# Non-Radial Technical Efficiency of Water and Nitrogen Usage in Arkansas Rice Production

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## Abstract

Arkansas rice production is highly dependent on energy related inputs such as water and nitrogen. This analysis uses Data Envelopment analysis (DEA) to calculate non-radial technical efficiency scores and quantifies input overuse for rice fields enrolled in the University of Arkansas, Rice Research Verification Program (RRVP), with special emphasis placed on estimation of water and nitrogen input overuse. The results reveal technical inefficiency exists in both water and nitrogen application, but other inputs may play more of a role in the overall technical inefficiency on rice fields. Average estimated overuse of water and nitrogen was 27.9% and 14.7%, respectively.

Arkansas rice production is highly dependent on energy related inputs. Agricultural production expenses have trended upward since 2001 as a result of higher energy costs (Trostle 2008, Beckman et al., 2013). Fuel and fertilizer prices increased significantly due to increased energy demand in developing countries such as China (Trostle, 2008). One important rice input linked closely with energy costs is irrigation water. Rice has the largest water requirement of any row crop grown in the state, averaging 30 acre inches of irrigation water in a normal growing season (Hardke et al., 2013). Arkansas rice production is also heavily dependent on fertilizer inputs, particularly nitrogen. Rice fertilizer expenses range from $137 to $156/acre depending on the variety, and nitrogen fertilizer accounts for 60% of fertilizer expenses (Flanders et al, 2012). The nitrogen requirement for rice ranges from 150 to 180 lbs per acre for silt loam and clay soils, respectively (Hardke et al., 2013).

Because of the large expenses associated with rice production and the large dependence on energy related inputs like fertilizer, and irrigation water in particular, rice producers in Arkansas and the U.S. seek production systems that utilize inputs efficiently. Several studies have looked at input-oriented technical efficiency in rice production (see Watkins et al., 2014 for a thorough overview of the rice production efficiency literature), but these studies have been confined to radial measures of technical efficiency. Radial technical efficiency assumes technically inefficient fields have the same degree of input overuse for all inputs. While this approach is appropriate for comparison with other radial efficiency studies, the approach may become more restrictive and problematic when quantifying overuse of specific inputs, such as water or nitrogen.

This analysis seeks to quantify the technical efficiency of rice production at the field-level using non-radial analysis. Non-radial analysis allows the user to shrink each component of the observed input vector as much as possible until the frontier is reached (Fernandez-Cornejo, 1994). Non-radial analysis allows for a more accurate accounting of input overuse for technically inefficient fields. This study seeks to quantify non-radial technical efficiency of both irrigation and nitrogen use in rice production in an effort to identify production practices that limit overuse of these key rice production inputs. Data for this study are obtained from 98 fields enrolled in the University of Arkansas, Rice Research Verification Program (RRVP) for the period 2005 through 2013. Radial and non-radial technical efficiency scores are calculated by field using data envelopment analysis (DEA), and input overuse of irrigation water, nitrogen, and other rice production inputs is estimated by field based on non-radial efficiency scores calculated for each input. Impacts of field characteristics on overall non-radial technical efficiency scores and on water and nitrogen overuse scores are evaluated using Tobit analysis.

## Radial and Non-Radial Technical Efficiency DEA Model Specifications

Using the DEA model specification, the radial TE score for a given field *n* is obtained by solving the following LP problem:

(1) $$RTE_n = \min_{\lambda_i \theta_n} \theta_n$$

Subject to:

$$\sum_{i=1}^{I} \lambda_i x_{ij} - \theta_n x_{nj} \leq 0$$

$$\sum_{i=1}^{I} \lambda_i y_{ik} - y_{nk} \geq 0$$

$$\sum_{i=1}^{I} \lambda_i = 1$$

$$\lambda_i \geq 0$$

where $RTE_n$ = the radial technical efficiency score for field n; $i$ = 1 to $I$ fields; $j$ = 1 to $J$ inputs; $k$ = 1 to $K$ outputs; $\lambda_i$ = the nonnegative weights for $I$ fields; $x_{ij}$ = the amount of input $j$ utilized on field $i$; $x_{nj}$ = the amount of input $j$ used on field $n$; $y_{ik}$ = the amount of output $k$ produced on field $i$; $y_{nk}$ = the amount of output $k$ produced on field $n$; and $\theta_n$ = a scalar ≤ 1 that defines the TE of field n, with a value of 1 indicating a technically efficient field and a value less than 1 indicating a technically inefficient field, with the level of technical inefficiency equal to 1 - $TE_n$ (Coelli, 1995). The constraint $\sum_{i=1}^{I}\lambda_i = 1$ in equation (1) ensures the $TE_n$ in equation (1) is calculated under the variable returns to scale (VRS) assumption (Coelli, 1995). Equation (1) is therefore the TE formulation proposed by Banker et al. (1984). When the $\sum_{i=1}^{I}\lambda_i = 1$ constraint is omitted, constant returns to scale (CRS) is assumed, and equation (1) becomes the TE formulation proposed by Charnes et al. (1978).

