Simulating the U.S. Impacts of Alternative Asian Soybean Rust Treatment Regimes

Robert C. Johansson, Michael J. Livingston, John Westra, and Kurt Guidry

Asian soybean rust (rust) is an emerging issue in U.S. crop production and was identified in nine states during 2004. Recent farm surveys indicate that many producers are adjusting their management practices to the possibility of a rust infestation. The economic and environmental impacts of such adjustments are not known in the medium run given these new developments. We combine 2005 data on the geographical distribution of the fungal pathogen that causes rust with 2005 information on the availability and material costs of fungicides to analyze three treatment strategies. Our results indicate a higher range of economic impacts than previous research has indicated, but are consistent with earlier findings indicating that rust infestations will likely result in reduced soybean production, reduced exports, and higher prices.

Key Words: Asian soybean rust, invasive species, *Phakopsora pachyrhizi*, preventative and curative fungicides

Yield reductions and production cost increases have been attributed to Asian soybean rust (rust), a plant disease caused by *Phakopsora pachyrhizi*, in Africa (Caldwell and Laing 2002), Asia (Yang et al. 1991), Australia (Bromfield 1984), and South America (Yorinori et al. 2003). This virulent fungal pathogen can travel long distances in wind currents and storms. Moreover, it can infect over 95 species of plants (Miles, Frederick, and Hartman 2003), including soybeans, other cultivated plants such as peas and beans, and wild hosts such as kudzu, which has served as an efficient source of inoculum in Brazil (Yorinori et al. 2003). The detection of rust in South America during 2000 heightened concerns regarding the threat this invasive species poses to domestic agriculture. In response, the U.S. Department of Agriculture (USDA) established a rust surveillance, information, and education program to enhance the ability of domestic producers to respond effectively to potential rust epidemics (USDA 2002).

As part of this effort, USDA's Economic Research Service (ERS) published an examination of potential economic and environmental consequences of rust epidemics (Livingston et al. 2004). The ERS study estimated that acreage planted to soybeans could decline between two and six percent in the medium term, which was consistent with reported planting intentions for the 2005 season (USDA 2005a). Furthermore, the ERS study found that the annual sum of producer losses in domestic crop and livestock sectors, and associated domestic consumer losses, could vary widely between \$0.2 and \$2.0 billion, depending on the geographical extent and severity of rust epidemics.

In the fall of 2004, soybean rust was observed in Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, Missouri, South Carolina, and Tennessee. *P. pachyrhizi* spores had apparently arrived from South America, likely in conjunction with Hurricanes Francis and Ivan (USDA 2005b). In response, USDA, in cooperation with state departments of agriculture, universities, and the private sector, established a coordinated rust sur-

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veillance, reporting, forecasting, and research framework to improve the ability of domestic soybean and legume producers to reduce potential yield losses effectively. As part of this effort, sentinel soybean plots were planted in potential spore source areas in the south and in the major soybean-producing states and were monitored for evidence of rust. As of September 8, 2005, rust had been confirmed from kudzu, sentinel soybean plots, research farms, and commercial soybean fields in 13 counties in Alabama, 21 counties in Florida, 15 counties in Georgia, 2 counties in Mississippi, and 3 counties in South Carolina (USDA 2005c).

Given these developments, the primary objective of this analysis is to re-examine potential producer responses (both in planting and with fungicide treatments) and the attendant economic and environmental consequences of regional rust epidemics. We note first that the probabilities that rust epidemics may occur in U.S. soybean production regions will have changed from those estimated in the previous ERS study. Here, we use updated likelihoods for regional rust outbreaks based on historical experience with stem rust (*Puccinia graminis*) epidemics of wheat, because it is believed that *P. pachyrhizi* will follow the same aerial pathways as *P. graminis* (USDA 2005b). Also, information on fungicide material costs was preliminary at the time of the previous ERS study. Here, we use recent cost estimates and treatment strategies developed at Louisiana State University Agricultural Center to improve our analysis.

Our analysis contributes to an understanding of this emerging issue in crop production by simulating alternative treatment responses by farmers to expected outbreaks of soybean rust in the United States based on the best information available. First, we develop estimates of possible yield impacts, for treated and untreated soybean fields, and cost impacts based on available treatment options. Next, we estimate probabilities that rust epidemics will occur, by major domestic soybean production region, which are used to specify yield and cost impact scenarios that characterize the geographic extent and severity of rust epidemics over the medium run. Farmer adjustments to soybean rust epidemics are simulated using a regional agricultural sector model, and potential impacts on farm incomes are discussed at the national and regional levels.

