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Developing an Effective Push–Pull System for Managing Outbreaks of the Invasive Pest *Bactrocera dorsalis* (Diptera: Tephritidae) in *Nephelium lappaceum* Orchards

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Abstract: Outbreaks of the oriental fruit fly, *Bactrocera dorsalis* (Hendel), present significant challenges to global fruit production, necessitating effective control measures that minimize environmental risks and pesticide resistance. This study aimed to develop and evaluate the effectiveness of four distinct push–pull control strategies for managing *B. dorsalis* outbreaks in a *Nephelium lappaceum* orchard. These strategies involved the inclusion of low-concentration abamectin, spraying repellent with a drone or manually, using methyl eugenol (ME) or food bait and employing either two types of attractants and repellents or a single type. The findings indicated that incorporating the low-concentration abamectin into the push–pull system, utilizing ME as an attractant instead of food lures and manually applying abamectin and attractants were all effective in reducing the *B. dorsalis* population size and minimizing fruit damage. While increasing the diversity of repellents and attractants enhanced the long-term effectiveness of the system, it did not result in a significant decrease in *B. dorsalis* population size or fruit damage rate compared to using a single repellent or attractant. In conclusion, the push–pull strategy emerged as a viable method for managing *B. dorsalis* outbreaks, offering potential benefits in reducing environmental risks and pesticide resistance. However, the study underscored the importance of the context-specific construction of push–pull strategies to optimize their effectiveness in orchard settings.

Keywords: integrated pest management; invasive pests; tropical fruits; pest behavior

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1. Introduction

The oriental fruit fly (*Bactrocera dorsalis*) is a highly destructive pest that poses a significant threat to global fruit production [1–4]. Originating from tropical and subtropical regions of Asia, this pest has a broad adaptability to various host plants [5] and exhibits robust reproductive capacities [6,7]. As a result, it has significantly expanded its geographical range from China, Southeast Asia and India to the Hawaiian Islands [8]. Due to its widespread distribution and economic impact, it is considered a globally recognized quarantine pest [1,4].

There are various methods available for controlling *B. dorsalis*, typically employed preemptively before outbreaks occur [9,10]. These methods include biological control [11,12], pheromone traps [10,13] and the sterile insect technique [14,15]. While chemical control is widely recognized as an effective measure for managing pest outbreaks [16], it also poses risks of environmental contamination and can contribute to the development of insecticide resistance [17], thereby hindering sustainable long-term pest management efforts. Consequently, there is an urgent need to develop effective integrated *B. dorsalis* management methods that can reduce pesticide resistance development and systemic resistance in insects [18], thus, reducing damage in fruit production.

The push–pull strategy is an integrated behavioral control method that is widely applied in agricultural and medical insect control [19–23]. Its core concept is to repel pests from protected resources while simultaneously attracting them to an alternative attractive source, resulting in pest elimination [20], and to manipulate the abundance and distribution of natural enemies [24]. There are two implementation approaches for the push–pull strategy [20]. The first involves planting non-crop plants with repellent properties and combining them with trap crops [25]. The second approach utilizes the combination of repellents and attractants to lure and trap pests [26]. Usually, non-toxic components are used in the push–pull strategy, aiming to reduce pesticide usage, while combining different stimuli and coordinating pest distributions to enhance efficiency [20].

The push–pull strategy has demonstrated significant effectiveness in controlling crop pests such as fall armyworm *Spodoptera frugiperda* (J.E. Smith) [27], cotton bollworm *Helicoverpa armigera* (Hübner) [28] and Colorado potato beetle *Leptinotarsa decemlineata* (Say) [29]. It has also shown success in the integrated management of medical insects [30] and *B. dorsalis* [31]. In conclusion, the push–pull strategy holds promise as an integrated pest control method for managing *B. dorsalis* [31]. It has the potential to reduce pesticide resistance and mitigate environmental pollution [20]. However, there is currently no literature available regarding the effectiveness of the push–pull strategy during pest outbreaks or how to construct a push–pull system suitable for outbreak control.

The objective of this study was to develop an effective push–pull strategy to manage *B. dorsalis* in a commercial rambutan orchard. The approach was to test four variations of a push–pull strategy in comparison to the use of a standard insecticide. The four experiments (Experiments 1–4) were systematically conducted in a single orchard, with a 30-day respite between each experiment. According to the different push–pull strategy designs (see below), the "push" was established by using allicin and/or d-limonene as the repellents. Allicin has been proven to repel *B. dorsalis* and other fruit fly species, acting as a repellent [32–34]. Additionally, d-limonene, a natural compound found in plants of the Rutaceae family, can also serve as a deterrent for *B. dorsalis* [35]. The "pull" was established by using methyl eugenol (ME bait) and/or food bait.

