Economic Impacts of the U.S. Soybean Aphid Infestation: A Multi-Regional Competitive Dynamic Analysis

C.S. Kim, Glenn Schaible, Lynn Garrett, Ruben Lubowski, and Donna Lee

We estimated the economic benefits resulting from controlling soybean aphid infestation by using a multi-regional competitive dynamic equilibrium model. Results indicate that the reduction of soybean production resulting from a soybean aphid infestation is largely absorbed by reducing soybean exports, due to the higher price elasticity of export demand compared to domestic demand. Producer benefits resulting from controlling soybean aphids would increase by between $949 million and $1.623 billion in ten years under various scenarios. Results also suggest that it is economically more efficient to control soybean aphids when the rate of intrinsic growth is relatively lower, the supply price elasticity of soybean acreage is relatively more elastic, and insecticide treatment costs per acre are lower. However, if the discovery of the gene *Rag*-1 (TF04048) leads to new cultivars that withstand the soybean aphid, our estimates will overestimate the actual damages. Even so, our analysis demonstrates that it is critical to control soybean aphids early in their infestation cycle to avoid a rapid increase in damages.

Key Words: soybean aphid, invasive species, producer surplus, consumer surplus, *Rag*-1

Soybeans are the second highest cash crop following corn in the United States. Farmers annually produced on average nearly 2.8 billion bushels, valued at more than $15 billion, on 72.4 million acres during the 2000–2002 period. Most soybeans produced in the United States are used by domestic consumers and the livestock sector, with any remainder exported to foreign consumers. Exports from the 2003 crop were 887 million bushels out of a total crop of 2,454 million bushels, or 36 percent of production (World Agricultural Outlook Board 2008). However, recently this valuable crop for U.S. farmers has come under attack by invasive species—the soybean aphid from the North and soybean rust from the South (Livingston et al. 2004, Lee, Kim, and Schaible 2006).

The soybean aphid, known as *Aphis glycines Matsumura*, is native to eastern Asia, including China and Japan. It was first discovered in the United States in 1995 in Wisconsin, but in 2000 was officially confirmed as soybean aphid nearly simultaneously in 10 Midwestern states.[1] By 2003, the soybean aphid had already been detected in 21 states, and its coverage is still spreading up to 600 miles a year (North Central Soybean Research Program 2004). The seasonal cycle of the soybean aphid is complex. Eighteen or more generations can be produced during the summer because of parthenogenesis. Most soybean aphids do not colonize the soybean plant. They lay eggs on the common *buckthorn* (*Rhamnus cathartica*), which is the only known wintering host and which is found throughout the upper Midwest and Northern Plains. For soybean aphids, the optimum temperatures for reproduction are

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The authors thank the anonymous ARER reviewers for their valued and helpful suggestions. The views are the authors' and do not necessarily represent the policies of the U.S. Department of Agriculture, Environmental Defense Fund, or Entrix.

[1] The ten Midwestern states were Illinois, Indiana, Iowa, Kentucky, Michigan, Minnesota, Missouri, Ohio, West Virginia, and Wisconsin.

Agricultural and Resource Economics Review 37/2 (October 2008) 227–242

70–80°F, while the developmental time is lengthened when temperatures exceed 81°F; soybean aphids are intolerant to temperatures above 95°F (North Central Soybean Research Program 2004, Rice, O'Neal, and Pedersen 2005). Consequently, more soybean aphids were found in the northern states, where weighted-average soybean yields are the highest, at 42 bushels per acre (during the 2000–2002 period), than in the southern states, where weighted-average yields are the lowest, at 30 bushels per acre.

Soybean aphids cause damage, including plant stunting, reduced pod and seed counts, and puckering and yellowing of plant leaves. Additionally, soybean aphids are capable of transmitting viruses, including alfalfa mosaic, soybean mosaic, and bean yellow mosaic (Grau et al. 2002). Soybean aphid-induced yield reductions associated with grower strip trials (without the treatment of an insecticide) have ranged from more than five to nineteen bushels (Ostlie 2005, McCornack, Ragsdale, and Venette 2004), while the timely treatment of insecticides on soybean aphids could make a difference (reducing the loss) of between five to more than ten bushels per acre (North Central Soybean Research Program 2004). However, the potential for an extremely rapid population increase makes timely treatment of insecticides a difficult mitigation issue (Potter and Hansen 2003). Therefore, the USDA has established a soybean aphid tracking system, which reports the number of soybean aphids per plant in soybean-producing states (http://sbrusa.net). The reported economic threshold for insecticide treatment of soybean aphids is 250 aphids per plant, with more than 80 percent of plants infested.

While there is an increasing need to respond to invasive pests, empirical analyses of invasive pests are often hampered by a lack of data. For our study, we use the USDA Agricultural Resource Management Survey (ARMS), which collected information on the detection of soybean aphid on the sampled soybean field, insecticide treatments, and scouting. First, our study measures the effects of the U.S. soybean aphid infestation on the volumes of U.S. soybean production, its domestic demand, and exports. The reduction of soybean production resulting from a soybean aphid infestation includes reduced yield, increased production costs due to increasing insecticide application, and reduced acreage due to acreage conversion from soybean production to alternative crop production. Even though a soybean aphid infestation reduces soybean quality, the costs associated with the reduced soybean quality are not included in our research due to the lack of information. Second, we estimate the economic benefits of controlling for soybean aphids.

To achieve these goals, soybean-producing states are divided into three regions based on the distributions of *buckthorn* and soybean yields. A logistic growth model is used to estimate the dispersion rate of infested soybean acreage with the soybean aphid. We then apply a competitive dynamic economic-equilibrium simulation model by incorporating the logistic growth function into an equilibrium condition obtained from integrating three regional soybean supply functions, a domestic soybean demand function, and an export soybean demand function. Since soybean aphids do not colonize the soybean plant and lay their eggs on the common *buckthorn*, soybean aphids can reappear on the same field in the year following treatment with insecticides. This implies that controlling soybean aphids is a pest management problem, rather than an optimal-control problem, and therefore, in the following section, a competitive dynamic-economic model is established.

The Model

We address the economic impacts of the soybean aphid within the context of a multi-region, dynamic equilibrium framework, assuming both differential regional logistic acreage infestation growth functions and their regional soybean yield effects. We begin first by assuming that the regional soybean supply functions, the U.S. domestic demand function for soybeans, and the U.S. soybean export demand function are linear, similar to Piggott and Wohlgenant (2002), and expressed as follows:

U.S. soybean supply (see Appendix):[2]

$$(1)\quad \sum_{i=1}^{n} Q_{si}(t) = \sum_{i=1}^{n} \begin{Bmatrix} [\alpha_{si} - A_i(t)\tilde{Y}_i(Z_i) - q_{si}(t) \\ -q_{wi}(t)] + \beta_{si} P(t) \end{Bmatrix}$$

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[2] The variables $A_i(t)\tilde{Y}_i(Z_i)$, $q_{si}(t)$, and $q_{wi}(t)$ are considered as supply shifters in our model.

