Simulating Soybean Yield Potential under Optimum Management

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Core Ideas

- Soybean yield and crop growth was measured in high-yield contest fields.
- Radiation use efficiency and nitrogen uptake were greater than recorded values.
- Yield was grossly under-predicted using default growth parameters.
- Yield predictions were greatly improved using measured growth parameters.

ABSTRACT

Crop models have played important roles in identifying potential constraints for crop growth and yield. A relatively simple soybean [Glycine max (L.) Merr.] model consisting of a daily C, N, and water budget was used to simulate yields for optimum production environments at Fayetteville, AR, and at a farmer’s contest field in Missouri for 2012 to 2013. Data were collected on radiation use efficiency (RUE), N accumulation rate, specific leaf nitrogen (SLN), and the dry matter accumulation coefficient (DMAC) as a measure of whole-crop seed growth rate. In Fayetteville, measured yields ranged from 4977 to 7144 kg ha⁻¹, and simulated yields averaged 34.0% below the measured yields using the default model parameters. Using measured parameters in a modified model, predicted yields were 2.8% above observed. Default parameter simulations for the contest fields were 39.0% below measured yield and were 18.7% below measured yield when using measured parameters. Sensitivity analyses indicated that lower DMAC values increased yields due to slower seedfill rates, allowing additional N accumulation and a slower translocation of N to the growing seeds. Simulating an increased SLN and RUE increased predicted yields in 2012 and 2013 when N accumulation rates were great enough to supply the required N for 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 metabolism and that current bounds for crop growth characteristics should be reconsidered.

Abbreviations: DMAC, dry matter accumulation coefficient; DOY, day of year; HI, harvest index; LAI, leaf area index; RMSE, root mean square error; RUE, radiation use efficiency; SLN, specific leaf nitrogen; SSM, Simple Soybean Model.

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 the testing of hypotheses and potential constraints to crop growth and yield. One of the earliest models estimated maximum crop productivity based on available solar radiation for photosynthesis (Loomis and Williams, 1963). Eventually, complex models for soybean [Glycine max (L.) Merr.] were developed that characterized plant development, leaf photosynthesis and other biochemical processes (e.g., GOSSYM, Whisler et al., 1986; DSSAT-CropGro, Boote et al., 1998; APSIM, Keating et al., 2003).

Despite their complexity, some of the more recent models fell short of accurately explaining many of the processes within the crops and were sometimes outperformed by less complex 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 an early version of SOYGRO was less accurate in predicting soybean yield than 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). Crop models are capable of partially reproducing genotype × environment interactions, which can help breeders target physiological traits for cultivar improvement within specific

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environments (Boote et al., 2001; Salmerón et al., 2017). Crop models have also been used in the prediction of the theoretical maximum yield of crops in non-limiting environments. For an Australian environment, simulations predicted that the maximum yield potential of soybean was 8290 kg ha⁻¹ (Muchow and Sinclair, 1986), and Van Roekel et al. (2015) simulated yields up to 9900 kg ha⁻¹. Simulated soybean yield potential in the US Corn Belt was 3300 to 5300 kg ha⁻¹ in rainfed areas and 5300 to 5600 kg ha⁻¹ for irrigated conditions (Rattalino Edreira et al., 2017), and in the Western Corn Belt simulated yield was about 4600 kg ha⁻¹ (Balboa et al., 2019). Long-term simulation of soybean yield in Japan indicated a maximum yield potential of 5100 kg ha⁻¹ (Spaeth et al., 1987) and 5400 kg ha⁻¹ in India (Bhatia et al., 2008).

