Biological Invasions: The Case of Soybean Aphid Infestation

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ABSTRACT

Soybeans, the second highest cash crop following corn in the U.S., have come under attack by invasive species, the soybean aphid from the North and soybean rust from the South. We estimated the economic losses resulting from soybean aphid infestation by using a dynamic equilibrium model. Results indicate that, first, the reduction of soybean production resulting from soybean aphid infestation is largely absorbed by reducing soybean exports, due to the higher price elasticity of export demand compared to the domestic demand. Second, the economic losses to U.S. soybean producers would grow on average annually between $12.8 million and $23.4 million during the first five years of infestation. In the longer-run, soybean producers would suffer greater economic losses as the dispersion rate of infested soybean acreage with soybean aphids rises. However, the successful discovery of the soybean aphid gene (TF04048) *Rag*-1 (which confers resistance) does not at this time warrant soybean growers and policy-makers becoming too seriously alarmed. Even so, time is an important factor in the eventual control of the soybean aphid.

Keywords: Soybean aphid, invasive species, producer surplus, consumer surplus, *Rag*-1.

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Soybeans are the second highest cash crop following corn in the United States. Farmers annually produced on average nearly 2.8 billion bushels from 72.4 million acres during the 2000-2002 period, which were valued at more than $15 billion (Table 2). Most soybeans produced in the U.S. 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 (USDA World Board). However, recently this valuable crop for U.S. farmers has come under attack by an invasive species, the soybean aphid from the North.

Soybean aphid, known as *Aphis glycines Matsumura*, was first discovered in 1995 in Wisconsin, but not officially confirmed as soybean aphids until 2000. By 2003, the soybean aphid had already spread to 21 states, and they are still expanding up to 600 miles a year (North Central Soybean Research Program, 2004). The soybean aphid's only known wintering host is the common *buckthorn* (*Rhamnus cathartica*), which is distributed throughout the upper Midwest and Northern Plains (Regions 1 and 2, Figure 1). Furthermore, soybean aphids are intolerant to temperatures above 95^{0}F. Consequently, more soybean aphids are found in the northern states of Region 1, where a weighted-average yield is the highest at 42 bushels per acre during the 2000-2002 periods, than in the southern states of Region 3, where a weighted-average yield is the lowest at 30 bushels per acre. Soybean aphid-induced yield reductions associated with grower strip trials (without the treatment of an insecticide) have ranged from 12 to 45 percent (Ostlie, 2001; 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; Potter and

Hansen, 2003). However, the potential for an extremely rapid population increase, where soybean aphids may be able to produce up to 18 generations per year (Ostlie, 2004), makes timely treatment of insecticides a difficult mitigation issue (Potter and Hansen, 2003).

This study measures the economic effects of soybean aphid control on the volume of U.S. soybean production, its domestic demand, exports, and its consumer/producer surpluses. 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 soybean aphid. We then apply a dynamic economic equilibrium 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.

The Model

We address the economic impacts of the soybean aphid within the contexts of a multi-region, dynamic equilibrium framework assuming both differential regional logistic acreage infestation growth functions and their regional soybean yield effects. We first begin 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 and expressed as follows:

U.S. soybean supply (see Appendix 1)**:**

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

U.S. soybean domestic demand[1]**:**

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

[1] Soybean domestic demand includes changes in stocks, similar to Piggott and Wohlgenant, 2002).

U.S. soybean export demand:

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

where Q(t) and P(t) represent the quantity and expected price of soybeans in year t, α and β are parameters, the variable A_i represents the soybean acreage infested in the i^{th} region and the variable $\tilde{Y}_i$ represents the per acre reduction in soybean yield (or yield loss) associated with the aphid infested acres, Z_i represents 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 other crop production, and the subscripts s, c, and x represent domestic supply, domestic demand, and exports, respectively.

An equilibrium soybean price is obtained by equating the domestic soybean supply in equation (1) to the sum of the domestic demand in equation (2) and the export demand in equation (3). The result is then represented as follows:

(4) $$P(t) = [\alpha_c + \alpha_x - \alpha_s + \sum_{i=1}^{n} (A_i(t)\tilde{Y}_i(Z_i) + q_{si}(t))] / (\beta_c + \beta_x + \beta_s),$$

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

The domestic soybean supply, the domestic soybean demand, and the soybean export demand are then obtained by inserting an equilibrium price from equation (4) into equations (1) through (3), respectively, which are represented as follows:

(5) $$Q_s(t) = \alpha_s - \sum_{i=1}^{n} [A_i\tilde{Y}_i(Z_i) + q_{si}(t)] + \beta_s[\alpha_c+\alpha_x-\alpha_s + \sum_{i=1}^{n} (\tilde{Y}_i(Z_i)A_i + q_{si}(t))] / (\beta_c+\beta_x+\beta_s),$$

