The Benefits of Public Rice Breeding

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Selected Paper prepared for presentation at the Southern Agricultural Economics Association (SAEA) Annual Meeting, Jacksonville, Florida, February 3-6, 2018

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Abstract

In this study, we estimate increases in producer revenue from the genetic gains of the rice breeding program at the University of Arkansas (UofA) Division of Agriculture from 1983 – 2016. Rice producers are paid based on both the quantity of rice and the quality of rice. Therefore, we implement a cluster specific fixed-effects model based on location and year to identify the contributions of the UofA breeding program for both paddy yields (quantity) and head rice yields (quality attribute) over time. Including spillover benefits from all UofA varieties, we find that on average US rice producers gain 30.9 million USD annually from the adoption of UofA rice varieties.

Keywords: *Rice Breeding, Public Agricultural R&D*

JEL codes: O32, Q11, Q17

1. Introduction

Researchers have extensively documented the economic benefits of agricultural research and development in both high and low-income countries (Alston 2010, Alston et al. 1995, Borlaug 1983, Evenson 2001, Fan et al. 2000, Morris and Heisey 2003, Norton and Davis 1981, Scobie and Posada 1978). Specifically, plant breeding programs play a crucial role in improving yields and managing evolving biotic and abiotic stresses in agricultural production (Russell 1978). When evaluating breeding programs in high-income countries, economists typically estimate benefits in terms of increased yields and subsequent returns on investment in the form of increased producer revenues. However, far less attention is given to the impacts of plant breeding and public research on decreasing food insecurity, which is likely due to lower food security concerns in most high income countries. A few studies demonstrate how investments in plant breeding in low and middle-income countries have affected food security (Rosegrant and Cline 2003, Scobie and Posada 1978), but most do not extend estimates of yield gain to analyze global trade implications and food insecurity reduction across borders. Fan et al. (2000) among others (Devereux and Maxwell 2001, Rosegrant and Cline 2003) have empirically shown the importance of government spending on agricultural research and development in impoverished areas to improve food security, which will be all the more important in coming decades as population growth increases food demand and resources for food production become more scarce. Likewise, as public funds are becoming more scarce in high-income countries, metrics of how public breeding programs in high-income countries impact global trade and food security are important for both maintaining support for public plant breeding and for alleviating food insecurity.

Rice consumption accounts for more than half of the daily caloric intake of over three billion people globally, most of whom are located in rapidly growing low-income countries (Muthayya et al. 2014). Global rice supply must increase by approximately 30% by 2050 to meet projected demand (Mohanty et al. 2010, Ray et al. 2013). Thus, public breeding could help meet this projected demand. Many studies have investigated public breeding benefits in both high (Nalley et al. 2016; Nalley et al. 2011; Taylaran et al. 2009) and low-/middle-income countries (Peng et al. 2000; Laborte et al. 2012; Zhang et al. 2010; Breseghello et al. 2011, and Aggarwal et al. 2008) by quantifying the yield increase associated with genetic gains for rice. In their meta-analysis Fischer et al. (2014) analyzed 13 global case studies in rice growing environments to estimate and compare growth in yield potential attributed to rice breeding. They found the average growth rate associated with genetic gains to be 0.8% annually, ranging from 0.3% (in Punjab, India; Pathak et al. 2003) to 1.3% (in Indonesia; Brennan and Malabayabas, 2011). The authors concluded that there is no empirical evidence that rice breeding has plateaued; however, they also state that recent progress in genetic gains is “definitely lacking”. While many existing studies analyzed the genetic impact of rice breeding in terms of yield gains, few have estimated how those yield gains are distributed globally in terms of reductions to food insecurity.

Rice is unique compared to other major row crops because it requires extensive postharvest milling before pricing and exporting. As a result, profitability and the volume of rice exported is based on both the total production yield and quality, which consists of head rice yield, color, and kernel integrity, among other attributes (USDA-FGIS 2009). Rice kernel integrity is a function of how much production (percentage) becomes milled rice yield (MRY), where MRY is an estimate of the quantity of whole kernels plus broken kernels produced in the milling of rough rice. In other words, MRY is all rice kernel content remaining after the husk, bran, and other foreign material is removed. Whole kernels (also called head rice yield or HRY) are those that are greater than three fourths of their unbroken length; the rest are categorized as broken grains or simply brokens (Lyman & Nalley 2013). A small percentage, set by each importing country, of broken rice is allowed in exports but a large portion of broken rice is ground into flour, used in breweries, or made into pet food, which makes it less favorable due to its lower value. The composition of broken rice (second heads, screenings, brewers' rice, etc.) also affects the price farmers receive, but these are treated as a single factor for this study. Currently, brokens are valued at 68.5% of HRY (Lyman et al. 2013). Milling quality is specifically important to this study because if the percentage of broken rice is increasing over time, then the percentage of exportable yield is decreasing. Thus, brokens both negatively affect domestic producer revenue as well as the total volume of rice exported. Ideally, 100 percent of rice would be HRY, and the next best would be the lowest percentage of brokens.