The first push–pull strategy compared the effectiveness of a push (allicin)–pull (ME) system with and without the use of low-concentration abamectin in controlling the outbreak of *B. dorsalis*. Abamectin is considered environmentally friendly, displaying minimal residue levels in water and easy biodegradability by soil microorganisms [36]. It is also known to have low toxicity towards avian species and humans [37,38]. However, certain studies show that it is classified as a highly toxic pesticide for mice and rats and has negative effects on soil microbial communities in the short term [39]. To preserve the eco-friendliness of these push–pull strategies, a low concentration of abamectin was used in all the experiments. The second approach compared the effectiveness of a manually sprayed repellent (allicin) and abamectin in the push–pull system (with ME as the attractant) with drone spraying in controlling *B. dorsalis*. The third approach compared the control efficacy of push–pull systems using food bait as an attractant to those using ME as an attractant, with allicin as the repellent in both systems. Finally, the fourth approach evaluated the impact of increasing the variety of attractants (ME + food bait) and repellents (allicin + d-limonene) on the effectiveness of the push–pull system.

The series of research holds substantial implications for implementing context-specific push–pull control strategies to manage *B. dorsalis* outbreaks and reduce pesticide usage.

2. Materials and Methods

2.1. Study Site

These experiments were conducted in a commercial rambutan, *Nephelium lappaceum* (Sapindales: Sapindaceae), orchard located in Baotang Li and Miao Autonomous County, Hainan Province, China (18°36′39.0″ N, 109°43′12.9″ E). The orchard spanned an area of approximately 60,000 m^2 and comprised approximately 450 *N. lappaceum* trees, all of which were over 5 years old. Situated in a hilly area at an elevation ranging from 120 to 150 m, the orchard experienced severe infestations by *B. dorsalis* during the fruit maturation period from May to October. Based on our preliminary investigations, the *B. dorsalis* infestation began in early May, with trap counts ranging from 30 flies/trap/day. By early June, this count escalated to 300–500 flies/trap/day, and this peak infestation period persisted until late September when fruit harvesting was completed. Importantly, the orchard had not utilized chemical pesticides for approximately 8 months (from October 2022 to June 2023).

In the orchard, a total of 9 large plots (Figure 1a) were selected, with each plot covering an area of approximately 2500 m^2 and containing approximately 35 trees. The distance between these plots exceeded 100 m. To minimize variability between plots, treatments in each experiment (Experiments 1–4) were randomly allocated to different plots, with each treatment having 3 replicates (plots). Furthermore, measures were taken to position the plots as far away from the edges of the orchard as feasible.

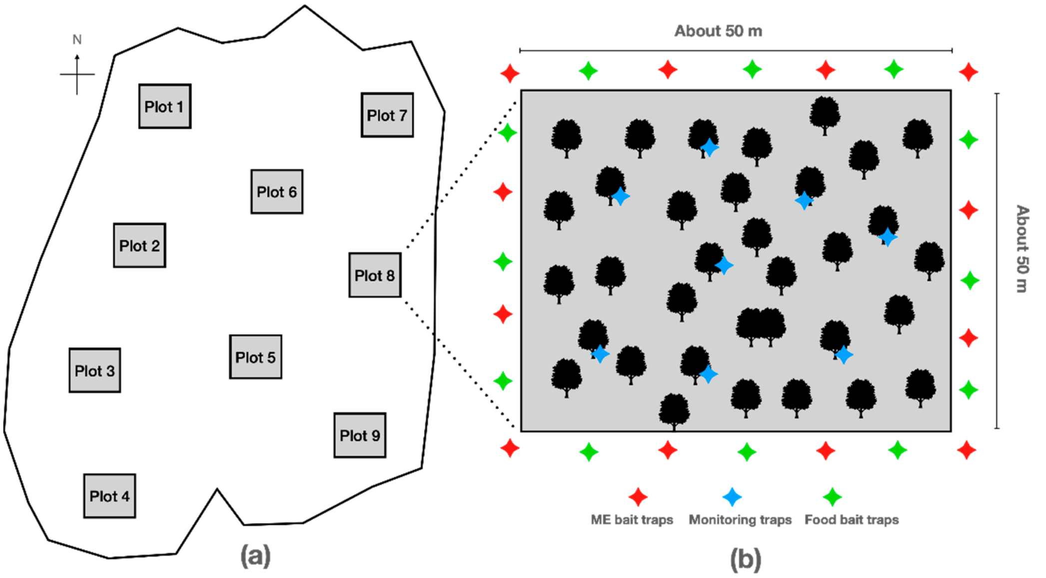

Figure 1. The orchard was divided into nine plots (**a**). In Experiments 1, 2, 3 and 4, each plot was randomly assigned a different push–pull strategy or a control treatment using bromophos + β-cypermethrin without employing the push–pull strategy. (**b**) The schematic representation of the trap distribution in the push–pull system. In Experiments 1 and 2, methyl eugenol (ME) bait traps (red) were used as attractants in the push–pull systems, while food bait traps (green) were not used. In Experiment 3, the ME traps were removed from the push–pull strategy with only food bait. In Experiment 4, both ME traps and food bait traps were deployed for the push–pull strategy using two types of attractants and repellents. For strategies using a single type of repellent and attractant, the food bait traps were not utilized.

