Fertilizer Nitrogen Recovery Efficiency of Furrow-Irrigated Corn

Trenton L. Roberts,* Nathan A. Slaton, Jason P. Kelley, Chester E. Greub, and Anthony M. Fulford

ABSTRACT
Corn (Zea mays L.) yield under irrigated production systems is influenced by N rate and timing of application. This study was conducted to determine how current N application strategies (two-way vs. three-way split application) and N rate (optimal vs. suboptimal) influence fertilizer-nitrogen recovery efficiency (FNRE) for furrow-irrigated corn production in the mid-South. The effects of N rate and application timing on corn FNRE were investigated in Rohwer, AR, on a Herbert silt loam (fine-silty, mixed, active, thermic Aeric Epiaqualf). Corn grain yield and total-N uptake were both influenced by the interaction of N treatment and year (p < 0.0001). Corn grain yields were maximized when an optimal-N rate of 235 kg N ha–1 was applied in a two-way split application with 50 kg N ha–1 pre-plant and 185 kg N ha–1 sidedressed at the V6 stage. The ANOVA for FNRE indicated that N treatment was the only significant factor (p < 0.0001) and varied based on N rate and time of application. The lowest FNRE was 61% and occurred when 50 kg N ha–1 was applied pre-plant. The highest overall FNRE was 91% when 50 kg N ha–1 was applied pre-tassel in the suboptimal-N rate treatment. The FNRE of N sidedressed at V6 ranged from 81 to 91% and was influenced by N rate with the suboptimal-N rate treatments tending to have significantly higher FNRE values. The results presented in this paper highlight the high FNRE that can be achieved in furrow-irrigated corn production.

Core Ideas
• Fertilizer N recovery efficiency ranged from 61 to 91%.
• Fertilizer N recovery efficiency influenced by rate and application timing.
• High fertilizer N recovery efficiency can be achieved in irrigated corn production systems.

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SOIL FERTILITY & CROP NUTRITION

FNRE is an important crop both globally and within the United States and is produced on roughly 28 to 32 million hectares annually (Bebeli and Smith, 2004). The primary corn producing area of the United States is referred to as the Corn Belt and the majority of corn produced in these regions are under non-irrigated conditions. Although high yields are achievable, they can be sporadic due the reliance on adequate rainfall for maximal corn grain yield production. In the south central United States, commonly referred to as the mid-South, corn production is an important component of many crop rotations and is most commonly rotated with soybean [Glycine max (L.) Merr.]. Corn production in the mid-South, although performed on significantly less areas than the Corn Belt, constitutes roughly 540,000 ha annually between Arkansas, Louisiana, and Mississippi (NASS, 2016) and can fluctuate depending on commodity prices and weather patterns. The majority of corn in the mid-South is irrigated with the most common form being furrow-irrigation.

Current estimates of global nitrogen use efficiency (NUE) for cereal crops that include corn is roughly 33%, with developed countries having a mean reported NUE of 42% (Raun and Johnson, 1999). This NUE value suggests that there is room for improvement in regards to how N is managed in corn production systems and that development of best management practices for specific regions could lead to improvement in corn NUE. Work conducted by Russelle et al. (1981) and Welch et al. (1971) indicated that NUE in corn could be greatly improved simply by applying fertilizer-N as close to the growth stage of peak N demand as possible. Delayed application of N in-season, when corn N demand is high, can greatly influence NUE as well as corn grain yield (Miller et al., 1975). Although delaying N applications in corn can lead to greater NUE and potential for increased yields, work by Scharf et al. (2002) indicated that there was a distinct cut-off (V12) for applying the season-total N rate in a single application with little to no yield loss.