U.S. soybean domestic demand:

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

U.S. soybean export demand:

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

where $Q(t)$ represents the quantity of soybeans in year t; $P(t)$ represents the expected price of soybeans in equation (1), the U.S. domestic soybean price in equation (2), and the domestic soybean price of an importing country in equation (3), where all prices are identical at equilibrium; α and β are supply/demand parameters; the variable $A_i(t)$ represents the soybean acreage infested in the ith region during year t; and the variable $\tilde{Y}_i$ represents the per acre reduction in soybean yield (or yield loss) associated with the aphid infested acres. The variable Z_i represents aphid control measures such as scouting and insecticide application, q_{si} represents the reduction in soybean production as farmers switch acreages from soybean production to corn or some other crop production, while $q_{wi}(t)$ represents the reduction in soybean production as a result of increased insecticide application cost for managing the soybean aphid. The subscripts s, c, and x represent soybean domestic supply, domestic demand, and exports, respectively.

Following Huffaker and Cooper (1995) and Kim, Wang, and Yang (2005), we assume a logistic growth function for the soybean acreage infested with aphids as follows:

$$(4) \qquad \frac{\partial A_i(t)}{\partial t} = g_i(E_i(t))A_i(t)\left[1 - \frac{A_i(t)}{V_i}\right],$$

$$\partial g_i / \partial E_i(t) < 0 \quad (\text{for } i = 1, 2, ..., n),$$

where the variable g_i represents the intrinsic growth rate of infested acreage in the ith region, $E_i(t)$ represents the pest management efforts such as treatment with insecticides, and V_i represents the maximum acreage available for soybean aphid infestation. A solution of the first-order differential equation (4) is presented as

$$(5) \qquad A_i(t) = \left[\frac{V_i}{1 + (k_i - 1)\exp[-g_i(E_i(t))t]}\right]$$

$$(i = 1, 2, ..., n),$$

where

$$k_i = \left[\frac{V_i}{A_i(t_1)}\right]$$

and t_1 represent the base period. The typical pattern of a logistic growth model shows small initial changes in growth rates which then accelerate up to an inflection point, after which the growth rate slows down toward a limiting value as A_i approaches V_i. Consequently, economic costs resulting from a soybean aphid infestation are assumed to be less significant during the early periods of infestation, but increase as the rate of aphid infestation accelerates.

Inserting equation (5) into equation (1), an equilibrium soybean price is obtained by equating the domestic soybean supply,

$$Q_s(t) = \sum_{i=1}^{n} Q_{si}(t)\,,$$

from equation (1) to the sum of the domestic demand, $Q_c(t)$, in equation (2), and the export demand, $Q_x(t)$, in equation (3). The result is then represented as follows:

$$(6) \qquad P^*(t) = \left[\frac{(\alpha_c + \alpha_x - \alpha_s) + \sum_{i=1}^{n} M_i}{(\beta_c + \beta_x + \beta_s)}\right],$$

where

$$M_i = \left\{\begin{array}{l} q_{si}(t) + q_{wi}(t) \\ \quad + \left[\dfrac{\tilde{Y}_i(Z_i)\,V_i}{\left(1 + (k_i - 1)\exp(-g_i t)\right)}\right] \end{array}\right\},$$

and where

$$\alpha_s = \sum_{i=1}^{n} \alpha_{si} \;\text{ and }\; \beta_s = \sum_{i=1}^{n} \beta_{si}\,.$$

Similarly, the equilibrium quantities of domestic production, domestic demand, and export demand are obtained by inserting equation (6) into equations (1) through (3) and solved as follows:

$$(7)\quad Q_s^*(t) = \alpha_s - \sum_{i=1}^{n} M_i + \left[\beta_s/(\beta_c+\beta_x+\beta_s)\right]\left\{\alpha_c+\alpha_x-\alpha_s+\sum_{i=1}^{n} M_i\right\},$$

$$(8)\quad Q_c^*(t) = \alpha_c - [\beta_c/(\beta_c+\beta_x+\beta_s)]\left\{\alpha_c+\alpha_x-\alpha_s+\sum_{i=1}^{n} M_i\right\},$$

$$(9)\quad Q_x^*(t) = \alpha_x - \left[\beta_x/(\beta_c+\beta_x+\beta_s)\right]\left\{\alpha_c+\alpha_x+\alpha_s+\sum_{i=1}^{n} M_i\right\}.$$

The dynamic equilibrium solutions presented in equations (6) through (9) are consistent with optimal solutions derived from revenue maximization subject to a quantity constraint such that total domestic production equals the sum of domestic demand and export demand.

Producer surpluses at equilibrium by time period are then obtained by using equations (1), (6), and (7), represented as follows:

$$(10)\quad PS^*(T) = \int_{t=0}^{T} \exp(-rt)\left\{\begin{aligned}&\left[P^*(t)+(\alpha_s/\beta_s)-\sum_{i=1}^{n} N_i/\beta_s\right]Q_s^*(t)\\ &-\left[\left(Q_s^*(t)\right)^2/2\beta_s\right]\end{aligned}\right\}\delta t,$$

where

$$N_i = \left\{\begin{aligned}&q_{si}(t)+q_{wi}(t)\\ &+\frac{\tilde{Y}_i(Z_i)\,A_i(t_1)}{\left[\left(\frac{V_i}{A_i(t_1)}\right)\left(1+(k_i-1)\exp(-g_i t)\right)\right]}\end{aligned}\right\},$$

and where r is the rate of time preference, t_1 is the base period, and T is a terminal time period. Similarly, the U.S. soybean consumer surpluses (CS) are represented by using equations (2), (6), and (8), as follows:

$$(11)\quad CS^*(T) = \int_{t=0}^{T} \exp(-rt)\left\{\begin{aligned}&[\alpha_c/\beta_c - P^*(t)]Q_c^*(t)\\ &-[(Q_c^*(t))^2/2\beta_c]\end{aligned}\right\}\delta t.$$

Data Sources and Analysis

Average soybean acreage and soybean yield per acre during the 2000–2002 period represent a base year environment. Regional soybean harvested acreage, soybean yield, soybean acreage treated with insecticides, and acreage infested with soybean aphids (2002) were obtained from USDA's Economic Research Service (USDA-ERS) and USDA's Agricultural Resource Management Survey (ARMS) for soybeans.[3] Annual soybean price and loan rate, domestic soybean demand, domestic production, and exports were also acquired from USDA-ERS.

An application of a competitive dynamic equilibrium model presented in the previous section also requires advanced knowledge on the intrinsic growth rate for the soybean aphid in each soybean-producing region, a soybean acreage response function, and various soybean price elasticities. Sources and/or parameter estimation procedures are provided for each as follows.