(6) $$Q_c(t) = \alpha_c - \beta_c[\alpha_c+\alpha_x-\alpha_s + \sum_{i=1}^{n} (\tilde{Y}_i(Z_i)A_i + q_{si}(t))] / (\beta_c+\beta_x+\beta_s),$$

(7) $$Q_x(t) = \alpha_x - \beta_x[\alpha_c+\alpha_x-\alpha_s + \sum_{i=1}^{n} (\tilde{Y}_i(Z_i)A_i + q_{si}(t))] / (\beta_c+\beta_x+\beta_s),$$

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

Following Huffaker and Cooper (1995), Kim, et al. (2005), and Vargas and Ramadan (2000), we assume a logistic growth function for the soybean aphid, acreage infestation as follows:

$$(8) \qquad \partial A_i(t)/\partial t = g_i A_i(t)[1- (A_i(t)/ V_i)], \qquad \text{(for } i = 1, 2, \ldots, n)$$

where the variable g represents the intrinsic growth rate of infested acreage and V_i represents the maximum acreage available for soybean aphid infestation in the i^{th} region. A solution of the first-order differential equation (8) is presented as (see Appendix 2):

$$(9) \qquad A_i(t) = \left[\frac{V_i}{1 + (k_i - 1)\, exp(-g_i t)} \right]$$

where $k_i = [V_i / A_i(t=0)]$; $\partial A_i/\partial g_i > 0$, and $i = 1, 2, \ldots, n$.

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

Inserting equation (9) into equation (4), an equilibrium price is represented by:

$$(10) \qquad P^*(t) = \left[\frac{(\alpha_c + \alpha_x - \alpha_s) + \sum_{i=1}^{n} \{\tilde{Y}_i(Z_i)[\, V_i / (1+(k_i-1)exp(-g_i t))] + q_{si}(t)\}}{(\beta_c + \beta_x + \beta_s)} \right]$$

where $k_i = [A_i(t=0) / V_i]$ from equation (9). Similarly, the equilibrium quantity of domestic production, domestic demand, and export demand are obtained by inserting equation (10) into equations (5) through (7) as follows:

(11) $$Q_s^*(t) = \alpha_s - \sum_{i=1}^{n} \{q_{si}(t) + \tilde{Y}_i(Z_i)[V_i/(1+(k_i-1)exp(-g_i t))]\}$$

$$+ [\beta_s/(\beta_c+\beta_x+\beta_s)]\{\alpha_c+\alpha_x-\alpha_s+\sum_{i=1}^{n} \{q_{si}(t) + \tilde{Y}_i(Z_i)[V_i/(1+(k_i-1)exp(-g_i t))]\}\},$$

(12) $$Q_c^*(t)=\alpha_c-[\beta_c/(\beta_c+\beta_x+\beta_s)]\{\alpha_c+\alpha_x-\alpha_s+\sum_{i=1}^{n} \{q_{si}(t) +\tilde{Y}_i(Z_i)[V_i/(1+(k_i-1)exp(-g_i t))]\}\},$$

(13) $$Q_x^*(t)=\alpha_x-[\beta_x/(\beta_c+\beta_x+\beta_s)]\{\alpha_c+\alpha_x-\alpha_s+\sum_{i=1}^{n} \{q_{si}(t) + \tilde{Y}_i(Z_i)[V_i/(1+(k_i-1)exp(-g_i t))]\}\},$$

where $k_i = [A_i(t=0) / V_i]$ from equation (9).

The U.S. soybean producer surplus (PS) is estimated using equation (1) as follows:[2]

(14) $$PS = \int_{t=0}^{T} \exp(-rt)\, \{P(t)Q_s(t) - \int_{0}^{Qs} \{[-\alpha_s + \sum_{i=1}^{n} (A_i(t)\tilde{Y}_i(Z_i)) + q_{si}(t))] / \beta_s + x/\beta_s]\}\delta x\}\delta t$$

$$= \int_{t=0}^{T} \exp(-rt)\, \{\{P(t) + (\alpha_s/\beta_s) - \sum_{i=1}^{n} [A_i(t)\tilde{Y}_i(Z_i) + q_{si}(t)]/\beta_s\}Q_s(t) - [Q_s^2(t)/2\beta_s]\}\delta t$$

where T is the terminal time period, $Q_s(t) = \sum_{i=1}^{n} Q_{si}(t)$, $\alpha_s = \sum_{i=1}^{n} \alpha_{si}$, and $\beta_s = \sum_{i=1}^{n} \beta_{si}$ as shown in equations (4) through (7). Producer surpluses at equilibrium are then obtained by inserting equations (9) through (11) into equation (14), represented as follows:

(15) $$PS^* = \int_{t=0}^{T} \exp(-rt)\, \{\{P^*(t)+(\alpha_s/\beta_s)$$

$$- \sum_{i=1}^{n} \{q_{si}(t)+\tilde{Y}_i(Z_i)[A_i(t=0)/(V_i/(1+(k_i-1)exp(-gt))]\}/\beta_s\}Q_s^*(t) - [(Q_s^*(t))^2/2\beta_s]\}\delta t,$$

where r is the rate of time preference and T is a terminal time period.

