Fungicide Cost Reduction with Soybean Rust-Resistant Cultivars in Paraguay: A Supply and Demand Approach

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Abstract: Soybean rust (SBR) is one of the most serious diseases for Paraguay’s economy. To avoid excessive financial losses due to SBR, farmers utilize fungicides. Increasing fungicide costs are, therefore, becoming a threat to farmers’ incomes. Developing SBR-resistant cultivars is a possible solution to this problem. To investigate the effects of SBR-resistant cultivars on soybean farmers in Paraguay, we constructed a model for the supply and demand of soybeans considering yields, cultivated area, changes in the stock quantity of soybeans, exports of soybeans and soybean products, feed demand for soybean cake and price linkage functions. We established three scenarios: an SBR pandemic in which fungicides become ineffective (Scenario 1) and the adoption of SBR-resistant cultivars in 33% (Scenarios 2) and 75% (Scenarios 3) of cultivated areas. The estimation of these three scenarios demonstrates that SBR-resistant cultivar adoption will significantly reduce current fungicide costs for farmers by 112–253 million United States dollars (USD). The potential benefits of the widespread dissemination of SBR-resistant cultivars are also considered in terms of economic disparities and environmental risks. To establish a more sustainable agricultural industry, earlier dissemination of such cultivars is required.

Keywords: soybean rust (SBR); SBR-resistant cultivars; cost savings; fungicide application; small farmer; soybean market

1. Introduction

Soybean rust (SBR), first detected in Paraguay in 2001, is a crop disease occurring in Paraguay that has become economically significant [1]. SBR subsequently spread to Paraguay’s neighbor, Brazil [2], and by the 2003/2004 crop season, it had spread to all of Brazil, resulting in 1.22 billion United States dollars (USD) worth of grain losses and 2.08 billion USD being expended on SBR control efforts [3]. The SBR pandemic can ultimately cause yield losses of up to 80% [2]. In Paraguay, significant grain losses did not occur because of local environmental conditions [2]; however, many farmers began utilizing fungicides to address SBR-related damage to their crops [4]. For example, the number of fungicide applications has more than doubled over the last few years, and farmers fear that this trend will continue [4]. Because the main soybean-producing region in Paraguay is adjacent to southern Brazil, one of the country’s main soybean-producing regions, events in one country influence the other [5]. SBR-resistant cultivars have been developed in Latin American countries and can be used to reduce fungicide costs [6,7]. In Paraguay, 71.9% of soybean farmers are small farmers and the increasing number of fungicides required to control SBR threatens their incomes. However, these new cultivars have not spread throughout Paraguay. The 2017 adoption rate in the cultivated areas was only 1.47% [8].

As of 2020, Paraguay is the fourth-largest exporter and sixth-highest producer of soybeans in the world [9]. Soybeans are oil and protein-rich grains and that can be processed
into soybean oil and cake for use as edible oil and/or biodiesel and feed for livestock animals, respectively. In Paraguay, about 60% of the soybeans produced are exported and the remainder is crushed and exported as soybean products, with small amounts being used for domestic consumption [9]. Paraguayan soybeans contain high levels of protein, which is beneficial for producers [10]. The main destination for Paraguayan soybeans is Argentina. When environmental conditions in Argentina are not appropriate for soybean cultivation, soybeans are imported from Paraguay [10]. Argentina is the third-highest exporter of soybeans and the top exporter of soybean products. Therefore, trends in Paraguay affect the global soybean market.

Econometric approaches to forecasting soybean production and the Latin American market have been used by many researchers [6,7,11–13], although such efforts have been quite limited in regard to Paraguay. Because SBR and SBR-resistant cultivars affect the global soybean market and producers’ production costs, an econometric approach should be applied. The purpose of the present study is to investigate the effects of SBR-resistant cultivars on the soybean market and soybean production cost reduction efforts in Paraguay. To clarify these effects, we applied an econometric approach to a supply and demand model and compared farmers’ chemical costs with other main soybean producers as well as discussed the effects of introducing SBR-resistant cultivars. We also discussed the potential economic benefits for small farmers in Paraguay through a comparison with the Brazilian case.