The non-radial TE DEA specification is obtained by solving the following LP problem as shown in Fernandez-Cornejo 1994 and Piot-Lepetit et al., 1997:

$$(2) \qquad NRTE_n = \min_{\lambda_i \theta_{nj}} \sum_{j=1}^{\tilde{J}} \frac{\theta_{nj}}{\tilde{J}}$$

Subject to:

$$\sum_{i=1}^{I}\lambda_i x_{ij} - \theta_{nj} x_{nj} \le 0$$

$$\sum_{i=1}^{I}\lambda_i y_{ik} - y_{nk} \ge 0$$

$$\sum_{i=1}^{I}\lambda_i = 1$$

$$\lambda_i \ge 0$$

where $NRTE_n$ = the overall non-radial TE for the field, $\theta_{nj}$ = the non-radial technical efficiency for input $j$ on field $n$, and $\tilde{J}$ = the number of nonzero inputs for each field and can vary by field. All other variables in equation 2 are as previously defined. As with $RTE_n$ in equation 1, $NRTE_n$ in equation 2 takes on a value ≤ 1, with a value of 1 indicating an overall non-radial technically efficient field and a value less than 1 indicating an overall non-radial technically inefficient field, with the level of technical inefficiency equal to 1 - $NRTE_n$. However, the non-radial efficiencies for each input in equation 2 ($\theta_{nj}$) can take on values ≥ 1 depending on the relationship between input j on field n ($x_{nj}$) and the weighted sum of input j across all fields $\left(\sum_{i=1}^{I} \lambda_i x_{ij}\right)$ in equation 2. Since $\theta_{nj}$ is calculated as a ratio of $\sum_{i=1}^{I} \lambda_i x_{ij}$ and $x_{nj}$, $\theta_{nj}$ will be ≤ 1 if $x_{nj} \geq \sum_{i=1}^{I} \lambda_i x_{ij}$. In this instance, the input is either being overused ($\theta_{nj} < 1$) or used efficiently ($\theta_{nj} = 1$). If, however $x_{nj} < \sum_{i=1}^{I} \lambda_i x_{ij}$ (the level of input j on field n is less than the weighted sum of input j across fields), then $\theta_{nj} > 1$. This condition is similar to something known as “super efficiency” proposed by Anderson and Petersen (1993), where the amount of input j on field n can be increased to a specific upper level without impacting efficiency.

## Data

Radial and non-radial technical efficiency scores are calculated for Arkansas rice production using data from fields enrolled in the University of Arkansas, Rice Research Verification Program (RRVP). The RRVP was originally established in 1983 as a means of public demonstration of research-based UA Extension recommendations in actual farming environments using on-farm field trials. The goals of the RRVP are to 1) educate producers on the benefits of utilizing UA Extension recommendations, 2) verify UA Extension recommendations on farm-field settings, 3) identify research areas needing additional study, 4) improve or refine existing UA Extension recommendations, 5) incorporate RRVP data into state and local education programs, and 6) provide in-field training for county agents. From 1983 to 2012, the RRVP has been conducted on 378 commercial rice fields in 33 rice-producing counties in Arkansas (Schmidt et al., 2013).

Because this study focuses specifically on water and nitrogen usage, input quantities and output data for the DEA analysis were obtained from 98 rice fields enrolled in 2005 through 2013 in which water usage was measured for the growing season using flow meters (Table 1). Inputs for the DEA analysis include field size (acres); irrigation water (acre inches); diesel fuel (gallons); nitrogen, phosphorus, and potassium (lbs); seed (lbs); costs of other soil amendments ($); herbicide, insecticide, and fungicide costs ($); and custom charges ($). Output for the DEA analysis is measured as the value of rice production (rice yield x milling yield adjusted rice price x field size). All economic data (prices and costs) are converted to 2012 dollars using the Producer Price Index.

**Tobit Analysis**

Regression analysis was conducted to determine impacts of different field characteristics on overall non-radial technical efficiency ($NRTE_n$ in equation 2) and on water and nitrogen overuse derived from the non-radial technical efficiency scores for water and nitrogen obtained from equation 2. Input overuse scores for water, nitrogen, and other rice production inputs were calculated as follows:

3) $\delta_{ij} = 0 \text{ if } \theta_{ij} \geq 1; \ \delta_i = (1 - \theta_{ij}) \text{ if } \theta_{ij} < 1$

where $\delta_{ij}$ = the input overuse score for input *j* on field *i*, and $\theta_{ij}$ = the non-radial technical efficiency score for input *j* on field *i*.

