0007668	-0.3023287	30.9126951	0.00003742	-0.01742726	2.22312913	-0.00001785	0.00653006	-0.28517962
	S46-G9	0.0009425	-0.3813442	39.7757489	0.00006313	-0.02997794	3.75735678	-0.00001785	0.00652523	-0.27162928
	S49-F8	0.0005915	-0.2253841	22.5857519	0.00000744	-0.00429745	0.82746475	-0.00001785	0.00663737	-0.30344611

† Based upon concentration expressed as a percentage.

‡ Based upon concentration expressed as mg kg⁻¹.

Appendix 5-3 cont.

Year	Cultivar	Na \ddagger			Fe \ddagger			Mn \ddagger		
		ax 2	bx	c	ax 2	bx	c	ax 2	bx	c
2011	AG4303	-0.08130	37.31076	-4206.14196	0.03948	-19.61960	2499.28599	0.03777	-16.16680	1844.06296
	AG4531	-0.08130	37.31076	-4206.14196	0.03948	-19.61960	2499.28599	0.03777	-16.99656	2002.17684
	AG4907	-0.08130	37.31076	-4206.14196	0.03948	-19.61960	2499.28599	0.03777	-17.25417	2050.90909
	AG5331	-0.08130	37.31076	-4206.14196	0.03948	-19.61960	2499.28599	0.03777	-17.02652	2018.97777
	AG5503	-0.08130	37.31076	-4206.14196	0.03948	-19.61960	2499.28599	0.03777	-17.83207	2176.06482
	P94Y80	-0.08130	37.31076	-4206.14196	0.03948	-19.61960	2499.28599	0.03777	-17.22027	2059.45071
	P94Y81	-0.08130	37.31076	-4206.14196	0.03948	-19.61960	2499.28599	0.03777	-16.49102	1894.10645
	P94Y82	-0.08130	37.31076	-4206.14196	0.03948	-19.61960	2499.28599	0.03777	-16.72451	1947.06996
	P94Y91	-0.08130	37.31076	-4206.14196	0.03948	-19.61960	2499.28599	0.03777	-16.45165	1915.28164
	P94Y92	-0.08130	37.31076	-4206.14196	0.03948	-19.61960	2499.28599	0.03777	-16.52347	1898.20990
	P95Y10	-0.08130	37.31076	-4206.14196	0.03948	-19.61960	2499.28599	0.03777	-17.31826	2058.45123
	S44-K7	-0.08130	37.31076	-4206.14196	0.03948	-19.61960	2499.28599	0.03777	-16.76145	1941.36295
	S46-U6	-0.08130	37.31076	-4206.14196	0.03948	-19.61960	2499.28599	0.03777	-16.82571	1958.55468
	S49-A5	-0.08130	37.31076	-4206.14196	0.03948	-19.61960	2499.28599	0.03777	-16.58204	1926.08157
2012	AG4303	-0.005128	1.908516	-152.445312	-0.0059851	1.9776616	-69.2507561	.	2.717698	-390.698095
	AG4531	-0.005128	1.908516	-152.681633	-0.0059851	1.9776616	-63.6492361	.	2.717698	-430.150045
	AG4907	-0.005128	1.908516	-148.957571	-0.0059851	1.9776616	-64.7219111	.	2.717698	-454.507395
	AG5332	-0.005128	1.908516	-147.658691	-0.0059851	1.9776616	-61.9124861	.	2.717698	-419.722695
	AG5503	-0.005128	1.908516	-154.183394	-0.0059851	1.9776616	-63.6387511	.	2.717698	-456.311845
	P94Y23	-0.005128	1.908516	-153.259106	-0.0059851	1.9776616	-69.0064611	.	2.717698	-409.233195
	P94Y80	-0.005128	1.908516	-152.480441	-0.0059851	1.9776616	-62.3737561	.	2.717698	-432.286645
	P94Y81	-0.005128	1.908516	-155.727354	-0.0059851	1.9776616	-60.7057361	.	2.717698	-441.194545

