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Determinants of the adoption of biological control of the *Diaphorina citri* by citrus growers in São Paulo State, Brazil

RESEARCH ARTICLE

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Abstract

This study evaluates the adoption of biological control of the *Diaphorina citri* and the citrus growers' willingness to pay for biopesticides. The citrus greening continues to spread over Brazilian orchards, reaching 17.89% of all citrus trees in 2015. Utilizing data from a survey with decision-making agents from the sector, this paper used a logit model to obtain the determinants and a contingent valuation method to elicit growers' willingness to pay for a biopesticide. Results showed high acceptability of growers to the biocontrol. Important factors regarding its adoption included experience in growing citrus, a high level of education and dependence on citrus production. Producers from São Paulo's southern region paid the highest value for the biopesticide. We observed that worsening of the disease has led players from citrus chain to search for new forms of insect control.

Keywords: biological control, greening, willingness to adopt, contingent valuation, citrus
JEL code: Q15, Q51

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1. Introduction

This study aims to evaluate key factors regarding the adoption of biological controls for the *Diaphorina citri* vector insect of the bacterial disease Huanglongbing (HLB), known as Citrus Greening, as well as potential barriers to its adoption in the Brazilian state of São Paulo, the world's largest orange grower.

Worldwide, pests and diseases cause damage significant enough to compromise the economic viability and sustainability of citrus production, including orange juice. The HLB, or Citrus Greening, illustrates this situation, because this disease was responsible for declines in the citrus industry in several Asian and African countries (Bové, 2006; Gottwald, 2007).

HLB now causes serious economic losses in Brazil and in the US, the two major producing countries of orange and orange juice in the world. In the US, the disease was first reported in Florida in 2005, where it caused loss of more than 50% of the citrus production in 2014-15, compared to 2004-05 (USDA, 2017). This problem was related to a control strategy adopted by Florida citrus growers, who did not eradicate HLB symptomatic plants, instead improved their nutrition to increase trees productivity. However, this citrus greening control strategy did not limit the spread of the disease. In 2015, 10 years after the first symptoms, more than 70% of citrus trees in Florida were contaminated (Browning, 2015; Trejo-Pech *et al.*, 2018).

In Brazil, the citrus greening disease was found in São Paulo state in 2004 (Coletta-Filho *et al.*, 2004; Carmo Teixeira *et al.*, 2005). In 2005, it appeared in Minas Gerais, and in 2007 in the state of Paraná. In 2015, a Fundecitrus (Fund for Citrus Protection) survey showed an increase of more than 159% in the incidence rate of HLB in the São Paulo citrus groves and also in various municipalities of the Triângulo Mineiro region (Minas Gerais state), compared to the 2012 incidence levels. Fundecitrus estimates that infected plants reached 17.89% of the total crop in these regions. The same survey estimated a total of 35 million diseased plants, of which 44% had severe symptoms, causing a production loss close to 50% in infected trees, because of smaller fruit and premature fruit drop (Fundecitrus, 2015a).

Brazil is the world's most important orange producer, accounting for, respectively, 33 and 54% of the world's production of oranges and orange juice in the 2014-15 crop (USDA, 2017). Data from the Brazilian institute of geography and statistics (IBGE, 2017) showed that in 2014, Brazilian production reached 363 million boxes, and the harvested area was 648 thousand hectares.

São Paulo state is the main citrus producer in Brazil, accounting for 72.6% of the national production in 2014 (IBGE, 2017). Most of this production is exported as orange juice to Europe and US, accounting for an average of approximately USD $2.1 billion in exports between 2012 and 2014 (BRASIL, 2017).

Over the last years, HLB has spread quickly in São Paulo state and caused an increase in the number of chemical sprays used to control its vector, impacting the costs of production. Even so, the incidence of the disease has been increasing. So far, there is no effective method to control HLB, and the efforts are focused to limit its dissemination. Besides the economic aspects, the intensification of chemical spraying raises more environmental and public health concerns for society. In this scope, biological control seems to be a good alternative to combine with the traditional methods and to include in the regional management toolset, recommended by experts in plant health, as explained below. The intensification of the bioproducts' usage in food production reduces the risks of contamination to the human health as well as the environmental damages (Sigsgaard *et al.*, 2011).

Due to the seriousness of the infestation problem and considering that chemical insecticides are currently the main way to control the vector insect *D. citri*, we aim to evaluate the willingness of citrus growers and managers to adopt and pay for a new biological product (a biopesticide or a bioproduct) to control *D. citri* population. To this end, we used a questionnaire based on stated preference method, seeking to identify the socio-economic and demographic profile of citrus growers and managers, as well as management and control strategies adopted to fight against *D. citri*. The questionnaire also investigated growers' perceptions about biological pest control, notably the main barriers and drivers for its adoption. Moreover, we used a contingent valuation method to elicit growers' willingness to pay (WTP) for the biopesticide.