A two-limit Tobit model was used in this analysis (Maddala, 1983), because the non-radial TE scores and input overuse scores are bounded between 0 and 1 (unity). The Tobit model is expressed as follows:

$$(6) \qquad y_i^* = \beta_0 + \sum_{m=1}^{M} \beta_m x_{im} + \varepsilon_i, \quad \varepsilon_i \sim IN\left(0, \sigma^2\right)$$

where $y_i^*$ = a latent variable representing either the non-radial TE efficiency score or the water and nitrogen input overuse score for field *i*; $\beta_0$ and $\beta_m$ are unknown parameters to estimate; $x_{im}$ =1 to *M* explanatory field characteristic variables associated with field *i*; and $\varepsilon_i$ = an error term that is independently and normally distributed with zero mean and constant variance $\sigma^2$.

The explanatory variables used in the Tobit regression were derived from data listed in Table 4. Explanatory variables include field size, the year the field was in the program (2005, 2006, …, 2013), the field location (Northeast Region, Central East Region, Other Locations), whether or not the field used hybrid instead of non-hybrid varieties, the soil type of the field (silt loam or clay), the crop grown in the previous year (soybean or some other crop), whether or not the field had levees, whether or not the field used surface water in place of groundwater from wells, whether or not the field used electric rather than diesel power as the irrigation power source, and whether or not the field used multiple inlet irrigation. Field size is measured in acres. All other explanatory variables are zero-one dummy variables (1 if field was enrolled in 2012, zero otherwise; 1 if the field was planted to a “Hybrid” rice variety, zero otherwise, et cetera).

Field size is included to determine if larger fields lead to increased efficiency scores or reduced input overuse. Year dummies are included to account for the effect of weather on efficiency scores and input overuse. Rice fields are distributed fairly uniformly across the 2005 –

2012 period. Rice is primarily grown in eastern Arkansas in NASS Statistical Reporting Districts 3, 6, and 9. Thus the majority of fields enrolled from 2005 to 2012 are in eastern Arkansas. The majority of RRVP field observations in Table 2 occur in the Northeast and Central East regions, (36 and 34 fields, respectively) while the remaining fields are located in the Southeast Region (22 fields) and outside eastern Arkansas (6 fields defined as “Other Locations” in Table 6). Thus, three locational dummy variables were constructed; one for the Northeast Region, one for the Central East Region, and one merging the Southeast Region with “Other Locations.” Rice is grown mostly on silt loam or clay texture fields (Hardke and Wilson, 2013). The majority of RRVP fields in Table 2 have silt loam texture (55 fields), while all but one of the remaining 43 fields have clay texture. Soybean is the typical crop rotated with rice (Hardke and Wilson, 2013), and most RRVP fields in Table 2 have soybean as the previous crop in the rotation (61 fields).

Rice producers have the choice of planting a range of rice variety types, including conventional public varieties, Clearfield varieties, hybrid varieties, and Clearfield-hybrid combinations (Nalley et al., 2009). Conventional varieties include both long and medium grain variety types. These variety types differ in the size and shape of the kernel, with long grain rice having a longer, more slender kernel than medium grain rice. Clearfield varieties are resistant to imidazolinone herbicides and allow for greater control of red rice without killing rice growing in the field. Hybrids provide greater disease resistance and higher yields and use less nitrogen relative to conventional varieties. Clearfield-hybrids combine the red rice control of Clearfield lines with the higher yielding and disease resistant traits of hybrids. Zero-one dummy variables were constructed to indicate if the field used hybrid varieties (Hybrids and Clearfield-Hybrids in Table 2) or non-hybrid varieties (Conventional, Medium Grain, and Clearfield in Table 2).

