The Economic Benefits of Sheath Blight Resistance in Rice

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Abstract

The most tangible outcome of a breeding program of any type is increased yield; however, breeding for biotic stresses (maintenance breeding) generally results in pathogen resistance, which can be viewed as mitigating potential crop losses. Economists tend to undervalue the opportunity cost of this type of agricultural research. This study estimates the loss (volume and revenue) in rice production in the Mid-South attributed to the presence of sheath blight, a common fungus in the US. We then ask the counterfactual question: what would the implications be if sheath blight was not present in US rice production. To do this we estimated the additional rice supply from sheath blight resistance and entered it into the RiceFlow model. The RiceFlow model generates global estimates of changes in rice price given an increase supply, as well as changes in consumer and producer welfare. Finally, the counterfactual increased yield and decreased fungicide usage from the absence of sheath blight were analyzed in a Life Cycle Assessment (LCA) model to assess the environmental impact that would have resulted if sheath blight was not present. These results provide insight on how potential genetic resistance to sheath blight could affect producer livelihoods, food security, and environmental sustainability.

Introduction

Rice consumption accounts for more than half of the daily caloric intake of over three billion people globally, most of which are located in rapidly growing low-income countries (Pareja et al., 2011). Accordingly, rice supply must increase by approximately 30% to meet the projected demand in 2050 (Mohanty, Wailes, and Chavez, 2010; Food and Agriculture Organization, 2015). Because rice provides 21% of global human per capita energy and 15% of per capita protein (International Rice Research Institute [IRRI] , 2013), even moderate supply shocks can have large impacts on low-income rice consumers. For example, in 2008 when rice prices tripled due largely to trade restrictions in India and Egypt, the World Bank estimated that an additional 105 million people were pushed into poverty (World Bank, 2013). This event was occurred following a reduction of only 8% in trade from 2007 (Childs, 2009).

While supply shocks typically manifest themselves through trade restrictions or abiotic events such as drought and heat, biotic events such as disease and fungus can alter global supply. In China alone, 15 to 20 million ha of rice are affected with Sheath Blight (*Rhizoctonia solani*) annually, causing losses of up to six million tons (Xie et al. , 2008); equivalent to about 1% of global rice production. Losses due to sheath blight (ShB) are estimated at 10% annually in India and 20% in Thailand (Boukaew and Prasertsan, 2014). Average global yield losses attributable to ShB range from 10-30% (Xie et al. , 2008), and can reach over 50% during years with severe outbreaks (Qingzhong et al. , 2001). Unlike abiotic events which cannot be altered, losses from biotic stresses in rice production such as rice ShB and rice blast (*Magnaporthe oryzae)* can be reduced through both fungicide application and various levels of genetic resistance via rice breeding programs.

Unlike rice blast for which there are resistant cultivars available to rice producers in the United States, there are currently no available ShB resistant cultivars for commercial production. This is mainly due to the lack of sources for resistance in cultivated and wild rice species possessing ShB resistance traits (Brooks, 2007). As such, integrated measures of fungicide treatment combined with moderately resistant varieties are the principle means to control ShB globally; however, this is both expensive (for producers in low-income countries) and possess a toxicity problem to the environment (for both low and high-income countries) (Baby and Manibhushanrao, 1993; Qingzhong et al. , 2001).

The relatively high yields of American rice production ha^{-1} are partly attributed to the large public investment in rice breeding, pathology, entomology and agronomy. However, U.S rice production is still affected by various biotic stresses such as ShB. In the mid-south of the United States (Arkansas, Louisiana and Mississippi) losses from ShB can be severe and prevalence can be widespread. During the 2001 growing season, it was reported that 50-66% of Arkansas (the largest rice producing state in the United States) rice fields were infected with ShB, subsequently leading to yield losses between 5-15% (Tan et al. , 2007; Reddy MS, 2014).

Symptoms of ShB in rice production include, lesion formation on infected sheaths of lower rice leaves which may lead to softness of the stem and subsequently stem lodging (Wu et al. , 2012). The ShB fungus is spread on rice fields by lesion formation from tiller to tiller on an infected plant or across water surface to nearby plants. The fungus is also spread across touching plant parts (leaf to leaf), thus causing infections on adjoining plants. In addition, the fungus survives between crops as “sclerotia” that can lie dormant in the soil for at least two to three years (University of Arkansas Cooperative Extension Service [UACES], 2015). Furthermore, ShB severity is impacted by, the ecology, development stage of rice at infection, cultural practices, excessive nitrogen fertilizer rates at pre-flood, and cultivar resistance to ShB (D. E. Groth, Rush, and Hollier, 1992).

Breeding efforts for rice ShB resistance in the U.S and globally have not been fruitful to date, as the fungus continuously evolves making even short term resistance difficult to achieve. Historical planting of rice varieties in the Mid-South of the U.S. from 2000-2014 indicate that only 3.91% -equivalent to 148,315 ha - of seeded area - were classified moderately-resistant to ShB (Rice Technical Working Group [RTWG] , various years). The low incident of even moderately resistant ShB cultivars has been partly attributed to the lack of source for resistant genes in both domesticated rice and its related wild species (Hashiba, 1984; D. E. Groth, Rush, and Hollier, 1992). Of the twelve rice chromosomes identified, only one out of six quantitative trait loci associated with ShB resistance appears to be independent of plant height, a morphological trait associated with ShB resistance (Z. Li et al. , 1995). Accordingly, identifying genes that offer high levels of partial ShB resistance and pyramiding these genes through biotechnology, could offer complete ShB resistance (Pan et al. , 1999; Reddy MS, 2014). However, the speed with which this can be achieved, which is important given that ShB continuously evolves, thorough breeding could be constrained by current genetically modified food (GM) regulations.

In practice, plant breeding programs generally have two objectives; breeding for high yields and breeding for resistance against biotic and abiotic stresses (maintenance breeding). Whiles the former leads to tangible outcomes such as increased production ha^{-1}, the later generally results in pathogen resistance for a crop specimen which are often times less tangible. Thus, policy makers tend to undervalue the opportunity cost of informative agricultural research, specifically in maintenance breeding. Thus, this study sets out to quantify the economic and environmental impact of ShB resistance in the Mid-South of the US.

From an economic/producer standpoint, ShB resistance allows for higher yields as genetic yield potential is not undermined by ShB outbreaks and subsequent yield losses. Accordingly, the economic impact of maintenance breeding, or maintaining yield at its genetic potential, can be as great, if not greater than the impact of the genetic yield increases experienced by breeding programs (Marasas, Smale, and Singh 2003). In addition, the literature as also shown that a lack of maintenance breeding is causing a slower rate of rice yield increase in South Asia (Pan et al. 1999). Thus reinforcing the idea that if maintenance breeding programs are discontinued or diminished, meeting the increasing demand for rice will be stifled globally.