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[2] In the case that $\alpha_s>0$, producer surplus is estimated by a trapezoid area surrounded by the supply curve, an equilibrium price (P*), and the horizontal axis, due to a lack of information on a soybean production cost function, as follows: $PS(t) = \{[\alpha_s - \sum_{i=1}^{n} (A_i(t)\tilde{Y}_i(Z_i)+q_{si}(t))]+(\beta_s/2)P^*(t)\}P^*(t)$.

Similarly, the U.S. soybean consumer surplus (CS) is represented by using equation (2) as follows:

$$(16) \quad CS = \int_{t=0}^{T} \exp(-rt) \left\{ \int_{0}^{Qc} (\alpha_c/\beta_c - x/\beta_c)\delta x - P(t)Q_c(t) \right\} \delta t$$

$$= \int_{t=0}^{T} \exp(-rt) \left\{ [\alpha_c/\beta_c - P(t)]Q_c(t) - [Q_c^2(t)/2\beta_c] \right\} \delta t.$$

Consumer surplus at equilibrium is then estimated by inserting equations (10) and (12) into equation (16), represented as follows:

$$(17) \quad CS^* = \int_{t=0}^{T} \exp(-rt) \left\{ [\alpha_c/\beta_c - P^*(t)]Q_c^*(t) - [(Q_c^*(t))^2/2\beta_c] \right\} \delta t.$$

Empirical Analysis

Data Sources and Analysis

Average soybean acreage, yield, and infested acreage during the 2000-2002 period represent a base year environment. Regional soybean harvested acreage, soybean yield, and soybean acreage treated with insecticides in 2000 and 2002 were obtained from USDA's Agricultural Resource Management Survey (ARMS) for soybeans[3]. Regional soybean supply price elasticities are from a USDA-ERS study by Lin et al. (2000)[4]. Annual soybean price and loan rate, domestic soybean demand, domestic production, and exports were acquired from

[3] Region 1 includes DE, IL, IN, IW, MD, MI, MN, MO, NJ, NY, OH, PA, WI, WV; Region 2 includes KS, NB, ND, SD; Region 3 includes AL, AR, FL, GA, LA, MS, KY, NC, OK, SC, TN, TX, and VA.

[4] Lin et al. derived the expected price from the November soybean futures price at the Chicago Board of Trade in mid-March. Expected price is further adjusted by a State-specific, 5-year average basis, 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.

USDA-ERS (Ash). The price elasticities of the domestic demand and an export demand are also from USDA-ERS (Price).

In 2002, the ARMS questionnaire asked respondents whether soybean aphid was detected on the sampled soybean field. Respondents were also asked whether scouting was conducted and whether insecticide treatments were applied to the soybean field (but not necessarily for soybean aphids). Therefore, ARMS data on soybean acreage, where soybean aphid was detected, scouted, and whether insecticides were applied, are used to estimate soybean acreage infested with the soybean aphid.

Meanwhile, because soybean aphids had not been officially identified before the 2000 production year, no question about soybean aphids was included on the 2000 ARMS questionnaire. According to the 2000 USDA-ERS ARMS data, soybean fields treated with insecticides in the U.S. during 2000 accounted for 267 thousands acres. Therefore, the ratio of soybean acreage treated with insecticides to the soybean acreage infested with the soybean aphid in 2002 (which includes detection, scouting, and insecticide treatment) is used to extrapolate soybean acreage infested with soybean aphid for 2000. Soybean acreage infested with the soybean aphid in 2000 was estimated to be 72,090 acres, compared to nearly 145 thousand acres for 2002.

