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Research article

Epidemiological and economic model to estimate the optimal edge width of citrus block to be weekly sprayed with insecticide for huanglongbing management

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ABSTRACT: A modeling approach was implemented to assist growers in estimating the most economical edge width to be sprayed weekly (EWSW) with insecticides for the management of the Asian citrus psyllid (ACP) *Diaphorina citri*, vector of the causal agent of huanglongbing (HLB), in the periphery of sweet orange farms. The model was developed based on epidemiological and economic data. Different scenarios of EWSW with fortnightly sprays in the rest of the block were compared. Four regions within the São Paulo/Triângulo Mineiro (SPTM) citrus belt were selected for analysis: Frutal, located in Triângulo Mineiro (TM), as well as the municipalities of Bebedouro, situated in the north (NO), Araraquara, located in the center (CE), and Avaré, situated in the south (SO) of the state of São Paulo (SP), Brazil. The model inputs used to estimate the number of HLB-symptomatic trees in each region included the number of immigrating ACPs, percentage of ACPs infected with '*Candidatus* Liberibacter asiaticus' (CLas), infection efficiency, and insecticide spray efficacy. Four economic simulations (panels) were performed, considering general or specific regional costs and yields. Accumulated costs, which encompassed expenses with insecticide spray, removal of infected trees, and reset, and benefits, which includes revenue received from the remaining bearing trees, were considered according to tree age (3-15 years old) in order to calculate the net present value (NPV). The highest NPV was standardized as 100, and this index was used to compare scenarios and panels. Across all scenarios and panels, the most economical EWSW remained consistent, ranging from 1 (in the first row), 217, 189, and 497 m (across the entire plot) at TM, NO, CE, and SO, respectively. This indicates that while costs and yields can alter the NPV, they do not alter the optimal EWSW.

Keywords: HLB management, economic valuation, greening, simulation model

Introduction

Huanglongbing (HLB) is a destructive citrus disease associated with '*Candidatus* Liberibacter asiaticus' (CLas), vectored by the Asian citrus psyllid (ACP) *Diaphorina citri* Kuwayama (Hemiptera: Psyllidae). The strategy against HLB in Brazil is predicated on using healthy nursery trees, eradicating symptomatic trees, and preventive control of the insect vector on a regional scale (Bové, 2012; Bassanezi et al., 2020). The vector control measures, primarily through insecticide applications, have been a central aspect of the strategy (Miranda et al., 2021). The efficacy of this approach is evident in suppressing ACP development within orchards, and mitigating secondary disease spread, particularly when the insecticide sprays are administered at fortnight intervals (Bergamin Filho et al., 2016). However, more frequent sprays are necessary to counteract primary infections caused by ACPs from external sources effectively. The spread pattern of migrating ACPs exhibits a concentration at the orchard's edge, with a decline from the edge to the interior of the orchard (Sétamou and Bartels, 2015). Consequently, a decrease in HLB-symptomatic trees within the orchards is observed (Gasparoto et al., 2018). This has led to a recurring inquiry of growers regarding the optimal edge width to be treated with weekly sprays (EWSW) to achieve efficient economic performance compared to fortnightly treatments.

In order to respond to the aforementioned inquiry, it is imperative to ascertain the financial implications of various intervention strategies, namely the costs associated with spraying, the eradication of trees, and the planting of a young nursery tree to replace the eradicated tree (reset), as well as the profits derived from tree production. Blocks exhibiting a higher EWSW may lead to a decline in disease incidence over time, resulting in augmented revenue. However, it is acknowledged that, in this scenario, the financial burden may exceed that of the fortnightly spray, primarily due to the increased frequency of sprays. The economic optimization of EWSW entails the identification of a spray scheme that yields the maximum net present value (NPV), taking into account the anticipated cash flow over the years and the time value of money (Kay et al., 2012). This study aimed to develop a model for primary HLB infection to ascertain the maximum EWSW, thereby ensuring the maximum NPV as a function of the ACP population and disease favorability. To this end, a process-based model was executed, incorporating HLB epidemic variables from four distinct regions within the São Paulo/Triângulo Mineiro (SPTM) citrus belt in Brazil, where notable variations in HLB incidence have been documented (FUNDECITRUS, 2023b). Using plant disease models to guide growers is a strategy that has been employed to overcome the complexity inherent in conducting field trials in several regions with different spray combinations within citrus blocks (González-Domínguez et al., 2023).

Materials and Methods

Description of the scenarios

A series of hypothetical scenarios were elaborated to analyze the most economical EWSW and to compare the feasibility of insecticide spray treatment. A process-based model was developed to calculate the number of symptomatic trees using data from the literature, previous field trials, and the Fundecitrus Alert System (FAS) (FUNDECITRUS, 2023a). Information was obtained from four regions across the SPTM citrus belt: i) Frutal, located in the Triângulo Mineiro (TM) region in Minas Gerais state, ii) Bebedouro, located in the north (NO) in São Paulo (SP) state, iii) Araraquara, situated in the center (CE) region in SP state, and iv) Avaré, located in the south (SO) in SP state (Figure 1). The TM, NO, CE, and SO regions encompass 20, 21, 19, and 17 municipalities, respectively (FUNDECITRUS, 2023b).

The model was constructed with a hypothetical 3-year-old citrus block situated at the periphery of the orchard. This block's dimensions were 497 × 500 m, and the spacing between rows and trees was 7 and 2.5 m, respectively (72 rows of 201 trees, resulting in 14,472 trees). The planting direction within the citrus block was oriented parallel to the orchard border.

