The Impacts of Enhanced Rice Quality Genetics on Food Security and Producer Profitability

Lawton Lanier Nalley and Alvaro Durand-Morat

Increasing milling potential could provide more food for human consumption at current yields and input uses. We estimate the impact of increasing rice milling yields in Arkansas from 2004 to 2020 using actual yields by variety. The results suggest that a marginal 1% increase in the percentage of whole kernels could increase the number of rice rations by 0.89 million to 1.05 million annually, or up to 2.94 million and 3.5 million annually if the genetics of all Arkansas rice were least at the standard of a popular purebred variety. Improving rice milling yields can have significant food security implications.

Key words: broken rice, rice breeding

Introduction

Rice is unique among the major global staple crops (rice, wheat, and maize) as producers derive a substantial portion of their revenue from production quality attributes. One of the largest drivers of rice price, both to producers and importers, is the percentage of broken kernels relative to whole kernels. For instance, in December 2020 the average free on board (FOB) price for US No. 2 (4% broken) was US$550/metric ton, relative to US$525/metric ton for US No. 3 (15% broken), and US$465/metric ton for US No. 5 (20% broken) (Creed Rice Co., 2020). Rice that contains more than 20% broken kernels is typically not priced by established contracts and enters specialty markets (e.g., pet food, rice flour) on a case-by-case basis at a substantial price discount. Broken rice is either mixed with whole kernels (at various ratios) and sold for human consumption, milled into rice flour, or used in the pet food and brewing industries in the United States. The USDA reported that 10% of rice consumed in the United States, the majority of which is broken rice, is used for the pet food or brewery industries (US Department of Agriculture, 2016). There is also evidence of a growing use of broken rice as animal feed globally (Skorbiansky, Childs, and Hansen, 2018).

Beyond market motivations, there are sustainability issues with the production of large amounts of broken kernels being funneled into nonfood uses. Irrigated paddy rice is a water-intensive crop, accounting for approximately 25% of total global annual freshwater usage (Shew et al., 2019) and 34%–43% of total global irrigation use (International Rice Research Institute, 2021). Growing 1 kg of rice, on average, takes 2–3 times more water than other cereal grain crops (Tuong, Bouman, and Mortimer, 2005; Grassi et al., 2009). Given that two-thirds of the global population are now confront water scarcity (Mekonnen and Hoekstra, 2016) and the fact that rice uses such large amounts of water, it is becoming increasingly important for sustainably reasons that all rice go to human consumption and not to an alternative use because of poor quality.

There is often a positive correlation between broken rice (negative quality) and paddy yield (positive quantity) in the US Mid-South (defined here as Arkansas, Louisiana, Mississippi, Missouri,

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and Texas). Between 2003 and 2020 the correlation between yield (kg/ha) and broken percentage was 0.21, indicating that higher-yielding varieties can lead to a higher percentage of broken kernels (Arkansas Agricultural Experiment Station, 2021). This is problematic because this results in more broken kernels in both an absolute and a relative sense in the US rice supply. In October 2012, more than 50 rice producers from Arkansas, Louisiana, and Texas announced a mass tort action—similar to a class action lawsuit—against RiceTec, Inc. The producers claimed that

> The poor milling quality… of RiceTec's hybrid rice has caused the reputation of U.S. rice to suffer, even causing some markets to reject U.S. long grain rice and/or pay less for U.S. long grain rice because of its lesser quality and/or injured reputation. (Quoted in PRWeb, 2012)

Studies (Lyman et al., 2013) have shown that hybrid rice, on average, does not have a higher percentage broken compared to nonhybrid rice, but since hybrid rice has yields between 15% (Li et al., 2009) and 18% (Nalley et al., 2016) higher than nonhybrid rice, the broken rice supply has increased since the commercialization of hybrid rice in the United States started in 2002.

Physiology of Broken Rice

Many factors influence the eventual whole grain yield of rice, including genotype (Siebenmorgen, Bautista, and Counce, 2007), environment (Counce et al., 2005; Cooper et al., 2006; Lanning et al., 2011), the interaction of genotype and environment (Lyman et al., 2013), and the moisture content at which the paddy rice was harvested (Siebenmorgen, Bautista, and Counce, 2007; Nalley et al., 2016). Genetics is a major driver of broken kernels, with some varieties having a higher average whole grain yield than others through selective breeding. Rice varieties have differences in their genetic resistance to fissuring or stress fractures, which develop in the endosperm and can ultimately lead to a higher percentage of broken kernels. Producers can be penalized for broken kernels, and incorporating higher levels of resistance to fissuring (broken kernels) in a common practice in US breeding programs (Linscombe, 2006).

Breeders can struggle with genetic drag when only trying to increase the percentage of whole kernels (head rice yield, HRY) and maintaining paddy yield because rice quality consists of more than simply the percentage of broken kernels (e.g., chalk, length, width, aroma, and texture). However, with the increased availability of rice genome sequencing information and data on metabolic networks, genotype–phenotype associations, and gene regulatory networks, the rice breeding community is poised to make major advances in its understanding of the molecular, genetic, and biochemical bases of important grain quality traits, including increasing HRY (Fitzgerald, McCouch, and Hall, 2009). Breeders respond to the wants and needs of producers, who respond to wants and needs of the market. As such, a better understanding of the economic value of the broken market, and the implications of reducing broken relative to whole kernels, is important to both producers—who could benefit economically—and breeders—who could better evaluate the benefits of working on specific traits.

US Rice Production and Milling

Although a relatively small rice producer, the United States is one of a few net rice-exporting countries. From 2014 to 2016, the United States exported an annual average of 3.4 million metric tons (milled basis) of rice to over 120 countries, which accounted for 7.7% of global rice trade (US Department of Agriculture, 2022c). Globally, rice is thinly traded, with only around 6%–7% of the production being traded internationally (Lakkakula et al., 2015). Because of this, exporting countries are highly concentrated, with only five countries (India, Thailand, Vietnam, Pakistan, and the United States) accounting for over 90% of rice exports (Dorosh et al., 2010). As such, any supply shocks in these few rice exporting countries could have significant implications for global food security.

Even moderate supply shocks can have large impacts on low-income rice consumers because rice provides over 20% of the world's calories and is a staple for over half of the global population (Fukagawa and Ziska, 2019). Arkansas is the largest rice producer (over 480,000 hectares in 2021, worth US$1.3 billion) in the United States, with over 40% of the crop dedicated to the export market (US Department of Agriculture, 2022a).

   Understanding the milling process of rice is crucial to understanding how US rice producers are paid. After the hull and bran have been removed from rough or paddy rice through processing, the resulting polished or milled rice is then separated into broken kernels and head rice. As an illustrative example, if 1 metric ton of clean paddy rice is delivered to a mill, the rough/paddy rice would be initially milled to remove the hull and bran. Because the hull and bran have mass, the resulting mass of rice would be less than 1,000 kg. The rice futures market in the United States is traded on an average of 70% milled rice, which means that the milled rice yield (MRY) of a metric ton of paddy rice is 700 kg. Of this 700 kg of remaining mass, some kernels would remain intact and some would break, creating broken kernels, during the milling process. The rice futures market in the United States is traded assuming that 55% of the initial mass is whole kernels or head rice yield (HRY). Thus, in this example, 1 metric ton of paddy rice with a HRY of 55% will generate 550 kg of head rice. The difference between MRY and HRY is the percentage of the initial mass that are broken kernels, 15% (150 kg of broken kernels) in this example. The ratio 55/70 (HRY/MRY) is the standard on which futures contracts for paddy rice are traded in the United States.

   Rice producers are paid on the quantity of rice they bring to the mill, assuming a benchmark of a milling rate of 55/70 (quality). They are docked if their rice mills at less than 55/70 and receive a premium if it mills above that level. Table S1 in the online supplement (see www.jareonline.org) provides the historical prices for 100% whole rice and 100% broken rice in the Mid-South from 2004 to 2020. Broken kernels range from 50% to 72% of the value of whole kernels.