Fungicides are used by most farmers worldwide although their use can precipitate soil and water pollution and possibly alter the aquatic biota [14]. The risks of pesticides use have historically been focused on insecticides [15–17] and less so on fungicides [14,18]. Because fungicides are generally lipophilic, they might absorb sediments as organic carbon and persist on the water surface [19,20]. Despite the risks, no academic research has been conducted examining the potential risk of environmental pollution associated with the use of pesticides to address SBR in Paraguay. Most previous research has focused on the effectiveness of agricultural fungicides in maintaining crop yields [21,22]. In the present study, the influence of SBR-resistant cultivar propagation on the environment, especially aquatic ecosystems, was evaluated in terms of fungicide use in Paraguay.

In this study, we address the following five questions:

- How much damage does SBR impose on soybean production in Paraguay?
- To what extent can SBR-resistant cultivars alleviate the soybean production problems caused by SBR-related damage?
- How much cost savings are created by the use of SBR-resistant cultivars?
- Who will benefit from the adoption of SBR-resistant cultivars?
- What are the possible effects of SBR-resistant cultivar dissemination on Paraguay’s environment?

The limitations of this research also considered and discussed in the concluding remarks.

2. Materials and Methods
2.1. Soybean Supply and Demand Model

To investigate the effects of SBR damages and the dissemination of SBR-resistant cultivars on the supply and demand for soybeans and soybean products, we used a supply and demand model based on the work of Ishikawa-Ishiwata and Furuya [6]. The supply and demand model for soybeans in Paraguay is comprised 28 structural equations and five identities, as follows.

Ten yield (Y) functions for soybeans for each of Paraguay’s 10 geographic departments all depend on time trend, T:

\[ Y_{i,t} = \alpha_{yi} + \beta_{yi}T + \epsilon_{yi,t} \]  

where \( \alpha \) and \( \beta \) are parameters, subscripts \( i \) and \( t \) represent the department and year, respectively, and \( \epsilon \) is an error term. \( T \) indicates the level of technological advancement. Thus, \( Y \) increases with \( T \).
Planted areas of soybeans in each of Paraguay’s 10 departments depend on previously planted areas and the farm price of soybeans (FP):

\[ A_{i,t} = \alpha_{ai} + \beta_{a1} A_{i,t-1} + \beta_{a2} sbRFP_{t-1} + \epsilon_{ai,t}, \quad (2) \]

where sbRFP is the real farm price of soybeans, deflated as per sbFP/(CPI/100). CPI represents the consumer price index (2010 = 100). Here, sbFP denotes the soybean farm price. If the lags of A and sbRFP increase, A is also expected to increase.

Country-level production (sbQ) is calculated by summing the production of each department:

\[ sbQ_t = \sum_i Y_{i,t} A_{i,t} , \quad (3) \]

The export function (sbEX) depends on T, sbQ, and sbRFP, as follows:

\[ sbEX_t = \alpha_e + \beta_{e1} T + \beta_{e2} sbQ_t + \beta_{e3} sbRFP_t + \epsilon_{te} . \quad (4) \]

If sbQ increases and sbRFP decreases, sbEX is expected to increase.

The stock change (sbSTC) function depends on the difference in sbQ, as follows:

\[ sbSTC_t = \alpha_s + \beta_{s1} (sbQ_t - sbQ_{t-1}) + \epsilon_{st} . \quad (5) \]

If the difference in sbQ increases, sbSTC is expected to increase.

The identity of the soybean supply is, therefore, as follows:

\[ sbPR_t = sbQ_t + sbIM_t - sbEX_t - sbSTC_t - sbFE_t , \quad (6) \]

where sbPR, sbIM, and sbFE represent the quantity of soybeans processed, imported and used as livestock feed, respectively.

The identity of the soybean processing is as follows:

\[ sbPR_t = oilQ_t + cakQ_t + LO_t , \quad (7) \]

where oilQ is the quantity of soybean oil production, cakQ is the quantity of soybean cake production, and LO denotes soybean losses from processing.

The export function of soybean oil (oilEX) depends on sbQ as follows:

\[ oilEX_t = \alpha_{oe} + \beta_{oe} sbQ_t + \epsilon_{ote} . \quad (8) \]

If sbQ increases, oilEX is expected to increase.

The stock change function for soybean oil (oilSTC) depends on the difference in oilQ as follows:

\[ oilSTC_t = \alpha_s + \beta_{s1} (oilQ_t - oilQ_{t-1}) + \epsilon_{st} . \quad (9) \]

If the difference in oilQ increases, oilSTC is expected to increase.