Our hypothesis is that growers' willingness to replace chemicals with biopesticides and to pay for bioproducts is influenced by socio-economic and demographic factors. It is expected to find positive effects of school years and the years of experience in citrus production on the willingness to adopt biological controls, because these factors would provide more knowledge and better understanding about their intangible benefits. It is also expected that the economic dependence on citrus crop could affect positively the bioproduct adoption, once the fact that the growers' income relies solely on citrus production should make them more concerned about the damages of the disease compared to growers who diversify their agricultural activities. Additionally, regions differ in terms of farm features and disease incidence levels which can affect the acceptance of the biopesticide and its WTP.

This paper is comprised of four sections, plus this introduction. Section 2 traces the historical evolution of HLB in Brazil and its effects on citrus orchards, as well as management practices applied for disease and *D. citri* control. Section 3 summarizes the methodology and data collection. Section 4 contains results and discussion, and Section 5 provides conclusions.

2. Huanglongbing history and management in Brazil

The Brazilian citrus industry is of great economic importance for the state of São Paulo, which is facing rising rates of HLB-infected trees. In 2012, the percentage of diseased plants in the field (the incidence rate) was 6.9%, and researchers from Fundecitrus estimated that at least one infected plant could be found in 64% of citrus groves in that year (Fundecitrus, 2012). In 2015, a new survey showed a 159% increase in the HLB incidence rate in these citrus groves, with 17.89% of all plants infected (Fundecitrus, 2015b).

HLB is the major citrus disease for which no curative treatment or resistant varieties exist. When contaminated, young plants may not produce fruit, and adult plants become unproductive within two to five years. Bassanezi and Bassanezi (2008) and Belasque *et al.* (2010b) state that regular inspections aimed at the detection of infected plants and their eradication are a more effective way to keep the disease under control. In addition, to control the population of the insect *D. citri*, chemical insecticides are frequently sprayed on Brazilian citrus orchards.

Data from the Coordination of Agricultural Defense of the São Paulo State (CDA, 2017) showed that between 2005 and 2016, growers lost more than 51 million citrus trees due to HLB, only from 2012 to 2015 the number of productive farms declining by 30%, from 16,329 to 11,561. Additionally, in the crop year 2011/12, the Brazilian citrus sector faced one of the worst economic crises in its history, in 2012 Brazil harvested the largest citrus crop in 12 years (IBGE, 2017), so in addition to the disease damages, which increased the costs of production, low prices worsened the situation for the citrus growers (Palmieri *et al.*, 2016).

This disease affects several citrus species, including sweet oranges, mandarins, pomelos, and limes as well as other related species, such as Myrtle (*Murrayaexotica*). Once a plant is infected, its productivity decreases rapidly. Fruits are deformed, they drop prematurely, and are of poor quality before processing and consumption. High populations of the vector insect *D. citri* and its great mobility have stimulated a rapid spread of HLB within and between orchards (Bassanezi *et al.*, 2010).

Brazilian growers have to follow normative instruction no. 53/2008 of the Ministry of Agriculture, Livestock, and Supply (MAPA), to inspect and remove symptomatic plants from orchards for disease control. The inspections should occur every three months, and the results should be reported to the CDA, through semester reports (the greening report). This legislation requires that orchards whose infestation of symptomatic plants is greater than 28% be completely eliminated. However, this regulation has not been effectively enforced, which can be seen by statistics reported by Fundecitrus (Fundecitrus, 2015a).

Chemical control of *D. citri* is the main strategy adopted by growers in Brazil. The availability of equipment and insecticides already used to control other pests and vectors of citrus diseases favors chemical use (Bassanezi *et al.*, 2013a,b). Some producers spray insecticides more than 40 times during a crop year in attempts to limit economic losses caused by this pest.

Besides impacting the citrus production costs, this considerable increase in the use of agrochemicals also affects negatively the environment, by potentially contaminating water resources, reducing the populations of other organisms, increasing pest resistance, and posing health risks to workers who have direct contact with these products. Recent studies have shown that despite frequent applications of insecticides in isolated orchards, HLB control has not been successful, especially when the area under control is relatively small and there are symptomatic plants and infectious insects in surrounding areas (Belasque *et al.*, 2010a; Bassanezi *et al.*, 2013b).