The scenarios differed based on the EWSW, ranging from the first row (first scenario: "1 + 496 m") to the entire block ("497 + 0 m"). In the first scenario, trees of the plot's first row (1 m) were sprayed weekly, while the remaining 71 rows (496 m) were sprayed every 14 days. The scenario "497 + 0 m" represented weekly spraying of the entire plot (Figure 2A-D). The sprays were coincident and recurrent over time; in one week the entire plot of all scenarios was sprayed, and in the following week, only the EWSW defined for each scenario was sprayed.

Description of the epidemiological model

The model considered that secondary spread within the orchard was nonexistent, given that the maximum interval of insecticide sprays adopted in all treatments did not exceed 14 days. This period is shorter than the lowest ACP egg-to-adult cycle of 14 days (Liu and Tsai, 2000) and is detrimental to ACP development. Consequently, all infections were traced back to bacterialiferous ACP that had migrated from outside the property, consistent with the primary spread (Figure 3). The model inputs utilized for estimating the number of HLB-symptomatic trees included the insecticide spray efficacy, the number of migrating ACP, the percentage of ACP with CLas (bacterialiferous ACP), and the inoculation efficiency. The efficacy of the insecticide spray was estimated based on prior experiments (described below) that resulted in 66.4 and 43.9 % ACP mortality when the spray was administered every one or two weeks, respectively.

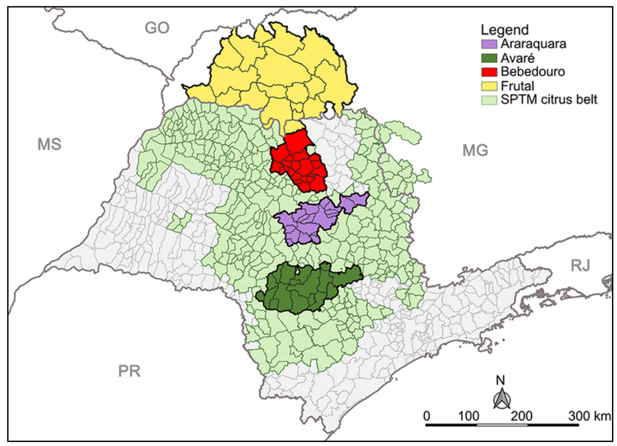

Figure 1 – Location of the four regions within the São Paulo/Triângulo Mineiro (SPTM) citrus belt selected for the present study: Frutal, in the Triângulo Mineiro region in Minas Gerais (MG) state; Bebedouro, in the north in São Paulo state; Araraquara, in the center region in São Paulo state; and Avaré, in the south in São Paulo state. GO = Goiás state; MS = Mato Grosso do Sul state; RJ = Rio de Janeiro state; PR = Paraná state.

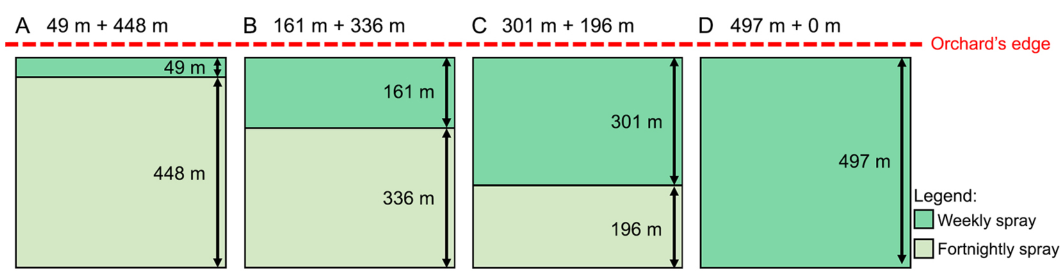

Figure 2 – Schematic representation (aerial view) of some scenarios of insecticide spray related to the different edge widths that received the insecticide weekly: A) 49 m from the edge, B) 161 m from the edge, C) 301 m from the edge, and the entire length of plot, and D) 497 m from the edge. The remaining area of the plot was sprayed every 14 days: A) 448 m, B) 336 m, C) 196 m, and D) 0 m. The plot was located at the border of a farm.

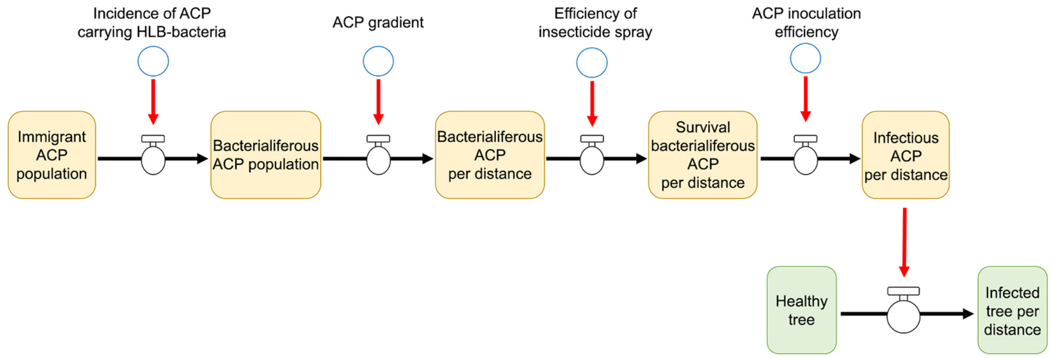

Figure 3 – Representation of the process-based model to calculate the number of infected trees per distance. The disease cycle moves from Asian citrus psyllid (ACP) primary spread (immigrant ACP population) to infectious ACP per distance via the flux of incidence of ACP carrying huanglongbing (HLB) bacteria, ACP gradient, efficacy of insecticide spray, and ACP inoculation efficiency. Infectious ACP per distance results in infected trees per distance.