The export function for soybean cake (cakEX) depends on the global price of soybean cake (cakRWP) as follows:

\[ cakEX_t = \alpha_{ce} + \beta_{ce1} cakRWP_t + \epsilon_{cet} , \quad (10) \]

where cakRWP is the real-world price of soybean cake in USD per metric ton (MT), which is defined as cakWP·EXR/(CPI/100). Here, cakWP is the global soybean price in USD, represented by Brazilian pellets of 48% protein, CIF Rotterdam. EXR is guarani (PYG)–USD exchange rate; PYG is the local currency in Paraguay. If cakRWP increases, cakEX is expected to increase.

The stock change function of soybean cake (cakSTC) depends on cakQ:

\[ cakSTC_t = \alpha_s + \beta_{s1} (cakQ_t - cakQ_{t-1}) + \epsilon_{st} . \quad (11) \]
If the difference in \( cakQ \) increases, \( cakSTC \) is expected to increase. The demand function of soybean cake feed is, therefore, as follows:

\[
cakFE_t = \alpha_{cd1} T_{12} + \beta_{cd2} \text{sFRP}_t + \beta_{cd3} \text{mzRFP}_t + \beta_{cd4} \text{GDPPC}_t + \epsilon_{cdt},
\]

where \( T_{12} \) is the time trend from 2012, \( cakFE \) is the quantity of soybean cake used for feed, \( \text{mzRFP} \) is the real maize farm price, defined as \( \text{mzFP}/(\text{CPI}/100) \), and \( GDPPC \) is real gross domestic product (GDP) per capita (in PYG/person), converted to 2010 constant international dollars using purchasing power parity rates. Here, \( \text{mzFP} \) is the farm price of maize. If \( \text{sFRP} \) decreases and \( \text{mzRFP} \) increases, \( cakFE \) is expected to increase.

The identity for soybean oil is as follows:

\[
oilQ_t = oilED_t + oilEX_t + oilSTC_t - oilIM_t,
\]

where \( oilED \) and \( oilIM \) represent edible soybean oil and soybean oil imports, respectively.

The identity for soybean cake is as follows:

\[
cakQ_t = cakFE_t + cakEX_t + cakSTC_t - cakIM_t,
\]

where \( cakIM \) represents imports of soybean cake.

The price linkage function is as follows:

\[
cakWP_t = \alpha_c + \beta_c \text{sbFP}_t + \epsilon_{ct}.
\]

The farm price is the equilibrium price resulting from the intersection of the soybean demand and supply curves.

In Figure 1, the supply and demand model for soybeans in Paraguay is illustrated in a flowchart. Total production is the aggregate of the production of all of Paraguay’s 10 departments. The supply of soybeans is influenced by total production, stock changes, feed, exports, and imports of soybeans. Soybean processing is divided into the production of soybean oil and cake. The supply of soybean oil is influenced by exports, imports, and stock changes in soybean oil quantity. The demand for soybean oil is represented by the quantity of edible soybean oil produced. Soybean cake production is influenced by exports, imports, and stock changes of soybean cake. Soybean cake demand is influenced by the domestic maize farm price and the global price of soybean cake. When supply and demand are at equilibrium, farm prices can be estimated. The price of soybean cake is connected to the soybean farm price by the price linkage function. The farm price influences the next year’s supply vis-à-vis the planted area function. The quantity of soybean imports, soybean-related products such as soybean edible oil, soybean feed, the domestic farm price of maize, population, and GDP are exogenous variables. Two-stage least squares (2SLS) regressions were used to measure each function.

2.2. Data

Department-based production is shown in Figure 2. The departmental levels of \( Y_i \) and \( A_i \) for soybeans in Paraguay were obtained from the Paraguayan Grain and Oilseed Merchandizers and Exporters Association (CAPECO) [23]. The following data for the whole country were obtained from the Food and Agriculture Organization Statistical Database (FAO-STAT) [24]: \( Y, A, \text{sbFP}, \text{sbEX}, \text{sbSTC}, \text{sbFE}, \text{sblM}, \text{sbQ}, \text{sbPR}, \text{oilQ}, \text{oilEX}, \text{oilIM}, \text{oilSTC}, \text{oilED}, \text{cakQ}, \text{cakEX}, \text{cakFE}, \text{cakIM}, \text{cakSTC}, \text{mzFP}, \text{GDP}, \text{and POP} \). The data for CPI, EXR, and \( cakWP \) were obtained from the World Bank (WB) [25].
Hayes have been developed, they have been digested were obtained from the Paraguayan Grain and Oilseed. We adopted the actual case of new cultivars because breeders have developed cultivars to maintain similar yields [6].