2.2. Works Taken before All Experiments

Prior to each of the four experiments (on 1 June, 8 July, 15 August and 22 September 2023), the initial population of *B. dorsalis* was monitored across the 9 plots. The ME trap method described by Biasazin et al. [40] was employed. Unlike their use of McPhail traps, we utilized a white bottle and covered it with a black lip (h = 20 cm, d = 10 cm, see Figure S1a in the Supplementary Material) and treated it with 1 mL of methyl eugenol (ME, Pherobio Technology Co., Ltd., Beijing, China). Eight traps were suspended at a height of 1.8 m above the ground, positioned approximately 30 m apart within the plot (see Figure 1b). After a one-day period, the numbers of captured *B. dorsalis* were counted.

Subsequently, four independent experiments were conducted in a single orchard from 2 June to 29 September 2023, with a 30-day interval, while comparing the reduction rates of *B. dorsalis* populations and the rates of fruit damage among them (calculation of these rates was provided below). The investigations revealed that treatments involving early spraying did not yield a significant impact on the *B. dorsalis* population after a period of 30 days. The average initial number among the four experiments was 502.5, 466.2, 507.5 and 483.8 flies, respectively, and no significant differences were found (Kruskal–Wallis test: $\chi^2 = 2.43$, df = 3, $p = 0.225$; performed using GraphPad Prism software version 8.0 for Windows (San Diego, CA, USA, www.graphpad.com (accessed on 4 September 2023))) as the population returned to pre-spraying levels. Concurrently, the 30-day break aligned with the harvest cycle of mature *N. lappaceum* fruits, effectively curtailing the interference of residual fruit bodies on the potency of ensuing treatments. Moreover, within this temporal scope, the tropical climate of Hainan Island provided a relatively stable thermal range of 28 to 32 °C, mitigating the potential distortion of experimental outcomes attributable to thermal fluctuations. Additionally, the methods summary for these four experiments is shown in Table 1.

Table 1. The methods summary for these four push–pull strategies involved the use of repellents and attractants to represent the push and pull components, respectively.

Push (Repellent Used)	**Pull (Attractant Used)**
Experiment 1: Push–Pull System with and without Low-Concentration Pesticide	
Allicin	Methyl eugenol
Allicin + abamectin	Methyl eugenol
Experiment 2: Drone-Based System vs. Manual-Based System	
Drone-applied allicin + abamectin	Methyl eugenol
Manually applied allicin + abamectin	Methyl eugenol
Experiment 3: Food Bait vs. ME Bait	
Manually applied allicin + abamectin	Food bait
Manually applied allicin + abamectin	Methyl eugenol
Experiment 4: Two Types of Repellents and Attractants vs. a Single Type	
Allicin + d-limonene + abamectin	Food bait + methyl eugenol
Allicin	Methyl eugenol

2.3. Experiment 1: Push–Pull System with and without Low-Concentration Pesticide

Based on our pre-experimental monitoring, we found a high population density of *B. dorsalis* in the orchard, with 502.5 flies per trap per day at the beginning of June 2023. The traditional push–pull system is typically most effective as a preventive measure against pest outbreaks when pest populations are relatively low [20,38,41,42]. However, when pest populations become too high, they can overwhelm the control system, leading to saturation and reduced efficacy. To mitigate the issues associated, we incorporated low-concentration abamectin into the push–pull strategy.

The experiments were conducted from 2 June to 9 June 2023. Out of nine plots, three were randomly selected for the implementation of push–pull systems without the use of abamectin in each plot. Within each selected plot, manual spraying of the repellent (allicin) was performed, while attractants (ME traps) were placed around the plot's perimeter.

For the spraying application, allicin (80%, Xinwolong Biochemical Co., Ltd., Nanyang, China) was dissolved in water at a concentration of 3.2 ppm (recommended concentration: 3–5 ppm). A volume of 360 mL per hectare was applied (recommended rate: 300–900 mL/ha). This solution was evenly sprayed on the tree canopy and lower levels between 10:00 a.m. and 11:00 a.m. The spraying process utilized a high-pressure agricultural sprayer (YL-160Lsnx2, Fujiwara, Taizhou, China) (refer to Figure S1b in the Supplementary Material).