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. Since soybean aphids were not detected in Region 3 for 2000, the regional intrinsic growth rate cannot be estimated for Region 3. Therefore, an intrinsic growth rate of infested soybean acres is estimated at the aggregate level, where for equation (9) $A(t=2) = 144{,}727$ acres for 2002, $A(t=0) = 72{,}090$ acres for 2000, and an average harvested soybean acres of 72 million acres is assumed for the 2000–2002 period (Table 1). The estimated intrinsic growth rate is g = 0.349.[5] Using the estimated aggregate intrinsic growth rate and equation (9), acreage infested with soybean aphids in year t for each of three regions is represented as follows:[6]

(18) $A_1(t) = 48{,}215{,}000 / [1 + 421.2792\, exp(-0.349t)]$,

(19) $A_2(t) = 13{,}782{,}000 / [1 + 557.3600\, exp(-0.349t)]$,

(20) $A_3(t) = 10{,}359{,}000 / [1 + 1{,}764.9393\, exp(-0.349t)]$.

It should be noted from equation (18) that as time approaches infinity, soybean acreage infested with soybean aphids approaches the level of annually harvested acreage of soybeans for the 2000-2002 years. This result contradicts estimates of invasive species infestation of soybeans by previous studies. For instance, the North Central Soybean Research Program (2004) presented a GIS map of soybean aphid infestation covering almost all of the major U.S. soybean producing areas in 2002. Similarly, Livingston et al. (2004), for instance, used a regional suitability index for soybean rust, so that 70 percent of soybean acres in the Corn Belt region needed to be treated with pesticides from the first year of infestation to after establishment.[7] However, for soybean aphids, equation (18) is used to show that 20 years are needed for soybean aphids to infest 70 percent of soybean acreage in Region 1. Furthermore, USDA's ARMS data reveal that on average only 0.2 of one percent of more than 72 million acres of soybean production were infested with soybean aphids in 2002 (Table 1). The soybean acreage infested with soybean aphids is the highest in Region 1, which accounts for 0.24 of one

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[5] McCornack, et al. (2004), reported that the intrinsic growth rate for the soybean aphid depends on temperature, varying between 0.368 and 0.474 under normal temperature conditions. Therefore, simulation was conducted at g=0.349 and g=0.474 in Tables 4 through 7.

[6] The maximum acreage available for aphid infestation is assumed to be constant at the base period. Therefore, the acreage infestation presented in equations (18) through (20) would represent upper limits of infestations.

[7] A species is considered established when it attains a self-sustaining population.

percent of total soybean acreage harvested, while it is the lowest in Region 3 which accounts for 0.06 of one percent of soybean acreage harvested.

To apply the dynamic equilibrium model presented in equations (1) through (13), advanced knowledge of $q_i(t)$ is required, which represents reduced soybean production due to producers switching acreages from soybeans to corn or cotton production as a result of increased production costs and reduced yields. The reduction in soybean production as a result of acreage conversion from soybeans to corn or cotton production is estimated by using results from an earlier econometric study. Lin et al (2000) estimated regression coefficients for soybean acreage response to changing soybean net returns assuming the theoretical restrictions of linear homogeneity and/or symmetry. Estimated regression coefficients in soybean acreage response functions are represented by producing region as follows:

(21) Region 1: $\%SOY = \underset{(7.81)}{0.324}\ SNR - \underset{(-5.19)}{0.324}CRNR$

(22) Region 2: $\%SOY = \underset{(2.18)}{0.103}\ SNR - \underset{(-1.32)}{0.050}\ CRNR - \underset{(-0.91)}{0.053}\ WNR$

(23) 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 percent of soybean normal flex acreage planted to soybean, corn, wheat, or cotton, 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. Changes in expected per acre net returns for soybean, ΔSNR, resulting from soybean aphid infestation are estimated by:

(24) $\Delta SNR(t) = \sum_{i=1}^{n} [(A_i \tilde{Y}_i(Z_i)P(t)) / S_i(t)],$

where $S_i(t)$ is the acreage allocated for soybean production in the *i*th region and P(t) is an expected price of soybean per bushel. Since the unit soybean price and soybean acreage response are simultaneously determined, the observed soybean price per bushel in the previous year is used for expected soybean unit price in equation (24).

Results

Simulation analyses were conducted for three scenarios. The first scenario assumes that there was no insecticide treatment on soybean aphid infested acres and that soybean yield declines by 26 percent on average. The second scenario assumes that all soybean aphid infested acres are treated with an insecticide at $12 per acre, while yield declines by 12 percent. The third scenario 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 where soybean yield declines by 12 percent. Since soybean yields are relatively lower in Region 3 (Table 2), economic benefits resulting from an insecticide treatment would be less than the treatment cost of $25 per acre. Therefore, soybean acres in Regions 1 and 2 are assumed to be treated with an insecticide, while no insecticide treatments are applied in Region 3, when treatment costs are $25 per acre. 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), Hartman (2005) reports that an average treatment cost ranges from $12 to $25 per acre. Therefore, a lower and upper bound for insecticide treatment costs are used in this study.

