# IMPACTS OF HERBICIDE RESISTANT RICE TECHNOLOGY ON RICE-SOYBEANS ROTATION

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Herbicide resistant (HR) rice biotechnology provides control of the red rice weed in commercial rice. This technology may alter the traditional soybeans-rice rotation practice in southern United States. Mathematical programming is used to analyze the effects of HR rice on the current rotation system. Optimal crop rotations subject to weed dynamics and technology costs are identified.

*Key Words:* biotechnology; herbicide resistant; mathematical programming; red rice; rice; rotation; soybeans; technology.

Rice-soybean rotation is regarded as an effective component of weed control in rice production areas of the southern United States (US).[1] In 2000, this region planted 2.5 million acres of rice and produced 148 million hundredweight of rice accounting for 77 percent of US production. Red rice (*Oryza sativa)* poses a serious weed problem to rice production. Red rice is in the same genus and species as cultivated conventional rice, a characteristic that makes it a competitor with commercial rice for nutrients and a difficult weed to eliminate in rice fields (Diarra, Smith, & Talbert, 1985). Red rice control requires a costly and multi-stage strategy involving pre-emergence herbicides, flooding, and crop rotation. Typically, producers alternate one year of rice for two years of soybeans to break the cycle of red rice seed production and deplete the seed bank in the soil (Smith, 1981; Baldwin, 1978).

The development of herbicide resistant (HR) rice is likely to alter the current production practice by offering producers an alternative to soybean rotation for red rice control. Producers can eliminate red rice in commercial rice, improve overall weed control and respond to market incentives more quickly. The problem is to identify which rotation among soybeans, conventional and HR rice is most profitable given the dynamics of red rice in the field. The problem with red rice is that it reduces commercial rice yields and quality. Smith (1981) found that three red rice plants per square meter reduced conventional rice yield by 10 percent. Fisher and Ramirez (1993) found that a five percent density of red rice decreased conventional rice yields by 40 percent. Brorsen, Grant, and Rister (1988), who studied the effects of red rice on commercial rice in Texas, reported a price discount between 0.9 and 3.2 percent due to red rice seed contamination. The allowance for red rice for US rough rice grades 1, 2, and 3 are 0.5%, 1.5%, and 2.5%, respectively.

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Three companies are currently testing three rice varieties for commercial production: the transgenic Liberty Link® rice is being developed by Aventis to resist glufosinate ammonium herbicide; the Roundup Ready® rice from Monsanto is also a transgenic variety that tolerates glyphosate Roundup herbicides; and Clearfield® or Imi rice was engineered through mutation to tolerate imidazolinone herbicides and is being tested by BASF. In this study, the term HR rice technology is used to portray the herbicide resistant rice technologies such as those mentioned above.

## Model And Data

We address the rotation problem through a deterministic mathematical programming formulation of a typical producer's cropping decision where only one crop is chosen yearly among conventional rice, HR rice, and soybeans. The model is highly simplified and does not examine price or yield risk. However, it does capture the essential considerations involved in the decision to switch from rice production to soybean production for weed control purposes. The producer seeks to maximize the present value gross margins per acre, $V_t$, over a 9-year planning horizon. A discount rate of 5 percent is applied to the gross margin values. The producer maximizes the following objective function:

$$V_t = \sum_{t=1}^{T=9}(1/(1+d)^t)[(P_{ct} - C_{ct})Y_{ct}X_{ct} + (P_{st} - C_{st})Y_{st}X_{st} + (P_{ht} - C_{ht})Y_{ht}X_{ht}]K \quad (1)$$

where d is the discount rate, $Y_{ct}$, $Y_{ht}$, and $Y_{st}$ are the yields for conventional rice, HR rice, and soybeans, respectively. K is a constant conversion factor to convert gross margins per square meter to a per acre basis. Soybean yield is assumed fixed at 55 bushels per acre. Producers receive a price $P_{ct}$ for conventional rice, $P_{ht}$ for HR rice, and a price $P_{st}$ for soybeans. Government loan rates were used for the producer prices. Producers incur costs of $C_{ct}$, $C_{st}$, and $C_{ht}$ to produce conventional rice, soybeans, and HR rice, respectively. There are three binary variables in the gross margin equation: $X_{ct}$ takes a value of 1 if conventional rice is grown, zero otherwise; $X_{st}$ takes a value of 1 if soybeans are grown, zero otherwise; and $X_{ht}$ takes a value of 1 if HR rice is grown and zero otherwise.