	P94Y82	-0.005128	1.908516	-152.519252	-0.0059851	1.9776616	-62.3221461	.	2.717698	-427.246095
	S44-K7	-0.005128	1.908516	-148.284523	-0.0059851	1.9776616	-77.3233411	.	2.717698	-418.837395
	S46-U6	-0.005128	1.908516	-148.268990	-0.0059851	1.9776616	-68.9797511	.	2.717698	-445.448695
	S49-A5	-0.005128	1.908516	-147.514745	-0.0059851	1.9776616	-62.1431061	.	2.717698	-391.909295
2013	AG4531	.	-0.0826346	32.2925820	0.02397	-11.01356	1340.94730	0.026367	-9.788122	965.679437
	AG4632	.	-0.0826346	32.2925820	0.03541	-16.55835	2000.42089	0.026367	-9.788122	965.679437
	AG4933	.	-0.0826346	32.2925820	0.01508	-7.35661	976.42176	0.026367	-9.788122	965.679437
	AG5332	.	-0.0826346	32.2925820	0.00172	-1.27948	298.02482	0.026367	-9.788122	965.679437
	AG5503	.	-0.0826346	32.2925820	0.00707	-3.55941	525.77523	0.026367	-9.788122	965.679437
	P94Y23	.	-0.0826346	32.2925820	0.01654	-7.82060	998.06852	0.026367	-9.788122	965.679437
	P46T21	.	-0.0826346	32.2925820	0.01999	-9.27037	1152.13240	0.026367	-9.788122	965.679437
	P47T36	.	-0.0826346	32.2925820	0.00987	-4.67690	638.19761	0.026367	-9.788122	965.679437
	P94Y80	.	-0.0826346	32.2925820	0.01610	-7.88566	1035.84518	0.026367	-9.788122	965.679437
	P94Y81	.	-0.0826346	32.2925820	0.01383	-6.55500	852.40924	0.026367	-9.788122	965.679437
	P94Y82	.	-0.0826346	32.2925820	0.00712	-3.79239	576.98002	0.026367	-9.788122	965.679437
	P95Y10	.	-0.0826346	32.2925820	0.00569	-3.17550	511.58831	0.026367	-9.788122	965.679437
	S44-K7	.	-0.0826346	32.2925820	0.01942	-9.46518	1222.04254	0.026367	-9.788122	965.679437
	S46-G9	.	-0.0826346	32.2925820	0.01200	-5.64028	750.47378	0.026367	-9.788122	965.679437
	S49-F8	.	-0.0826346	32.2925820	0.01578	-7.46880	959.89139	0.026367	-9.788122	965.679437

† Based upon concentration expressed as a percentage.

‡ Based upon concentration expressed as mg kg⁻¹.

Appendix 5-3 cont.

Year	Cultivar	Zn‡			Cu‡			B‡		
		ax ²	bx	c	ax ²	bx	c	ax ²	bx	c
2011	AG4303	0.02557	-12.14471	1487.71454	0.004373	-2.214775	284.124895	0.02142	-10.35322	1281.86250
	AG4531	0.02557	-12.14471	1487.24787	0.004373	-2.223773	287.653902	0.01407	-6.99771	897.05096
	AG4907	0.02557	-12.14471	1480.03120	0.004373	-2.214384	284.950808	0.01573	-7.80499	994.28462
	AG5331	0.02557	-12.14471	1505.78954	0.004373	-2.207841	284.524409	0.01919	-9.13867	1113.84231
	AG5503	0.02557	-12.14471	1478.69787	0.004373	-2.239811	290.391479	-0.00175	0.28182	74.40385
	P94Y80	0.02557	-12.14471	1481.96454	0.004373	-2.237393	290.013788	0.02482	-12.00982	1475.78558
	P94Y81	0.02557	-12.14471	1483.67287	0.004373	-2.184903	276.386263	0.02223	-10.74527	1324.04135
	P94Y82	0.02557	-12.14471	1485.68954	0.004373	-2.286397	302.299444	0.01931	-9.44747	1182.01827
	P94Y91	0.02557	-12.14471	1488.13120	0.004373	-2.180138	274.714049	0.01175	-6.08790	816.79712
	P94Y92	0.02557	-12.14471	1479.72287	0.004373	-2.219523	286.167984	0.00517	-2.96269	450.54615
	P95Y10	0.02557	-12.14471	1476.74787	0.004373	-2.218492	284.703724	0.01122	-5.75449	765.66731
	S44-K7	0.02557	-12.14471	1477.17287	0.004373	-2.226422	287.710220	0.01552	-7.73162	991.15769
	S46-U6	0.02557	-12.14471	1472.85620	0.004373	-2.181685	276.372939	-0.00022	-0.41987	151.28942
	S49-A5	0.02557	-12.14471	1497.10620	0.004373	-2.176458	274.185137	0.01250	-6.21786	804.27981
2012	AG4303	.	2.426189	-299.687138	-0.0003597	.	24.0669436	-0.0295	12.90523	-1329.29269
	AG4531	.	2.426189	-339.834138	-0.0003597	.	26.0360196	-0.0295	12.90523	-1334.38588
	AG4907	.	2.426189	-359.591538	-0.0003597	.	24.8901721	-0.0295	12.90523	-1337.76402
	AG5332	.	2.426189	-359.380988	-0.0003597	.	25.2010316	-0.0295	12.90523	-1334.52131
	AG5503	.	2.426189	-369.971908	-0.0003597	.	24.7591671	-0.0295	12.90523	-1328.03089
	P94Y23	.	2.426189	-332.664238	-0.0003597	.	23.9402936	-0.0295	12.90523	-1338.42200
	P94Y80	.	2.426189	-350.166538	-0.0003597	.	25.0079006	-0.0295	12.90523	-1345.40278
	P94Y81	.	2.426189	-339.592988	-0.0003597	.	24.7964391	-0.0295	12.90523	-1333.14857