Economics of Broken Rice

One of the confounding factors of broken rice is the economic incentive given to producers regarding the quality/quantity trade-off. According to the University of Arkansas Rice Enterprise budget (University of Arkansas Cooperative Extension Service, 2020) and the loan values for whole and broken rice (US Department of Agriculture, 2022b), in 2020 the revenue loss due to a 5% increase of broken kernels (a relatively large increase) could be offset by a 2.25% increase in yield per acre.[1] Thus, producers can likely power through any reduction in quality dockage by simply choosing a high yielding variety of lower milling quality. As such, producers have historically gravitated toward quantity over quality. As rice yields have increased over time through improved genetics, broken percentages have remained constant, resulting in an increased volume of broken kernels. Shew et al. (2018) found that while progression of rice yield from varieties released by the University of Arkansas increased at 0.35% per year, there was no change in the percentage broken from 1983 to 2016. Increasing yields in a non-GM crop like rice is challenging and is typically the focus of most rice breeding programs. But as the Shew et al. (2018) study has illustrated, holding broken percentage constant while increasing paddy yields results in an increased volume of broken kernels.

The Food Security Issue of Broken Rice

While it is known that broken rice can affect producer profitability and affect US export markets, until now there has been no effort to quantify the volume of broken rice produced at a macro level. Importantly, this study will make a first effort to estimate the volume and value of the broken rice in Arkansas, the largest rice-producing state in the United States, from 2004 to 2020, based on

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   [1] Assuming a rice price of $5.00/bu, an average yield of 190 bu/acre, a baseline profitability of $120.24/acre, and a discount of 0.1125 cents/bushel for a 5% reduction (going from 55/70 to 50/70) in milling yields.

actual area planted to specific varieties and their respective yields and broken percentages. From these estimates we can simulate the impact of improving milling yield via enhanced genetics. While there is obvious genetic drag from moving genes around in a non-GM crop like rice, these estimates provide a snapshot to producers and rice breeders about the economic value of increased milling yields via enhanced genetics.

Beyond the economic value of reduced broken kernels there is also a food security component. Rice is the staple for 4 billion people globally (80% of the world's undernourished eat rice as their staple) and provides 27% of the calories in low- and middle-income countries (Consultive Group on International Agriculture, 2022). While decreasing the percentage of broken kernels does not increase net calories, it does increase calories that could end up on the plates of the poor. Many countries have import restrictions about the maximum acceptable percentage of broken kernels. As such, many of the broken grains produced in the United States and other rice exporting countries are used in the pet food and brewing industries. We estimate the impact of reducing broken kernels via enhanced genetics on the number of rice rations produced assuming the per capita global consumption of rice of 61.2 kg/year (Consultive Group on International Agriculture, 2022). While the total volume of rice would not change, the volume of head rice (whole kernels) would increase, allowing for access to increased exports for human consumption. Given that each country has different standards for rice, we estimate the increased rations, assuming of four consumption scenarios: 100% head rice, 95% head rice (5% broken), 90% head rice (10% broken) and 85% head rice (15% broken). These results have important implications for two of the UN's Sustainable Development Goals: Zero Hunger and Responsible Consumption and Production. Increasing the percentage of paddy rice that reaches the plates of the poor can reduce food insecurity. Moreover, increasing the number of rice rations produced from every metric ton of rice can help make rice production systems environmentally more sustainable by using fewer production resources per rice ration produced.

Data and Methods

This study is comprised of three primary methodological components: (i) varietal rice yield, quality, and area data were collected and examined for all rice varieties planted in Arkansas from 2004 to 2020, (ii) several genetic quality enhancements were used to proxy the changes in the volume of milled rice; and (iii) the RiceFlow trade model was used to evaluate the impacts of genetic enhancements on food security in countries that import US rice.

Varietal Rice Paddy (Quantity) and Milled (Quality) Yield Data

Historical area harvested by rice variety was obtained for Arkansas from 2004 to 2020 (Hardke, 2018) and paired with yearly variety-specific yield and milling rates from the Arkansas Rice Performance Trials (Arkansas Agricultural Experiment Station, 2021). Although a gap between experimental and actual yields (and in this case milling yields) exists, Brennan (1984) concluded that the most reliable sources of relative yield ceilings (in our case quality ceilings) are cultivar trials. So, despite yields often being greater in experimental test plots compared with producers' fields, the relative yield differences between varieties are comparable. Importantly, while paddy (quantity) yield observations used in this study are likely larger than on-farm yields, milling yields are also likely better than on-farm milling rates. Given the economies of scale in rice production and the large rice farms that exist as a result, many producers start harvesting rice above the optimal harvest moisture content (HMC) and finish below the optimal HMC because of equipment and labor constraints. Because of this, producers often do not observe HRY up to the genetic potential of their chosen variety (Nalley et al., 2016). Given the size and homogeneity of a test plot, harvest can take place quickly and at the optimal HMC, increasing milling yields. Thus, importantly for this study, we are conservative in our estimates because there is likely a greater difference between on-farm milling head rice ceilings (milling to genetic potential) compared to test plot ceilings.

Empirical Framework

The volume (in paddy basis) of production of rice variety i in year t in Arkansas (QRI_{it}) was estimated as

$$(1) \qquad QRI_{it} = A_{it} \times Y_{it},$$

where A_{it} is harvested hectares in year t sown to variety i and Y_{it} is the yearly average yield of variety i in metric tons/hectare (mt/ha) from all Arkansas Rice Performance Trials (ARPT) test plots across Arkansas. The statewide volume of rice produced yearly (QR_t) was estimated as

$$(2) \qquad QR_t = \sum_i QRI_{it}.$$

The volumes of milled rice (QM_{it}), head rice (QH_{it}), and broken rice (QB_{it}) for rice variety i produced in Arkansas in year t were estimated, respectively, as

$$(3) \qquad QM_{it} = QRI_{it} \times MRY_{it},$$

$$(4) \qquad QH_{it} = QRI_{it} \times HRY_{it},$$

$$(5) \qquad QB_{it} = QM_{it} - QH_{it},$$

where MRY_{it} is the average milled rice yield (percentage) and HRY_{it} is the average head rice yield (percentage) for variety i across all ARPT test plots in year t.

   The price (US\$ per metric ton of paddy rice) for rice variety i in year t, PR_{it}, was estimated using the marketing year average price for long-grain rice in year t ($MYAP_t$) (US Department of Agriculture, 2022d), corrected by quality. The quality premium is estimated relative to a standard 55/70 paddy rice quality (i.e., paddy rice yielding 70% milled rice, 55% head rice, and, by difference, 15% broken rice). For instance, a paddy rice that mills a 70/58 quality will carry a premium for head rice ($P\%H_{it}$) of 3% (58% − 55%), and a premium for broken rice ($P\%B_{it}$) of −3% ([70% − 58%] − 15%). To obtain the economic value of the quality premium, $P\%H_{it}$ and $P\%B_{it}$ are multiplied by the USDA's year t loan rates (US Department of Agriculture, 2022b) for head rice (LRH_t) and broken rice (LRB_t), respectively, and added to $MYAP_t$ to estimate PR_{it}:

$$(6) \qquad PR_{it} = MYAP_t + LRH_t \times P\%H_{it} + LRB_t \times P\%H_{it}.$$

Thus, the value of rice variety i in year t in Arkansas was estimated as

$$(7) \qquad VRI_{it} = QRI_{it} \times PR_{it}.$$

The value to the total rice crop in Arkansas in year t was estimated as

$$(8) \qquad VR_t = \sum_i VRI_{it}.$$

   Among other quality attributes, milled rice (Harmonized System code 100630) is commercialized based on the percentage of broken rice, defined as

$$(9) \qquad \%B = (MRY - HRY)/MRY \times 100.$$

We estimated the quantity (in kilograms) of milled rice with a specific quality (as defined by the percentage of broken rice), $QM_{\%B}$, produced from 1 metric ton of paddy rice of a specific quality as

$$(10) \qquad QM_{\%B} = \frac{HRY}{100} \times 1000/(1 - \%B).$$

Table 1. Volume of Milled Produced, Broken Rice Used, and Rice Rations Produced, from 1 Metric Ton of 55/70 Paddy Rice under Different Milled Rice Quality Standards

Milled Rice Quality (% broken)	Milled Rice Production (kg)	Broken Rice Use (kg)	Broken Rice Surplus (kg)	Rice Rations Produced
21.4	700.0	150.0	0.0	11.4
15	647.1	97.1	52.9	10.6
10	611.1	61.1	88.9	10.0
5	578.9	28.9	121.1	9.5
0	550.0	0.0	150.0	9.0

Notes: Rice rations produced is estimated using an average global per capita consumption of 61.2 kg/year (Consultive Group on International Agriculture, 2022).

