Journal of Agricultural and Resource Economics 42(2):215–235 ISSN 1068-5502

The Economic and Environmental Benefits of Sheath Blight Resistance in Rice

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The producer, consumer, and environmental impacts of a counterfactual of ShB-resistant rice production were calculated using data from U.S. county-level rice production in the Mid-South and simulated Sheath Blight (ShB) infection and yield-loss rates. Results indicate a $43 million increase in consumer surplus via ShB alleviation, with enough additional rice produced to feed 1.7 million people. A life cycle assessment (LCA) also shows that the counterfactual has lower environmental impacts than the status quo of ShB-prone rice production. These estimates provide important economic and environmental information to donors, policy makers, and breeding programs globally on the importance of increasing and maintaining genetic disease resistance.

Key words: LCA, maintenance breeding, rice, sheath blight

Introduction

Rice consumption accounts for more than half of the daily caloric intake of over three billion people globally, most of whom are located in rapidly growing low-income countries (Pareja et al., 2011). Global rice supply must increase by approximately 30% by 2050 to meet projected demand (Mohanty, Wailes, and Chavez, 2010; Food and Agriculture Organization of the United Nations, 2015). Even moderate supply shocks can have large impacts on low-income rice consumers given that rice provides 21% of global human per capita energy and 15% of per capita protein (International Rice Research Institute, 2013). For example, when rice prices tripled in 2008 (mainly because of trade restrictions in India and Egypt) the World Bank estimated that an additional 105 million people were pushed into poverty (World Bank, 2013) following an 8% reduction of trade in 2007 (Childs, 2009). While supply shocks typically manifest themselves in trade restrictions and abiotic events such as drought and heat, biotic events such as disease can alter global supply. In China alone, 15–20 million ha of rice are affected by Sheath Blight (*Rhizoctonia solani*) annually, causing losses of up to six million metric tons (MT) (Xie et al., 2008), which is equivalent to about 1% of global rice production. Furthermore, annual losses due to Sheath Blight (ShB) are estimated to be 10% 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) to 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 ShB and rice blast (*Magnaporthe oryzae*) can be reduced through fungicide application and breeding programs to improve genetic resistance.

While rice blast-resistance cultivars are available to U.S. rice producers, there are currently no ShB-resistant cultivars available for commercial production in the United States. This unavailability 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

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Review coordinated by David K. Lambert.

moderately resistant varieties are the principle means of controlling ShB globally, but this regime is expensive for producers in low-income countries and presents toxicity problems for the environment (in both low- and high-income countries) (Baby and Manibhushanrao, 1993; Qingzhong et al., 2001). The relatively high yields of American rice production per hectare are partly attributable to major public investment in rice breeding, pathology, entomology, and agronomy. Nevertheless, U.S rice production is still affected by various biotic stresses akin to ShB. In the Mid-South of the United States (Arkansas, Louisiana, and Mississippi), ShB is widespread and resulting losses can be severe. In Arkansas, the largest rice-producing state in the United States during the 2001 growing season, 50–66% of rice fields were infected with ShB, which subsequently led to yield losses of 5–15% (Tan et al., 2007; Yellareddygari et al., 2014).

ShB forms lesions on infected sheaths of lower rice leaves, which may lead to stem softness and subsequent stem lodging (Wu et al., 2012). The ShB fungus is spread on rice fields from tiller to tiller on an infected plant, or across water surface to nearby plants. The fungus can also spread when plant parts touch (leaf to leaf), causing infections on adjacent 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, 2015). The severity of ShB infection is affected by the ecology, the development stage of rice at infection, cultural practices, excessive nitrogen fertilizer rates during the pre-flood stage, and cultivar resistance to ShB (Groth, Rush, and Hollier, 1992). Efforts to breed rice with ShB resistance in the United States and globally have not been fruitful to date, as the fungus continuously evolves, making even short-term resistance difficult to achieve. Only 3.91% (equivalent to 148,315 ha) of seeded areas in the Mid-South of the United States from 2000–2014 were classified as moderately resistant to ShB (Rice Technical Working Group, 2001–2014). The low incidence of even moderately ShB-resistant cultivars is partly attributed to the lack of sources for resistant genes in both domesticated rice and related wild species (Hashiba, 1984; Groth, Rush, and Hollier, 1992). Plant height is a morphological trait associated with ShB resistance; of the twelve rice chromosomes that have been identified, only one out of six quantitative trait loci associated with ShB resistance appears to be independent of plant height (Li et al., 1995). Accordingly, identifying genes that offer high levels of partial ShB resistance and then pyramiding these genes through biotechnology could offer complete ShB resistance (Pan et al., 1999; Yellareddygari et al., 2014). Notably, the speed at which this effort can be achieved through breeding, which is an important factor given that ShB continuously evolves, could be constrained by current food regulations pertaining to genetic modification (GM) of rice.

In practice, plant-breeding programs generally have two objectives: high yields and resistance to biotic and abiotic stresses (maintenance breeding). While the former leads to tangible outcomes such as increased production per hectare, the latter generally results in pathogen resistance for a crop specimen, which is often less tangible. For this reason, policymakers tend to undervalue the opportunity cost of informative agricultural research, specifically concerning maintenance breeding. Considering this, our study quantifies the economic and environmental impact of ShB resistance in the Mid-South. 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 observed in breeding programs (Marasas, 2003). In addition, the literature has shown that a lack of maintenance breeding has caused a slower rate of rice yield increase in South Asia (Pan et al., 1999), which in turn reinforces the idea that discontinuing or diminishing maintenance breeding programs would stifle the ability of the industry to meet increasing demand for rice on a global level.

Higher yields and the mitigation of fungicide application are beneficial to producers, and consumers also benefit as higher supplies lead to lower market prices. Many low-income countries are highly price inelastic to changes in rice prices, as there are no substitutes for rice in many cultures. Notably, the literature has shown that a 50% increase in rice price would lead to at least 32 million people and possibly as many as 100 million people falling back into poverty (Asian

Development Bank, 2008; Ivanic and Martin, 2008). Conversely, any price reduction in rice could have sweeping positive impacts on alleviating poverty. Breeding for pathogen resistance is one way to increase supply without increasing genetic yield potential, since yield potential has become increasingly difficult to consistently obtain.

ShB 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 ShB are Quilt Xcel^{TM}(active ingredients: 13.5% Azoxystrobin and 11.7% Propiconazole) and Quadris^{TM}(active ingredient: 22.9% Azoxystrobin). These fungicides could have adverse effects on human health and the environment given their toxicity levels for humans and the length of their residual effects (Ragsdale and Sisler, 1994; Cornell University, 2017).