Rice field typography varies across Arkansas depending on the amount of precision leveling conducted on each field. Contour levee fields account for over 34% of rice acres in Arkansas (Hardke and Wilson, 2013) and have minimal land improvements. Contour levees are constructed annually in order to manage water across uneven terrain. An estimated 56% of Arkansas rice acres are precision leveled to some degree (Hardke and Wilson, 2013), with most fields graded to a 0.05 to 0.2% slope. Most precision leveled fields have straight levees. Some rice fields in Arkansas are leveled to a zero slope and are referred to as zero-grade rice fields. Zero-grade rice production accounts for approximately 10% of planted rice acres in Arkansas (Hardke and Wilson, 2013). Zero-grade rice production eliminates the need to build levees each year and results in significantly less irrigation and fuel when compared with contour-levee rice production. A small number of rice acres in Arkansas (no more than 0.3%) are managed using furrow irrigation (Hardke and Wilson, 2013). Furrow-irrigated rice or row rice management refers to planting rice in furrows on raised beds. Water is applied in the furrows to maintain adequate soil moisture. Four RRVP fields in Table 2 were furrow-irrigated fields. Zero-one dummy variables were constructed to indicate if the field contained levees (Contour Levees and Straight Levees in Table 2) or no levees (Zero-grade and Furrow in Table 2).

The majority of irrigation water for rice production in Arkansas comes from groundwater via wells. Wells account for over 76% of irrigation water in rice production, while surface water sources (streams, rivers, and reservoirs) account for less than 24% of irrigation water in Arkansas rice production (Hardke and Wilson, 2013). Eighty-one RRVP fields use wells while 17 RRVP fields use some surface water source for irrigation water in Table 2. Zero-one dummy variables were constructed to indicate if the field obtained water from a surface water source or a well source. Irrigation water in Arkansas rice production is pumped using either diesel or electric power. There are presently no statistics available to determine the proportion of diesel versus electric power units in Arkansas rice production. However, 77 of the RRVP fields used diesel power while 21 used electric power in Table 2. Thus zero-one dummy variables were constructed to indicate if the field used either diesel or electric power.

Multiple inlet (MI) irrigation uses poly pipe to distribute irrigation water to all paddies simultaneously. This differs from conventional flood irrigation in which water is applied to the first paddy at the top of the field and then flows over spills to lower paddies until the entire field is flooded (Vories et al. 2005). Multiple inlet irrigation allows the field to be flooded much faster than conventional flood irrigation. Water savings may be achieved using MI over conventional flood irrigation because the field is flooded quicker and irrigation efficiency is increased through reduced pumping time during the season. Other possible benefits of MI include reduced irrigation labor and possible higher grain yields (Vories et al. 2005). Multiple inlet irrigation is estimated to be used on over 38% of rice acres in Arkansas (Hardke and Wilson, 2013). Zero-one dummy variables were constructed to indicate if the field did or did not use multiple inlet irrigation.

## Results

### *Radial, Non-Radial, and Input Specific Technical Efficiency Scores*

Radial, non-radial, and input technical efficiency score summary statistics are presented in Table 3. The LINDO What's Best! spreadsheet solver was used to conduct the DEA linear programming analysis for each field in the study (Lindo Systems, 2013). The mean radial technical efficiency (RTE in Table 3) is 0.912. The median RTE score is 1, implying that over one-half of the 98 fields evaluated have full radial technical efficiency. The mean non-radial technical efficiency (NRTE in Table 3) is 0.724 and is lower than the mean RTE, which is the typical finding of studies comparing the two (Fernandez-Cornejo, 1994; Piot-Lepetit et al. 1997). Irrigation and nitrogen have mean efficiency scores of 0.775 and 0.912, implying these inputs have mean technical inefficiencies of 0.225 and 0.088, respectively. However, other inputs appear to contribute more to technical inefficiency than either irrigation water or nitrogen. Phosphorus, potassium, seed, other fertilizer, insecticides, and fungicides all have larger mean technical inefficiencies than either irrigation water or nitrogen. Many of these inputs are applied on an "as need" basis. For example, insecticides and fungicides may or may not be applied unless insect or disease pressures reach a certain threshold level to warrant their necessity. Herbicides contribute the least towards overall technical inefficiency, with a mean efficiency score of 1.057 and a median efficiency score of 1.

Input overuse summary statistics are presented in Table 4. Irrigation water and nitrogen are over-applied on average by 27.9% and 14.7%, respectively, across the 98 RRVP fields. The majority of the 98 RRVP fields evaluated in the analysis over-apply irrigation water and nitrogen (59% over-apply irrigation water; 55% over-apply nitrogen in Table 4). Of the 12 inputs evaluated, Other Fertilizers have the highest mean overuse score (0.450), while herbicides have the lowest mean overuse score (0.109).

### *Impact of Field Characteristics on Non-Radial Efficiency Scores and Water and Nitrogen Overuse Scores*

Tobit analysis results of field characteristic impacts on efficiency scores are presented in Table 5. Tobit models were estimated using the SAS QLIM procedure (SAS Institute, 2011). Tobit analysis was conducted on non-radial technical efficiency scores (NRTE in Table 5), water overuse scores, and nitrogen overuse scores. Coefficients are interpreted differently for the three models. Significantly positive coefficients for the NRTE mode would indicate the field characteristic increases non-radial technical efficiency, while significant negative coefficients for either the water or nitrogen overuse models would indicate the field characteristic reduces input overuse.