The abundance of migrating ACPs (ACP per yellow sticky card per fortnight) for each region was based on the FAS database from 30 June 2017 to 30 June 2023. FAS is present in all regions of the citrus belt, and the yellow sticky cards were placed exclusively on trees in the first row from the border of the citrus block. ACPs were counted, and all cards were replaced every 14 days. The dataset thus comprised an average of 2,233 yellow sticky cards per region per fortnight. Consequently, the following ACP values were obtained per yellow sticky card per fortnight: 0.005, 0.219, 0.135, and 0.379 for TM, NO, CE, and SO regions, respectively.

The abundance of ACP in subsequent rows was estimated by model parameterization, which accounts for a gradual reduction of ACP spread from the periphery to the center of the block. This understanding, supported by extant literature (Sétamou and Bartels, 2015; Tomaseto et al., 2016) and field trial data, informed the selection of the most suitable model for ACP spread within a farm edge block (Table 1). The model was constructed using data from 67 blocks of field trials in various regions (Ribeirão Bonito, São Pedro do Turvo, Santa Rita do Passa Quatro, Mococa, Nova Europa, Reginópolis, and Guaraci) within the SPTM citrus belt. In these regions, yellow sticky cards were replaced every two weeks and evaluated until July 2021. The decay exponential [$y = a^*e^{(-be^*x)}$] and inverse power [$y = a^*(x^{(-bp)})$] functions were fitted to the data for each block by nonlinear regression using the STATISTICA® software (version 13.0). In this model, y corresponds to the average abundance of ACPs at a given distance x; a is the value of y at the initial distance from the edge; b determines the steepness of the ACP gradient; and x is the distance from the edge of the field, measured in meters. Once the ACP abundance at each distance from the border was calculated, the total number of ACPs per fortnight was determined by multiplying the estimated ACP abundance by the number of cards at each distance. It was hypothesized that all trees per row would have one yellow sticky card.

Not all ACPs invariably harbor bacteria, and not all bacterialiferous ACPs infect trees (i.e., they do not demonstrate inoculation efficiency). Therefore, the incidence of bacterialiferous ACP was determined by calculating the average of the data from the literature (Wulff et al., 2020) and unpublished field trial data (Guaraci, Reginópolis, and São Pedro do Turvo). The incidence of bacterialiferous ACP was thus determined to be 23.67, 35.07, 42.85, and 53.38 % for the TM, NO, CE, and SO regions, respectively. The number of bacteria cells within bacterialiferous ACPs was estimated as the cycle threshold (Ct) generated through quantitative PCR (Li et al., 2007). The mean Ct was then used to calculate the probability of inoculation as a function of Ct in ACP using a logistic model described by Lopes and Cifuentes-Arenas (2021). The average Ct was obtained from the literature (Wulff et al., 2020) and unpublished data from field trials (Guaraci, Reginópolis, and São Pedro do Turvo). Consequently, the average Ct for TM, NO, CE, and SO regions were, respectively, 28.92, 28.83, 27.67, and 28.43. These data yielded a probability of inoculation of 21.05, 21.37, 25.97, and 22.89 % for the TM, NO, CE, and SO regions, respectively.

Utilizing the aforementioned premises, the following values were estimated in each distance from the border: total bacterialiferous ACPs (total number of ACP per fortnight in each distance × incidence of bacterialiferous ACPs), total bacterialiferous ACPs that survive after spraying (total bacterialiferous ACPs per fortnight × spray efficacy), and, finally, total HLB-infected trees (total bacterialiferous ACPs per fortnight × inoculation efficiency). Subsequently, the total number of HLB-infected trees was multiplied by 26 fortnights, yielding the cumulative total of HLB-symptomatic trees per year in each scenario.

The total number of HLB-symptomatic trees in each scenario corresponded to the sum of HLB-symptomatic trees at the EWSW with HLB-symptomatic trees at the rest of the block sprayed fortnightly. The total number of HLB-symptomatic trees per year was divided

Table 1 – Estimated parameters and coefficient of determination (R^2) of the decay exponential and inverse power models fitted to the data of average abundance of Asian citrus psyllid (ACP), captured in blocks from several regions of São Paulo/Triângulo Mineiro (SPTM) citrus belt, in Brazil.