In Brazil, researchers from public and private institutions have developed strategies to fight against *D. citri* through integrated pest management (IPM), which uses biological control in addition to chemical products. Biological control is a natural phenomenon, consisting of regulating the number of plants and animals by using natural enemies. One alternative to biological control of *D. citri* in citrus orchards is the parasitoid *Tamarixia radiata*, organisms found naturally in the field that can survive in organic acreages or in areas with low levels of chemical use. There is also the option of using new products, developed by Brazilian researchers and based on entomopathogenic fungi, such as *Isaria fumosorosea* and *Beauveria bassiana* (Fundecitrus, 2015a). The effectiveness of these new pesticides has been proven by Ausique *et al.* (2017).

This research evaluates citrus growers' acceptance of the new biopesticide based on entomopathogenic fungi. In this context, it is essential to examine their willingness to adopt this biopesticide to control *D. citri*, determining the main factors likely to affect their decisions. There is a scarce literature in Brazil regarding the socioeconomic aspects of biopesticides adoption, which makes this paper a relevant contribution.

3. Methods

Due to the importance of reducing the use of agrochemicals, in this study, we developed a questionnaire to identify relevant factors relating to growers' attitudes about the adoption of the biological agent (biopesticide) to combat the *D. citri*. The questionnaire assesses growers' perceptions about biological control and their willingness to adopt, a new technology (Barham *et al.*, 2015; Kallas *et al.*, 2010; Ochieng and Hobbs, 2017; Tian and Li, 2012).

In the questionnaire, biological control was the only option presented to respondents as an alternative to the current management practice of applying insecticides. This type of experiment, known as the Contingent Valuation Method (CVM), is widely used to assess public goods and environmental impacts (Arrow *et al.*, 1993; Ross, 2001). This method asks respondents to declare directly the maximum values for which they are willing to pay (stated preference method), rather than deducting these values from actual choices. Recent works that used contingent valuation in agricultural markets include those by Kpadé *et al.* (2017), Parcell *et al.* (2010), and Voltaire *et al.* (2017).

3.1 Data collection

Field research, which was limited to São Paulo state, took place from June, 2014, to May, 2015. Although a higher number of people were interviewed, the final sample comprised 74 agents, once it was considered only those involved with the citrus production in São Paulo state. Respondents comprised citrus producers, consultants, and managers of large companies and cooperatives, who are responsible for farm management and practices. We conducted face-to-face interviews at citrus farms and during the 2015 Citrus Week, the industry's main meeting in São Paulo state. The sampling was nonrandom, although it allowed to represent a great share of citrus production in São Paulo state. The sampled area has approximately 80,000 ha of citrus cultivated in São Paulo (20% of the total area harvested in the state), equivalent to roughly 59.5 million boxes, or 23% of the production in the state. The large number of citrus orchards, the distance between them and consequently the time and cost of visiting a numerous number of farms limited the choice of sampling.

During Citrus Week, we interviewed producers and managers from all citrus regions in São Paulo state, as well as others in Paraná and Minas Gerais. The questionnaires covered more than 74 municipalities in São Paulo because some respondents owned and/or managed more than one farm. The municipalities were grouped into five regions according to Fundecitrus: north, northwest, center, south, and southwest (Figure 1).

The five regions surveyed by Fundecitrus in 2015 contained 11,561 farms, spread over 320 municipalities producing citrus (orange) in São Paulo state (Fundecitrus, 2015b). According to this survey (Fundecitrus, 2015b), roughly 86,2% of the orchards in São Paulo state were small, less than 50 ha, 11,8% were between 51 and 500 ha, and only 2.02% were larger than 500 ha. Additionally, the survey showed that medium and large orchards (more than 50 ha), accounted for 13,8% of the farms in Sao Paulo state and represented more than 81% of the area harvested. It is important to mention that the sample reflects the profile of the sector, since the area harvested sampled represents 20% of the total harvested area, and the farms sampled account for almost 1% of the properties of the state.

Table 1 compares the relative importance of the sampled regions in terms of area harvested and number of farms, and their presence in our survey's data and from Fundecitrus (2015b). Our research covers all producing regions and, in general, the area surveyed in each region was similar to that for all of São Paulo.

The questionnaire had five sections. The first described the characteristics of growers or farm managers (the decision-makers regarding pest management practices). The second identified a farm's profile. The third aimed to obtain the orchards' characteristic, pest management practices and the control strategy for *D. citri*. The fourth evaluated growers' willingness to adopt and pay for bioproducts. Finally, the fifth section examined market conditions for citrus.

We used a bidding game procedure to elicit WTP values from respondents. The price options were determined at the following levels: the minimum bioproduct price at USD \$11.50, the maximum at USD \$23.00 and the average price at USD \$17.30 per application per hectare. Prices were converted from BRL (R\$) to American dollars using an exchange rate of 2.60 BRL/USD.

