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Estimating the Cost of Invasive Species on U.S. Agriculture: The U.S. Soybean Market

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Estimating the Cost of Invasive Species on U.S. Agriculture:

The U.S. Soybean Market

Soybean production ranks among the largest agricultural cash crops in the U.S., second only to corn. U.S. soybean production topped 3 billion bushels in 2005 with sales of $17 billion. Approximately 58% of U.S. soybeans are grown in Iowa, Illinois, Minnesota, Indiana, and Nebraska. A small percentage of the U.S. soybean crop, 2%, goes to human consumption in the form of whole beans, soybean oil, and soybean meal products. A third of the crop, 1 billion bushels per year is exported annually to China, EU, Mexico, Japan, and Taiwan, and other countries. Most of the crop, 2 billion bushels, goes to the U.S. livestock industry to feed poultry, hogs, and cattle. Variations in the supply of soybeans thus directly impact livestock production. In recent years, soybean prices have exceeded the $5 per bushel U.S. loan rate fluctuating from $5 to over $7 per bushel. Continued success of this crop is threatened by the introduction of two new invasive species, soybean rust and soybean aphid.

Soybean aphid (*Aphis glycines*), an insect pest, thrives on plants in the North and Midwest. Soybean aphids were first detected in Wisconsin in 1995, but confirmation of the pest did not occur until five years later in 2000. The delay in confirmation may have enabled the pest's dissemination. Spreading at the rate of 600 miles per year, by 2003 soybean aphids had infested crops in 21 states (North Central Soybean Research Program, 2004). Because the soybean aphid's wintering host (*buckton*) is not found outside the Midwest and Northern plains, the extent of aphid damage may be limited to these regions. Furthermore, studies have shown the insect to be intolerant to temperatures above 95°F further precluding widespread infestation in the South.

Soybean rust (*Phakopsora pachyrhizi*), is an established disease in Australia, Africa, Asia, India, and South America. First detected in Louisiana in 2004, soybean rust rapidly spread through the South. By 2005, soybean rust had spread to crops in Alabama, Florida, Georgia, Mississippi, and South Carolina (Bissonnette, 2005). The fungus is most damaging to cultivated soybean, but documentation shows it can reproduce on 95 other plant species including peas, beans, and kudzu, a widespread, invasive plant. Soybean rust spores are disseminated naturally by wind. Constructed windbreaks can provide a first level of defense against spore deposition. Complete protection, however, is impossible.

Chemical options include pre-infection (preventative) fungicide spraying and post infection (curative) fungicide spraying. Another option is to plant alternate non-legume crops such as corn, wheat, and cotton. For partial protection against yield and price risk, federal crop insurance is available. Participating farmers can choose from several programs and coverage levels. If rust disease becomes widespread, coverage and premiums would likely adjust over time. Pre-infection spraying has been shown to be very effective at mitigating yield loss. For the treatment to work, however, application timing is critical. Spraying "too late" after the spores arrive allows the crop to become infected. Spraying "too early" before the spores arrive offers little or no protection against infection necessitating another treatment.

Previous work

Kim, et al. (2006) specified a dynamic equilibrium model to project the impacts of soybean aphid spread on the soybean industry. The authors simulated various rates of spread, treatment scenarios, and treatment cost scenarios using 2002 as the baseline when 144,727 acres were plagued by aphids. Results showed that after 10 years, producer surplus loss would be between

$96 million and $596 million per year. Consumer surplus loss in the tenth year was estimated to be between $43 million and $272 million. These results suggest the upper limit on losses would be a 4.4% reduction in producer surplus and a 0.9% reduction in consumer surplus.

Livingston et al (2004) forecasted losses from soybean rust before the disease reached the U.S. Included in the analysis were probability of spore arrivals, range of expected yield losses with the disease (from +.9% to -9.5%), and cost of applying fungicide ($25 per acre). Planting alternate crops was excluded as an option in year one, but included as an option in year three. Complete establishment of the pest was assumed to occur in three years. Using the USMP, a spatial equilibrium mathematical programming model of U.S. agriculture and a climate suitability index, the authors estimated losses of $240 million to $2 billion per year.

Roberts, et al. (2006) conducted a study to value USDA's early warning system[1] for soybean rust applying the theory of public goods to the information provided by the early warning system and assessing the total value based on a range of assumptions regarding information quality and prior beliefs. The authors also conjectured about how the value of information to individual farmers might vary depending on their risk preferences. The estimated gain to farmers, $11 million to $299 million, well exceeded the system cost of $2.6 million to $5 million in 2005 when the incidence of rust infection was relatively low. These findings bode well for the system. In the event of a widespread outbreak, the benefit to farmers will likely be much larger.

Empirical Approach

[1]USDA developed a website in 2005 to provide farmers with information on spore monitoring to serve as an early warning system for soybean rust. Website is located at www.sbrusa.net.

This study models the combined impact on U.S. welfare from two invasive species, soybean rust and soybean aphid. Included in the model are the following: the supply of U.S. soybeans, domestic demand for U.S. soybeans, and foreign demand for U.S. soybeans. Production of U.S. soybeans includes inputs, alternative crops, crop losses due to invasive species, and the cost and effectiveness of control alternatives. Also included are dynamic growth functions for each pest to simulate the spread of the two species over time to regions deemed vulnerable but not presently infested. Domestic welfare is specified as the net present value of the sum of producer surplus (aggregated over multiple producing regions), consumer surplus (including soybeans as a production input), and government expenditures (for mitigating damages from soybean rust and soybean aphid). The model is used to evaluate the economic implications of the following scenarios: (I) Losses due to soybean aphid assuming no additional rust infestation. (II) Losses due to soybean rust assuming no additional aphid infestation. (III) Losses from both pests summed but considered separately. (IV) Losses from concurrent spread of soybean aphid and soybean rust evaluated jointly.