Region of SPTM	Latitude, longitude, and altitude	Block	Parameters – exponential decay model[a]			Parameters – inverse power model[a]		
			a	*b*	R^2	*a*	*b*	R^2
Ribeirão Bonito	22°04'00" S, 48°10'34" W, 590 m	Block 1	0.075	**–0.020**	0.75	0.081	–0.335	0.89
		Block 2	0.112	–0.080	0.99	0.112	–0.858	0.99
		Block 3	0.091	–0.032	0.93	0.093	–0.413	0.98
		Block 4	0.215	–0.060	0.99	0.216	–0.625	0.99
		Block 5	0.090	**–0.025**	0.83	0.095	–0.358	0.99
		Block 6	0.434	–0.078	0.99	0.434	–0.750	0.98
		Block 7	0.181	–0.034	0.93	0.185	–0.430	0.99
		Block 8	0.189	–0.037	0.98	0.191	–0.468	0.98
		Block 9	0.093	–0.021	0.90	0.096	–0.328	0.98
		Block 10	0.096	–0.024	0.96	0.099	–0.355	0.93
São Pedro do Turvo	22°33'08.8" S, 49°45'04.3" W, 495 m	Block 1	0.009	**–0.002**	0.17	-	-	-
		Block 2	0.089	–0.019	0.53	0.092	–0.316	0.75
		Block 3	0.186	**–0.064**	0.61	0.185	–0.389	0.96
Santa Rita do Passa Quatro	21°41'44.24" S, 47°41'21.79" W, 600 m	Block 1	0.016	**–0.001**	0.05	**0.010**	**–0.064**	0.16
		Block 2	0.011	**–0.003**	0.44	**0.010**	**–0.086**	0.04
		Block 3	**0.011**	**–0.002**	0.08	0.016	**–0.174**	0.33
		Block 4	0.013	**–0.001**	0.04	-	-	-
		Block 5	0.090	–0.024	0.89	0.092	–0.423	0.94
Mococa	21°29'14.01" S, 47°4'34.51" W, 630 m	Block 1	0.033	**–0.044**	0.89	0.034	–0.463	0.98
		Block 2	**0.010**	**–0.005**	0.05	**0.012**	**–0.157**	0.25
		Block 3	0.138	**–0.152**	0.96	0.137	**–0.802**	0.98
		Block 4	0.290	**–0.078**	0.97	0.303	–0.590	0.99
		Block 5	0.012	**–0.541**	0.92	0.012	**–0.800**	0.94
		Block 6	0.027	–0.139	0.99	0.028	–0.943	0.99
		Block 7	0.021	–0.124	0.99	0.021	–0.868	0.98
		Block 8	0.009	–0.079	0.98	0.009	**–0.626**	0.90
		Block 9	**0.018**	**0.528**	0.83	0.018	**–0.729**	0.87
Nova Europa	21°44'27.75" S, 48°28'12.53" W, 575 m	Block 1	0.034	–0.032	0.83	0.037	–0.420	0.99
		Block 2	0.035	–0.012	0.89	0.034	–0.177	0.69
Reginópolis	22°02'36" S, 49°08'35" W, 540 m	Block 1	-	-	-	0.647	–0.188	0.93
		Block 2	-	-	-	**0.980**	**–0.027**	0.06
		Block 3	-	-	-	1.273	–0.269	0.60
Guaraci	20°29'13" S, 48°54'47" W, 465 m	-	0.018	**–0.254**	0.93	0.018	–0.681	0.95
Mean of *b*							–0.484	

[a]The decay exponential [$y = a \times e^{(-b \times x)}$] and inverse power [$y = a \times (x^{(-bp)})$] models were fitted to the data for each block by nonlinear regression, using the STATISTICA® software (version 13.0), where *y* corresponded the average abundance of ACP at distance *x*; *a* means the value of *y* at the first distance from the edge; *b* determines the steepness of the ACP gradient; and *x* was the distance from the edge of the field, in meters. Data in bold were not significant and were not considered in the mean of *b*. (–) represents the absence of model fitting.

by the total number of trees in the block, resulting in the annual HLB incidence. A 13-year cumulative HLB incidence, ranging from orchard age 3 to 15, was employed for the economic analysis.

Insecticide spray efficacy

A series of experiments were conducted to ascertain the efficacy of an insecticide spray when applied to a steady influx of immigrant ACPs. This methodology was adapted from that previously outlined by Primiano et al. (2023). To simulate a tree branch, eighty six-month-old potted seedlings (3.8 × 21.0 cm pots containing coconut coir, Amafibra Golden Mix) of 'Valencia' orange (*Citrus* × *sinensis* [L.] Osbeck) were placed in the middle third of sweet orange trees. The orchard under study was comprised of sweet orange cv. 'Pera' (*Citrus* × *sinensis* [L.] Osbeck) grafted on 'Swingle' citrumelo (*C. paradisi* Macfad. cv. Duncan × *Poncirus trifoliata* [L.] Raf.), with 21 m^3 of tree canopy size, 6- to 7-year-old, and spacing of 5.25 between rows by 2 m between trees. The seedlings were fixed on the tree with a piece of wire (one seedling per tree). Subsequently, the orchard was sprayed with bifenthrin (Talstar® 100 EC, 400 mL 2000 L^{-1} tank volume) at a volume of 40 mL m^{-3} tree canopy, resulting in an average spray coverage of 34 %. The tractor speed was 7 km h^{-1} (36.67 Hz), with 9 Hz in the power take-off and a pressure of 1.03 MPa in the pump. The Thal-

300 digital thermo-hygro-anemometer (Instrutherm) recorded the environmental air conditions for each experiment and spraying. This experiment was carried out three times. After the spraying process, the seedlings were placed to dry for approximately 1 h, after which they were extracted from the orchard and transferred to a screenhouse. During experiments, an average air temperature of 24.9 ± 0.5 °C and a relative humidity of 65 ± 2 % were kept inside the screenhouse.

The efficacy of the spraying method was determined by the mortality rate of ACPs confined within seedlings, with and without the application of the spraying method. A total of 20 seedlings were selected at 1- or 2-day intervals for the confinement of ACPs. One hundred ACPs were confined (ten ACPs per seedling) in seedlings subjected to the spraying process, and another 100 ACPs were confined in seedlings not subjected to the spraying process (control treatment). The purpose of the control treatment was to assess the natural mortality rate of these insects. The number of dead ACPs was evaluated daily after each confinement. To simulate the constant influx of migrant ACPs from external sources, 100 ACPs were confined to new seedlings daily. The confinement was performed in new seedlings and seedlings that already had ACPs. For instance, the first confinement occurred on new seedlings on the same day of the spray (seedlings of 0 day after spraying = DAS). The second confinement occurred at one DAS in new seedlings (seedlings of 1 DAS) and seedlings of 0 DAS. This was carried out until the fourteenth DAS, resulting in 12,000 ACPs accumulated. The ACPs were 15-20 days old, without distinction of sex for selection, and originated from a colony free of CLas in *Murraya paniculata* (L.) Jack (Rutaceae) at Fundecitrus.