The yield of SBR-resistant cultivars was assumed to be the same as for conventional cultivars [28]. The new cultivars will expand starting in 2017 [23]. If the production is less than 1000 MT, then the quantity is not shown.

Figure 2. Soybean production (in millions of metric ton, MT) in each department of Paraguay as of 2017 [23]. If the production is less than 1000 MT, then the quantity is not shown.

Figure 1. Flowchart illustrating the econometric supply and demand model for soybeans in Paraguay. Legend: SB = soybean; SBR = soybean rust; MZ = maize.
2.3. Scenario Setting

Three scenarios were set to simulate the effects of SBR-resistant cultivars on soybean production (Table 1). The base scenario represents the current situation. In Scenario 1, fungicide efficacy declines and the SBR pandemic gradually depresses soybean production in Paraguay. Scenarios 2 and 3 represent cases in which SBR-resistant cultivars are introduced and disseminated in Paraguay. In Scenario 2, the dissemination in planted areas is 33%, whereas in Scenario 3, it is 75%. The detailed scenario settings are as follows.

Table 1. Scenario setting.

| Setting                | Assumptions                                                                 |
|------------------------|-----------------------------------------------------------------------------|
| Baseline               | Continuation of the current situation                                      | The outlook starting in 2021. |
| Scenario 1 (Loss)      | Soybean production declines in Paraguay                                     | Fungicide efficacy gradually declines and 8.49% of production in Paraguay will be lost. |
| Scenario 2 (Cultivar 33%) | SBR-resistant cultivars are disseminated                                   | SBR-resistant cultivars will be adopted in up to 33% of the cultivated areas in Paraguay. |
| Scenario 3 (Cultivar 75%) | SBR-resistant cultivars are disseminated                                   | SBR-resistant cultivar will be adopted in up to 75% of the cultivated areas in Paraguay. |

Legend: SBR = soybean rust.

For the SBR pandemic scenario (Scenario 1), we assumed that fungicides become ineffective because their efficacy is decreasing year by year [26]. The percentage of production losses refers to the case of Brazil [3] because actual losses are unclear in Paraguay. For the damage (Scenario 1) and cultivar adoption scenarios (Scenarios 2 and 3), we refer to the technological dissemination model of Ishikawa-Ishiwata and Furuya [6,7] based on Griliches [27]. The cultivar dissemination scenarios adopted the actual case of new cultivars that had been disseminated in Paraguay [28]. The new cultivars will expand starting in 2025 because of the lag time between technology being developed and dissemination by farmers [29]. As of 2017, the adoption area for SBR-resistant cultivars in Paraguay was only 1.47% [8]. To set the disseminated planted area of SBR-resistant cultivars, we assumed that there will be adoption rates of 33% or 75% by 2029 for Scenarios 2 and 3, respectively. In Paraguay, when new cultivars have been developed, they have been adopted in one-third (33.3%) of the total soybean cultivation area [28]. The main cultivars are herbicide-resistant, Roundup Ready (RR) and about 75% of them have been used in Paraguay [5]. In the case of a RR SBR-resistant cultivar, it is assumed to have a 75% adoption rate. By subtracting the cultivation area of SBR-resistant cultivars from the soybean planted area, the total planted area of conventional cultivars was estimated for each department. The yield of SBR-resistant cultivars was assumed to be the same as for conventional cultivars because breeders have developed cultivars to maintain similar yields [6].

3. Results

3.1. Baseline Analysis

The estimation period was 1970–2017 for all of Paraguay. For departmental yields and area, data were limited to the 2008–2017 period. To estimate the model, the following assumptions were set: (1) the CPI growth is equal to the annual average growth between 2011 and 2018, (2) the population growth is given by the annual average growth between 2016 and 2018, (3) the real GDP growth is provided by the annual average between 2015 and 2017, (4) the time trends of the yield functions flatten during the simulation period, except in the Misiones Department, and (5) the base year for simulations of sbEX, STC, oilEX, oilSTC, cakFE, cakEX, and cakSTC is 2020 and the base year for simulations of Y and A for each department is 2017. The outlook period expands from the base year through 2040.

