THE INFLUENCE OF LANDSCAPE POSITION, NITROGEN, AND AVAILABLE WATER ON SOYBEAN QUALITY

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ABSTRACT

Nodules may not provide enough N for optimum growth for irrigated and soybean (*Glycine max*) plants undergoing extreme water stress. The objective of this study was to develop and test a model that relates soil water, N supply, and N demand to grain protein. The model suggested that three different types of environments exist. In the first environment, water stress reduces N_2 fixation more than CO_2 fixation (high water stress). These plants may have low yields and relatively low protein concentrations. In the second environment, N_2 fixation exceeds or matches soybean N requirement. These plants may have moderately high yields and high protein concentrations (moderate water stress). In the third environment, the plants are actively growing and N_2 fixation can not provide enough N to the plant (low water stress). These plants may have high yields and relatively low protein concentrations. Soil water, ^{13}C discrimination ( )), yield, total N, and protein information collected from 145 sampling points in three production fields were used to test the model. Grain yield (kg ha^{-1}), grain protein (g g^{-1}), and grain total N (g g^{-1}) were used to calculate a N deficit (kg ha^{-1}) using the equation, N deficit$_i$ = (Yield$_i$ * 0.062 – yield * N$_i$). The N deficit was a function of water stress, as expressed by) . The N deficit decreased with decreasing water stress ( ) increased from 16 to18‰) to a minimum value of near zero at a) value 18.5 ‰. Further reductions in water stress ( ) increased from 18.5 to 20.5 ‰) resulted in lower protein concentrations and higher N deficits (1.5 to 6 kg N ha^{-1}). This non-linear relationship between N deficit and) provides evidence that the model was conceptually correct.

Key words: ^{13}C isotopic discrimination, protein, total N

INTRODUCTION

In the Great Plains, either too little or too much water are the primary factors that limit crop growth. Most C_3 plants, including soybean, respond to water stress by closing the stomata in the leaves. Closing the stomata reduces the CO_2 concentration in the leaves, which in turn can reduce CO_2 fixation during photosynthesis, leaf size, leaf area index, biomass production, seed size and numbers, and accelerate leaf senescence (Souza et al., 1998). In addition water stress in leguminous plants such as soybean can reduce nodule activity (Serraj and Sinclair, 1996; Serraj et al., 1998). Serraj et al. (1998) hypothesized that water stressed plant maybe N limited. Purcell and King (1996) tested this concept and reported that due to the extreme sensitivity of nodules to drought, yields can be increased by adding N fertilizer. However, not all soybean cultivars are equally sensitive to water stress, as Sall and Sinclair (1991) reported that Jackson has a higher tolerance to water stress than other cultivars. The potential also exists that soybean growth in plants not undergoing water stress maybe limited by N availability (Wesley et al., 1998). Grain protein concentration is likely to be reduced when the plant is N limited. The objective of this study was to develop and test a model that relates water stress to grain protein.

MATERIALS AND METHODS

Research was conducted in three (Moody 2000, SDSU 2001, and Lovjoy 2000) eastern South Dakota fields. The field designations, soil types, latitude and longitude coordinates, crop varieties, tillage, rotations, and plant populations of each field are reported in Table 1. Elevation at all sampling sites was measured with a carrier-phase differentially corrected global positioning system (DGPS). A weather station located within 15 km of each site was used to measure precipitation and air temperature. Growing degree days were calculated using base 10^{o} C. In the year prior to planting soybean, soil samples (minimum 8 cores per composite sample) were collected from a 0 to15 cm depth from at least a 1 ha grid. These samples were analyzed for Olsen P and K (Frank et al., 1998; Warncke and Brown, 1998). Based on the laboratory analysis, P and K fertilizers were applied for the two-year rotation.