In order to estimate the efficacy of the spraying protocol administered at a 14-day interval, the total number of dead ACPs was divided by the total number of ACPs confined (accumulated immigrant ACPs) over the 14-days. To evaluate the effectiveness of the spraying protocol administered at 7-day intervals, it was hypothesized that all ACPs confined until the sixth DAS would be killed by a subsequent spraying on the seventh day, simulating the weekly spraying. After the initial spraying, the mortality observed in the first week was also accumulated in the following week.

Economic analysis

The economic analysis was performed using four simulations (economic panels), with consideration given to the particularities of each region in terms of costs (Table 2) and yields (Table 3). Yield data were obtained from the historical Crop Estimation Survey (data not published) of Fundecitrus. Panel 1 considered the following: i) the same costs of a non-irrigated orchard in all regions and ii) the same average yield of the SPTM

Table 2 – Operational, huanglongbing (HLB), and irrigation costs considered at the calculated cost of each economic panel and region.

Economic panel	Region	Description	Costs in each age of the orchard			
			years-old			
			3 to 6	7 to 9	10 to 14	15
			US$ ha^{-1}			
1 and 2	TM, NO, CE, and SO	Operational cost	4,615.00	6,073.58	6,683.33	5,650.96
		HLB cost	831.89	831.89	831.89	831.89
		Operational cost - HLB cost	3,783.11	5,241.69	5,851.45	4,819.07
3 and 4	TM and NO	Operational cost	4,615.00	6,073.58	6,683.33	5,650.96
		HLB cost	831.89	831.89	831.89	831.89
		Irrigation cost	381.67	381.67	381.67	381.67
		Operational cost - HLB cost + irrigation cost	4,164.78	5,623.36	6,233.11	5,200.74
	CE and SO	Operational cost	4,615.00	6,073.58	6,683.33	5,650.96
		HLB cost	831.89	831.89	831.89	831.89
		Operational cost - HLB cost	3,783.11	5,241.69	5,851.45	4,819.07

TM = Triângulo Mineiro region in Minas Gerais state; NO = north region of São Paulo state; CE = central region of São Paulo state; SO = south of São Paulo state. Adapted from Ribeiro et al. (2023), converting values from real to dollar using the exchange rate of 5.00 from September 2023 (BCB, 2023).

Table 3 – Estimated yield of trees in similar density of these study in each age and each region at the four economic panels.

Economic panel	Region	Estimated yield in each age of the orchard												
		years-old												
		3	4	5	6	7	8	9	10	11	12	13	14	15
		box of 40.8 kg per tree												
1 and 3	SPTM citrus belt	0.5	0.8	1.0	1.3	1.5	1.6	1.8	1.9	2.0	2.1	2.1	2.2	2.2
2 and 4	TM and NO	0.5	0.7	0.9	1.1	1.3	1.5	1.6	1.8	2.0	2.1	2.2	2.4	2.5
	CE	0.6	0.9	1.1	1.4	1.6	1.7	1.9	2.0	2.1	2.1	2.1	2.1	2.1
	SO	1.1	1.3	1.5	1.7	1.9	2.0	2.1	2.2	2.2	2.3	2.2	2.2	2.1

SPTM = São Paulo/Triângulo Mineiro; TM = Triângulo Mineiro region in Minas Gerais state; NO = north region of São Paulo state; CE = central region of São Paulo state; SO = south region of São Paulo state. Data not published, from Fundecitrus Crop Estimation Survey.

citrus belt. Panel 2 considered i) the same costs of a non-irrigated orchard in all regions, as well as ii) the specific yield of each region. Panel 3 considered i) the costs of an irrigated orchard in TM and NO regions, and of a non-irrigated orchard in CE and SO regions, as well as ii) the same average yield of the SPTM belt. Panel 4 considered i) the costs of an irrigated orchard in TM and NO regions, and of a non-irrigated orchard in CE and SO regions, along with ii) the specific yield of each region.

The NPV was calculated according to Eq. (1) for each region based on the total number of HLB-symptomatic trees per year in each scenario, as provided by the epidemiological model. To that end, the sum of the revenues and costs for each block edge width in present (current) values was considered, for the projected 13 years, discounted by a real interest rate (discounting inflation) (Clayman et al., 2012; Vera-Villagrán et al., 2016).

$$NPV = \sum_{j=0}^{n} \frac{B_j - C_j}{(1+r)^t} \quad (1)$$

in Eq. (1), B_j means the benefit (revenue obtained from the sale of oranges) achieved by management in year j; C_j represents the operational cost associated with management in year j; t represents the years in the period of analysis (from 0 to n) where n is the thirteenth year; and r is the discount rate.

The discount rate employed was 3.4 %, corresponding to the average real interest rate from 2015 to 2019 (2020 and 2021 were excluded due to their atypical nature due to the COVID-19 pandemic). This rate was obtained by calculating the average nominal value of the annual Brazilian basic interest rate (Selic rate), discounting Brazilian inflation given by the General Price Index - Internal Availability, according to the Banco Central do Brasil (BCB, 2023).