Little work has been conducted on FNRE as this research is often costly and requires increased management. Research by Stevens et al. (2005) found that FNRE was not significantly influenced by N rate in a long-term dryland corn N response trial in Illinois and averaged around 34% across N rates ranging from

Abbreviations: FNRE, fertilizer nitrogen recovery efficiency; NUE, nitrogen use efficiency; RRS, Rohwer Research Station.
indicated that FNRE under irrigated conditions was influenced by the interaction of N rate and application timing with N rates applied at sidedress tending to have significantly higher FNRE values than those applied pre-plant. Overall, the highest FNRE value reported in that study was 59.4% when 56 kg N ha$^{-1}$ was applied at sidedress (45 cm tall corn). In a similar trial focused on the influence of N rate and irrigation rate on FNRE, Russelle et al. (1981) found FNRE values as high as 62.5% when 112 kg N ha$^{-1}$ was applied at sidedress (45 cm tall corn). In a similar trial conducted systems. Understanding that irrigation and N rate have a profound influence on corn FNRE, the objective of this study was to determine how current N application strategies (two-way vs. three-way split application) and N rate (optimal vs. suboptimal) influenced corn grain yield, total-N uptake, and FNRE in a furrow-irrigated corn production system in the mid-South.

**MATERIALS AND METHODS**

**Experimental Sites and Treatments**

Trials were established at the Rohwer Research Station (RRS) near Rohwer, AR, (33°48’34.96” N, 91°16’12.00” W) on a Herbert silt loam during the 2011 and 2012 growing seasons to determine the influence of N rate and N application strategy on corn, total-N uptake, grain yield, and FNRE. Soybean was the previous crop grown each year of the trial and represents the most common rotation for furrow-irrigated corn producers in the mid-South. Selected agronomic information from the two growing seasons are presented in Table 1 and include dates for pre-plant N application, planting, sidedress-N application, pre-tassel-N application and R6 plant sampling.

The experiment included a no fertilizer-N control plus seven fertilizer-N treatments that represented two season-total N rates [157 (suboptimal) and 235 (optimal) kg N ha$^{-1}$] (Slaton et al., 2014) and two fertilizer-N application strategies (two- or three-way split applications) for furrow-irrigated corn in Arkansas (Table 2). For each of the seven treatments receiving fertilizer-N, 50 kg N ha$^{-1}$ was applied pre-plant to a tilled soil surface and incorporated into the beds (96.5-cm spacing) prior to planting. Treatments that were applied in a two-way split received the 50 kg fertilizer-N ha$^{-1}$ pre-plant N with the remainder of the season-total N rate (107 or 185 kg N ha$^{-1}$) applied as a sidedress application at the V6 growth stage (Ritchie et al., 1996). The three-way split application received 50 kg fertilizer-N ha$^{-1}$ pre-plant, 50 kg fertilizer-N ha$^{-1}$ at the V12 growth stage

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### Table 1. Selected agronomic information and N application timing for research trials conducted at the Rohwer Research Station (RRS) in 2011 and 2012.

<table>
<thead>
<tr>
<th>Year</th>
<th>Pre-plant N application</th>
<th>Date planted</th>
<th>V6 N application†</th>
<th>V12 N application†</th>
<th>R6 wholeplant sampling†</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>31 March</td>
<td>31 March</td>
<td>11 May</td>
<td>8 June</td>
<td>20 July</td>
</tr>
<tr>
<td>2012</td>
<td>29 March</td>
<td>29 March</td>
<td>15 May</td>
<td>6 June</td>
<td>19 July</td>
</tr>
</tbody>
</table>

† Corn growth stages were determined using the collared-leaf method outlined by Ritchie et al. (1996).