Intrinsic Growth Rate

McCornack, Ragsdale, and Venette (2004) estimated the intrinsic growth rate for the soybean aphid under controlled lab experiments as varying between 0.368 and 0.474 under normal temperature conditions. However, the intrinsic growth rate declines as the adoption of control measures such as scouting and insecticide treatment increase (Kim et al. 2006). Furthermore, the soybean aphid is intolerant to temperatures above 95°F, and the distribution of *buckthorn*, the soybean aphid's wintering host, varies across regions, which suggests that intrinsic growth rates of the soybean aphid are also quite different among the three regions.

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[3] Region 1 includes Delaware, Illinois, Indiana, Iowa, Maryland, Michigan, Minnesota, Missouri, New Jersey, New York, Ohio, Pennsylvania, West Virginia, and Wisconsin. Region 2 includes Kansas, Nebraska, North Dakota, and South Dakota. Region 3 includes Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, Oklahoma, South Carolina, Tennessee, Texas, and Virginia (see Lin et al. 2000).

Voronov (2005) proposed an estimation procedure for the intrinsic growth rate with observed data, which is appropriate for estimating the intrinsic growth rate associated with a complex logistic growth model such as a logistic *net* growth model (Kim et al. 2007).[4] For a conventional logistic growth model as we specified in equation (4), however, Voronov's procedure produces biased estimates of the intrinsic growth rate. Therefore, we derive the intrinsic growth rate directly from equation (5) for each soybean-producing region as follows:

$$(12)\ g_i = [\ln(\frac{V_i}{A_i(t_1)} - 1) - \ln(\frac{V_i}{A_i(t_2)} - 1)]/(t_2 - t_1)$$
$$= [\ln(\frac{V_i - A_i(t_1)}{V_i - A_i(t_2)}) + \ln(\frac{A_i(t_2)}{A_i(t_1)})]/(t_2 - t_1),$$

where t_1 and t_2 represent the initial and terminal time period, respectively. Application of equation (12) requires an advanced knowledge of the soybean acreages infested in the initial and terminal time periods and the maximum soybean acreages available for aphid infestation.

For the first time, in 2002 the USDA Agricultural Resource Management Survey (ARMS) questionnaire asked respondents whether the soybean aphid was detected on the sampled soybean field. Therefore, the year 2002 is selected as the terminal time period [t_2 in equation (12)] for estimating the intrinsic growth rate. Soybean acreage infested with the soybean aphid in 2002 was reported to be $A_1(t_2)$ = 744,100 acres for Region 1, $A_2(t_2)$ = 335,200 acres for Region 2, and $A_3(t_2)$ = 39,300 acres for Region 3 (Table 1).

Meanwhile, no information is available as to when soybean aphids were introduced into each region, so the initial time period t_1 in equation (12) must be arbitrarily selected. Soybean acreage has steadily increased since 1950, but it began to really expand beginning in the early 1970s. Soybean acreage had increased to more than 70 million harvested acres in 1978, which is comparable to the current level of soybean acreage. Therefore, we select the year 1972 as an initial time period [t_1 in equation (12)] for the estimation of the intrinsic growth rate by comparing the annual harvested soybean acreage to the maximum acreage available for soybean aphid infestation (i.e., V_i).[5] The estimated intrinsic growth rates for soybean aphids (with the initial time period in 1972 and the terminal time period in 2002) are g_1 = 0.4845 for Region 1, g_2 = 0.4602 for Region 2, and g_3 = 0.3861 for Region 3.[6]

Next, once the intrinsic growth rates for soybean aphids are estimated, we estimate the infested acreage-response function with soybean aphids [i.e., equation (5)] by using the estimated intrinsic growth rates for each of the three regions. Since the economic simulation analysis is to measure the economic effects of soybean aphid infestation in coming years, compared to the base year period, we selected the years 2000–2002 as the base period for simulation. Using soybean summary data presented in Table 1, the infested acreage-response functions for each of the three regions are represented as follows:

(13)
$$A_1(t) = 48{,}215{,}000/[1 + 63.7964\exp(-0.4845t)],$$

where

$$(k_1 - 1) = \left(\frac{48{,}215}{744.1} - 1\right) = 63.7964$$

(14)
$$A_2(t) = 13{,}782{,}000/[1 + 40.1158\exp(-0.4602t)],$$

where

$$(k_2 - 1) = \left(\frac{13{,}782}{335.2} - 1\right) = 40.1158$$

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[4] Voronov's (2005) model is represented by

$$g_i = \ln\left\{\left[\frac{A_i(t_2)}{V_i} - \frac{A_i(t_1)}{V_i}\right] \times 100\%\right\}/(t_2 - t_1),$$

where t_1 and t_2 represent the initial and terminal time periods, respectively.

[5] Since equation (12) is undefined for $A_i(t_1) = 0$, we assume that only one acre was infested with soybean aphids during the initial time period, so $A_i(t_1) = 1$.

[6] When the initial time period is chosen as 1987, the estimated intrinsic growth rates for the three regions are g_1 = 0.9690, g_2 = 0.9204, and g_3 = 0.7722, which appear very high.

Table 1. Average Soybean Summary Statistics in 2000–2002

	Region 1	Region 2	Region 3	Total
Yield (bu./ac.)	41.7	34.1	29.8	
Harvested acres (1,000)	48,215	13,782	10,359	72,356
Production (mil. bu.)	2,010	470	308	2,788
Acres scouted, insecticide treated, and aphid detected in 2002 (1,000 acres)	744.1	335.2	39.3	1,118.6

Source: USDA's Economic Research Service, ARMS Phase II, 2002.

(15)

$$A_3(t) = 10{,}359{,}000 / [1 + 262.5878 \exp(-0.3861t)],$$

where

$$(k_3 - 1) = \left(\frac{10{,}359}{39.3} - 1 \right) = 262.5878.$$

Soybean Acreage Response Functions

The variable $q_{si}(t)$ represents reduced soybean production due to producers switching acreages from soybean to other commodity production as a result of reduced yields associated with an aphid infestation. The reduction in soybean production as a result of acreage conversion from soybean to corn or cotton production is estimated by using results from an earlier econometric study by Lin et al. (2000). Lin et al. estimated regression coefficients for soybean acreage response to changing soybean net returns assuming the theoretical restrictions of linear homogeneity and/or symmetry.[7] Reduced soybean production due to producers switching acreages from soybean to other crop production in the ith region, $q_{si}(t)$, is estimated by

$$(16) \qquad q_{si}(t) = \theta_i [A_i \tilde{Y}_i(Z_i) P(t) / S_i(t)],$$

where θ_i is the parameter associated with the variable SNR (see footnote 7), $S_i(t)$ is the acreage allocated for soybean production in the ith region, and $P(t)$ is an expected price of soybeans per bushel. However, futures market prices for soybeans (for the next ten years) are not available for simulation analyses using equation (16). Furthermore, $q_{si}(t)$ is considered as a supply shifter in our model (see footnote 2), so therefore we use the observed soybean price per bushel in the previous year for the expected soybean unit price in equation (16).[8]