During the base year 2000-2002, the U.S. soybean industry produced 2,788 million bushels of soybeans, where 64 percent of domestic production was used for domestic demand

and the remainder exported, while less than 145 thousands acres were infested with soybean aphids. Producers' and domestic consumers' surpluses were estimated to be nearly $13 billion and $30 billion, respectively (Tables 4, 5, and 6). During the first five years of soybean aphid infestation, the largest economic damage occurs under Scenario 1 (assuming no insecticide treatment), where reductions in producer and consumer surpluses would annually average $23.4 million and $10.6 million, respectively, during the first five years (Table 7). Soybean production would decline on average by 7.8 million bushels annually during the same time period (Table 4). Reduction of soybean production resulting from soybean aphid infestation is primarily absorbed by a reduction in soybean exports due to a higher price elasticity of export demand than for domestic demand (Table 3).

When acres infested with soybean aphids are treated with insecticides at $12 per acre (Scenario 2), reductions in producer and consumer surpluses would annually average $12.8 million and $5.8 million, respectively, during the first five years of infestation (Table 7). Soybean production would decline on average by more than 4.2 million bushels annually during the same time period (Table 5). When costs associated with insecticide treatment increase to $25 per acre (Scenario 3), both producer and consumer losses would annually grow on average at $15.2 million and $6.6 million (Table 7), respectively, and soybean production declines on average by 5 million bushels annually during the first five years (Table 6). Economic losses to soybean growers and consumers would increase at an increasing rate as infested acreage increases.

As the intrinsic growth rate increases by 36 percent to g=0.474 (McCornack, et al. 2004), declines in soybean production are magnified approximately 59 percent, specifically to 12.4 million, 6.7 million, and 7.9 million bushels under Scenarios 1, 2, and 3, respectively (Tables 4, 5, and 6), while producer and consumer surplus losses approximately double under all three Scenarios.

Without the successful development of soybean aphid resistant varieties through germplasm and breeding in the near future, however, soybean growers will suffer greater economic losses from soybean aphid infestation in the future. Since logistic acreage infestation functions are used, small initial social costs of U.S. soybean aphid infestation during the first five years accelerate during the following second five year period (Table 7). Producer surplus losses range between $59 million per year to Scenario 2 and more than $109 million per year under Scenario 1. As the intrinsic growth rate increases from 0.349 to 0.474, producer surplus losses also increase to $190 million per year under Scenario 2 to more than $353 per year under Scenario 1. These results suggest that before soybean growers face these levels of economic losses from an invasive insect, greater efforts should be made to develop new higher-yielding varieties which are resistant to soybean aphids. For example, in 2004, scientists from USDA's Agricultural Research Service (ARS) and the University of Illinois collaborated in the discovery of a single gene, tentatively named *Rag*1, which confers resistance to soybean aphids. This development has set the stage for seed companies to breed high-yielding cultivars that should withstand soybean aphids without help from insecticides (Hartman 2005; Wang et al. 2005).

Conclusions

Soybean yields are affected quantitatively and qualitatively by soybean aphids. We estimate the economic losses resulting from soybean aphid infestation by considering soybean yield decline and increased control costs. Soybean-producing States are divided into three regions based on the distributions of *buckthorn* which is the 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, are incorporated into a dynamic equilibrium model.

We conducted simulation analyses for three scenarios. The first scenario assumed that there was 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. The third scenario assumed 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 where soybean yield declines by 12 percent, while the yield on untreated acres declines 26 percent.

Results indicate that the reduction in soybean production resulting from 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 on average grow annually at between $12.8 million and $23.4 million during the first five years of infestation. Since infested acreage increases are modeled by a logistic acreage infestation, soybean producers suffer greater economic losses as the intrinsic growth rate of infested soybean acreage with soybean aphids rises and infested acreage increases as time progresses. When the intrinsic growth rate increases from 0.349 to 0.474, producer surplus losses increase by more than 50 percent to between $25.8 million per year and $48 million per year. As time progresses to the following second five-year period, producer surplus losses increase by more than 4.5 times to between $59 million per year and $109.2 million per year under Scenarios 2 and 1, respectively. These results suggest that time is an important factor in the control of soybean aphids. However, considering the relatively small economic losses to producers during the first five years of infestation and the successful discovery of *Rag*-1, which confers resistance to soybean aphids, it is not likely warranted at this time for soybean growers or policy-makers to become too seriously alarmed. [Note: While the Rag-1 gene is not resistant, the gene induces phenotypic resistance to the soybean plant as a whole.]

Table 1. Summary statistics on soybean aphid detection and insecticide treatment acres by region,[1] 2002.

