Subsurface Fertigation In Highly Productive Soils

Increases nutrient use and grain yield of corn and soybeans.

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Summary: *Precision fertilizer application technologies may help producers sustain improvement of crop productivity to feed a growing world population. Subsurface fertigation (through subsurface drip irrigation, or SDI) was investigated as a possible strategy to improve the efficiency of nutrient uptake when applied at key growth stages across a range of corn (n = 3) and soybean (n = 15) genotypes. Across all corn hybrids, marked yield improvements (20 to 22 bu/A) occurred due to season-long fertilization of N, K, and S along with higher populations. Nutrients (N, K, and S) were also fertigated in soybeans and improved grain yield by as much as 6.1 bu/A. Six soybean varieties measured significant yield increases due to fertigation (average of +4.8 bu/A) classified as yield 'responsive' with the remaining nine varieties exhibiting more variation (classified as yield 'non-responsive'). Responsive varieties measured significantly greater plant biomass, improving the recovery efficiency of N, K, and S by as much as three-fold over 'non-responsive' varieties. Varietal differences in response to fertigation suggest that the tool may be used to classify soybean varieties for their responsiveness to agronomic management which, to our knowledge, has never been demonstrated. These findings highlight significant corn and soybean yield increases associated with in-season nutrient fertigation, and how agronomic management and cultivar selection can be used to complement improvements in nutrient recovery.*

Sub-surface drip irrigation (SDI) has traditionally been used for high-value vegetable and fruit crops such as the tomato. More recently, it has been adopted for commodity row crops such as corn, soybeans, and cotton as an alternative to center-pivot or flood irrigation. The benefits of a SDI system relative to other traditional irrigation forms include reduced water use brought about by up to a 50% reduction in evaporation losses (Lamm and Trooien, 2003) and the ability to adapt to any field size, geometry, or topography (Netafim, 2010). Additionally, SDI provides the opportunity to increase the efficiency of nutrient application through the practice of fertigation (i.e., fluid fertilizer supplied with irrigation water). Fertigation of nutrients directly into the root microenvironment, particularly during periods of rapid uptake, can minimize nutrient losses associated with immobilization, volatilization, or surface runoff (Hartz and Hochmuth, 1996). Currently, fertigated corn and soybean acreage in Illinois is limited in scope (90,000 acres or less than 1% of total crop acres as of a 2013 survey, USDA-NASS, 2015a & 2015b). However, factors may accelerate fertigation and SDI system adoption in traditionally non-irrigated parts of the Corn Belt, including: 1) high commodity and input prices, 2) catastrophic weather events such as the 2012 drought, and 3) the demand for increased agricultural productivity in response to world population growth.

The season-long nutritional needs for modern corn and soybean cultivars have recently been quantified by Bender et al. (2013, 2015). Macronutrient accumulation varies considerably between crops and the mineral nutrient of interest. In corn, the majority of nitrogen (N) and potassium (K) accumulation occurs before flowering compared to uptake of phosphorus (P), sulfur (S), and zinc (Zn), which primarily occurs during grain-filling (Bender et al, 2013). Total requirements for some nutrients by soybeans (Bender et al., 2015) are similar to those of corn, despite the misconception that nutrient management in soybeans is less critical because of N fixation as well as the notion that fertilizer supplied to a corn crop will also meet subsequent soybean fertility requirements. In soybeans, the majority of K accumulation occurs during vegetative and early reproductive growth, compared to the uptake of N, P, S, and micronutrients during seed-filling. Nutrient harvest index values (i.e., the portion of total nutrient uptake present in the grain) of N, P, S, are between 60 to 80% for both corn and soybeans, which further necessitates adequate nutrient availability during seed filling. The unique partitioning of these nutrients to harvestable seed may partially explain the decreases in soil P, K, S, and Zn fertility levels reported by a recent IPNI summary (Fixen et al., 2010). Achieving maximum yields while also sustaining the productivity of Illinois soils will likely require a comprehensive season-long fertility plan designed to meet the uptake needs of well-managed corn and soybean crops.