U.S. Soybean Market

The economic implications of soybean rust and soybean aphid to the U.S. are examined with a multi-region framework. The regional supply $Q_{si}(t)$ is assumed linear in price P(t) and defined

(1a) $Q_{si}(t) = \alpha_{si}(t) + \beta_{si}P(t)$

Shocks to regional supply are modeled with an intercept shifter, $\Delta\alpha_{si}$

(1b) $\Delta\alpha_{si} = \alpha_{si}(t) - \alpha_{si}^{o}$

Total U.S. supply $Q_s(t)$ is obtained by aggregating over regional supplies,

(1c) $Q_s(t) = \sum_{i=1}^{n} Q_{si}(t) = \alpha_s(t) + \beta_s P(t)$ *where* $\alpha_s(t) = \sum_{i=1}^{n} \alpha_{si}(t)$ *and* $\beta_s = \sum_{i=1}^{n} \beta_{si}$.

U.S. demand for soybeans $Q_c(t)$ is assumed linear in price P(t):

(2) $Q_c(t) = \alpha_c - \beta_c P(t)$

Export demand for U.S. soybeans $Q_x(t)$ is assumed linear in price P(t):

(3) $Q_x(t) = \alpha_x - \beta_x P(t)$

The subscripts s, c, and x refer to supply, demand, and export quantity. The supply and demand function intercept and slope parameters are indicated by α and β.

A graphic illustration of the soybean market is shown in Figure 1. Here D and S are the inverse domestic demand and domestic supply curves, and ED and ES are export demand and excess supply. P and Q are equilibrium soybean price and quantity in year 2005. With the introduction of soybean rust and soybean aphid, domestic soybean supply and excess supply shifts left and becomes S' and ES'. Equilibrium market price rises to P'. Quantity supplied Q_s', domestic consumption Q_d' and export quantity Q_x' all decline. Producer surplus loss is shown by area Paα_s less area P'a'α_s'. Consumer surplus loss is shown by area P' b' b P.

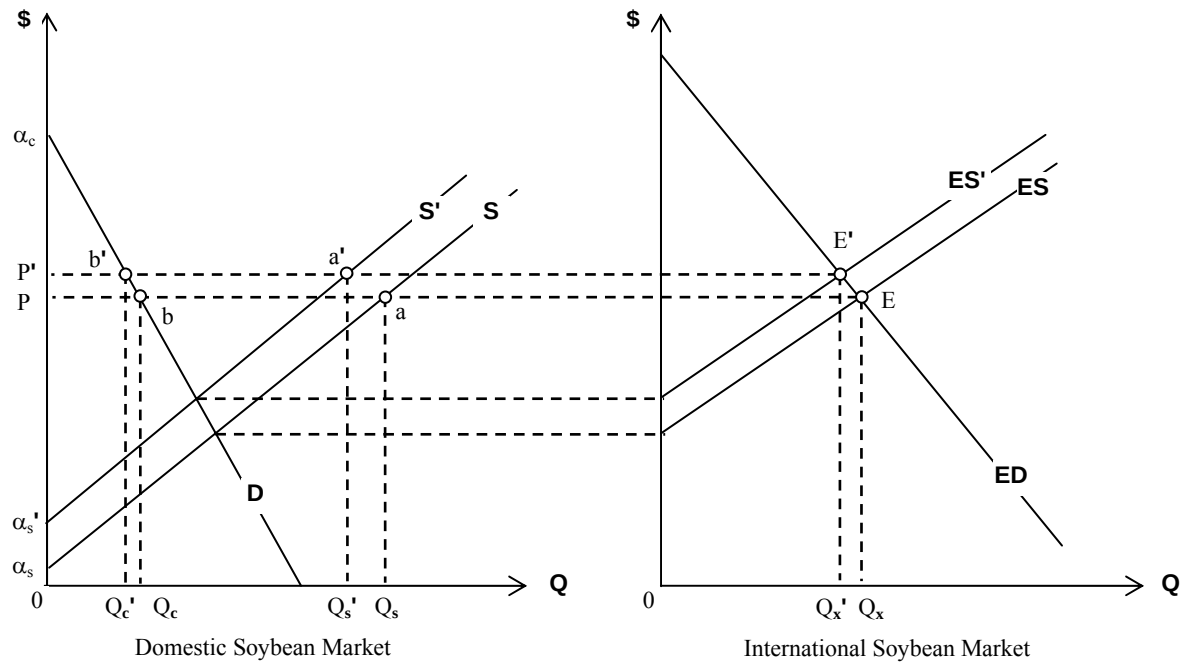

Figure 1. Equilibrium price and quantity of the U.S. domestic and international soybean markets

Analytically, equilibrium price P(t)* can be obtained by equating the domestic soybean supply equation (1c) with domestic consumption (2) plus export demand (3). Solving for P(t) yields

(4a) $P(t)^* = (\alpha_c + \alpha_x - \alpha_s + \Delta\alpha_s)/(\beta_c + \beta_x + \beta_s)$

Equilibrium quantities for domestic supply, domestic demand, and export demand are then obtained by substituting (4a) into equations (1c), (2), and (3) as follows:

(5a) $Q_s(t)^* = \alpha_s + \beta_s P(t)^*$

(6a) $Q_c(t)^* = \alpha_c - \beta_s P(t)^*$

(7a) $Q_x(t)^* = \alpha_x - \beta_s P(t)^*$

Invasive pest spread over time

Shifts in soybean supply from soybean aphid and soybean rust are modeled as follows. Aphid infestation is modeled following Huffaker and Cooper (1995), Kim, et al. (2005), and Vargas and Ramadan (2000) with a logistic acreage spread function,

$$\text{(8a)} \qquad \dot{A}_i(t) = g_i A_i(t)\left[1 - \frac{A_i(t)}{V_i}\right] \text{ for i = 1, 2, ..., n}$$

Here $A_i(t)$ is acreage infested at time t, g_i is the intrinsic rate of spread, and V_i is soybean acreage available for aphid infestation in region *i*. Solving the first-order differential equation (8a) yields,[2]

$$\text{(8b)} \qquad A_i(t) = \left[\frac{V_i}{1 + (k_i - 1)e^{-g_i t}}\right] \quad where \quad k_i = \frac{V_i}{A_i(t)_{t=0}} \quad and \quad \frac{\partial A_i}{\partial g_i} > 0$$

Soybean rust infestation is modeled with a similar logistic acreage spread function,

$$\text{(9a)} \qquad \dot{a}_i(t) = \sigma_i a_i(t)\left[1 - \frac{a_i(t)}{v_i}\right] \text{ for i = 1, 2, ..., n}$$

Here $a_i(t)$ is acreage infested, σ_i is the intrinsic rate at which rust infestation spreads, and v_i is the soybean acreage available for rust infestation in region *i*. Solving the first-order differential equation (9a) yields,[2]

$$\text{(9b)} \qquad a_i(t) = \left[\frac{v_i}{1 + (h_i - 1)e^{-\sigma_i t}}\right] \quad where \quad h_i = \frac{v_i}{a_i(t)_{t=0}} \quad and \quad \frac{\partial a_i}{\partial \sigma_i} > 0$$

[2] More detail on the derivation of this solution is provided in the Appendix.