Coefficients for Field Size were insignificant in all three models. Likewise, locational coefficients were for the most part not significant across the three models with the exception of the coefficient for Central East Region for the NRTE model, which was significantly positive at the 10% level. Coefficients for the year in which the field was enrolled in the RRVP were also for the most part insignificant, with the exception of 2010 in both the NRTE and nitrogen overuse models, 2009 in the water overuse model, and 2005 and 2006 in the nitrogen overuse model. The years 2005 and 2010 were hot and dry, impacting yield variability and negatively affecting nitrogen use efficiency. The year 2006 had a cool and wet spring, which also affected yield variability and thus nitrogen use efficiency. The year 2009 was a relatively wet year with timely rains during the growing season. Thus, the negative and significant 2009 coefficient for water overuse would be expected, as less irrigation water would have been needed that year.

The coefficients for Hybrid were significant for both the NRTE model (significantly positive at the 1% level) and the nitrogen overuse model (significantly negative at the 5% level). These results indicate that hybrid rice varieties increase overall non-radial technical efficiency and reduce nitrogen overuse. Hybrids tend to have higher yields relative to conventional and Clearfield varieties on marginal fields. Hybrids provide greater disease resistance and higher yields and use less nitrogen relative to conventional varieties.

Coefficients for Silt Loam were significant for both the NTRE model (significantly negative at the 1% level) and the water overuse model (significantly positive at the 1% level), indicating rice planted to silt loam fields reduces overall non-radial technical efficiency and increases overuse of irrigation water. This result is likely due to the terrain of most fields with silt loam soils. Fields with silt loam soils are found in higher concentrations in areas of eastern Arkansas where the terrain is more rolling and where water management across fields is more difficult. The coefficients for Soybean were significant for both the NTRE model (significantly negative at the 1% level) and the nitrogen overuse model (significantly positive at the 5% level), indicating fields in which rice is planted after soybeans in the rotation reduce overall non-radial technical efficiency and increase nitrogen overuse. This result may be related to the use of levees on fields where rice is rotated with soybeans. The coefficients for Levees have the same signs as those for Soybean in both the NRTE and nitrogen overuse models, but nether coefficient is significant. The Levee coefficient is positive and significant at the 5% level for the water overuse model however, indicating fields with levees increase water overuse as opposed fields without levees. Fields without levees in this analysis are primarily zero-grade fields (non-levee fields include 14 zero grade fields; 4 furrow fields, Table 2). Zero grade fields use significantly less irrigation water and fuel than fields with levees.

Coefficients for Electric Power are not significant across the three models. However, the coefficient for Surface Water is negative and significant at the 5% level in the water overuse model, indicating fields supplied by surface water have less water overuse relative to fields supplied by groundwater via wells. This result is likely due to better irrigation water management on the part of rice producers on fields supplied with surface water. Areas using surface water are often areas for which groundwater supplies are either highly variable, dwindling, or non-existent. Many rice producers in Arkansas have dealt with decreasing groundwater supplies by constructing on-farm reservoirs and tailwater pits to capture precipitation and field runoff. These producers have developed the infrastructure necessary to capture and reuse water and thus may exhibit a mindset for greater water management.

Coefficients for Multiple Inlet are significant in both the NRTE and water overuse models. The Multiple Inlet coefficient is positive and significant at the 10% level for the NRTE model and is negative and significant at the 5% level for the water overuse model. These results imply that rice fields with multiple inlet irrigation reduce water overuse and increase overall technical efficiency. It is estimated that over 38% of rice acres in Arkansas use multiple inlet irrigation (Hardke and Wilson, 2013). Thus, potential is available to increase water use efficiency in the state by greater adoption of multiple inlet irrigation based on these results.

## Summary and Conclusions

This study uses Data Envelopment analysis (DEA) to calculate non-radial technical efficiency scores and quantifies input overuse for 98 rice fields enrolled in the University of Arkansas Rice Research Verification Program (RRVP). Special emphasis is placed on estimation of input overuse for two key production inputs in rice production: water and nitrogen.

The results reveal technical inefficiency does exist in the application of both water and nitrogen on rice fields. However, the results also indicate that other inputs may play more of a role in the overall technical inefficiency on rice fields than either water or nitrogen, such as phosphorus, potassium, other fertilizers (other soil amendments, such as chicken litter, zinc, and urease inhibitors), insecticides, and fungicides. These latter inputs are applied on an “as needed” basis. Average input overuse of water and nitrogen across the 98 RRVP fields was 27.9% and 14.7%, respectively. Over half the RRVP fields in the analysis overused both water and nitrogen. Average overuse of other rice production inputs ranged from 10.9% for herbicides to 45% for other fertilizers.