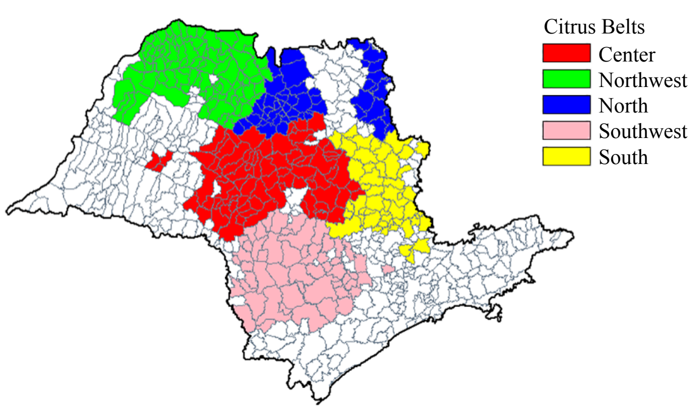

Figure 1. Citrus belts in São Paulo State covered by Fundecitrus research in 2015.

Table 1. Distribution of citrus orchards in terms of area and number of farms in citrus regions, and their shares in the sample.

Region	**Share of each region in**		
	harvested area sampled (%)[1]	**harvested citrus areas – São Paulo state (%)**[2]	**number of farms in the state (%)**[2]
Southwest	15.48%	16.51%	3.54%
South	33.83%	20.87%	23.66%
Center	28.83%	29.87%	21.72%
Northwest	11.70%	11.07%	23.84%
North	10.17%	22.28%	27.24%

[1] Data from our survey.

[2] Data from Fundecitrus (2015b).

In order to manage the start point bias, the bioproduct manufacturers decided the range of prices for the product based on its cost of production. The interviews adopted a face-to-face approach. As stated by Arrow *et al.* (1993), face-to-face interviews are likely to yield the most reliable results. In addition, prior to the survey, we did a pre-test applying the questionnaire to some agents of the citrus sector as well as to the product developers.

3.2. Econometric model

The literature suggests a logistic regression to model problems in which the response variable is categorical (Agresti, 2002). A logistic regression analyzes data distributed binomially, such as in Equation (1) below:

$$Yi \mid Xi \sim Bernoulli(ni; pi), i = 1,...,m \qquad (1)$$

Here, *ni* is the n^{th} Bernoulli trial and the probability of success *pi* is unknown. In this study, *Yi*=1 means that a grower *i* is willing to adopt biological control of *D. citri* in an orchard, replacing chemical control, and *Yi*=0 otherwise.

The logistic regression model fitted to respondents' answers and the set of explanatory and independent variables, either categorical or continuous, is a *k*-dimensional vector *Xi*. The model follows the form given by Equation 2:

$$p_i = \Pr ob(Y_i = 1 / X) = \frac{\exp(x'\beta)}{1 + \exp(x'\beta)} \qquad (2)$$

The probability of success in adopting biological control (odds ratio) can be defined as a linear function of the explanatory variables *xi*, described by Equation 3:

$$oddsratio = \left(\frac{pi}{1 - pi}\right) = e^{\beta_0 + \beta_1 x_{1,i} + \ldots + \beta_k x_{k,i}} \qquad (3)$$

Using a logistic link function, we can obtain the results of a linear regression model with estimated coefficients that provide information about the marginal contribution of the explanatory variable *xi* to the probability of success of adopting biological products to control *D. citri* (Equation 4):

$$\log it(pi) = \ln\left(\frac{pi}{1 - pi}\right) = \beta_0 + \beta_1 x_1 + \ldots + \beta_i x_i \qquad (4)$$

In Equation 4, the β_k parameters are estimated by maximum likelihood. Interpretation of the estimated values of βi is similar to the additive effects of each variable x_i included in the model for the probability of success of biopesticide adoption, adjusting for other predictors (Agresti, 2002).

The tested explanatory variables consist of the following socio-economic and demographic factors: region, education, experience, farm size, and dependence on the activity, when citrus is the only crop at the farm.

We considered two levels for the education variable: college or high school (high school includes elementary, secondary, and/or technical school). We expected higher education to lead to a better understanding of the characteristics (or attributes) of the bioproduct and its intangible benefits, which could positively affect the decision to adopt it. Likewise, farming experience was a dummy variable. In this case, we expected a positive relationship between the adoption of the bioproduct when the respondent had more than 10 years of experience growing citrus. In the pre-test questionnaire, sector´s experts collaborated to define 10 years of experience as the bound of the classes´ range, considering that this period represents half of the orchards economic lifecycle in the Brazilian production system. In the literature, some studies have found positive impact of knowledge variables as in the work of the Ochieng and Hobbs (2017) and Padilla-Bernal *et al.* (2018).