The acreages in $A_i(t)$ and $a_i(t)$ in (8b) and (9b) enter the regional supply intercept shift term from (1b) as follows,

$$\text{(10a)} \quad \Delta\alpha_{si}(t) = A_i(t)\tilde{Y}(Z_i) + q_{si}(t) + a_i(t)\tilde{y}_i(z_i) + \rho_{si}(t)$$

In equation (10a), A_i is acres of soybean in region i exposed to the aphid, $\tilde{Y}_i$ is the per acre reduction in yield due to aphids which is a function of level of treatment undertaken Z_i, and q_{si} is the reduction in output as a result of shifting acreage to other crops.[3] Rust acreage is modeled similarly as follows: a_i is the number of acres of soybean in region i exposed to rust spores, $\hat{y}_i$ is the per acre reduction in yield due to rust which is a function of the treatment undertaken z_i, and p_{si} is the reduction in output from shifting soybean acreage to other crops.

Substituting (8b) and (9b) into equation (10a) yields an expression for the impact each year t on regional supply from the progressive spread of the two invasive pests,

$$\text{(10b)} \quad \Delta\alpha_{si}(t) = \left[\frac{V_i}{1+(k_i-1)e^{-g_i t}}\right]\tilde{Y}_i(Z_i) + q_{si}(t) + \left[\frac{v_i}{1+(h_i-1)e^{-\sigma_i t}}\right]\hat{y}_i(z_i) + p_{si}(t)$$

Substituting (10b) into (1b) and substituting (1b) into (1c) and equating (1c) with (2) plus (3) then solving for P(t) yields the post-shock equilibrium price equation,

[3] The percent of soybean acreage taken out of production and planted in other crops was estimated by Lin et al. (2000). Where M_s, M_c, M_w, and M_e are net returns per acre from soybean, corn, wheat and cotton, and b_i, c_i , d_i, and e_i are linear parameters, the percent of the soybean acreage converted is u_i and assumed to follow,

(1') $u_i = b_iM_{si} + c_iM_{ci} + d_iM_{wi} + e_iM_{ei}$

Where Ks_i is the per acre cost of growing soybeans and y_i is baseline soybean yield in region i, soybean net returns per acre can be expressed as,

(2') $M_s = P(t)*y_i\,[(1-\tilde{Y}_i(Z_i))\,(1-\hat{y}_i(z_i))] - Ks_i$

Thus $q_{si}(t)$ and $p_{si}(t)$ are determined by:

(3') $q_{si}(t) = u_i\, y_i\, L_i(t)$

(4') $p_{si}(t) = u_i\, y_i\, L_i(t)$

$$\text{(4c)}\ P(t)^* = \frac{\alpha_c + \alpha_x - \alpha_s(t) + \sum_{i=1}^{n}\left[\frac{V_i}{1+(k_i-1)e^{-g_i t}}\widetilde{Y}_i(Z_i) + q_{si}(t) + \frac{v_i}{1+(h_i-1)e^{-\sigma_i t}}\hat{y}_i(z_i) + p_{si}(t)\right]}{\beta_c + \beta_x + \beta_s}$$

Plugging (4c) into equations (5a), (6a), and (7a) yields the post-shock equilibrium quantities of soybean supplied, consumed, and exported as follows:

(5b)

$$Q_s(t)^* = \alpha_s(t) + \frac{\beta_s}{\beta_c + \beta_x + \beta_s}\left\{\alpha_c + \alpha_x - \alpha_s(t) + \sum_{i=1}^{n}\left[\frac{V_i}{1+(k_i-1)e^{-g_i t}}\widetilde{Y}_i(Z_i) + q_{si}(t) + \frac{v_i}{1+(h_i-1)e^{-\sigma_i t}}\hat{y}_i(z_i) + p_{si}(t)\right]\right\}$$

(6b)

$$Q_c(t)^* = \alpha_c(t) - \frac{\beta_c}{\beta_c + \beta_x + \beta_s}\left\{\alpha_c + \alpha_x - \alpha_s(t) + \sum_{i=1}^{n}\left[\frac{V_i}{1+(k_i-1)e^{-g_i t}}\widetilde{Y}_i(Z_i) + q_{si}(t) + \frac{v_i}{1+(h_i-1)e^{-\sigma_i t}}\hat{y}_i(z_i) + p_{si}(t)\right]\right\}$$

(7b)

$$Q_x(t)^* = \alpha_x(t) - \frac{\beta_x}{\beta_c + \beta_x + \beta_s}\left\{\alpha_c + \alpha_x - \alpha_s(t) + \sum_{i=1}^{n}\left[\frac{V_i}{1+(k_i-1)e^{-g_i t}}\widetilde{Y}_i(Z_i) + q_{si}(t) + \frac{v_i}{1+(h_i-1)e^{-\sigma_i t}}\hat{y}_i(z_i) + p_{si}(t)\right]\right\}$$

Welfare effects

From equation (5a), an expression for U.S. soybean producer surplus (PS) is derived as,[4]

$$\text{(11a)}\quad PS(t) = \frac{Q_s^{\,2}(t)^*}{2\beta_s}$$

Loss in producer surplus at each time t is defined as,

(11b) $\Delta PS(t) = (Q_s^2{}_{t=0} - Q_s^2(t)^*)/2\beta_s$.