The Simple Soybean Model (SSM, Sinclair, 1986; Sinclair et al., 2003) is a dynamic simulation model utilizing daily weather inputs and relatively few variables to quantify leaf area development, crop mass and N accumulation, seed growth, and the response to soil-moisture deficits on crop growth and seed yield. This model, or similar models with other crops, has been used to evaluate traits that are potentially advantageous under drought for soybean (Sinclair et al., 2010), maize (Zea mays L.) (Messina et al., 2015), and for wheat (Triticum aestivum L.) (Sciarresi et al., 2019; Sadok et al., 2019). Likewise, a model similar to the SSM has been used to assess resource use efficiency and maximum attainable yields for wheat in the US Southern Great Plains (Lollato and Edwards, 2015). A primary advantage of the SSM over more complex models such as DSSAT-CropGro (Boote et al., 1998) or APSIM (Keating et al., 2003) is that there are relatively fewer coefficients required and many of the coefficients are considered as constants or as bounded by an upper limit (Soltani and Sinclair, 2015). In the present research, the SSM (Sinclair, 1986; Sinclair et al., 2003) was used to evaluate simulated soybean yield using the original default coefficients defining upper limits of yield (Sinclair et al., 2003) and compared with predicted yield response using coefficients measured under management conditions optimized for soybean yield.

**MODEL DESCRIPTION**

The SSM (Sinclair, 1986; Sinclair et al., 2003) is a relatively simple mechanistic model capturing daily changes in crop growth and development in response to daily weather inputs (maximum and minimum temperatures, solar radiation, rainfall, and irrigation) and predicted soil-moisture availability. In general, vegetative development of individual plants is modeled as a function of thermal time, and leaf area per plant is predicted from the relationship of phyllochron and leaf area. Radiation interception (MJ m⁻² d⁻¹) for a given day is predicted from the product of leaf area per plant (m² plant⁻¹), the population density (plants m⁻²), and the incident solar radiation (MJ m⁻²), assuming an extinction coefficient of 0.6. Crop mass accumulation each day is based on the product of intercepted radiation and radiation use efficiency (RUE, g MJ⁻¹) with an upper limit of 0.9 g MJ⁻¹. Nitrogen in the SSM (Sinclair et al., 2003) accumulates in proportion to plant mass with a maximum specific leaf nitrogen content (SLN) of 2.5 g N m⁻² and maximum stem N concentration of 20 mg N g⁻¹ such that the maximum N accumulation rate does not exceed 0.6 g N m⁻² d⁻¹.

During reproductive development, seed mass is modeled to accumulate as a linear increase in harvest index (HI). This is a unitless variable referred to as the dry matter allocation coefficient, DMAC, which has a nominal value of 0.011 d⁻¹ and a seed N concentration of 65 mg N g⁻¹ (Sinclair et al., 2003). If the N accumulation rate is insufficient to meet the N requirements of the developing seeds, N is remobilized from leaves and stems to minimum values of 0.8 g N m⁻² and 8 mg N g⁻¹, respectively. The loss of N from leaves results in decreased RUE and further decreases in SLN to the minimum value leads to senescence and decreased leaf area index (LAI). Simulations are terminated when LAI reaches 0.10.

The SSM (Sinclair, 1986; Sinclair et al., 2003) is also sensitive to soil-moisture deficits such that leaf area development, RUE, and N accumulation begin to decrease at specific values of soil-moisture availability. In the present research, frequent irrigation maintained soil moisture above the soil-moisture thresholds that would impact crop growth and development.

In the present research, the 2003 version of the SSM (Sinclair et al., 2003) with default values of RUE, maximum SLN, maximum N accumulation rate, and DMAC were compared with values of these same variables measured in experiments managed for optimum yield. Using the parameters measured from the experiments, LAI values did not decrease to 0.10 during seedfill, and the model was terminated once simulated HI values reached measured HI values.

**MATERIALS AND METHODS**

**Experimental Studies**

Measurements were made in 2012 and 2013 from a high yield contest field near Stark City, MO (36°51’ N, 94°11’ W) and in a small-plot trial that was conducted at the Arkansas Agricultural Research and Extension Center in Fayetteville, AR (36°05’ N, 94°10’ W). Table 1 includes the planting date, soil series, and cultivars for each location. Measurements included RUE, N accumulation rate, SLN, and DMAC as a measure of whole-crop seed growth rate.