As an illustrative example, if 100 kg of rice is delivered to a mill, the rough/paddy rice would be initially cleaned to remove foreign materials (dockage), and then milled to remove the hull and bran. Because the hull, bran, and dockage have mass, the resulting mass of rice would be less than 100 kg. The rice futures market is traded on an average of 70% milled rice, so the milled rice yield (MRY) would be 70 kg for this example. Of this 70 kg of remaining mass, some kernels would stay intact and some would break (brokens) during the milling process. The rice futures market is traded assuming that 55% of the initial mass is whole kernels (HRY). Thus, in this example, there would be 55 kg of head rice for a head rice yield (HRY) of 55%. The difference between MRY and HRY is the percentage of the initial mass which are broken kernels. Thus 70%-55% results in 15% (in this case 15 kg of brokens). The ratio 55/70

(HRY/MRY) is the standard upon which the futures contracts are bought and sold in the Mid-South.

The purpose of this study is two-fold: (1) to estimate the increases in genetic yield enhancements from University of Arkansas rice variaties, to domestic (US) producer revenues using empirical data from 1983-2016, and (2) estimate the changes in HRY and its effects on producer welfare from 1983-2016 associated with University of Arkansas rice varieties. This analysis will provide key insights for public funding agencies regarding the importance of public plant breeding in terms of economic enhancement for rice producers.

Data

This study is comprised of three primary methodological components: (1) varietal rice yield data was collected and examined for the UofA rice breeding program; (2) several multiple regression models were implemented to estimate genetic enhancements through time for total yield, HRY, and MRY; and (3) a benefit-cost ratio was used to calculate the returns-on-investment from the UofA public rice breeding program.

A total of 1,813 yield (kg ha^{-1}) observations of UofA inbred non-fragrant long grain rice varieties were obtained from Arkansas Rice Performance Trials (ARPT) between 1992 and 2016 across seven locations in Arkansas and one in Missouri (UACES/AAES, various years). The data set included 17 long grain rice varieties commercially released between 1983-2016 (Table A1). Cultural practices varied somewhat across the ARPT locations over time, but overall the rice variety trials were conducted under conditions for high yield. Data on the historical area seeded to UofA rice cultivars by state were collected from various annual publications of the Proceedings of the Rice Technical Working Group (RTWG 2001-2017). Further, the data include milling quality information on kernel integrity, i.e., the percent of MRY and HRY discussed above, in addition to the field (paddy) yields.

Although a gap between experimental and actual yields exists, Brennan (1984) concluded that the most reliable sources of relative yields are cultivar trials outside actual farm observations. Although yields are often greater in experimental test plots as compared with producers' fields, the relative yield differences between varieties are assumed to be comparable. The rice milling industry requires a minimum milling benchmark of 55/70 (HRY/MRY) and the average milling rate for the data set was 60/70. Producer revenue decreases when the 55/70 milling benchmark is not met because the higher percentage of broken rice decreases the overall value. If broken rice increases nationwide it can negatively affect exports due to strict standards on broken rice percentages in many rice importing countries.

Methods

To estimate changes in genetic gains for yield, MRY, and HRY, several panel fixed-effects regression models were implemented with cluster-robust standard errors for years based on procedures outlined in Cameron and Miller (2015). Observations for yield (n=1,812), HRY (n=1,012), and MRY (n=1,012) included rice variety, year, and location of the research trials in the Arkansas Delta region, as well as the year the variety was publically released (Release Year, *RLYR*) and whether the variety was semi-dwarf or not. The cluster-specific two way fixed effects (CSFE) regression equation (1) provides the platform to estimate yield, HRY, and MRY changes during the period of 1983-2016 while clustering standard errors on year. The CSFE equation (1) takes the following form:

$$y_{ilt} = \boldsymbol{x}'_{ilt}\boldsymbol{\beta} + \delta_l + \alpha_t + \mu_{ilt} = \boldsymbol{x}'_{ilt}\boldsymbol{\beta} + \sum_{h=1}^{l} \delta_l dh_{il} + \sum_{h=1}^{t} \alpha_t dh_{it} + \mu_{ilat} \, , \qquad (1)$$

where y_{ilt} is the yield observation, $\boldsymbol{x}'_{ilt}$ is a vector of variables that affect yield, including *RLYR*, *RLYR*^{2}, and semi-dwarf, δ_l is a vector for location factors, and α_t is a vector of observation year factors. In this case, $dh_{i\mathrm{l}}$ and $dh_{i\mathrm{t}}$ are one if the il^{th} or it^{th} observation are in the same cluster year *h* and are zero otherwise. Implicit in this model is the assumption that errors are uncorrelated across years but may be correlated within years due to common management practices or weather within a given year. Thus, the model controls for the effects of location and year as fixed effects vis-à-vis δ_{l} and α_{t}, respectively, and also addresses within-year correlations by clustering errors for location and year factors within each year. *RLYR* and $RLYR^2$ were estimated in separate models for paddy yield to elicit whether gains are linear or non-linear in nature. Ordinary Least Squares (OLS) was used in R Statistical Software to estimate parameters $\boldsymbol{\beta}$ with a cluster-robust variance estimator to obtain heteroscedasticity-consistent standard errors (Cameron and Miller 2015; Stock and Watson 2008). From these models, increases in rice volume (yield) and change in quality (milling yield) associated from the UofA breeding program are derived based on historical UofA varietal adoption from 1983-2016 in the US.