While higher yields (and the mitigation of fungicide application) is beneficial to producers, consumers also benefit as higher supplies lead to lower market prices. Many low-income countries are highly price inelastic to movements in rice price as there are no substitutes for rice in many cultures. The literature as shown that, a 50% increase in rice price would lead to at least 32 million people falling back into poverty with the possibility of up to 100 million people (Asian Development Bank, 2008; Ivanic and Martin, 2008). Conversely, any price reduction in rice could have large positive impacts on alleviating poverty. While increased yield potential is becoming increasingly difficult, breeding for pathogen resistance could be one way to increase supply without increasing genetic yield potential.

Sheath blight resistance would also provide environmental benefits in the form of reduced fungicide applications and greenhouse gas emissions associated with the production and application of fungicide. The fungicides used in the mid-south to combat rice ShB are Quilt Xcel™ (active ingredients: 13.5% Azoxystrobin and 11.7% Propiconazole) and Quadris™ (active ingredient: 22.9% Azoxystrobin). These fungicides, given their toxicity levels for humans and length of their residual effects could have adverse effects on human health and the environment.

Currently, rice producers who experience elevated costs and yield losses and consumers who experience higher prices due to a diminished supply as a function of ShB, assume the costs of the absence of ShB resistance. While the literature is rich on the economic impacts of breeding programs for rice (Alpuerto, Norton, and Alwang, 2008; Annou, Wailes, and Cramer, 2000; Guimaraes, 2009; Nalley and Barkley, 2010; Singh et al. , 2013) it is nearly void of the economic impacts of rice maintenance breeding programs. Thus, we ask the counterfactual question, if all cultivars in the mid-south were ShB resistant, benefits could be realized by producers, consumers, and the environment? To do this, this study utilizes (1) county/parish-level rice varietal yields with their associated ShB susceptibility rating and seeded area in Arkansas, Louisiana and Mississippi for 2002-2014, (2) simulates ShB infection rates based off historical infection data and (3) from those simulated infected hectares simulate yield loss based on historical yield loss data. From this, we estimated the additional rice volume that would have been available in the absence of ShB for 2002-2014.

This estimated additional supply from ShB resistance was then put into the RiceFlow model (Durand-Morat and Wailes, 2010) in order to answer the counterfactual question: what would the implications be if ShB was not present in US rice production. The RiceFlow model generates domestic and global estimates of changes in rice price given an increase supply, as well as changes in consumer and producer welfare. Finally, the counterfactual increased yield and decreased fungicide usage from the absence of ShB were analyzed in a Life Cycle Assessment (LCA) model to assess the environmental impact that would have resulted if ShB and its associated fungicide applications were not present. These comprehensive results provide insight on how potential genetic resistance to ShB in the Mid-South could affect producer livelihoods, food security via increased rice supply, and environmental sustainability. Furthermore, these estimates provide important information to donors and breeding programs globally on the importance of not just increasing genetic yield potential but maintaining it simultaneously.

Materials and Methods

Following similar studies in the literature (Nalley et al. , 2016), this study calculates the potential benefit of genetic ShB resistance for rice production in Arkansas, Mississippi and Louisiana using two ShB outbreak and response scenarios.[1] Actual annual varietal planting area was collected from RTWG (various years) for each rice- growing county/parish in Arkansas, Louisiana, and Mississippi from 2002 to 2014. Additionally, annual varietal yield data for each county/parish - viewed as “yield potential” -were also collected from university-run experiment stations (Arkansas Agricultural Experiment Station [AAES], various years.; Louisiana State University Agricultural Center [LSU AgCenter] , various years; Mississippi Agricultural and Forester Experiment Station [MAFES], various years). The yields form the experiment stations are viewed as “yield potential” because, the rice cultivars are grown in conditions that favor its growth; with biotic and abiotic stresses effectively controlled, and with proper supply of nutrients and water. Nonetheless, yields are often greater on experimental test plots than on producers’ fields, but the relative yield difference between varieties is comparable. According to Brennan (1984), the most reliable sources of relative yields are cultivar trials outside of actual farm observations.

Note that, for some years, data on county/parish specific varietal yields form the experiment stations were missing. As such, for a given year in which no county/parish specific

[1] In 2015, the percentage of US rice harvested in Arkansas, Louisiana, and Mississippi was 49.94%,16.12%, and 5.79%, respectively (United States Department of Agriculture 2016).

varietal yields were available, the annual county/parish average yield was used for that year. The dataset consists of 47 rice varieties (8 hybrids and 39 conventional), 33 rice-growing counties in Arkansas, 35 parishes in Louisiana, and 18 counties in Mississippi for a total of 5,733 yield observations.

Sheath Blight Ratings

Annual ShB susceptibility ratings for each variety derived from historical observations of test plots and in grower fields across each state, conducted by university-run experiment stations were used in this study (AAES; LSU AgCenter; MAFES). Given that varieties can become more susceptible to ShB over time as even partial genetic resistance can break down, the most recent rating was used for each year. A Likert scale of ShB susceptibility is used by the University run stations to classify rice cultivars as; Moderately Resistant (MR), Moderately Susceptible (MS), Susceptible (S) and Very Susceptible (VS). In 2014, two verities seeded across the Mid-South of the United States were rated as MR, seven as MS, eleven as S, and three as VS; and their respective area sown are approximately equal to 32,000 ha, 219,000 ha, 419,000 ha, and 94,000 ha, respectively. A list of ShB susceptibility rating by variety as of 2015 can be found on Table A1.

Sheath Blight Outbreak and Yield Loss Rate

It is common amongst University extension services to annually rate ShB susceptibility, however, it is uncommon to obtain detailed reports ShB outbreaks, or their associated yield losses. Extensive, systematic field-level yield and quality loss estimates due to rice ShB have not been developed in the U.S. This is partly due to a lack of data on the numerous and often simultaneous diseases affecting rice, as well as the underground damage associated with root diseases, and the lack of qualitative information on distribution and severity on commercial fields. In addition, field-level estimates of ShB loss have also been difficult to estimate. Often times outbreaks are contained to one portion of a field and as such do not warrant the attention of extension agents to collect extensive data. Crop consultants will typically scout for ShB and give producers recommendations based on field observations. To our knowledge there is not an extensive database of locations or magnitude of ShB outbreaks or losses in the Mid-South of the United States.

Whilst, ShB outbreak acreage are scarce in the literature, Norman and Moldenhauer (various years) provide estimates of the annual percentage of sampled commercial rice fields across Arkansas that required a fungicide application for ShB. According to Norman and Moldenhauer (various years), on average from 2002 to 2014 19.05% of sampled commercial rice fields across Arkansas were annually treated with fungicide application for ShB; with a maximum of 31.89%. However, similar studies for Louisiana and Mississippi did not exist at the time of the study, as such it was assumed that there were proportional fungicide applications in all three states based on the Arkansas data. Ideally, state- specific distributions would be preferred given all three states have different ecologies, cultural practices, and distribution of cultivar resistance. Thus, using the Arkansas historical data reported by Norman and Moldenhauer (various years), a triangular distribution with a mean of 19.05% truncated between 0.00% and 31.89% infected area was used to simulate ShB infection rate.