Two successive 0.5-m² aboveground biomass samples were taken at growth stage R1 or R2 (Fehr and Caviness, 1977) and

<table>
<thead>
<tr>
<th>Year</th>
<th>Location</th>
<th>Planting date</th>
<th>Soil series</th>
<th>Cultivars</th>
</tr>
</thead>
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<tr>
<td>2012</td>
<td>Fayetteville, AR</td>
<td>11 April</td>
<td>Captina silt loam†</td>
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<tr>
<td>2012</td>
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<td>11 April</td>
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<tr>
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<td>15 May</td>
<td>Leaf silt loam§</td>
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<td>27 May</td>
<td>Newtonia silt loam§</td>
<td>AG5332, 94873, P48T53R, P49T79R, and P50T40R</td>
</tr>
</tbody>
</table>

† Fine-silty, siliceous, active, mesic Typic Fragiaquults.
‡ Fine-silty, mixed, superactive, thermic, Typic Paleudolls.
§ Fine, mixed, active, thermic, Typic Albaquults.
again at R3 along with measurements of the fractional canopy radiation interception (Purcell, 2000). The RUE (g biomass MJ⁻¹ on a total solar radiation basis) was determined by regressing the increase in aboveground biomass (g m⁻²) against the cumulative amount of radiation intercepted (MJ m⁻²). Aboveground biomass samples were analyzed for N concentration to determine the N accumulation rate (g N m⁻² d⁻¹). Leaf samples at the R5 growth stage were used to determine the SLN. The rate of increase of HI was used as the DMAC from immature HI samples collected at mid-R5 and 14-d later, disregarding fallen leaves and petioles.

Both locations were managed intensively for high yields. Fertility inputs were supplied with varying combinations of broadcast fertilizers, poultry litter, and in-season fertigation or foliar applications. Overhead irrigation was applied frequently in an effort to prevent water deficit stress, and multiple pesticide applications were made to eliminate weed, insect, and disease pressure. Additional methodology details, sampling dates, and management practices were described by Van Roekel and Purcell (2014).

### Simulation Studies

The SSM (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 and at soybean yield-contest fields in southwestern Missouri. At Fayetteville, daily temperature, rainfall, and irrigation amounts were measured at the field. Total solar radiation was calculated from temperature data using the methods of Ball et al. (2004). At the contest fields, daily temperature and solar radiation were measured on-site with a weather station (Hobo Micro Station, Onset Computer Corp., Pocasset, MA). Rainfall was not measured on-site but was obtained from the Joplin, MO, regional airport weather station (NCDC-NOAA, 2013) approximately 55 km from the field location. Frequent irrigation was simulated as 20 mm of irrigation whenever the fraction of available soil moisture was predicted to be less than 0.50. Although records for irrigation amounts and soil moisture data were not available, irrigation was usually applied daily (~13 mm) when maximum temperatures exceeded 33°C and there was no rainfall (Van Roekel and Purcell, 2014). Therefore, it was assumed that the producer’s frequent irrigation schedule eliminated all soil-moisture deficits.

The day of year (DOY) when cultivars first entered the R5 growth stage was used for the input date when leaf growth was terminated. It was assumed that 10 d following the beginning of R5 marked the beginning of the linear increase in HI. The measured values of DMAC were used as inputs to describe seed growth. Additional inputs included the mean plant density and date for the V1 growth stage for all cultivars at each site-year.