Three additional plots were randomly selected, maintaining the same treatment procedure but including a low concentration of abamectin in the allicin spray. Initially, a mixture was prepared by combining allicin (3.2 ppm) and abamectin (0.2 ppm, Guanyongqiaodi Agricultural Technology Co., Ltd., Zhoukou, China) at a 1:1 ratio. Subsequently, 720 mL of the resulting blend was applied per hectare (each component at 360 mL per hectare). The abamectin concentration recommended by the manufacturer for application on fruit trees ranged from 2 to 5 ppm, with an application rate of 800 to 1200 mL per hectare. In this experiment, a lower concentration of abamectin was used than the recommended level to maintain the non-toxic nature of the push–pull system. The resulting solution was manually sprayed within the orchard, following the previously outlined procedure.

In the three remaining plots, a standard insecticidal control mixture commonly used in China was applied. This mixture comprised 22% β-cypermethrin (2 ppm, Henglida Technology Co., Ltd., Jinan, China) and 50% bromophos (2 ppm, Xianda Technology Co., Ltd., Zhoukou, China) pesticides in a 1:1 ratio. Each component was applied at a rate of 360 mL and 300 g per hectare, respectively (recommended concentrations for both were 2–5 ppm and the application rates were 300–1200 mL and 300–1000 g per hectare, respectively). The application was carried out manually, following established methodologies. It is worth noting that as this experiment was conducted in a commercial orchard, there was no blank control group, as non-treatment was not permitted by the farmers due to economic reasons.

We deployed 12 attraction ME traps around the perimeter (Figure 1b). These traps were hung at a height of 1.8 m and positioned 3–5 m away from the edge of each plot to serve as the "push" attractant. On the third and seventh day of the experiment, 8 monitoring traps were suspended inside each plot (Figure 1b), following the same procedure as described earlier.

For assessing the fruit damage rate, we employed the five-point sampling method, which entailed selecting five *N. lappaceum* trees from each plot and collecting five mature fruits from each cardinal direction (east, south, west and north; height = 1–2 m) per tree, totaling twenty fruits per tree. These fruits were peeled and meticulously examined to detect *B. dorsalis* larvae and calculate the damage rate. Since most larvae did not hatch within the first three days and did not cause visible damage symptoms (visible damage symptoms typically appeared after five days of infection), we assessed the fruit damage rate only on the seventh day. This technique was also applied in Experiments 2, 3 and 4.

2.4. Experiment 2: Drone-Based System vs. Manual-Based System

In these experiments, we incorporated drone or manual spraying techniques to apply repellent and abamectin. The experiments took place across identical nine experimental plots spanning from 9 July to 16 July 2023, precisely one month after the conclusion of Experiment 1. Due to finding out in Experiment 1 that including abamectin in the spraying system could reduce the fruit fly population and fruit damage rate (see Section 3 and Figure 2) more efficiently than without, in Experiments 2, 3 and 4, all the spraying systems included abamectin.

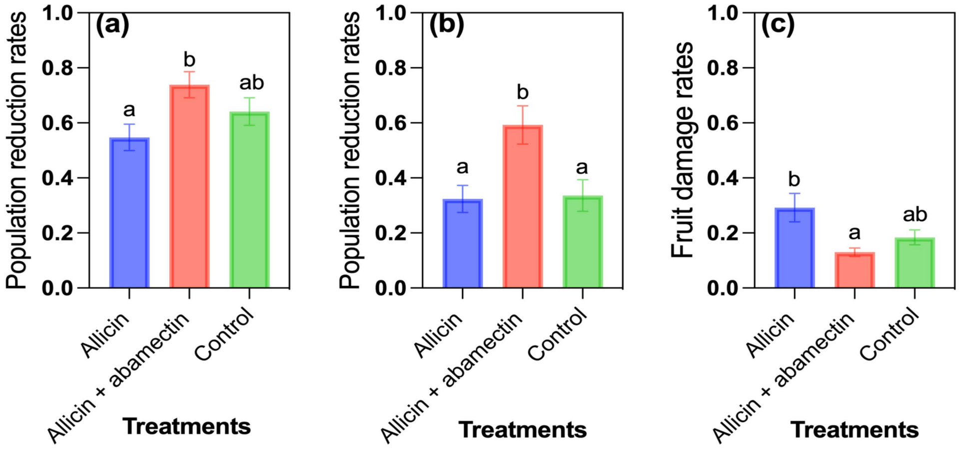

Figure 2. The effects of incorporating abamectin into the push–pull system on the population reduction rate of *B. dorsalis* after 3 days (**a**) and 7 days (**b**), as well as the fruit damage rate (**c**), were tested by using the Kruskal–Wallis tests. "Allicin" indicates the system with allicin as the push repellent, while "allicin + abamectin" refers to the push repellent incorporating abamectin. Both systems used ME as the attractant. "Control" represents the pesticide treatment (bromophos + β-cypermethrin) without using the push–pull strategy. The absence of significant differences between treatments is indicated by the same letters above the distinct bars ($p < 0.05$).