The literature is also scarce regarding replicated field trials that document yield loss associated with ShB on commonly cultivated rice varieties in the U.S. To illustrate, several studies base on field experiments have analyzed varietal difference in ShB development and its associated with yield loss at different levels of nitrogen fertilizer application, fungicide application, or both (D. E. Groth and Bond, 2006; D. E. Groth, 2008; D. E. Groth and Bond, 2007; D. Li et al. , 2012; Tang et al. , 2007; Savary, Castilla, and Elazegui, 1995; Andersson et al. , 2012). However, none of these studies provide estimates of yield differences between ShB inoculated and un-inoculated for the same variety or across different varieties. The overall findings from the aforementioned studies are that, fungicide application improved canopy light interception rate, and grain filling reduced the degree of ShB. Groth (2016) does provide typical yield losses associated with ShB for the four susceptibility ratings normally used by extension services across the United States. Groth (2016) indicates that typical yield losses associated ShB in the field are 15-25%, 10-20%, < 10%, and 5-10% for rice varieties that are rated as VS, S, MS, and MR, respectively.

Given the lack of locational and varietal- specific rates of yield response to ShB, the estimates put forth by Groth (2016) were used in this study to estimate yield losses based on ShB susceptibility ratings as they were similar to the other two ranges +/- 15% put forth in the Mid-South (Tan et al. , 2007; Reddy MS, 2014). Furthermore, because yield loss caused by ShB are determined by the severity and timing of the infection, a static percentage yield loss would not be appropriate in this study; as such, a simulated range of yield loss was developed based on susceptibility rankings and empirical losses, as reported by Groth (2016). For each susceptibility ranking, the study simulates its yield loss rate 1000 times, assuming a triangular distribution such that the possible minimum and maximum of the simulations are equivalent to those reported by Groth (2016). The mean percentage yield loss for the various ShB susceptibility ratings are: 0.00%, 5.00%, 7.50%, 15.00%, and 20.00%, for R, MR, MS, S, and VS, respectively (Table 1).

Cost of Sheath Blight Mitigation

The prices of the two most common fungicides (Quilt Xcel™ and Quadris™) used in the U.S. to combat rice ShB vary by retailer, region and are affected by dealer rebates. In 2015, the average cost for Quilt Xcel to a rice producer was \$46.23 liter^{-1} in the Arkansas Delta region (Driggs, 2015). Comparatively, the average cost for Quadris was \$72.65 liter^{-1}. The recommended application rate for Quilt Xcel for ShB is 1.56 l ha^{-1}, and for Quadris, it is 0.77 l ha^{-1}. Thus, the estimated per application cost of Quadris is $72.13 ha^{-1}, and for Quilt Xcel, it is US $55.79 ha^{-1}.

Four crop dusting services in the Delta of Arkansas and Mississippi were contacted in August, 2015, and the average aerial fungicide application charge $ha^{-1}$was $19.77. Given that the data does not exist on which fungicide producers actually used to mitigate ShB we assume that it's evenly split. As such, the average price of both fungicides (Quadris and Quilt Xcel), $63.96 ha^{-1}, was taken and then added to the cost of aerial application for a total cost per application of fungicide of $83.73 ha^{-1}. Finally, because both the historical cost of aerial application and fungicide costs were prohibitive to obtain, they were assumed as constant across time, although adjusted for inflation.

Sheath Blight Outbreak Scenario One

Scenario one simulates the area of rice produced in all three states that are infected with ShB based on empirical data (Norman and Moldenhauer, various years). The infected area is then treated with two applications of fungicide to mitigate this outbreak with no associated yield loss. Extension recommendations suggest using two applications of fungicide for severe ShB conditions on S and VS cultivars (UACES, 2015). Thus, scenario one mimics many rice producing years where an outbreak occurs but either a producer or a crop consultant catches the fungi in its early stages and its treated early and only costs are incurred not yield losses.   Scenario one was modeled as follows:

$$TC_t^1 = 2C_h\lambda \sum_t A_{ilt} \qquad (1)$$

Where the annual total cost of ShB for scenario one (TC_t^1) is the summation of all actual historic hectares of susceptible rice varieties (i) sown in each rice-producing county/parish (l) in a given year (t), multiplied by the simulated infection rate of ShB (λ), and twice the cost of fungicide application per hectare (C_h). Equation (1) is a function of time; this is because county level varietal distribution and the area sown to ShB susceptible varieties changes annually. In addition, all non-ShB-resistant varieties have equal probabilities of infection. That is, each variety, regardless of susceptibility ratings, has the equivalent probability of an infection based on historical data and the simulations run in the model. Individual ratings effect probability of yield loss but not probability of infection.

Blight Outbreak Outbreak Scenario Two

Scenario two simulates a corresponding yield loss associated with the infections simulated in scenario one, based on the loss estimates put forth by Groth (2016). Similar to scenario one, the infected areas are assumed to be associated with two applications of fungicide, but with an associated yield loss which is a function of the ShB susceptibility rating. While a percentage yield loss is simulated for each susceptible variety, it is recognized that each variety has a different yield potential. As such, each variety's average yield is denoted by county, as reported by each state's extension service (AAES; LSU AgCenter; MAFES). Thus a simulated 5% yield loss for two MS varieties would be different given that the two varieties had different yield potentials. Scenario two was modeled as follows:

$$TC_t^2 = TC_t^1 + \sum_t \gamma_i Y_{il} P_{gt} \tag{3}$$

Total cost (for all three states) of ShB for scenario two (TC_t^2) is the summation of the annual, total cost simulated for scenario one (TC_t^1), and the product of the yield associated with variety *i* (Y_{il}), simulated yield loss rate due to ShB (γ_i), and the season-average farm price for rice (P_{gt}), relevant to variety *i*. The price (P_{gt}), is measured in \$ Mg^{-1} and aggregated at grain type level

(g = 0 for medium, g = 1 for long grain) as reported by United States Department of Agriculture (2016). The variable γ_i is simulated a 1000 times.

Impact on the U.S. Rice Market

In order to assess the impact of rice ShB on the U.S. rice market according to the findings reported for each scenario, the RiceFlow model (Durand-Morat and Wailes, 2010) is used. RiceFlow is a multi-region, multi-product, spatial partial equilibrium model of the world rice economy that is used extensively to assess different aspects of the global rice economy. For instance, Thompson et al. (2015) used RiceFlow to assess the impact of the U.S. Liberty Link rice contamination. Furthermore, Briones et al. (2012) and Wailes, Durand-Morat, and Diagne (2015) have used the model to assess alternative rice policy options in Southeast Asia and West Africa, respectively. In the model, the global rice economy is disaggregated into 73 regional markets and 9 rice commodities derived from the combination of rice type (long, medium, and fragrant rice) and milling degree (paddy, brown, and milled rice), which allowed us to analyze the impact of ShB on the prices consumers obtain in local markets.