	Region 1	Region 2	Region3	Total
Insecticide treatment (acres)	281,437	136,560	116,921	534,918
Soybean aphid detection, scouting, and insecticide treatment (acres)[2]	114,178	24,683	5,866	144,727
Aphid infested acres of total insecticide treated acres (%)	40.57	18.07	5.02	27.06

[1] See Figure 1 for region designations.
[2] Source: USDA's ARMS Phase II, 2002.

Table 2. Average soybean summary statistics for the period 2000 to 2002, and price elasticities of soybean supply by region.

	Region 1	Region 2	Region3	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.)	2,011	470	309	2,790
Supply elasticity of soybeans[1]	0.298	0.198	0.221	

[1] Source: Lin et al. (July 2000). Supply elasticities of soybeans estimated during the 1970's were higher (Gardner (1976), 0.45 to 0.73; Houck, Ryan, and Subotnik (1972), 0.84), but those estimated since 1990 are relatively smaller (Meilke and Jay (1997), 0.30; Meyers, Devadoss, and Helma (1991), 0.24; Piggott, Wohlgenant, and Zering (2001), 0.12 to 0.15.

Table 3. Soybean model parameter statistics (averaged over the period 2000-2002).

Domestic demand (mil. bu.)	1,776
Export (mil. bu.)	1,012
Price ($/bu.)[1]	5.35
Price elasticity of domestic demand[2]	-0.16
Export demand elasticity[2]	-0.79
α_{s1} (supply intercept for the region 1)	1,410.32
α_{s2} (supply intercept for the region 2)	376.94
α_{s3} (supply intercept for the 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 the region 1)	111.90
β_{s2} (supply slope for the region 2)	17.39
β_{s3} (supply slope for the region 3)	12.76
β_{c} (domestic demand slope)	53.11
β_{x} (export demand slope)	149.44

[1] Season average soybean price ($/bu.) was $4.54, $4.38, and $5.53 during the years between 2000 and 2002, while soybean loan rates ($/bu.) were $5.26, $5.26, and $5.00 during the same period. Therefore, an average soybean price per bushel is estimated from $5.26 for 2000 and 2001, and $5.53 for 2002.
[2] Source: USDA's Food and Agricultural Policy Simulator (Price). According to Piggott and Wohlgenant (2002), a price elasticity of domestic demand for US soybeans is between -0.13 and -0.29, while the export demand elasticity is -0.63.

Table 4. Effects of soybean aphid infestation: Without insecticide treatment.

Year	Infested acreage			Production loss	P*	Q*s	Q*c	Q*x	ΔPS*[1]	ΔCS*[1]
	Region1	Region2	Region3							
		(acres)		(mil.bu.)	($/bu.)		(mil.bu.)		($mil.)[2]	
Base year (2002)	114,178	24,683	5,866	2.448	5.35	2,787	1,776	1,011	12,890	29,683
Intrinsic growth rate = 0.349										
2003	161,704	34,966	8,314	3.469	5.36	2,786	1,776	1,010	-11	-5
2004	228,919	49,517	11,782	4.912	5.36	2,785	1,775	1,010	-16	-7
2005	323,885	70,092	16,695	6.952	5.37	2,784	1,775	1,009	-21	-10
2006	457,871	99,155	23,652	9.833	5.38	2,782	1,775	1,008	-29	-13
2007	646,536	140,146	33,498	13.896	5.39	2,780	1,774	1,006	-40	-18
2008	911,457	197,838	47,425	19.611	5.41	2,776	1,773	1,003	-55	-25
2009	1,282,005	278,793	67,104	27.625	5.43	2,772	1,772	1,000	-75	-33
2010	1,797,472	391,920	94,873	38.816	5.46	2,765	1,770	995	-101	-45
2011	2,509,118	549,084	133,984	54.346	5.51	2,756	1,768	988	-135	-61
2012	3,481,382	765,668	188,922	75.716	5.57	2,743	1,764	979	-180	-81
Intrinsic growth rate = 0.474										
2003	183,153	39,608	9,420	3.929	5.36	2,786	1,775	1,010	-17	-7
2004	293,543	63,516	15,124	6.299	5.37	2,784	1,775	1,009	-26	-12
2005	469,814	101,748	24,274	10.088	5.38	2,782	1,775	1,008	-40	-18
2006	750,280	162,720	38,938	16.128	5.40	2,778	1,774	1,005	-62	-28
2007	1,193,988	259,536	62,408	25.708	5.42	2,773	1,772	1,001	-95	-42
2008	1,889,653	412,213	99,888	40.794	5.47	2,764	1,770	994	-144	-65
2009	2,965,083	650,386	159,528	64.275	5.54	2,750	1,766	984	-217	-98
2010	4,591,888	1,015,718	253,896	100.179	5.64	2,729	1,761	969	-320	-145
2011	6,973,690	1,561,855	401,887	153.628	5.80	2,698	1,752	945	-458	-208
2012	10,299,247	2,347,642	630,755	230.160	6.02	2,653	1,741	912	-628	-287

[1] See Appendix II.
[2] A three percent rate of discount is used.