We also calculated the benefit-cost ratio (BCR) of public investments in the UofA rice breeding programs using equation (2). To do this, we follow the BCR as defined by Tassey (2003), which is calculated as a measure of gross research benefits via the following equation:

$$BCR = \frac{\sum_t \frac{B_t}{1+4^t}}{\sum_t \frac{C_t}{(1+r)^t}}, \tag{2}$$

where B_t is the total economic benefit in year *t*, $C_{t\text{-}10}$ represents annual breeding costs 10 years prior to release, which represents the traditional 10 year lag from an initial cross to a commercial release of a rice variety, and *r* is the assumed rate of discount of 4 percent.

Results

Table 1 shows the RLYR results from the paddy, HRY and MRY models. The full fixed effects results are presented in the appendix (Tables A2 and A3). The non-linear specification of RLYR on paddy yield (Paddy Yield 2, Table 1) indicates that there is no concavity or convexity in the genetic gains overtime, thus genetic gains were assumed to be linear. The linear model (Paddy Yield 1, Table 1) suggests statistically significant and constant yield gains through time ($p < 0.05$). The linear results suggest that on average, from 1983 to 2016 the UofA rice breeding program increased yields by 29.16 kg ha^{-1}. The average yield for the data set was 8,381.03 (kg ha^{-1}) resulting in a yearly increase of 0.35%. This result is in line with the findings of Fischer et al. (2014) who analyzed 13 global case studies in rice growing environments to estimate and compare growth in yield potential attributed to rice breeding. Their findings ranged from 0.3%-1.3%. These results are also similar to Nalley et al. (2011) who found that genetic gains from rice breeding in the USA resulted in a 0.42% annual increase. Furthermore, given insignificance of the non-linear specification for genetic gains (Table 1), we can conclude that the genetic gains from rice breeding from the UofA rice breeding program have not reached a genetic plateau. Thus, from the commercial release of Newbonnet in 1983 to the commercial release of Diamond in 2016, the UofA breeding program increased producer yields by 11.55% (33*.035%).

Table 1 also indicates that while paddy yield was increasing there was no statistical ($p > 0.1$) effect on MRY. Furthermore, Table 1 illustrates that HRY (quality), or the percentage of rice kernels that remain intact after milling, has actually increased, albeit marginally (0.000993%), over the test period. Given the small magnitude of this coefficient, the authors assume HRY to be constant over time in estimating the annual effects below. This is an important, but often overlooked, aspect of global rice trade, and ultimately the fight against global food insecurity. If HRY decreases, then the amount of brokens increases resulting in less volume (of a given paddy rice yield) being exported. Many countries, even those who are food insecure, require a maximum percentage of brokens to be allowed in international trade contracts. Although brokens may still be exported (and in a few cases are preferred), it is at a significantly lower price and often for processing into other food items rather than for raw consumption. Broken rice not exported from the US is often used to make pet food. In other words, brokens generally never reach the plates of food insecure people. As such, higher yields at the expense of HRY has been a consistent criticism of hybrid rice in the United States because it could lead to a loss in US rice exports (Lyman and Nalley 2013, Lyman et al. 2013). Here, our results suggest that paddy yield (quantity) is increasing with no change in milled rice yield, and head rice yield (quality) is actually marginally increasing. In terms of battling global food insecurity the importance of HRY not decreasing is that a larger percentage (in terms of volume) of paddy rice yield can be exported for consumption, driving global prices down and reaching the plates of more consumers.

Using the coefficients from Table 1, yearly genetic gains were estimated based on the actual hectares planted to UofA rice varieties (Table 2). Further, year specific gains were used to estimate the total rice supply increase due to the UofA rice breeding program. An important feature of the calculation of genetic gains associated with a breeding program is to take into account the cumulative effects of the breeding program over the entire period. That is, the yields gained via the breeding program in 2016 are those observed in 2016 plus those seen in 2015. So, the genetic gains for 2016 would be the sum of the year specific genetic gain from 1983 to 2016 from the release of Newbonnet (1983) to Diamond (2016). Table 3 shows the total gain (kg) by state (several rice producing states surrounding Arkansas also sow UofA varieties) associated with the UofA breeding program from 1983-2016 based on cumulative gains and hectares sown to UofA varieties. An estimated 4.157 million additional metric tonnes were added to the global food supply through the genetic gains attributed to the UofA breeding program. Furthermore, Table 4 illustrates that this estimated increase in yield attributed to the UofA breeding program is associated with an average yearly increase in producer revenue of $30,916,290 (2016 USD). Thus, over the time period of this study, producers who adopted UofA rice varieties experienced a cumulative revenue gain of $1,051,153,857 (2016 USD).