Currently, rice producers who experience elevated costs and yield losses—and consumers who experience higher prices due to 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; Guimarães, 2009; Nalley and Barkley, 2010; Singh et al., 2013), there is a lack of research on the economic impacts of rice maintenance breeding programs. We therefore ask the counterfactual question:, What benefits would be realized by producers, consumers, and the environment if all cultivars in the Mid-South were ShB resistant? To explore this question, data were collected from (i) county- or parish-level rice varietal yields (with associated ShB susceptibility ratings) and seeded areas in Arkansas, Louisiana, and Mississippi for 2002–2014, (ii) simulated ShB infection rates based on historical infection data, and (iii) simulated infected hectares as well as simulated yield loss based on historical ShB yield-loss data. From these data 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 entered into the RiceFlow model (Durand-Morat and Wailes, 2010) to answer the counterfactual question: What would the implications for U.S. rice production have been if ShB had not been present? Notably, the RiceFlow model generates domestic and global estimates of changes in rice price given an increased supply as well as changes in consumer and producer welfare. Finally, we analyzed the counterfactual increased yield and decreased fungicide usage from the absence of ShB using a Life Cycle Assessment (LCA) model to analyze the environmental impact that would have resulted if ShB and its associated fungicide applications had not been present. These comprehensive results provide insight on how potential genetic resistance to ShB in the Mid-South could enhance producer livelihoods, food security via increased rice supply/decreased price, and environmental sustainability through reduced toxicity. These estimates provide important information on the importance of not just increasing genetic yield potential but also maintaining it to policy makers, donors, stakeholders, and breeding programs around the world.

Materials and Methods

Following similar studies (Nalley et al., 2016), we calculate the potential benefit of genetic ShB resistance for rice production in Arkansas, Mississippi, and Louisiana using two ShB outbreak and response scenarios.[1] The dataset consists of 47 rice varieties (8 hybrids and 39 conventional/inbred), 33 rice-growing counties in Arkansas, 35 parishes in Louisiana, and 18 counties in Mississippi, for a total of 5,733 yield observations. Average yields by variety and state are reported in table A1.

Annual varietal yield data for each county and parish were collected from university-run experiment stations (Arkansas Agricultural Experiment Station, 2002–2015; Louisiana State University Agricultural Center, 1999, 2009, 2014; Louisiana State University Agricultural Center; Mississippi Agricultural and Forester Experiment Station, 2002–2015). Experiment station yields

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[1] In 2015, the percentage of U.S. rice harvested in Arkansas, Louisiana, and Mississippi was 49.94%, 16.12%, and 5.79%, respectively (U.S. Department of Agriculture, National Agricultural Statistics Service, 2016).

are considered "yield potential" given the well-maintained growing conditions typically associated with test plots. Yields are often greater on experimental test plots than on producers' fields, but the relative yield difference between varieties is comparable. The most reliable sources of relative yields are cultivar trials outside of actual farm observations (Brennan, 1984). Some years were missing data on county- or parish-specific varietal yields from experiment stations. In these cases, the annual county or parish average yield was used for that year.

Data on actual annual varietal planting areas were collected from the Rice Technical Working Group (2001–2014) for each rice-growing county and parish in Arkansas, Louisiana, and Mississippi from 2002–2014.

Sheath Blight Ratings

Annual ShB susceptibility ratings for each variety were derived from historical observations of university-run experiment station (AAES, LSU AgCenter, MAFES) test plots and grower fields in each state. The experiment stations used a Likert scale to rate the ShB susceptibility of rice cultivars as Moderately Resistant (MR), Moderately Susceptible (MS), Susceptible (S), and Very Susceptible (VS). In 2014, two varieties seeded across the Mid-South were rated as MR, seven as MS, eleven as S, and three as VS; and their respective areas sown were approximately equal to 32,000 ha, 219,000 ha, 419,000 ha, and 94,000 ha, respectively. Given that varieties can become more susceptible to ShB over time (because even partial genetic resistance can break down), we used the most recent rating for each production year. Table A1 lists ShB susceptibility ratings by variety as of 2015.

Sheath Blight Outbreak and Yield-Loss Rate

University extension services commonly rate ShB susceptibility on an annual basis, but it is uncommon for them to obtain detailed annual county-level reports on ShB outbreaks or associated yield losses. Extensive, systematic field-level yield and quality loss estimates due to ShB in rice have not been developed in the United States because there is little data on the numerous and often simultaneous diseases affecting rice, the underground damage associated with root diseases, and the lack of qualitative information on distribution and severity in commercial fields. It has also been difficult to estimate field-level ShB loss. Often, outbreaks are contained to one portion of a field and therefore do not warrant the attention of extension agents or crop consultants to collect extensive data. Typically, crop consultants will scout for ShB and give producers recommendations based on field observations. To our knowledge, no extensive database of either locations or magnitude of ShB outbreaks and losses in the Mid-South exists.

Although detailed reporting of ShB outbreak acreage is scarce, Norman and Moldenhauer (2002–2014) provide estimates of the annual percentage of sampled commercial rice fields across Arkansas that required a fungicide application for ShB. From 2002 to 2014, an average 19.05% of sampled commercial rice fields across Arkansas were treated annually with fungicide application for ShB, with a maximum annual rate of 31.89%. Because similar studies for Louisiana and Mississippi did not exist at the time of the study, we assumed proportional fungicide applications in all three states based on the Arkansas data. Ideally, state-specific distributions are preferable, given that the three states have different ecologies, cultural practices, and distribution of cultivar resistance; thus, using the Arkansas historical data reported by Norman and Moldenhauer (2002–2014), we used a triangular distribution with a mean of 19.05%, truncated between 0.00% (the observed minimum) and 31.89% (the observed maximum) of the infected area, to simulate ShB infection rate.

The literature is also scarce on replicated field trials that document yield loss associated with ShB on commonly cultivated rice varieties in the United States. Several studies based on field experiments have analyzed varietal differences in ShB development and its associated yield loss at different levels of nitrogen fertilizer application, fungicide application, or both (Groth and Bond, 2006; Groth, 2008; Groth and Bond, 2007; Li et al., 2012; Tang et al., 2007; Savary et al., 1995;

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

	Mean	Max	Min
Infection rate (percentage)	19.05	31.89	0.00
Yield-loss rate by susceptibility rating (percentage)			
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

Notes: Infection rate simulated using estimates of the yearly percentage of Arkansas rice acreage requiring fungicide application, reported by Norman and Moldenhauer (2002–2014). Yield-loss rates by susceptibility ratings are from Groth and Hollier (2016).