Table 5. Effects of soybean aphid infestation: With insecticide treatment at $12 per acre.

Year	Infested acreage Region1	Infested acreage Region2	Infested acreage Region3	Production loss	P*	Q*s	Q*c	Q*x	ΔPS*[1]	ΔCS*[1]
	(acres)			(mil.bu)	($/bu.)		(mil.bu.)		($mil.)[2]	
Base year (2002)	114,178	24,683	5,866	1.328	5.35	2,787	1,776	1,011	12,887	29,688
Intrinsic growth rate=0.349										
2003	161,704	34,966	8,314	1.881	5.36	2,787	1,776	1,011	-6	-3
2004	228,919	49,517	11,782	2.664	5.36	2,786	1,776	1,011	-8	-4
2005	323,885	70,092	16,695	3.770	5.36	2,786	1,776	1,010	-12	-5
2006	457,871	99,155	23,652	5.331	5.37	2,785	1,775	1,010	-16	-7
2007	646,536	140,146	33,498	7.530	5.37	2,784	1,775	1,009	-22	-10
2008	911,457	197,838	47,425	10.623	5.38	2,782	1,774	1,007	-30	-13
2009	1,282,005	278,793	67,104	14.954	5.39	2,779	1,774	1,005	-40	-18
2010	1,797,472	391,920	94,873	20.992	5.41	2,776	1,773	1,003	-55	-24
2011	2,509,118	549,084	133,984	29.352	5.44	2,771	1,772	999	-73	-33
2012	3,481,382	765,668	188,922	40.822	5.47	2,764	1,770	994	-97	-44
Intrinsic growth rate = 0.474										
2003	183,153	39,608	9,420	2.131	5.36	2,787	1,776	1,011	-9	-4
2004	293,543	63,516	15,124	3.416	5.36	2,786	1,776	1,010	-14	-6
2005	469,814	101,748	24,274	5.469	5.37	2,785	1,775	1,010	-22	-10
2006	750,280	162,720	38,938	8.740	5.38	2,783	1,775	1,008	-33	-15
2007	1,193,988	259,536	62,408	13.922	5.39	2,780	1,774	1,006	-51	-23
2008	1,889,653	412,213	99,888	22.066	5.41	2,775	1,773	1,002	-78	-35
2009	2,965,083	650,386	159,528	34.707	5.45	2,768	1,771	997	-117	-53
2010	4,591,888	1,015,718	253,896	53.947	5.51	2,756	1,768	989	-173	-78
2011	6,973,690	1,561,855	401,887	82.389	5.59	2,740	1,763	976	-247	-111
2012	10,299,247	2,347,642	630,755	122.685	5.71	2,716	1,757	959	-337	-152

[1] See Appendix II.
[2] A three percent rate of discount is used.

Table 6. Effects of soybean aphid infestation: With insecticide treatment at $25 per acre.

Year	Infested acreage Region1	Region2	Region3	Production loss	P*	Q*s	Q*c	Q*x	ΔPS*[1,2]	ΔCS*[1,2]
	(acres)			(mil.bu)	($/bu.)		(mil.bu.)		($mil.)[3]	
Base year (2002)	114,178	24,683	5,866	1.567	5.35	2,787	1,776	1,011	12,887	29,688
Intrinsic growth rate=0.349										
2003	161,704	34,966	8,314	2.219	5.36	2,787	1,776	1,011	-7	-3
2004	228,919	49,517	11,782	3.143	5.36	2,786	1,776	1,011	-10	-4
2005	323,885	70,092	16,695	4.447	5.36	2,785	1,775	1,010	-14	-6
2006	457,871	99,155	23,652	6.289	5.37	2,784	1,775	1,009	-19	-8
2007	646,536	140,146	33,498	8.885	5.38	2,783	1,775	1,008	-26	-12
2008	911,457	197,838	47,425	12.534	5.39	2,781	1,774	1,007	-35	-16
2009	1,282,005	278,793	67,104	17.646	5.40	2,778	1,773	1,004	-48	-21
2010	1,797,472	391,920	94,873	24.773	5.42	2,773	1,772	1,001	-64	-29
2011	2,509,118	549,084	133,984	34.645	5.45	2,768	1,771	997	-86	-39
2012	3,481,382	765,668	188,922	48.192	5.49	2,760	1,769	991	-115	-52
Intrinsic growth rate = 0.474										
2003	183,153	39,608	9,420	2.514	5.36	2,786	1,776	1,011	-11	-5
2004	293,543	63,516	15,124	4.030	5.36	2,786	1,775	1,010	-16	-7
2005	469,814	101,748	24,274	6.453	5.37	2,784	1,775	1,009	-26	-11
2006	750,280	162,720	38,938	10.312	5.38	2,782	1,775	1,007	-39	-18
2007	1,193,988	259,536	62,408	16.427	5.40	2,778	1,774	1,005	-61	-27
2008	1,889,653	412,213	99,888	26.041	5.43	2,773	1,772	1,001	-92	-41
2009	2,965,083	650,386	159,528	40.969	5.47	2,764	1,770	994	-139	-62
2010	4,591,888	1,015,718	253,896	63.703	5.54	2,751	1,766	984	-204	-92
2011	6,973,690	1,561,855	401,887	97.345	5.63	2,731	1,761	970	-291	-131
2012	10,299,247	2,347,642	630,755	145.084	5.77	2,703	1,754	949	-398	-180