Using revenue benefits calculated above (Table 4) and actual costs of the UofA rice breeding program from 1973-2016 (Table 5), we determine the BCR both on returns in the form of revenue and additional mouths fed internationally via the increased yield attributable to the UofA breeding program. Notably, cost data for the UofA breeding program was not available from 1973-1984 and as such a linear extrapolation of costs from 1985-1990 was used as a proxy. This most likely overestimated the actual cost—thus providing a conservative BCR. Assuming a discount rate of 4% to calculate the discounted costs and benefits, and accounting for the 10 year lag between the initial cross of a variety and its commercial release, the BCR was estimated to be 20.27:1. That is, for every dollar invested in the UofA rice breeding program, $20.27 benefits result. Regardless of the metric for BCR, increased revenue or additional people fed, the returns to the UofA rice breeding program are both substantial and sustained.

Conclusions

Using multiple regression analysis we find that on average between 1983 and 2016 the UofA rice breeding program increased yields by 29.16 kg/ha resulting in a yearly increase of 0.35%. These results are consistent with those found by Fischer, Byerlee, and Edmeades (2014) who found rice breeding yield gain contributions to range between 0.3% and 1.3% annually across 13 case studies. Furthermore, the estimates from our study suggest that this yield increase was not at the expense of milling yields with even a slight increase in HRY. Results also suggest that genetic yields have not plateaued, which is encouraging for both returns-on-investment, as well as alleviating global food insecurity. Using actual adoption rates of UofA varieties, we find that the average yield enhancement due to the UofA rice breeding program to be 122,292 metric tons. This results in a total revenue gain for US rice producers of 1.051 billion (2016 USD) from 1983-2016.

From this study, we may conclude that the UofA public rice breeding program provides significant benefits to rice farmers in the USA in the form of increased yields, consistent quality, and subsequent improvements to revenue. Public breeding programs, especially those focused on rice and other staple foods, must continue if we are to meet growing global food demand and maintain the genetic enhancements that directly benefit producers.

Acknowledgements

This work was supported by the National Science Foundation Graduate Research Fellowship Program [Grant No. DGE-1450079] and the University of Arkansas Division of Agriculture.

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Tables

Table 1. Effects of Release Year (RLYR) on Paddy Yield, HRY, and MRY

	Paddy Yield (kg/ha)		HRY (%)		MRY (%)	
	(1)	(2)†	(1)	(2)‡	(1)	(2)
RLYR	29.16 [14.04]*	-1469.19 [4427.70]	0.00 [0.05]	-29.50 [14.38]*	-0.01 [0.02]	9.68 [5.68]
RLYR^2	-	0.38 [1.11]	-	0.01 [0.00]*	-	0.00 [0.00]

Note: The full fixed effects results can be found on Tables (A2 and A3). The mean RLYR was 1995.18.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$
† Marginal effect of RLYR was 28.55.
‡ The marginal effect of RLYR on HRY was 0.000993%. Given the small magnitude of this estimated coefficient, the authors assume that HRY remains constant overtime because the estimated annual effects are so marginal that they are lost in rounding. These notations will be used for all tables and appendices.

Table 2. Cumulative Genetic Gain and Total Hectares Associated with the UofA Rice Breeding Program