EFSA Panel on Genetically Modified Organisms (GMO), 2012). However, none of these studies provides 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 that grain filling reduced the degree of ShB. Specifically, Groth and Hollier (2016) provides typical yield losses associated with ShB for the four susceptibility ratings used by extension services across the United States; typical yield losses associated with ShB in the field are 15–25% for VS, 10–20% for S, < 10% for MS, and 5–10% for MR.

Given the lack of location- and varietal-specific rates of yield response to ShB, we used the estimates suggested by Groth and Hollier (2016) to estimate yield losses based on ShB susceptibility ratings, as these were similar to the other two ranges estimated in the Mid-South (Tan et al., 2007; Yellareddygari et al., 2014). Furthermore, because yield loss caused by ShB is determined by the severity and timing of the infection, a static percentage yield loss would not be appropriate in this case; therefore, we developed a simulated range of yield loss based on susceptibility rankings and empirical losses as reported by Groth and Hollier (2016). For each susceptibility ranking, yield-loss rate was simulated 1,000 times, assuming a triangular distribution such that the possible minimum and maximum of the simulations were equivalent to those reported by Groth and Hollier (2016). The mean percentage yield loss for the various ShB susceptibility ratings were 0% for resistant (R), 5% for MR, 7.5% for MS, 15% for S, and 20% for VS (table 1).

Cost of Sheath Blight Mitigation

The prices of the two most common fungicides (Quilt Xcel^{TM}and Quadris^{TM}) used to combat ShB in the United States vary by retailer and region and are affected by dealer rebates. In 2015, the average cost for Quilt Xcel was $46.23/liter for rice producers in the Arkansas Delta region (Driggs, 2015) and the average cost for Quadris was $72.65/liter. The recommended application rate for ShB is 1.56/ha for Quilt Xcel and 0.77/ha for Quadris. Thus, the estimated per application cost is $72.13/ha for Quadris and $55.79/ha for Quilt Xcel. We also contacted four crop-dusting services in the Arkansas and Mississippi Delta in August of 2015; the average charge for aerial fungicide application $19.77/ha. Given that no data on which fungicide producers used to mitigate ShB are available, we assumed an even split. As such, we added the average price of both fungicides (Quadris and Quilt Xcel) at $63.96/ha to the cost of aerial application for a total cost per fungicide application of $83.73/ha. Finally, because both the historical cost of aerial application and fungicide costs were prohibitively difficult to obtain, we assumed them to be constant across time (although we adjusted for inflation).

Sheath Blight Outbreak Scenario 1

Scenario 1 simulates the area of rice produced in all three states infected with ShB based on empirical county- or parish-level varietal adoption (Norman and Moldenhauer, 2002–2014). Infected areas were treated with two applications of fungicide to mitigate the outbreak with no associated yield loss (extension recommendations suggest using two applications of fungicide for severe ShB conditions on S and VS cultivars, University of Arkansas Cooperative Extension Service, 2015). Scenario 1 therefore imitates years in which an outbreak occurs but a producer or a crop consultant catches and treats the fungus in its early stages and the only costs are incurred not yield losses. Specifically, Scenario 1 is modeled as

$$TC_t^1 = 2C_h\lambda \sum A_{ilt}, \tag{1}$$

where the annual total cost of ShB for Scenario 1 (TC_t^1) is the sum of all actual historic hectares of susceptible rice varieties (i) sown in each rice-producing county or 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 because county-level varietal distribution and the area sown to ShB-susceptible varieties change annually. In addition, all non-ShB-resistant varieties have equal probabilities of infection. That is, each variety, regardless of susceptibility rating, has an equivalent probability of infection based on historical data and the simulations run in the model. Notably, individual ratings affect probability of yield loss but not probability of infection.

Sheath Blight Outbreak Scenario 2

Based on the loss estimates from Groth and Hollier (2016), Scenario 2 further develops Scenario 1 by simulating yield loss associated with ShB infections. As in Scenario 1, infected areas were assumed to be associated with two applications of fungicide; associated yield losses were a function of ShB susceptibility rating. While a percentage yield loss was simulated for each susceptible variety, it was recognized that each variety has a different yield potential. Each variety's average yield was therefore denoted by county or parish as reported by each state's extension service (AAES, LSU AgCenter, MAFES). A simulated 5% yield loss for two MS varieties would be different given their different yield potentials. Scenario 2 is modeled as

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

where total cost (for all three states) of ShB for Scenario 2 (TC_t^2) is the sum of the annual total cost simulated for Scenario 1 (TC_t^1), 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. Price (P_{gt}) was measured in \$/MT and aggregated at the grain-type level ($g = 0$ for medium, $g = 1$ for long grain) as reported by the U.S. Department of Agriculture, National Agricultural Statistics Service (2016). The variable γ_i was simulated 1,000 times. Table A2 summarizes each scenario.

Impact on the U.S. Rice Market

We used the RiceFlow model to assess the impact of ShB on the U.S. rice market according to the findings reported for each scenario (Durand-Morat and Wailes, 2010). RiceFlow is a multi-region, multi-product, spatial partial equilibrium model of the world rice economy used extensively in the literature. Thompson et al. (2015) used RiceFlow to assess the impact of the U.S. Liberty Link rice contamination, while Briones et al. (2012) and Wailes, Durand-Morat, and Diagne (2015) used the model to assess alternative rice policy options in Southeast Asia and West Africa. The model disaggregates the global rice economy into seventy-three regional markets and nine rice commodities derived from the combination of rice type (long, medium, and fragrant) and milling degree (paddy,

Table 2. Environmental Impact Categories Used in the Life Cycle Analysis (LCA) for Sheath Blight Resistant versus Susceptible Rice Production

Category	Units	Description
Ozone depletion	kg CFC-11	Accumulated ozone-depleting compounds emissions
Global warming potential	kg CO_2 eq	Accumulated greenhouse gas emissions (IPCC 2006 characterization factors)
Smog	kg O_3 eq	Small forming potential
Acidification	kg SO_2 eq	Terrestrial acidification driven by acid gases
Eutrophication	kg N eq	Freshwater and marine eutrophication driven by nutrient runoff
Carcinogenics	CTUh	Human toxicity units
Noncarcinogenics	CTUh	Human toxicity units
Fossil fuel depletion	MJ surplus	Nonrenewable energy consumption
Eco-toxicity	CTUe	Ecosystems toxicity units
Respiratory effects	kg PM2.5 eq	Primary and secondary particulate emissions

brown, and milled), allowing us to analyze the impact of ShB on prices that consumers obtain in local markets.