We assume a completely fixed supply of land and limited mobility of land across rice types in all countries. This, coupled with Leontief technology assumptions at each level of the production tree, results in very inelastic output supply functions. Hence, the results presented in this study can be understood as short-run outcomes controlling for potential supply-expansionary effects in other countries induced by rice ShB outbreak in the U.S. The most up to date calibrated version of the RiceFlow model is for production year 2013 and thus all results elicited from it will only be from 2013. Thus, RiceFlow is augmented with the counterfactual yield increases due to the elimination of ShB and the subsequent producer and consumer surplus changes estimated.

Environmental Impacts of Sheath Blight Resistance

Following similar studies in the literature (Nalley et al. , 2016), we use a lifecycle assessment (LCA) to provide a quantitative comparison of the cradle-to-farm gate environmental benefits of rice ShB elimination in the Mid-South. The goal was to provide a comparison (rice production with and without the presence of ShB) for the functional unit kg^{-1} of rice that is dried to 12.5% moisture at the farm-gate ready for transportation to milling. The principal differences between the scenarios are yield (loss associated with ShB infection) and fungicide application to susceptible varieties. Sheath blight-susceptible varieties subject to infection rates and yield losses are described on Table 1 and were subsequently sprayed with two applications of fungicide. The inputs for each system in terms of land preparation, planting, fertilizer and pesticide application (except as noted), and harvesting ha^{-1} were taken from the University of Arkansas extension budgets (UACES, 2016) and used in the LCA.

The TRACI 2.1 LCA framework, which was developed by the US Environmental Protection Agency for conditions in the United States, was used to estimate potential environmental impacts arising from differences in production (Bare, Gloria, and Norris, 2006). In order to minimize bias in the comparison between the two scenarios, a paired Monte Carlo simulation approach was adopted using SimaPro 8.1, which selects variates from each unit process in the supply chain and computes the difference between the two (ShB susceptible vs. resistance) production systems. This approach ensures that additional variability from independent simulations of the supply chains is not introduced.

From this methodology, the differences were ascertained between the ShB-prone and ShB -resistant rice production from a holistic environmental standpoint. Most importantly this methodology allows for testing for statistical differences and magnitudes for ten environmental categories between ShB-prone and ShB -resistant rice production, *ceteris paribus*.

Results

Producer Impacts

Tables 3 and 4, present the results for the total (aggregated annual) economic cost of scenarios one and two, Table 4 present the results for the U.S. rice market effects of ShB, and Table 5 presents the results of the LCA. Monetary values throughout the paper are converted to 2014 monetary terms using annual CPI retrieved from (International Monetary Fund [IMF] 2016).

In scenario one, ShB infected hectares of rice were simulated and an associated cost was estimated according to spraying these hectares twice with the appropriate fungicide at a cost of \$167.50 ha^{-1}. [2] The results indicate that given an assumed infestation rate of 19.05%, the historical mean of all susceptible varieties, applied to all ShB susceptible hectares, producers spend on average \$21.44 million on ShB mitigation annually. This can be viewed as a best case scenario as there is no assumed yield loss and the costs are simply absorbed by the producer but there are no supply effects in the market.

The results from scenario two shows that given an assumed infestation rate of 19.05% applied to all ShB susceptible hectares, producers lose on average \$68.48 million annually due to ShB mitigation; thus a \$47.04 million yield loss in in addition to the \$21.44 million lost to ShB mitigation. At the State level the annual average cost of ShB for scenario two are estimated at \$45.94 million, \$14.66 million, and \$7.88 million, respectively for Arkansas, Louisiana, and

[2] Fungicide cost are adjusted for inflation.

Mississippi. The calculated potential economic loss as a share of the total value of rice production in each state for the period 2002-2014 is estimated at 3.89%, 4.23%, and 4.57%, respectively, for Arkansas, Louisiana, and Mississippi. [3] Overall, the potential economic loss due to ShB is estimated at 4.03% for scenario two as a share of the total value of rice production in the Mid-South, U.S. Furthermore, these yield losses have more than simple revenue implications for producers. Reduced supply also affects consumers. As such the results from scenario two are inputted into the RiceFlow model to calculate market price implications and subsequent consumer welfare changes.

Consumer Impacts

We use the RiceFlow model to assess the market impact of ShB mitigation and its effect on consumer prices. In other words, the simulation entails estimating the conditions in the rice market in the absence of ShB. Table 4 below presents the results for the key selected variables from the estimated counterfactual decreased costs and increased yields associated with ShB from the scenarios. That is, we present the counterfactual results from Table 3 asking the question, "what if the yield losses and increased costs of production calculated from scenario two did not exist?"

The cost savings due to lower fungicide use (scenarios 1 and 2) are small relative to the total production cost, and consequently, the cost savings generate no significant changes in the U.S. rice supply chain. However, U.S. consumers are expected to save an estimated $51 million annually when the yield losses and mitigation costs are accounted for (scenario 2). Most of the benefits are due to lower retail prices as aggregate rice demand changes only marginally. Most of the benefits ($43 million) come from the consumption of long-grain rice, which undergoes a price decrease of about \$19 ton^{-1}. These results suggest that ShB alleviation increases rice yields and production, as well as subsequently lowers long-grain rice price.

In turn, ShB alleviation improves the competitiveness of U.S. rice and expands long-grain exports by 101,000 Mg or 3.0% and all rice exports by 111,000 Mg or 2.4%. In other words, the results suggest that the excess supply generated by the alleviation of rice ShB in the US could be sufficient enough to feed 1.7 million people every year at the average per-capita consumption of 65 Kg. This suggestion is impressive considering the US is a small rice producer by global standards and likely experiences less loss from ShB than the global average because of its ongoing investment in production technology and management.

Environmental Impacts

The Study evaluated the environmental impacts associated with ShB through a counterfactual argument. Specifically, we present comparisons of the current average condition in which an acre of a susceptible variety is produced compared to a variety that is resistant to ShB. The difference between the two groups is expressed in yield loss, whose probability is derived from Table 1. The ranges for infection rate in yield loss of a susceptible variety are compared in Table 4. The susceptible rating was chosen to analyze from all possibilities of susceptible ratings (MR, MS, S and VS) because, in 2014, it accounted for the highest amount of acreage sown in the Mid-South, 29.14%.

The cradle-to-farm gate LCA approach was followed in performing the comparison; meaning that all inputs from production of fertilizers, through cultivation, harvest, and drying to a moisture content of 12%, have been included. The only differences between the two scenarios were yield differences and the elimination of fungicide usage for the resistant variety. Because these differences are uni-directional, and no other differences between the scenarios were introduced, the Monte Carlo simulations did not result in uncertainty regarding whether or not there are benefits from the elimination of ShB. Notably, because there is uncertainty inherent in the system model, there is also uncertainty in the mean values for both scenarios, but no uncertainty that they are significantly different. The students t-tests show that for a pairwise comparison of 1000 simulations, the P value is less than 10^{-8} (Table 5).