Year	Genetic Gain (kg/ha)	Cumulative Genetic Gain (kg/ha)	Rice Price (2016 USD/kg)	Hectares of UofA Varieties in Arkansas	Hectares of UofA Varieties in Missouri	Hectares of UofA Varieties in Mississippi	Hectares of UofA Varieties in Louisiana	Hectares of UofA Varieties in Texas	Total UofA Rice Hectares
1983	19.41	19.41	$0.48	199,955	-	-	-	-	199,955
1984	20.16	39.57	$0.43	274,580	-	-	-	-	274,580
1985	20.91	60.48	$0.33	331,438	-	-	-	-	331,438
1986	21.66	82.14	$0.18	359,119	-	-	-	-	359,119
1987	22.41	104.55	$0.35	326,987	-	-	-	-	326,987
1988	23.16	127.71	$0.30	323,182	-	-	-	-	323,182
1989	23.91	151.62	$0.31	369,074	-	-	-	-	369,074
1990	24.66	176.29	$0.27	320,512	1,973	26,934	64,910	838	415,166
1991	25.41	201.70	$0.30	351,834	8,283	14,842	61,189	1,098	437,246
1992	26.16	227.86	$0.22	424,435	17,992	15,864	40,792	2,662	501,746
1993	26.92	254.78	$0.29	378,301	17,847	13,759	53,815	3,467	467,189
1994	27.67	282.45	$0.23	316,060	16,911	9,178	32,881	1,139	376,169
1995	28.42	310.86	$0.32	227,757	13,051	5,868	7,446	1,010	255,133
1996	29.17	340.03	$0.34	217,802	8,283	7,649	26,197	10,447	270,377
1997	29.92	369.95	$0.33	277,210	10,220	4,497	13,944	10,479	316,350
1998	30.67	400.62	$0.29	351,774	29,222	7,922	2,732	28,398	420,047
1999	31.42	432.04	$0.18	339,512	37,636	3,933	13,925	14,747	409,753
2000	32.17	464.21	$0.17	256,409	24,010	1,896	4,632	6,352	293,300
2001	32.92	497.13	$0.12	327,998	25,275	5,036	16,100	6,227	380,636
2002	33.67	530.80	$0.12	316,287	30,064	5,201	19,777	5,995	377,324
2003	34.42	565.22	$0.22	335,627	46,011	4,470	6,279	3,530	395,917
2004	35.17	600.39	$0.20	339,815	54,175	7,323	3,113	4,826	409,252
2005	35.92	636.32	$0.20	378,531	48,951	8,365	4,225	4,310	444,382
2006	36.67	672.99	$0.25	255,519	44,152	-	1,176	1,791	302,638
2007	37.42	710.42	$0.31	273,467	49,271	5,844	984	1,160	330,726
2008	38.18	748.59	$0.38	286,672	28,686	16,823	18,586	-	350,767
2009	38.93	787.52	$0.33	194,024	17,393	43	6,446	-	217,907
2010	39.68	827.19	$0.27	152,087	8,085	614	-	-	160,786
2011	40.43	867.62	$0.32	30,449	3,911	-	-	-	34,360
2012	41.18	908.80	$0.33	64,735	6,669	179	-	-	71,583
2013	41.93	950.73	$0.35	75,301	2,115	158	13	-	77,587
2014	42.68	993.41	$0.27	92,262	845	215	-	-	93,322
2015	43.43	1036.84	$0.25	102,923	845	-	-	-	103,768
2016	44.18	1081.02	$0.21	160,653	1,215	-	-	-	161,868

Note: Coefficients for year are derived based on the regression in appendix table A2. The mean RLYR was 1995.18.

Table 3. Additional Rice Output (kg/yr) Attributed to the UofA Rice Breeding Program by States in the Mid-South of the United States: 1983-2016

Year	Additional kg in Arkansas	Additional kg in Missouri	Additional kg in Mississippi	Additional kg in Louisiana	Additional kg in Texas	Total Additional kg
1983	3,880,821	-	-	-	-	3,880,821
1984	10,864,439	-	-	-	-	10,864,439
1985	20,044,487	-	-	-	-	20,044,487
1986	29,497,210	-	-	-	-	29,497,210
1987	34,186,096	-	-	-	-	34,186,096
1988	41,273,886	-	-	-	-	41,273,886
1989	55,960,202	-	-	-	-	55,960,202
1990	56,501,858	347,857	4,748,082	11,442,696	147,750	73,188,245
1991	70,965,106	1,670,627	2,993,611	12,341,758	221,493	88,192,594
1992	96,713,856	4,099,826	3,614,782	9,295,153	606,643	114,330,260
1993	96,383,538	4,546,977	3,505,606	13,711,043	883,331	119,030,495
1994	89,269,921	4,776,569	2,592,371	9,287,044	321,632	106,247,538
1995	70,801,303	4,056,985	1,824,127	2,314,755	314,110	79,311,281
1996	74,059,277	2,816,372	2,600,744	8,907,892	3,552,133	91,936,416
1997	102,553,329	3,780,849	1,663,610	5,158,582	3,876,576	117,032,945
1998	140,926,352	11,706,979	3,173,579	1,094,338	11,376,759	168,278,006
1999	146,681,222	16,260,032	1,698,998	6,016,212	6,371,440	177,027,904
2000	119,026,714	11,145,604	880,302	2,150,221	2,948,684	136,151,525
2001	163,056,696	12,564,922	2,503,489	8,003,921	3,095,500	189,224,527
2002	167,884,346	15,957,992	2,760,696	10,497,605	3,182,116	200,282,754
2003	189,702,921	26,006,467	2,526,399	3,548,967	1,995,357	223,780,110
2004	204,022,579	32,526,015	4,396,557	1,869,272	2,897,317	245,711,740
2005	240,865,745	31,148,231	5,322,701	2,688,646	2,742,378	282,767,701
2006	171,961,811	29,713,824	-	791,177	1,205,549	203,672,361
2007	194,274,974	35,003,132	4,151,433	699,189	823,956	234,952,683
2008	214,600,079	21,473,852	12,593,733	13,913,244	-	262,580,909
2009	152,797,338	13,697,611	34,037	5,076,568	-	171,605,553
2010	125,805,203	6,688,251	507,500	-	-	133,000,955
2011	26,418,133	3,393,170	-	-	-	29,811,303
2012	58,831,542	6,060,515	162,742	-	-	65,054,799
2013	71,590,985	2,010,687	150,051	12,712	-	73,764,435
2014	91,654,022	839,174	214,075	-	-	92,707,271
2015	106,714,143	876,113	-	-	-	107,590,256
2016	173,668,730	1,313,733	-	-	-	174,982,463
TOTAL						**4,157,924,171**