Another explanatory variable is farming as a sole occupation (economic dependence on the citrus crop), included as a dummy variable. The fact that growers' incomes rely exclusively on citrus production should make them more concerned with management's practices and, therefore, with greater acceptance of the bioproduct, compared to producers who diversify their agricultural activities. This is true particularly because the disease affects fruit quality, in addition to causing premature fruit drop. In short, crop specialization can influence adoption.

To capture the influence of farm size on the analysis, we considered three categories for the variable area harvested: (a) citrus in small farms covered less than 50 hectares (ha); (b) medium-sized farms ranged from 51 to 350 ha; and (c) large farms grew more than 350 ha of citrus plants. Initially, the size ranges were defined according to Fundecitrus (2012) and Palmieri *et al.* (2016). In the pre-test questionnaire, sector´s experts collaborated to redefine those categories.

Since regions differed in terms of farm features and disease incidence levels, dummy variables were included to capture the influence of farms' locations (south, southwest, central, north, and northwest) on their acceptance of the biopesticide and its WTP.

We used a multiple regression analysis to calculate WTP for the biopesticide. The value to respondents willing to pay for this technology is the dependent variable in the model, and the above-mentioned socio-economic and demographic variables are the explanatory variables. The models were fitted using the statistical software R from r-project.

4. Results

The managers of citrus orchards interviewed showed familiarity with the concept and practice of IPM, and 38% of them reported using bacteria *Bacillus thuringiensis* to fight against the citrus fruit borer (*Gymnandrosoma aurantianum*). To control the population of *D. citri*, the parasitoid *T. radiata* was applied in abandoned areas, in orchards with low level of chemical control, and in organic acreage. It is also possible to control this pest population using entomopathogenic fungi, such as *I. fumosorosea*, which obtained approval for commercial use in 2018. Acceptance of this biological agent by growers is the focus of this research.

Table 2 presents data about control strategies mentioned by respondents to fight against *D. citri*. The percentage of respondents who perform pest monitoring was high. About 96% reported carrying out regular inspections of plants with HLB symptoms, and 60% used a yellow trap to detect the *D. citri*. Moreover, 90% of interviewed managers stated that they eradicated symptomatic plants mainly the younger up to 8 years

Table 2. Strategies to control *Diaphorina citri* adopted by citrus growers in São Paulo State during the 2014-2015 season.

Practice	Respondents (%)
Apply agrochemicals only to control all pests in the orchards (not only *D. citri*)	62
Perform monitoring of pests	96
Inspect plants for symptoms of HLB	90
Use a yellow trap for *D. citri* detection	60
Eradicate symptomatic plants with greening (HLB)	90
Apply more than 12 sprays with chemicals in the orchard per season	65
Apply more than 24 sprays with chemicals in the orchard per season	14
Apply more than 12 sprays with chemicals per season, exclusively for *D. citri*	63

old, which were eradicated most often. The survey pointed that 65% of respondents sprayed their orchards more than 12 times per season, and 14% of them sprayed 24 times or more. Exclusively for *D. citri*, 63% of respondents reported sprayed at least 12 times per harvest year. Furthermore, 72% stated that combating *D. citri* now is the greatest challenge regarding pest and disease control for the citrus sector in São Paulo state.

Table 3 includes managers who, in some cases, also own farms. The average size for the farms sampled was 1,193 ha, and the difference between sizes is relevant, because the smallest farm is 4 hectare and the largest one is 24,000 hectare. In smaller farms, the owner makes decisions about pest management, while in large- and medium-sized groves, a consultant or an agronomist is the one responsible for that decision on behalf of many producers and farms. In the sample, large- and medium-sized farms predominate, 73% have a production area larger than 50 ha. Besides citrus, 41% of them also cultivate other crops, such as sugarcane and grains (41%).

For the farms sampled, 98% of managers are male, and 62% of them had a college degree; 54% of the sample's respondents were members of associations or cooperatives, and 77% had more than 10 years experience in citrus production. In addition, 76% of growers hired technical assistance, provided by agronomists or consultants, and only 5% of growers employed only family members (family farming).

Survey data showed that HLB spreads in Brazilian orchards even when eradication measures are adopted. This has had a significant effect on cash flow and reinvestment in citrus farms. The speed at which trees are infected has alarmed sector agents. Since 2008, incidence levels have grown at increasing rates, and the situation in the southern region of São Paulo state is worrisome, because 42.46% of its plants were estimated to be infected in 2015 (Ayres, 2015). Considering that many plants may be infected but still are asymptomatic, additional citrus production in this region could be compromised in the near future. Moreover, in regions with high levels of infection, *D. citri* control becomes more difficult and costly (Bassanezi, *et al.*, 2013b).

Table 3. Characteristics of managers and citrus growers interviewed in São Paulo State.