Yields were simulated for each cultivar at both locations (Table 1) from 2012 and 2013 with the default upper limits for SLN (2.5 g N m⁻²) and N accumulation rates (0.6 g N m⁻² d⁻¹), respectively (Sinclair, 1986; Sinclair et al., 2003). The original upper limit for RUE was assumed to be 1.2 g MJ⁻¹ total solar radiation (Sinclai, 1986), but except for conditions where a high proportion of the radiation is diffuse, a more conservative estimate for the upper bounds of RUE is 0.9 g MJ⁻¹ (Sinclair et al., 2007), which was used in the default simulations. Expression of RUE can be based on total solar radiation or on photosynthetically active radiation; all measurements and simulations discussed in the current research were based on total solar radiation. In addition to the default simulations, we conducted additional simulations for each year, location, and cultivar using measured values for RUE, DMAC, N accumulation rate, and SLN.

Finally, a sensitivity analysis was conducted using two representative cultivars, AG5503 and S44-K7, for both years at Fayetteville. The simulations were modified with the measured values

<table>
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<tr>
<th>Year</th>
<th>Location</th>
<th>Cultivar</th>
<th>DOYTLG</th>
<th>DOYBLHI</th>
<th>DMAC</th>
<th>SLN</th>
<th>RUE</th>
<th>NAR</th>
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for SLN, RUE, and N accumulation rate and with DMAC values ranging from 0.004 to 0.014, in 0.002 increments, while holding all other parameters constant. Sensitivity simulations were also conducted for SLN with values ranging from 2.5 to 3.3 g N m⁻², in 0.2 g N m⁻² increments; 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. A second sensitivity analysis was conducted with measured 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

Experimental Studies

In 2012, temperatures were above average during the summer months of June and July and cultivar grain yields ranged from 6399 to 7144 kg ha⁻¹ in Fayetteville and 5521 to 6979 in the contest field (Table 2). Temperatures during 2013 were similar to long-term averages, although rainfall delayed planting. Cultivar yields ranged from 4977 to 7144 kg ha⁻¹ in Fayetteville and 6158 to 7953 kg ha⁻¹ in the contest field.

Radiation use efficiency in 2012 ranged from 1.14 to 1.51 g MJ⁻¹ in Fayetteville and 0.84 to 1.15 g MJ⁻¹ in the contest field. In 2013, RUE was generally higher than in 2012 and ranged from 1.39 to 1.71 g MJ⁻¹ in Fayetteville and 1.46 to 1.89 g MJ⁻¹ in the contest field. Nitrogen accumulation rates in 2012 ranged from 0.94 to 1.26 g N m⁻² d⁻¹ in Fayetteville and 0.83 to 0.90 g N m⁻² d⁻¹ in the contest field. In 2013, N accumulation rates were also higher than in 2012 and ranged from 1.26 to 1.52 g N m⁻² d⁻¹ in Fayetteville and 1.43 to 2.08 g N m⁻² d⁻¹ in the contest field. Prior to this research, the highest published RUE and N accumulation rate were 1.36 g MJ⁻¹ and 0.80 g N m⁻² d⁻¹, respectively (Nakaseko and Gotoh, 1983; Pal and Saxena, 1976; Van Roekel and Parcell, 2014).

Specific leaf N in 2012 ranged from 2.81 to 3.22 g N m⁻² in Fayetteville and 2.84 to 3.01 g N m⁻² in the contest field. In 2013, SLN ranged from 2.85 to 3.20 g N m⁻² in Fayetteville and 3.17 to 3.84 g N m⁻² in the contest field. Likewise, SLN values measured were greater than those measured or predicted in prior reports

![Fig. 1. Predicted grain yield vs. measured grain yield for default and modified model simulations from Fayetteville in 2012 and 2013. Each data point represents different cultivars each year. Dashed lines represent ±15% of the observed 1:1 solid line.](image1)

![Fig. 2. Predicted grain yield vs. measured grain yield for default and modified model simulations from the contest field in 2012 and 2013. Each data point represents different cultivars each year. Dashed lines represent ±15% of the observed 1:1 solid line.](image2)

Dry matter allocation coefficients in 2012 ranged from 0.0046 to 0.0101 in Fayetteville and 0.0086 to 0.0121 in the contest field. In 2013, DMAC ranged from 0.0089 to 0.0122 in Fayetteville and 0.0089 to 0.0132 in the contest field. For comparison, cultivar DMAC values ranged from 0.0122 to 0.0156 (Salado-Navarro et al., 1993), with a mean DMAC of 0.0132 across three tests with several different genotypes (Salado-Navarro et al., 1986).