The surplus of broken rice, $QB_{\%B}$ (kilogram) generated by 1 metric ton of paddy rice used to produce $VMR_{\%B}$ was estimated as

$$(11) \qquad QB_{\%B} = \frac{(MRY - HRY)}{100} \times 1000 - \%B \times QM_{\%B}.$$

Using equations (10) and (11), we estimated that 1 metric ton of 55/70 paddy rice produces 700 kg of milled rice with 21.4% broken rice and 0 surplus of broken rice.[2] At the average global per capita consumption of 61.2 kg per year, 1 metric ton of 55/70 paddy rice can produce 11.4 rations per year of milled rice with 21.4% broken. However, if the goal is to produce milled rice with 10% broken, a common standard of commercialization, then according to equations (10) and (11), a metric ton of 55/70 paddy rice will yield 611.1 kilograms of milled rice (or 10.0 rice rations) and a surplus of 88.9 kilograms of broken rice. Table 1 reports the volume of milled rice and broken rice surplus produced for different milled rice quality standards. In the extreme case of 100% head rice (milled rice with 0% of broken), 1 metric ton of 55/70 paddy rice produces only 550 kg of milled rice or 9.0 rice rations per year and generates 150 kg of broken rice surplus.

Increased HRY through Genetic Improvements

Two scenarios were simulated from the baseline production in equations (1)–(5). The first scenario assumes an across-the-board improvement in milling quality resulting in a 1-percentage-point increase in *HRY* and no changes in *MRY* for each variety in each year, which consequently reduces the broken rice rate by 1 percentage point. Paddy rice production was assumed constant, which together with the assumption of no changes in *MRY*, results in no changes in milled rice production (*QM*) relative to the baseline. This scenario captures the impact of enhancements in milling quality through changes in *HRY*, a stated goal of many rice breeding programs. This scenario has the potential to change the value of the crop (*VR_t*) as the ratio of broken rice and whole rice changes, thus changing the price producers receive (*PR_{it}*). Moreover, the number of rice rations produced could change depending on the change in the quality of milled rice produced.

   In the second scenario, we use the University of Arkansas RoyJ variety as our benchmark for *MRY* and *HRY*. RoyJ was selected from among the progeny of a cross made in the year 2000 to combine desired genes from 12 parent lines. RoyJ is described as having "good milling potential" and was selected because it was pure line (meaning a breeding program does not have to have hybrid breeding capabilities to generate its traits) and it was not the top milling variety as some varieties are described as having "excellent milling potential" (Hardke, 2018). While the time and effort to move a gene in a non-GM crop like rice is not trivial, selecting the milling qualities of RoyJ would seem

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[2] The common 55/70 milling standard results in 700 kg of HRY and 150 kg of broken kernels after milling, per metric ton. Thus, after milling is completed, there is a resulting 21.4% (150/700) broken kernels.

to be feasible given its subjective milling ranking of "good."[3] As such, any variety i in year t that had either an *MRY* or *HRY* less than the average milling rate of RoyJ is replaced with the average RoyJ milling values. If a variety had an *MRY* or *HRY* higher than RoyJ, it remained at its actual value. This would represent genetic enhancement to the standard of RoyJ's milling potential. This scenario seems more probable than simply increasing the milling yield for all varieties by 1% as this focuses on only improving those varieties that mill below some given standard, in this case, the popular variety RoyJ. Since RoyJ was released in 2010, we used the average RoyJ milling quality in 2010 for all varieties produced in prior years (2004–2009) and after its commercial release. In this scenario, we also assume no changes in paddy rice production, but there is a potential for a change in the volume of milled rice produced (*QM*) if a variety in any given year had an *MRY* lower than that of RoyJ. This scenario has the potential to change the value of the crop (VR_t) via changes in the volume of milled rice produced (*QM*) and the price producers receive (PR_{it}), depending on the quality of the crop.

Estimation of Global Market Impacts

The two scenarios described above could potentially affect the efficiency of milling, in the sense that the rice industry may obtain more milled rice per unit of paddy rice processed because of the assumed changes in rice quality. The increase in milled rice production will have an impact not only on the domestic rice market in the United States but also in other markets through exports of paddy and processed rice. This is particularly important for the United States, considering that roughly 41% of the long-grain rice exports between 2016 and 2021 were of paddy rice, particularly to Mexico, Central America, and Venezuela (US Department of Agriculture, 2022c). In other words, the improvements in quality in the US rice crop will spill over and benefit the milling industries in countries importing US paddy rice, thus potentially creating more competition for US milled rice in those same markets.

We use a partial equilibrium model (Durand-Morat and Wailes, 2010, see Table S1 in the online supplement for a description of the model) to elicit the impact of an increase in the volume of milled rice yielded per unit of paddy rice produced in the United States due to the genetic improvements specified in both scenarios. The model has been used extensively to assess the impact of technology changes affecting the global rice economy (Nalley et al., 2017; Durand-Morat, Nalley, and Thoma, 2018; Shew et al., 2018, 2019). The model allows us to answer the counterfactual question: What would the implications be for the global rice market if the milling yield and quality of rice varieties produced in the United States improved as specified in scenarios 1 and 2? Notably, the model generates domestic and global estimates of changes in rice production, consumption, trade, prices, and consumer and producer welfare in each importing/exporting region. The model disaggregates the global rice economy into 76 regional markets and nine rice commodities derived from the combination of rice type (long, medium, and fragrant) and milling degree (paddy, brown, and milled).

The model is calibrated to a database representing the global rice market situation for the 2013–2015 period, including the power of the most relevant rice trade and domestic support policies. Therefore, the results represent the annual change in all relevant market variables resulting solely from the change in US rice supply estimated in scenarios 1 and 2, holding everything else (e.g., policies and technology) constant at their 2013–2015 levels.

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[3] Like other genetic attributes (e.g., disease resistance, fungi resistance, lodging potential, yield potential) milling quality is subjectively ranked from poor to excellent by variety. RoyJ was selected because it had the highest milling rates of any of the purebred (nonhybrid, non-Clearfield) long-grain varieties that had more than 4% area planted to it. Being purebred, there are fewer intellectual property rights associated with the genetics and thus could be seen as a hypothetical ceiling for public breeding programs.
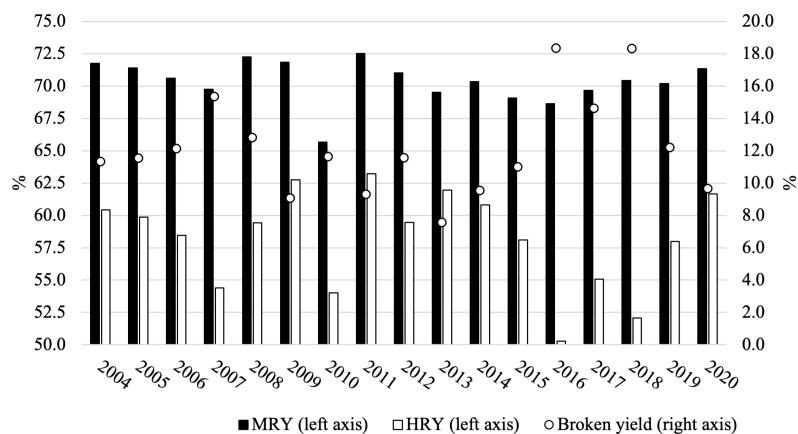
Figure 1. Annual Average Milled Rice Yield (MRY), Head Rice Yield (HRY), and Broken (MRY-HRY) Yield across All Rice Varieties Produced in Arkansas, 2004–2020

Results

Average Historical Quality and Quantity of Rice Production

Table 2 shows the historical area, production, and average yield and quality attributes for rice varieties in Arkansas from 2004 to 2020. The average paddy yield across time and varieties is 9.9 mt/ha, and the average milling yield is 58.6/70.2, resulting in a 16.5% broken rate. This average milling yield is higher than the commercial benchmark of 55/70 (which results in milled rice with a 21.4% broken rate) and likely the result of the flexibility to harvest small homogeneous test plots quickly to ensure the correct HMC to maximize genetic milling potential. Looking at the average quality attributes for the five most popular long-grain rice varieties in Arkansas during the 2004–2020 period based on planted area (Wells, CLXL745, XL753, CL151, and CLXL729), quality decreases to 56.6/70.4 (resulting in a 19.6% broken rate) but yield increases to 10.0 mt/ha. This would indicate that either producers are largely indifferent to quality and simply focus on yield potential, that there is a positive correlation between broken percentage and yield potential, or both.