We assumed a completely fixed supply of land and limited mobility of land across rice types in all countries. Coupled with Leontief technology assumptions at each level of the production tree, this assumption resulted in very inelastic output supply functions. Hence, our results are best understood as short-run outcomes controlling for potential supply expansionary effects in other countries induced by ShB outbreak in the United States. 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. Accordingly, RiceFlow is augmented with the counterfactual yield increases due to the elimination of ShB and the subsequent producer and consumer surplus changes estimated. Yield changes are specified by shocking a technology variable representing the efficiency in the use of land in the production of paddy rice. Efficiency changes trigger expansionary and substitution effects. At a given level of output, an increase in the efficiency of land use will result in a decrease in its derived demand. Moreover, the effective price of land decreases with an increase in the efficiency of land use, which results in an increase in the derived demand for land.

Environmental Impacts of Sheath Blight Resistance

Following similar studies in the literature (Nalley et al., 2016), we used a Life Cycle Assessment (LCA) to quantitatively compare the cradle-to-farm gate environmental benefits of ShB-resistant and ShB-susceptible rice production in the Mid-South. The cradle-to-farm gate LCA in this study includes extracting raw materials to produce rice as well as producing and manufacturing inputs used in rice production and all activities and inputs used for rice planting, irrigation, and harvesting. The goal was to compare rice production with and without the presence of ShB for the functional unit of a kilogram of rice that is dried to 12.5% moisture delivered to the farm gate and ready for transportation to milling. The principal differences between the scenarios were yield (loss associated with ShB infection) and fungicide application to susceptible varieties. ShB-susceptible varieties subject to infection rates and yield losses described in table 1 were subsequently sprayed with two applications of fungicide. Inputs for each system used in the LCA—in terms of land preparation, planting, fertilizer and pesticide application (except as noted), and harvesting per hectare—were from University of Arkansas extension budgets (University of Arkansas Cooperative Extension Service, 2016). The TRACI 2.1 LCA framework, which was developed by the U.S. Environmental Protection Agency for conditions in the United States, was used to estimate potential environmental impacts arising from production differences (Bare, Gloria, and Norris, 2006). Table 2 presents the impact categories included in this method.

Table 3. Total Economic Cost of Sheath Blight Simulated Mitigation by Fungicide Application to All Susceptible Rice Hectares in the Mid-South: 2002–2014

Year	Rice Area Susceptible to Sheath Blight (ha)[a]	Rice Area Infected with Sheath Blight (ha)[b]		Mitigation Cost for Sheath Blight Infected Area ($)[c]	
		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

Notes: Scenario 1: Simulated ShB outbreak with probabilities from table 1 on susceptible hectares sprayed twice with fungicide (the average for Quilt Xcel and Quadris) with no associated yield loss. See table A3 for state-specific results.

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

[b] Simulated using infection rates shown in table 1 and ShB-susceptible hectares.

[c] Areal fungicide application at a rate of 1.16/ha at a cost $83.7338/ha ($19.77/ha for areal application and $63.96/ha for fungicide). Values are in 2014 $, deflated using the International Monetary Fund (2016) consumer price index.

Average yield losses and the probabilities of ShB infections were taken from table 1 and incorporated into the LCA simulations. In order to minimize bias when comparing the two scenarios, we adopted a paired Monte Carlo simulation approach using SimaPro 8.1, which selects variates from each unit process in the supply chain and computes the difference between the two (ShB susceptible versus resistant) production systems. This approach ensures that additional variability from independent simulations of the supply chains are not introduced. Using this methodology, we ascertained the differences between ShB-susceptible and ShB-resistant rice production from a holistic environmental standpoint. Most importantly, this methodology allows us to test for statistical differences and magnitudes for ten environmental categories between ShB-susceptible and ShB-resistant rice production, *ceteris paribus*.

Results

Producer Impacts

Tables 3 and 4 present results for the total (aggregated annual) economic costs of Scenarios 1 and 2, table 5 presents results for the U.S. rice market effects of ShB, and table 6 presents the results of the LCA. Appendix tables A3 and A4 show state-level results. Monetary values throughout the paper were converted to 2014 dollars using annual CPI (International Monetary Fund, 2016). In Scenario 1, we simulated ShB-infected hectares and estimated the cost associated with spraying those hectares twice with the appropriate fungicide at a cost of $167.50/ha. Given an assumed infection rate of 19.05% (the historical mean of all susceptible varieties applied to all ShB-susceptible hectares), producers spend an average $21.44 million on ShB mitigation annually. This result can be viewed as a best-case scenario, as there is no assumed yield loss and producers simply absorb the costs, but there are no supply effects on the market.

Table 4. Total Cost (Mitigation and Yield Loss) of Sheath Blight in the Mid-South: 2002–2014

	Real Season-Average Rice Price ($/MT)[a]		Total Yield Loss on ShB-Infected Area (MT)		Total Yield Loss on ShB-Infected Area ($)		Average Total Loss on ShB-Infected Area ($)[b]	
Year	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

Notes: Scenario 2: All ShB-susceptible hectares are infected with the simulated ShB rate in table 1 and then subsequently sprayed twice with fungicide (the average for Quilt Xcel and Quadris). An associated yield loss occurs dependent on the ShB resistance rate presented in table 1. See table A4 for state-specific results. Dollar values are in 2014 $, deflated using the International Monetary Fund (2016) consumer price index.

[a] 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 U.S. Department of Agriculture, National Agricultural Statistics Service (2016).

[b] Calculated as the sum of the mitigation costs presented in table 2 and total yield loss.

Table 5. Impact of Simulated Sheath Blight-Infected Hectares in the Mid-South with Yield Loss on Selected U.S. Rice Market Variables in 2013

	All Rice			Long Grain Rice			Medium Grain Rice		
	Base	Counter	Change	Base	Counter	Change	Base	Counter	Change
Variables	1,000 MT, paddy basis			1,000 MT, paddy basis			1,000 MT, 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[a]	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 ($/MT)[b]	351	347	-4	337	333	-4	380	379	-1
Milled rice retail ($/MT)[b]	2.397	2.383	-14	2.134	2.115	-19	2.683	2.676	-7
Farm gate production ($ million)[b]	3.173	3.191	18	2.107	2.124	17	1.066	1.067	1
Retail consumption ($ million)[a,b]	9.116	9.066	-51	4.677	4.634	-43	2.953	2.945	-8

Notes: "Base" simulates the domestic rice market as if all cost increases and yield losses estimated in scenario 3 were present. "Counter" simulates the domestic rice market as if all cost increases and yield losses estimated in scenario 3 were eliminated.
[a] For all rice, includes 730 MT of fragrant rice imported in the benchmark.
[b] Dollar values are in 2014 $, deflated using the International Monetary Fund (2016) consumer price index.