Modeling Assumptions

Yield Impacts

We use data from fungicide efficacy trials conducted in Brazil and Paraguay during 2001–2003 (BASF 2003; Bayer 2003a, 2003b), aggregate yield data for 10 Brazilian states during 1993–2002 (USDA, *Brazil Oilseeds and Products*, various years), and data on the introduction of *P. pachyrhizi* into those states (Yorinori et al. 2003) to estimate treated and untreated yield impacts of soybean rust (Table 1). Nine efficacy trials examined the impact of not spraying rust-infected soybean plots with fungicides during the 2001/2002 and 2002/2003 growing seasons. Untreated yields were an average 25.05 percent lower than our estimates of rust-free yields for those years and for Brazilian states in or nearby the Brazilian states or Paraguayan cities in which the efficacy trials were conducted. Fourteen efficacy trials examined the impacts of one preventative fungicide application on soybean yields; the treated yields were an average 0.97 percent (± 6.72 percent) lower than our estimates of rust-free yields for those years and trial locations.[1] Similarly, seven efficacy trials examined the impacts of two curative fungicide applications, and 11 efficacy trials evaluated the impacts of one curative fungicide application. Curatively treated soybean yields were an average 6.95 percent (± 7.98 percent) lower than our estimates of rust-free yields for those years and trial locations. We use our estimates of average yield impacts and the 99 percent confidence level for the average preventatively treated yield impact to specify yield-impact scenarios to examine potential economic and environmental consequences of soybean rust epidemics in the United States. However, the yield impact estimates (Table 1) are combined with estimates of the probabilities that rust epidemics may occur, in the various U.S. regions in which soybeans are produced, to specify these scenarios.

[1] The 99 percent confidence level is reported. The application of preventative and curative fungicides might actually improve soybean yield, relative to rust-free yield, because they also kill fungi that cause yield losses, which are too small to abate profitably using fungicides (Livingston et al. 2004).

Table 1. Estimates and 95 Percent Confidence Levels for Untreated and Treated Yield Impacts of Soybean Rust*

	Untreated Yield Impact	Preventative Yield Impact	Curative Yield Impact
Mean	-25.05%	-0.97%	-6.95%
Standard deviation	22.61%	9.76%	13.15%
Observations	9	14	18
99% confidence level	19.41%	6.72%	7.98%

* The lower bound of the rust-free yield estimate for Mato Grasso do Sul, 2.678 ± 0.455, during 2001–2002, was used to estimate yield impacts relative to trials 1 and 2 reported by Bayer (2003a). The estimate for rust-free yield in Minas Gerais, 2.549 ± 0.488, during 2002–2003, was used to estimate yield impacts relative to trial 14 reported by Bayer (2003b). The estimate for rust-free yield in Minas Gerais, 2.549 ± 0.488, during 2002–2003, was used to estimate yield impacts relative to trial 15 reported by Bayer (2003b). The estimate for rust-free yield in Minas Gerais, 2.549 ± 0.488, during 2002–2003, was used to estimate yield impacts relative to trial 16 reported by Bayer (2003b). The upper bound of the rust-free yield estimate for Parana, 2.862 ± 0.497, during 2002–2003, was used to estimate yield impacts relative to the Jesus, Paraguay, trial reported by BASF (2003). The estimate for rust-free yield in Mato Grasso do Sul, 2.750 ± 0.476, during 2002–2003, and the weighted average rust-free yield estimate for Parana, Mato Grasso do Sul, Rio Grande do Sul, and Santa Catarina, 3.003, were used to estimate yield impacts relative to the Pirapo, Paraguay, trial reported by BASF (2003).

Regional Probabilities of Soybean Rust Epidemics

Under appropriate environmental conditions, rust may infect soybean fields and inflict economic damage across most U.S. soybean-growing regions (Figure 1). However, because of temperature extremes, *P. pachyrhizi* may be able to overwinter successfully only along the coastlines of Alabama, Florida, Georgia, Louisiana, Mississippi, and Texas, as well as potential source areas in Mexico, Central America, and the Caribbean islands (Pivonia and Yang 2003). It is therefore not surprising that rust was confirmed in all of these states during 2005 (USDA 2005c). Because the majority of soybeans are produced in other states, the occurrence of major rust epidemics will depend on the arrival of fungal spores from the south. In addition, if spores are transported aerially from southern source regions, daily temperature minima and maxima must not be too low and high, respectively; soybean plants must be present; and there must be a sufficient amount of leaf wetness for rust to occur.