The Cj calculation in this study was based on the citrus production operational cost, as reported by Ribeiro et al. (2023), with a distinction made for each block width-related HLB cost. The HLB cost calculated for each management was determined by subtracting the Centro de Estudos Avançados em Economia Aplicada (CEPEA) HLB cost (Ribeiro et al., 2023) from the CEPEA citrus production operational costs for each panel, presented in Table 2. The HLB cost encompassed insecticide applications (C_{jIA}), eradication and replanting (C_{jER}), considering prices of products, machinery, and labor. The insecticide application rates for the control of *D. citri* were determined to be 40 mL m^{-3} of tree canopy (Miranda et al., 2021), with the volume of orchard canopy varying according to the tree age. For each tree age (ranging from 3 to 15 years), the labor cost and the tractor-mounted sprayer to spray one hectare was calculated. The cost of each insecticide (US\$ ha^{-1} per application) was based on a rotation scheme of three different chemical groups, with one-third of the applications throughout the year carried out with insecticide from the pyrethroid group, one-third from the neonicotinoid group, and one-third from the organophosphate group. The cost of each application was extended to a complete crop year with a spray interval of 7 or 14 days. This approach enabled the calculation of the cost of annual spraying in one hectare with weekly and fortnightly insecticide spray for each orchard age (US\$ ha^{-1} yr^{-1}). To calculate the cost of spraying for each width of the orchard, each edge width was transformed into an area measured in hectares. The cost of spraying an area of the orchard in the j year every seven days (C_{j7}) and the cost of spraying the rest of the orchard in the j year every 14 days (Cj_{14}) were estimated. Therefore, the C_{jIA} in the j year in the entire orchard for each edge width at each age (US\$ yr^{-1}) was the sum of C_{j7} with C_{j14}.

The C_{jIA} was incorporated into the C_{jER} HLB-affected trees in the j year, with the number of HLB-affected trees in each scenario (obtained from the epidemiological analysis), taken into account. The analysis encompassed all processes associated with eradication and replanting, including tree inspection, tree cutting, herbicide application to prevent regrowth from the tree stump, resetting, and irrigation. Consequently, the final cost of each management strategy at each age is the sum of the C_{jIA} and C_{jER}.

Each management's B_j was based on the revenue earned by the estimated production for each of the 13 years projected and according to the orchard age (Table 3). The revenue was calculated by taking into account the number of productive trees in the orchard (over three years), the fruit production rate of the reset (after three years of planting), the number of trees in the orchard (obtained by epidemiological analysis), and the average spot price of a 40.8 kg orange box from Feb to July of 2023 (CEPEA, 2023). The production of resets from the initial period (3-year-old orchard) was considered in the third evaluation period (6-year-old orchard). Concurrently, the yield of the fifth period (7-year-old orchard) was derived from the cumulative production of resets from the first and second periods (resets with three and four years, respectively). This process was repeated until the thirteenth year.

Finally, the NPV was transformed into an NPV index, in which the highest value was standardized as 100 and the other values were transformed to proportion. Consequently, for each region, the EWSW that presented the highest NPV index was recommended as a strategy to control or mitigate the reinfection of orchards by ACPs.

Results

Insecticide spray efficacy

The environmental conditions were similar across the experimental setups. The air temperature was 36.9, 41.4, and 43.0 °C, while the relative air humidity was 30.3, 30.4, and 28.5 %, with the maximum wind speed of 6.3, 6.3, and 2.2 km h^{-1} in experiments 1, 2, and 3, respectively.

Following the fortnightly spraying regime, the number of dead ACPs recorded was 4,347, 6,731, and 4,714 ACPs for experiments 1, 2, and 3, respectively. This corresponds to spray efficacies of 36.2, 56.1, and 39.3 %, respectively (averaging 43.9 %). Conversely, when the spraying occurred on the seventh day after the initial spray (weekly spray regime), the number of dead ACPs increased to 7,542, 8,481, and 7,889 in experiments 1, 2, and 3, respectively. As a result, the spray efficacy increased to 62.9, 70.7 and 65.7 % (averaging 66.4 %).

Development of a process-based model

In accordance with the estimated parameters and coefficients of determination of the decay exponential and inverse power models (Table 1), the inverse power model demonstrated the optimal fit to the ACP abundance data over the edge width. The average of parameter b (0.484) was employed to estimate the ACP gradient for the epidemiological model, resulting in Eq. (2) to estimate ACP in each distance from the block edge:

$$y = a \times x^{-0.484} \quad (2)$$

in Eq. (2), y corresponded to the average abundance of ACPs at distance x, a represented the value of ACP abundance from FAS of each region, and x was the distance from the edge of the field in meters.

The annual HLB incidence rate was calculated for each region and scenario (Figure 4A, C, E, and G). The annual HLB incidence rate in the scenario involving the application of the spray to the entire plot at 7-day intervals for the TM, NO, CE, and SO regions was 0.02 % (Figure 4A), 1.45 % (Figure 4C), 1.33 % (Figure 4E), and 4.10 % (Figure 4G), respectively. In contrast, the scenario involving the application of the same treatments at 14-day intervals yielded higher HLB incidence rates. Specifically, the annual HLB incidence for the TM, NO, CE, and SO regions were 0.04, 2.43, 2.22, and 6.84 %, respectively (Figure 4A, C, E, and G).

The TM region exhibited the lowest cumulative incidence of HLB over the projected 13-year period in both scenarios, with the largest EWSW (497 + 0 m) and with the entire plot sprayed every 14 days (0 + 497 m) (Figure 4B). In the NO region, the cumulative incidence of HLB over the 13 years was 18.89 and 31.55 % in scenarios where the entire plot was sprayed every 7 and 14 days, respectively (Figure 4D). Cumulative HLB