Table 2 indicates the elasticity of the cultivated area in each department of Paraguay. The supply and demand model accounts for farmer behavior, which depends on the previous year’s farm price of soybeans. The planted area will increase when the previous
year’s farm price rises, but the reaction to the farm price will differ between the various departments. Because the average yield in each department in 2017 exceeded 3.0 MT/ha and might not increase much further and the planted area in Paraguay cannot expand [4], production in Paraguay will not significantly increase by 2040. Figure 3 illustrates the baseline outlook for all of Paraguay and the main producing regions: Alto Paraná, Itapúa, and Caaguazú. The planted area in the main producing regions cannot expand because they are already at the maximum and other potential areas such as the Chaco region are not suitable for soybean cultivation due to extremely hot temperatures, intense competition with the livestock sector and the lack of infrastructure [4,10]. Thus, production will not increase markedly and will stabilize at approximately 2.67, 1.96, 1.39, and 9.88 million MT in Alto Paraná, Itapúa, Caaguazú, and all of Paraguay, respectively, by 2040.

Table 2. Elasticity of the lagged real farm price of soybeans (sbRFP<sub>t−1</sub>) and the adjusted coefficients of determination (Adj. r^2) in the area function for each department in Paraguay.

| Department       | sbRFP<sub>t−1</sub> | Adj. r^2 |
|------------------|---------------------|----------|
| North            |                     |          |
| Concepción       | 0.234               | 0.904    |
| San Pedro        | 0.009               | 0.908    |
| Amambay          | 0.065               | 0.860    |
| East Central     |                     |          |
| Guairá           | 0.441               | 0.692    |
| Caaguazú         | 0.220               | 0.959    |
| Caazapá          | 0.208               | 0.654    |
| South            |                     |          |
| Itapúa           | 0.300               | 0.905    |
| South Central    |                     |          |
| Misiones         | 0.038               | 0.661    |
| East             |                     |          |
| Canindeyú        | 0.101               | 0.987    |
| Alto Paraná      | 0.022               | 0.679    |

Over half (60.8%) of the soybeans produced in Paraguay was exported as grain and 38.2% was processed as of 2020 [9]. Oil is extracted from processed soybeans and is exported, leaving the residue known as soybean cake. In Paraguay, domestic consumption of soybean cake as stock feed is relatively small; 17.8% of it was used for feed as of 2020 [9]. Figure 4 shows the simulation results for exports of soybeans and soybean products. In 2013, exports of soybean products increased sharply (Figure 4) due to three main reasons [30]. First, the crushing company using Paraguayan soybeans improved their infrastructure by means of adding large crushing plants and grain terminals. Second, a new law allowed public–private alliances, which enabled the expansion and improvement of the public infrastructure. Third, the Paraguayan government eliminated the 10% export tax on soybeans and replaced it with a value-added tax (5%) on all agricultural products. Thus, exports of soybeans, oil, and cake will stabilize at approximately 6.07, 0.71, and 2.55 million MT, respectively, by 2040.
Figure 3. Baseline outlook on soybean production in (a) Alto Paraná, (b) Itapúa, (c) Caaguazú, and (d) all of Paraguay.

Figure 4. Baseline outlook on (a) soybean exports, (b) soybean oil exports, and (c) soybean cake exports in Paraguay.
3.2. Simulation Analysis

Figure 5 illustrates the estimates for soybean production in Alto Paraná, Itapúa, Caaguazú, and all of Paraguay. If fungicide efficacy declines and SBR becomes pandemic, soybean production will decrease significantly (Scenario 1), assuming that the damage caused by SBR is the same as in Brazil [6]. When SBR-resistant cultivars are introduced and disseminated throughout the country, production will recover to some extent, assuming that cultivars are disseminated in 33% and 75% of the total planted area (Figure 5).

![Graphs illustrating soybean production](image)

**Figure 5.** Outlook on soybean production in (a) Alto Paraná, (b) Itapúa, (c) Caaguazú, and (d) all of Paraguay under the three scenarios.