	P94Y82	.	2.426189	-345.659388	-0.0003597	.	25.6109741	-0.0295	12.90523	-1340.51094
	S44-K7	.	2.426189	-334.141788	-0.0003597	.	25.0154436	-0.0295	12.90523	-1334.12443
	S46-U6	.	2.426189	-355.874688	-0.0003597	.	27.7353036	-0.0295	12.90523	-1330.14376
	S49-A5	.	2.426189	-329.298038	-0.0003597	.	23.9653151	-0.0295	12.90523	-1336.40514
2013	AG4531	0.004302	-2.021779	278.830970	-0.0001641	.	14.5805996	-0.0015991	0.4775905	3.6959103
	AG4632	0.004302	-2.021779	278.830970	-0.0001641	.	12.6350299	-0.0015991	0.5374873	-6.2274719
	AG4933	0.004302	-2.021779	278.830970	-0.0001641	.	13.5322819	-0.0015991	0.6435932	-36.8346673
	AG5332	0.004302	-2.021779	278.830970	-0.0001641	.	13.6421389	-0.0015991	0.6069058	-25.5588817
	AG5503	0.004302	-2.021779	278.830970	-0.0001641	.	13.0434693	-0.0015991	0.6509832	-30.5009914
	P94Y23	0.004302	-2.021779	278.830970	-0.0001641	.	13.5396906	-0.0015991	0.5035805	-2.5444102
	P46T21	0.004302	-2.021779	278.830970	-0.0001641	.	13.2372819	-0.0015991	0.5039457	-3.8946758
	P47T36	0.004302	-2.021779	278.830970	-0.0001641	.	12.8061974	-0.0015991	0.5358937	-7.4975250
	P94Y80	0.004302	-2.021779	278.830970	-0.0001641	.	13.3618732	-0.0015991	0.5782063	-20.2296752
	P94Y81	0.004302	-2.021779	278.830970	-0.0001641	.	12.9847230	-0.0015991	0.483965	4.4094562
	P94Y82	0.004302	-2.021779	278.830970	-0.0001641	.	13.0622819	-0.0015991	0.6489566	-36.2970391
	P95Y10	0.004302	-2.021779	278.830970	-0.0001641	.	13.3190597	-0.0015991	0.6119414	-22.5440498
	S44-K7	0.004302	-2.021779	278.830970	-0.0001641	.	13.8179746	-0.0015991	0.4989687	3.4836684
	S46-G9	0.004302	-2.021779	278.830970	-0.0001641	.	13.0620783	-0.0015991	0.5006015	-2.4589792
	S49-F8	0.004302	-2.021779	278.830970	-0.0001641	.	14.2721440	-0.0015991	0.5856002	-12.8079180

† Based upon concentration expressed as a percentage.

‡ Based upon concentration expressed as mg kg⁻¹.

Appendix 5-4. Pearson correlation coefficients for biomass accumulation rate (BAR), radiation use efficiency (RUE), nitrogen accumulation rate (NAR), specific leaf weight (SLW), specific leaf nitrogen (SLN), harvest index (HI), dry matter allocation coefficient (DMAC), seedfill period (SFP), yield, individual seed weight (Seedwt), and seeds m⁻² (Seed#) for all cultivars and years from Fayetteville.