(11b) $$\Delta PS(t) = \frac{Q_s^{\,2}{}_{t=0} - Q_s^{\,2}(t)^*}{2\beta_s}$$

From equation (6a), an equation for consumer surplus (CS) is defined,

(12a) $$CS(t) = \frac{Q_c^{\,2}(t)^*}{2\beta_c}$$

Loss in consumer surplus at each year t can be expressed,

(12b) $$\Delta CS(t) = \frac{Q_c^{\,2}{}_{t=0} - Q_c^{\,2}(t)^*}{2\beta_c}$$

Data Sources and Model Parameters

Eight soybean producing areas are aggregated into three regions as shown in Table 1.

Table 1. Soybean Production States by Region

	Region 1	Region 2	Region 3
Northeast	CT, DE, MA, MD, ME, NH, NJ, NY, PA, RI, VT		
Lake	MI, MN, WI		
Corn Belt	IA, IL, IN, MO, OH		
Northern Plains		KS, ND, NE, SD	
Appalachia			KY, NC, TN, VA, WV
Southeast			AL, FL, GA, SC
Delta			AR, LA, MS
Southern Plains			OK, TX

[4] When $\alpha_s>0$, producer surplus is estimated by the trapezoid area bounded by the supply curve, the equilibrium price line, and the horizontal axis as such, $PS(t) = \{[\alpha_s - \sum_{i=1}^{n} (A_i(t)\tilde{Y}_i(Z_i)+q_{si}(t))]+(\beta_s/2)P^*(t)\}P^*(t)$.

Soybean acreage, yield, infested acreage and treated acreage values were obtained from the Agricultural Resource Management Survey (USDA, 2005). Regional supply price elasticity values are from Lin et al. (2000). Soybean price, loan rate, production quantity, consumption quantity, export quantity, domestic demand price elasticity, and export demand price elasticity are from USDA-ERS (2002). Spread rate function parameters for soybean aphid and rust are estimated. Values used in the model are displayed in Table 2.

Table 2. Data and Model Parameters

	unit	**Region 1**	**Region 2**	**Region 3**	**Total**
Yield	*bushels/acre*	46.2	41.1	33.7	
Land	*million acres*	46.058	14.260	11.043	71.361
Production	*million bushels*	2127.641	586.680	372.111	3086.432
Consumption					1103.000
Export					1983.432
HSI rust	*%*	67.5	54.0	71.0	
price	*$/bushels*				$5.88
loan rate					$5.00
supply price	*elasticity*	.298	.198	.221	
demand price	*elasticity*				-.16
export demand	*elasticity*				-.79
α_s	*million bushels*	1493.6041	470.5171	286.8745	2253.9957
β_s		107.8294	19.7556	13.9858	141.5708
α_c	*million bushels*				2300.7809
β_c					-53.9709
α_x	*million bushels*				1974.3701
β_x					-148.1922
V_i		46.058	14.260	11.043	
$A_i(t=0)$		.457871	.099155	.023652	
k_i					
g_i		.349	.349	.349	
$h_i - 1$		1106.6718	1957.9578	4.1645	
σ_i		.376	.376	.376	
b		.324	.103	.132	
c		.324	.050	-.054	
d		0	-.053	-.072	
e		0	0	-.234	

Results

(I) Aphid only. With no further spread of rust, U.S. soybean output weakens during the first 10 years of infestation, and then descends rapidly during years 10 through 20. By year 21, the extent of planted soybean is at 60 million acres and annual production is 2,639 million bushels. Price rises to $8.09 per bushel.

(II) Rust only. With no further spread of aphid, soybean planting remains fairly steady through the first ten years of rust infestation then plummets 10% to 64 million acres in the course of 3 years. Soybean acreage levels off through year 21. The reduction in acreage causes output to fall to 2,743 million bushels and price to rise to $7.58 by year 21.

(III) Rust only plus Aphid only. This simulation is included to determine the extent of the bias from summing rust and aphid economic impacts without considering the joint effects these two pests have on soybean farming decisions, market price, and economic returns. This simulation projects that by year 21 100% of the soybean acreage will be infested with aphids, rust, or both, but 61.7 million acres remain in production. Price per bushel would rise to $9.73. Loss in producer surplus is $15.7 billion, loss in consumer surplus is $7.4 billion, and loss in exports sales is $4.1 million in year 21.

(IV) Rust and Aphid infestation modeled concurrently. This scenario captures the most likely outcome in the event that both rust and aphid spread to all soybean producing regions. By year 5, soybean acreage is projected to fall 1.4%. Total U.S. soybean production will drop 1.6% from 3.1 billion bushels to 3.0 billion bushels. Although price rises 4% in the interim, the downturn in sales causes producers to realize a 3.1% reduction in surplus for a loss of $1 billion. The increase in price leads to a 0.29% reduction in consumer purchases and a 1.3% dip in consumer surplus

for a loss $467 million. Export sales volume drops 3.21% while export sales revenue goes up $42 million for a 0.65% increase over the 2005 sales baseline. By year 10, soybean acreage will slide 4.4% to 68 million acres from current cultivation of 71 million acres. The reduction in acreage and decline in yields from pest infestation causes production to drop 5.2% from 3.1 billion bushels to 2.9 billion bushels. Price rises 13.4% by year 10 somewhat tempering producer losses to $3.4 billion a 10% reduction in surplus. Consumer purchases dip 1.8% and consumer surplus slips $1.6 billion or 4.3%. Soybean exports wane by 10.7% but sales revenue continues to ascend slightly by 1.2% for an increase of $75 million in year 10. In year 21, soybean acreage shrinks to 39 million acres, a 45% decline in harvested acreage. Total U.S. soybean production tumbles by about one-third to 2.1 billion bushels. Although price rises 85% in the interim, producers suffer a 56% reduction in surplus for a loss of $18.6 billion. Consumer purchases subside 14% and consumer surplus dissipates by 26% for a loss of $9.4 billion. Export volume quantity plunges 69% and sales revenue dissolves by 42%. Export sales revenue sinks $2.7 billion in year 21 relative to the baseline.

A summary of the model results comparing scenarios III and IV through year 21 is displayed in Table 3.