### Table 2. Description of N treatments used in this study and the influence of N application rate and time of application on corn grain yield, total nitrogen (TN) uptake and fertilizer nitrogen recovery efficiency (FNRE) using 15N labeled urea in furrow-irrigated corn.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Total N rate</th>
<th>Pre-plant N rate</th>
<th>Pre-tassel N rate†</th>
<th>V6 N rate</th>
<th>Pre-tassel N rate†</th>
<th>Total N uptake‡</th>
<th>Corn grain yield§</th>
<th>FNRE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kg N ha$^{-1}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2011 2012</td>
<td>2011 2012</td>
<td>%</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>164c 52c</td>
<td>780c 280c</td>
<td>–</td>
</tr>
<tr>
<td>2</td>
<td>235</td>
<td>50†</td>
<td>185</td>
<td>–</td>
<td>–</td>
<td>306a 301a</td>
<td>1200a 1590a</td>
<td>61c</td>
</tr>
<tr>
<td>3</td>
<td>235</td>
<td>50</td>
<td>185§</td>
<td>283ab</td>
<td>282a</td>
<td>1190a 1590a</td>
<td>1060b 1480b</td>
<td>81b</td>
</tr>
<tr>
<td>4</td>
<td>235</td>
<td>50</td>
<td>135</td>
<td>283ab</td>
<td>291a</td>
<td>1040b 1470bc</td>
<td>1060b 1400c</td>
<td>87a</td>
</tr>
<tr>
<td>5</td>
<td>235</td>
<td>50</td>
<td>135§</td>
<td>282ab</td>
<td>284a</td>
<td>1040b 1470bc</td>
<td>1040b 1290d</td>
<td>91a</td>
</tr>
<tr>
<td>6</td>
<td>157</td>
<td>50</td>
<td>107§</td>
<td>–</td>
<td>272</td>
<td>1060b 1400c</td>
<td>1010b 1270d</td>
<td>91a</td>
</tr>
<tr>
<td>7</td>
<td>157</td>
<td>50</td>
<td>57§</td>
<td>267b</td>
<td>226b</td>
<td>1040b 1290d</td>
<td>1010b 1270d</td>
<td>91a</td>
</tr>
<tr>
<td>8</td>
<td>157</td>
<td>50</td>
<td>57§</td>
<td>268b</td>
<td>208b</td>
<td>1040b 1290d</td>
<td>1010b 1270d</td>
<td>91a</td>
</tr>
</tbody>
</table>

† Applied prior to tassel exertion near the V12 growth stage.
‡ Means within total N uptake within a year separated by a different letter are statistically different at the α = 0.05 level.
§ Means within corn grain yield within a year separated by a different letter are statistically different at the α = 0.05 level.
‡‡ Denotes $^{15}$N-labeled urea fertilizer application.
(pre-tassel), and the remainder (57 or 135 kg N ha⁻¹) of the season-total N rate was applied at the V6 growth stage. All fertilizer-N for this trial was hand-applied as granular urea (460 g N kg⁻¹) treated at a rate of 0.89 g N-(n-butyl) thiophosphoric triamide (NBPT) kg⁻¹ urea (Agrotain Ultra [285 g NBPT L⁻¹], Koch Fertilizer LLC., Wichita, KS). To directly determine the FNRE of the different N rates and application strategies represented among the specific treatment combinations, 2.5 atom % ¹⁵N-labeled urea (Isotec, Miamisburg, OH) was applied at the specific rates and application timings outlined in Table 1. All other N applications were made using standard fertilizer grade urea that was not enriched with ¹⁵N. All postemergence N applications including sidedress- and pre-tassel-N application timings were incorporated with rainfall or irrigation within 2 d of hand-broadcast application to the soil surface.

**Crop Management**

To ensure that nutrients other than N were not yield-limiting, one composite soil sample composed of four, 3-cm diam. cores were taken from each replication of the experimental area to a depth of 15 cm. Soil samples were oven-dried at 60°C, crushed to pass a 2-mm sieve, extracted with Mehlich-3 solution (Zhang et al., 2014), and the extract was analyzed for nutrient concentrations by inductively coupled plasma atomic emission spectroscopy (Arcos-160 SOP, Spectro, Mahwah, NJ). Soil pH was determined in a 1:2 v/v (soil/water) mixture. Soil organic matter content was determined using the weight loss-on-ignition method (Schulte and Hopkins, 1996). Soil concentrations of P, K, and Zn were not significantly different for each year of the trial and the mean concentrations were 45 mg P kg⁻¹, 137 mg K kg⁻¹, and 4.2 mg Zn kg⁻¹. There were differences across years for soil pH (6.3 vs. 6.0) and Zn (22.0 vs. 18.1 g kg⁻¹) for 2011 and 2012, respectively. Each site was fertilized prior to planting with 39 kg P ha⁻¹, 112 kg K ha⁻¹, and 11 kg Zn ha⁻¹, which was broadcast and mechanically incorporated before beds were formed.