Table 3 reports the estimated annual production volume and value of the Arkansas rice crop based on paddy and milled yields from planted varieties. From 2004 to 2020, Arkansas produced an average of 5.40 million metric tons (mmt) of paddy rice, equivalent to 3.79 mmt of milled rice a year, valued at an average of $1.38 billion a year. Because rice is sold with different ratios of broken to whole kernels, Table 3 shows the volume of milled rice with four different quality standards and the surplus of broken rice, produced for each of the four quality standards from the Arkansas rice crop annually. On average, the Arkansas rice crop produced 3.13 mmt of 100% head milled rice, generating a surplus of 659,000 mt of broken rice. Likewise, the average Arkansas rice crop was enough to produce 3.69 mmt of milled rice with 15% of broken rice, generating 106,000 mt of broken rice surplus. Table 3 also highlights the yearly variability (likely attributed to genotype by environment interactions) in the volume of broken rice generated by the milling industry. For instance, assuming the industry produces milled rice with a 10% broken rate, the surplus of broken rice surpassed 700,000 mt in 2016 and 2018 and was as low as 28,000 mt in other years. Figure 1 shows the average annual *MRY*, *HRY*, and broken yield (*MRY − HRY*) for the Arkansas rice crop from 2004 to 2020, and we can see that 2016 and 2018 were years of particularly high broken yields, while 2013 produced the lowest broken yield crop.

Given that many countries that import US long-grain rice have high commercial quality requirements (e.g., Haiti and Iraq primarily import rice with 4% broken kernels), our results indicate that the surplus of broken rice is an issue for the rice industry (exacerbated in some years) and that

Table 2. Rice Varietal Adoption and Quality and Quantity Traits in Arkansas, 2004–2020

Variety	Release Year	Total Area (ha)	Avg. Yield (mt/ha)	Production (1,000 mt)	Avg. HRY (%)	Avg. MRY (%)
Banks	2004	23,830	10.6	253.7	57.0	70.0
Bengal	1992	232,744	9.0	2,086.1	60.5	70.1
Cheniere	2003	210,862	8.9	1,876.6	58.5	69.1
CL111	2008	99,605	8.9	885.6	62.7	70.5
CL131	2008	95,337	8.9	852.6	57.9	69.7
CL142	2009	35,508	8.9	317.1	59.0	73.0
CL151	2007	665,395	9.0	5,981.0	59.6	68.7
CL152	2011	53,563	8.8	473.3	63.9	69.4
CL153	2016	105,632	9.9	1,041.0	60.2	71.0
CL161	2001	317,917	9.4	2,974.5	61.6	70.7
CL171	2007	159,890	8.2	1,309.4	60.3	71.5
CL172	2016	16,091	9.1	146.1	60.0	70.0
CL7311	2017	18,235	10.4	190.5	59.0	70.0
CLL15	2019	28,587	10.1	288.5	62.0	70.0
CLXL729	2007	434,950	9.6	4,165.6	59.2	70.2
CLXL730	2006	102,289	9.4	957.0	58.7	71.2
CLXL745	2008	1,146,488	10.0	11,432.2	56.8	70.3
CLXL8	2003	74,261	9.9	737.9	55.4	69.8
CLXP756	2011	9,853	11.7	114.8	45.0	67.0
Cocodrie	1997	236,134	8.9	2,106.1	61.0	71.0
Diamond	2016	270,183	10.4	2,803.5	56.3	70.1
Francis	2002	421,811	9.5	4,016.2	59.2	70.6
Gemini 214CL	2016	252,712	11.2	2,821.8	58.7	70.5
Jupiter	2006	616,703	9.8	6,029.8	61.3	69.3
LaKast	2014	74,680	8.8	659.6	55.3	68.7
Mermentau	2012	50,707	8.8	445.9	63.2	70.2
RoyJ	2010	370,474	9.5	3,525.7	60.0	69.9
RT7301	2019	37,338	11.7	435.2	60.0	72.0
RT7311CL	2016	25,420	10.4	264.2	51.0	70.0
RT7321FP	2018	21,586	11.5	248.3	59.0	72.0
RT7521FP	2018	65,341	11.5	751.7	61.0	71.0
Titan	2016	87,101	10.9	945.3	55.9	69.7
Wells	1999	1,284,555	9.6	12,341.9	56.3	71.4
XL723	2005	137,309	10.6	1,458.1	60.9	69.4
XL753	2011	694,467	11.9	8,243.2	53.4	70.3
XL760	2014	20,970	10.4	219.0	59.0	70.0
Average			9.9	2,316.6	58.6	70.2

Notes: All varieties are classified as long grain, except Bengal, Jupiter, and Titan. Release year refers to the year in which the variety was commercial released to the public. Average yield is the average across all test plot locations for both time and location from 2004 to 2020.

a portion of that surplus is likely funneled into nonfood uses, such as pet food or other biproduct industries. Improvements in milling genetics will not increase the volume of the rice crop but could increase the amount of milled rice and the value of the rice crop as well as the number of rice rations, via export, and ultimately the number of people that could be fed, which can have important food security implications.

Table 3. Baseline Production and Value of the Rice Crop, and of Milled and Broken Rice by Milled Rice Quality in Arkansas, 2004–2020

Year	Production			Production Milled Rice by Quality (1,000 mt)				Broken Rice Surplus (1,000 mt)			
	Paddy (1,000 mt)	Milled (1,000 mt)	Value ($millions)	100% Head	5% Broken	10% Broken	15% Broken	100% Head	5% Broken	10% Broken	15% Broken
2020	6,424	4,582	1,825	3,961	4,169	4,401	4,660	621	412	181	−78
2019	5,243	3,680	1,393	3,041	3,201	3,379	3,578	639	479	301	103
2018	6,283	4,424	1,468	3,273	3,445	3,636	3,850	1,152	980	788	574
2017	4,581	3,192	1,118	2,522	2,655	2,803	2,968	670	537	390	225
2016	5,796	3,978	1,167	2,914	3,067	3,238	3,428	1,064	910	740	550
2015	4,686	3,238	1,131	2,722	2,866	3,025	3,203	515	372	213	35
2014	6,385	4,491	1,727	3,882	4,086	4,313	4,567	609	405	178	−76
2013	4,116	2,861	1,407	2,550	2,684	2,833	3,000	311	177	28	−139
2012	4,930	3,502	1,583	2,931	3,085	3,257	3,448	571	416	245	53
2011	4,306	3,123	1,316	2,722	2,865	3,024	3,202	401	257	98	−80
2010	6,896	4,528	1,656	3,726	3,922	4,140	4,383	802	606	388	145
2009	5,449	3,914	1,661	3,419	3,599	3,799	4,023	495	315	115	−109
2008	4,501	3,252	1,523	2,675	2,816	2,972	3,147	577	436	280	105
2007	5,200	3,628	1,381	2,829	2,978	3,143	3,328	799	650	485	300
2006	5,570	3,932	1,190	3,256	3,427	3,617	3,830	676	505	314	102
2005	6,401	4,571	1,087	3,832	4,034	4,258	4,508	739	537	313	63
2004	5,011	3,595	844	3,028	3,187	3,364	3,562	568	408	231	33
Average	5,399	3,794	1,381	3,134	3,299	3,483	3,687	659	494	311	106
Total	91,779	64,491	23,477	53,282	56,087	59,203	62,685	11,208	8,404	5,288	1,805

Notes: Milled rice production is estimated by multiplying the production of paddy rice by the milled rice yield (MRY) for each variety and year. The value of production is estimated by multiplying the production of paddy rice by the market price. The market price is estimated using USDA yearly average market price for long grain rice, adjusted by quality using the USDA's loan rates for whole and broken rice and the USDA's milling yield premium and discount calculator.