Features	Percentage in sample
Gender of manager – male	98
Managers with a college degree	62
Member of a cooperative	54
Farmer has more than 10 years' experience in citrus production	77
Average area under management (in ha)	1,193
Family farming	5
Farms growing only citrus	59
Farms use technical assistance	76

Central regions produce the most citrus in São Paulo, and HLB incidence there reached 23.57% (Ayres, 2015; Fundecitrus, 2015b), in the southwestern, northern, and northwestern regions in 2015 HLB contamination rates are lower: 4.72%, 6.81%, and 2.23%, respectively (Figure 2). Despite lower rates, growers intensively control their crops by spraying insecticides. In the Northwestern region, which presented the lowest incidence of HLB in 2015, respondents stated that they perform at least 18 and at most 24 sprays throughout the season. In the southwestern region, this number varies from 8 to 30, in the Northern region, the number of sprays varied from 12 to 36, and in the southern region, the area most affected by the greening, 6 to 30 insecticide applications were made, compared to 6 to 36 in the central region.

This scenario shows that the HLB situation requires urgent action to stimulate the IPM, targeting not only a more sustainable production model from a socio-economic and environmental perspective but also a more effective method to control the spread of the disease. Therefore, the survey included questions about growers' and managers' perceptions about biological pest control. Their answers showed that both have a good understanding of biological and microbial controls. However, the respondents highlighted the increasing difficulty of adopting these controls in recent years, because of the large number of pesticide sprays available to fight against *D. citri*.

Regarding the use of chemicals, respondents stated that they followed the recommendations established by the Committee of Agrochemicals for the Integrated Production of Citrus (PIC Brazil) because of their great concern about laws established by major importing countries of Brazilian orange juice, once Brazil exports more than 90% of its national production (Neves, *et al.*, 2010). The sample replicates this profile, because 89% of growers reported that they supply the juice industry.

About 97% of managers interviewed were interested in adopting a biological control to combat *D. citri*, noting that the intensive use of chemicals has led to the extinction of natural enemies that before were commonly found in groves. Respondents also mentioned that the indiscriminate use of chemicals could cause pest resistance, suggesting that while their use is growing, their effectiveness is decreasing.

The outcome above is interesting, once it shows a large share of producers/managers with a positive view about the adoption of biological control and surprisingly sensitive to the environmental problem of chemicals´ impacts over natural enemies. This last point should be probably due to the effective observation that natural enemies are more scarce. Although, it is important to mention that most of answers relate to farms that count on technical assistance (76%) and also the majority of people sampled has college degree (62%), which could be contributing to enhance the sensitiveness to this problem.

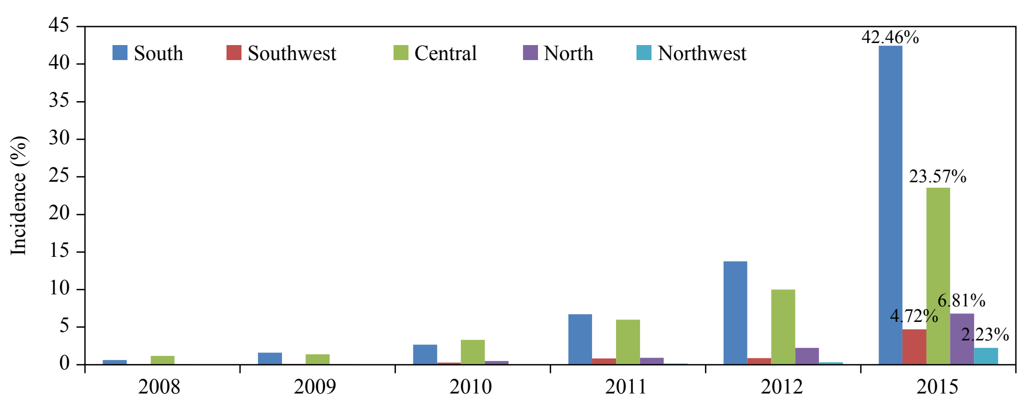

Figure 2. Incidence of HLB (percentage of infected plants) in citrus groves, by region, from 2008 to 2015, in São Paulo State.

To measure the influence of socio-economic and demographic factors on the willingness of managers and producers to adopt biopesticides to control *D. citri* in orchards, as part of a pest management strategy, a logit model was fitted to respondents' answers. Since the goal was to identify these factors' contribution to the adoption of biological controls, all socio-economic and demographic variables were treated as explanatory. However, several iterations between the variables and the significance of the parameters were tested, and the likelihood ratio was used to compare models.

Table 4 presents the estimated parameters for socio-economic and demographic factors, with respective standard deviations and confidence intervals (lower and upper). The Bayesian approach was used to penalize the likelihood function. In logistic regression, when the outcome has low (or high) prevalence, or when there are several interacted categorical predictors, it can happen that for some combination of the predictors, all the observations have the same event status, a similar event occurs when continuous covariates predict the outcome too perfectly. It is known as 'separation' (including complete and quasi-complete separation) and will cause problems fitting the model, sometimes the only evidence of separation will be extremely large standard errors (Firth, 1993).