The experiment was arranged in four blocks with the four-row wide plots of the eight treatments within each block oriented in adjacent rows (e.g., side-by-side). The four blocks were parallel with the furrow direction and were separated from the previous block boundary by a 6.1 m wide planted buffer. The fertilized area of each plot was 3.86 m wide (four rows) by 3.05 m long. Irrigation and pest management closely followed the recommendations for furrow-irrigated corn provided by the University of Arkansas Cooperative Extension Service (Espinoza and Ross, 2003). Corn irrigation was scheduled according to the Arkansas Irrigation Scheduler and was set for a 5-cm soil profile water deficit. Corn was irrigated six times during 2011 on 17 May, 2 June, 9 June, 30 June, 13 July, and 19 July and five times during 2012 on 17 May, 30 May, 10 June, 26 June, and 4 July. Each year the corn hybrid DKC 67-88 GenuityVT TriplePro (Monsanto, St. Louis, MO) (117 d relative maturity) was planted on 96.5 cm centers on the top-center of the raised beds with a seed population of 84,000 seed ha⁻¹.

**Plant Sampling and Analysis**

Following physiological maturity, seven plants from a 1 m section of one of the two middle rows (row 2 or 3) in each plot were dissected in the field into ears, husks and shanks, collared leaves, and stalks (cut 5 cm above the soil surface). The 1-m section of corn taken from the middle two rows of the plot was completed to ensure that there was no border effect and that the plants collected were well within the ¹⁵N fertilized area. Upon returning to the lab, ears were hand-shelled to separate the grain from the cobs. The grain was weighed, moisture determined, and grain yield was calculated and adjusted to a moisture of 155 g H₂O kg grain⁻¹. The individual plant parts (husks and shanks, cob, grain, leaves, and stalks) were then air dried at 60°C until a constant moisture was reached, weighed, and ground to pass through a 1-mm sieve. Subsamples of each plant segment were sent to the University of California Davis Stable Isotope Facility (Davis, CA) to determine corn total-nitrogen (TN) content and atom% ¹⁵N, using an elemental analyzer interfaced to a continuous flow isotope ratio mass spectrometer (Europa, Sercon, Ltd., Cheshire, UK). Fertilizer enrichment within the plant was calculated from atom % ¹⁵N change according to the equation:

\[ F = \frac{TN (x - y/z - y)}{\text{R}} \times 100 \]

where \( F \) is the mass of ¹⁵N-labeled fertilizer N taken up by the individual plant component (i.e., grain) (kg N ha⁻¹), \( TN \) is the total nitrogen uptake in the aboveground biomass of the specific plant component (kg N ha⁻¹), \( x \) is the atom % ¹⁵N measured in the plant component, \( y \) is the average atom % ¹⁵N measured in the untreated control, and \( z \) is the atom % ¹⁵N of the enriched urea fertilizer applied. The mass of ¹⁵N-labeled fertilizer N recovered in each individual plant component was summed to determine the total mass of ¹⁵N-labeled fertilizer N contained in the aboveground biomass of each treatment. The percent FNRE was calculated based on the equation:

\[ \text{FNRE} = \left( \frac{F}{R} \right) \times 100 \]

where \( F \) is the total mass of ¹⁵N-labeled fertilizer N taken up by the plant (kg N ha⁻¹) and \( R \) is the ¹⁵N labeled fertilizer-N application rate (kg N ha⁻¹).

**Statistical Analysis**

The experiment was a randomized complete block design with eight fertilizer-N treatments and four blocks. Corn grain yield, TN uptake and FNRE were initially analyzed using a split-plot treatment structure with year as the main plot factor and N treatment (combination of N rates and application times) as the subplot factor. The FNRE comparison represents only on the fertilizer-N application within each treatment that was fertilized with ¹⁵N-labeled urea. For grain yield and TN uptake the year × N treatment interaction was significant (Table 3), therefore grain yield and TN uptake data were analyzed by year since the primary interest of this experiment was to compare among fertilizer-N treatments. Means were separated using Fisher’s protected LSD at a = 0.05 where appropriate.