Additional Crop Value and Rations from Enhanced Genetics

Table 4 presents the main findings from our two scenarios, namely, (i) an across-the-board improvement in milling quality resulting in a 1-percentage-point increase in *HRY* and no changes in *MRY* for each variety in each year and (ii) an increase in the milling yield (*MRY* and *HRY*) to that of variety RoyJ or above (if the actual was higher than RoyJ) for each variety in each year. Looking at the results for scenario 1, we find that a 1-percentage-point increase in *HRY* would increase the value of the Arkansas rice crop by an average of $5.54 million annually (in 2020 US$), or 0.4% relative to the baseline average annual value of the rice crop. Moreover, such improvement in rice milling quality generates an additional volume of milled rice, averaging from 54,750 mt to 64,410 mt a year depending on the quality of milled rice produced, a 1.75% increase in the volume of milled rice produced relative to the baseline. Because the MRY remains constant under this scenario, then increase in milled rice production is exactly equal to the reduction in the surplus of broken rice. From a food security standpoint, we estimate that the increase in milling yield assumed in this scenario would provide between 895,000 to 1.05 million additional rice rations annually (Table 5), or between 15.2 million and 17.9 million rations over the 2004–2020 period, at the global average per capita consumption of 61.2 kg/year, depending on the quality standard of the milled rice produced. This is important because as yield ceilings are approached, increasing milling potential could provide more food for human consumption without having to increase paddy yield.

The results from scenario 2 are larger in magnitude than those from scenario 1, which stems from the fact that for some varieties and years milling up to RoyJ's standard result in a larger improvement in milling yield than a marginal 1% increase. For example, looking at Table 2, we see that upgrading the milling yield of Wells, the most popular variety in terms of total area planted in 2004–2020, to the RoyJ's standard would mean a 1.5-percentage-point decrease in *MRY* and a 3.7-percentage-point increase in *HRY*. Conversely, in 2009, all varieties milled better than RoyJ's average in terms of both *MRY* and *HRY*, except for CL 151, which yielded a slightly lower *MRY* than RoyJ. This explains why in 2009 there are no additional gains in milled rice production and a slight increase in broken rice surplus relative to the baseline (Table 4). The average economic value of the Arkansas rice crop increases by $24.48 million annually, or a 1.8% increase from the baseline. Depending on the quality standard of milled rice produced, the new milling yields assumed in scenario 2 would result in between 179,760 mt and 211,480 mt a year of additional milled rice produced, a 5.74% increase in the volume of milled rice produced relative to the baseline. Moreover, under scenario 2, the broken rice surplus is estimated to decrease by between 129,750 mt and 161,470 mt a year as less broken rice is produced. The gains in milled rice production would be sufficient to feed between an additional 2.94–3.46 million people a year (Table 5), or 49.93–58.75 million people over the 2004–2020 period, at the average global per capita consumption of 61.2 kg/year, despite the fact that actual paddy yield did not change.

Market and Food Security Impact of Improved Milling Yields

The previous results highlight the static impact of improving rice milling yields without accounting for the impact of such shocks on the US and global rice markets. An increase in the supply of milled rice as expected under scenarios 1 and 2 will lead to a new market equilibrium that could potentially result in changes in prices, supply, demand, and trade. We used the RiceFlow model to ascertain these market changes, assuming that under scenarios 1 and 2 the productivity of the US rice milling industry would increase by 1.75% and 5.74%, respectively. Moreover, since the United States exports paddy rice to several countries, we also shocked the RiceFlow model to account for the milling gains realized in these import markets, considering the share of US paddy imports in their total supply of paddy rice. For example, 73% of the volume of paddy rice processed in Mexico between 2013 and 2015 was imported from the United States; hence, we estimated the increase in milling productivity

Table 4. Changes in the Value of the Rice Crop, Additional Rice Rations Produced and Broken Rice Surplus in Arkansas by Quality of Milled Rice, 2004–2020

	Added Crop Value ($millions)	Additional Production of Milled Rice (1,000 metric tons)				Reduction in Broken Rice Surplus (1,000 metric tons)			
Year		100% Head	5% Broken	10% Broken	15% Broken	100% Head	5% Broken	10% Broken	15% Broken
Scenario 1: Marginal milling increase (increase HRY for each variety by 1%)									
2020	7.90	77.15	81.21	85.72	90.76	77.15	81.21	85.72	90.76
2019	5.82	52.43	55.19	58.26	61.69	52.43	55.19	58.26	61.69
2018	5.62	62.83	66.14	69.81	73.92	62.83	66.14	69.81	73.92
2017	3.25	45.81	48.22	50.90	53.90	45.81	48.22	50.90	53.90
2016	3.88	57.96	61.01	64.40	68.18	57.96	61.01	64.40	68.18
2015	4.18	46.86	49.33	52.07	55.13	46.86	49.33	52.07	55.13
2014	6.26	63.85	67.21	70.95	75.12	63.85	67.21	70.95	75.12
2013	4.54	41.16	43.33	45.73	48.42	41.16	43.33	45.73	48.42
2012	5.02	49.30	51.90	54.78	58.00	49.30	51.90	54.78	58.00
2011	3.13	43.06	45.32	47.84	50.65	43.06	45.32	47.84	50.65
2010	5.23	68.96	72.59	76.62	81.13	68.96	72.59	76.62	81.13
2009	4.49	54.49	57.36	60.54	64.11	54.49	57.36	60.54	64.11
2008	3.97	45.01	47.38	50.02	52.96	45.01	47.38	50.02	52.96
2007	4.73	52.00	54.74	57.78	61.18	52.00	54.74	57.78	61.18
2006	8.29	55.70	58.63	61.88	65.52	55.70	58.63	61.88	65.52
2005	9.84	64.01	67.38	71.12	75.31	64.01	67.38	71.12	75.31
2004	8.02	50.11	52.75	55.68	58.96	50.11	52.75	55.68	58.96
Avg.	5.54	54.75	57.63	60.83	64.41	54.75	57.63	60.83	64.41
Total	94.17	930.70	979.68	1,034.11	1,094.94	930.70	979.68	1,034.11	1,094.94
Scenario 2: Increase milling yield (MRY and HRY) to Roy J or above									
2020	2.45	20.79	21.89	23.10	24.46	18.51	19.60	20.82	22.17
2019	22.00	155.96	164.17	173.29	183.49	121.66	129.87	138.99	149.19
2018	52.05	539.43	567.82	599.37	634.63	512.25	540.64	572.19	607.44
2017	26.44	259.69	273.36	288.54	305.52	210.12	223.79	238.98	255.95
2016	60.80	602.11	633.80	669.01	708.36	481.89	513.58	548.79	588.14
2015	23.41	129.17	135.97	143.52	151.97	53.26	60.05	67.61	76.05
2014	12.02	68.75	72.37	76.39	80.89	33.28	36.90	40.92	45.41
2013	7.80	6.68	7.04	7.43	7.86	-42.82	-42.47	-42.08	-41.64
2012	12.24	95.78	100.82	106.42	112.68	79.18	84.22	89.82	96.08
2011	2.65	12.92	13.60	14.36	15.20	3.34	4.02	4.78	5.62
2010	98.56	458.29	482.42	509.22	539.17	109.98	134.10	160.90	190.86
2009	0.75	0.00	0.00	0.00	0.00	−4.11	−4.11	−4.11	−4.11
2008	7.18	81.41	85.69	90.45	95.77	81.41	85.69	90.45	95.77
2007	40.68	338.88	356.72	376.54	398.68	286.29	304.13	323.94	346.09
2006	24.34	146.69	154.41	162.99	172.58	129.82	137.54	146.12	155.71
2005	17.29	109.16	114.91	121.29	128.43	105.90	111.65	118.03	125.16
2004	5.54	30.20	31.79	33.56	35.53	25.79	27.38	29.15	31.12
Avg.	24.48	179.76	189.22	199.73	211.48	129.75	139.21	149.72	161.47
Total	416.18	3,055.93	3,216.77	3,395.48	3,595.22	2,205.74	2,366.58	2,545.29	2,745.03

Notes: Dollar values for added crop value are 2020 USD equivalents.

in Mexico to be 1.27% (73% of 1.75, the average increase in US milling productivity) in scenario 1 and 4.18% in scenario 2.