Drip fertigation may become a component of the future agricultural landscape in Illinois and across the Corn Belt when coupled with efficient fertilizer placement, timing, and source technologies. The importance of supplying nutrients at key growth stages may be more vital for intensively managed corn and soybean production systems where other factors such as germplasm, pest control, plant density, and row spacing have been optimized. This research is designed to assess how fertigation might be used to increase corn and soybean productivity while also improving nutrient recovery efficiency

Methodology

Site characteristics. Experiments were conducted at the Crop Sciences Research and Education Center at Champaign, Illinois, using adjacent plots maintained in a corn-soybean rotation. Plots were planted on 15 June 2014. The site has been established by the University of Illinois Crop Physiology Laboratory as a long-term study site on a Drummer silty clay loam (fine silty mixed, super-active, mesic Typic Endoaquolls)- Flanagan silt loam (fine, smectitic, mesic, Aquic Argiudolls) soil. Site characteristics included 3.6% organic matter, 21.1 meq/100g CEC, 5.8 pH, 22 ppm P, 99 ppm K, and 9.5 ppm S using Mehlich-3 extraction. Corn and soybean experiments were managed with herbicide and fungicide applications and were well-suited to provide evenly distributed soil fertility, pH, soil organic matter, and water availability. Commercially available corn and soybean

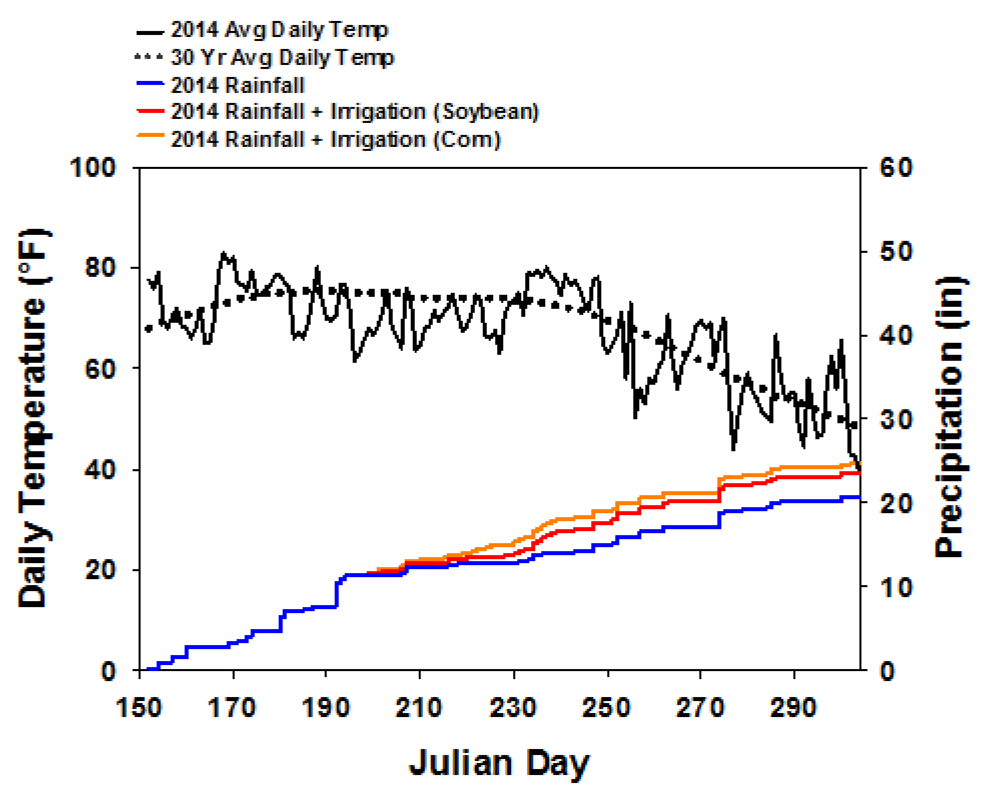

Figure 1. Actual and 30 yr avgs for daily avg temp and cumulative precip & cumulative precip + irrigation measured at Champaign, IL during 2014. Water volume supplied for corn and soybean trials totaled 4.04 and 2.94 inches, respectively.

Table 1. Effect of hybrid selection and fertigation treatment on corn grain yield at Champaign, IL during 2014. A total of 80 lb N, 70 lb K_2O, and 14 lb S on a per acre basis were applied during six fertigation periods between V6 and R2.