**RESULTS AND DISCUSSION**

**Total Nitrogen Uptake**

Corn TN uptake data at physiological maturity were analyzed and presented by year since the year × N treatment interaction was significant (Table 3). The TN uptake by corn
receiving no fertilizer-N suggests that native or residual-N in the soil profile was quite different between the 2 site-years, with the no-N control having TN uptake values of 164 kg N ha\(^{-1}\) for 2011 and 52 kg N ha\(^{-1}\) for 2012. Total-N uptake values were highest in the optimal-N treatments and there were statistical differences within the two application strategies within the optimal-N treatments for both growing seasons (Table 2). In 2011, TN uptake in the optimal-N treatment ranged from 282 to 306 kg N ha\(^{-1}\) and similarly, in 2012, ranged from 282 to 301 kg N ha\(^{-1}\). During the 2012 growing season, the TN uptake measured for corn fertilized with the optimal-N rate treatments was 56 to 79 kg N ha\(^{-1}\) greater than any treatment combination for the suboptimal-N rate treatment. The difference in optimal and suboptimal TN uptake values across years is what contributed to the year × N treatment interaction and is evidence that native and residual-N values were much higher in 2011 than in 2012. Biggeriego et al. (1979) also studied optimal and suboptimal-N rate treatments applied both pre-plant and at sidedress and found little difference between TN uptake among treatments, especially when residual soil-N was high. The magnitude of difference in TN uptake values between the optimal and suboptimal-N treatments (56–79 kg N ha\(^{-1}\)) during 2012 was similar to the difference in the season-total N rates for the optimal and suboptimal treatments (78 kg N ha\(^{-1}\)) suggesting that fertilizer-N was the main source of N for corn growth and development. These results are in contrast to work by researchers in the Corn Belt region of the United States, that indicate 50% or more of the TN uptake by the corn plant is accounted for at R6 (Leikam et al., 2010). Although there were no direct measurements of native soil-N availability for the locations used in this trial, the soil organic matter means, soil NO\(_3\)–N concentrations, and differences in grain yield and TN uptake of corn that received no fertilizer-N support the notion that there were substantial differences.

### Corn Grain Yield

Corn grain yield is influenced by many factors including environment, N fertilization, irrigation/rainfall, and hybrid selection. In a long-term management trial conducted in Minnesota, researchers found that year-to-year variation in corn grain yield varied by as much as 7 Mg ha\(^{-1}\) and that 67% of yield variation could be explained by weather and planting date (Huggins and Alderfer, 1995). Corn grain yields obtained in this trial were indicative of yields obtained from many furrow-irrigated corn fields across Arkansas and were maximized for both years when the optimal fertilizer-N rate of 235 kg N ha\(^{-1}\) was applied in a two-way split application (Table 2). Yield was maximized at 1200 and 1590 g m\(^{-2}\) for the 2011 and 2012 growing seasons, respectively. Previous research has indicated that split-N applications, especially those including in-season N applications can significantly affect NUE and corn grain yield (Miller et al., 1975; Olson et al., 1986). During 2011, there were no statistical differences among treatments involving the optimal-N rate applied in a three-way split and any of the suboptimal-N rates and timing combinations although they were significantly less than the optimal-N rate applied in a two-way split. A similar trend occurred in 2012, but there were greater yield differences among the N rate and timing combinations than in 2011. Corn fertilized with the optimal-N rate applied in a three-way split produced a similar or greater yield than corn receiving the suboptimal-N rate applied in a two-way split, but was significantly greater than the suboptimal-N rate applied in a three-way split. As seen in Table 2, corn grain yield potential in 2012 was numerically higher than in 2011, but the 2012 site appeared to have lower native soil-N availability due to the relatively low grain yield of the corn receiving no fertilizer-N compared to 2011 (280 vs. 780 g m\(^{-2}\)). The difference in native soil-N availability or residual soil-N highlights the importance of V6 N applications for maximizing corn grain yield in furrow-irrigated production systems. For the 2012 growing season, corn grain yield was linked to the V6 N application rate as evidenced by the statistical differences between two- and three-way split application strategies within the same season-total N rate. Although grain yields reported for all treatments in 2012 were outstanding, the results indicate that the corn receiving the greater V6 N rates tended to produce significantly greater grain yields. Also, yield potential lost due to suboptimal-N rates and low soil-N availability early in the season, prior to the V12 pre-tassel-N application, cannot apparently be overcome with a pre-tassel-N application even when the season-total N rate is the same. This is supported by the work of Scharf et al. (2002) which indicated corn response to delayed-N applications varied by location and that areas with higher check-plot grain yield were less susceptible to yield loss from delayed-N applications.