Table 3. Estimated Impacts when Pests are Consider Separately (III) vs. Jointly (IV)

		Year 5		Year 10		Year 21	
		III	IV	III	IV	III	IV
		Rust only + Aphid only	Aphid & Rust	Rust only + Aphid only	Aphid & Rust	Rust only + Aphid only	Aphid & Rust
Soybean	*mil acs*	70.85	70.35	69.96	68.25	61.74	39.34
Rust	*mil acs*	8.16	10.48	9.87	13.05	46.63	39.34
Aphid	*mil acs*	3.19	3.19	14.80	14.80	58.12	39.34
Total Infested	*mil acs*	11.35	13.67	24.66	27.85	61.74	39.34
% Infested	*%*	16.0%	19.4%	35%	38%	100%	100%
Price	*$/bu*	$6.24	$6.17	$7.97	$6.73	$9.73	$11.01
U.S. Output	*mil bu*	3,013	3,027	2,663	2,915	2,309	2,050
U.S. Consumption	*mil bu*	1,964	1,968	1,870	1,938	1,776	1,707
Export volume	*mil bu*	1,049	1,060	793	977	533	343
Producer surplus loss	*$ mil*	$1,195	$1,032	$3,161	$3,392	$15,737	$18,559
Consumer surplus loss	*$ mil*	$540	$467	$1,436	$1,554	$7,378	$9,351
Export sales loss	*$ mil*	$106	$ (40)	$982	$(74.81)	$2,325	$2,725

Complete results for crop acreage, infested acreage, soybean price, production, consumption, exports, producer surplus, consumer surplus, and export sales are illustrated in Figures 2 through 11.

Conclusion

This paper offers projections of national damages from two recently introduced agricultural pests. To allow for multiple heterogeneous producing regions, variable price, domestic demand inelasticity, and export demand, a market equilibrium approach was used. Within the model, the reduction in soybean output due to crop damages from two pests contribute to a rise in soybean market prices tempering overall producer loss. The rise in domestic price in turn causes export quantities to fall, thereby stabilizing domestic consumption quantities and buffering consumer

losses. The dynamic elements of the model simulate the spatial spread of the introduced pests over time and the extent of future damages.

Findings show the magnitude of the damages and further reveal the importance of modeling the impacts of the two pests concurrently. Examining the pests separately may underestimate the long term fate of the industry. Considering the impacts of both pests independently and summing the impact may result in underestimating the rise in price, underestimating production in the intermediate term, overestimating production in the long term, overestimating welfare loss in the middle term, and underestimating welfare loss in the long term.

Further work

Additional scenarios worth considering include:

- The directional spread of the two soybean diseases aphid from North to South and rust from South to North.
- Faster rates of spread for each of the diseases for example over 3 to 5 years instead of 10 years

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Appendix

The first-order differential equation (8) can be rewritten as follows:

(A1) $$g_i \delta t = \frac{\delta A_i(t)}{A_i(t)[1 - A_i(t)/V_i]}$$

$$= \left[\frac{1}{A_i(t)} - \frac{(-1/V_i)}{[1 - A_i(t)/V_i]} \right] \delta A_i(t)$$

Integrating both sides from the equality in (A1) results in the following:

(A2) $$g_i t = ln\,[A_i(t)] - ln\,[1 - A_i(t)/V_i] + C$$
$$= ln\,\{A_i(t) / [1 - A_i(t)/V_i]\} + C,$$

where C is a constant. Assuming that $A_i(t=2002) = A_i(t=0)$ at the base year, the constant term is obtained from equation (A2) as follow;

(A3) $$C = -\,ln \left[\frac{A_i(t=0)}{(1 - A_i(t=0)/V_i)} \right]$$

Inserting equation (A3) into equation (A2), a solution of the first-order differential equation (8) is presented as follow:

(A4) $$A_i(t) = V_i / [1 + ((V_i / A_i(t=0)) - 1)exp(-g_i t)].$$

Estimating the Cost of Invasive Species on U.S. Agriculture: The U.S. Soybean Market – Figures 2 through 11