Results from Scenario 2 show that producers lose an average $68.48 million annually due to ShB mitigation (assuming an infection rate of 19.05% on all ShB-susceptible hectares); this is a $47.04 million yield loss in addition to the $21.44 million lost to ShB mitigation. At the state level, the average annual cost of ShB for Scenario 2 is estimated to be $45.94 million for Arkansas, $14.66 million for Louisiana, and $7.88 million for Mississippi. The calculated potential economic loss as a share of the total value of rice production in each state for 2002–2014 is estimated to be 3.89% for Arkansas, 4.23% for Louisiana, and 4.57% for Mississippi. Overall, the potential economic loss in Scenario 2 due to ShB as a share of the total value of rice production in the Mid-South is estimated to be 4.03%. These yield losses have more than simple revenue implications for producers; reduced supply also affects consumers.

Consumer Impacts

We used the RiceFlow model to assess the market impact of ShB mitigation and its effect on consumer prices. We estimate these benefits based on Scenario 2 with the counterfactual absence of ShB by simulating the change in land use efficiency commensurate with losses from ShB to estimate a counterfactual scenario without ShB. Table 5 presents the results for the key selected variables from the estimated counterfactual decreased costs and increased yields associated with ShB from the scenarios. Specifically, we present the counterfactual results from table 4 to determine cost savings if the yield losses and increased costs of production calculated from Scenario 2 did not exist. Cost savings due to lower fungicide use (Scenarios 1 and 2) are small relative to total production cost and do not generate any significant changes in the U.S. rice supply chain. Nevertheless, U.S. consumers would be expected to save an estimated $51 million annually when yield losses and mitigation costs are accounted for (Scenario 2). Most of the benefits are due to lower retail prices,

Table 6. Results of the Categories in the Life Cycle Analysis Comparison of Sheath Blight-Resistant versus Susceptible Rice Production Based on 1,000 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	$p<0.0001$

Notes: All inputs are assumed to be identical with the exception of one application of Quilt Xcel (13.5% Azoxystrobin and 11.7% Propiconazole) at a rate of 1.56 liters/ha and one application of Quadris (22.9% Azoxystrobin) at a rate of 0.77 liters/ha for ShB-infected varieties with probabilities given in table 1.

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

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

as aggregate rice demand changes only marginally. Furthermore, most of the benefits ($43 million) come from the consumption of long-grain rice, which undergoes a price decrease of about $19/ton. These results suggest that ShB alleviation increases rice yields and production and subsequently lowers long-grain rice prices. In turn, ShB alleviation improves the competitiveness of U.S. rice and expands long-grain exports by 101,000 MT (3.0%) and all rice exports by 111,000 MT (2.4%). The excess supply generated by the alleviation of ShB in the United States could be sufficient to feed 1.7 million people every year at the average per capita consumption rate of 65 kg/year, which is impressive considering that the United States is a small rice producer by global standards and likely experiences less loss from ShB than the global average because of ongoing investment in production technology and management.

Environmental Impacts

Our study also evaluated the environmental impacts associated with ShB through a counterfactual argument. Specifically, we compare the current average conditions in which an acre of a ShB-susceptible variety is produced compared to an ShB-resistant variety. The difference between the two groups is expressed in the elimination of fungicide for ShB mitigation and in yield loss—its probability is derived from table 1. The ranges for infection rate in yield loss of a susceptible variety are compared in table 5. The "susceptible" rating was chosen to analyze all possibilities of susceptibility ratings (MR, MS, S, and VS) because it accounted for the largest amount of acreage rice varieties actually sown on producer's fields in the Mid-South in 2014 at 29.14%. We followed the cradle-to-farm gate LCA approach to perform the comparison and included all inputs from production of fertilizers through cultivation, harvest, and drying to a moisture content of 12%. The only differences between the two scenarios were yield differences and the elimination of fungicide usage for the resistant variety. Because these differences are unidirectional and no other differences between the scenarios were introduced, the Monte Carlo simulations did not result in uncertainty regarding whether there were benefits from the elimination of ShB or not. Notably, because uncertainty is inherent in the system model, uncertainty also exists in the mean values for both scenarios, but there is no uncertainty that they are significantly different. The Student's t-tests have a P value of less than 10^{-8} (table 6) for a pairwise comparison of 1,000 simulations.

The environmental benefits of ShB resistance highlight two important concepts. First, by simply obtaining yield potential, input use efficiency is improved per unit of output and environmental impact is reduced. Second, by breeding resistance to ShB, we reduce the environmental load of the fungicide that would have to be applied also lessening our environmental impact per metric ton of rice. Our simulations show that introducing ShB resistance in rice production has the potential to reduce global warming, carcinogenicity, ecotoxicity, eutrophication, fossil fuel depletion, and smog and ozone depletion (table 6). The negative results for non-carcinogens come from modeling heavy metal uptake by rice plants (higher yields equal higher uptake), which results in decreased ecotoxicity at the farm level. Importantly, in using the well-established categories defined by the TRACI 2.1 LCA framework, it is evident from table 6 that ShB resistance in rice leads to multiple environmental improvements over ShB-susceptible varietals. Overall, the results from the producer, consumer, and environmental portions of this study are significant as agricultural scientists attempt to sustainably produce 70% more calories projected to be needed by 2050 for a growing human population (Adhya et al., 2014).

Discussion

In 2013, the United Nations estimated that global population will increase by 33% to 9.6 billion by 2050 (United Nations Department of Ecnomic and Social Affairs, 2013). Because rice provides 21% of global human per capita energy and 15% of per capita protein (International Rice Research Institute, 2013), moderate price or supply shocks could have large impacts on low-income rice consumers. While the United States is a relatively small producer compared to other rice-producing countries, supplying only 1.3% of the world's rice, it has been among the top five rice exporters for several decades (Lakkakula et al., 2015). Consequently, any change in supply in the U.S. market could have global ripple effects in terms of price and food security.

Maintenance breeding to alleviate ShB could have significant impacts on domestic rice producers, global rice consumers, and, in turn, food security. The objective of most breeding programs is to increase the yield ceiling, but the on-farm yield ceiling is approaching quickly with crops such as rice and wheat that have not been approved for genetic modification in the United States. As the gap between yield potential and on-farm yields closes, our study indicates that maintenance breeding for pathogen resistance like ShB is one way to increase food supply without increasing yield potential. This study sheds economic and environmental light on the importance of valuing yield-loss avoidance. Most cost-benefit analyses of breeding programs only focus on yield enhancements and not yield-loss avoidance through pathogen resistance.

The positive externalities of disease resistance are often overlooked in most cost-benefit analyses. For example, in the Mid-South, where rice and soybeans are traditionally rotated, one of the most prevalent soybean diseases is aerial blight, which is caused by the same fungus that causes ShB in rice. Eliminating the host by breeding for resistance in rice could create positive spillover benefits for soybeans, which can face 40–50% losses due to aerial blight (Faske and Kirkpatrick).