Table 6 shows the impact of both scenarios on the US rice market. At equilibrium, the increase in milling productivity resulting from scenario 1 leads to a 2.10% reduction in the price of milled rice, which makes US exports of milled rice more competitive and leads to a 4.24% expansion in milled rice exports. However, because of its inelastic nature, the domestic demand for milled rice remains flat. Upstream in the rice supply chain, the gain in milling efficiency is expected to put downward pressure on farm prices, which decrease by 0.52%, and marginally reduce long-grain rice production in the United States by 0.21%. Overall, consumers benefit the most through lower market prices, while rice producers absorb a slight decline in the value of production as gross revenue. The results

Table 5. Additional Rations (thousands) of Rice from Baseline Milling Rates via Genetic Improvements Given Various Head Rice Percentage Requirements

Year	Scenario 1				Scenario 2			
	100% Head	5% Broken	10% Broken	15% Broken	100% Head	5% Broken	10% Broken	15% Broken
2020	1,261	1,327	1,401	1,483	340	358	377	400
2019	857	902	952	1,008	2,548	2,683	2,832	2,998
2018	1,027	1,081	1,141	1,208	8,814	9,278	9,794	10,370
2017	749	788	832	881	4,243	4,467	4,715	4,992
2016	947	997	1,052	1,114	9,838	10,356	10,932	11,575
2015	766	806	851	901	2,111	2,222	2,345	2,483
2014	1,043	1,098	1,159	1,227	1,123	1,183	1,248	1,322
2013	673	708	747	791	109	115	121	129
2012	806	848	895	948	1,565	1,647	1,739	1,841
2011	704	741	782	828	211	222	235	248
2010	1,127	1,186	1,252	1,326	7,488	7,883	8,321	8,810
2009	890	937	989	1,047	0	0	0	0
2008	736	774	817	865	1,330	1,400	1,478	1,565
2007	850	894	944	1,000	5,537	5,829	6,153	6,514
2006	910	958	1,011	1,071	2,397	2,523	2,663	2,820
2005	1,046	1,101	1,162	1,231	1,784	1,878	1,982	2,098
2004	819	862	910	963	493	519	548	581
Average	895	942	994	1,052	2,937	3,092	3,264	3,456
Total	15,207	16,008	16,897	17,891	49,934	52,562	55,482	58,745

Notes: Scenario 1 is a marginal milling increase (increase HRY for each variety by 1%). Scenario is an increase in milling yield (MRY and HRY) to Roy J or above.

Table 6. Changes in the US Long Grain Rice Markets because of the Improvements in Milling Quality Assumed for Improved Milling Genetics in Scenarios 1 and 2

Market Variables (in 1,000 mt, milled basis)	Baseline 2013–2015	Scenario 1 (% change from baseline)	Scenario 2 (% change from baseline)
Production paddy rice	4,676	−0.21	−0.68
Export paddy rice	1,036	−0.48	−1.64
Export brown rice	41	−0.52	−1.74
Import brown rice	10	−0.57	−1.77
Export milled rice	1,207	4.24	14.13
Import milled rice	148	−5.01	−15.29
total exports	2,284	2.02	6.69
Total imports	158	−4.74	−14.46
Domestic demand milled rice	2,581	0.01	0.03
Paddy price at farm gate ($/mt)	306	−0.52	−1.68
Milled rice retail price ($/mt)	1,468	−2.10	−6.62
Value production ($millions)	2,047	−0.73	−2.34
Value consumption ($millions)	3,789	−2.09	−6.58

Notes: Scenario 1 is a marginal milling increase (increase HRY for each variety by 1%). Scenario is an increase in milling yield (MRY and HRY) to Roy J or above. Source: Own estimations based on partial equilibrium model results.
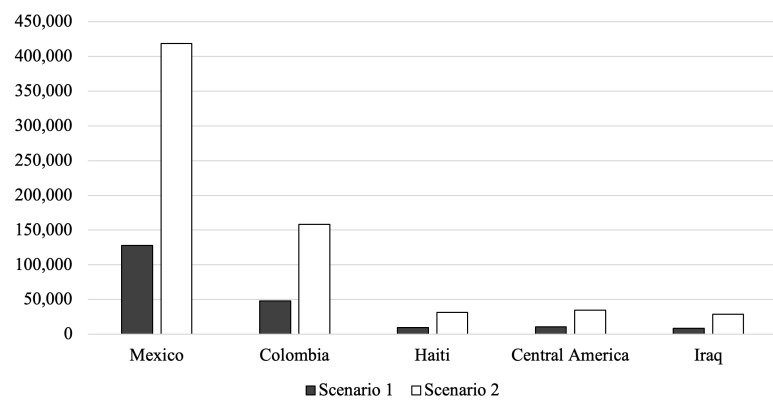
Figure 2. Additional Number Rice Rations in Selected Countries by Milling Scenario

from scenario 2 follow a similar pattern as scenario 1 but are larger in magnitude as a result of the larger shocks. The increase in milling efficiency leads to a 6.60% reduction in milled rice prices, which bolsters milled rice exports by 14.13% but is not enough to push domestic demand up in any significant amount. The lower cost of producing milled rice puts downward pressure on prices upstream in the supply chain and results in a decrease in farm prices of 1.68%, which ultimately drives down long-grain rice production by 0.68%. Again, the main winners are US consumers, who can satisfy their demand for rice at lower prices. These results suggest that, from a food security point of view, the main benefit for US consumers will be through lower rice prices, which will free up disposable income.

Globally, the impacts are modest in relative terms due to the fact that the United States is a small producer of rice. However, the increase in US rice quality and associated increase in milling efficiency results in an expansion of global rice consumption of 34,190 mt and 111,630 mt for scenarios 1 and 2, respectively. When converted to additional rice rations at the average global per capita rate of 61.2 kg annually, these gains represent an additional 0.559 million and 1.82 million people fed under scenarios 1 and 2, respectively. Figure 2 shows the five countries that will benefit the most from the increase in US rice milling yields in terms of additional people fed. Mexico stands to gain the most, in part due to its close trade relationship with the United States but also since it has a low per capita rice consumption rate of 5.64 kg/year.

Conclusions

Globally, there is evidence that rice yields are plateauing (Grassini, Eskridge, and Cassman, 2013), and little genetic progress has been made in indica rice yield gains (Fischer, Byerlee, and Edmeades, 2014). This could be due to a variety of factors, including increased environmental concerns leading to less input usage, the lack of a GM/GE rice commercialization, breeders focusing more on rice quality or disease resistance, and increased organic rice production. Regardless of the cause, increasing the efficiency in the amount of rice that is ultimately used as food is of growing importance due to both population growth and the plateau/reduction of suitable land globally to produce rice. Given the economic market incentives for producers, rice breeding programs in the United States have primarily focused on increasing rice yields (increased revenue) and disease resistance packages (decreased costs). These breeding programs have increased average rice long-grain rice yields in the United States by 20% between 2001 and 2021, an outstanding scientific achievement (US Department of Agriculture, 2022d). However, increased yields and constant broken percentages have increased the total volumes of broken kernels domestically, which are now having to find alternative markets. New uses of broken rice for human consumption (rice flour, gluten-free snacks) may lower the

leakage of broken rice into nonhuman food uses, but the USDA reported that 10% of the total rice consumed in the United States is used for the pet food or brewery industries.