The model to estimate the dynamics of red rice and its effects on rice yield is based on research on competition of red rice and cultivated rice (Pantone & Baker, 1991).

$$Y_{rt} = (a_r + a_{rr}D_{rt} + a_{rc}D_{ct}X_{ct} + a_{rh}D_{ht}X_{ht})^{-1}D_{rt} \quad (2)$$

$$Y_{ct} = (a_c + a_{cc}D_{ct} + a_{cr}D_{rt})^{-1}D_{ct} \quad (3)$$

$$Y_{ht} = (a_h + a_{hh}D_{ht} + a_{hr}D_{rt})^{-1}D_{ht} \quad (4)$$

$$D_{rt} = B_t\,[G_t(1-k_{jt})]; \text{ where j = conventional rice, HR rice, or soybeans} \quad (5)$$

$$B_t = B_{t-1} + S_{t-1}Y_{rt-1} + dorm_{t-2} + dorm_{t-3} \quad (6)$$

where $Y_{rt}$ is red rice yield in seeds per square meter, $D_{rt}$ is the density of red rice (measured in the number of plants per square meter), $B_t$ is the red rice seed bank at the beginning of current year, $D_{ct}$ and $D_{ht}$ are densities of conventional and HR rice, and $S_t$ is the red rice shatter rate. At t = 0, the initial seed bank and initial red rice density are given, not estimated. The red rice germination rate is $G_t$ and $k_{jt}$ represents the kill rate associated with crop j. The parameters, $dorm_{t-2}$ and $dorm_{t-3}$, are germination rates for dormant red rice seeds produced in previous periods.

In equations (2) through (4), the arguments within the bracket are an inverse yield function that provides an estimate of the number of seeds per single rice plant. Inside the brackets, the intercepts $a_r$, $a_c$, and $a_h$ represent the maximum yield per plant, growing without interference. The maximum yield declines as competition for nutrients and space among same variety plants and between red rice and cultivated (conventional or HR) rice increases. The coefficients $a_{rr}$, $a_{cc}$, and $a_{hh}$ measure the effect of intra-variety competition on yield while the coefficients $a_{rc}$, $a_{cr}$, and $a_{hr}$ represent the yield loss due to inter-variety competition between red rice and conventional or HR rice.[2] The product of plant yield and density gives the yield per square meter. Yields are then converted into bushels per acre. The model included several other constraints used to tie red rice yields in one period to densities in following periods and to model crop rotation dynamics across the several periods. These are not reported due to space limitations.

As no field data of HR rice are available, the costs of production are taken from extension crop budgets for a no-till, silt-loam farm situation in Arkansas (University of Arkansas, 2000). In equation (5) the red rice density is specified with an 80 percent germination rate and herbicide kill rates of 75 percent for conventional rice, 85 percent for HR rice, and 95 percent for soybeans in the baseline. In fact, HR rice can achieve higher kill rates but such rates result in injury to cultivated rice (Sankula, Braverman, & Linscombe, 1997). The initial red rice density was set at 1.474 plants per square meter for all rotation scenarios. A technology fee of $25 per acre is assumed to account for the price premium on HR seeds and herbicide (Annou, Wailes, & Cramer, 2000).

## Results

The program was solved as a mixed integer non-linear program using the DICOPT solver in GAMS. Appendices 1 and 2 describe the baseline parameters and report the gross margin for the baseline optimal rotation cycle. The results presented in tables 1 and 2 give the optimal crop decisions and the corresponding red rice density in each year in the planning horizon. The results of the baseline and alternative scenarios suggest that HR rice reduces the length of the rotation cycle but the cost of the technology is important in determining the extent of HR rice adoption.

<u>HR Rice Technology Leads to More Rice Production</u>

Under the current system that restricts cropping to conventional rice and soybeans, the optimal rotation consists of three years of rice for six years of soybeans (table 1). Two consecutive years of soybeans are needed to decrease red rice density such that one year of rice production enters into the optimal rotation solution for an annual gross margin of $84 per acre.

In the baseline scenario, producers can plant conventional rice, HR rice, or soybeans. Yet, crop decisions depend on the red rice density as red rice in the preceding years determines which crop is optimal in the current year. For example, given the density of red rice of 0.731 in year 2, HR rice rather than conventional rice was chosen in year 3. But planting HR rice in year 3 increased red rice density to 1.414, which induced a rotation to soybeans in year 4 in order to grow HR rice in year 5. The main result is that the introduction of HR rice changes the crop rotation structure. HR rice replaced regular rice over the entire period. It also displaced soybeans, as soybeans are selected only every other year. HR rice and soybeans alternate, showing that a single year of soybeans is sufficient to control red rice. As a result, rice production increases by 60 percent over the planning period. Gross margins increase to an average $104 per acre per year. However, the fact that red rice density increased with HR rice suggests that at an 85 percent kill rate HR rice technology represents an inadequate substitute to soybeans for controlling red rice beyond a limited time horizon.

<u>Technology Fee Determines Rotation</u>

Farmers producing HR rice must purchase HR seeds by paying a price that includes a technology fee to a seed producer. Hence, the cost of seeds is an important element in the decision to adopt. Two scenarios are used to test the sensitivity of crop rotation to the technology fee (table 2).