4. Discussion

To what extent can the SBR-resistant cultivars alleviate chemical costs? Table 3 indicates the chemical costs for conventional and SBR-resistant cultivars in Paraguay, which were between 29% and 33% as of 1999 [31] but reached 50% by 2018 (Table 3). However, chemical costs in Paraguay were significantly higher than those of the other main soybean producers (Table 4). The chemical cost data exhibited in Table 3 were provided by the Pirapó cooperative, which is in Itapúa’s main producing district, and does not represent a national average. Based on a cross-section of various producers, soybean production costs totaled 590 USD per hectare (ha) [32]. The ratio of chemical cost to total production cost may differ. Nevertheless, the fourth-highest soybean exporter and sixth-highest soybean producer worldwide, reducing chemical costs could represent a competitive advantage for Paraguay in the global soybean market. To estimate the effect of SBR-resistant cultivars on production costs in Paraguay, cost savings were estimated when these cultivars are disseminated throughout Paraguay based on the scenario outlook (Table 5). Adopting SBR-resistant rather than conventional cultivars could enable 112.3–252.6 million USD in fungicide cost savings in Paraguay.
### Table 3. Chemical costs (in USD/ha) in Pirapó, Itapúa in 2018.

|                      | Conventional Cultivar | SBR-Resistant Cultivar |
|----------------------|-----------------------|------------------------|
| Herbicides           | 13.7                  | 11.3                   |
| Insecticides         | 38.9                  | 8.0                    |
| Fungicides           | 146.0                 | 55.8                   |
| Chemical costs total | 198.6                 | 75.0                   |
| Other costs          | 198.7                 | 168.1                  |
| Total costs          | 397.3                 | 243.1                  |

Source: the data were provided by the Pirapó Cooperative. Legend: USD = United States dollars.

### Table 4. Comparison of soybean chemical costs.

|                      | United States | Brazil | Argentina |
|----------------------|---------------|--------|-----------|
| Chemical costs       | 17.0          | 46.9   | 28.6      |
| (USD/ha)             |               |        |           |
| Chemical costs (% of | 4.7           | 14.5   | 8.8       |
| total costs)         |               |        |           |
| Other costs (USD/ha) | 347.1         | 277.4  | 294.3     |
| Total costs (USD/ha) | 364.1         | 324.3  | 322.9     |

Source: Meade et al. [34]. Legend: ha = hectare.

In Paraguay, 71.9% of soybean farmers are small farmers (i.e., cultivating less than 50 ha of land) and the average farm size is 7.8 ha [33]. On a small farmer basis, cost savings would be between 396.9 USD (33% dissemination) and 902.1 USD (75% dissemination), corresponding to between 3.3% and 8.9% reductions in costs (Table 6). The increasing number of spraying applications has become a burden on farmers. Therefore, disseminating SBR-resistant cultivars could mitigate this burden, especially for small farmers.

### Table 5. Cost savings due to the adoption of soybean rust (SBR)-resistant cultivars in the main soybean-producing departments and all of Paraguay.

|                      | Alto Paraná | Itapúa | Caaguazú | Paraguay |
|----------------------|-------------|--------|-----------|----------|
| Planted area (millions of ha) | 0.906      | 0.540  | 0.413     | 3.734    |
| Total cost of fungicide application in Scenario 1 (conventional cultivar) (millions of USD) | 132.3      | 78.9   | 60.3      | 545.1    |
| Total cost of fungicide application in Scenario 2 (33% dissemination) (millions of USD) | 105.0      | 62.7   | 47.9      | 432.8    |
| Total cost of fungicide application in Scenario 3 (75% dissemination) (millions of USD) | 71.0       | 42.3   | 32.4      | 292.5    |
| Cost savings (Scenario 1–Scenario 2) (millions of USD) | 27.2       | 16.2   | 12.4      | 112.3    |
| Cost savings (Scenario 1–Scenario 3) (millions of USD) | 61.3       | 36.6   | 27.9      | 252.6    |

Note: fungicide application costs were assumed to be the same as those in Table 3.

What can be inferred from the fungicide reduction afforded by the introduction of these cultivars? There is a significant difference in not only the planted area according to country area but also in farm size between Paraguay and Brazil. Approximately, 72% of farmers’ cultivation areas are smaller than 50 ha in Paraguay [33], while only 7.1% of all farmers are peasants (i.e., have farms smaller than 10 ha) in the central western region, which included the highest-ranked producer state, Mato Grosso, Brazil, in 2008 [35]. The cost savings of SBR-resistant cultivar adoption for a 60.9% dissemination rate in the planted area can be estimated at 1.28 billion USD for all of Brazil in 2030 [6]. In spite of the huge amount of cost savings in Brazil, the benefit of the cost reduction might trigger the development of an economic disparity between farmers, since typical soybean farm size is 1300 ha in Mato Grosso, according to Osaki and Batalha [36]. If small farmers in Paraguay adopt SBR-resistant cultivates and thereby reduce their production costs, the cost savings...
benefits will extend to many farmers. From this perspective, spreading these cultivars has the potential to improve many farmers’ profits in Paraguay.