1 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.x14%x$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.

2 See Appendix II.

3 A three percent rate of discount is used.

Table 7. Average annual economic costs of a U.S. soybean aphid infestation during the first five-year (FFY) period and the following second five-year (SFY) periods.

	Scenario 1[1]		Scenario 2[1]		Scenario 3[1]	
	($mil.)[2]					
g = 0.349:	**FFY**	**SFY**	**FFY**	**SFY**	**FFY**	**SFY**
Annual ΔPS	-23.4	-109.2	-12.8	-59.0	-15.2	-69.6
Annual ΔCS	-10.6	-49.0	-5.8	-26.4	-6.6	-31.4
Annual (ΔCS+ΔPS)	-34.0	-158.2	-18.6	-85.4	-21.8	-101.0
g = 0.474:						
Annual ΔPS	-48.0	-353.4	-25.8	-190.4	-30.6	-224.8
Annual ΔCS	-21.4	-160.6	-11.6	-85.8	-13.6	-101.2
Annual (ΔCS+ΔPS)	-69.4	-514.0	-37.4	-276.2	-44.2	-326.0

[1] Scenario 1 assumes no insecticide treatment, Scenario 2 assumes insecticide treatment at $12 per acre, and Scenario 3 assumes insecticide treatment in Regions 1 and 2 only at $25 per acre.

[2] The rate of discount is 3 percent.

Appendix 1.

Derivation of equation (1), $\sum_{i=1}^{n}$ **[$Q_{si}(t) + A_i(t)\tilde{Y}_i(Z_i) + q_{si}(t)$] =** $\sum_{i=1}^{n}$ **[$\alpha_{si} + \beta_{si}P(t)$].**

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:

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

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

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

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

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

(A4) $TVC(Q_{si}(t)) = [- \alpha_{si} /\beta_{si}][Q_{si}(t) + A_i(t)\tilde{Y}_i(Z_i) + q_{si}(t)] + [Q_{si}(t) + A_i(t)\tilde{Y}_i(Z_i) + q_{si}(t)]^2 / 2\beta_{si}$.

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

(A5) $MC(Q_{si}(t)) = [- \alpha_{si} /\beta_{si}] + [Q_{si}(t) + A_i(t)\tilde{Y}_i(Z_i) + q_{si}(t)] / \beta_{si} = P(t)$,

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

(A6) $[Q_{si}(t) + A_i(t)\tilde{Y}_i(Z_i) + q_{si}(t)] = \alpha_{si} + \beta_{si} P(t)$.

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

(A7) $\sum_{i=1}^{n} [Q_{si}(t) + A_i(t)\tilde{Y}_i(Z_i) + q_{si}(t)] = \sum_{i=1}^{n} [\alpha_{si} + \beta_{si}P(t)]$. Q.E.D.

Appendix 2.

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

(B1) $$g_i \delta t = \frac{\delta A_i(t)}{A_i(t)[1 - A_i(t)/V_i]}$$

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

Integrating both sides from the equality in (B1) results in the following:

(B2) $$g_i t = ln\,[A_i(t)] - ln\,[1 - A_i(t)/V_i] + C$$

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

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 (B2) as follow;

(B3) $$C = -\,ln \left[\frac{A_i(t{=}0)}{(1 - A_i(t{=}0)/V_i)} \right]$$

Inserting equation (B3) into equation (B2), a solution of the first-order differential equation (8) is presented as follows:

(B4) $$A_i(t) = V_i / [1 + ((V_i / A_i(t{=}0)) - 1)\,exp(-g_i t)].$$

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