For the drone spraying method, we employed a DJIT30 drone (Dajiang Innovation Technology Inc., Shenzhen, China; see Figure S1c) in three randomly selected plots. The drone featured a flow rate of 0.379 L/min, producing fog droplets ranging from 130 to 250 μm in size. The spray mixture, comprising 80% allicin (repellent) and 5% abamectin (3.2 ppm and 0.2 ppm, respectively), was prepared following the procedures outlined in Experiment 1. Spraying operations were conducted by the drone at a height of 1.8 m above the tree canopy, with application occurring between 10:00 a.m. and 11:00 a.m.

For the manual-based system, we utilized the same materials (allicin, abamectin and ME) and preparation methods as in the drone spraying method. However, we applied the repellents and abamectin manually within the experimental plots (three plots), following the manual spraying treatment outlined in Experiment 1. The remaining three plots served as the standard insecticidal control, with the same preparation and application protocols as outlined in Experiment 1.

2.5. Experiment 3: Food Bait vs. ME Bait

The study aimed to ascertain the most suitable bait type for establishing an effective pull–push control system for *B. dorsalis*. Food baits typically consist of hydrolyzed proteins or sugars, which appeal to both male and female flies [43–45]. In contrast, ME bait contains components of sex pheromones, specifically targeting male flies [10,13]. Therefore, these baits operate through distinct mechanisms [1,46].

The experiments took place from 16 August to 23 August 2023. In this trial set, three random plots received the same treatments as outlined in the manual-based system described in Experiment 2. Additionally, three other plots were subjected to a combination of food bait and ME bait, forming a food and ME bait system. The food bait used was a commercial product (Q/BI001-2022, Bioglobal Agricultural Science Co., Ltd., Shenzhen, China), primarily composed of fermented sucrose. These food baits were mixed with abamectin and water at a ratio of 1:0.1:20, resulting in a solution of 3000 mL of food bait, 300 mL of abamectin (0.2 ppm) and 60 L of water per hectare. This mixture was then added to the food bait traps (each containing 30 mL). The food baits were suspended according to the depiction in Figure S1d and arranged following the layout illustrated in Figure 1b. The remaining three plots functioned as the standard insecticidal control, following the previously described protocols.

2.6. Experiment 4: Two Types of Repellents and Attractants vs. a Single Type

In the fourth experiment, conducted from 23 September to 29 September 2023, we introduced 95% d-limonene (Macklin Biochemical Co., Ltd., Shanghai, China) as an additional repellent and food bait (as described previously) as an additional attractant. The aim was to evaluate whether incorporating multiple types of repellents and attractants could enhance the efficacy of the push–pull system.

For the push–pull systems incorporating two types of repellents and attractants, we prepared a concoction comprising allicin (repellent 1, 3.2 ppm), d-limonene (repellent 2) and 5% abamectin (0.2 ppm) mixed in a ratio of 1:0.5:1. This mixture was then diluted at a ratio of 1:2500, resulting in 360 mL per hectare, and manually applied to the *N. lappaceum* trees. Additionally, 12 food bait traps (as attractant 1) and ME bait traps (as attractant 2) were strategically positioned around the plot's perimeter, following the layout depicted in Figure 1b.

For treatments utilizing a single type of repellent (allicin) or attractant (ME), the "push" involved manually applying allicin combined with abamectin, while the "pull" utilized ME bait. The remaining three plots functioned as the standard insecticidal control.

2.7. Data Analysis

For each plot, the reduction rate of *B. dorsalis* population was calculated by subtracting the final average number of flies caught in the 8 ME monitoring traps from the initial average number, then dividing the result by the initial average number. The fruit damage rate was determined by counting the number of damaged fruits and dividing it by the total number of fruits collected from five trees. To assess the normality and homogeneity of variance, the Shapiro–Wilk test and Levene's test were employed, respectively. Due to the non-normal distribution of the data, the variance analysis of *B. dorsalis* population reduction rates and fruit damage rates among different treatments within the same experiment (Experiment 1, 2, 3 or 4) and days (third or seventh day) was conducted using the Kruskal–Wallis test [47]. Multiple comparisons were carried out using the two-stage linear step-up procedure of Benjamini, Krieger and Yekutieli. All statistical analyses were performed using GraphPad Prism software version 8.0 for Windows (San Diego, CA, USA, www.graphpad.com (accessed on 4 September 2023)).