Table 6. Cost savings for small farmers (with farms smaller than 50 ha) in Paraguay.

|                                           | 33% Dissemination | 75% Dissemination |
|-------------------------------------------|-------------------|-------------------|
| Fungicide application costs for conventional cultivars (USD) | 1138.8            | 1138.8            |
| Fungicide application costs for SBR-resistant cultivars (USD) | 904.5             | 611.1             |
| Total cost of conventional cultivars (USD) | 3098.9            | 3098.9            |
| Total cost of SBR-resistant cultivars (USD) | 2702.0            | 2196.9            |
| Cost savings (USD)                         | 396.9             | 902.1             |
| Fungicide costs/total costs for conventional cultivars (%) | 36.7              | 36.7              |
| Fungicide costs/total costs for SBR-resistant cultivars (%) | 33.5              | 27.8              |
| Cost savings (%)                           | 3.3               | 8.9               |

Note: fungicide application costs were assumed to be the same as in Table 3.

In terms of the limitations of this research, several issues should be considered. Since the yield data on SBR-resistant cultivars in Paraguay is unavailable, in the present study, we assumed that the yield of such cultivars is the same as conventional cultivars. Therefore, our estimations for SBR-resistant cultivars might differ from the real-world situation. Other possible soybean diseases such as charcoal rot should also be examined [37,38]. Like SBR, charcoal rot, which is caused by the fungus *Macrophomina phaseolina* [39], impacts Paraguay economically. To cope with charcoal rot, fungicides are applied. Nonetheless, fungicide use to address charcoal rot was not considered in the present study. For this reason, our estimation for fungicide usage might be underestimated to some extent. In general, cultivars have been developed with resistant characteristics to accommodate not only one disease. For example, SBR-resistant cultivar TMG 7262 Inox is tolerant to several diseases [40]. Thus, the present study’s estimations cover other diseases. Because charcoal rot is also an economic threat to Paraguayan soybean production and might not be included in SBR-resistant cultivars, fungicide application for this disease should be considered in future research.

Using pesticides has polluted the soil and aquatic ecosystems as well as decreased water quality in Paraguay [41]. However, most previous reports have analyzed insecticides [15–17] rather than fungicides, e.g., [14]. Because most fungicides are lipophilic and therefore highly mobile in the soil and water matrix as well as persistent in water, they have polluted the soil, decreased water quality, and negatively affected organisms in aquatic environments globally [14]. While laboratory-based research has been conducted to investigate the risks to organisms, Ochoa-Acuña et al. [42] demonstrated that the SBR fungicides might affect microorganisms such as algae and zooplankton in the midwestern United States. In Table 7, the fungicides used for soybean cultivation in Paraguay and the organisms that can be affected by them are listed. There have been reports that fungicides have polluted the environment of Paraguay, although the fungicide groups that have been used in Paraguay should be detected in the environment. The most toxic fungicide used in Paraguay is tebuconazole, which inhibits the respiration and photosynthesis of plankton communities at a low concentration, 2 µg L⁻¹ [43]. Azoxyystrobin also has negative effects at the lower concentration of 3.3 µg L⁻¹ and can trigger changes in zooplankton population composition [44]. Due to the fact that the half-lives of those fungicides are similar to other pesticides [14], the increasing application of such fungicides to address SBR will seriously influence Paraguay’s environment. Therefore, adopting SBR-resistant cultivars can lessen the negative influence of fungicides in addition to providing cost savings. Due to the lack of reports on environmental risk based on field surveys in Paraguay, additional research will be needed in the future.
Table 7. Fungicides that have been used in Paraguay and possible organisms influenced by them. The cross mark indicates the group of fungicides that have been used.