The results of logistic regression are presented in terms of odds ratio, so when the estimated coefficient tends to zero, the odds ratio of bioproduct adoption tends to one. Therefore, since the effect is multiplicative, there is no differential effect between the specific category under analysis and the category taken as reference. On the other hand, when the estimated coefficient is greater than zero, the chance of success of an analyzed category increases more than once compared to the reference category. In this case, the central region was chosen as the reference category (intercept).

Analyzing the results in terms of impact, or evaluating the signs of the estimated coefficients, we can infer that managers who have completed higher education (college degrees) could be more willing to adopt biological controls than managers and growers without a college degree. This result confirms the hypothesis about the role of college education in promoting the adoption of bioproducts.

Likewise, agents who managed small- or medium-sized orchards could be more interested in adopting bio control than managers of large farms. The likelihood of bioproduct adoption was higher in medium- and small-sized farms than in large ones. One possible explanation is that smaller orchards show higher levels of HLB, and it is more difficult to control the disease in smaller farms. Indeed, the evidence that the disease

Table 4. Results of the logit model regarding the probability of citrus growers in São Paulo State to adopt the product – willingness to adopt.[1,2]

Variable	Penalized ML estimate	Standard error	Lower 0.95	Upper 0.95	*P*-value
Intercept	2.534	2.013	-2.918	9.274	0.300
Northwest	-1.242	2.115	-2.103	5.965	0.504
North	-0.836	1.775	-4.690	1.672	0.439
Southwest	0.032	1.839	-3.618	2.473	0.946
South	-1.385	1.362	-2.136	7.371	0.458
Experience (less than 10 years)	-0.993	1.065	-6.837	4.162	0.796
Diversified farm	-0.086	0.999	-6.051	4.472	0.578
Medium-size area	1.446	1.685	-5.238	5.501	0.686
Small area	0.405	1.321	-6.302	1.157	0.987
College degree	1.075	1.319	-2.709	5.159	0.311

[1] Likelihood ratio test =2.63867 on 9 df, *P*=0.9769187, n=74.

[2] Wald test =3.071911 on 9 df, *P*=0.9613755.

was easier to manage in larger areas of citrus production than in smaller, Fundecitrus researchers have drawn attention to the importance of joint management, so-called 'regional management' (Bassanezi, *et al*, 2013).

The coefficients representing producers with more experience in growing citrus, as well as those with higher education levels, shows positive effects on the willing to adopt the biological product to manage *D. citri*, compared to managers with less experience and lower education levels. Although, none of estimated ones presented statistical significance at 5% of probability (Table 4), the signs are in accordance with the hypotheses of this paper, relating the possible effects of the characteristics of decision-makers on their adoption of bioproducts. However, new studies testing these effects are needed to corroborate the impacts of explanatory variables on adoption of bioproduct.

We can predict the probability of success of adoption of the biological product considering the five regions and the socio-demographic factors. Since there are many combinations of socio-demographic profiles, we chose to describe those that presented the lowest and the greatest chance of success for each region. So, the estimated probabilities of successful adoption of the bioproduct are higher, in all regions, for managers with college degree, more than 10 years of experience in citrus production and in farms cultivating only citrus. Considering these characteristics of the agents, in all regions the estimated probability of successful adoption of the biological control was high, between 98 and 99%. Regarding managers who work in large diversified properties, with lower level of education and less experience in the activity, the probability of success drops to between 65 and 81%, depending on the region.

When asked about relevant features driving the adoption of biopesticides to fight against the *D. citri*, respondents primarily considered that biological control could become an alternative to product rotation with insecticides. Clearly, there is an expectation that the combined use of all management techniques could even lead to improvements in the effectiveness of chemicals currently used. Moreover, biopesticides reduce chemical residues in fruits and possibly cause fewer imbalances to the environment, as well as to human health. Respondents also mentioned the possible reduction of insect resistance to insecticides as a driver for adopting biological products, which would lower the incidence of secondary pests.

Table 5 presents the results of the WTP regression model. Managers and growers from the southern and central (intercept) regions, which are the most affected by the HLB, showed the highest willingness to pay for the biopesticide. Managers in the northern, northwestern, and southwestern regions showed a lower average WTP than agents from others. And, finally, managers in the southern region were willing to pay a higher amount than those from the central region. These results confirm that the level of incidence of the HLB is an important factor increasing sensitiveness of managers/farmers to alternative tools to control the disease.