3. Results

3.1. Push–Pull System with and without Low-Toxicity Pesticide

The incorporation of abamectin into the push–pull system significantly influenced both the population reduction rates and fruit damage rates of *B. dorsalis*. The statistical analysis revealed significant effects at both 3 days ($\chi^2 = 6.15$, df = 2, $p = 0.046$) and 7 days ($\chi^2 = 8.67$, df = 2, $p = 0.013$) on the population reduction rates. After a 3-day period, the push–pull system with abamectin achieved a 74.9% reduction rate in the *B. dorsalis* population, which was significantly higher than the 54.6% reduction observed in the push–pull system without abamectin (Figure 2a). After 7 days, the system containing abamectin had a notable reduction rate of approximately 60%, significantly outperforming both the system without abamectin and the control (Figure 2b). Additionally, the inclusion of abamectin resulted in a significant decrease in the fruit damage rate to 13.0% after 7 days, markedly lower than that observed in the system without abamectin (Figure 2c).

3.2. Drone-Based System vs. Manual-Based System

The method of manual spraying exhibited significant effects on the population reduction rate (3d: $\chi^2 = 10.59$, df = 2, $p = 0.005$; 7d: $\chi^2 = 8.84$, df = 2, $p = 0.012$) of *B. dorsalis* and fruit damage rates ($\chi^2 = 6.03$, df = 2, $p = 0.042$) compared to drone spraying. After 3 days, the reduction rate of *B. dorsalis* populations in the drone spraying treatment was only 35.4%, significantly lower than both manual spraying (65.5%, Figure 3a) and the control (62.4%, Figure 3a). Following 7 days, the reduction rate of *B. dorsalis* populations in the manual spraying treatment was 57.4%, whereas the drone spraying treatment had declined to 28.0%, significantly lower than the manual spraying treatment (Figure 3b). In terms of fruit damage rate, although the variance analysis revealed differences, multiple comparisons indicated no significant distinctions among the fruit damage rates of drone spraying, manual spraying and control treatments (Figure 3c).

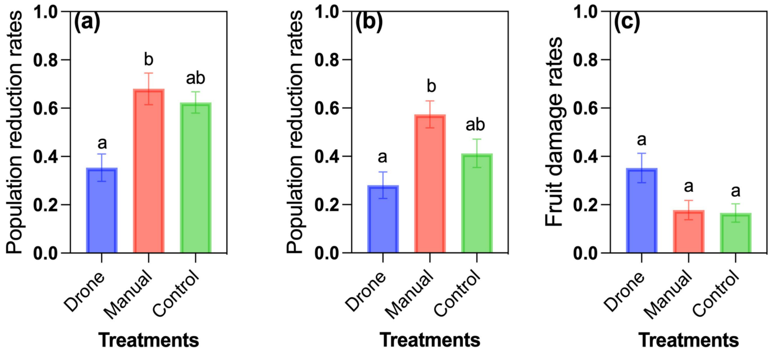

Figure 3. The impact of a drone-based push–pull system and a manual-based push–pull system on the population reduction rate of *B. dorsalis* after 3 days (**a**) and 7 days (**b**), as well as the fruit damage rate (**c**), was tested by using Kruskal–Wallis tests. "Drone" refers to the push–pull system utilizing drones, while "Manual" denotes the push–pull system operated manually. "Control" represents the pesticide treatment (bromophos + β-cypermethrin) without using the push–pull strategy. The absence of significant differences between treatments is indicated by the same letters above the distinct bars ($p < 0.05$).

3.3. Food Bait vs. ME Bait

The choice of bait (ME bait or food bait) employed to establish the push–pull system significantly affected the population reduction rate (3d: $\chi^2 = 6.41$, df = 2, $p = 0.040$; 7d: $\chi^2 = 8.14$, df = 2, $p = 0.018$) of *B. dorsalis* and fruit damage rate ($\chi^2 = 8.72$, df = 2, $p = 0.006$). After 3 days, the push–pull system established with food bait resulted in a population reduction rate of 45.5% for *B. dorsalis*, significantly lower than the reduction rates of 70.9% in the ME bait system and 63.4% in the control (Figure 4a). After 7 days, the reduction rate of *B. dorsalis* populations in the push–pull system using food bait remained significantly lower than that of the ME bait system (Figure 4b). In terms of the fruit damage rate, both the ME bait system and the control demonstrated notably lower rates compared to the push–pull system using food bait (Figure 4c).