Data on daily temperature extremes, rainfall, and humidity during 1992–2001 are used to estimate the proportion of years climatic conditions may favor the development of soybean rust in each of the major soybean production regions. Livingston et al. (2004) report that the climatic conditions were most likely to favor rust regionally during April–May, June–July, and August–September periods during 1992–2001. Because periods of climate suitability will differ from periods during which soybeans are available for infection, we scale the regional climate suitability fractions by regional soybean plant availability fractions. The average number of days from seed planting to plant emergence is 10.5 days (Iowa State University Extension 1994), which are added to the most active beginning soybean planting dates (USDA 1997) for each soybean-producing state in order to estimate the initial date that rust may occur. Further, because rust does not affect yield if infection occurs after the end of the reproductive growth stage known as R6 (on average 98.5 days from seed planting; Dorrance, Draper, and Hershman 2005), 98.5 days are added to soybean planting dates in order to estimate the last day that rust may occur in each state.

Historical experience indicates that the windborne fungus, *P. graminis*, which causes wheat stem rust, emanates from source regions in Mexico and Central America and traverses the Southern Plains, Corn Belt, Northern Plains, and Lake States. Furthermore, it is believed that the aerial dispersion of *P. pachyrhizi* spores, which overwinter along or south of the coastlines of Texas and Louisiana, will likely follow the "*Puccinia* pathway" (USDA 2005b). Therefore, the product of the fraction of years that stem rust epidemics occurred in durum, winter, and other spring wheat in U.S. soybean-producing states during 1921–

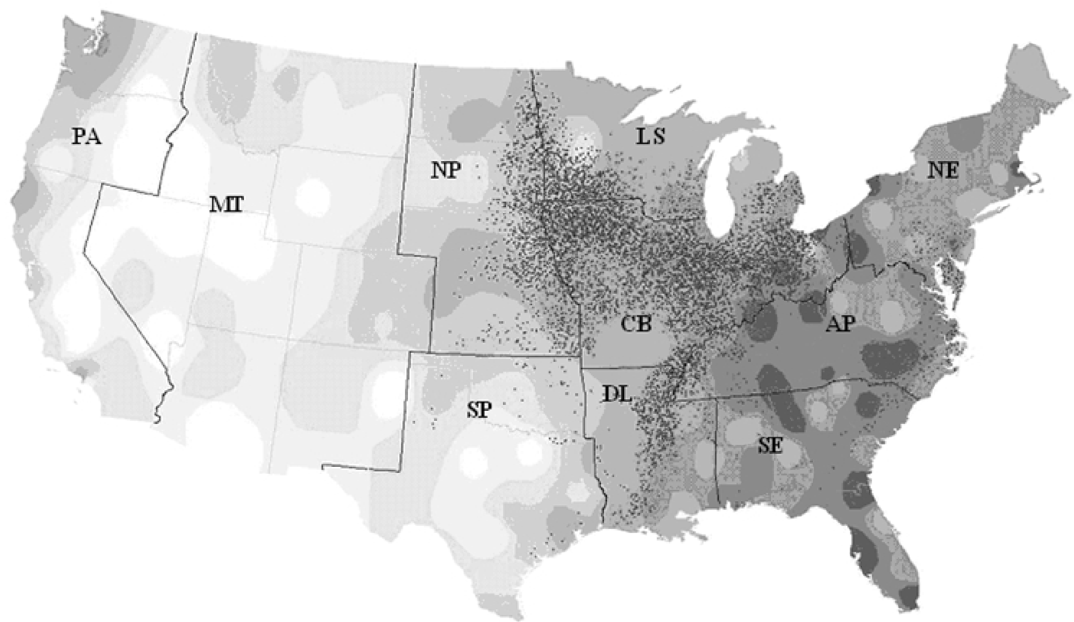

Figure 1. Soybean Production and Climatic Suitability for Asian Soybean Rust

Source: Adapted from Livingston et al. (2004).

Notes: NE = Northeast, LS = Lake States, CB = Corn Belt, NP = Northern Plains, AP = Appalachia, SE = Southeast, DL = Delta, SP = Southern Plains, MT = Mountain States, PA = Pacific. One dot represents 300,000 bushels of soybean produced in 2003. Climatic suitability for Asian soybean rust production ranges from dark shading (75 percent of the time) to white shading (0 percent of the time)

1962 and the plant-availability–scaled, climate-suitability fraction is used to estimate probabilities that rust epidemics may occur in each state. In soybean-producing states where *P. pachyrhizi* may overwinter (Pivonia and Yang 2003), however, we set the rust occurrence probability to one. Finally, regional rust occurrence probabilities (Table 2) are given by the state rust occurrence probabilities weighted by average soybean production in each region's states during 1995–2004 (USDA, *Agricultural Statistics*, various years).