Figure 2. Soybean acreage

Figure 3. Infested soybean acreage

Figure 4. Percent soybean acreage infested

Figure 5. Soybean price

Figure 6. Soybean production

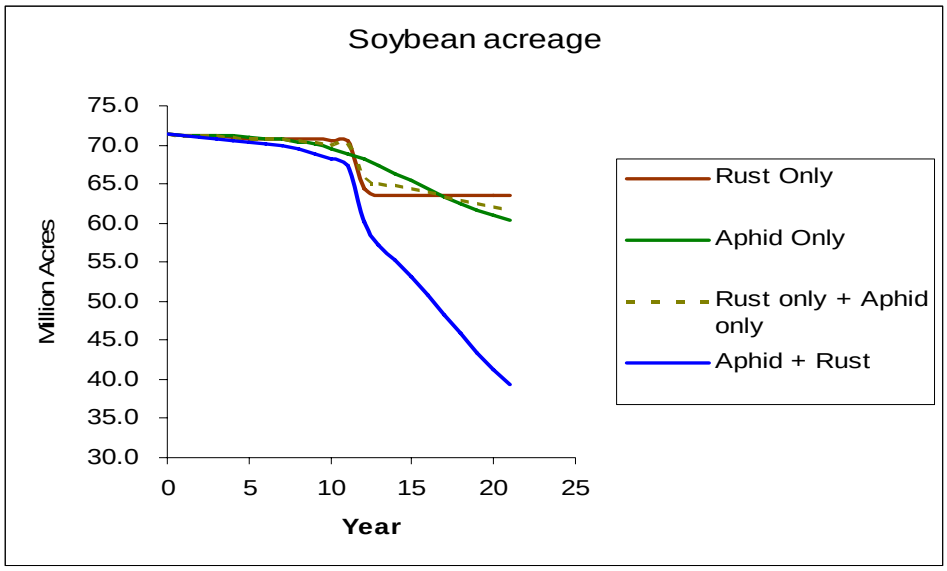
Figure 7. Soybean consumption

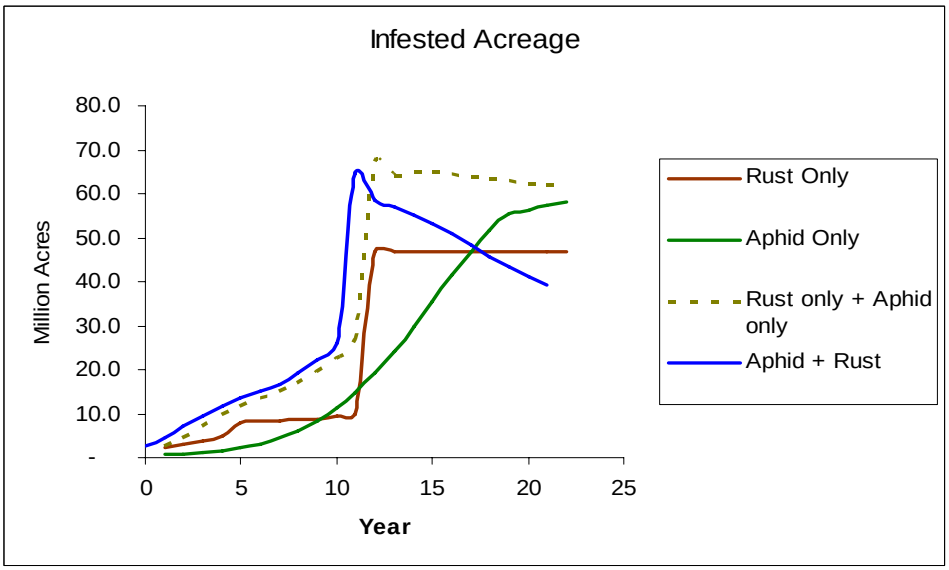
Figure 8. Soybean exports

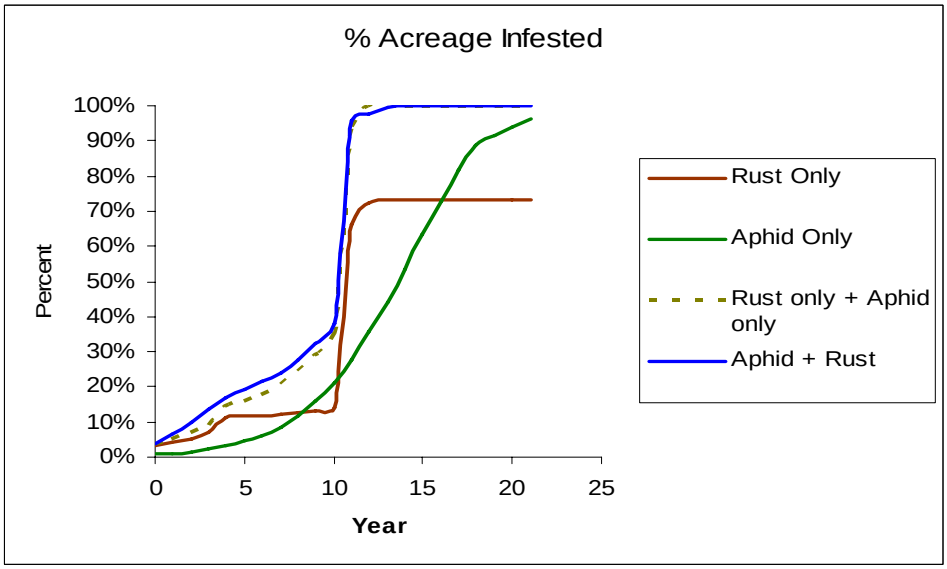
Figure 9. Soybean producer surplus loss

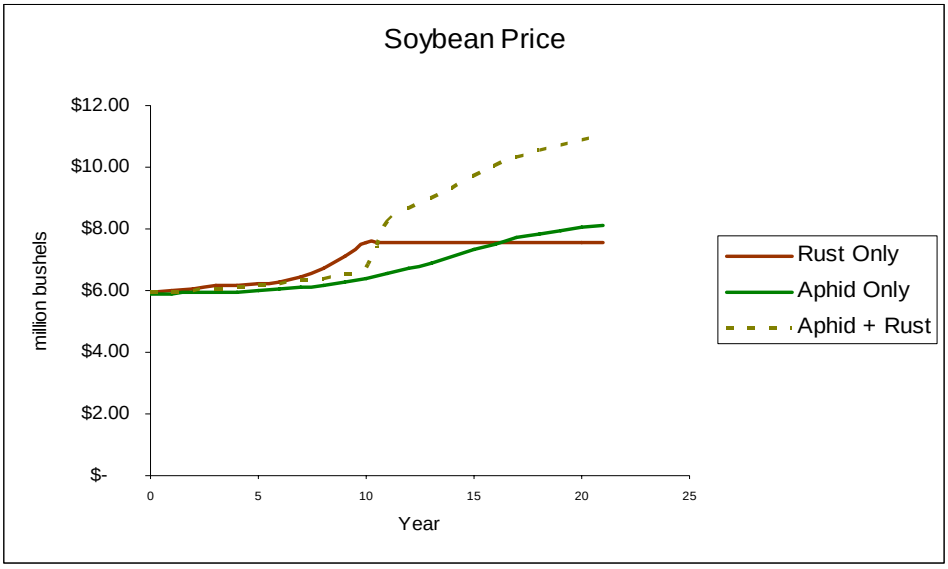
Figure 10. Soybean consumer surplus loss