Table 4. Additional Producer Revenue Gains (2016 USD/yr) Attributed to the UofA Rice Breeding Program by States in the Mid-South of the United States: 1983-2016

Year	Additional Gains in Arkansas	Additional Gains in Missouri	Additional Gains in Mississippi	Additional Gains in Louisiana	Additional Gains in Texas	Total Gains
1983	$1,871,995	-	-	-	-	$1,871,995
1984	$4,673,027	-	-	-	-	$4,673,027
1985	$6,540,191	-	-	-	-	$6,540,191
1986	$5,228,423	-	-	-	-	$5,228,423
1987	$11,983,409	-	-	-	-	$11,983,409
1988	$12,575,266	-	-	-	-	$12,575,266
1989	$17,617,377	-	-	-	-	$17,617,377
1990	$15,172,033	$93,408	$1,274,968	$3,072,624	$39,674	$19,652,707
1991	$21,058,318	$495,745	$888,330	$3,662,316	$65,726	$26,170,435
1992	$21,513,627	$911,991	$804,094	$2,067,671	$134,945	$25,432,328
1993	$28,048,559	$1,323,215	$1,020,166	$3,990,049	$257,058	$34,639,047
1994	$20,704,019	$1,107,811	$601,238	$2,153,907	$74,595	$24,641,570
1995	$22,445,739	$1,286,163	$578,293	$733,834	$99,581	$25,143,609
1996	$25,356,230	$964,262	$890,436	$3,049,862	$1,216,170	$31,476,960
1997	$33,393,660	$1,231,129	$541,709	$1,679,750	$1,262,300	$38,108,547
1998	$40,607,061	$3,373,294	$914,447	$315,327	$3,278,143	$48,488,272
1999	$26,484,525	$2,935,885	$306,768	$1,086,277	$1,150,417	$31,963,873
2000	$20,389,155	$1,909,231	$150,795	$368,331	$505,107	$23,322,618
2001	$19,303,972	$1,487,537	$296,383	$947,569	$366,470	$22,401,932
2002	$20,541,727	$1,952,563	$337,789	$1,284,449	$389,352	$24,505,880
2003	$42,198,688	$5,785,039	$561,988	$789,454	$443,859	$49,779,028
2004	$40,706,201	$6,489,529	$877,193	$372,954	$578,067	$49,023,944
2005	$47,366,758	$6,125,365	$1,046,720	$528,728	$539,295	$55,606,866
2006	$42,763,660	$7,389,268	-	$196,751	$299,797	$50,649,476
2007	$59,576,879	$10,734,153	$1,273,089	$214,415	$252,676	$72,051,214
2008	$81,517,137	$8,156,973	$4,783,806	$5,285,030	-	$99,742,945
2009	$50,461,640	$4,523,665	$11,241	$1,676,547	-	$56,673,093
2010	$34,530,409	$1,835,759	$139,296	-	-	$36,505,464
2011	$8,351,895	$1,072,725	-	-	-	$9,424,621
2012	$19,507,061	$2,009,514	$53,961	-	-	$21,570,536
2013	$24,858,371	$698,166	$52,102	$4,414	-	$25,613,053
2014	$24,934,488	$228,297	$58,239	-	-	$25,221,024
2015	$26,184,899	$214,975	-	-	-	$26,399,875
2016	$36,181,553	$273,699	-	-	-	$36,455,251
TOTAL						**$1,051,153,857**