Hybrid	Irrigated	Fertigated	Difference
	------------------------ Yield (Bu Ac^{-1}) ------------------------		
DKC62-08	155	175	20*
DKC63-33	180	202	22*
N63R-3000GT	180	200	20*
Average	172	192	20*

(*) Significantly different than zero at α=0.10.

Table 2. Effect of hybrid selection and fertigation treatment on R6 biomass for corn hybrids grown at Champaign, IL during 2014. A total of 80 lb N, 70 lb K2O, and 14 lb S on a per acre basis were applied during six fertigation periods between V6 and R2. Recovery efficiency represents the percentage of total applied nutrients accumulated in above-ground biomass.

Hybrid	Irrigated	Fertigated	Difference	Recovery Efficiency (%)		
	R6 Biomass (lb Ac^{-1})			N	K	S
DKC62-08	20911	22440	1529	53.6	58.9	21.3
DKC63-33	22134	23476	1342	44.8	37.1	17.0
N63R-3000GT	23762	25436	1674	37.7	53.6	16.5
LSD (α=0.10)	583	587	711	14.1	13.6	6.8

Table 3. Effect of planting density and fertigation treatment on corn grain yield at Champaign, IL during 2014. A total of 80 lb N, 70 lb K_2O, and 14 lb S on a per acre basis were applied during six fertigation periods between V6 and R2.

Planting Density	Irrigated	Fertigated	Difference
	------------------------- Yield (Bu Ac^{-1}) ---------------------------		
24,000	170	185	15*
30,000	180	194	14*
36,000	171	197	26*
42,000	168	194	26*
48,000	170	192	22*
Average	172	192	20*

(*) Significantly different than zero at α=0.10.

Table 4. Effect of planting density and fertigation treatment on R6 biomass for corn hybrids grown at Champaign, IL during 2014. A total of 80 lb N, 70 lb K_2O, and 14 lb S on a per acre basis were applied during six fertigation periods between V6 and R2. Recovery efficiency represents the percentage of total applied nutrients accumulated in above-ground biomass.

Hybrid	Irrigated	Fertigated	Difference	Recovery Efficiency (%)		
	R6 Biomass (lb Ac^{-1})			N	K	S
24,000	20112	21144	1032	32.8	52.9	15.7
30,000	21989	23313	1324	44.7	46.6	15.8
36,000	22852	24213	1361	42.8	42.0	17.1
42,000	22195	24741	2546	57.6	53.7	19.8
48,000	24197	25509	1312	49.3	54.2	23.0
LSD (α=0.10)	753	758	727	18.2	17.6	8.8

Table 5. Effect of variety selection and fertigation treatment on soybean grain yield Champaign, IL during 2014. Grain yield is presented at 13% grain moisture concentration. Varieties with significant yield increases due to the fertigation treatment were grouped into a yield 'responsive' category. Varieties with no significant yield increases due to fertigation were grouped into the 'non-responsive' category.

Variety	RM	Irrigated	Fertigated	Difference
		----------------------- Yield (Bu Ac^{-1}) --------------------------		
Non-Responsive Varieties				
S27-J7	2.7	62.5	61.7	-0.8
R2C3822	3.8	61.8	61.1	-0.7
R2C3323	3.3	66.1	66.3	0.2
AG3432	3.4	66.6	67.1	0.6
S32-L8	3.2	59.6	60.2	0.6
42A12	4.2	61.4	62.1¬¬	0.7
R2C3113	3.1	60.7	62.1	1.4
S39-U2	3.9	59.3	61.3	2.0
S29-G4	2.9	63.1	65.6	2.5
Average	62.3	63.1	0.7	
Responsive Varieties				
39A22	3.9	64.4	67.8	3.4*
R2C3783	3.7	58.9	62.9	4.0*
AG3634	3.6	60.2	64.6	4.4*
31A32	3.1	61.2	66.3	5.2*
AG3832	3.8	57.0	62.5	5.5*
AG2933	2.9	62.1	68.1	6.1*
Average	60.6	65.4	4.8*	

(*) Significantly different than zero at α=0.10.

varieties that have been previously identified as having a high yield potential were used. Plots were 37.5 feet (corn) or 36 feet (soybean) in length with 30-inch row spacing and four rows in width.