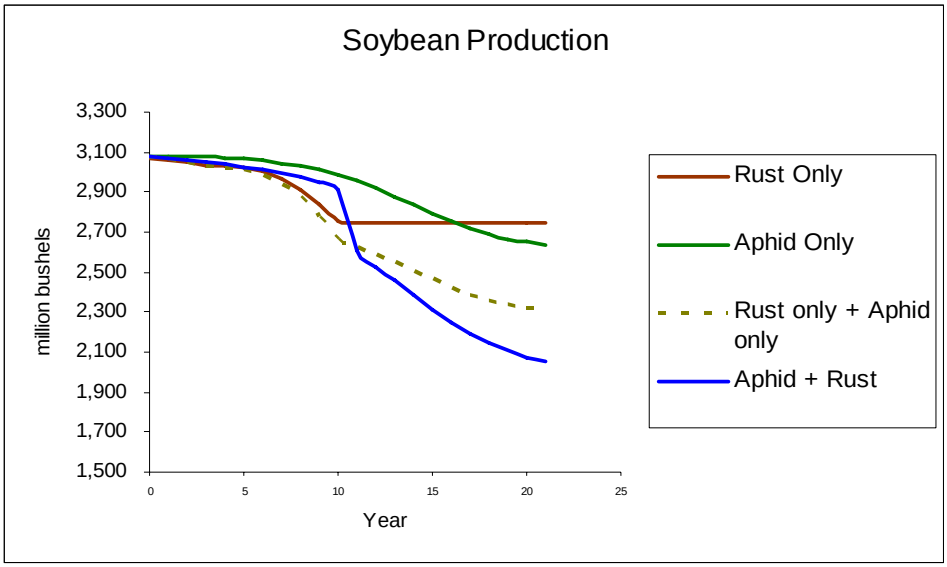
Figure 11. Soybean export sales loss

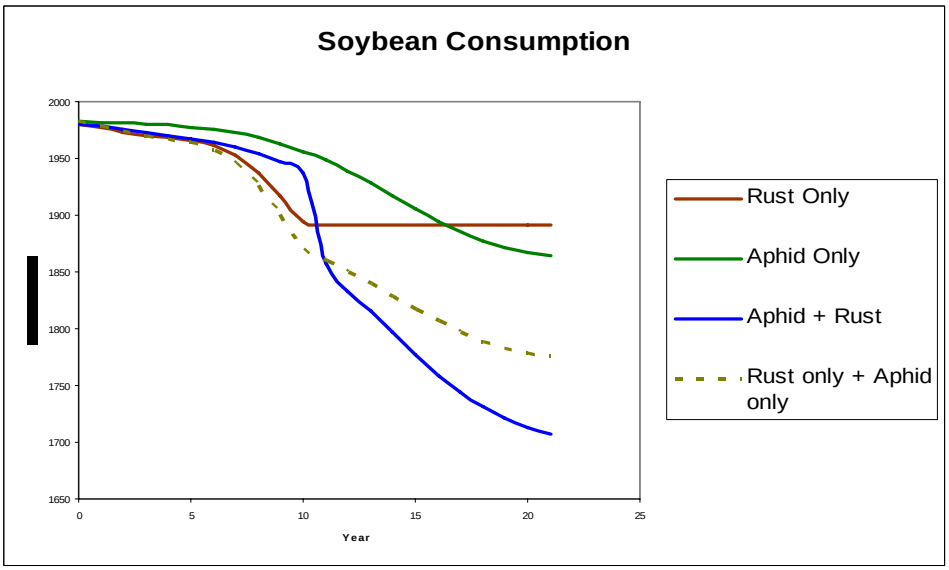

Soybean acreage
75.0
70.0
65.0
60.0
55.0
50.0
45.0
40.0
35.0
30.0
Million Acres
0
5
10
15
20
25
Year
Rust Only
Aphid Only
Rust only + Aphid only
Aphid + Rust

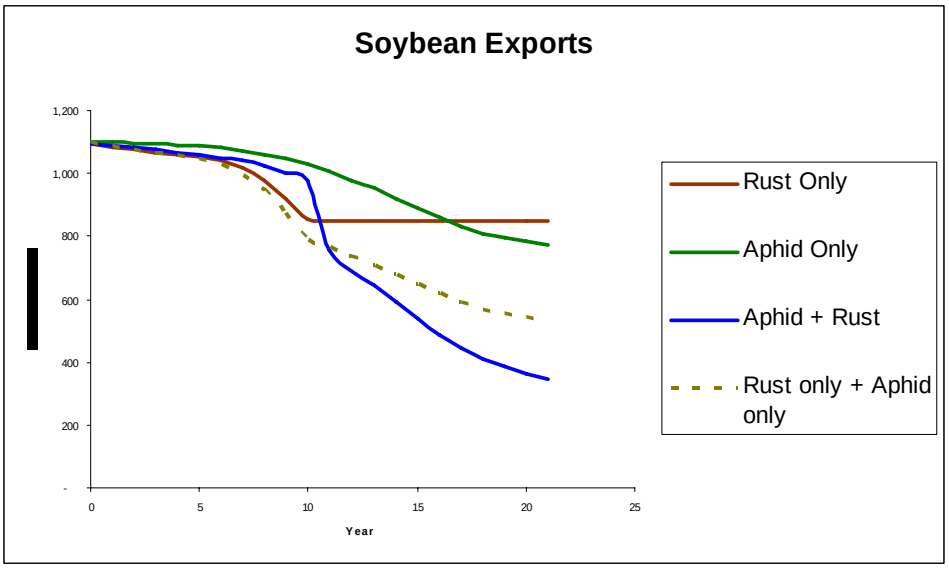

Infested Acreage
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
-
Million Acres
0
5
10
15
20
25
Year
Rust Only
Aphid Only
Rust only + Aphid only
Aphid + Rust

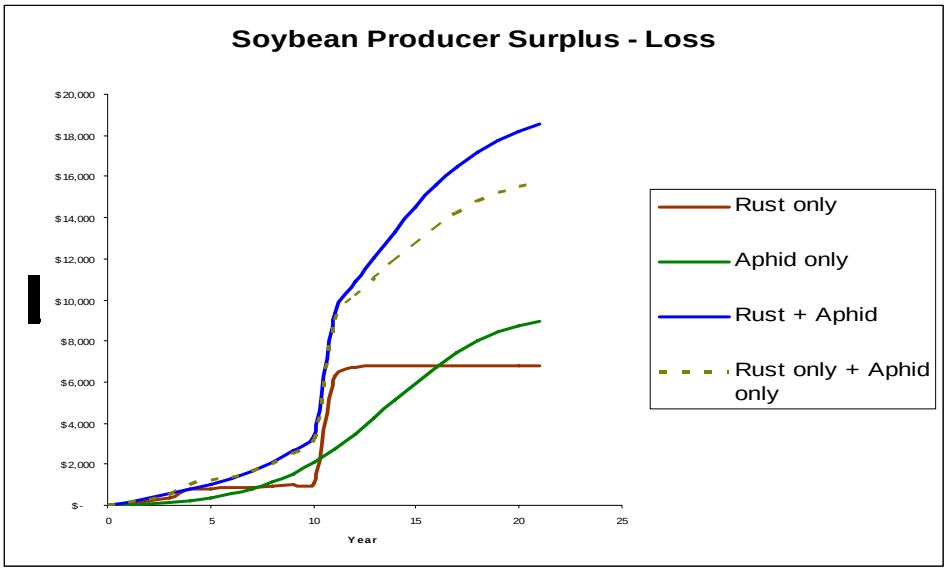

% Acreage Infested
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Percent
0
5
10
15
20
25
Year
Rust Only
Aphid Only
Rust only + Aphid only
Aphid + Rust