Yield and Cost Impact Scenarios

We examine the economic and environmental consequences of three yield and cost impact scenarios (Table 3): one in which producers do not apply fungicides (*notreat*); a scenario in which producers apply a single preventative fungicide treatment (*treat*); and a scenario in which producers apply a single curative fungicide treatment (*cure*). Under *notreat*, the regional yield impacts are given by the product of the region's rust occurrence probability and the average untreated yield impact, -25.05 percent (Table 1). Similarly, under *cure*, regional yield impacts are given by the product of a region's rust probabilities and the average curatively treated yield impact, -6.95 percent (Table 1). That is, we use each region's expected yield impact to specify regional yield losses under *notreat* and *cure*. Under *treat*, expected yield impacts for each region are given by the sum of the product of the region's rust probability and the average preventatively treated yield impact, -0.97 percent, and the product of one minus the region's rust probability and the upper limit of the 99 percent confidence interval for the average preventatively treated yield impact, 5.75 percent. That is, under *treat*, it is necessary to incorporate the probability that rust does not occur and the yield impact of a preventative

Table 2. Probability of Soybean Rust Occurring by Region[*]

Region [a]	Emerge [b]	R6	Years with Stem Rust [c]	Years Climate Suitable for *P. pachyrhizi* [d]	Probability of Soybean Rust [e]
Appalachia	June 3	August 30	0.82	0.90	0.75
Corn Belt	May 24	August 20	0.95	0.58	0.55
Delta	May 26	August 22	0.89	0.68	0.63
Lake States	May 26	August 22	0.95	0.52	0.49
Northeast	June 10	September 6	0.75	0.84	0.62
Northern Plains	May 30	August 26	0.92	0.47	0.43
Southeast	June 5	September 1	0.91	0.94	0.86
Southern Plains	May 20	August 16	0.91	0.63	0.61

[*] Regional values for the reported variables are given by state-level values weighted by average soybean production in each region's states during 1995–2004 (USDA, *Agricultural Statistics,* various years).
[a] Regional definitions: Northeast (NE) = CT, DE, MA, MD, ME, NH, NJ, NY, PN, RI, and VT; Lake States (LS) = MI, MN, and WI; Corn Belt (CB) = IA, IL, IN, MO, and OH; Northern Plains (NP) = KS, ND, NE, and SD; Appalachia (AP) = KY, NC, TN, VA, and WV; Southeast (SE) = AL, FL, GA, and SC; Delta (DL) = AR, LA, and MS; Southern Plains (SP) = OK and TX; Mountain States (MT) = AZ, CO, ID, MT, NM, NV, UT, and WY; Pacific (PA) = CA, OR, and WA; United States (US).
[b] We assume that it takes one to two weeks (10.5 days) for soybean plants to emerge after planting (Iowa State University Extension 1994). Therefore, 10.5 was added to the first, most active beginning planting date in order to estimate when soybean plants are first available for infection by *P. pachyrhizi* (USDA 1997).
[c] The mean fraction of years that stem rust epidemics of durum, winter, or other spring wheat occurred during 1921–1962 (Hamilton and Stakman 1967). A fraction was assigned to each state latitudinally if data for that state were not reported by Hamilton and Stakman (1967). The fraction was set to 1.00 for AL, FL, GA, LA, MS, and TX, where *P. pachyrhizi* may overwinter (Pivonia and Yang 2003).
[d] The fraction of years during 1992–2001 in which climates were suitable for soybean rust epidemics (Livingston et al. 2004) weighted by the proportion of each period (e.g., April–May) in which soybeans are available for infection. We assume that this latter period is bounded by plant emergence and the end of R6. The fraction was set to 1.00 for AL, FL, GA, LA, MS, and TX, where *P. pachyrhizi* may overwinter (Pivonia and Yang 2003).
[e] The product of the preceding two columns. Note that the probability of soybean rust is lower in the Delta region than one might expect due to the large percentage of soybean production in Arkansas, thus far unaffected by soybean rust.

fungicide treatment with no rust. Because data are not available to estimate this latter yield impact, we use the upper bound of the 99 percent confidence interval for the average preventatively treated yield impact to approximate this value.

Under *notreat* and *treat*, expected cost impacts are fixed for each region at $0.00 and $25.63 per acre, respectively, because these costs are assumed to be incurred with certainty. The latter specification is for 12.0 ounces (University of Minnesota 2005) of pyraclostrobin at $20.53 per acre (BASF 2005) plus an air application cost of $5.00 (Livingston et al. 2004). For one curative fungicide treatment, we assume 4.0 ounces at $8.81 per acre (Bayer 2005) plus the $5.00 air application cost for a total of $13.81 per acre. Because we assume that regional curative fungicide treatment costs under *cure* occur only if rust epidemics occur, regional cost impacts are given by the region's rust occurrence probabilities and $13.81.[2]

Simulation Analysis

We use a regional, mathematical-programming model of U.S. agriculture sectors developed at ERS (House et al. 1999) to simulate the expected regional yield and cost impacts and the subsequent changes in equilibrium prices and production levels.[3] We use this model because it is able

[2] For the simulation, we assume an adjustment period of approximately 5 years. Therefore these treatment costs are inflated to 2010 $US in the model, using the multiplier $1.2971 = 1.0534^5$, where the annual interest rate is from Lence (2000). Economic impacts are also reported in 2010 $US.