Increased Insecticide Treatment Costs

The variable $q_{wi}(t)$ represents reduced soybean production due to increased insecticide treatment costs. First, let $P^*(t)$ be a unit price associated with $Q^*_{si}(t)$, which represents potential production without a soybean aphid infestation (see Appendix). Then the inverse supply function is represented by

$$(17) \qquad P^*(t) = [-\alpha_{si} / \beta_{si}] + Q^*_{si}(t) / \beta_{si}.$$

An increase in soybean production costs per acre, as a result of increased insecticide treatment, is represented by $w_i A_i / V_i$, where w_i is the per acre

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[7] Region 1:

$$\%SOY = \underset{(7.81)}{0.324\ SNR} - \underset{(-5.19)}{0.324CRNR}$$

Region 2:

$$\%SOY = \underset{(2.18)}{0.103\ SNR} - \underset{(-1.32)}{0.050\ CRNR} - \underset{(-0.91)}{0.053\ WNR}$$

Region 3:

$$\%SOY = \underset{(9.13)}{0.132\ SNR} - \underset{(-2.44)}{0.054\ CRNR} - \underset{(-2.87)}{0.072\ WNR} - \underset{(-2.92)}{0.234\ CNNR},$$

where %SOY is the percentage of soybean normal flex acreage planted to soybean, SNR is expected per acre net returns for soybeans, CRNR is expected per acre net returns for corn, WNR is expected per acre net returns for wheat, and CNNR is expected per acre net returns for cotton.

[8] For the case where $E(P_t) = P_t$, the supply curve in equation (1) rotates to the left as farmers switch acreage from soybean production to other crop production, and therefore the equilibrium price and quantities would differ from those presented in equations (6) through (9).

cost of applying an insecticide for the purpose of controlling soybean aphids in the ith region. Adding $w_i A_i / V_i$ to both sides of equation (17) results in the following:

$$(18)\quad P(t) = [-\alpha_{si} / \beta_{si} + w_i A_i / V_i] + Q_{si}(t) / \beta_{si},$$

where $P(t) = P^*(t) + w_i A_i / V_i$, and $Q_{si}(t)$ is the soybean production associated with $P(t)$. The reduced soybean production associated with an increase in insecticide treatment costs is estimated from equation (18) as follows:

$$(19)\qquad q_{wi}(t) = -[\beta_{si} w_i / V_i] \Delta A_i .$$

Soybean Price Elasticities

The price elasticities for domestic soybean demand and export demand are from USDA's Food and Agricultural Policy Simulator (Table 2). The price elasticity of domestic soybean demand, -0.16, is within the range of -0.13 and -0.29, which were recently estimated by Piggott and Wohlgenant (2002). The price elasticity of domestic soybean demand, obtained from the Food and Agricultural Policy Research Institute (FAPRI), is -1.17, which is greater than other estimates. Meanwhile, the price elasticity of soybean export demand, -0.79, is greater in absolute value than Piggott and Wohlgenant's estimate of -0.63, but less than the FAPRI estimates, which range between -1.07 and -1.44.

Regional soybean supply price elasticities are from a USDA study by Lin et al. (2000),[9] and range between 0.2 for Region 2 and 0.3 for Region 1. These estimates are also within a reasonable range when compared with estimates from FAPRI for Regions 1 and 3. However, the FAPRI estimates for Region 2 are twice that of USDA estimates (Table 2). Other previous studies are based on aggregate analyses using estimates that range between 0.12 ~ 0.14 by Piggott, Wohlgenant, and Zering (2001) and 0.3 by Meilke and Jay (1997), which are also within a reasonable range.

Results

Scenarios for Simulations

Using data presented in Tables 1 and 2, parameters associated with the domestic supply, domestic demand, and export demand of soybeans are estimated and presented in Table 3. Using these parameters, simulation analyses were conducted for five scenarios. Scenario 1 assumes that there was no insecticide treatment on soybean aphid infested acres and that soybean yield declines by 26 percent on average. Scenario 2 assumes that all soybean aphid infested acres are treated with an insecticide at \$12 per acre, while yield declines by 12 percent on average. Scenario 3 assumes that all infested acres are treated with an insecticide (as long as the yield loss is greater than the costs associated with an insecticide treatment) at \$25 per acre, and that soybean yield declines by 12 percent on average. Since soybean yields are relatively lower in Region 3 (Table 1), economic benefits resulting from an insecticide treatment would be less than the treatment cost of \$25 per acre. Therefore, under the third scenario, when treatment costs are \$25 per acre, then only soybean acres in Regions 1 and 2 are assumed to be treated with an insecticide. In addition, soybean yields in Regions 1 and 2 are reduced by 12 percent (with insecticide treatment costs of \$25 per acre), while soybean yields in Region 3 decline by 26 percent (with no insecticide treatment). While the North Central Soybean Research Program (2004) reports that insecticide treatments cost \$12 per acre (on average), Suszkiw (2005) reports that an average treatment cost ranges from \$12 to \$25 per acre. Therefore, both a lower and upper bound for insecticide treatment costs are used in our simulation analyses.

Scenarios 4 and 5 are associated with sensitivity analyses. Scenario 4 is the same as Scenario 2, except that the intrinsic growth rates are increased by 25 percent to $g_1 = 0.6056$, $g_2 = 0.5753$, and $g_3 = 0.4826$. Meanwhile, Scenario 5 is the same as Scenario 2, but the supply price elasticity of soybean acreage is increased by 25 percent, so the supply intercept and slope parameters are assumed to be $\alpha_1 = 1{,}261.275$, $\alpha_2 = 353.675$, $\alpha_3 =$

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[9] Lin et al. (2000) used the November soybean futures price at the Chicago Board of Trade in mid-March as the expected per-bushel price of soybeans. Expected price is further adjusted on a state-specific 5-year average basis—specifically, by the difference between the future prices and cash prices received by farmers in the delivery month of the futures—thus arriving at a farm-level equivalent price.