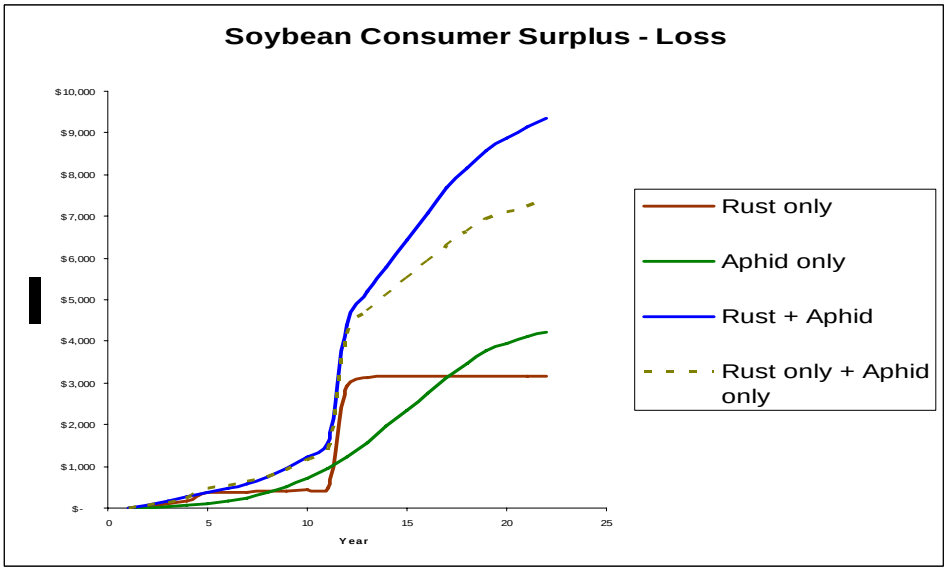

Soybean Price
$12.00
$10.00
$8.00
$6.00
$4.00
$2.00
$-
million bushels
0
5
10
15
20
25
Year
Rust Only
Aphid Only
Aphid + Rust

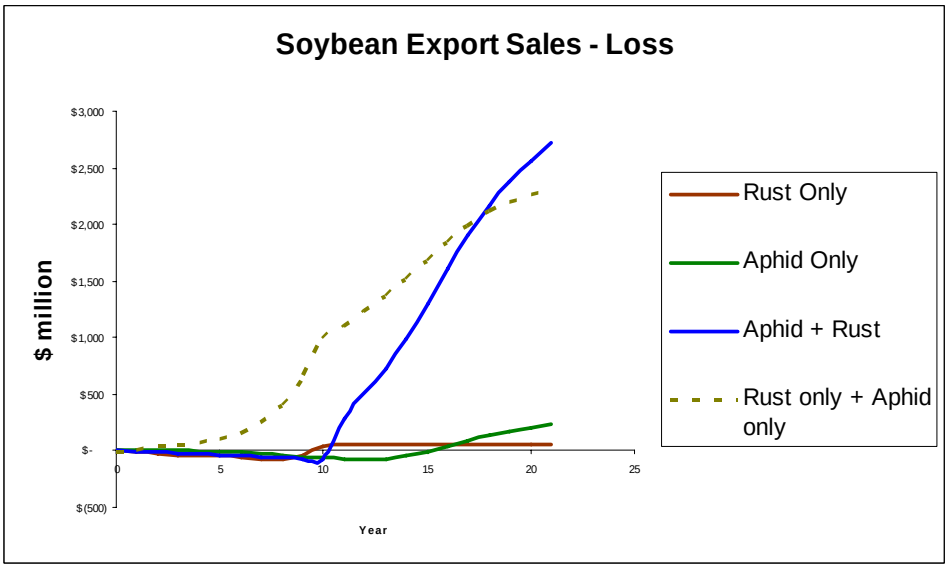

Soybean Production
3,300
3,100
2,900
2,700
2,500
2,300
2,100
1,900
1,700
1,500
million bushels
0
5
10
15
20
25
Year
Rust Only
Aphid Only
Rust only + Aphid only
Aphid + Rust


Soybean Consumption
2000
1950
1900
1850
1800
1750
1700
1650
0
5
10
15
20
25
Year
Rust Only
Aphid Only
Aphid + Rust
Rust only + Aphid only


Soybean Exports
1,200
1,000
800
600
400
200
-
0
5
10
15
20
25
Year
Rust Only
Aphid Only
Aphid + Rust
Rust only + Aphid only


Soybean Producer Surplus - Loss
$20,000
$18,000
$16,000
$14,000
$12,000
$10,000
$8,000
$6,000
$4,000
$2,000
$-
0
5
10
15
20
25
Year
Rust only
Aphid only
Rust + Aphid
Rust only + Aphid only


Soybean Consumer Surplus - Loss
$10,000
$9,000
$8,000
$7,000
$6,000
$5,000
$4,000
$3,000
$2,000
$1,000
$-
0
5
10
15
20
25
Year
Rust only
Aphid only
Rust + Aphid
Rust only + Aphid only


Soybean Export Sales - Loss
$ million
$3,000
$2,500
$2,000
$1,500
$1,000
$500
$-
$(500)
0
5
10
15
20
25
Year
Rust Only
Aphid Only
Aphid + Rust
Rust only + Aphid only