Weeds were controlled with appropriate herbicides. Yields at Moody and Lovjoy were measured with a calibrated yield monitor (Lems et al., 2001). At SDSU yields in a 1.52 by 6.1 m area were measured with a plot combine. At Moody, gravimetric soil water contents were measured on soil samples (0-15 and 15-60 cm) collected from 50 sampling points on 7 June, 28 June, 18 July, 5 September, and 27 September. At SDSU, gravimetric water contents were determined on samples collected at 50 points from the 0-15 and 15-60 cm depths on 21 June, 12 July, 26 July, and 16 August 2001. Grain samples collected from all fields were analyzed for oil and protein on a NIR S5000 Foss Tech (Silver Spring, MD). Grain samples were also analyzed for total N and the amounts of ^{13}C and ^{12}C in the sample on a 20- 20 Europa ratio mass spectrometer (Europa Scientific Ltd., UK) (Clay et al., 2002). The ratio between C^{13} and C^{12} was the R value (O'Leary, 1993). The R value was used to calculate $*^{13}$C using the equation:

$$*^{13}\mathrm{C} = [\mathrm{R(sample)/R(standard)}-1] \times 1000\text{‰} \qquad (1)$$

where R(sample) was the ^{13}C/^{12}C ratio of the sample and R(standard) was the ^{13}C/^{12}C ratio of PDB, a limestone from the Pee Dee formation in South Carolina (O'Leary, 1993; Farquhar and Lloyd, 1993). Typically, $*^{13}$C values for air, C_3, and C_4 plants are -8, -27, and -13‰, respectively. A negative sign indicates that the sample has a lower ^{13}C/^{12}C ratio than PDB. In many cases, it is convenient to report ^{13}C discrimination ( )), which is calculated using the equation:

$$) = (*^{13}\mathrm{C}_a - *^{13}\mathrm{C}_p)/(1+ *^{13}\mathrm{C}_p/1000) \qquad (2)$$

where $*^{13}\mathrm{C}_a$ is the $*^{13}$C value of air(-8‰) and $*^{13}\mathrm{C}_p$ is the measured value of the plant.

Table 1. The dominant soil types, tillage, rotations, plant population, and variety at the different study sites.

	Field		
Parameter	Moody	SDSU	Lovjoy
Study year	2000	2001	2000
Latitude(N)	44.17	44.35	44.25
Longitude(W)	96.62	96.81	96.93
Rainfall (May-Oct.) cm	40.8	42.6	35.7
Growing degree days	1308	1361	1355
Dominant soil types	Cubden Aeric Calciaquoll Waubay Pachic Hapludoll Kranzburg Calcic Hapludoll Vienna Calcic Hapludoll	Barnes Calcic Hapludoll Svea Pachic Hapludoll	Hamerly Aeric Calciaquoll Barnes Calcic Hapludoll Vienna Calcic Hapludoll
Sampling points	50	50	45
Tillage	Strip tillage	Chisel	Strip tillage
Rotation	Soybean/corn	Soybean/corn	Soybean/corn
Soybean variety	Pioneer 92B05	Zillers 1750	Pioneer 91B91
Population (plants ha^{-1})	371,000	317,000	71,000
Fertilizer applied	At all sites N, P, and K fertilizer applied to corn		

Nitrogen deficit (ND) was defined using the equation:

$$ND = (\text{Yield}^* \ 0.062 - \text{Yield}^* \ \text{total N}) \quad (3)$$

where yield was measured in kg ha^{-1}, and 0.062 (=0.3875g protein g^{-1} grain/6.25) or 38.75% protein was defined as the optimal N level. The data set from the three fields was used to estimate the optimum value.

RESULTS AND DISCUSSION

Model Development

Based on the findings of Wesley et al. (1998), Purcell and King (1996), and Serraj and Sinclair (1996) a conceptual model and relational diagram relating soil water, photosynthesis, and nodule activity was developed (Fig. 1). The model was based on several relationships. First, plant growth, N demand, and N supply are functions of available water (Fig. 2). Second, nodule activity may be reduced more by water stress than plant activity (Serraj and Sinclair, 1996; Serraj et al., 1997), and third, the nodules may not provide enough N to the plant when water stress does not limit growth and the plant is growing rapidly (Wesley et al., 1998). Given these relationships, the model predicts that the N supply may be less than the demand when water stress limits nodule activity and the plant is growing faster than the nodules can fix N_2. When the N supply is less than the N demand, the protein concentration may be reduced. The model suggests that three different types of conditions can exist. In the first environment, water stress reduces N_2 fixation more than CO_2 fixation (high water stress). These plants may have low yields and relatively low protein concentrations. In the second environment, N_2 fixation exceeds or matches the plants N requirement. These plants may have moderately high yields and high protein concentrations (moderate water stress). In the low water stress environment, the plants are actively growing and N_2 fixation can not