Table 2. Various Soybean Price Elasticities

	Our Study	Other Studies
DOMESTIC DEMAND ELASTICITY		
Price (2006)	-0.16	
Piggott and Wohlgenant (2002)		(-0.13) ~ (-0.29)
Westhoff et al. (1990), FAPRI (2004)		(-1.17)
EXPORT DEMAND ELASTICITY		
Price (2006)	-0.79	
Westhoff et al. (1990), FAPRI (2004)		(-1.07) ~ (-1.44)
Piggott and Wohlgenant (2002)		-0.63
ACREAGE SUPPLY ELASTICITY – REGION 1		
Lin et al. (2000)	0.298	
FAPRI (2004)		0.21 ~ 0.333
ACREAGE SUPPLY ELASTICITY – REGION 2		
Lin et al. (2000)	0.198	
FAPRI (2004)		0.41
ACREAGE SUPPLY ELASTICITY – REGION 3		
Lin et al. (2000)	0.221	
FAPRI (2004)		0.222 ~ 0.337
U.S. SUPPLY PRICE ELASTICITY		
Meilke and Jay (1997)		0.30
Meyers, Devadoss, and Helmar (1991)		0.24
Piggott, Wohlgenant, and Zering (2001)		0.12 ~ 0.15

222.90, $\beta_1 = 139.9486$, $\beta_2 = 21.7430$, and $\beta_3 = 15.9066$.

Results and Policy Implications

During the base year period of 2000–2002, the U.S. soybean industry produced nearly 2.8 billion bushels of soybeans, 64 percent of which was used for domestic demand and the remainder exported, while more than one million acres were infested with soybean aphids. Producers' and domestic consumers' surpluses at the base year were estimated to be nearly $13 billion and $30 billion, respectively (Tables 4 through 8). The largest economic damage associated with a soybean aphid infestation occurs under Scenario 1 (assuming no insecticide treatment), where reductions in producer and consumer surpluses reach $1.2 billion and $546 million, respectively, in five years, and $4.9 billion and $2.3 billion, respectively, in ten years (Table 4). Meanwhile, the reduction in soybean production (ΔQ^*_s) reaches 71 million bushels in five years, but it reaches 329 million bushels in ten years, which accounts for about 12 percent of U.S. soybean production during the base year period. This reduction, however, is largely absorbed by reducing soybean exports due to a higher price elasticity of export demand than for domestic demand (Table 2).

When acres infested with soybean aphids are treated with insecticides at $12 per acre (Scenario 2), reductions in producer and consumer surpluses reach $829 million and $373 million, respectively, in five years, and reach $3.6 billion

Table 3. Soybean Model Parameter Statistics at the Base-Year Period, 2000–2002

Model Parameter	Parameter Value
Domestic demand (mil. bu.)	1,776
Exports (mil. bu.)	1,012
Price ($/bu.)	5.35
α_{s1} (supply intercept for Region 1)	1,410.32
α_{s2} (supply intercept for Region 2)	376.94
α_{s3} (supply intercept for Region 3)	240.71
α_c (domestic demand intercept)	2,060.16
α_x (export demand intercept)	1,811.48
β_{s1}(supply slope for Region 1)	111.90
β_{s2} (supply slope for Region 2)	17.39
β_{s3} (supply slope for Region 3)	12.76
β_c (domestic demand slope)	53.11
β_x (export demand slope)	149.44

and $1.6 billion, respectively, in ten years (Table 5). Soybean production would decline on average by some 47 million bushels in five years (ΔQ^*_s), but by 236 million bushels in ten years. When costs associated with insecticide treatment increase to $25 per acre (Scenario 3), both producer and consumer losses would grow to $956 million and $430 million, respectively, in five years, and $3.9 billion and $1.8 billion, respectively, in ten years (Table 6). Meanwhile, soybean production declines by 55 million bushels in five years (Table 6), but by 261 million bushels in ten years.

The soybean aphid-infested acreage initially grows slowly, then its growth begins to accelerate up to an inflection point, and thereafter the increase of infested acreage begins to slow. That is, aphid-infested soybean acreage would increase to 10.3 million acres in five years, but it would increase to 43.5 million acres in ten years, which accounts for 60 percent of soybean acreage harvested during the base year. Furthermore, reductions in producer and consumer surpluses presented in Tables 4, 5, and 6 also increase slowly at the beginning, but begin to accelerate as time progresses as a result of employing a logistic aphid-infested acreage growth function. Therefore, it is important to get the timing right for controlling soybean aphids.

Sensitivity Analyses

Economic effects of a soybean aphid infestation on producers and consumers will vary across the relative sizes of the parameters in our model. Therefore, we conduct sensitivity analyses associated with two major parameters in our model, including the intrinsic growth rate of soybean aphid infestation and the price elasticities of soybean acreage supply.

First, we assume that the rate of intrinsic growth in each region increases by 25 percent—from $g_1 = 0.4845$, $g_2 = 0.4602$, and $g_3 = 0.3861$ to $g_1 = 0.6056$, $g_2 = 0.5753$, and $g_3 = 0.4826$—while insecticide treatment cost remains at $12 per acre (Scenario 4). The effects of an increased rate of intrinsic growth can be found by comparing the results presented in Table 5 for Scenario 2 with results in Table 7 for Scenario 4. Results show that as the intrinsic growth rate of soybean aphids increases by 25 percent, acreage infested with soybean aphids increases by 32 percent in ten years, from 43.5 million acres to 57.5 million acres, which would lead to a further reduction in soybean production of 84 million bushels, which is largely absorbed by reducing soybean exports. Furthermore, producer surplus would further decline by an additional $1.26 billion, due largely to the increase in acreage infested with soybean aphids (over that for Scenario 2), while consumer surplus would further decline by nearly $600 million, largely due to an increased soybean price from $6.54 per bushel to $6.96 per bushel during the same time period (as a result of reduced soybean production).

Next, we assume that the price elasticity of soybean acreage in each region increases by 25 percent—from $\varepsilon_1 = 0.298$, $\varepsilon_2 = 0.198$, and $\varepsilon_3 = 0.221$ to $\varepsilon_1 = 0.3725$, $\varepsilon_2 = 0.2475$, and $\varepsilon_3 = 0.2763$—while insecticide treatment costs remain at $12 per acre and the rates of intrinsic growth remain the same as $g_1 = 0.4845$, $g_2 = 0.4602$, and $g_3 = 0.3861$ (Scenario 5).[10] The effects of increasing the supply price elasticity of soybean acreage by 25 percent can be found by comparing results

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[10] The intercept and slope parameters of the soybean acreage supply function associated with an increase in the supply price elasticities by 25 percent are $\alpha_1 = 1261.275$, $\alpha_2 = 353.675$, $\alpha_3 = 222.90$, $\beta_1 = 139.9486$, $\beta_2 = 21.7430$, and $\beta_3 = 15.9066$.