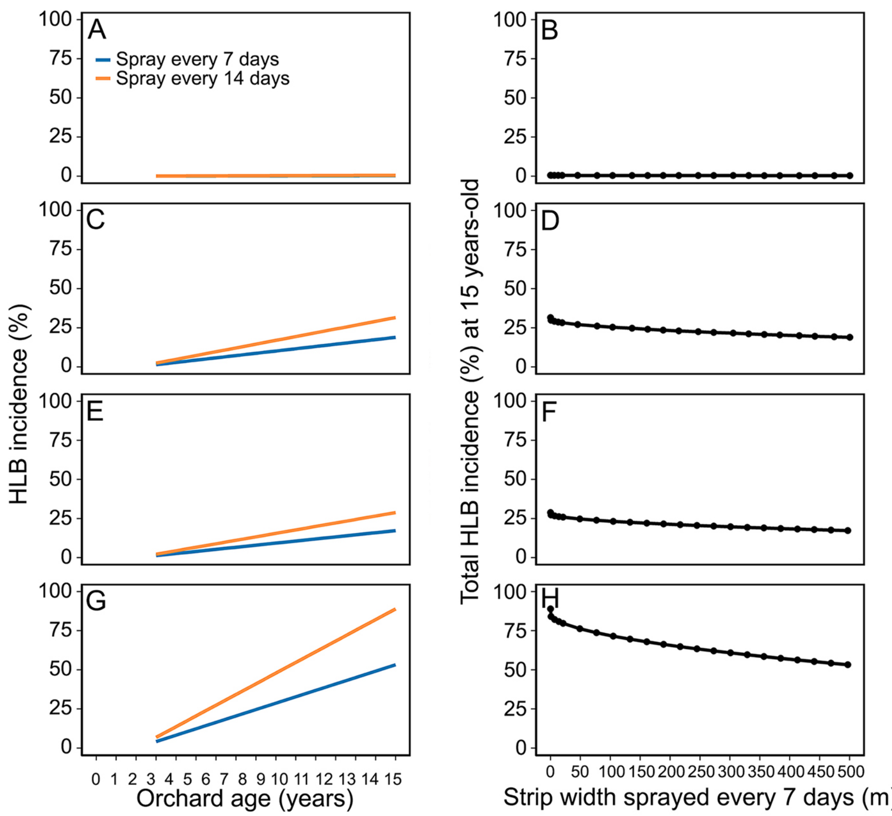

Figure 4 – A, C, E, and G) Cumulative incidence of huanglongbing (HLB) throughout 13 years, from 3- to 15-year-old orchards, and B, D, F, and H) total HLB incidence in a 15-year-old orchard with different edge widths that received insecticide spray weekly. The remaining area of the plot was sprayed every 14 days. The scenarios were projected for four regions: A and B) in the Triângulo Mineiro region in Minas Gerais state, C and D) in the north region of São Paulo state, E and F) in the center region in São Paulo state, and G and H) in the south region in São Paulo state. The plots were located at the border of an orchard.

incidence after 13 years in CE and SO regions were, respectively, 28.87 and 88.97 % in the scenario with the entire plot sprayed every 14 days (Figure 4F and H). The cumulative HLB incidence in both CE and SO regions decreased to a maximum of 17.29 and 53.29 %, respectively, in the scenario with the entire plot sprayed weekly (Figure 4F and H).

Economic analysis

The insecticide spray scenario "0 + 497" in the TM region presented the highest NPV among the scenarios. It was used as the reference NPV index (= 100) for all other economic panels (Figure 5A). For instance, in Panel 1, the scenario "0 + 497" exhibited a NPV of US$ 471,755 in the TM region, US$ 167,454 in the NO region, US$ 193,151 in the CE region, and –US$ 397,689 in the SO region. Consequently, the index of the insecticide spray scenario "0 + 497" in the NO, CE, and SO regions were 35.5, 40.9, and –84.3, respectively (Figure 5B-D).

The optimal EWSW was consistent across all economic panels within a given region. The EWSW that yielded the highest cost-benefit ratio was 1 m (first row, sprayed on both sides of the tree) in the TM region, 217 m in the NO region, 189 m in the CE region, and 497 m (entire plot) in the SO region (Figure 5A-D).

Discussion

Many citrus growers increase the frequency of insecticide sprays from fortnightly to weekly at the edge blocks of orchards to substantially reduce primary spread of the pathogen. In this study, we demonstrated that spraying the entire block every week at the periphery may not result in optimal economic performance depending on the region in which the orchard is located. To address this, we integrated theoretical and empirical data concerning the interaction between sweet orange, CLas, and ACP, and the orchard management practices to calculated the NPV of each insecticide spray scenario. Consequently, the primary research question was addressed, enabling the identification of the optimal EWSW for each region. These findings revealed a positive correlation between the population of ACP within a region and the cumulative HLB incidence, resulting in a higher EWSW.

The insecticide sprays administered at each block edge width are generally regarded as a capital investment, meaning that the grower incurs a higher cost for weekly sprays, anticipating a reduced incidence of HLB and, consequently, a smaller number of affected trees and an augmented revenue. In these cases, the most suitable economic methodology for evaluating the financial performance of investment opportunities is the NPV. This is because the NPV considers the time value of money and the magnitude of cash flow in each year over the entire duration of the investment (Kay et al., 2012). The calculation of NPV of each insecticide spray scenario was performed with the estimated costs and incomes of bearing trees.

The management and yield of citrus orchards may vary across the SPTM citrus belt. For instance, tree-planting with an irrigation system is more prevalent in orchards in the TM and NO regions due to lower precipitation levels and drier weather conditions than in the CE and SO regions. However, orchards located at the CE and SO regions can also be irrigated, but this management increase the production costs.