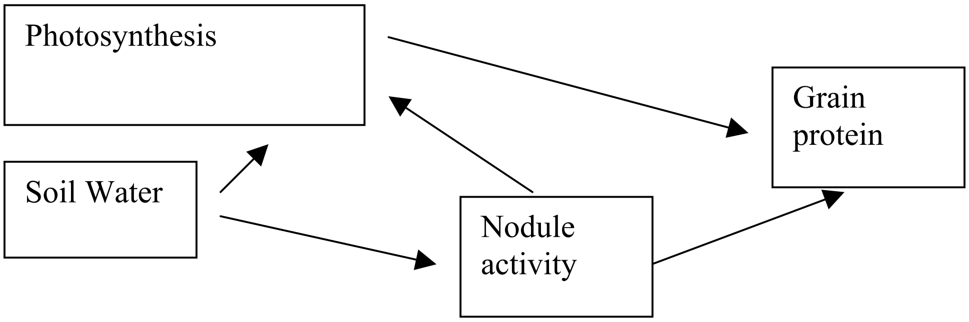

Figure 1. A relational diagram showing the interactions between soil water, photosynthesis, nodule activity, and grain protein.

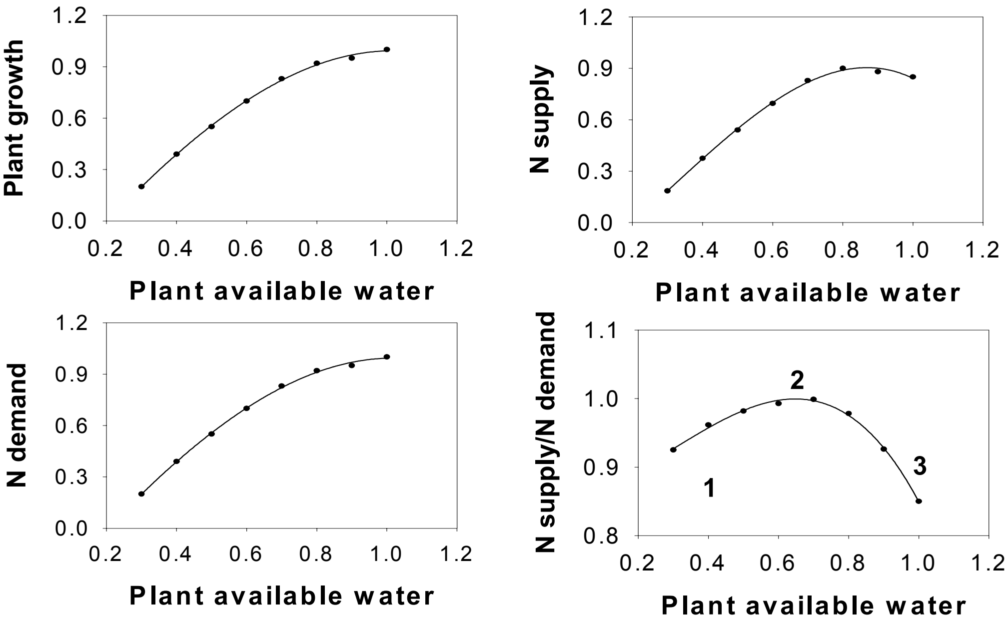

Figure 2. Predicted relationships between plant available water, N supply, and N demand. The 1, 2, and 3 on the graph represent, high, moderate, and low water stress environments, respectively.

provide enough N to the plant. These plants may have high yields and relatively low protein concentrations. In high and low water stress environments, N is deficient, while in moderate water stress environments N is sufficient. Research suggests that in both low and high water stress environments, adding N fertilizer may increase yield (Wesley et al., 1998; Serraj et al., 1998).

Model validation- protein

A previous analysis of the research sites used in this paper showed that at Moody, SDSU, and Lovjoy, water stress in the divergent summit/shoulder area was responsible for yield losses of between 25 and 60%, and that ^{13}C discrimination could be used as an index for water stress in soybean (Clay et al., 2002). In transect 1 at Moody, there was an elevation change of approximately 15 m (Fig.3). Soil water content in the highest elevation areas were less than soil water content in low elevation areas. Yield was negatively correlated to elevation and positively correlated to) (data not shown). In the high elevation areas, adding water increased yield and). Based on protein and) information, low, moderate, and high water stressed areas were identified. Soybean plants growing at low elevation sampling points had low water stress, while plants growing at high elevation sampling points had high water stress. Plants growing in a low water stress (sampling points 26, 28, and 30) environment had low protein concentrations and high) values and yields. Plants growing in a high water stress environment (sampling point 14) had low) and yields and a slightly positive N deficit (0.164 kg N ha^{-1}). The remaining sampling points were moderately water stressed. These points had moderate yields, relatively high protein concentrations, moderate) values, and near zero N deficits.