These simulations show that the introduction of ShB resistance in rice production results in lower global warming potential, carcinogenicity, ecotoxicity, eutrophication, fossil fuel depletion, and smog and ozone depletion (Table 5). The negative results for non-carcinogens are the result of modeling heavy metal uptake by the rice plants-the higher the yield, the greater the uptake, which results in decreased ecotoxicity at the farm; however, there is high uncertainty in these results, and we do not recommend any mitigation actions be taken on the basis of this result. Importantly, in using the well-established categories defined by the TRACI 2.1 LCA framework, it is evident from Table 5 that, ShB resistance in rice leads to multiple environmental improvements, as compared to ShB -susceptible varietal production.

These results are important as agricultural scientists attempt to sustainably produce 70% more calories for a growing human population, which is projected to be demanded by 2050 (Adhya et al., 2014). The environmental benefits of ShB resistance highlight two important concepts. First, by simply obtaining yield potential we improve our input use efficiency per unit of output and lessen our environmental impact. Second, by breeding resistance to a pathogen we reduce the environmental load of the fungicide that would have to be applied also lessening our environmental impact Mg^{-1}.

Discussion

The United Nations estimates that by 2050, global population would have increased by 33% to 9.6 billion. Because rice provides 21% of global human per capita energy and 15% of per capita protein (IRRI, 2013), the moderate price/supply shocks can have large impacts on low-income rice consumers. In comparison to other rice-producing countries, the U.S is a relatively small producer supplying only 1.3% of the world's rice; however, the U.S has been among the top five rice exporters for several decades (Lakkakula et al. , 2015). Thus, any change in supply in the U.S. market could have global ripple effects in terms of price and food security. This study has illustrated that maintenance breeding, for the alleviation of ShB, could have significant impacts on domestic rice producers, global rice consumers and thus food security. As the rice yield gap closes and the yield ceiling approaches, maintenance breeding for pathogen resistance like ShB is one way to increase food supply without increasing yield potential.

The objective of most breeding programs is to increase the yield celling, but with crops such as rice and wheat which have not been approved for genetic modification in the U.S, the yield ceiling is approaching quickly. This study indicates that there are still large gains to be made through maintenance breeding that would not need to raise the yield ceiling. Most cost-benefit analysis of breeding programs only focus on yield enhancements and not yield loss avoidance through pathogen resistance. This study sheds economic and environmental light on the importance of valuing yield loss avoidance.

As genetic gains for crops like rice and wheat continue on their increasing at a decreasing rate pace, breeding programs may need to shift their focus from yield enhancement to yield loss avoidance via biotic and abiotic stress resistance. The results of this study shed light on the fact that not only are the economic effects of yield loss avoidance through breeding programs significant but as are the environmental effects. This paper highlights two important aspects of future breeding programs for potential donors or evaluators. First, while increasing yields should be a priority moving forward, it should not be at the expense of maintenance breeding as that could simply increase the yield gap. Second, to properly evaluate a breeding program, yield loss avoidance from biotic and abiotic stress resistance must be estimated, else the program could be vastly undervalued both from an economic and environmental perspective.

References

Adhya, K., B. Linquist, T.Searchinger, R. Wassmann and X. Yan. Wetting and drying: reducing greenhouse gas emissions and saving water from rice production. Working Paper, Installment 8 of Creating a Sustainable Food Future. Washington, DC: World Resources Institute, 2014. Available at: http://agritech.tnau.ac.in/ta/Agriculture/pdf/csa_pdf/Wetting_and_drying.pdf. Accessed Nov. 17, 2016.

Alpuerto, V., G. Norton and J. Alwang. Economic impact analysis of marker-assisted breeding in rice. American Agricultural Economics Association Annual Meeting, 1‐28, 2008. Available online at http://vtechworks.lib.vt.edu/handle/10919/34340. Accessed Nov. 1, 2016.

Andersson, H., S. Arpaia, D. Bartsch, J. Casacuberta, H. Davies, P. du Jardin and G.Flachowsky Scientific opinion addressing the safety assessment of plants developed through cisgenesis and intragenesis. EFSA Journal 10, no 2 (2012), 2561. doi:10.2903/j.efsa.2012.2561.

Annou, M., E. Wailes and G. Cramer. Economic analysis of adopting Liberty Link rice. Rice Situation and Outlook, 2000. Available online at http://usda.mannlib.cornell.edu/usda/ers/RCS-yearbook//2000s/2000/RCS-yearbook-11-29-2000.pdf Accessed Mar. 5, 2016.

Arkansas Agricultural Experiment Station (AAES). Arkansas Rice Performance Trials (ARPT). Various years; for 2002 to 2015 2015. Available online at http://arkansasvarietytesting.com/home/rice/. Accessed Apr. 8, 2016.

Asian Development Bank. Food Prices and Inflation in Developing Asia: Is Poverty Reduction Coming to an End?, 2008. Available online at http://www.adb.org/sites/default/files/publication/29075/food-prices-inflation.pdf. Accessed May 18, 2016.

Baby, U. and K. Manibhushanrao. Control of rice sheath blight through the integration of fungal antagonists and organic amendments. Tropical Agriculture 70(1993): 240‐244.

Bare, J., T. Gloria and G. Norris. Development of the method and U.S. normalization database for Life Cycle Impact Assessment and sustainability metrics. Environmental science & technology 40(2006): 5108‐5115.

Boukaew, S. and P. Prasertsan. Suppression of rice sheath blight disease using a heat stable culture filtrate from Streptomyces philanthi RM-1-138. Crop Protection 61(2014): 1‑ 10. doi:10.1016/j.cropro.2014.02.012.

Brennan, John. Measuring the Contribution of New Varieties to Increasing Wheat Yields. Review of Marketing and Agricultural Economics 52(1984): 175-195.

Briones, R., A. Durand-Morat, E. Wailes and E. Chavez. Climate Change and Price Volatility: Can We Count on the ASEAN Plus Three Emergency Rice Reserve? ADB Sustainable Development Working Paper Series 24,2012. Available online at http://www.adb.org/sites/default/files/publication/29971/adb-wp-24-climate-change-price-volatility.pdf Accessed Mar 4, 2016.

Brooks, Steven. Sensitivity to a Phytotoxin from Rhizoctonia solani Correlates with Sheath Blight Susceptibility in Rice. Phytopathology 97(2007): 1207‑ 1212. doi:10.1094/PHYTO-97-10-1207.

Childs, Nathan. Rice Situation and Outlook Yearbook/RCS-2008/February 2009, 2009. Available online at http://usda.mannlib.cornell.edu/usda/ers/RCS-yearbook/2000s/2009/RCS-yearbook-02-17-2009.pdf. Accessed Nov 2, 2016.

Driggs, K. Personal Communications with Agronomic Service Representative for Syngenta, Little Rock Arkansas. Communications August 27, 2015., 2015.