As genetic gains for crops like rice and wheat continue to increase at a decreasing rate, breeding programs may need to shift their focus from yield enhancement to yield-loss avoidance via biotic and abiotic stress resistance. Sparger et al. (2013) found that the proportion of agricultural research in the United States dedicated to maintenance breeding is rising and concluded that failure to understand the economic significance of maintenance breeding and the losses it avoids may lead to a scenario in which science loses ground in agricultural research.

Our results reveal significant economic and environmental effects of yield-loss avoidance through maintenance breeding programs for ShB resistance. 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, they should not come at the expense of maintenance breeding, which could simply increase the yield gap. Second, to properly evaluate a breeding program, yield-loss avoidance from biotic and abiotic stress resistance should be estimated or the program could be vastly undervalued from both an economic and environmental perspective.

[Received November 2016; final revision received March 2017.]

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Table A1. Summary Statistics of Varieties by State

		Sheath Blight	Highest State Percentage of Rice Hectares			Yield (MT/ha)		
Variety	N	Susceptibility	AR	LA	MS	AR	LA	MS
Ahrent	46	MS	2.55	–	–	8.44	–	–
Banks	23	MS	3.27	–	–	10.58	–	–
Bengal	252	MS	11.75	4.00	–	9.05	7.57	–
Bowman	7	MS	–	–	2.43	–	–	9.94
Caffey	8	MS	–	1.01	–	–	9.19	–
Catahoula	46	S	–	5.08	–	–	7.31	–
Cheniere	385	S	11.54	24.35	18.26	8.79	7.84	10.41
CL111	245	VS	6.66	33.78	12.45	8.76	8.29	11.90
CL121	47	S	1.39	2.23	–	8.01	6.32	–
CL131	144	VS	14.17	23.26	19.93	8.82	7.64	9.02
CL141	4	S	–	0.14	–	–	5.36	–
CL142	30	MS	8.53	0.14	–	7.87	7.87	–
CL151	348	S	24.57	34.13	27.77	9.18	9.03	11.89
CL152	130	S	8.63	3.92	17.06	8.53	8.29	11.57
CL161	373	VS	20.43	31.46	18.47	8.80	7.72	8.27
CL171	86	VS	20.10	12.19	20.56	7.91	7.56	8.88
CL261	58	S	6.52	3.59	–	8.52	7.55	–
CL271	4	MS	–	0.15	–	–	9.17	–
CLXL4534	18	R	–	–	8.10	–	–	14.81
CLXL710	6	MR	–	0.15	–	–	9.40	–
XL723	175	MS	11.15	2.69	7.21	10.29	11.47	12.07
CLXL729	329	MS	17.19	8.79	14.42	9.94	10.81	12.33
CLXL730	81	S	5.25	3.23	0.73	10.55	10.48	10.35
CLXL745	359	S	33.41	15.75	22.67	8.64	10.59	12.80
XL753	111	MS	12.84	5.83	4.50	12.18	11.07	14.26
CLXL8	148	MS	5.97	1.86	2.93	10.43	9.05	9.41
Cocodrie	648	VS	30.59	58.05	78.17	8.97	7.71	10.36
Cypress	169	VS	4.09	31.97	2.12	7.61	7.28	7.28
Drew	23	MS	4.61	–	0.08	9.09	–	9.09
Earl	2	MS	–	0.09	–	–	7.31	–
Francis	217	MS	17.26	0.91	2.06	9.72	7.28	10.11
Jazzman2	15	S	–	8.94	–	–	6.41	–
Jefferson	27	S	–	1.35	1.93	–	6.42	6.42
Jupiter	291	S	15.25	14.19	–	10.09	8.53	–
Lagrue	29	MS	3.57	–	–	10.02	–	–
Lemont	11	VS	–	–	5.88	–	–	7.83
Maybelle	9	VS	–	0.79	–	–	5.07	–
Mermentau	44	S	5.30	4.30	–	9.44	8.55	–
Neptune	23	MS	–	1.64	–	–	7.22	–
Pirogue	13	MR	–	0.29	–	–	6.68	–
Priscilla	40	MS	–	–	16.67	–	–	9.36
Rex	50	S	–	–	17.18	–	–	11.78
Roy J	75	MS	15.47	–	–	10.86	–	–
Saber	6	S	–	0.45	0.10	–	6.73	8.02
Sabine	62	S	–	–	3.23	–	–	10.39
Trenasse	43	S	–	10.40	–	–	8.20	–
Wells	473	S	47.51	7.76	6.06	9.51	7.92	9.63

Notes: Calculated by authors using annual data retrieved from the Proceedings of the Rice Technical Working Group RTWG (various years). Counties in AR: Arkansas, Ashley, Chicot, Clay, Conway, Craighead, Crittenden, Cross, Desha, Drew, Faulkner, Greene, Independence, Jackson, Jefferson, Lafayette, Lawrence, Lee, Lincoln, Lonoke, Miller, Mississippi, Monroe, Perry, Phillips, Poinsett, Pope, Prairie, Pulaski, Randolph, St. Francis, White, and Woodruff. Locations in LA: Acadia, Allen, Avoyelles, Beauregard, Bossier, Caddo, Calcasieu, Caldwell, Cameron, Catahoula, Concordia, East Carroll, Evangeline, Franklin, Grant, Iberia, Iberville, Jefferson Davis, La Salle, Lafayette, Madison, Morehouse, Natchitoches, Ouachita, Point Coupee, Rapides, Red River, Richland, St Mary, St. Landry, St. Martin, Tensas, Vermilion, West Baton Rouge, and West Carroll. Locations in MS: Adams, Bolivar, Coahoma, Desoto, Grenada, Holmes, Humphreys, Issaquena, Leflore, Panola, Quitman, Sharkey, Sunflower, Tallahatchie, Tate, Tunica, Washington, and Yazoo.

Table A2. Summary of Sheath Blight Infection Scenarios

	Scenario 1	**Scenario 2**	**Scenario 3**[a]
Sheath Blight Infection	Yes	Yes	No
Quilt Xcel Application (per hectare)	1.56	1.56	0
Quadris Application (per hectare)	0.77	0.77	0
Yield Loss	No	Yes	No
Yield Loss (%)	0	5–20[b]	0

Notes: [a]Used in the LCA analysis as the counterfactual Sheath Blight resistant production system.
[b]Derived for individual varieties from data presented in table 1.