In 2012 and 2013, we completed four preliminary experiments using a surface drip irrigation system sponsored in part by Netafim USA. Based on this initial experience and success, we installed a permanent subsurface drip irrigation system equipped with programmable controllers and fertilizer injection equipment during fall 2013/spring 2014. Dripper lines were placed 14 to 16 inches beneath the soil surface with 30-inch spacing between lines. A total of 48 independently controlled zones were included; 24 for corn plots and 24 for soybean plots. Nutrient applications were varied according to each zone.

Research approach. Two studies were conducted during 2014 to adapt drip irrigation and fertigation to modern management practices in a corn-soybean rotation.

The first experiment used a nutrient application schedule based on the patterns of nutrient acquisition and timing for corn as described by Bender et al. (2013). The study used a split-block experimental design to evaluate the responsiveness of various hybrid germplasm (n=3) and planting population (24,000, 30,000, 36,000, 42,000 and 48,000 pl/A) treatment combinations to fertigation and were compared to an unfertilized irrigated control.

The second experiment incorporated an application schedule designed by using nutrient uptake patterns for soybeans (Bender et al., 2015) that were compared to an unfertilized irrigated control. This study similarly incorporated a split-block design with individual germplasm (n = 15 varieties) randomly arranged within treatment blocks. The 15 varieties ranged in RM from 2.7 to 4.2, which presumably bracket the ideal maturity range of 3.2 to 3.8 estimated for Champaign, IL. Both studies were conducted across six replications and balanced for total applied water across treatments.

Scheduling. Nutrient uptake patterns describing the quantity and timing of nutrient accumulation were used for corn (Bender et al., 2013) and soybeans (Bender et al., 2015) to estimate seasonal nutrient application rates. Total nutritional requirements needed to produce 230 bu/A of corn were measured in the

Table 6. Effect of fertigation treatment on R8 biomass accumulation and nutrient recovery for a subset of six soybean varieties grown at Champaign, IL during 2014. Based on yield results from Table 5, varieties were classified as yield 'responsive' or 'non-responsive' to the fertigation regime and corresponding differences in biomass production were compared. A total of 50 lb N, 76 lb K_2O, and 16 lb S on a per acre basis were applied during six fertigation periods between V4 and R7. Recovery efficiency represents the percentage of total applied nutrients accumulated in above-ground biomass.

Variety/ Category	Irrigated	Fertigated	Difference	Recovery Efficiency (%)		
Non-Responsive	------ R8 Biomass (lb Ac^{-1}) -------			N	K	S
R2C3113	7162	7492	329	20	21*	3
R2C3822	8211	8114	-96	10	21*	8
S32-L8	7471	7473	2	3	-4	1
S39-U2	8084	8020	-64	14	-26*	9
Average	7733	7774	43	12	3	5
Responsive						
AG3634	7117	7436	319	26	11	16*
AG3832	7345	7848	503	44*	2	11*
Average	7231	7642	411*	35*	6	14*

(*) Significantly different than zero at α=0.10.

previous study, but in a non-irrigated environment. Using this information, a seasonal fertigation schedule was used to supply 80 lbs N, 70 lbs K_2O and 14 lbs S per acre during seven fertigation periods between V6 to R2 for the fertigation treatment, in addition to a standard application of 180 lbs N/A as urea at V4 broadcasted across all treatments.

The schedule of nutrient fertigation in soybeans was based largely upon nutrient uptake patterns (Bender et al., 2015) and recommendations for soybean fertigation by Bar (2004). A total of 50 lbs N, 76 lbs K_2O and 16 lbs S were applied per acre during six fertigation periods between V4 and R7. Applied K and S were split between the V4, V6, R2, and R4 growth stages in contrast to N, which was applied at R5 and R6.

For both experiments, calculation of nutrient recovery efficiency (Eq. 1) was used to measure the proportion of applied nutrients recovered in above-ground biomass.

$$\text{Nutrient Recovery Efficiency} = \frac{(\text{Content}_F) - (\text{Content}_I)}{\text{Application Rate}} \text{ X } 100$$

in which "ContentF" (lbs/A) corresponds to above-ground nutrient content of the fertigated treatment relative to the nutrient content of the irrigated control, "ContentI" (lbs/A) at a specific "Application Rate" (lbs/A).

Parameters. Cumulative rainfall, irrigation events, and temperature data were collected throughout the season. At physiological maturity, above-ground whole plant biomass and nutrient accumulation were measured for each corn hybrid and a subset of soybean varieties to estimate the recovery efficiency of applied nutrients. The center two rows of each plot were mechanically harvested for grain yield.