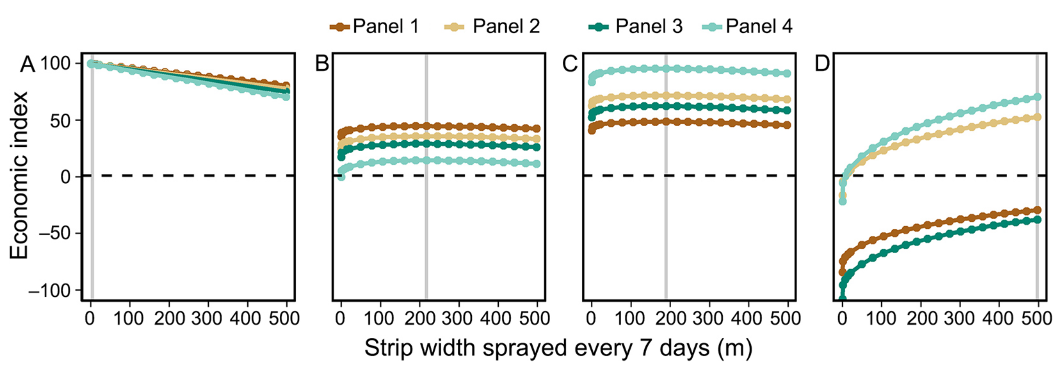

Figure 5 – Economic index of several scenarios related to the different edge widths that received the insecticide spray weekly. The remaining area was sprayed every 14 days. A) The scenario "0 + 497" in the Triângulo Mineiro region in Minas Gerais state was the reference net present value index (=100) for each panel. Four regions were studied: A) the Triângulo Mineiro (TM) region in Minas Gerais state, B) in the north (NO) in São Paulo state, C) in the center (CE) region in São Paulo state, and D) in the south (SO) in São Paulo state. Four economic panels were performed: Panel 1 (same costs of a non-irrigated orchard in all regions + same average yield of São Paulo citrus belt), Panel 2 (same costs of a non-irrigated orchard in all regions + specific yield of each region), Panel 3 (costs of irrigated orchard in TM and NO and not irrigated orchard in CE and SO + same average yield of São Paulo citrus belt), Panel 4 (costs of irrigated orchard in TM and NO and not irrigated orchard in CE and SO + specific yield of each region). Vertical grey lines correspond to the edge width weekly sprayed with the maximum economic index within each region.

The estimated yield in orchards in the SO region is higher than those in the CE region, which, in turn, is higher than those in the NO region (Table 3). This discrepancy can lead to changes in income. It is evident that differences in costs and incomes can impact the NPV index. Based on these variations, the present study proposes four economic panels, considering the particularities of costs and yields in each region and the average yield. Notably, the optimal ESWS remains consistent in each region and panel. This indicates that while costs and yields can influence the NPV, they do not alter the optimal ESWS. Notably, across all regions, the strategy entails eradicating all HLB-symptomatic trees, accompanied by the replanting of resets annually from 3 to 15 years of age. This is in contrast to the legislation enacted by the SP state, which mandates the removal of trees affected by HLB from orchards up to eight years of age (SAA, 2021).

The average migrating ACP population, the percentage of bacterialiferous ACP, and the probability of infection may increase or decrease over the year. Typically, the ACP population is lower during the dormancy period (autumn and winter periods) than during intense flush shooting (spring and summer) (Bassanezi and Primiano, 2021). Furthermore, fluctuations in the incidence of bacterialiferous ACPs, and consequently in the probability of infection, are observed throughout the year (Wulff et al., 2020). Despite these fluctuations, all variables were standardized throughout the year, and average values were used to compare the main regions. Another assumption of this model is related to secondary spread, in which commercial orchards that perform the correct management for ACPs, it is rare or extremely low the detection of eggs or nymphs from ACPs (Bassanezi et al., 2013b; Pazolini et al., 2021). Additionally, primary spread has a higher weight on HLB epidemic than secondary spread (Bassanezi et al., 2013a).

Citrus trees exhibit an increased susceptibility to HLB infection during the early stages of shoot development. However, the transmission of the bacteria persists until the V5 stage of citrus leaf development, which corresponds to fully expanded young leaves (Lopes and Cifuentes-Arenas, 2021). Furthermore, shoots at the V1 to V3 stage provide a more conducive environment for insect oviposition and reproduction (Cifuentes-Arenas et al., 2018). Despite these findings, the prevailing view is that citrus trees are inherently susceptible to HLB infection by immigrating ACPs.

A variability in the estimated HLB incidence was observed throughout the assessed and representative regions of the SPTM citrus belt, ranging from 0.02 to 4.1 % from the TM to the SO region that received weekly spraying in the entire plot. These variations in HLB incidence among regions were anticipated. Significant variations in the actual HLB incidence were documented across the citrus belt, both from NO to SO and west to east, with the 2023 incidence ranging from 1.8 % in the TM and NO regions to 73 % in the CE region (FUNDECITRUS, 2023b). This variability in total HLB incidence within the SPTM citrus belt is associated with several factors, including conducive climatic conditions for ACP development, ACP feeding, and bacterial colonization, the number of small orchards within the region, the eradication of symptomatic trees, and HLB control associated or not with area-wide management (FUNDECITRUS, 2023b). For instance, in the NO region of SP state, temperatures are higher than in the SO region, and there are fewer orchards, associated with area-wide management. These factors have led to a smaller ACP population, reduced bacteria colonization, less incidence of bacterialiferous ACP, and, consequently, a lower HLB incidence in the NO region compared to the SO region (FUNDECITRUS, 2023b).

In regions experiencing high pressure from ACP populations originating from outside the property, it is economically feasible to apply insecticide on a weekly basis using a wider edge width of the block. Nevertheless, growers should engage in regional control initiatives to diminish ACP density within the region, thereby reducing the edge width that requires weekly insecticide spray. This approach will lead to a reduction in operational costs and an increase in revenue, accompanied by a reduction in HLB incidence.

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Conflict of interest

The authors declare no conflict of interest.

Data availability statement

The data supporting this study's findings are available in the Fundecitrus Research Data Repository at https://rdp.fundecitrus.com.br/.

Declaration of use of AI Technologies

The authors declare that AI technologies were not used in the production of this study.

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