Table A3. Total Economic Cost of Sheath Blight Mitigation with No Yield Loss: 2002–2014

	Rice Area Susceptible to	Rice Area Infected with Sheath Blight (ha)[b]			Mitigation Cost for Sheath Blight Infected Area ($)[c]			Sheath Blight Mitigation Fungicide Spraying (l)[d]		
Year	Sheath Blight (ha)[a]	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
Arkansas										
2002	575,852	2,026	109,672	183,538	257,922	13,958,503	23,359,820	4,720	255,464	427,523
2003	558,540	1,966	106,375	178,020	256,751	13,895,169	23,253,829	4,578	247,784	414,671
2004	583,415	2,053	111,112	185,948	275,062	14,886,145	24,912,246	4,782	258,819	433,138
2005	616,178	2,168	117,352	196,390	297,772	16,115,157	26,969,021	5,051	273,353	457,462
2006	520,548	1,832	99,139	165,911	260,761	14,112,189	23,617,017	4,267	230,929	386,465
2007	492,633	1,734	93,823	157,014	255,488	13,826,779	23,139,377	4,038	218,546	365,740
2008	384,862	1,354	73,298	122,665	206,400	11,170,217	18,693,571	3,155	170,736	285,729
2009	514,376	1,810	97,964	163,944	275,858	14,929,212	24,984,321	4,216	228,191	381,883
2010	649,670	2,286	123,730	207,065	352,245	19,063,190	31,902,610	5,325	288,212	482,328
2011	402,249	1,416	76,609	128,206	225,207	12,188,035	20,396,908	3,297	178,449	298,638
2012	439,399	1,546	83,684	140,047	251,185	13,593,932	22,749,703	3,602	194,929	326,218
2013	385,940	1,358	73,503	123,008	222,900	12,063,143	20,187,899	3,164	171,214	286,529
2014	549,533	1,934	104,659	175,149	323,860	17,527,029	29,331,816	4,505	243,788	407,984
Louisiana										
2002	214,359	754	40,825	68,321	96,011	5,196,019	8,695,636	1,757	95,096	159,144
2003	179,578	632	34,201	57,236	82,549	4,467,483	7,476,418	1,472	79,666	133,322
2004	213,711	752	40,701	68,115	100,758	5,452,941	9,125,600	1,752	94,808	158,663
2005	207,253	729	39,472	66,056	100,156	5,420,366	9,071,086	1,699	91,943	153,868
2006	138,463	487	26,370	44,131	69,361	3,753,754	6,281,979	1,135	61,426	102,797
2007	139,222	490	26,515	44,373	72,203	3,907,548	6,539,355	1,141	61,763	103,361
2008	149,545	526	28,481	47,663	80,200	4,340,377	7,263,704	1,226	66,342	111,025
2009	172,676	608	32,886	55,036	92,605	5,011,731	8,387,227	1,415	76,604	128,198
2010	199,348	702	37,966	63,537	108,085	5,849,451	9,789,167	1,634	88,436	148,000
2011	157,550	554	30,005	50,215	88,207	4,773,703	7,988,882	1,291	69,893	116,968
2012	146,720	516	27,943	46,763	83,873	4,539,154	7,596,360	1,203	65,089	108,928
2013	149,507	526	28,474	47,651	86,348	4,673,076	7,820,482	1,226	66,325	110,997
2014	172,052	605	32,768	54,837	101,397	5,487,507	9,183,447	1,410	76,327	127,735
Mississippi										
2002	103,750	365	19,759	33,068	46,469	2,514,869	4,208,681	850	46,026	77,026
2003	83,438	294	15,891	26,594	38,355	2,075,745	3,473,799	684	37,015	61,946
2004	100,303	353	19,103	31,969	47,290	2,559,275	4,282,996	822	44,497	74,467
2005	105,235	370	20,042	33,541	50,855	2,752,244	4,605,932	863	46,685	78,128
2006	72,907	257	13,885	23,237	36,522	1,976,539	3,307,775	598	32,344	54,128
2007	70,774	249	13,479	22,557	36,704	1,986,406	3,324,289	580	31,397	52,544
2008	84,286	297	16,052	26,864	45,202	2,446,309	4,093,945	691	37,392	62,576
2009	98,955	348	18,846	31,539	53,069	2,872,051	4,806,432	811	43,899	73,466
2010	116,587	410	22,204	37,159	63,212	3,421,003	5,725,113	956	51,721	86,557
2011	61,272	216	11,669	19,529	34,305	1,856,532	3,106,941	502	27,182	45,490
2012	44,436	156	8,463	14,163	25,402	1,374,753	2,300,675	364	19,713	32,990
2013	42,974	151	8,184	13,697	24,820	1,343,214	2,247,894	352	19,064	31,905
2014	40,995	144	7,807	13,066	24,160	1,307,500	2,188,126	336	18,186	30,435

Notes: Scenario 2: Simulated ShB outbreaks (table 1) on susceptible hectares are sprayed twice with no associated yield loss.

[a] Annual varietal area planted to ShB-susceptible varieties in Arkansas, Louisiana, and Mississippi (Proceedings of the Rice Technical Working Group, various years).

[b] Simulated using infection rates as shown in table 1 and ShB-susceptible hectares.

[c] Dollar values are in 2014 $, deflated using the International Monetary Fund (2016) consumer price index.

[d] Fungicide spraying is done at a rate of 1.16/ha and at a cost $83.7338/ha ($19.77/ha for areal application and $63.96/ha for fungicide).

Table A4. Total Economic Cost of Sheath Blight Mitigation with Associated Yield Loss: 2002–2014