In transect 2, plants growing at 11 of 15 sampling points had low protein concentrations, high yields and low) (Fig. 4). Based on these results, these plants were characterized as growing in a low water stress environment. The differences between transect 1 and 2 might have resulted from transect 2 being slightly wetter than transect 1.

Similar results were observed at SDSU (Fig.5). However, soil in the high elevation areas of SDSU were dryer than either transect in Moody. Drier soil most likely was responsible for 6 of the 9 sampling points being characterized as high water stress and only 1 point being identified as low water stress. High water stress points had relatively low protein concentrations, low yields, and low). The low water stress point had a large N deficit, low protein concentration, high) and relatively high yield.

The model predicts that soybean plants may be N deficient under both high and low water stress conditions. The experimental data showed that the N deficit was a function of) (Fig. 6). In a previous paper, Clay et al. (2002) showed that water stress and yield increase with decreasing) (yield kg/ha= -5230 + 397) ; r^2 =0.62**). To expand this analysis, data collected from the three fields (Moody, SDSU, and Lovjoy) were used to define the relationship between N deficit and). In this joint analysis,) was a function of N deficit. The N deficit increased from 1.5 to 6.5 kg N ha^{-1} as) increased from 19 to 21‰. A positive N deficit indicates that the protein concentration was

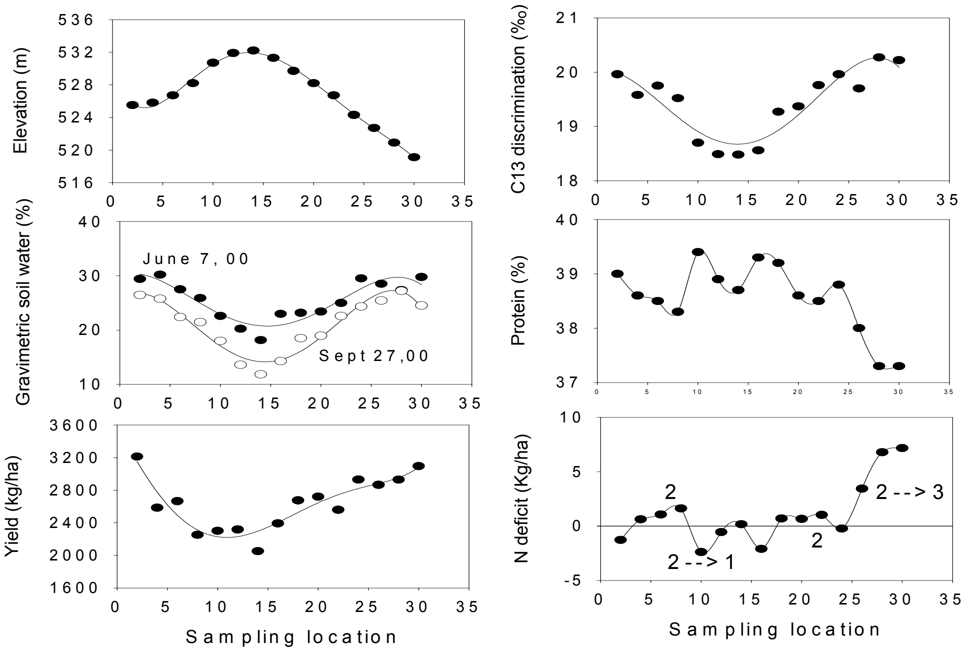

Figure 3. Elevation, soil water contents, yield, ^{13}C discrimination, protein, and N deficit at 15 sampling points along transect 1 in the Moody field in 2000. The 1,2, and 3 represent high, moderate, and low water stress environments, respectively.