The Tobit analysis provides evidence that water efficiency may be improved by capital investments made either by leveling the land for better water delivery across the field (zero grade) or by building reservoirs and tailwater pits to capture precipitation and field runoff. The Tobit analysis also provided evidence that greater water efficiency could also be obtained by using a relatively inexpensive mode of water delivery know as multiple inlet irrigation. Multiple inlet irrigation also increased overall non-radial technical efficiency based on the Tobit analysis. Multiple inlet irrigation is estimated to be in use on 38% of rice acres. Thus, potential is available to increase water use efficiency in the state by greater adoption of multiple inlet irrigation based on these results. Hybrid rice varieties were found to increase both non-radial technical efficiency and nitrogen use efficiency, based on the Tobit analysis.

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Table 1. Output and Inputs Summary Statistics Used in the DEA Analysis.

| Variable | Mean [a] | SD | CV | Minimum | Median | Maximum |
|---|---|---|---|---|---|---|
| **Output** [b] | | | | | | |
| Rice Production Value ($) [c] | 55,246 | 34,966 | 63 | 14,743 | 46,073 | 228,122 |
| **Inputs** | | | | | | |
| Field Size (acres) | 51 | 26 | 51 | 12 | 45 | 146 |
| Irrigation water (acre inches) | 1,541 | 851 | 55 | 288 | 1,329 | 4,453 |
| Nitrogen (lbs) [d] | 8,606 | 4,592 | 53 | 1,932 | 7,205 | 27,472 |
| Phosphorus (lbs) [d] | 1,587 | 1,682 | 106 | 0 | 1,310 | 6,845 |
| Potassium (lbs) [d] | 1,966 | 2,538 | 129 | 0 | 1,236 | 12,611 |
| Machinery Diesel (gallons) | 456 | 270 | 59 | 56 | 392 | 1,515 |
| Seed (lbs) | 3,567 | 2,593 | 73 | 644 | 2,840 | 11,560 |
| Other Soil Amendments ($) [e] | 595 | 1,396 | 235 | 0 | 186 | 9,420 |
| Herbicides ($) | 3,388 | 2,117 | 62 | 397 | 2,819 | 13,298 |
| Insecticides ($) | 206 | 385 | 187 | 0 | 0 | 2,259 |
| Fungicides ($) | 477 | 703 | 147 | 0 | 0 | 2,912 |
| Custom Charges ($) | 2,479 | 1,619 | 65 | 526 | 2,087 | 9,577 |
| Number of Inputs | 10 | 1 | 13 | 7 | 10 | 12 |

[a] Summary statistics calculated from 98 fields with water usage measured by flow meter enrolled in the University of Arkansas Rice Research Verification Program for the period 2005 – 2013.

[b] Rice values and input costs are adjusted to 2012 dollars using the Producer Price Index.

[c] Rice production value = field yield (bu/acre) * rice price adjusted for milling quality ($/bu) * field size (acres)

[d] Input levels for nitrogen, phosphorus, and potassium are in elemental levels.

[e] Other soil amendments include chicken litter, zinc, and/or urease inhibitors.