**Table 1: Current Rotation System and HR Rice Baseline Scenario.**

| | **Current Rotation System** | | **Baseline Scenario Technology Fee = $ 25 per acre** | |
|---|---|---|---|---|
| **Year** | **Crops** | **Red Rice Density** | **Crops** | **Red Rice Density** |
| **1** | Conventional Rice | 1.474 | Conventional Rice | 1.474 |
| **2** | Soybeans | 0.731 | Soybeans | 0.731 |
| **3** | Soybeans | 0.471 | HR Rice | 1.414 |
| **4** | Conventional Rice | 1.815 | Soybeans | 0.808 |
| **5** | Soybeans | 0.931 | HR Rice | 1.562 |
| **6** | Soybeans | 0.587 | Soybeans | 0.877 |
| **7** | Conventional Rice | 2.250 | HR Rice | 1.700 |
| **8** | Soybeans | 1.143 | Soybeans | 0.952 |
| **9** | Soybeans | 0.717 | HR Rice | 1.842 |
| | Average annual gross margin = $ 84 per acre | | Average annual gross margin = $ 104 per acre | |

**Table 2: Sensitivity of Crop Rotation to Technology Fee.**

| | **Low Cost Scenario Technology Fee = $15 per acre** | | **High Cost Scenario Technology Fee = $35 per acre** | |
|---|---|---|---|---|
| **Years** | **Crops** | **Red Rice Density** | **Crops** | **Red Rice Density** |
| **1** | Conventional Rice | 1.474 | Conventional Rice | 1.474 |
| **2** | Soybeans | 0.731 | Soybeans | 0.731 |
| **3** | HR Rice | 1.414 | Soybeans | 0.471 |
| **4** | Soybeans | 0.808 | HR Rice | 1.089 |
| **5** | HR Rice | 1.562 | Soybeans | 0.598 |
| **6** | HR Rice | 2.630 | HR Rice | 1.159 |
| **7** | Soybeans | 1.359 | Soybeans | 0.659 |
| **8** | HR Rice | 2.685 | HR Rice | 1.282 |
| **9** | Soybeans | 1.474 | Soybeans | 0.724 |
| | Average Annual Gross Margin = $107 per acre | | Average Annual Gross Margin = $92 per acre | |

The first scenario evaluates a technology fee of $15 per acre compared to the baseline fee of $25. This low cost did not encourage more HR rice production compared to the baseline since HR rice is planted four out of eight years in both scenarios. While the baseline allows no continuous rice, the low cost scenario solution repeats HR rice in years 5 and 6, suggesting that the relative profitability of HR rice to soybeans improved to make HR rice optimal in year 6. As for the red rice impacts on rotation, HR rice remained profitable even when red rice density reached 1.562 in year 5. The cost savings on technology fee and the early adoption improved the average annual gross margin to $107 per acre compared to $104 in the baseline.

The second cost scenario increased the technology fee to $35 per acre. The higher fee reduced HR rice from four to three years in the planning period, with soybeans replacing HR rice in year 2. Changes in optimal solution as the technology fee changes suggest that there exists maximum red rice density that allows rice in the optimal rotation cycle. This threshold of red rice density to switch from soybeans to HR rice is higher under the low cost HR rice technology but declines as the level of the technology fee increases. For instance, in the low cost scenario a density of 1.562 red rice plants per square meter was found adequate for selecting HR rice but at $25 technology fee HR rice enters the solution only if red rice density does not exceed 0.952 red rice plants per square meter. The threshold decreased to 0.659 red rice plants per square meter in the high cost scenario. As a result in the high cost scenario, HR rice was not optimal in year 3 due a 0.731 red rice density in year 2, requiring two consecutive years of soybeans to reduce red rice before alternating HR rice with soybeans between year 4 and 9. As anticipated, the high cost scenario results in a reduced average annual gross margin of $92 per acre, a decline of $8 per acre compared to the baseline.

## Conclusion

HR rice technology can provide greater flexibility in rice farming through various rotation schemes. This research suggests that HR rice can alter the current rice-soybeans rotation system but the cost of the technology is an important consideration in the decision to adopt. While the baseline scenario suggests that HR rice technology is beneficial, the cost scenarios imply that a high technology fee could delay adoption.