Simulation Studies

Default simulations for Fayetteville using only the measured DOY for leaf growth termination and linear HI increase and DMAC (Table 2) from 2012 and 2013 predicted an average yield of 4170 kg ha⁻¹. This underestimated the grain yield of all cultivars by 34% on average with a root mean square error (RMSE) of 665 kg ha⁻¹ and a bias of −2145 kg ha⁻¹ (Fig. 1). Using the measured values of SLN, RUE, DMAC, and N accumulation rate in the simulations increased grain yield compared with default simulations for all cultivars in both 2012 and 2013 (Fig. 1). Modified simulations predicted an average yield of 6491 kg ha⁻¹ and overpredicted yield by 3% on average (Fig. 1). Compared with the default simulations, the modified simulations decreased the RMSE approximately 2.5-fold to 259 kg ha⁻¹ and decreased the absolute magnitude of the bias 12-fold to 175 kg ha⁻¹.

For the contest field, simulations averaged over years using the default setting underpredicted yield by 39% (4102 vs. 6727 kg ha⁻¹) (Table 2) with an RMSE of 957 kg ha⁻¹ and a bias of −2625 kg ha⁻¹. Using the measured inputs from the contest field in 2012 and 2013 (Table 2), modified simulations predicted an average yield of 5471 kg ha⁻¹, underestimating yield by 19% with an RMSE of 508 kg ha⁻¹ and a bias of −1255 kg ha⁻¹ (Fig. 2). The reasons for the poorer performance of the modified simulations at the contest field compared with the simulations at Fayetteville are unknown. At the contest field, irrigation dates and amounts were unavailable, and the simulated irrigations may not have accurately reflected the management practices at this location. Altering the model to simulate irrigation when the fraction of total soil water was predicted below 0.60, however, did not increase simulated yields (data not shown).
Modifying the simulations to include values for RUE, DMAC, NAR, and SLN that were measured for specific cultivars in a specific location and year, rather than using default values, greatly improved the precision and accuracy of the simulations (Fig. 1 and 2). It is noteworthy, however, that there was generally little consistency for values of RUE, DMAC, NAR, and SLN for cultivars between years and locations (Table 2). For example, consider the differences among environments for the cultivar P94Y82: DMAC values differed by 2.65-fold, SLN differed by 1.13-fold, RUE differed by 1.46-fold, and NAR differed by 1.49-fold (Table 2). There was similar variability among these measurements within other cultivars. It appears that although these variables are critical for yield, these variables also have a large amount of genotype × environment interaction, which effectively limits the predictive ability of the model for a given cultivar in a given environment.

With regard to the N budget, a 2003 version of the SSM (Sinclair et al., 2003) simulates N accumulation from both the soil and N$_2$ fixation together. Thus, the assumption is that N$_2$ fixation can provide any additional N required beyond what exists in the soil, provided water deficiency or flooded conditions do not limit N$_2$ fixation. In the environments simulated in this research, there was an abundance of soil N provided though 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 N$_2$ fixation, provided that excess photosynthetic rate is available. Given the low measured DMAC values and high N accumulation rates, abundant photosynthesis was simulated to be available and N accumulation was simulated to continue throughout reproductive development. This agrees well with other work illustrating that N$_2$ fixation and N accumulation can continue late (Bender et al., 2011; Hanway and Weber, 1971; Leffel et al., 1992; Nelson and Weaver, 1980; Spaeth and Sinclair, 1983; Zapata et al., 1987) or until the end (Mastrodomenico and Purcell, 2012) of seedfill. It is likely that all these factors contributed to the modified model being able to reasonably simulate grain yields in these environments.