| Active Ingredient | Chemical Group | Miles et al. [21] | Present Study * | Organism |
|-------------------|----------------|-------------------|-----------------|----------|
| Azoxystrobin      | Strobilurin    | ×                 | ×               | Microorganisms, macrophytes, invertebrates, vertebrates [14,19] |
| Boscalid          | Carboxiamide   | ×                 |                 | Microorganisms, invertebrates, vertebrates [19] |
| Chlorothalonil    | Chlorothalonil | ×                 |                 | Microorganisms, macrophytes, invertebrates, vertebrates [14] |
| Cyproconazole     | Triazole       | ×                 | ×               | Vertebrates [14] |
| Difenconazole     | Triazole       | ×                 |                 | Microorganisms [42] |
| Mancozeb          | Dithiocarbamate| ×                 | ×               | Vertebrates [14] |
| Myclobutanil      | Triazole       | ×                 |                 | Microorganisms, invertebrates, vertebrates [19] |
| Picoxystrobin     | Strobilurin    | ×                 |                 | Microorganisms, invertebrates, vertebrates [19] |
| Propiconazole     | Triazole       | ×                 |                 | Microorganisms [42] |
| Prothioconazole   | Triazole       | ×                 |                 | Microorganisms, invertebrates, vertebrates [14] |
| Pyraclostrobin    | Strobilurin    | ×                 |                 | Microorganisms, invertebrates, vertebrates [19] |
| Solatenol         | SDHI †         |                    | ×               | Microorganisms [42] |
| Tebuconazole      | Triazole       | ×                 |                 | Microorganisms [42] |
| Tetraconazole     | Triazole       | ×                 |                 | Microorganisms [42] |
| Thiamethoxam      | Neonicotinoid  | ×                 |                 | Vertebrates [14] |
| Trifloxystrobin   | Triazole       | ×                 |                 | Vertebrates [14] |

Note: * fungicide data were provided by the Pirapó Cooperative. SDHI †: succinate dehydrogenase inhibitor.

5. Conclusions

The number of fungicide applications has been increasing due to the SBR threat in Paraguay. We investigated the effect of SBR-resistant cultivars on cost savings for Paraguayan farmers using a supply and demand model. We estimated the production in three scenarios in which SBR is pandemic and fungicide efficacy declines: SBR-resistant cultivars are introduced and disseminated throughout Paraguay (Scenario 1), and 33% (Scenario 2) and 75% (Scenario 3) of the cultivated area adopts SBR-resistant cultivars. The baseline scenario is the continuation of the current situation.

For the baseline estimation, the production of soybeans in Paraguay will not increase by much because both yields and planted areas do not increase and will be stable at approximately 2.67, 1.96, 1.39, and 9.88 million MT in Alto Paraná, Itapúa, Caaguazú, and all of Paraguay, respectively. If SBR spreads throughout Paraguay and fungicides are not used or effective, then production will decline significantly. The negative effects of this situation could be addressed using SBR-resistant cultivars. Disseminating SBR-resistant cultivars could result in fungicide cost savings of 27.2–61.3, 16.2–36.6, 12.4–27.9, and 112.3–252.6 millions of USD in Alto Paraná, Itapúa, Caaguazú, and all of Paraguay, respectively. This would also help to reduce farmers’ financial burdens. In terms of the possible limitations of the present study, the following issues should be tackled. First, the actual yield data for SBR-resistant cultivars that are unclear might possibly alter our estimations. Second, other diseases such as charcoal rot should be considered due to their economic importance. To cope with such issues, the actual yield data for these cultivars and the effects of fungicides on charcoal rot should be considered in future research.

In addition to lessening farmers’ financial burden, adopting SBR-resistant cultivars might reduce environmental pollution to areas such as aquatic biota. However, research investigating the effects of fungicides on Paraguay’s environment has not yet been conducted. Further research is needed to demonstrate the reduction in the environmental load of SBR-resistant cultivars in situ. The present research demonstrated the cost savings afforded by the dissemination of SBR-resistant cultivars and estimated the resulting reduction in environmental pollution in Paraguay. The adoption of such cultivars is required to develop sustainable agriculture in Paraguay and establish a stable global market for soybeans.
Author Contributions: Conceptualization, Y.I.-I.; methodology, Y.I.-I.; software, Y.I.-I.; formal analysis, Y.I.-I.; investigation, J.F.; writing—original draft preparation, Y.I.-I.; writing—review and editing, Y.I.-I.; visualization, Y.I.-I.; supervision, J.F.; All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Acknowledgments: We would like to thank Wataru Ohishi at the University of Tsukuba for the useful suggestions regarding the cost analysis.

Conflicts of Interest: The authors declare no conflict of interest.

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