		BAR	RUE	NAR	SLW	SLN	HI	DMAC	SFP	Yield	Seedwt	Seed#	Protein	Oil
BAR	Pearson	1.000	0.995	0.897	-0.120	-0.062	-0.078	-0.337	0.317	0.185	-0.399	0.414	-0.052	-0.047
	Prob		<0.0001	<0.0001	0.2318	0.5364	0.4430	0.0009	0.0023	0.0915	0.0002	<0.0001	0.6082	0.6435
	n=	102	102	100	101	101	98	93	90	84	84	84	99	99
RUE	Pearson		1.000	0.912	-0.122	-0.076	-0.012	-0.350	0.366	0.253	-0.351	0.413	-0.053	0.059
	Prob			<0.0001	0.2158	0.4416	0.8812	<0.0001	<0.0001	0.0029	<0.0001	<0.0001	0.5086	0.4702
	n=		158	104	105	105	152	126	123	136	136	136	155	154
NAR	Pearson			1.000	-0.116	-0.088	-0.174	-0.500	0.489	0.078	-0.543	0.434	-0.095	-0.068
	Prob				0.2414	0.3753	0.0834	<0.0001	<0.0001	0.4751	<0.0001	<0.0001	0.344	0.4977
	n=			104	103	103	100	95	92	86	86	86	101	101
SLW	Pearson				1.000	0.939	0.006	0.071	-0.074	0.091	0.194	-0.057	0.073	-0.044
	Prob					<0.0001	0.9505	0.4858	0.4778	0.3944	0.0691	0.5964	0.4626	0.6563
	n=				107	107	102	98	94	89	89	89	104	104
SLN	Pearson					1.000	0.019	0.092	-0.070	0.114	0.158	-0.016	0.123	-0.041
	Prob						0.8527	0.3664	0.5007	0.2866	0.1399	0.8842	0.2137	0.6796
	n=					107	102	98	94	89	89	89	104	104
HI	Pearson						1.000	0.273	-0.025	0.405	0.118	0.256	0.247	0.038
	Prob							0.0021	0.7862	<0.0001	0.1700	0.0026	0.0020	0.6443
	n=						157	125	122	136	136	136	154	153
DMAC	Pearson							1.000	-0.839	-0.080	0.418	-0.324	0.105	-0.057
	Prob								<0.0001	0.3952	<0.0001	0.0004	0.2404	0.5275
	n=							130	126	114	114	114	128	127
SFP	Pearson								1.000	0.229	-0.395	0.418	-0.038	0.102
	Prob									0.0159	<0.0001	<0.0001	0.6718	0.2636
	n=								126	110	110	110	124	123
Yield	Pearson									1.000	-0.112	0.847	0.078	0.046
	Prob										0.1839	<0.0001	0.3581	0.5932

	n=		142	142	142	140	139
Seedwt	Pearson			1.000	-0.600	0.291	-0.087
	Prob				<0.0001	0.0005	0.3068
	n=			142	142	140	139
Seed#	Pearson				1.000	-0.056	0.053
	Prob					0.5106	0.5317
	n=				142	140	139
Protein	Pearson					1.000	-0.544
	Prob						<0.0001
	n=					161	160
Oil	Pearson						1.000
	Prob						
	n=						160

Appendix 6-1. Significance of *F*-values for the cultivar, treatment, and interaction as sources of variation from statistical analyses for dependent variables grain yield, seeds m⁻², and seed weight within each year of study at Fayetteville.

Year	Dependent variable	Cultivar (C)	Treatment (T)	C*T
		<i>P</i> > <i>F</i>		
2011	Yield	0.1645	0.0367	0.8700
	Seeds m ⁻²	<0.0001	0.6001	0.5582
	Seed weight	<0.0001	0.3635	0.2660
2012	Yield	0.1578	0.0142	0.0569
	Seeds m ⁻²	0.0003	0.9131	0.8206
	Seed weight	<0.0001	0.5136	0.8893
2013	Yield	0.0956	0.0448	0.0078
	Seeds m ⁻²	0.9827	0.0342	0.0140
	Seed weight	<0.0001	0.1173	0.1331

Appendix 7-1. Significance of *F*-values for the cultivar source of variation from statistical analyses for dependent variables grain yield, seeds m⁻², seed weight, final main-stem nodes (Nodes), final plant height (Height), protein and oil concentrations within each year of study at England, Helena, and Newport.

Year	Dependent variable	<i>P</i> > <i>F</i>		
		England	Helena	Newport
2011	Yield	0.0928	<0.0001	.
	Seeds m ⁻²	0.0299	<0.0001	.
	Seed weight	0.0003	<0.0001	.
	Nodes	0.0256	<0.0001	.
	Height	0.0001	0.0005	.
	Protein	<0.0001	<0.0001	.
	Oil	<0.0001	<0.0001	.
2012	Yield	0.0105	<0.0001	<0.0001
	Seeds m ⁻²	0.0747	0.0379	<0.0001
	Seed weight	0.0141	0.0076	0.0017
	Nodes	0.0002	<0.0001	0.0071
	Height	<0.0001	<0.0001	<0.0001
	Protein	0.0006	<0.0001	<0.0001
	Oil	0.0082	<0.0001	<0.0001
2013	Yield	<0.0001	<0.0001	<0.0001
	Seeds m ⁻²	<0.0001	0.0135	<0.0001
	Seed weight	<0.0001	0.1828	0.0038
	Nodes	0.0254	0.0002	0.5246
	Height	<0.0001	<0.0001	0.0003
	Protein	0.5050	0.0183	<0.0001
	Oil	<0.0001	<0.0001	<0.0001