Table 5. Benefit-Cost Ratio of the UofA Rice Breeding Program: 1973-2016

Year	Discounted Benefits 2016 USD	Discounted Costs 2016 USD	Year	Discounted Benefits 2016 USD	Discounted Costs 2016 USD
1973	0	1,395,699	1995	10,201,424	503,884
1974	0	1,226,823	1996	12,279,838	555,951
1975	0	1,055,108	1997	14,295,156	377,147
1976	0	95,859	1998	17,489,198	321,373
1977	0	868,784	1999	11,085,601	395,970
1978	0	781,906	2000	7,777,568	398,559
1979	0	687,988	2001	7,183,211	380,490
1980	0	580,749	2002	7,555,620	373,221
1981	0	499,362	2003	14,757,503	354,692
1982	0	442,986	2004	13,974,665	352,675
1983	1,216,012	410,704	2005	15,241,518	339,241
1984	2,918,759	379,019	2006	13,348,775	326,194
1985	3,927,869	210,394	2007	18,258,892	0
1986	3,019,284	224,693	2008	24,304,236	0
1987	6,653,962	211,759	2009	13,278,327	0
1988	6,714,037	295,183	2010	8,224,149	0
1989	9,044,290	317,373	2011	2,041,567	0
1990	9,701,129	426,026	2012	4,492,906	0
1991	12,421,599	411,537	2013	5,129,729	0
1992	11,606,983	421,465	2014	4,856,937	0
1993	15,200,778	348,036	2015	4,888,417	0
1994	10,397,643	310,089	2016	6,490,724	0
			TOTAL	**$329,978,308**	**$16,280,940**
			BCR	**20.27**	

Note: We assume a 10 year lag from initial cross to commercial release and a 4% discount rate.

Appendix

Table A1. Summary Statistics of Paddy and Milling Yields.

Variety	Release Year	Yield Obs.	Yield (kg/ha)	Yield Standard Deviation	Milling Obs.	MRY (%)	HRY (%)	MRY Standard Deviation	HRY Standard Deviation
Ahrent	2001	118	8173	1760	71	68.59	58.10	3.16	10.08
Alan	1990	107	7242	1394	24	71.69	61.38	1.49	3.40
Banks	2004	50	9845	1944	57	70.03	59.10	2.59	9.98
Cybonnet	2004	83	8891	1687	91	70.99	61.43	3.35	9.79
Diamond	2016	8	10078	1088	7	68.93	57.82	1.16	4.60
Drew	1996	145	8607	1440	96	71.19	61.17	2.58	9.32
Francis	2002	126	9886	1806	121	70.29	59.94	3.45	9.36
Katy	1989	145	7058	979	32	70.66	62.99	2.14	5.11
Kaybonnet	1994	88	8082	1485	45	71.62	63.26	2.24	11.45
LaGrue	1993	253	8823	1832	126	70.24	59.21	2.65	9.65
Millie	1990	119	7140	1133	25	72.17	64.95	1.65	2.88
Newbonnet	1983	159	7448	1265	23	72.19	64.66	1.97	4.43
Roy J	2010	46	10024	1825	42	68.92	58.83	4.32	8.10
Taggart	2009	56	9239	1533	52	69.23	54.03	3.65	11.14
Teabonnet	1984	92	7401	1296	10	71.70	61.95	1.03	1.82
Templeton	2009	40	8533	2029	40	68.92	56.46	4.30	10.51
Wells	1999	177	9510	1533	139	71.13	56.99	3.80	10.44
Average/Count	**1998**	**1,812**	**8587**	**1531**	**1,001**	**70.50**	**60.13**	**2.68**	**7.77**

Table A2. Paddy Yield (kg/ha) Regression Results for the UofA Rice Breeding Program: 1988-2016

	Yield (kg/ha)			Yield (kg/ha)	
Parameter	(1)	(2)†	Parameter	(1)	(2)†
Intercept	-49576.64 [27837.04]	1445737.30 [4426666.73]	2010	389.10 [332.33]	388.40 [333.57]
1989	-538.16 [85.99] ***	-538.22 [85.94] ***	2012	1334.10 [360.62] **	1327.91 [353.64] **
1990	-413.90 [105.30] ***	-408.87 [109.82] **	2013	1293.34 [352.71] **	1292.18 [353.21] **
1991	-828.51 [125.22] ***	-815.66 [138.85] ***	2014	1349.43 [413.68] **	1314.21 [356.43] **
1997	-1639.97 [220.67] ***	-1618.66 [251.76] ***	2015	-268.18 [364.04]	-277.62 [348.28]
1998	-1013.40 [152.95] ***	-992.17 [203.24] ***	2016	145.35 [393.87]	109.98 [351.49]
1999	-262.49 [166.50]	-239.82 [220.51]	CottonBranch	-1315.84 [508.15] **	-1316.75 [507.97] **
2000	-203.17 [258.05]	-170.79 [318.99]	Keiser	-448.79 [446.10]	-448.60 [446.38]
2001	368.66 [214.81]	400.01 [288.93]	Missouri	-1118.01 [916.40]	-1117.81 [916.72]
2002	956.86 [297.15] **	988.76 [361.11] **	Newport	-190.59 [442.51]	-190.18 [442.80]
2003	1781.49 [401.21] ***	1813.86 [443.24] ***	PineTree	-292.38 [517.60]	-292.42 [517.74]
2004	-199.67 [301.11]	-170.61 [354.37]	Rohwer	-240.50 [517.16]	-240.55 [517.35]
2005	1653.36 [335.00] ***	1680.62 [376.07] ***	Stuttgart	-278.79 [401.38]	-278.86 [401.47]
2006	1189.11 [291.51] ***	1216.52 [344.83] **	SemiDwarf	-217.14 [207.56]	-225.42 [202.72]
2007	563.47 [336.31]	590.87 [377.60]	RLYR	29.16 [14.04] *	-1469.19 [4427.70]
2008	-288.20 [306.59]	-258.19 [348.91]	RLYR2	-	0.38 [1.11]
2009	-137.79 [287.38]	-122.56 [323.69]			