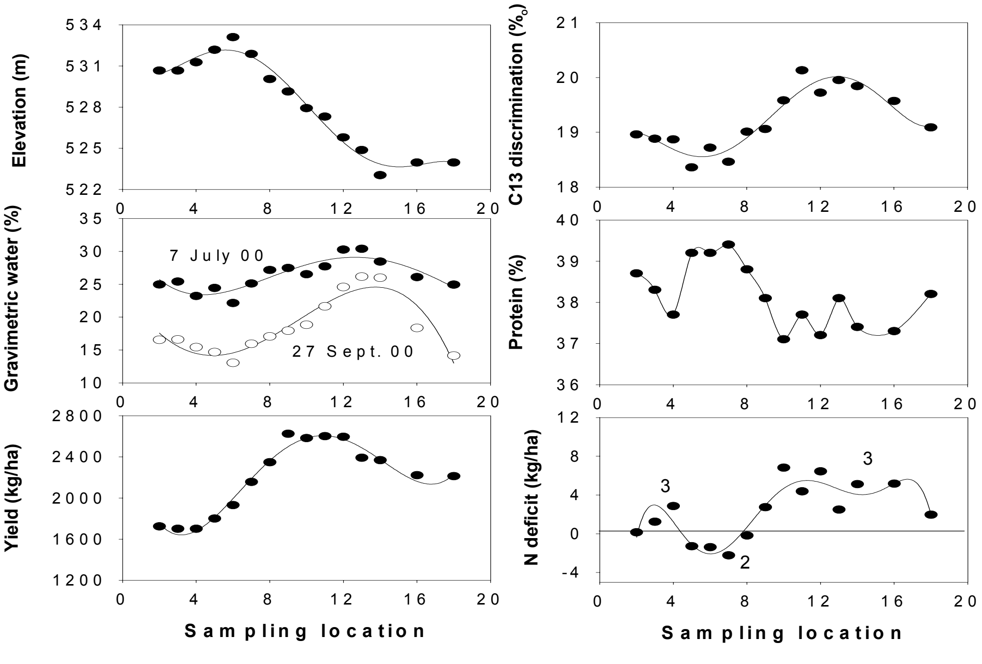

Figure 4. Elevation, soil water contents, yield, ^{13}C discrimination, protein, and N deficit at 15 sampling points along transect 2 in the Moody field in 2000. The 1,2, and 3 on the graph represent high, moderate, and low water stress environments, respectively.

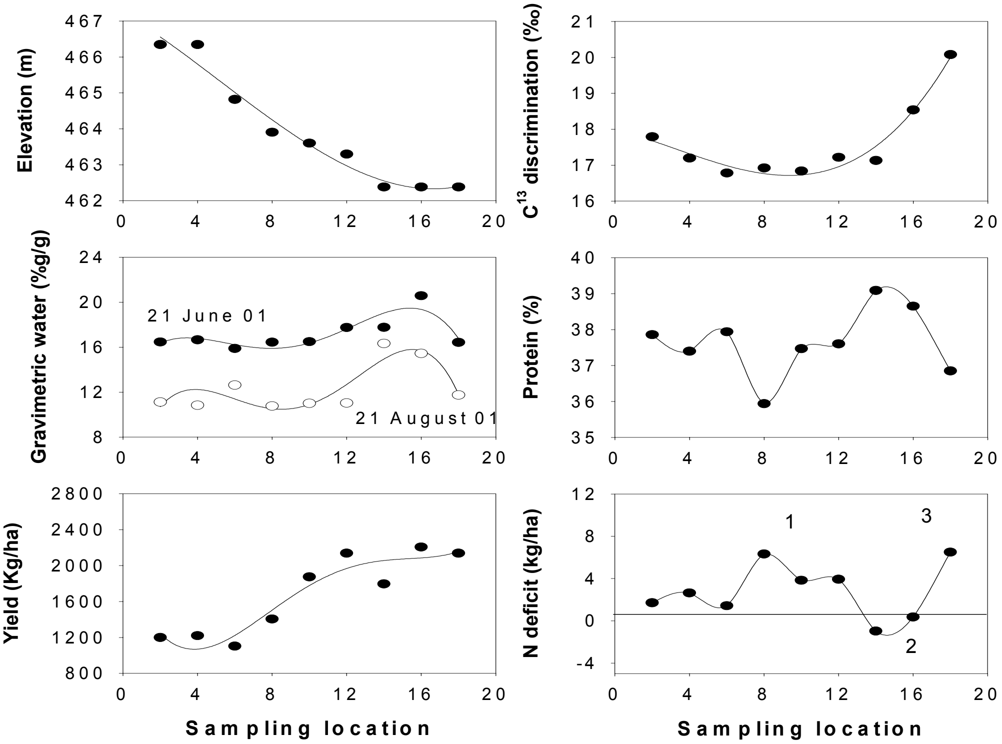

Figure 5. Elevation, soil water contents, yield, ^{13}C discrimination, protein, and N deficit at 10 sampling points along a transect at SDSU.