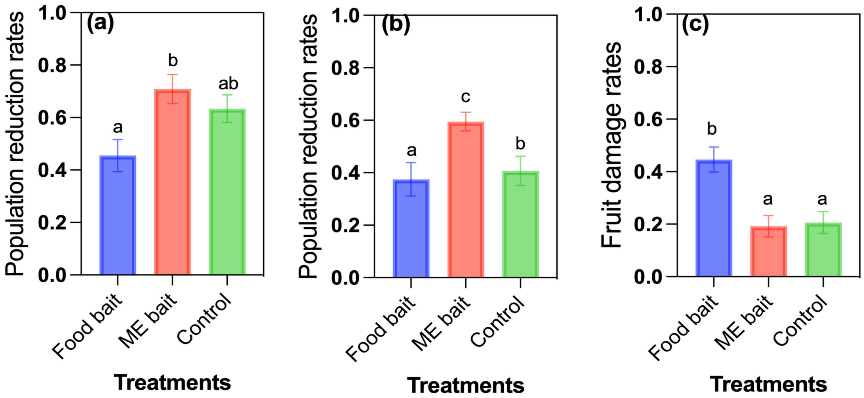

Figure 4. The influence of a food bait push–pull system and a ME bait push–pull system on the population reduction rate of *B. dorsalis* after 3 days (**a**) and 7 days (**b**), as well as the fruit damage rate (**c**), was tested by using Kruskal–Wallis tests. "Food bait" refers to the push–pull system employing food bait, while "ME bait" indicates the push–pull system using ME bait. "Control" represents the pesticide treatment (bromophos + β-cypermethrin) without using the push–pull strategy. The absence of significant differences between treatments is denoted by the same letters above the distinct bars ($p < 0.05$).

3.4. Two Types of Repellents and Attractants vs. A Single Type

Comparing push–pull systems established with two types of repellents and attractants to the push–pull system established with a single type, no significant impact on the reduction rate of *B. dorsalis* populations was observed after 3 days ($\chi^2 = 4.47$, df = 2, $p = 0.107$; Figure 5a). However, after 7 days, the push–pull systems constructed with two types exhibited higher reduction rates than the single-type system ($\chi^2 = 13.93$, df = 2, $p = 0.001$; Figure 5b), although the differences were not statistically significant. Nevertheless, all three treatments displayed similar fruit damage rates of approximately 20%, with no significant distinctions observed among them ($\chi^2 = 0.08$, df = 2, $p = 0.968$; Figure 5c).

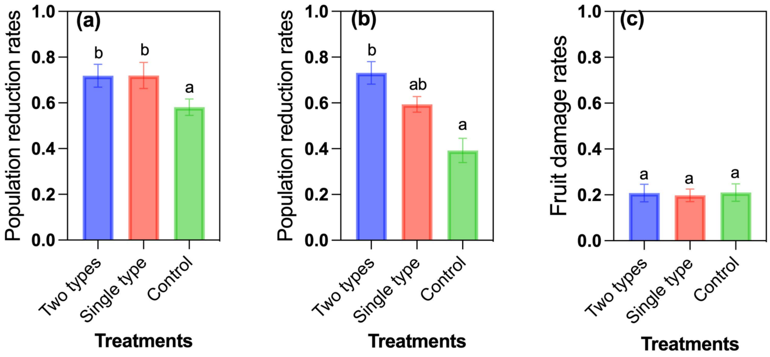

Figure 5. The effects of a push–pull system with two types of repellents and attractants and a push–pull system with a single type on the population reduction rate of *B. dorsalis* after 3 days (**a**) and

7 days (**b**), as well as the fruit damage rate (**c**), were tested by using Kruskal–Wallis tests. “Two types” refer to the push–pull system utilizing two types of repellents and attractants, while “Single type” indicates the push–pull system using a single type of repellents and attractants. “Control” represents the pesticide treatment (bromophos + β-cypermethrin) without using the push–pull strategy. The absence of significant differences between treatments is indicated by the same letters above the distinct bars ($p < 0.05$).

4. Discussion

The current study, conducted within a rambutan orchard, aimed to compare and evaluate various push–pull strategies for mitigating the outbreak of *B. dorsalis* and minimizing damage to fruit crops. The results indicated that integrating the low-concentration pesticide abamectin into the push–pull system, along with using methyl eugenol (ME) as an attractant instead of food bait and employing manual application, effectively reduced the population of *B. dorsalis* and fruit damage. Additionally, the introduction of a variety of attractants and repellents did not enhance the control’s effectiveness compared to systems containing only single attractants and repellents.

The outcomes of this investigation clearly demonstrated an improvement in suppressing the *B. dorsalis* population with the integration of abamectin into the push–pull system. In scenarios without abamectin, the reduction rate of *B. dorsalis* population did not exceed 60%, whereas with abamectin, it surpassed 70%, accompanied by a significant reduction in fruit damage. While prior literature often favored non-toxic practices in push–pull strategies to align with their underlying philosophy [20,32], this investigation provided evidence that incorporating low-concentration compounds like abamectin during pest outbreaks offers a practical and effective approach. This strategy deviated from conventional push–pull usage, which typically focuses on pre-outbreak prevention. However, this study highlighted the need for further research to elucidate the mechanisms underlying abamectin-induced population regulation and to explore potential synergistic effects. To achieve this, subsequent experiments should employ a factorial design with main factors of interest: abamectin (with and without), attractant (ME and food) and repellent (allicin and d-limonene).