### Fertilizer Nitrogen Recovery Efficiency

The ANOVA indicated that N treatment was the only factor influencing FNRE, suggesting that, even though corn grain yield and TN were influenced by year or environmental factors, FNRE in this high-yielding, irrigated production system was consistent across years (Table 3). Recovery of pre-plant incorporated \(^{15}\)N-labeled urea at R6 indicated that 61% of the 50 kg N ha\(^{-1}\) applied was actually accumulated by the corn plant during the growing season (Table 2). Pre-plant N that was accumulated early in the growing season (prior to V8) was most likely translocated to other plant organs prior to early growth stage leaf senescence, but high yielding V6 corn will only contain ~30 kg N ha\(^{-1}\) when the sidedress N is applied suggesting that most of the pre-plant N taken up by the corn plant is accounted for at R6 (Leikam et al., 2010). Although

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**Table 3. Analysis of variance to determine the influence of nitrogen (N) fertilizer treatment and year on corn grain yield, total N uptake and fertilizer N recover efficiency (FNRE) of furrow-irrigated corn.**

<table>
<thead>
<tr>
<th>Source</th>
<th>Total N uptake</th>
<th>Corn grain yield</th>
<th>FNRE</th>
</tr>
</thead>
<tbody>
<tr>
<td>N Treatment (N)</td>
<td>df  7</td>
<td>p value &lt;0.0001</td>
<td>df  7</td>
</tr>
<tr>
<td>Year (Y)</td>
<td>df  1</td>
<td>p value &lt;0.0001</td>
<td>df  1</td>
</tr>
<tr>
<td>Y × N</td>
<td>df  7</td>
<td>p value &lt;0.0001</td>
<td>df  6</td>
</tr>
</tbody>
</table>
this seems high compared to other results for FNRE by corn, the production system that was used in this trial combined with the relatively low N application rate (50 kg N ha\(^{-1}\)) make it highly plausible. Russelle et al. (1981) indicated that FNRE of irrigated corn in Nebraska was 48% when 12 kg N ha\(^{-1}\) was applied pre-plant, but that FNRE decreased with increasing N rates. Lower fertilizer-N rates tend to lead to higher NUE as highlighted by Walsh et al. (2012) who reported the highest NUE values were found in the lowest fertilizer-N rates (45 kg N ha\(^{-1}\)) applied pre-plant. In the furrow-irrigated, corn production system, the main loss mechanism for pre-plant-applied N would either be denitrification or leaching. Pre-plant-applied fertilizer N is expected to have the lowest FNRE because N loss is more likely to occur due to the length of time fertilizer is in the field prior to maximal N uptake by corn (~60 d, Table 1) and the relatively small demand for nutrients by corn early in the growing season (Leikam et al., 2010).

Fertilizer-N recovery efficiency of fertilizer N sidedressed at the V6 growth stage was significantly higher than the pre-plant-applied N and ranged from 81 to 91% and appeared to be influenced by N rate. The two highest V6 fertilizer-N application rates of 135 and 185 kg N ha\(^{-1}\), resulted in the lowest FNRE values for V6 stage applied fertilizer-N (Table 2). Although these FNRE values were significantly higher than the pre-plant FNRE they were also significantly less than the two other application rates at the V6 growth stage of 57 and 107 kg N ha\(^{-1}\). The two lower N rates of 57 and 107 kg N ha\(^{-1}\) applied at the V6 growth stage resulted in FNRE values of 91 and 87%, respectively. Lower application rates at the V6 growth stage tended to have higher FNRE values, but also tended to have significantly lower corn grain yield and lower TN uptake values due presumably to the suboptimal season-total N rate. The results presented for FNRE of various N application rates at the V6 growth stage indicates that high FNRE and high corn grain yields can be achieved with N application rates ranging from 57 to 185 kg N ha\(^{-1}\), and that increasing FNRE may come at the cost of reducing overall corn grain yield.