Results

Weather. Environmental conditions during 2014 generally consisted of above-average precipitation with below-average temperatures with little weather-induced stress (Figure 1). As a result, record yields were recorded for soybeans and corn at the local, state, regional, and national levels. Limited in-season irrigation was necessary because of above-average rainfall during 2014 and therefore, irrigation was primarily used as a medium for fertigation in the current studies. Despite the delayed planting of corn and soybean trials due to the construction of the SDI system, measured yield responses to fertigation and agronomic management provided critical insight regarding opportunities for improved nutrient management.

Corn yield. Hybrid ($P < 0.001$), planting density ($P = 0.004$), and fertigation ($P < 0.001$) treatments significantly influenced grain yield. Overall, fertigation improved yield by an average of 20 bu/A across all treatments. Individual hybrids measured similar yield increases to fertigated nutrients, which ranged from +20 to +22 bu/A (Table 1). Responses to fertigation exhibited no relationship with yield or biomass levels (Table 2) measured in the control irrigation treatment, indicating that benefits from nutrient fertigation may be expected regardless of typical hybrid yield levels.

Complementary agronomic practices necessary to maximize yield in a fertigated environment may also include greater planting densities. Previous studies by the University of Illinois Crop Physiology Laboratory characterized the evaluated hybrids as tolerant of high planting populations. As such, grain yields in the current study tended to increase with greater planting densities to a maximum yield level, and then decline with subsequent increases in plant population (Table 3). Under irrigated conditions, maximum yields were measured at 30,000 pl/A, contrary to treatments receiving fertigation, which were numerically greatest at 36,000 pl/A. Newer hybrids not only tolerate higher planting densities relative to historical germplasm (Tokatlidis and Koutroubas, 2004), but their increased nutrient recovery at higher populations (Boomsma et al., 2009) suggests that there's a greater necessity for nutrient management in these environments. Responses to fertigation were greatest at the 36,000 pl/A density, where a 26 bu/A ($P < 0.10$) increase in grain yield resulted from both greater plant biomass (Table 4) and a 2.8% improvement in dry weight harvest index (data not shown).

Biomass & nutrient recovery. Across all corn hybrids and planting densities, fertigation improved total biomass production at R6 by 1,515 lbs/A and resulted in a net recovery of 45.4% of N, 49.9% of K, and 18.3% of S (Table 2). Although fertigation similarly increased R6 biomass across hybrids, differences in total biomass influenced nutrient recovery efficiencies. Hybrid DKC62-08, for example, measured the least biomass accumulation and grain yield (Table 1), though it had the greatest recovery of applied nutrients (Table 2). Alternatively, DKC66-33 and N63R-3000GT measured greater biomass and grain yields with a general tendency for reduced nutrient uptake and greater nutrient use efficiency. These data highlight the contrasting response characteristics among elite germplasm and emphasize that hybrid selection is a critical decision that influences the response of many agronomic inputs (Ruffo et al., 2015)

Biomass and grain production are significant factors influencing total nutrient accumulation (Ning et al., 2012), and would presumably influence fertilizer recovery. Nutrients with high harvest index values (i.e., high relative partitioning of total nutrient accumulation to corn grain) typically require soil availability for a longer duration in combination with unique remobilization tendencies to supply grain with needed nutrients (Bender et al., 2013). When combined with the increased yield responses observed at high populations (Table 3), this may at least partially explain the greater recovery efficiency of N and S with increasing densities (Table 4). At the highest planting population, the increase of N and S recovery efficiencies represents an additional 13.2 lbs N and 1.0 lbs S on a per acre basis. Potassium accumulation occurs during a relatively abbreviated period before flowering and has a low nutrient harvest index, which may explain the limited effect of population level on K recovery efficiency

Soybean yield. Significant sources of variation for grain yield in soybeans included fertigation (P = 0.001), variety selection (P < 0.001), and the interaction between variety and fertigation (P < 0.063). Fertigated soybean yields ranged from 60.2 to 68.1 bu/A (Table 5) with an average yield response of +2.3 bu/A (P = 0.001) over the irrigated treatment. The effect of relative maturity as a function of variety selection did not influence the response to fertigation, though we believe the highest yield potential requires a well-managed responsive soybean variety that is planted as early as permissible for the region. Findings from the current study suggest that six of the 15 varieties had significant yield increases from fertigation averaging 4.8 bu/A, and subsequently were classified as ‘Responsive’ (Table 5). The remaining varieties were classified as ‘Non-Responsive’ to supplemental fertigation. Individual seed mass was most consistently increased with fertigation (+3.7 mg/seed; P = 0.002), unlike seed number, which varied among varieties (data not shown).