The results of this study have provided several important findings regarding broken kernels. First, even marginal improvements in the genetic milling potential of commercially released varieties can have large impacts on food security. A 1% increase in HRY for rice produced in Arkansas was estimated to increase the number of rice rations by between 0.89 million and 1.05 million annually. If the genetics of all Arkansas rice was at least at the standard of the popular purebred variety RoyJ, rice rations would increase by between 2.94 million and 3.5 million annually, all without increasing rice yields. As yield enhancements slow and globally breeders start focusing more on quality, the results found from this study could suggest an alternative way to help fight food insecurity. Second, marginal improvements in milling genetics have the potential to significantly increase producer revenue without increasing input use or productivity. Currently, it appears that the economic incentives put forth to US rice producers is simply to choose the highest yielding varieties since the dockage for broken rice can quickly be overcome by marginal increases in yields. Hopefully, studies such as this one can be used to update price schemes to be more reflective of rice quality and to show the importance of producing a quality rice crop from a pure economic as well as a sustainability and food security point of view.

While pressure relief valves do exist for an increased volume of broken rice,[4] these markets are quickly saturated, and remaining broken kernels are often funneled into nonhuman uses. This study has estimated the economic and food security implications of genetic improvements in broken rice reductions. Rice breeders—including those in the Green Revolution who increased yields, averting a Malthusian catastrophe—have been responsible for one of mankind's greatest scientific success stories. Given the slowed genetic gains in rice yields, until the commercialization of GM/GE rice, it appears that major gains in food security from rice breeding could be captured via reduced post-harvest loss or through reductions in broken rice, as highlighted in this study.

An important factor not quantified in this study is the environmental efficiency gains that would be made through a reduction in broken rice. While total production inputs and rice outputs (and consequently the environmental cost per kg of rice produced) do not change in the scenarios analyzed in this study, the number of rice rations increases and the environmental impact per rice ration consequently decreases. Given the number of people who rely on rice as a staple and that rice is such a water-intensive crop, improving input-use efficiency—particularly water—for rice consumed by humans is important. This can be achieved in two ways: (i) reducing the amount of water used for rice production, a complex goal that requires investments in research and extension to develop and deploy more efficiency crop management practices, including irrigation, and potentially changes in genetics to make rice less water intensive, or (ii) increasing the amount of rice currently produced that reaches the plates of consumers by, for example, reducing food waste or improving processing efficiency. Given that two-thirds of the global population are now confronting water scarcity (Mekonnen and Hoekstra, 2016) and the fact that rice uses such large amounts of water, it is becoming increasingly important for sustainably reasons that all rice goes to human consumption and not to an alternative use because of poor quality.

Arkansas is a small player on the global rice market, but the results from this study are not trivial and show that even small changes in rice quality in a small rice-producing area can have economic and food security implications. Genetic improvements, like the ones analyzed in this study, enhance one of the United Nations Millennium Development Goals (MDG): Sustainable Consumption and Production. Through increased milling genetics, plant breeders will be able to feed more people and increase producer profits using the same production inputs.

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[4] Some countries (e.g., Mauritania, Senegal, and other West African nations) prefer 100% broken rice.

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Online Supplement:
The Impacts of Enhanced Rice Quality Genetics on Food Security and Producer Profitability

Lawton Lanier Nalley and Alvaro Durand-Morat

RiceFlow Model Description

The RiceFlow model is a partial, spatial equilibrium model of the global rice economy. It simulates the behavior of the entire rice supply chain, from input markets all the way up to the aggregate final demand, in multiple countries/regions (set R) around the world. The production of endogenous rice commodities (set CE)[1] is specified as a weakly separable, constant return to scale production function.

(S1) $$Y_{c,r} = H_{c,r}\{G_{c,r}(FAC_{c,r}), INT_{c,r}\} \ \forall c \in CE, r \in R$$

where Y represents output, H and G are technology functional forms, FAC is the set of factors of production,[2] and INT is the set of intermediate inputs.[3]

Defining G in equation (1) as a constant elasticity of substitution (CES) function, the derived demand for factor of production, QFC, is

(S2) $$QFC_{f,c,r} * AFC_{f,c,r} = QVA_{c,r} * SVA_{f,c,r} * \left[\frac{PFC_{f,c,r}}{PVA_{c,r}*AFC_{f,c,r}}\right]^{-\sigma VA_{c,r}}$$
$$\forall f \in FAC, c \in CE, r \in R$$

(S3) $$PVA_{c,r} = \left[\sum_f SVA_{f,c,r} * \left(\frac{PFC_{f,c,r}}{AFC_{f,c,r}}\right)^{1-\sigma VA_{c,r}}\right]^{\frac{1}{1-\sigma VA_{c,r}}} \ \forall c \in CE, r \in R$$

where AFC, PFC, and SVA are a factor-, sector-, and region-specific augmenting technical change variable, factor price variable, and cost share in value added, respectively, and QVA and PVA are a sector- and region-specific derived demand and price for the value-added composite, respectively. Finally, σVA is the sector- and region-specific elasticity of substitution in value added.

Defining H in equation (1) as a constant elasticity of substitution (CES) function, the derived demands for intermediate inputs QIC, and for the composite value added $QVA_{c,r}$, are

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[1] $CE = \{LGP, LGB, LGW, MGP, MGB, MGW, FRP, FRB, FRW\}$, where LG, MG, and FR stand for long grain, medium/short grain, and fragrant rice, and P, B, W stand for paddy/rough, brown/whole, and white/milled rice.
[2] $FAC = \{L, T, K\}$, where L is land, T labor, and K capital.
[3] $INT = \{seeds, herbicides, pesticides, water, energy, LGP, LGB, MGP, MGB, FRP, FRB\}$

(S4) $$QIC_{i,c,r} * AIC_{i,c,r} = \frac{Y_{c,r}}{AY_{c,r}} * SITC_{i,c,r} * \left[\frac{PIC_{i,c,r}}{PY_{c,r}} * AIC_{f,c,r} * AY_{c,r}\right]^{-\sigma Y_{c,r}},$$

$$\forall i \in INT, c \in CE, r \in R$$

(S5) $$QVA_{c,r} * AVA_{c,r} = \frac{Y_{c,r}}{AY_{c,r}} * SVATC_{c,r} * \left[\frac{PVA_{c,r}}{PY_{c,r}} * AVA_{c,r} * AY_{c,r}\right]^{-\sigma Y_{c,r}}, \forall c \in CE, r \in R$$

where AIC, PIC, and $SITC$ are input-, sector-, and region-specific input augmenting technical change variable, input price variable, and input cost share in total cost, respectively. Further, AVA, AY, and PY, and $SVATC$ are sector- and region-specific value-added augmenting technical change variable, output augmenting technical change variable, output price variable, and value-added cost share in total cost, respectively. Finally, σY is the sector- and region-specific elasticity of substitution in final output.

The model assumes zero profits in production (equation 6) and equilibrium in output markets (equation 7a for paddy rice commodities[4], and equation 7b for other rice commodities[5]).

(S6) $$PY_{c,r} = \frac{\left[SVATC_{c,r} * \left(\frac{PVA_{c,r}}{AVA_{c,r}}\right)^{1-\sigma Y_{c,r}} + \sum_i SITC_{i,c,r} * \left(\frac{PIC_{i,c,r}}{AIC_{i,c,r}}\right)^{1-\sigma Y_{c,r}}\right]^{\frac{1}{1-\sigma Y_{c,r}}}}{AY_{c,r}}, \forall c \in CE, r \in R$$

(S7a) $$Y_{c,r} = QD_{c,r} + \sum_s QBX_{c,r,s} + QK_{c,r}, \forall c \in CP, r \in R$$

(S7b) $$Y_{c,r} = QD_{c,r} + \sum_s QBX_{c,r,s}, \forall c \in CCP, r \in R$$

where QD represent the volume of output c sold in the domestic market, QK is the change in stocks[6] of good c, and QBX is the volume of bilateral exports of c from region r to region s.

Import demand follows the Armington approach (Armington, 1969), by which imports by source and domestic production are treated as heterogeneous products. Agents first decide on the sourcing of imports (equation 8) based on the relative level of prices from each source (equation 9).