Table 4. Effects of Soybean Aphid Infestation, Where g_1 = 0.4845, g_2 = 0.4602, and g_3 = 0.3861, with No Insecticide Treatment (Scenario 1)

	Infested Acreage									
Year	Region 1	Region 2	Region 3	Production Loss[a]	P^*	Q^*_s	Q^*_c	Q^*_x	PS^*	CS^*
	(acres)			(mil. bu.)	($/bu.)[b]	(mil. bu.)			($mil.)[b]	
Base year	744,100	335,200	39,300	14.358	5.39	2,780	1,774	1,006	12,887	29,688
									ΔPS*[c]	ΔCS*[c]
2003	1,196,434	523,644	57,716	22.886	5.42	2,775	1,773	1,002	-95	-43
2004	1,912,661	811,636	84,692	36.270	5.46	2,767	1,771	996	-240	-107
2005	3,030,016	1,243,165	124,123	56.953	5.52	2,754	1,767	987	-456	-204
2006	4,733,389	1,871,031	181,588	88.170	5.61	2,736	1,763	974	-770	-346
2007	7,240,887	2,746,543	264,969	133.644	5.74	2,709	1,756	954	-1,211	-546
2008	10,748,368	3,897,674	385,188	196.577	5.92	2,672	1,746	927	-1,796	-813
2009	15,319,631	5,299,573	556,943	277.791	6.16	2,625	1,733	891	-2,518	-1,145
2010	20,757,913	6,855,959	799,145	373.691	6.43	2,568	1,719	850	-3,328	-1,523
2011	26,567,554	8,415,927	1,134.485	475.868	6.73	2,508	1,703	806	-4,148	-1,910
2012	32,102,121	9,827,216	1,587,180	573.735	7.02	2,451	1,688	763	-4,891	-2,267

[a] Estimates here include production losses from both infestation and acreage conversion.
[b] A 3 percent rate of discount is used.
[c] Estimates measure change in economic benefits from the base year period.

Table 5. Effects of Soybean Aphid Infestation, Where g_1 = 0.4845, g_2 = 0.4602, and g_3 = 0.3861, with Insecticide Treatment at $12 per Acre (Scenario 2)

	Infested Acreage									
Year	Region 1	Region 2	Region 3	Production loss[a]	P^*	Q^*_s	Q^*_c	Q^*_x	PS^* [b]	CS^* [b]
	(acres)			(mil. bu.)	($/bu.)[b]	(mil. bu.)			($mil.)[b]	
Base year	744,100	335,200	39,300	9.581	5.38	2,782	1,775	1,008	12,887	29,688
									ΔPS*[c]	ΔPS*[c]
2003	1,196,434	523,644	57,716	15.322	5.39	2,779	1,774	1,005	-64	-29
2004	1,912,661	811,636	84,692	24.348	5.42	2,774	1,772	1,001	-162	-72
2005	3,030,016	1,243,165	124,123	38.356	5.46	2,765	1,770	995	-308	-138
2006	4,733,389	1,871,031	181,588	59.626	5.52	2,753	1,767	986	-524	-235
2007	7,240,887	2,746,543	264,969	90.867	5.61	2,735	1,762	973	-829	-373
2008	10,748,368	3,897,674	385,188	134.606	5.74	2,709	1,755	954	-1,241	-559
2009	15,319,631	5,299,573	556,943	191.953	5.91	2,675	1,747	929	-1,758	-795
2010	20,757,913	6,855,959	799,145	261.094	6.11	2,634	1,736	899	-2,356	-1,070
2011	26,567,554	8,415,927	1,134,485	336.667	6.33	2,590	1,724	866	-2,980	-1,360
2012	32,102,121	9,827,216	1,587,180	411.138	6.54	2,546	1,713	834	-3,566	-1,635

[a] Estimates here include production losses from infestation, acreage conversion, and increased treatment costs.
[b] A 3 percent rate of discount is used.
[c] Estimates measure change in economic benefits from the base year period.

Table 6. Effects of Soybean Aphid Infestation, Where $g_1 = 0.4845$, $g_2 = 0.4602$, and $g_3 = 0.3861$, with Insecticide Treatment at $25 per Acre (Scenario 3)

	Infested Acreage									
Year	Region 1	Region 2	Region 3	Production loss[a]	P^*	Q^*_s	Q^*_c	Q^*_x	PS^* [b]	CS^* [b]
	(acres)			(mil. bu.)	($/bu.)[c]	(mil. bu.)			($mil.)[c]	
Base year	744,135	335,184	39,326	11.221	5.38	2,781	1,774	1,007	12,887	29,688
									ΔPS^* [c,d]	ΔPS^* [c,d]
2003	1,196,434	523,644	57,716	17.902	5.4	2,777	1,773	1,004	-75	-33
2004	1,912,661	811,636	84,692	28.402	5.43	2,771	1,772	1,000	-188	-84
2005	3,030,016	1,243,165	124,123	44.655	5.48	2,762	1,769	993	-358	-161
2006	4,733,389	1,871,031	181,588	69.236	5.55	2,747	1,765	982	-607	-272
2007	7,240,887	2,746,543	264,969	105.129	5.66	2,726	1,760	966	-956	-430
2008	10,748,368	3,897,674	385,188	154.948	5.8	2,697	1,752	945	-1,423	-642
2009	15,319,631	5,299,573	556,943	219.454	5.99	2,659	1,742	917	-2,003	-908
2010	20,757,913	6,855,959	799,145	295.911	6.21	2,614	1,730	884	-2,659	-1,211
2011	26,567,554	8,415,927	1,134,485	377.717	6.45	2,566	1,718	848	-3,328	-1,523
2012	32,102,121	9,827,216	1,587,180	456.470	6.67	2,520	1,706	814	-3,942	-1,813

[a] Estimates here include production losses from infestation, acreage conversion, and increased treatment costs.

[b] Cost of insecticide application is assumed to be $25 per infested acre. For Region 3, where an average yield is 29.8 bu./ac., per acre economic benefits from insecticide treatments are estimated to be $22.32 (29.8 bu./ac. × 14% × $5.35/bu.), which are less than the $25/ac. treatment costs. Therefore, there is no insecticide treatment applied for Region 3 when the cost of insecticide treatment is $25 per acre.

[c] A 3 percent rate of discount is used.

[d] Estimates measure change in economic benefits from the base year period.

Table 7. Effects of Soybean Aphid Infestation, Where $g_1 = 0.6056$, $g_2 = 0.5753$, and $g_3 = 0.4826$, with Insecticide Treatment at $12 per Acre (Scenario 4)

	Infested Acreage									
Year	Region 1	Region 2	Region 3	Production loss[a]	P^*	Q^*_s	Q^*_c	Q^*_x	PS^* [b]	CS^* [b]
	(acres)			(mil. bu.)	($/bu.)[b]	(mil. bu.)			($mil.)[b]	
Base year	744,100	335,200	39,300	9.581	5.38	2,782	1,775	1,008	12,887	29,688
									ΔPS^* [c]	ΔCS^* [c]
2003	1,346,160	584,811	63,528	17.21	5.4	2,778	1,773	1,004	-85	-38
2004	2,410,618	1,006,388	102,542	30.588	5.44	2,770	1,771	999	-230	-103
2005	4,240,624	1,692,887	165,134	53.448	5.51	2,757	1,768	989	-469	-210
2006	7,240,272	2,746,983	264,943	90.767	5.61	2,735	1,762	973	-845	-380
2007	11,792,734	4,227,884	422,579	147.425	5.78	2,701	1,753	948	-1,393	-628
2008	17,953,437	6,068,127	667,800	224.754	6.00	2,656	1,741	914	-2,109	-956
2009	25,113,443	8,035,672	1,040,420	316.589	6.27	2,602	1,727	875	-2,919	-1,331
2010	32,099,976	9,828,344	1,586,911	409.76	6.54	2,547	1,713	834	-3,700	-1,697
2011	37,845,988	11,238,760	2,348.12	491.016	6.78	2,499	1,700	799	-4,347	-2,004
2012	41,943,474	12,225,701	3,335,621	553.778	6.96	2,462	1,691	772	-4,824	-2,233

[a] Estimates here include production losses from infestation, acreage conversion, and increased treatment costs.