[3] The model has been used to examine economic and environmental consequences associated with water quality (Kaplan, Johansson, and Peters 2004, Johansson and Kaplan 2004) and wetlands (Claassen et al. 1998) policies, sustainable agriculture (Faeth 1995), and climate-change mitigation (Peters et al. 2001).

Table 3. Expected Yield and Cost Impact Scenarios Examined

	Yield Impacts[a]			Cost Impacts[b]		
Region	***notreat***	***treat***	***cure***	***notreat***	***treat***	***cure***
Appalachia	-18.81%	0.71%	-5.22%	$0.00	$33.24	$13.45
Corn Belt	-13.87%	2.03%	-3.85%	$0.00	$33.24	$9.92
Delta	-15.80%	1.51%	-4.38%	$0.00	$33.24	$11.30
Lake States	-12.32%	2.45%	-3.42%	$0.00	$33.24	$8.81
Northeast	-15.65%	1.55%	-4.34%	$0.00	$33.24	$11.19
Northern Plains	-10.73%	2.88%	-2.98%	$0.00	$33.24	$7.67
Southeast	-21.66%	-0.06%	-6.01%	$0.00	$33.24	$15.49
Southern Plains	-15.18%	1.68%	-4.21%	$0.00	$33.24	$10.86

[a] Regional yield impacts for *notreat* and *cure* are given by the products of the regional rust occurrence probabilities (Table 2) and the mean untreated and curatively treated yield impacts (Table 1), respectively. Regional yield impacts for *treat* are given by the sums of the products of the regional rust probabilities and the mean preventatively treated yield impacts and the products of one minus the regional rust probabilities and the upper bound of the 99 percent confidence interval for mean preventatively treated yield impacts.
[b] Under *notreat* and *treat*, expected cost impacts are fixed for each region at $0.00 and $25.63 per acre, respectively. The latter specification is for 12.0 ounces (University of Minnesota 2005) of pyraclostrobin at $20.53 per acre (BASF 2005) plus an air application cost of $5.00 (Livingston et al. 2004). For one curative fungicide treatment, we assume 4.0 ounces at $8.81 per acre (Bayer 2005) plus the $5.00 air application cost for a total of $13.81 per acre. Under *cure*, regional cost impacts are given by the product of the region's rust occurrence probabilities and $13.81. Pecuniary values are converted to 2010 US$, using the multiplier $1.2971 = 1.0534^5$, where the annual interest rate is from Lence (2000).

to simulate equilibrium prices and production changes at the national level based on region-specific shocks and producer adjustments. This model treats agriculture sectors as part of a spatially competitive, market-equilibrium system, which is partial equilibrium in the sense that U.S. agriculture does not compete with other sectors for factors of production. The model includes 45 geographic sub-regions, which are further distinguished by erodibility. Twenty-three inputs are included, as are the production and consumption of 44 agricultural commodities and processed products. Agricultural markets for inputs such as land (crop and pasture), labor (family and hired), and irrigation water are specified at the regional level, and the demand for roughly 23 other inputs (e.g., fertilizer and seed) are subject to fixed, national prices (Table 4).

Production levels and enterprises are calibrated to regularly updated production practice surveys using a positive math programming approach (Howitt 1995) and the USDA multi-year baseline (USDA 2003). Regionally specific extensive (animal and crop production levels) and intensive (crop rotations, tillage, and fertilizer practices) management practices are endogenously determined. Substitution among the cropping activities is achieved in the model using nested constant elasticity of transformation functions. These nonlinear supply response functions reflect declining marginal rates of transformation between crop rotations and between tillage activities. This implies that changes in land allocated to various production enterprises do not occur at corner solutions, as in linear programming models, but adjust smoothly to changes in relative returns across production enterprises. The transformation elasticities are specified so that model supply response at the national level is consistent with domestic supply responses in the USDA's Food and Agriculture Policy Simulator (FAPSIM) (Westcott, Young, and Price 2002) and with trade responses in the USDA Economic Research Service/Penn State Model (Stout and Abler 2003).[4]

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[4] Short-run arc elasticities from FAPSIM, holding all else constant, are used initially to calibrate supply functions. The initial arc elasticity for the price elasticity of soybean supply with respect to soybean price is assumed to be 0.27. This is adjusted upwards by 5 percent per year to account for medium-run simulations consistent with the literature (e.g., Williams, Shumway, and Love 2002). The price and quantity adjustments in the simulation model will also depend on cross-price elasticities, which can be larger than own-price effects (e.g., Lin et al. 2005).