Table 5. Willingness of citrus growers in São Paulo State to pay for biopesticides to control *Diaphorina citri* (USD/application/hectare).[1]

Variable	Estimate	Standard error	*P*-value
Intercept	15.61	1.10	0.0000**
South	1.44	1.01	0.0000**
Southwest	-1.09	1.35	0.0000**
Northwest	-2.02	1.84	0.0000**
North	-0.31	1.49	0.0000**
Experience (less than 10 years)	0.77	1.15	0.5016
Diversified farm	-0.64	0.93	0.4937
Medium-sized area	-2.27	1.33	0.0933*
Small area	-0.68	1.23	0.5788
College degree	1.17	1.14	0.3093

[1] Significant levels at 10%* and 1%**.

Although the coefficient was not significant, the sign for the explanatory variable diversification of farms showed to be in accordance with the hypothesis, i.e. less diversified farms (more specialized in citrus production) are more willing to pay for biocontrol than those are not so dependent from the citrus production. Likewise, the coefficient for high level of education (college degree), despite not statistically significant, was positive, indicating that it can favors the willingness to pay for biopesticides to control the *D. citri* compared to farmers/managers with less than college degree. On the other hand, the coefficient for farmers of medium-sized areas was found negative and significant at 10% level of significance, indicating that medium sized farms (and small sized, although not significant) are less willing to pay for the biopesticides compared to the big ones.

The survey also recognized important factors in the decision-making process against adopting biocontrol of *D. citri*, namely: (a) lower effectiveness of the bioproduct vis-à-vis chemicals; (b) lack of product and/or biopesticide manufacturer reliability; (c) inability to mix the bioproduct with fungicides; (d) lack of knowledge about where to purchase and how to use the biopesticide; (e) the product's limited application time; (f) a market price higher than the chemical price; and (g) restrictions regarding the bioproduct's shelf life.

These factors above-mentioned are, in fact, very important and they were somewhat pointed by farmers and managers as relevant for decision-making regarding the choice of bioproducts vis-à-vis conventional insecticides. It is noteworthy that some of these factors relate to information´s asymmetries such as the lack of information about the availability (sales point) and instructions of application. In addition, some factors highlighted by interviews were related to easiness and convenience of using chemicals compared to bioproducts. It is the case of the restrictions of shelf life and limited application time of the bioproducts and the inability to mix them with fungicides. These last factors relate to implied operational costs. These costs are relevant for farmers in the decision making process and they might be better addressed by fabricants and retailers in order to enhance the adoption of biopesticides.

5. Conclusions

Since 2004, when it was first reported in Brazil, HLB has spread across orchards, mainly in São Paulo state, the most important worldwide producer and exporter of citrus fruit and orange juice. Although thousands of plants were eradicated in recent years in an unsuccessful attempt to control spread of the disease, in 2015, the HLB reached 17.9% of citrus trees in the state.

It is difficult to control the insect *D. citri*, which can fly long distances disseminating the HLB across groves and orchards. A risk exists that the disease could spread to other citrus producing regions in Brazil. The attempt to control the insect by increasing the frequency of chemical spraying has shown little effectiveness, while also damaging the environment and compromising profitability of citrus orchards. This encourages the search for other solutions, complementary or alternative, such as the development of biological control.

Accordingly, in this study, we examined factors that can drive or limit the adoption of the biological control of *D. citri*, based on data collected directly from citrus growers or their consultants and other agents involved in citrus production. The findings showed higher acceptability of growers to the biopesticide than expected.

Some factors as farm size, experience of growers, higher levels of education (college degree), and dependence on citrus production can contribute positively to a successful adoption of a biological product. Agents expect that citrus growers will incorporate the biopesticide into the IPM when implementation becomes feasible and proves efficient.

Producers in the southern region, where the HLB incidence is the highest in São Paulo state, are willing to pay more than those of the central region, which has the second highest HLB incidence rate. Managers in the central and southern regions also may be willing to pay more than in the other three regions because they question the chemical treatment's desired effectiveness.

Aggravation of the disease has led sector agents to search for new pest control strategies. Incidence rates observed in 2015 should lead the industry to a new restructuring, reduce production in traditional areas, and growing in new ones. In fact, this process is already happening, as observed in surveys of the Secretariat of Agricultural Defense for São Paulo state and of Fundecitrus.

This topic is relevant for state agencies, agricultural defense, agrochemical companies, and enterprises and research institutes that invest in technology for biological control and IPM. It is also relevant to growers, whose decision will be crucial for the success or failure of these new pest management technologies, and to consumers, both fruit processors that need to guarantee their supply and final consumers, who can benefit from production systems that offer lower risk of contamination to human health and the environment.

Supplementary material

Supplementary material can be found online at https://doi.org/10.22434/IFAMR2018.0081.

Questionnaire – Citrus.

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