**Sensitivity Analysis**

We conducted sensitivity analyses of DMAC, SLN, RUE, and N accumulation rates to evaluate the impact of these inputs on yield at values substantially greater than the default or ceiling values. Using inputs for $S_{44}$-K7 and AG5503 provided a range in the timing of leaf growth termination, the beginning of linear harvest index increases, and the predicted date of physiological maturity. Predicted yield responses were similar between cultivars in all simulations (data not shown), and for simplicity, simulations are only presented for $S_{44}$-K7.

Predicted yields decreased as DMAC values increased (Fig. 3). This effect was greatest with low DMAC values. For example, as DMAC increased from 0.004 to 0.006, yield decreased by 1542 kg ha$^{-1}$ compared with a 518 kg ha$^{-1}$ yield decrease as DMAC increased from 0.012 to 0.014. Lower DMAC values would represent slower seedfill rates and reduced daily seed demands for photosynthesize and N. In the model, when photosynthetic rates are high and seedfill rates and seed N demands are low, an excess of photosynthesize allows for additional N accumulation (Sinclair et al., 2003). Thus, the low DMAC values 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 LAI to supply N to the growing seeds and a lengthened seedfill period, thereby increasing grain yield.

Simulated yields increased with increasing SLN (Fig. 4). Increasing the SLN increases the N requirement of new biomass, but the measured N accumulation rates used in the simulations were high enough to meet this requirement since simulated grain yield increased up to the highest SLN considered. Higher grain yields were the result of a larger pool of N to be available for remobilization to sustain seedfill. 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 (Fig. 5). In 2012, increasing RUE increased yield until a plateau was reached when RUE was about 1.5 g MJ$^{-1}$. In 2013, increasing RUE increased yield for all values. Because 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. In 2012, N accumulation rates were not as great as in 2013 and the increase in RUE resulted in a yield increase up until the N demand of the greater amount of biomass could not be fully met by the 2012 N accumulation rate. This resulted in a limited pool of N to be distributed among a greater leaf area and stem mass, and less N was available for seed growth and yield. Nitrogen
accumulation rates in 2013 were greater than in 2012, and yield increased for each increase in RUE because the N accumulation rate was high enough that all N demands could be fulfilled. The RUE and developing biomass also determine the water demand in the model, and therefore the consistency of the plateau at higher RUE values in 2012 was influenced by inconsistencies in simulated irrigations. On a few occasions, simulated irrigations overlapped with rainfall or actual irrigations and created flooded conditions that limited N accumulation for that day.

In both years, simulating increased N accumulation rates increased yield to a plateau (Fig. 6). This occurred when 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 concurrent increase in the RUE. This is demonstrated when both RUE and N accumulation rates were simulated to increase at the same time (Fig. 6). Using measured 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.

CONCLUSIONS

Empirical measurements from maximum yield research at the University of Arkansas and from the contest fields (Table 1) determined that several soybean growth characteristics can be greater in a maximum yield environment than previously measured. As a result, simulations using default parameters underpredicted measured yields. When the measured inputs were incorporated into C and N budget simulations, a classical crop growth model predicted yields similar to the measured grain yields at Fayetteville, ranging from 4125 to 7114 kg ha\(^{-1}\). Grain yields up to 7953 kg ha\(^{-1}\) were measured in the 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.

The management conditions and inputs used for these experiments were well beyond those typically encountered in farmers’ fields, but they provide insight on the physiological characteristics underpinning potential yield. Defining upper bounds for these modeling coefficients under optimum growing conditions may also provide insight into genetic and/or management strategies that limit yield under conditions with fewer inputs. 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 all of these processes must be optimized in concert to maximize soybean grain yields.

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