Table 4. Input and Output Parameters for Simulation Model*

Inputs		Outputs		
Regional	**National**	**Crops**	**Livestock**	**Processed**
cropland	nitrogen fertilizer	corn	fed beef for slaughter	soybean meal
pastureland	potassium fertilizer	soybeans	nonfed beef for slaughter	soybean oil
	potash fertilizer	sorghum	beef calves for slaughter	livestock feed mixes
	lime	barley	beef feeder yearlings	dairy feed supplements
	other variable costs	oats	beef feeder calves	swine feed supplements
	public grazing land	wheat	cull beef cows	fed beef
	custom farming operations	cotton	cull dairy cows	nonfed beef
	chemicals	rice	cull dairy calves	veal
	seed	silage	milk	pork
	interest on operating capital	hay	hogs for slaughter	broilers
	machinery and equipment repair		cull sows for slaughter	turkeys
	veterinary and medical costs		feeder pigs	eggs
	marketing and storage		other livestock	butter
	ownership costs			American cheese
	labor and management costs			other cheese
	land taxes and rent			ice cream
	general farm overhead			nonfat dry milk
	irrigation water application			manufacturing milk
	energy costs			ethanol
	insurance			corn syrup

* The U.S. Agriculture Sector Mathematical Programming (USMP) model accounts for production of the major crop (corn, soybeans, sorghum, oats, barley, wheat, cotton, rice, hay, silage) and confined livestock (beef, dairy, swine, poultry) categories comprising approximately 75 percent of agronomic production and more than 95 percent of confined livestock production. We do not consider potential applications of manure to rangeland, vegetable, horticulture, sugar, peanut, or silviculture operations.

In reduced form,[5] each simulation represents a medium-run steady-state solution, solving for spatially optimal production of crops and livestock:

(1)
$$\max_{xact_{rj},xact_{rk}} \sum_r \sum_j (P_j - VC_{rj}) xact_{rj} + \sum_r \sum_k \sum_i (P_i - VC_{ri}) y_{rik} xact_{rk} \forall\ r, j, k, i.$$

Here, $xact_{rj}$ represents regional production of livestock and poultry species j in region r;[6] $xact_{rk}$ represents regional acres planted under cropping enterprise k (designating the crop rotation and tillage regime) in region r; y_{rik} is the annual yield of crop i in enterprise k in region r; P_j and VC_j are equilibrium prices and variable costs for livestock and poultry products; and P_i and VC_i are equilibrium prices and variable costs for crops.

After initially calibrating the spatial equilibrium model to baseline conditions in 2010 (USDA 2003), we use the model to simulate farmer adjustments to our yield and cost impacts (Table 3) in the medium term. That is to say, we assume treatment costs and yield impacts to be

(2) $VC_{ri} = VC_{ri}^0 + AF_{ri}$ and $y_{rik} = \overline{y}_{rik} \times (1 - \alpha_{ri})$,

for i = *soybeans*. Here, AF_{ri} are additional fungicide costs for soybeans in region i; VC_{ri}^0 are vari-

[5] Further discussion of the extended model with non-linear nested, CET functions can be found in Johansson, Cooper, and Vasavada (2005).

[6] We include interactions between animal and crop production to capture the joint impacts of soybean rust on both soybean prices and animal production via the feed sector.

able costs for crop production prior to soybean rust expectations; $\bar{y}_{rik}$ are average soybean yields in a given region and enterprise in the absence of soybean rust or supplemental fungicides; and α_{ri} is the assumed yield shock for soybeans in region r under any given scenario.

Results

Each simulation represents a spatial, medium-term steady-state for U.S. agricultural production in 2010, given the scenario's assumptions. Estimated losses borne by soybean producers range between $623 and $1,422 million (Table 5), which is similar in magnitude to the range of losses, $182 and $1,346 million,[7] reported by Livingston et al. (2004), who examined the implications of different disease spread scenarios and yield and cost impacts. In the current analysis, estimated losses borne by soybean, other crop, and livestock producers range between $788 and $1,527 million, which is also similar to the range reported in the ERS study, $172 and $1,474 million.