Note: The average Release Year (RLYR) in dataset was 1995.181.
†Marginal effect of RLYR =28.55 kg/ha; * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table A3. MRY and HRY Regression Results for the UofA Rice Breeding Program: 1988-2016

	HRY (%)		MRY (%)	
Parameter	(1)	(2)†	(1)	(2)
Intercept	67.77 [98.59]	29555.16 [14347.33] *	101.27 [33.51] **	-9591.00 [5678.86]
1993	-2.84 [0.37] ***	-2.80 [0.37] ***	-1.49 [0.09] ***	-1.50 [0.09] ***
1994	0.84 [0.17] ***	1.36 [0.20] ***	-0.20 [0.06] **	-0.38 [0.11] **
1995	-9.81 [2.18] ***	-9.49 [2.20] ***	-2.63 [0.48] ***	-2.73 [0.49] ***
1996	0.63 [0.25] *	1.14 [0.21] ***	0.41 [0.08] ***	0.25 [0.12] *
1997	0.34 [0.73]	0.85 [0.76]	1.39 [0.18] ***	1.22 [0.22] ***
1998	0.68 [1.62]	1.19 [1.60]	-2.85 [0.45] ***	-3.02 [0.45] ***
1999	-3.30 [1.85]	-2.77 [1.83]	0.41 [0.51]	0.24 [0.50]
2000	-4.36 [2.32]	-3.58 [2.34]	-0.85 [0.62]	-1.11 [0.65]
2001	-4.70 [2.37] *	-3.89 [2.38]	-4.37 [0.55] ***	-4.63 [0.58] ***
2002	-3.63 [2.39]	-2.75 [2.40]	-1.30 [0.56] *	-1.58 [0.60] **
2003	-1.01 [3.43]	-0.13 [3.43]	-1.25 [0.96]	-1.54 [1.00]
2004	-6.20 [2.44] *	-5.34 [2.41] *	-1.06 [0.75]	-1.34 [0.76]
2005	-8.16 [3.77] *	-7.27 [3.76]	-1.81 [1.12]	-2.10 [1.14]
2006	-7.03 [2.39] **	-6.14 [2.37] **	-2.62 [0.73] **	-2.91 [0.75] **
2007	-13.90 [3.74] **	-13.02 [3.72] **	-3.05 [1.11] **	-3.34 [1.12] **
2008	-7.49 [3.46] *	-6.61 [3.45]	-0.53 [1.10]	-0.82 [1.10]
2009	-1.08 [1.04]	-0.37 [0.98]	-0.84 [0.32] **	-1.08 [0.32] **
2010	-18.61 [3.41] ***	-18.03 [3.41] ***	-6.53 [1.00] ***	-6.72 [1.00] ***
2012	-7.08 [3.48] *	-6.57 [3.49]	-0.80 [1.01]	-0.97 [1.01]
2013	-1.88 [2.18]	-1.30 [2.17]	-2.28 [0.66] **	-2.47 [0.66] **
2014	-3.37 [1.18] **	-3.30 [1.12] **	-2.07 [0.29] ***	-2.09 [0.28] ***
2016	-13.08 [3.61] **	-12.96 [3.65] **	-2.98 [1.06] **	-3.02 [1.04] **
Corning	1.74 [3.05]	1.74 [3.05]	1.35 [0.95]	1.35 [0.95]
Keiser	-3.11 [1.62]	-3.10 [1.62]	-2.84 [1.39] *	-2.84 [1.39] *
Missouri	0.53 [3.30]	0.53 [3.31]	0.49 [0.94]	0.49 [0.94]
Newport	-1.71 [1.97]	-1.71 [1.97]	-0.92 [0.48]	-0.92 [0.48]
Pinetree	-0.62 [3.75]	-0.61 [3.75]	-0.26 [0.86]	-0.26 [0.86]
Rohwer	-10.63 [9.38]	-10.64 [9.38]	-2.25 [2.57]	-2.25 [2.57]
Stuttgart	-1.14 [2.83]	-1.14 [2.83]	-1.10 [0.95]	-1.10 [0.95]
Semi-dwarf	4.27 [0.57] ***	4.28 [0.63] ***	1.42 [0.12] ***	1.42 [0.11] ***
RLYR	0.00 [0.05]	-29.50 [14.38] *	-0.01 [0.02]	9.68 [5.68]
RLYR2	-	0.01 [0.00] *	-	0.00 [0.00]

Note: The average Release Year (RLYR) in the milling dataset was 1990.109.
* p < 0.10, ** p < 0.05, *** p < 0.01