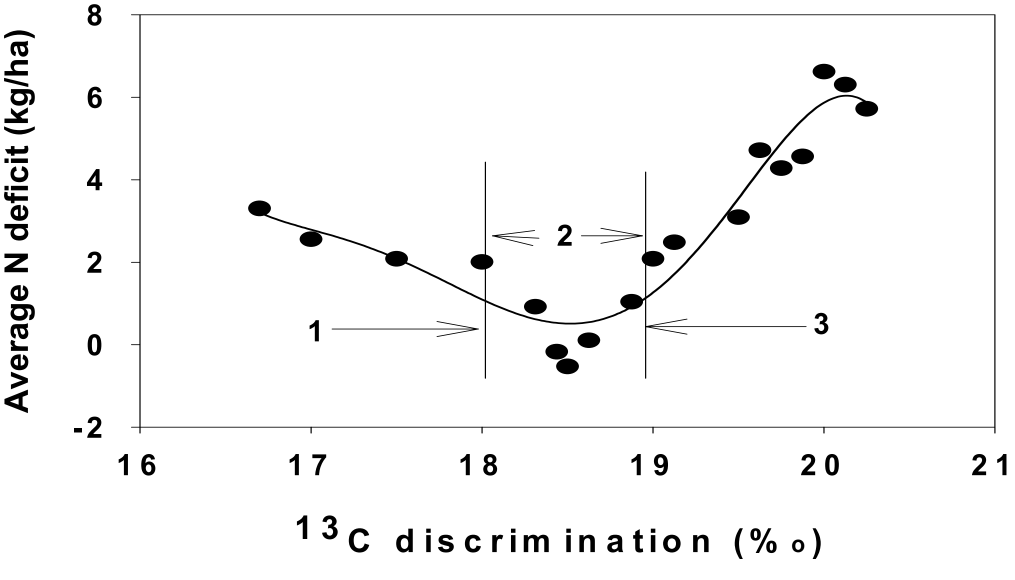

Figure 6. The relationship between N deficit and ^{13}C discrimination. This curve was based on data collected from three fields. The 1,2, and 3 on the graph represent high, moderate, and low water stress environments, respectively.

less than 38.75%. This area of the curve was consistent with the models classification of low water stress. Between 18 and 19‰, the average N deficit was low and ranged from 1 to –0.5 kg N ha^{-1}. This area of the curve was consistent with the models prediction of moderate water stress. In areas of the curve with) values less than 18‰, the N deficit increased with decreasing) value. This area of the curve was identified as high water stress. These results were consistent with the model. Kravchenko and Bullock (2002) had similar results and reported that field topography strongly affected soybean quality, however its influence was dependent on weather conditions. Higher grain protein was observed at higher elevation sites in years with sufficient or excessive precipitation (low water stress), while in dry years, protein concentrations in high elevation areas were relatively low (high water stress).

SUMMARY

Based on historic data, a model relating soil water availability, N supply, and N demand was developed. This model indicated that under low and high water stress, the plants nodules may not fix enough N_2 for plant development, and that under moderate water stress, the nodules can provide enough N to meet the plant's N requirement. Research was conducted in three fields to test this model. In these fields, N deficit was a function of water stress, as expressed as). The N deficit decreased with decreasing water stress () increased from 16 to18‰) to a minimum value of near zero at a) value 18.5 ‰. Further reductions in water stress () increased from 18.5 to 20.5 ‰) resulted in lower protein and higher N deficits (1 to –0.5 kg N ha^{-1}). This non-linear relationship between N deficit and) provides evidence that the model was conceptually correct. This model can be used to explain why protein spatial variability and differential response of soybean to late season N application has been observed in some production fields. Research needs to be conducted to quantify the relationship between water, biomass production, and N fixation in soybean.

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