In comparing methodologies within the push–pull system, manual spraying emerged as more effective than drone-assisted spraying. While the latter offered benefits such as labor reduction and the ability to reach elevated areas [48,49], its application was less effective in orchards characterized by complex terrains and dense foliage, particularly when addressing the upper canopy layers, where insecticides’ penetration is obstructed [50]. Migratory pests such as *B. dorsalis*, which might retreat to the lower canopy, thereby circumvent drone-delivered treatments, presenting an ongoing risk. As a result, drone spraying manifested a suboptimal control efficiency. In contrast, manual spraying, although labor-intensive, allowed for a more targeted dispersion of insecticides throughout the various strata of the canopy, effectively pressing the residual pest population to vacate the orchard, thus, bolstering the overall efficacy of pest control.

The choice of suitable repellents and attractants is crucial when designing a push–pull system. Our study demonstrated the superiority of using methyl eugenol (ME) in constructing the push–pull system for controlling *B. dorsalis*, which was consistent with the findings of Ugwu [51]. One possible reason for this is that the odor of food baits is more easily affected by environmental factors such as vegetation type and tree canopy density compared to ME [52]. Therefore, ME should be preferred in constructing a push–pull system for managing *B. dorsalis*.

While the integration of d-limonene and food bait did not significantly enhance the immediate efficacy of the push–pull system in mitigating *B. dorsalis* infestations, their inclusion was observed to extend control effectiveness for up to 7 days. Notably, even after seven days, the system’s ability to control the pest population remained robust, exceeding a 70% threshold. The underlying factors for this sustained effectiveness are yet to be fully elucidated; however, it may be attributed in part to the short-range killing effect of d-limonene on dipteran species, as demonstrated by Showler et al. [53]. Nevertheless, increasing the variety of attractants or repellents inevitably raises labor and material costs. Therefore, if cost efficiency is a concern, employing a single type of attractant or repellent can still yield satisfactory results. However, if a more long-lasting pest control effect is desired, it may be worth considering increasing the variety of attractants and repellents.

In this experiment, the implementation of a push–pull control system proved to be more effective in reducing both the *B. dorsalis* population and fruit damage compared to relying solely on chemical pesticides. This effectiveness may have stemmed from the push–pull system's ability to decrease *B. dorsalis* resistance, as noted by Hassanali et al. [54], through the integration of various control measures from different perspectives. This integration reduced the prolonged exposure of pests to specific control methods, thereby decreasing the frequency of contact and adaptation time to a single control method, ultimately, slowing down the development of resistance [20].

Although we used abamectin in this experiment, the concentration we employed (0.2 ppm) was significantly lower than the recommended concentration. Additionally, individuals not killed by low-concentration abamectin, such as those with higher resistance, are still regulated by the push–pull system, being lured into traps and subsequently killed, thereby reducing the opportunity for resistant individuals to reproduce. Consequently, this approach would aid in slowing the development of pesticide resistance in *B. dorsalis*. From an environmental pollution perspective, using abamectin alone at high concentrations for controlling *B. dorsalis* requires substantial amounts and yields poor control efficacy. Preliminary experiments showed that using abamectin alone at 5 ppm (recommended concentration) resulted in only a 61.44% reduction in the pest population after 7 days. Achieving a higher reduction rate (e.g., exceeding 70%) required combining abamectin with other pesticides like β-cypermethrin (unpublished data). In contrast, utilizing the push–pull system (see Figure 5a) with a low concentration of abamectin (0.2 ppm) achieved over a 70% reduction in pest population. Thus, our push–pull system reduced the need for abamectin and other pesticides, contributing to a reduction in pesticide resistance development and pesticide pollution.

5. Conclusions

These series of comparative experiments provided compelling evidence that integrating low-concentration abamectin into the push–pull system, along with using methyl eugenol (ME) as an attractant instead of food bait, combined with manual application, constituted an optimal push–pull strategy for reducing *B. dorsalis* populations and preserving fruit quality during pest outbreaks. Moreover, this integrated approach demonstrated potential in mitigating the development of *B. dorsalis* resistance and reducing pesticide usage, thereby minimizing environmental pollution. However, the push–pull system incurred higher labor and material costs and presented challenges in design and implementation compared to conventional control methods, necessitating professional training and guidance for farmers. Additionally, this optimal system may be more advantageous in mountainous terrains, while the use of drones may be a more ideal option in large, flat areas, emphasizing the need for context-dependent push–pull strategies [20,42].

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy14050890/s1.

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