Table 2. Field Characteristic Variables Used in the Tobit Analysis

| Field Characteristic | Description | N [a] | Mean |
|---|---|---|---|
| Field Size | Size of field (acres) | 98 | 51.49 |
| 2013 | Field in Rice Research Verification Program in 2013 | 9 | 0.09 |
| 2012 | Field in Rice Research Verification Program in 2012 | 8 | 0.08 |
| 2011 | Field in Rice Research Verification Program in 2011 | 12 | 0.12 |
| 2010 | Field in Rice Research Verification Program in 2010 | 9 | 0.09 |
| 2009 | Field in Rice Research Verification Program in 2009 | 13 | 0.13 |
| 2008 | Field in Rice Research Verification Program in 2008 | 12 | 0.12 |
| 2007 | Field in Rice Research Verification Program in 2007 | 8 | 0.08 |
| 2006 | Field in Rice Research Verification Program in 2006 | 12 | 0.12 |
| 2005 | Field in Rice Research Verification Program in 2005 | 15 | 0.15 |
| Northeast Region | Field in Northeast Arkansas (Statistical District 3) | 36 | 0.37 |
| Central East Region | Field in Central East Arkansas (Statistical District 6) | 34 | 0.35 |
| Southeast Region | Field in Southeast Arkansas (Statistical District 9) | 22 | 0.22 |
| Other Locations | Field located outside of Eastern Arkansas | 6 | 0.06 |
| Conventional | Conventional Long Grain Rice Varieties | 41 | 0.42 |
| Medium Grain | Conventional Medium Grain Rice Varieties | 8 | 0.08 |
| Clearfield | Clearfield Rice Varieties | 10 | 0.10 |
| Hybrid Rice | Hybrid Rice Varieties | 11 | 0.11 |
| Clearfield-Hybrid | Clearfield-Hybrid Rice Varieties | 28 | 0.29 |
| Silt Loam | Soils with silt loam texture | 55 | 0.56 |
| Clay | Soil with clay texture | 42 | 0.43 |
| Sand | Soil with sand texture | 1 | 0.01 |
| Soybean | Soybean planted on field previous year | 61 | 0.62 |
| Other Crop | Rice, grain sorghum, corn, fallow | 37 | 0.38 |
| Contour Levees | Field contains contour levees | 32 | 0.33 |
| Straight Levees | Field contains straight levees | 48 | 0.49 |
| Zero-Grade | Field has been graded to a zero slope | 14 | 0.14 |
| Furrow | Field contains furrows | 4 | 0.04 |
| Well | Water comes from a well | 81 | 0.83 |
| Surface Water | Water comes from a reservoir or stream | 17 | 0.17 |
| Diesel | Irrigation power unit is diesel | 77 | 0.79 |
| Electric | Irrigation power unit is electric | 21 | 0.21 |
| Multiple Inlet | Field using poly pipe to irrigate paddies | 31 | 0.32 |
| No Multiple Inlet | Field without poly pipe | 67 | 0.68 |

[a] N = number of fields.

Table 3. Technical Efficiency Score Summary Statistics of 98 University of Arkansas Rice Research Verification Program Fields

| Efficiency Score | Mean | SD | CV | Minimum | Median | Maximum |
|---|---|---|---|---|---|---|
| RTE [a] | 0.912 | 0.147 | 16 | 0.459 | 1.000 | 1.000 |
| NRTE [a] | 0.724 | 0.222 | 31 | 0.287 | 0.731 | 1.000 |
| Field Size | 0.868 | 0.180 | 21 | 0.468 | 0.890 | 1.255 |
| Irrigation | 0.775 | 0.373 | 48 | 0.134 | 0.779 | 2.184 |
| Nitrogen | 0.912 | 0.273 | 30 | 0.392 | 0.945 | 2.077 |
| Phosphorus | 0.390 | 0.416 | 107 | 0.000 | 0.339 | 1.926 |
| Potassium | 0.183 | 0.312 | 171 | 0.000 | 0.000 | 1.000 |
| Machinery Diesel | 0.762 | 0.314 | 41 | 0.165 | 0.781 | 1.590 |
| Seed | 0.667 | 0.350 | 53 | 0.091 | 0.725 | 1.691 |
| Other Fertilizer | 0.210 | 0.371 | 177 | 0.000 | 0.000 | 1.530 |
| Herbicides | 1.057 | 0.400 | 38 | 0.363 | 1.000 | 2.399 |
| Insecticides | 0.133 | 0.323 | 243 | 0.000 | 0.000 | 1.096 |
| Fungicides | 0.106 | 0.278 | 263 | 0.000 | 0.000 | 1.000 |
| Custom Applications | 0.766 | 0.316 | 41 | 0.236 | 0.722 | 1.971 |

[a] RTE = Radial Technical Efficiency; NRTE = Non-Radial Technical Efficiency

Table 4. Input Overuse Summary Statistics of 98 University of Arkansas Rice Research Verification Program Fields

| Input | Mean | SD | CV | Minimum | Median | Maximum | N | Percent |
|---|---|---|---|---|---|---|---|---|
| Field Size | 0.148 | 0.160 | 109 | 0.000 | 0.110 | 0.532 | 61 | 62% |
| Irrigation | 0.279 | 0.283 | 101 | 0.000 | 0.221 | 0.866 | 58 | 59% |
| Nitrogen | 0.147 | 0.174 | 118 | 0.000 | 0.055 | 0.608 | 54 | 55% |
| Phosphorus | 0.287 | 0.341 | 119 | 0.000 | 0.078 | 1.000 | 50 | 51% |
| Potassium | 0.337 | 0.415 | 123 | 0.000 | 0.000 | 1.000 | 44 | 45% |
| Machinery Diesel | 0.271 | 0.265 | 98 | 0.000 | 0.219 | 0.835 | 62 | 63% |
| Seed | 0.349 | 0.325 | 93 | 0.000 | 0.275 | 0.909 | 66 | 67% |
| Other Fertilizer | 0.450 | 0.458 | 102 | 0.000 | 0.414 | 1.000 | 48 | 49% |
| Herbicides | 0.109 | 0.184 | 169 | 0.000 | 0.000 | 0.637 | 36 | 37% |
| Insecticides | 0.256 | 0.423 | 165 | 0.000 | 0.000 | 1.000 | 27 | 28% |
| Fungicides | 0.302 | 0.442 | 146 | 0.000 | 0.000 | 1.000 | 32 | 33% |
| Custom Applications | 0.269 | 0.243 | 90 | 0.000 | 0.278 | 0.764 | 65 | 66% |