Durand-Morat, A. amd E. Wailes. Riceflow: A Multi-region, Multi-product, Spatial Partial Equilibrium Model of the World Rice Economy. University of Arkansas, Department of Agricultural Economics and Agribusiness, 1 juillet 2010. Available online at http://econpapers.repec.org/RePEc:ags:uarksp:92010. Accessed Oct 19, 2016.

Food and Agriculture Organization [FAO]. FAOSTAT. Food and Agriculture Organization of the United Nations, 2015. Available online at http://faostat.fao.org/. Accessed Oct. 31, 2016.

Groth, Don. Effects of cultivar resistance and single fungicide application on rice sheath blight, yield, and quality. Crop Protection 27(2008): 1125‑ 1130. doi:10.1016/j.cropro.2008.01.010.

Groth, D. and J. Bond. Effects of Cultivars and Fungicides on Rice Sheath Blight, Yield, and Quality. Plant Disease 91(2007): 1647‑ 1650. doi:10.1094/PDIS-91-12-1647.

Groth, D and J. Bond. Initiation of Rice Sheath Blight Epidemics and Effect of Application Timing of Azoxystrobin on Disease Incidence, Severity, Yield, and Milling Quality. Plant Disease 90(2006): 1073‑ 1076. doi:10.1094/PD-90-1073.

Groth, D., M. Rush and C. Hollier. Prediction of Rice Sheath Blight Severity and Yield Loss Based on Early Season Infection. Louisiana Agriculture - Louisiana Agricultural Experiment Station (USA), 1992. Available online at http://agris.fao.org/agris-search/search.do?recordID=US9333475. Accessed Sep. 3, 2016.

Groth, Don. Rice Sheath Blight Disease Management, 2016. Available online at http://www.lsuagcenter.com/~/media/system/e/7/c/9/e7c9e3c94769feffdd8a5283feed0687/sheathblightmanagement.pdf. Accessed Sep 7, 2016.

Guimaraes, E. Rice breeding. Cereals, 99‑ 126, 2009. doi:10.1007/978-0-387-72297-9.

Hashiba, T. Estimating method of severity and yield loss by rice sheath blight disease [Rhizoctonia solani]. Bulletin of the Hokuriku National Agricultural Experiment Station, 1984. Available online at http://agris.fao.org/agris-search/search.do?recordID=US201302012415. Accessed Oct. 4, 2016.

International Monetary Fund (IMF). International Financial Statistics (IFS). IMF elibrary Data, 2016. Available online at http://data.imf.org/?sk=5DABAFF2-C5AD-4D27-A175-1253419C02D1. Accessed Nov. 17, 2016.

International Rice Research Institute (IRRI). Rice knowledge bank, 2013. Available online at http://www.knowledgebank.irri.org/. Accessed May 8, 2016.

Ivanic, M. and W. Martin. Implications of higher global food prices for poverty in low-income countries. Agricultural Economics 39 (2008): 405‐416. doi:10.1111/j.1574-0862.2008.00347.x.

Lakkakula, P., B. Dixon, M. Thomsen, E. Wailes and D. Danforth. Global rice trade competitiveness: a shift-share analysis. Agricultural Economics 46(2015): 667‐676. doi:10.1111/agec.12162.

Li, D., Q.Tang, Y. Zhang, J. Qin, H. Li, L. Chen, S.i Yang, Y. .Zou and S.Peng. Effect of Nitrogen Regimes on Grain Yield, Nitrogen Utilization, Radiation Use Efficiency, and Sheath Blight Disease Intensity in Super Hybrid Rice. Journal of Integrative Agriculture 11(2012): 134‐143. doi:10.1016/S1671-2927(12)60791-60793.

Li, Z., S.Pinson, M. Marchetti, J. Stansel and W. Park. Characterization of quantitative trait loci (QTLs) in cultivated rice contributing to field resistance to sheath blight (Rhizoctonia solani). TAG. Theoretical and applied genetics. Theoretische und angewandte Genetik 91(995): 382‐388. doi:10.1007/BF00220903.

Louisiana State University Agricultural Center (LSU AgCenter). Louisiana Rice Production Handbook. Various years; 1999,2099, and 2014, s. d. Available online at http://www.lsuagcenter.com/portals/communications/publications/publications_catalog/crops_livestock/rice/rice-production-handbook1. Accessed on May 9, 2016.

———. Rice Varieties and Management Tips. Various years; 2003, 2014, 2015, and 2016. Available online at http://www.lsuagcenter.com/NR/rdonlyres/4F5F83A3-20FA-4391-813D-9BB69C54E99F/100040/pub2270RiceVarieties2015FINAL.pdf. Accessed May 3, 2016/

Marasas, C.., M. Smale and R. Singh. The economic impact of productivity maintenance research: Breeding for leaf rust resistance in modern wheat. Agricultural Economics, 29(2003):253‐263. doi:10.1016/S0169-5150(03)00052-5.

Mississippi Agricultural and Forester Experiment Station (MAFES). Mississippi Rice Variety Trials. Various years; for 2002 to 2015. Available online at http://www.mafes.msstate.edu/variety-trials/archive.asp#rice. Accessed Jun 3, 2016.

Mohanty, S., E. Wailes and E. Chavez. The global rice supply and demand outlook: the need for greater productivity growth to keep rice affordable. In Rice in the Global Economy, International Rice Research Institute (IRRI), 2010: 175‐87.

Nalley, L. and A. Barkley. Using portfolio theory to enhance wheat yield stability in low-income nations: An application in the Yaqui Valley of Northwestern Mexico. Journal of Agricultural and Resource Economics 35(2010): 334‐347.

Nalley, L., F. Tsiboe, A. Durand-Morat, A.Shew and G. Thoma. Economic and Environmental Impact of Rice Blast Pathogen (Magnaporthe oryzae) Alleviation in the United States. 2016. Forthcoming in the Public Library of Science (PLOS ONE).

Norman, R. and K Moldenhauer. B.R. Wells Arkansas Rice Research Studies. Various years; 2002-2014. Sous la direction de R Norman et K Moldenhauer, K, A. Arkansas Agricultural Experiment Station, s. d. Available online at http://arkansasagnews.uark.edu/1356.htm. Accssed Jul 4, 2016.

Pan, X., M. Rush, X. Sha, Q. Xie, S.Linscombe, S.Stetina and J. Oard. Major gene, nonallelic sheath blight resistance from the rice cultivars Jasmine 85 and Teqing. Crop Science 39(1999): 338‐346.

Pareja, L., A. Fernández-Alba, V. Cesio and H. Heinzen. Analytical methods for pesticide residues in rice. TrAC Trends in Analytical Chemistry 30(2011):270‐291. doi:10.1016/j.trac.2010.12.001.

Qingzhong, M., L. Zhiheng, W. Heying, Z. Shushen and W. Songhong. Research Progress in Rice Sheath Blight. Journal of Shenyang Agricultural University 32(2001): 376‐381.