Two (Treatments 5 and 8) of the three-way split fertilization treatments received \(^{15}\)N-labeled N at the V12 or pre-tassel growth stage (Table 2). The FNRE of the pre-tassel application timing resulted in both the highest and lowest numerical FNRE values of 91 and 63% for the suboptimal and optimal season-total N rate treatments, respectively. Although the FNRE of 91% for the pre-tassel application in the suboptimal N rate treatment was not statistically different than the two suboptimal V6 N rate treatments it was greater than all other N rate applications and timings. The FNRE of pre-tassel N when quantified at the R6 growth stage appears to be influenced by V6 N rate with the FNRE of the suboptimal season-total N rate having significantly higher FNRE than the pre-tassel FNRE of the optimal season-total N rate (Table 2). These results indicate that when pre-plant N and sidedress-N rates were suboptimal that the corn plant is very efficient at accumulating and using N applied at the V12 growth stage. However, when sidedress-N rates are relatively high, the FNRE of fertilizer N applied at V12 declines. Previous work by Leikam et al. (2010) suggested that in high yielding corn (>18 Mg ha\(^{-1}\)) there was a net loss of N (~19 kg N ha\(^{-1}\)) from the corn plant between the VT and R1 growth stages, which could be from pollen shed or NH\(_3\) loss from the plant. Corn that has received adequate or above optimal-N rates prior to the VT growth stage may indeed take up fertilizer-N applied at the pre-tassel timing, but may not retain that N within the plant as it is in excess of grain fill demand. Francis (1993) measured N losses from corn plants post-anthesis and found that higher N rates exacerbated N losses from the plant with an estimated N loss of as much as 67.2 kg N ha\(^{-1}\). More research on the efficiency of pre-tassel-N applications with high temporal resolution of plant sampling in optimal and suboptimal season-total N rates is needed to determine how these factors interact in high yielding irrigated production systems.

**CONCLUSIONS**

Global NUE for most cereal crops including corn is reported to be somewhere near 33% (Raun and Johnson, 1999). However, this global NUE mean includes a variety of environmental and production conditions that include both irrigated and dryland and mechanized and non-mechanized practices. Our results indicate that much higher FNRE values can be obtained when certain production practices and environmental conditions are present. Pre-plant FNRE was one of the lowest of all the fertilizer-N rates and application timings in this trial and suggests that for furrow-irrigated production systems this may be an area where more research is needed to identify best management practices to maximize the efficiency of pre-plant-applied fertilizer N. Knowing that corn demand for N does not significantly increase until the V8 growth stage, and that pre-plant FNRE is low will help advise producers to apply N at growth stages where FNRE and yield can both be maximized. The FNRE by corn for N applied at the V6 stage ranged from 81 to 91% and tended to increase as fertilizer-N rate decreased. Aside from the apparent N rate effect, this result indicates that furrow-irrigated corn production systems in the mid-South can achieve high FNRE values when urea is applied with a NBPT-based urease inhibitor and incorporated timely with rainfall or irrigation (less than 2 d). One of the more novel aspects of this research is the drastic difference in FNRE between the two pre-tassel N applications, with the pre-tassel N in the suboptimal N rate treatment having the highest overall FNRE and the pre-tassel N in the optimal N rate treatment having one of the lowest overall FNRE. Although the pre-tassel N in the suboptimal treatment resulted in higher FNRE when sampled at the R6 growth stage, the significantly lower FNRE of the pre-tassel N in the optimal treatment suggests that more research is needed in this area to determine if the pre-tassel was not taken up as efficiently in the optimal N rate treatment or taken up and expelled from the plant as NH\(_3\).

The results of this work indicate that high FNRE values can be obtained in furrow-irrigated corn production systems, but that there is still room for improvement to better refine the rates and timings of application. Pre-plant N applications are an area where more work needs to be conducted that directly evaluates the effect of rate on FNRE to develop best management practices to maximize preplant FNRE while maximizing corn yield potential. Similarly, these results support the need for more research on pre-tassel N applications and their influence on corn grain yield and FNRE. Our results suggest that when optimal season-total N rates are applied in a
two-way split that yield can be maximized with greater than 80% FNRE. However, suboptimal season-total N rates may maximize FNRE, but corn fertilized with suboptimal N rates often produces statistically lower yields. Furrow-irrigated corn production systems have the potential to be high-yielding and have high FNRE when N fertilizer application rates and timings are optimized.

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