[b] A 3 percent rate of discount is used.

[c] Estimates measure change in economic benefits from the base year period.

Table 8. Effects of Soybean Aphid Infestation, Where $g_1 = 0.4845$, $g_2 = 0.4602$, $g_3 = 0.3861$, and a 25 Percent Increase in the Price Elasticity of Soybean Acreage for Each Region with Insecticide Treatment at \$12 per Acre (Scenario 5)[a]

	Infested Acreage									
Year	Region 1	Region 2	Region 3	Production loss[b]	P^*	Q^*_s	Q^*_c	Q^*_x	$PS^{*\,c}$	$CS^{*\,c}$
	(acres)			(mil. bu.)	(\$/bu.)[c]	(mil. bu.)			(\$mil.)[c]	
Base year	744,100	335,200	39,300	9.581	5.38	2,783	1,775	1,008	12,887	29,688
									$\Delta PS^{*\,c,d}$	$\Delta CS^{*\,c,d}$
2003	1,196,434	523,644	57,716	15.32	5.39	2,780	1,774	1,006	-46	-26
2004	1,912,661	811,636	84,692	24.341	5.41	2,775	1,773	1,002	-117	-66
2005	3,030,016	1,243,165	124,123	38.341	5.45	2,768	1,771	997	-224	-125
2006	4,733,389	1,871,031	181,588	59.589	5.51	2,756	1,768	989	-380	-213
2007	7,240,887	2,746,543	264,969	90.779	5.59	2,740	1,763	976	-601	-338
2008	10,748,368	3,897,674	385,188	134.409	5.7	2,716	1,757	959	-899	-506
2009	15,319,631	5,299,573	556,943	191.536	5.85	2,686	1,749	937	-1,275	-720
2010	20,757,913	6,855,959	799,145	260.286	6.03	2,649	1,740	910	-1,707	-968
2011	26,567,554	8,415,927	1,134,485	335.253	6.23	2,609	1,729	880	-2,159	-1,229
2012	32,102,121	9,827,216	1,587,180	408.915	6.43	2,570	1,719	851	-2,583	-1,477

[a] Supply intercept and slope parameters are $\alpha_1 = 1261.275$, $\alpha_2 = 353.675$, $\alpha_3 = 222.90$, $\beta_1 = 139.9486$, $\beta_2 = 21.7430$, and $\beta_3 = 15.9066$.

[b] Estimates here include production losses from infestation, acreage conversion, and increased treatment costs.

[c] A 3 percent rate of discount is used.

[d] Estimates measure change in economic benefits from the base year period.

presented in Table 5 for Scenario 2 with results in Table 8 for Scenario 5. Results indicate that as the supply price elasticity increases by 25 percent, the reduction in soybean production is slowed by 24 million bushels in ten years, the rise in soybean price is slowed by \$0.11 per bushel, and the reduction of producer surpluses is slowed by \$983 million.

Table 9 provides a summary of the economic benefits resulting from controlling soybean aphids, where the economic benefits for each scenario are defined as the difference between producer or consumer surplus, respectively, under each scenario, and those for the scenario without insecticide treatment (Scenario 1). Both producer and consumer benefits resulting from insecticide treatment increase steadily over time under Scenarios 2, 3, and 5. However, the economic benefits resulting from controlling soybean aphids increase as the insecticide treatment costs decline, the price elasticity of acreage supply becomes more elastic, and the intrinsic growth rate declines. When the rate of intrinsic growth increases by 25 percent (Scenario 4), it is not economical to treat soybean aphids with insecticides. Even though consumer surplus is more than twice that of producer surplus at the base year, our results indicate that producer benefits resulting from controlling soybean aphids far exceed consumer benefits over time.

Results also suggest that before soybean growers face severe economic losses from this invasive insect, greater efforts should be made to develop new higher-yielding seed varieties that are resistant to the soybean aphid. However, without the successful development of soybean aphid resistant varieties through germplasm and breeding[11] in the near future, soybean growers are very likely to suffer greater economic losses from soybean aphid infestations in the future. For example, in 2004, scientists from USDA's Agricultural

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[11] These techniques include selective hybridization, but they do not include a genetically modified organism (GMO) whose genetic material has been altered using techniques in genetics generally known as recombinant DNA technology.

Table 9. Economic Benefits Resulting from Controlling Soybean Aphids under Various Scenarios[a,b]

Year	Scenario 2		Scenario 3		Scenario 4		Scenario 5	
	Producer Benefits	Consumer Benefits	Producer Benefits	Consumer Benefits	Producer Benefits	Consumer Benefits	Producer Benefits	Consumer Benefits
	($mil.)[c]							
2003	31	14	20	10	10	5	49	17
2004	78	35	52	23	-10	4	123	41
2005	148	66	98	43	-13	-6	232	79
2006	246	111	163	74	-75	-34	390	133
2007	382	173	255	116	-182	-82	610	208
2008	555	254	373	171	-313	-143	897	307
2009	760	350	515	237	-401	-186	1,243	425
2010	972	453	669	312	-372	-174	1,621	555
2011	1,168	550	820	387	-199	-94	1,989	681
2012	1,325	632	949	454	67	34	2,308	790

[a] Scenario 2 assumes that all soybean aphid infested acres are treated with an insecticide at $12 per acre, while yield declines by 12 percent on average, where $g_1 = 0.4845$, $g_2 = 0.4602$, and $g_3 = 0.3861$. Scenario 3 is the same as Scenario 2, but it assumes that all soybean aphid infested acres are treated with an insecticide at $25 per acre. Scenario 4 is the same as Scenario 2, except the intrinsic growth rates are increased by 25 percent, such that $g_1 = 0.6056$, $g_2 = 0.5753$, and $g_3 = 0.4826$. Finally, Scenario 5 is the same as Scenario 2, except the supply price elasticities are increased by 25 percent, so supply intercept and slope parameters are $\alpha_1 = 1261.275$, $\alpha_2 = 353.675$, $\alpha_3 = 222.90$, $\beta_1 = 139.9486$, $\beta_2 = 21.7430$, and $\beta_3 = 15.9066$.