Yellareddygari, S., M. Reddy, J. Kloepper, K. Lawerence and H. Fadamiro. Rice Sheath Blight: A Review of Disease and Pathogen Management Approaches. Journal of Plant Pathology & Microbiology 5(2014). doi:10.4172/2157-7471.1000241.

Rice Technical Working Group (RTWG). Rice Acreage Summaries. Proceedings of the Rice Technical Working Group (RTWG). Various years 2001-2014. CDROM, s. d.

Savary, S, N. Castilla and F. Elazegui. Direct and indirect effects of nitrogen supply and disease source structure on rice sheath blight spread. Phytopathology 85(1995): 959‐965.

Singh, H., S. Singh, U. Singh, J. Singh, N. Zaidi and S. Mohanty. Economic evaluation of Pusa Rice Hybrid 10 cultivation: A micro-economic evidence of Uttarakhand, India. Indian Journal of Traditional Knowledge 12(2013): 472‐477.

Tan, W., W. Zhang, Z. Ou, C. Li, G. Zhou, Z. Wang and L. Yin. Analyses of the Temporal Development and Yield Losses due to Sheath Blight of Rice (Rhizoctonia solani AG1.1a). Agricultural Sciences in China 6(2007): 1074‐1081. doi:10.1016/S1671-2927(07)60149-7.

Tang, Q., S. Peng, R. Buresh, Y. Zou, N. Castilla, T. Mew and X. Zhong. Rice varietal difference in sheath blight development and its association with yield loss at different levels of N fertilization. Field Crops Research 102(2007): 219‐227. doi:10.1016/j.fcr.2007.04.005.

Thompson, J., E.Wailes, A. Durand-Morat and A. Leister. Welfare Effects of U.S. Liberty Link Rice Contamination. Journal of Agricultural and Applied Economics 47(2015): 243‐259. doi:10.1017/aae.2015.7.

United States Department of Agriculture. (USDA) National Agricultural Statistics Service, Quick Stats 2.0, 2016. Available online at http://quickstats.nass.usda.gov/. Accessed Nov 2, 2016.

University of Arkansas Cooperative Extension Service (UACES). 2016 Crop Enterprise Budgets for Arkansas Field Crops Planted in 2016, 2016. Available online at http://uaex.edu/farm-ranch/economics-marketing/farm-planning/budgets/docs/budgets2016/Manuscript_2016.pdf. Accessed Mar. 17, 2016.

———. 2015. Rice Production Handbook, 2015. Available online at http://www.uaex.edu/publications/pdf/MP192/MP192.pdf. Accessed Mar 17, 2017.

Wailes, E., A. Durand-Morat and M. Diagne. Regional and National Rice Development Strategies for Food Security in West Africa. In Food Security in an Uncertain World (Frontiers of Economics and Globalization, Volume 15). Andrew Schmitz, P. Lynn Kennedy et Troy G. Schmitz. Emerald Group Publishing Limited, 2015: 255‑ 68. doi:10.1108/S1574-871520150000015025.

World Bank. Global Food Crisis Response Program, 2013. Available online at http://www.worldbank.org/en/results/2013/04/11/global-food-crisis-response-program-results-profile. Accessed Apr 26, 2016.

Wu, W., J. Huang, K. Cui, L. Nie, Q. Wang, F.Yang, F. Shah, F. Yao and S. Peng. Sheath blight reduces stem breaking resistance and increases lodging susceptibility of rice plants. Field Crops Research 128(2012): 101‑ 108. doi:10.1016/j.fcr.2012.01.002.

Xie, X., M. Xu, J. Zang, Y. Sun, L. Zhu, J. Xu, Y. Zhou and Z. Li. Genetic Background and Environmental Effects on QTLs for Sheath Blight Resistance Revealed by Reciprocal Introgression Lines in Rice. Acta Agronomica Sinica 34(2008): 1885‑1893. doi:10.1016/S1875-2780(09)60013-4.

Table 1: Simulated Sheath Blight Infection Rate and Yield Loss Rate by Sheath Blight Susceptibility Ratings

	Mean	Max	Min
Infection rate (percent) [a]	19.05	31.89	0.00
Sheath blight yield loss rate by susceptibility rating (percent) [b]			
Resistant	0.00	0.00	0.00
Moderately resistant	5.00	9.85	0.00
Moderately susceptible	7.50	9.91	0.00
Susceptible	15.00	19.87	0.00
Very susceptible	20.00	24.85	0.00

[a] Simulated using estimates of the yearly percentage of Arkansas rice acreage that required a fungicide application, reported by Norman and Moldenhauer (various years)

[b] (Groth 2016)

Table 2: Total Economic Cost of Sheath Blight Simulated Mitigation by Fungicide Application to all Susceptible Rice Hectares in the Mid-South (Arkansas, Louisiana and Mississippi): 2002-2014 [a]

Year	Rice area susceptible to sheath blight (ha)[b]	Rice area infected with sheath blight (ha)[c]		Mitigation cost for sheath blight infected area ($)[de]	
		Mean	Max	Mean	Max
2002	893,961	170,256	284,922	21,669,390	36,263,592
2003	821,557	156,466	261,846	20,438,397	34,203,531
2004	897,428	170,916	286,027	22,898,361	38,320,267
2005	928,665	176,865	295,983	24,287,767	40,645,428
2006	731,918	139,395	233,276	19,842,482	33,206,272
2007	702,628	133,816	223,941	19,720,733	33,002,525
2008	618,693	117,831	197,189	17,956,904	30,050,769
2009	786,007	149,696	250,515	22,812,994	38,177,406
2010	965,606	183,901	307,757	28,333,643	47,416,178
2011	621,071	118,284	197,947	18,818,269	31,492,258
2012	630,555	120,090	200,970	19,507,838	32,646,247
2013	578,421	110,161	184,354	18,079,433	30,255,820
2014	762,580	145,234	243,049	24,322,035	40,702,777
Avg.	764,545	145,609	243,675	21,437,557	35,875,621
Total	9,939,089	1,892,911	3,167,775	278,688,247	466,383,070

[a] Scenario one: Simulated sheath blight outbreak with probabilities from Table 1 on susceptible hectares are sprayed twice with fungicide (the average for Quilt Xcel and Quadris) with no associated yield loss.
See Table A2 for state specific results

[b] Annual area planted to sheath blight susceptible varieties in Arkansas, Louisiana and Mississippi (Proceedings of the Rice Technical Working Group, various years).

[c] Simulated using infection rates shown on Table 1 and sheath blight susceptible hectares listed on this table

[d] Areal fungicide application at a rate of 1.16 l ha^{-1} and at a cost $ 83.7338 ha^{-}1 ($19.77 ha-1 for areal application and $63.96 ha-1 for fungicide)

[e] Values in 2014 $; deflated with consumer price index retrieved from IMF (2015).