Aggregate returns to soybean production decline 15, 16, and 33 percent under *notreat*, *cure*, and *treat*, respectively, relative to the baseline. At $623 million, estimated losses in the medium term are lowest when soybean producers do not use fungicides (Table 5). Regional yield losses are highest under this scenario, and aggregate soybean production declines 19 percent; however, the decline in output leads to a 15 percent increase in the aggregate price level, which partially offsets the negative impacts on returns. At $669 million, estimated losses are slightly over 7 percent higher when soybean producers adopt a wait-and-see approach and apply a curative fungicide treatment. Aggregate output declines only 8 percent under *cure*, which leads to a 5 percent increase in the aggregate soybean price level; however, the $708 million increase in fungicide treatment costs offsets the beneficial impacts of the curative fungicide application on regional soybean yields. Finally, at $1.422 billion, estimated losses are highest when producers apply a preventative fungicide treatment (*treat*). Under *treat*, aggregate soybean production declines only 5 percent, the price level increases 4 percent, but the $2.181 billion increase in fungicide treatment costs results in a 128 percent increase in estimated losses relative to *notreat*.

Even though estimated losses in the U.S. soybean industry are lowest under *notreat*, estimated losses in all of the U.S. crop and livestock industries simulated in the model are lowest under *cure*. Relative to the baseline, estimated losses in these crop and livestock industries are $788, $921, and $1,527 million under *cure*, *notreat*, and *treat*, respectively. The U.S. livestock sector suffers profit losses because of the declines and increases in aggregate soybean output and price, respectively; therefore, livestock producers are least affected under *treat*, because output declines and price and increases are marginal, and most affected under *notreat*, because output declines and price and increases are more significant. Estimated losses in the livestock sector are roughly 69 percent higher under *cure* relative to *treat* and 49 percent lower under *cure* relative to *notreat*. Estimated losses borne by producers of all other crops simulated in the model are highest when soybean producers do not apply fungicides and next highest when soybean producers apply a preventative fungicide treatment; however, returns to producers of other crops actually increase an estimated $14 million per year when soybean producers apply a curative fungicide treatment. As a result, welfare losses in the U.S. agriculture sector are lowest under *cure*.[8]

As in Livingston et al. (2004), we also notice soybean substitution between regions associated with regional likelihoods of experiencing different yield and cost impacts (Table 6). Because returns to soybean production decline the most when soybean producers adopt the preventative treatment strategy, soybean acreage declines the most under *treat*, at slightly over 10 percent. Under *notreat* and *cure*, U.S. soybean acreage declines roughly 5 percent; however, acres planted to soybeans could increase in the Lake States under the former scenario. In addition, overall crop acreage could fall by a small amount in many regions in the medium term, due to the

[7] All economic results are presented in 2010 $US.

[8] It is important to note, however, that we are simulating homogenous treatment strategies, which are useful for estimating ranges of possible outcomes. Variable strategies based on notions of individual producers about how likely they are to experience an infestation are more likely for a given year.

Table 5. Simulated Economic Impacts

Scenario	Soybean Production (mil. bu.)	Soybean Exports (mil. bu.)	Soybean Price ($/bu.)	Soybean Returns ($ mil.)[a]	Treatment Costs ($ mil.)	Other Crop Returns	Livestock Returns ($ mil.)
Base[b]	3,045	930	5.50	4,282	n/a	13,174	43,938
notreat[c]	2,471	806	6.30	3,659	n/a	13,138	43,676
treat[d]	2,879	898	5.71	5,040	2,181	13,149	43,859
cure[e]	2,802	883	5.80	4,321	708	13,188	43,805

[a] Note that soybean returns here do not include treatment costs. *Net* returns to soybean production would be the difference between soybean returns and treatment costs.
[b] *base* = baseline values are taken for 2010 USDA baseline projections (USDA 2003).
[c] *notreat* = producers do not treat for potential rust infestations.
[d] *treat* = producers apply a pre-infection application of fungicide.
[e] *cure* = producers adopt a wait-and-see approach and apply a curative fungicide treatment only if an infestation is detected.

relative ubiquity of soybean rotations across regions. The joint influence of lower soybean and crop acreage overall and increased applications of fungicides under certain strategies, make it difficult to predict how overall use of pesticide active ingredients might evolve. Under most treatment strategies the increase in applications would outweigh the decrease in acres, resulting in a marginal increase in the overall use of pesticides across the United States.

Conclusions

The economic and environmental impacts of Asian soybean rust remain uncertain and are highly dependent upon assumptions made about the severity and extent of rust infestations and producer responses to them. Using the most recent available information on potential yield and cost impacts and regional likelihoods that rust outbreaks may occur, we estimate a range for potential economic and environmental consequences associated with three fungicide treatment strategies: producers do not use fungicides (*notreat*), all producers apply a curative fungicide (*cure*), and all producers apply a preventative fungicide (*treat*). Using a spatial model of the U.S. agriculture sector, which simulates regional crop and livestock producer responses to the specified yield and cost impacts, estimated losses in the soybean industry are lowest under *notreat*, next lowest under *cure*, and highest under *treat*. This occurs because the aggregate impacts of fungicide treatments on soybean output and price are not sufficient to cover the additional costs. Estimated losses in the U.S. agriculture sector, however, are lowest under *cure*, next lowest under *notreat*, and highest under *treat*. The aggregate impacts of soybean producer use of a curative fungicide treatment on soybean output and price in the U.S. agriculture sector are sufficient to cover the additional treatment costs.