[b] The rate of discount is 3 percent.

[c] Economic benefits are based on differences between producer and consumer surpluses under each scenario and those under no insecticide treatment (i.e., the baseline Scenario 1).

Research Service (ARS) and the University of Illinois collaborated on the discovery of a single gene, tentatively named *Rag*1, which confers resistance to soybean aphids (Suszkiw 2005, Wang et al. 2005). This development has set the stage for seed companies to breed existing high-yielding but susceptible cultivars that should withstand the soybean aphid (using backcrossing procedures) without help from insecticides (Hill, Li, and Hartman 2006).

Conclusions

Soybean yields in the United States have been affected by a soybean aphid infestation. We estimate the economic benefits resulting from controlling soybean aphid infestation by using a multi-regional competitive dynamic equilibrium model. Soybean-producing states are divided into three regions based on the distributions of *buckthorn*, the invasive species' only known wintering host, and soybean yields. The dispersion rate of infested soybean acreage with soybean aphids is modeled as a logistic growth function. The volume of U.S. soybean production, its domestic demand, and exports, as well as a logistic growth function for acreage infestation, are incorporated into a dynamic economic-equilibrium model.

We conducted simulation analyses for five scenarios. The first scenario assumed that there is no insecticide treatment on soybean aphid infested acres and that soybean yield on infested acres declines by 26 percent on average. The second scenario assumed that all soybean aphid infested acres are treated with an insecticide at $12 per acre, while yield declines by 12 percent on average. The third scenario assumed that all infested acres are treated with insecticides (as long as the yield loss is greater than the costs associated with an insecticide treatment) at $25 per acre, and soybean yield declines by 12 percent on average, while the yield on untreated acres (for Region 3) declines by 26 percent on average. The fourth scenario was assumed to be the same as the second scenario, but the rates of intrinsic growth increase by 25 percent, and the fifth scenario was also assumed to be the same as the second scenario, but supply price elasticities are increased by 25 percent.

Results for this study indicate that the reduction in soybean production resulting from a soybean aphid infestation is largely absorbed by reducing soybean exports, due to the higher price elasticity of export demand (i.e., -0.79) compared to the domestic demand price elasticity (-0.16). Results also indicate that under the assumed parameters we used, soybean producer surplus losses would grow at between \$46 million and \$95 million following the first year of infestation, but would grow to between nearly \$3.6 billion and \$4.9 billion following ten years, depending upon the costs of treating soybean plants with an insecticide, the rate of intrinsic growth, and the price elasticities of soybean supply. Since infested-acreage increases are modeled by a logistic acreage infestation function, soybean producers suffer greater economic losses as the intrinsic growth rate of infested soybean acreage rises and infested acreage increases as time progresses. Consequently, it is important to control soybean aphids early on to avoid the rapid growth phase of the infestation. Finally, results also suggest that it is economically efficient to control soybean aphids when the rate of intrinsic growth is lower, when the price elasticity of soybean acreage supply is more elastic, and when insecticide treatment costs per acre are lower.

Considering the relatively moderate economic losses to producers during the earlier period of infestation and the successful discovery of *Rag*-1, which confers resistance to soybean aphids, the damages we estimate for the later infestation phases may be avoided due to the development of new soybean varieties. However, given the likely growth rate for potential economic losses, and associated impacts on the export market for U.S. soybeans, continued research on long-term effective control options is likely warranted. This research could help to develop optimal policies for disease prevention control as well as to determine efficient strategies for compensating farmers for potential losses through crop insurance and other farm support programs.

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Appendix

Following is the derivation of equation (1),

$$\sum_{i=1}^{n} Q_{si}(t) = \sum_{i=1}^{n} \left\{ \begin{matrix} [\alpha_{si} - A_i(t)\tilde{Y}_i(Z_i) - q_{si}(t) \\ -q_{wi}(t)] + \beta_{si}P(t) \end{matrix} \right\}.$$

Let $P^*(t)$ be a unit price associated with $Q^*_{si}(t)$, which represents potential production without soybean aphids. The supply function is then represented by

$$\text{(A1)} \qquad Q^*_{si}(t) = \alpha_{si} + \beta_{si}P^*(t), \text{ or}$$

$$\text{(A2)} \qquad P^*(t) = [-\alpha_{si}/\beta_{si}] + Q^*_{si}(t)/\beta_{si}.$$

Since the supply curve represents the marginal cost curve, the total variable cost (TVC) function is obtained by integrating equation (A2) as follows:

$$\text{(A3)} \quad \text{TVC}(Q^*_{si}(t)) = \int_0^{Q^*si} [(-\alpha_{si}/\beta_{si}) + x/\beta_{si}]dx$$
$$= [-\alpha_{si}/\beta_{si}]Q^*_{si}(t) + [(Q^*_{si}(t))^2/2\beta_{si}].$$

Let $Q_{si}(t)$ be actual production such that $Q_{si}(t) = Q^*_{si}(t) - A_i(t)\tilde{Y}_i(Z_i) - q_{si}(t) - q_{wi}(t)$. Total variable cost of actual production is then represented as follows:

(A4)

$$\text{TVC}(Q_{si}(t)) = [-\alpha_{si}/\beta_{si}][Q_{si}(t) + A_i(t)\tilde{Y}_i(Z_i) + q_{si}(t) + q_{wi}(t)] + \{[Q_{si}(t) + A_i(t)\tilde{Y}_i(Z_i) + q_{si}(t) + q_{wi}(t)]^2/2\beta_{si}\}.$$

Differentiating equation (A4) with respect to Q_{si} results in the marginal cost function of $Q_{si}(t)$ as follows:

(A5)

$$MC(Q_{si}(t)) = [-\alpha_{si}/\beta_{si}] + [Q_{si}(t) + A_i(t)\tilde{Y}_i(Z_i) + q_{si}(t) + q_{wi}(t)]/\beta_{si} = P(t),$$

where $P(t)$ is a unit price associated with $Q_{si}(t)$. Equation (A5) can be rewritten as follows:

(A6)

$$Q_{si}(t) = [\alpha_{si} - A_i(t)\tilde{Y}_i(Z_i) - q_{si}(t) - q_{wi}(t)] + \beta_{si}P(t).$$

Summation of both sides from the equality in equation (A6) results in the following:

(A7)

$$\sum_{i=1}^{n} Q_{si}(t) = \sum_{i=1}^{n} \left\{ \begin{matrix} [\alpha_{si} - A_i(t)\tilde{Y}_i(Z_i) - q_{si}(t) \\ -q_{wi}(t)] + \beta_{si}P(t) \end{matrix} \right\}. \quad Q.E.D.$$