Table 3: Total Cost (Mitigation and Yield Loss) of Sheath Blight in the Mid-South: 2002-2014[a]

Year	Real season-average rice price ($ Mg^{-1}) [b]		Total yield loss on sheath blight infected area (Mg)		Total yield loss on sheath blight infected area ($) [c]		Average total loss on sheath blight infested area ($) [d]	
	Medium grain	Long grain	Medium grain	Long grain	Mean	Max	Mean	Max
2002	171.19	120.41	7,663	202,394	25,682,837	52,193,911	47,352,227	88,457,503
2003	282.01	215.62	9,712	204,949	46,930,287	93,364,005	67,368,684	127,567,536
2004	201.43	202.82	7,550	190,373	40,131,393	81,080,231	63,029,754	119,400,498
2005	253.62	195.09	4,906	238,238	47,722,211	95,704,458	72,009,977	136,349,886
2006	313.26	245.17	5,273	178,175	45,335,942	89,350,755	65,178,425	122,557,028
2007	367.51	312.13	9,801	149,232	50,181,241	97,957,249	69,901,973	130,959,774
2008	441.19	401.19	5,590	138,749	58,130,522	114,228,281	76,087,426	144,279,049
2009	381.94	324.12	13,648	140,176	50,645,916	98,032,474	73,458,910	136,209,880
2010	359.02	280.00	10,855	193,317	58,026,171	112,976,109	86,359,814	160,392,287
2011	331.79	287.71	22,546	112,141	39,744,916	79,705,366	58,563,185	111,197,624
2012	334.16	311.95	13,120	116,931	40,861,097	80,077,172	60,368,935	112,723,419
2013	346.89	337.44	12,422	118,539	44,308,512	86,810,247	62,387,945	117,066,067
2014	341.38	315.94	29,480	170,289	63,864,734	126,132,893	88,186,769	166,835,670
Avg.	317.34	273.05	11,736	165,654	47,043,521	92,893,319	68,481,079	128,768,940
Total	-	-	152,565	2,153,502	611,565,779	1,207,613,151	890,254,025	1,673,996,221

[a] Scenario two: All sheath blight susceptible hectares are infected with the simulated sheath blight rate on Table 1 and then subsequently sprayed twice with fungicide (the average for Quilt Xcel and Quadris) and an associated yield loss occurs dependent on the sheath blight resistance rate presented on Table 1.

[b] NASS reports medium grain prices from 2002-2008 as USA average and prices and reports 2009-2014 prices as Mid-South (Arkansas, Louisiana, Mississippi, Missouri, and Texas) averages. Price data retrieved from NASS (2016).
[c] Values in 2014 $; deflated with consumer price index retrieved from IMF (2015)
[d] Calculated as the summation of the mitigation costs presented on Table 2 and the total yield loss from this table.

Table 4: Impact of Simulated Sheath Blight Infested Hectares in the Mid-South with Yield Loss on Selected U.S. Rice Market Variables in 2013

Variables	All Rice			Long Grain Rice			Medium Grain Rice		
	Base[a]	Counter[b]	Change	Base[a]	Counter[b]	Change	Base[a]	Counter[b]	Change
	1000 Mg, paddy basis			1000 Mg, paddy basis			1000 Mg, paddy basis		
Production paddy rice	9.051	9.176	125	6.245	6.360	115	2.806	2.816	10
Change stock	-147	-147	0	-101	-101	0	-46	-46	0
Export paddy rice	1.520	1.550	30	1.520	1.550	30	0	0	0
Domestic sales paddy rice	7.678	7.773	95	4.826	4.911	85	2.852	2.862	10
Export brown rice	341	345	4	65	66	1	276	279	3
Import brown rice	14	14	0	14	14	0	0	0	0
Domestic sales brown rice	7.351	7.442	91	4.775	4.859	84	2.576	2.583	8
Export milled rice	2.774	2.851	77	1.770	1.840	70	1.004	1.011	7
Import milled rice	856	844	-11	124	119	-6	1	1	0
Domestic demand milled rice[c]	5.432	5.435	3	3.129	3.137	8	1.573	1.573	0
Exports	4.636	4.746	111	3.355	3.456	101	1.281	1.290	10
Imports	869	858	-11	138	132	-6	1	1	0
Paddy farm gate ($ Mg^{-1})[d]	351	347	-4	337	333	-4	380	379	-1
Milled rice retail ($ Mg^{-1})[d]	2.397	2.383	-14	2.134	2.115	-19	2.683	2.676	-7
Farm gate production ($ million)[d]	3.173	3.191	18	2.107	2.124	17	1.066	1.067	1
Retail consumption ($ million)[c,d]	9.116	9.066	-51	4.677	4.634	-43	2.953	2.945	-8

[a] Simulates the domestic rice market as if all the cost increases and yield losses estimated in the scenario three were present.

[b] Simulates the domestic rice market as if all the cost increases and yield losses estimated in the scenario three were eliminated.

[c] For all rice, it includes 730 Mg^{-1} of fragrant rice imported in the benchmark.

[d] Values in 2014 $; deflated with consumer price index retrieved from IMF (2015)

Table 5. Results of the Categories in the Life Cycle Analysis Comparison of Sheath Blight-Resistant Rice Production vs. Sheath Blight-Susceptible Rice Production, Based on 1000 Monte Carlo Simulations.

TRACI Impact category	Units	Description	Resistant	Susceptible[a]	P-value
Acidification	kg SO_2 eq	Terrestrial acidification driven by acid gases	6.786E-03	6.988E-03	p<0.0001
Carcinogens	CTUh	Human toxicity units	1.093E-07	1.125E-07	p<0.0001
Ecotoxicity	CTUe	Ecosystems toxicity units	3.691E+01	3.800E+01	p<0.0001
Eutrophication	kg N eq	Freshwater and marine eutrophication driven by nutrient runoff	5.320E-03	5.477E-03	p<0.0001
Fossil fuel depletion	MJ surplus	Nonrenewable energy consumption	1.026E+00	1.056E+00	p<0.0001
Global warming potential	kg CO_2 eq	Accumulated greenhouse gas emissions (IPCC 2006 characterization factors)	1.555E+00	1.601E+00	p<0.0001
Non-carcinogens	CTUh	Human toxicity units	-1.572E-07	-1.620E-07	p<0.0001
Ozone depletion	kg CFC-11	Accumulated ozone-depleting compounds emissions	1.133E-07	1.167E-07	p<0.0001
Respiratory effects	kg PM2.5 eq	Primary and secondary particulate emissions	5.238E-04	5.393E-04	p<0.0001
Smog	kg O_3 eq	Small forming potential	6.235E-02	6.420E-02	p<0.0001

[a] Yield loss (kg/ha) and probabilities associated with sheath blight-susceptible rice production are derived from Table 1.

All inputs are assumed to be identical with the exception of one application of Quilt Xcel (13.5 percent Azoxystrobin and 11.7 percent Propiconazole) at a rate of 1.56 liters ha^{-1} and one application of Quadris (22.9 percent Azoxystrobin) at a rate of 0.77 liters ha^{-1} for sheath blight-infected varieties with probabilities given on Table 1.

Method: TRACI 2.1 V1.03 / US 2008, confidence interval: 95 percent.