(S8) $$QBX_{c,s,r} = QM_{c,r} * SMS_{c,s,r} * \left[\frac{PMMS_{c,s,r}}{PMM_{c,r}}\right]^{-\sigma M_{c,r}}, \forall c \in CE, r \in R, s \in R$$

(S9) $$PMM_{c,r} = \left[\sum_s SMS_{c,s,r} * PMMS_{c,s,r}{}^{1-\sigma M_{c,r}}\right]^{\frac{1}{1-\sigma M_{c,r}}}, \forall c \in CE, r \in R$$

where $PMMS$ is the market price of import good c into region r from source s, PMM is the composite market price of import good c in r, QM is the demand for the composite import good c in r, and SMS is the value-share of good c's import into r by source s. $\sigma M_{c,r}$ is the elasticity of substitution of imported good c in r by source.

After sourcing imports, then agents decide on the optimal mix of imported and domestic products (equations 10 and 11) based on their relative price levels (equation 12).

(S10) $$QM_{c,r} = QQ_{c,r} * SMQ_{c,r} * \left[PMM_{c,r}/PQ_{c,r}\right]^{-\sigma Q_{c,r}}, \forall c \in CE, r \in R$$

(S11) $$QD_{c,r} = QQ_{c,r} * SDQ_{c,r} * \left[PY_{c,r}/PQ_{c,r}\right]^{-\sigma Q_{c,r}}, \forall c \in CE, r \in R$$

(S12) $$PQ_{c,r} = \left[SMQ_{c,r} * PMM_{c,r}{}^{1-\sigma Q_{c,r}} + SDQ_{c,r} * PY_{c,r}{}^{1-\sigma Q_{c,r}}\right]^{\frac{1}{1-\sigma Q_{c,r}}}, \forall c \in CE, r \in R$$

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[4] Set $CP = \{LGP, MGP, FRP\}. CP \in CE$
[5] Set $CCP = CE - CP = \{LGB, MGB, FRB, LGW, MGW, FRW\}$
[6] Only stocks of paddy rice are allowed. Thus $QK_{c,r}$ is defined over the commodity subset CP.

where PQ is the market price of composite good c in region r, QQ is the output of composite good c in r, and SMQ and SDQ are the value-shares of the import composite and domestic good c in r. $\sigma Q_{c,r}$ is the elasticity of substitution between domestic and imported good c in r.

Final demand for milled rice $c \in CFC$[7] in region r, is the product of population and per capita demand $D_{c,r}$, which is specified as a double log function of income and prices (equation 13). Z_r represents income by region, φ_r is the income demand elasticity, and $\omega_{c,g,r}$ is the matrix of own and cross-price demand elasticities.

(S13) $\qquad \log D_{c,r} = \varphi_r * \log Z_r + \sum_{g \in FC} \omega_{c,g,r} * \log PQ_{g,r} \ , \forall c \in CFC, r \in R$

The supply of exogenous intermediate inputs (seeds, fertilizers, pesticides, energy, and water), capital, and labor are specified as perfectly elastic, thus their prices (PFC) are treated as constant, exogenous variables. Land is considered the only factor with limited supply. Hence, sectoral output Y is constrained only by the supply of land $L_{c,r}$ used in the production of paddy rice, which is represented by a double log function of land rental rates $PL_{c,r}$.

(S14) $\qquad \log L_{c,r} = \theta_{c,r} \log PL_{c,r} \ , \forall c \in CP, r \in R$

The land own-price supply elasticity $\theta_{c,r}$ are calibrated following Keller (1976) to reflect rice supply elasticities found in the literature.

The model is calibrated to a benchmark 2013-15 period. It disaggregates the global rice market into 76 regional markets and nine rice commodities resulting from a combination of three rice types (long grain, medium/short grain, and fragrant rice) and three milling degrees (paddy, brown, and milled rice). Total rice supply and demand data comes primarily from USDA's production, Supply and Distribution and FAOSTAT. Bilateral volume and value of trade at the 6-digit harmonized system (HS) level comes from COMTRADE. The disaggregation of supply, demand, and trade by rice type is based on information from numerous country sources, including the Ministry of Commerce of Thailand (Government of Thailand, 2022), the Ministry of Commerce and Industry of India (Government of India, 2022), Pakistan's Bureau of Statistics (Government of Pakistan, 2022), and USDA Global Agricultural Trade Statistics (US Department of Agriculture, 2022). Information on input cost shares come primarily from GTAP 9 database (Aguiar, Narayanan, and McDougall (2016).

Table S2 shows a summary of the volume of production, demand, trade, and the value of key behavioral elasticity parameters used in RiceFlow. Estimates of own-price supply, demand, and income elasticities come primarily from US Department of Agriculture (2021a) and the Arkansas Global Rice Model[8] (Wailes and Chavez, 2010).

The RiceFlow database incorporates the power of a number of domestic and trade policies affecting the global rice market. Information about trade policies come from many different sources, including the World Trade Organization (2022), the Organisation for Economic Co-operation and Development (2022), the US Department of Agriculture (2021b), the Organization of American States (2022), and many other country-specific sources.

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[7] Set $CFC = \{LGW, MGW, FRW\}. CFC \in CE$

[8] The Arkansas Global Rice Model is updated twice a year, and elasticities are estimated regularly to account for recent changes in producer and consumer behavior.

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Table S1. Historical Broken and Whole Kernel Prices for Long Grain Nonfragrant Rice in the US Mid-South

Year	100% Whole Kernels (2020 \$/cwt)	100% Broken Kernels (2020 \$/cwt)	Broken Price as Percentage of Whole Kernel Price
2020	11.10	6.45	58
2019	11.23	6.19	55
2018	10.39	6.33	61
2017	10.57	7.35	70
2016	10.77	7.72	72
2015	11.16	7.11	64
2014	11.21	6.76	60
2013	11.49	6.48	56
2012	11.42	6.80	60
2011	11.43	8.12	71
2010	11.76	8.32	71
2009	11.99	8.25	69
2008	12.02	8.02	67
2007	12.63	8.50	67
2006	13.51	6.75	50
2005	13.96	6.98	50
2004	14.54	7.28	50

Source: US Department of Agriculture (2022).

Table S2. Volume of Production, Demand, and Trade, and Key Elasticities of Supply and Demand for the Top-25 Largest Rice Producing Countries, 2013–2015.

Country	Volume (1,000 metric tons)				Elasticities		
	Production	Demand	Export	Import	Own-Price Supply	Own-Price Demand	Income Demand
China	144,443	145,701	348	4,260	0.160	-0.160	-0.070
India	105,810	95,045	10,944	2	0.110	-0.200	-0.040
Indonesia	36,199	38,009	0	828	0.100	-0.140	-0.120
Bangladesh	34,280	35,076	0	419	0.250	-0.010	-0.040
Vietnam	28,009	21,885	6,546	133	0.080	-0.200	-0.230
Thailand	19,803	10,003	9,487	200	0.220	-0.050	-0.160
Myanmar	12,172	10,519	1,554	4	0.380	-0.100	0.130
Philippines	11,564	12,906	0	1,484	0.150	-0.250	0.150
Brazil	7,888	7,559	919	523	0.070	-0.100	-0.050
Japan	7,792	8,412	2	676	0.290	-0.110	-0.260
US	6,509	3,975	3,163	719	0.400	-0.010	0.340
Pakistan	6,501	2,185	4,082	28	0.290	-0.180	0.100
Cambodia	4,668	3,877	703	10	0.210	-0.200	-0.230
Egypt	4,402	4,273	185	45	0.160	-0.150	0.300
South Korea	4,159	4,355	0	413	0.300	-0.540	-0.270
Sri Lanka	2,901	2,840	0	152	0.210	-0.200	-0.040
Nigeria	2,638	4,698	0	1,877	0.100	-0.150	0.250
Peru	2,085	2,280	0	215	0.210	-0.100	-0.050
Malaysia	1,765	2,884	0	1,047	0.430	-0.300	0.090
Laos	1,758	1,814	0	80	0.210	-0.200	-0.230
Iran	1,683	2,836	0	1,142	0.010	-0.350	0.200
Tanzania	1,490	1,652	51	213	0.210	-0.150	0.250
Ivory Coast	1,392	2,737	16	1,495	0.570	-0.550	0.140
Mali	1,391	1,495	0	106	0.210	-0.150	0.140
Colombia	1,309	1,482	0	193	0.210	-0.100	-0.050
Others	33,420	59,463	2,967	24,703			
World	486,032	487,959	40,968	40,968			