The results provide some broad implications for the future of rice production in the southern United States. First, as a result of shorter rotations rice supply can increase. Given the low price elasticity of demand for rice, a supply shift will improve the welfare of early adopters and make non-adopters worse off. Herbicide resistant rice is likely to alter the use of common resources, such as water for irrigation. Rice requires substantially more water than soybeans, thus, intensive rice production will increase the demand for irrigation water. This could pose a problem as most rice farms in the southern US rely on underground water aquifers with little or no recharge. The last implication relates to the net effects of HR rice adoption on chemical use. While HR rice requires less herbicide applications, rice production, in general, requires more nitrogen than soybeans. The displacement of soybeans by rice results in a new pattern of chemical usage with more nitrogen and less herbicides in the rotation cycle. Understanding the net effect this new chemical use pattern is an area for further study.

Three limitations are apparent in this study. First, the study does not address differences across regions, soils, and climate, nor does it discuss how the control of red rice affects management costs. Second, the study used experimental data and a crop enterprise approach to identify the optimal rotation scheme among conventional rice, HR rice, and soybeans. As producers typically diversify crops to reduce production and market risks, a whole farm approach would be more appropriate to fully analyze the effects of HR rice on crop rotation. Third, the study does not account for the risk of technology adoption, especially GMO technology. Consumer acceptance of HR rice, in addition to the risk of yield drag between conventional and HR rice can discourage adoption. This study demonstrates the importance of red rice dynamics and technology fees on the adoption of HR rice in terms of net returns and crop rotation system.

## Endnotes

[1] Rice producing states include Arkansas, Louisiana, Mississippi, Missouri, and Texas.

[2] The competition coefficients used in the study are as follows: $a_r = 0.00745$; $a_{rr} = 0.00154$; $a_{rc} = a_{rh} = 0.00049$; $a_c = a_h = 0.001109$; $a_{cc} = a_{hh} = 0.000112$; $a_{cr} = a_{hr} = 0.000448$.

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**Appendix 1: Baseline Values for Parameters in the Programming Model.**

| Parameters | Description | Values |
|---|---|---|
| **Yield** | | |
| $Y_{st}$ | Soybean Yield | 45 bushels per acre |
| **Prices** | | |
| $P_{rt}$ | Conventional Rice Price | \$6.50 per cwt |
| $P_{ht}$ | Hr Rice Price | \$6.50 per cwt |
| $P_{st}$ | Soybean Price | \$5.40 per bushel |
| **Production Costs** | | |
| $C_{ct}$ | Production Cost for Conventional Rice | \$370 per acre |
| $C_{ht}$ | Production Cost for HR Rice | \$358 per acre |
| $C_{st}$ | Production Cost for Soybeans | \$207 per acre |
| crfr | Extra Fungicide Cost for Rice Follow Rice | \$8.40 per acre |
| techfee | Technology Fee | \$25 per acre |
| **Density** | | |
| $D_{r0}$ | Initial Red Rice Density | 1.474 per $m^2$ |
| $D_{ct}$ | Conventional Rice Density | 400 seeds per $m^2$ |
| $D_{ht}$ | HR Rice Density | 400 seeds per $m^2$ |
| $G_t$ | Germination Rate Year 1 | 80 percent |
| $dorm_{t-2}$ | Germination Rate Year 2 | 10 percent |
| $dorm_{t-3}$ | Germination Rate Year 3 | 10 percent |
| $S_t$ | Shatter Rate | 70 percent |
| $k_{ct}$ | Red Rice Kill Rate Under Conventional Rice | 75 percent |
| $k_{ht}$ | Red Rice Kill Rate Under HR Rice | 85 percent |
| $k_{st}$ | Red Rice Kill Rate Under Soybean | 95 percent |
| dock | Limit Percent of Red Rice in Commercial Rice | 2.0 percent |
| **Discount rate** | | |
| d | Discount Rate | 5 percent |

**Appendix 2: Present Value Gross Margin For Baseline Optimal Rotation Cycle.**

| | | Gross Margin per Square Meter Dollars | | | Present Value Gross Margin |
|---|---|---|---|---|---|
| **Years** | **Crop in Rotation** | ***Revenue*** | ***Costs*** | ***Gross margin*** | ***Dollars per acre*** |
| **1** | Conventional Rice | 0.130 | 0.091 | 0.039 | 157.83 |
| **2** | Soybeans | 0.061 | 0.051 | 0.010 | 38.54 |
| **3** | HR Rice | 0.131 | 0.095 | 0.036 | 132.14 |
| **4** | Soybeans | 0.061 | 0.051 | 0.010 | 34.96 |
| **5** | HR Rice | 0.130 | 0.095 | 0.035 | 116.53 |
| **6** | Soybeans | 0.061 | 0.051 | 0.010 | 31.71 |
| **7** | HR Rice | 0.129 | 0.095 | 0.034 | 105.70 |
| **8** | Soybeans | 0.061 | 0.051 | 0.010 | 28.76 |
| **9** | HR Rice | 0.129 | 0.095 | 0.034 | 93.13 |
| **Total Gross Margin** | | | | | 740.39 |
| **Average Annual Gross Margin** | | | | | 104.17 |