Understanding an individual variety’s genetic predisposition for tolerance to intensive management may have far-reaching implications. Hybrid management evaluations in corn using varying N fertilization rates and planting densities have been used by the University of Illinois Crop Physiology Laboratory (Haegele and Below, 2012) to classify a hybrid’s responsiveness to crop management. Further insight allows producers to position specific hybrids in certain field locations and/or environments for optimal crop performance. Because of the indeterminate nature of soybeans and its compensatory yield component responses, classification of soybean varieties for their responsiveness to agronomic management has been especially difficult. Findings from this research suggest that responsiveness to supplemental fertilization may be used as a proxy for tolerance of additional agronomic practices. Interestingly, a variety’s magnitude of yield response to fertigation in the current study was at least partially predictive of its responsiveness to other agronomic management factors (e.g., fertilization, row spacing, crop protection products, etc.) in separate university trials (Bender, 2015), highlighting the importance of proper variety selection.

Biomass & nutrient recovery. At physiological maturity (i.e., R8) a random subset of soybean varieties (n = 6) were sampled for measurement of biomass and nutrient accumulation. Varietal differences influenced total biomass accumulation, which ranged from 7,436 to 8,114 lbs/A in fertigated conditions (Table 6). Of sampled varieties, four were considered ‘Non-Responsive’ and two were described as ‘Responsive’ to the fertigation treatment. Only yield-responsive varieties measured significant increase in biomass accumulation (+411 lbs biomass/A) with fertigation. The increased total dry weight in yield–responsive varieties also resulted in greater N (+23%), K (+3%), and S (+9%) recovery efficiencies compared to the non-responsive varieties (Table 6).

The fertilizer industry and sustainability efforts promote increased nutrient use efficiency of applied fertilizers through best management practices such as the ‘4R Nutrient Stewardship’ program (Bruulsema et al., 2012). Nutrient recovery efficiencies vary widely across crops, soil conditions, fertilizer application practices, and yield levels, though typically range from 5% to 30% across nutrients in soybeans (Bhupinder et al., 2012; Bender et al., 2015). In the current study, recovery efficiencies ranged from 3 to 44% for N, -26 to 21% for K and 1 to 16% for S (Table 6). The delayed planting in 2014, due to the SDI system installation, shortened the period of vegetative growth and likely reduced total biomass production, yield potential, and ultimately nutrient uptake. The recovery efficiencies of yield-responsive varieties, however, were two to three-fold greater than non-responsive varieties and further highlight how variety selection interacts with agronomic management. Furthermore, we believe that cultural practices that permit a more timely planting date and the use of a full complement of nutrients (i.e., phosphorus and other micronutrients) will further improve crop yield potential and recovery efficiency of applied nutrients.

Summing up

The unique attributes of an SDI system include in-season application of crop nutrients positioned in or near the root zone microenvironment. In the current study, this tool was used to assess how these attributes not only improve crop productivity, but also achieve increased nutrient recovery.

Corn. Fertigated N, K, and S, in addition to a base N application, increased corn grain yield by 20 to 22 bu/A. Although significant yield increases to fertigation were realized at each population level, the greatest responses occurred at higher populations and suggest that improved nutrient management can be used as a strategy to ameliorate the negative effects associated with the increased planting densities that are needed for higher corn grain yields.

Soybean germplasm exhibited variation in response to fertigation, with an average yield improvement of 4.8 bu/A across ‘responsive’ varieties. ‘Responsive’ varieties also measured significantly greater plant biomass, improving the recovery efficiency of N, K, and S by as much as threefold over ‘non-responsive’ varieties.

Collectively, we believe these results highlight the utility of SDI fertigation to not only increase grain yield and nutrient recovery across genotypes, but also as a tool to characterize genotypes for response to other agronomic considerations.

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