It is likely that producers in different regions and with different attitudes toward risk will adopt different strategies—some may adjust soybean acreage and switch to other crops (e.g., USDA 2005a), some may not treat rust infestations, and others may choose to apply different fungicides at different times during the growing season (e.g., Dorrance, Draper, and Hershman 2005). Our assumption of a homogenous response, however, is a necessary simplification for modeling purposes and because medium-term producer responses to rust infestations are not known at this point. We assume that adjustments to rust infestations will be fully incorporated into producers' choices by the year 2010. However, it is likely that, as new technologies emerge and farmers have more experience dealing with this fungus, producer adjustments will continue to evolve and become more efficient.

Lastly, soybean rust epidemics may be more or less difficult to control than other fungal diseases. Research during the early twentieth century led to the successful development of several wheat varieties that tolerate stem rust. Although research into developing tolerant soybean varieties is being conducted, all varieties currently grown in the United States are known to be susceptible to soybean rust. The many and various assumptions

Table 6. Simulated Adjustments to Rust Infestations

Scenario		Region[a]										
		NE	LS	CB	NP	AP	SE	DL	SP	MT	PA	US
Base[b]	Soybean acres (mil. ac.)	1.10	8.50	37.00	8.30	5.30	3.20	9.30	0.30	0.00	0.00	73.00
	Total acres (mil. ac.)	14.50	38.50	97.50	64.40	18.90	7.80	18.10	29.70	21.60	8.00	319.00
	Pesticides (mil. lbs.)[f]	12.41	44.17	141.82	49.29	27.35	12.34	51.46	18.54	9.45	8.50	375.34
		Percent Change										
notreat[c]	Soybean acres	-100.00	0.20	-0.40	-14.00	-11.80	-8.40	-2.50	-1.30	0.00	0.00	-4.80
	Total acres	-9.60	0.00	-0.20	-1.40	-3.10	-2.50	-0.80	0.00	0.00	0.00	-1.10
	Pesticides	-2.24	-0.39	-0.25	1.54	0.19	-0.68	-0.77	0.01	0.46	0.00	0.12
treat[d]	Soybean acres	-17.50	-10.50	-2.50	-15.10	-25.40	-26.80	-20.20	-6.10	0.00	0.00	-10.10
	Total acres	-2.40	-1.80	-0.90	-1.80	-6.30	-11.00	-7.60	-0.20	-0.20	-0.10	-2.10
	Pesticides	4.68	13.56	19.12	10.99	11.92	13.31	16.26	1.20	0.00	0.00	13.47
cure[e]	Soybean acres	-100.00	-1.30	-0.90	-4.90	-13.00	-9.20	-5.50	-2.30	0.00	0.00	-4.70
	Total acres	-9.80	-0.20	-0.30	-0.50	-3.20	-3.10	-1.70	0.00	0.10	0.00	-1.00
	Pesticides	-2.24	3.06	4.70	2.41	4.76	6.48	5.90	0.33	0.46	0.00	3.51

[a] Regional definitions: Northeast (NE) = CT, DE, MA, MD, ME, NH, NJ, NY, PN, RI, and VT; Lake States (LS) = MI, MN, and WI; Corn Belt (CB) = IA, IL, IN, MO, and OH; Northern Plains (NP) = KS, ND, NE, and SD; Appalachia (AP) = KY, NC, TN, VA, and WV; Southeast (SE) = AL, FL, GA, and SC; Delta (DS) = AR, LA, and MS; Southern Plains (SP) = OK and TX; Mountain States (MT) = AZ, CO, ID, MT, NM, NV, UT, and WY; Pacific (PA) = CA, OR, and WA; United States (US).

[b] Baseline values are taken for 2010 USDA baseline projections (USDA 2003).

[c] *notreat* = producers do not treat for potential rust infestations.

[d] *treat* = producers apply a pre-infection application of fungicide.

[e] *cure* = producers adopt a wait-and-see approach and apply a curative fungicide treatment only if an infestation is detected.

[f] Pesticides are given in million of pounds of active ingredient applied to all crops in the model.

used in the current study are indicative of the high level of uncertainty that remains. We leave it to future studies to examine how yield and production cost are actually affected in different regions, and how producers actually respond to rust infestation.

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