	Total Yield Loss on Sheath Blight Infected Area (MT)			Total Yield Loss on Sheath Blight-Infected Area ($)			Average Total Loss on Sheath Blight-Infected Area ($)[a]		
Year	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
				Arkansas					
2002	61	137,917	282,816	7,519	16,979,760	34,594,688	15,121	30,938,263	57,762,376
2003	64	144,248	291,324	14,193	31,699,411	63,679,605	21,760	45,594,580	86,742,173
2004	58	128,637	256,525	11,832	26,080,250	52,013,586	19,939	40,966,395	76,720,930
2005	80	175,971	350,938	15,816	34,595,183	68,848,571	24,592	50,710,340	95,595,775
2006	60	129,609	252,400	14,805	32,090,570	62,336,534	22,491	46,202,760	85,759,304
2007	52	113,474	218,113	16,433	35,908,442	68,789,048	23,963	49,735,221	91,738,105
2008	40	86,120	167,478	16,146	34,751,892	67,481,968	22,229	45,922,109	86,021,786
2009	42	92,367	177,473	14,082	30,574,732	58,807,505	22,212	45,503,944	83,240,628
2010	62	136,561	263,763	17,740	38,992,211	75,377,548	28,121	58,055,401	106,576,332
2011	38	86,055	173,313	11,442	25,632,110	51,626,956	18,079	37,820,144	71,856,101
2012	40	85,977	167,024	12,545	27,085,460	52,609,672	19,948	40,679,392	74,857,478
2013	39	85,161	165,955	13,064	28,846,169	56,232,350	19,634	40,909,311	76,254,205
2014	65	145,457	288,406	20,962	46,628,399	92,548,729	30,507	64,155,428	121,639,293
				Louisiana					
2002	18	41,511	86,916	2,202	5,014,862	10,489,693	5,031	10,210,881	19,113,808
2003	22	45,112	88,565	4,664	9,775,572	19,166,570	7,097	14,243,055	26,581,495
2004	19	42,647	89,915	3,787	8,648,504	18,234,701	6,757	14,101,445	27,285,244
2005	20	46,227	97,307	3,963	9,040,788	19,015,908	6,915	14,461,154	28,012,385
2006	16	36,245	74,135	4,055	8,931,789	18,241,762	6,100	12,685,543	24,472,071
2007	12	26,724	54,564	3,717	8,393,740	17,107,158	5,845	12,301,287	23,592,728
2008	13	29,492	61,007	5,224	11,853,769	24,507,200	7,588	16,194,146	31,711,160
2009	17	37,047	74,279	5,496	12,159,558	24,295,467	8,226	17,171,289	32,613,710
2010	17	38,102	77,433	4,866	10,771,379	21,830,340	8,052	16,620,830	31,538,992
2011	15	32,695	66,232	4,326	9,527,488	19,273,571	6,926	14,301,190	27,196,745
2012	14	30,789	61,755	4,436	9,631,365	19,304,785	6,908	14,170,519	26,838,666
2013	15	33,080	65,555	5,215	11,170,291	22,132,026	7,760	15,843,367	29,888,185
2014	19	40,405	78,457	6,077	12,842,378	24,899,122	9,066	18,329,884	34,007,036
				Mississippi					
2002	15	30,630	59,043	1,812	3,688,214	7,109,530	3,181	6,203,083	11,114,389
2003	12	25,300	48,779	2,680	5,455,304	10,517,830	3,811	7,531,049	13,794,922
2004	12	26,638	53,408	2,459	5,402,638	10,831,945	3,853	7,961,914	15,079,714
2005	10	20,945	40,186	1,886	4,086,240	7,839,978	3,385	6,838,483	12,408,027
2006	8	17,594	35,780	1,935	4,313,583	8,772,459	3,011	6,290,122	12,053,028
2007	8	18,835	38,641	2,625	5,879,059	12,061,043	3,706	7,865,465	15,357,990
2008	14	28,727	55,433	5,669	11,524,861	22,239,113	7,002	13,971,171	26,178,643
2009	11	24,410	46,062	3,701	7,911,626	14,929,502	5,265	10,783,677	19,629,896
2010	14	29,509	56,315	3,848	8,262,581	15,768,221	5,711	11,683,584	21,367,028
2011	8	15,937	30,603	2,162	4,585,318	8,804,839	3,173	6,441,850	11,843,236
2012	6	13,285	26,166	1,887	4,144,271	8,162,715	2,636	5,519,024	10,444,466
2013	6	12,720	25,030	1,953	4,292,053	8,445,871	2,685	5,635,266	10,675,276
2014	6	13,908	27,490	1,999	4,393,957	8,685,041	2,711	5,701,457	10,855,170

Notes: All ShB-susceptible hectares are infected with the simulated ShB rate in table 1 and subsequently sprayed twice with fungicide. An associated yield loss occurs dependent on the ShB-resistance rate presented in table 1. Dollar values are in 2014 $, deflated using the International Monetary Fund (2016) consumer price index.

[a] Calculated as the sum of migration costs of ShB-infected area presented in table A3 and the average total yield loss on ShB-infected area from table A4.

Table A5. Varieties Associated with the Highest Annual County Cost of Sheath Blight Mitigation: 2002–2014

		Total Loss in Sheath Blight-Infected Area ($)		
Year	**Variety**	**Avg.**	**Max**	**Min**
		Arkansas		
2002	Wells	482,769	1,322,562	15,411
2003	Wells	796,515	2,084,832	37,017
2004	Wells	631,321	1,762,270	18,278
2005	Wells	768,908	2,129,368	18,808
2006	Wells	534,120	1,910,957	8,039
2007	Wells	718,560	2,362,125	30,338
2008	Cl171	401,955	1,706,454	14,640
2009	Wells	429,579	1,250,486	40,273
2010	Cl151	636,094	2,204,287	19,113
2011	Clxl745	516,161	1,791,874	30,918
2012	Cl151	325,680	1,208,151	23,682
2013	Clxl745	375,984	1,748,147	17,772
2014	Clxl745	559,194	2,901,897	35,043
		Louisiana		
2002	Cocodrie	185,322	846,238	172
2003	Cocodrie	324,619	1,340,416	8,035
2004	Cocodrie	228,871	1,168,554	1,296
2005	Cl161	192,152	1,247,917	2,064
2006	Cl131	146,684	704,091	3,387
2007	Cocodrie	241,538	1,014,904	902
2008	Cl161	273,821	1,561,992	1,327
2009	Cl151	237,723	1,247,868	4,854
2010	Cl151	269,647	1,378,196	4,674
2011	Cl151	267,751	1,256,414	5,009
2012	Cl111	246,028	1,178,324	419
2013	Cl111	390,960	1,604,799	8,230
2014	Cl111	416,317	1,908,316	3,169
		Mississippi		
2002	Cocodrie	377,271	1,522,591	7,895
2003	Cocodrie	544,095	1,880,126	12,551
2004	Cocodrie	360,791	1,552,684	6,952
2005	Cocodrie	257,080	949,415	15,009
2006	Cocodrie	385,043	1,430,191	33,743
2007	Cocodrie	508,192	1,707,930	37,814
2008	Cocodrie	619,105	1,781,808	4,616
2009	Cl151	334,876	1,703,104	5,380
2010	Cl151	305,932	1,359,711	4,949
2011	Cl151	98,559	612,348	5,472
2012	Rex	58,148	290,385	1,171
2013	Cl152	66,006	293,272	1,052
2014	Rex	66,664	293,112	1,051

Notes: Total loss is estimated as the value of yield loss and fungicide application costs after all hectares planted to variety are infected with the simulated ShB rate in table 1 and subsequently sprayed twice with fungicide. An associated yield lossoccurs dependent on the ShB-resistance rate presented in table 1. Dollar values are in 2014 $ deflated using the International Monetary Fund (2016) consumer price index.