Table 5. Tobit Analysis of Non-Radial Technical Efficiency, Water Overuse, and Nitrogen Overuse as a Function of Field Characteristics

| Independent Variables | NRTE[a] | | Water Overuse | | Nitrogen Overuse | |
|---|---|---|---|---|---|---|
| Intercept | 0.8829 | ***[b] | 0.0138 | | -0.1076 | |
| | (0.1094)[c] | | (0.1777) | | (0.1298) | |
| Field Size | 0.0001 | | -0.0025 | | 0.0016 | |
| | (0.0010) | | (0.0016) | | (0.0010) | |
| 2012 | -0.0236 | | 0.0161 | | 0.0471 | |
| | (0.1053) | | (0.1683) | | (0.1136) | |
| 2011 | -0.1062 | | -0.0281 | | 0.1128 | |
| | (0.0972) | | (0.1537) | | (0.1043) | |
| 2010 | -0.1768 | * | 0.2443 | | 0.3025 | *** |
| | (0.1034) | | (0.1616) | | (0.1089) | |
| 2009 | 0.0407 | | -0.3635 | ** | 0.0907 | |
| | (0.0999) | | (0.1710) | | (0.1112) | |
| 2008 | 0.1012 | | -0.2054 | | -0.1686 | |
| | (0.1017) | | (0.1714) | | (0.1379) | |
| 2007 | -0.0165 | | 0.1292 | | 0.0602 | |
| | (0.1122) | | (0.1808) | | (0.1192) | |
| 2006 | -0.0847 | | 0.0482 | | 0.2688 | ** |
| | (0.1013) | | (0.1622) | | (0.1062) | |
| 2005 | -0.1297 | | 0.1484 | | 0.2779 | *** |
| | (0.0981) | | (0.1569) | | (0.1028) | |
| Northeast Region | 0.0591 | | 0.0032 | | -0.0904 | |
| | (0.0769) | | (0.1240) | | (0.0781) | |
| Central East Region | 0.1412 | * | -0.0931 | | -0.0889 | |
| | (0.0781) | | (0.1283) | | (0.0773) | |
| Hybrid | 0.1459 | *** | -0.1333 | | -0.1255 | ** |
| | (0.0512) | | (0.0814) | | (0.0541) | |
| Silt Loam | -0.1696 | *** | 0.3034 | *** | 0.0089 | |
| | (0.0630) | | (0.1008) | | (0.0622) | |
| Soybean | -0.1348 | *** | 0.1038 | | 0.1113 | ** |
| | (0.0500) | | (0.0784) | | (0.0512) | |

Table 5 Continued.

| Independent Variables | NRTE | | Water Overuse | | Nitrogen Overuse | |
|---|---|---|---|---|---|---|
| Levees | -0.0760 | | 0.2477 | ** | 0.0472 | |
| | (0.0710) | | (0.1207) | | (0.0797) | |
| Surface Water | 0.0283 | | -0.2608 | ** | 0.0575 | |
| | (0.0677) | | (0.1116) | | (0.0695) | |
| Electric Power | -0.0337 | | 0.1596 | | -0.1038 | |
| | (0.0625) | | (0.0999) | | (0.0698) | |
| Multiple Inlet | 0.0956 | * | -0.1823 | ** | -0.0842 | |
| | (0.0550) | | (0.0866) | | (0.0562) | |
| σ | 0.2067 | *** | 0.3085 | *** | 0.1944 | *** |
| | (0.0178) | | (0.0311) | | (0.0203) | |
| Observations | 98 | | 98 | | 98 | |
| Log Likelihood | -8.437 | | -39.354 | | -13.237 | |

[a] NRTE = Non-Radial Technical Efficiency

[b] Asterisks ***, **, and * represent statistical significance at the 1%, 5%, and 10% levels, respectively.

[c] Numbers in parentheses are standard errors.