# The Use of Synthetic Herbivory-Induced Plant Volatiles That Attract Specialist Parasitoid Wasps, *Cotesia vestalis*, for Controlling the Incidence of Diamondback Moth Larvae in Open Agricultural Fields

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We evaluated the effectiveness of using a blend of volatiles that attract *Cotesia vestalis*, a specialist parasitoid wasp of diamondback moth (DBM) larvae, to control DBM larvae on cabbage plants under open field conditions. We set three dispensers of the synthetic *C. vestalis* attractant together with one sugary-food feeder in a cabbage plot (10 m × 1 m; the treated plot) on one side of a pesticide-free open agricultural field (approximately 20 m × 20 m) from June to September in 2010 and July to August in 2011. On the other side of the field, we created a control cabbage plot of the same size in which neither dispensers nor a feeder was set. The incidences of DBM larvae and *C. vestalis* cocoons in the control and treated plots were compared. In 2010, the incidence of DBM larvae in the treated plot was significantly lower than that in the control plot. Poisson regression analyses in 2010 showed that the rate of increase in the number of *C. vestalis* cocoons along with an increase in the number of DBM larvae in the treated plot was significantly higher than that in the control plot. In 2011, the incidence in both the treated and control plots remained low (five larvae per plant or less) with no significant difference between the plots. Poisson regression analyses in 2011 showed that the number of *C. vestalis* cocoons in the treated plot was significantly higher than that in the control plot, irrespective of the number of DBM larvae. This 2-year field study suggested that the dispensers recruited native *C. vestalis* from the surrounding environment to the treated plot, and the dispensers controlled the number of DBM larvae in 2010 when the density of DBM larvae exceeded the economic injury levels for the cabbage crop. We also compared the incidences

of other arthropods in the control and treated plots. The incidences of *Pieris rapae* larvae and Plusiinae spp. were not affected by the treatments. The number of aphids in the treated and control plots was inconsistent between the 2 years. Based on these 2-year results, the possible use of *C. vestalis* attractants in open agricultural fields is discussed.

# INTRODUCTION

Plants infested by herbivorous arthropods emit herbivory-induced plant volatiles (HIPVs); one of the ecological functions of HIPVs is to attract carnivorous natural enemies (i.e., parasitoid insects and predatory arthropods) of herbivorous arthropods (Takabayashi and Dicke, 1996; Arimura et al., 2009; McCormick et al., 2012; Takabayashi and Shiojiri, 2019). The attraction of natural enemies with HIPVs could be one of the induced indirect defence strategies of plants against herbivores when the emission reduces damage from herbivores. Interestingly, there are cases where plants attract the specific carnivorous natural enemies of currently infesting herbivorous arthropods by emitting herbivore species-specific blends of HIPVs (Takabayashi and Dicke, 1996; Arimura et al., 2009; McCormick et al., 2012; Takabayashi and Shiojiri, 2019).

Diamondback moth (DBM) (*Plutella xylostella*) larva is one of the most destructive pests of cruciferous crops worldwide, and it has developed resistance to many insecticides (Talekar and Shelton, 1993; Furlong et al., 2013). The annual cost for managing it is estimated to be USD 4–5 billion (Furlong et al., 2013). *Cotesia vestalis*, a solitary specialist parasitoid wasp of DBM larvae, can be effective in the control of DBM larvae (Talekar and Yang, 1993; Abe et al., 2007; Furlong et al., 2013). *C. vestalis* prefers DBM larvae-infested crucifer plants (cabbage or Japanese radish) to artificially damaged plants or plants infested by non-host larvae (cabbage white butterfly larvae, *Pieris rapae*) (Shiojiri et al., 2000), suggesting the above-mentioned specific responses to herbivore species-specific HIPVs. We also identified a *C. vestalis*-attractive blend of volatiles comprising (*Z*)-3-hexenyl acetate, α-pinene, sabinene, and *n*-heptanal from DBM larvae-infested cabbage plants, and the attractiveness of this synthetic blend to *C. vestalis* was confirmed under laboratory, greenhouse, and field conditions (Shiojiri et al., 2010; Uefune et al., 2012, 2020; Ohara et al., 2017).

The use of HIPVs for pest control has attracted interest (reviews, Khan et al., 2008; Kapran, 2012; Pappas et al., 2017; Turlings and Erb, 2018). Previous studies have used HIPVs commonly released by a wide range of infested plants to attract unspecified natural enemies (e.g., James, 2003a,b, 2005; for review Kapran, 2012). For example, James (2003a) found that (*Z*)-3-hexenyl acetate, one of the green leaf volatiles, attracted predatory mirids and anthocorids, whereas methyl salicylate attracted geocorids and hoverflies in hop yards. Artificial recruitment of specific natural enemies into a target agricultural field from the surrounding environment by utilising herbivore-species-specific HIPVs is another way to control

target pest arthropods. We recently reported that setting dispensers of a synthetic *C. vestalis*-attractive blend of volatiles, together with sugary-food feeders for *C. vestalis*, resulted in a significant reduction in the monthly incidence of DBM in commercial greenhouses, with a significantly higher number of *C. vestalis* recorded when the number of DBM adults increased (Uefune et al., 2020).

It remains to be answered whether *C. vestalis*-attractant can be used not only in greenhouses but also in open agricultural fields for DBM control. Here, as the first step to answer this question, we conducted field experiments using pesticide-free cabbage plots in Kyoto in 2010 and 2011. The possible use of HIPVs that attract specific natural enemies in open agricultural fields is discussed.

# MATERIALS AND METHODS

## Dispensers of *Cotesia vestalis* Attractants

Four HIPVs, (*Z*)-3-hexenyl acetate (>97%: Wako Pure Chemical Industries, Ltd., Osaka, Japan), α-pinene (a mixture of both isomers, >97%: Tokyo Kasei Kogyo Co. Ltd., Tokyo, Japan), sabinene (>70%: RC Treatt & Co. Ltd., Suffolk, United Kingdom), and *n*-heptanal, (>95%: Tokyo Kasei Kogyo Co. Ltd., Tokyo, Japan) were mixed in a mass ratio of 1.8:1.3:2.0:3.0 based on gas chromatographic analysis of emissions from DBM-infested cabbage plants (Shiojiri et al., 2010). The mixture was dissolved in triethyl citrate (TEC, >99%: Pfizer, New York, United States) to facilitate a low volatilisation rate.

Dispensers were constructed by saturating each of five cellulose blocks (22 mm × 35 mm × 2.8 mm) (Hioki Co Ltd. Tokyo, Japan) with 1.7 g of TEC. These blocks were aligned in a row and wrapped in micropore polyethylene film (30 mm × 40 mm × 100 μm) (Mitsui Plastic Trade Co., Tokyo, Japan) using a thermal sealing device to ensure a low volatilisation rate (for details, see Kugimiya et al., 2017). Based on the results of a previous field study, we used a dispenser with 425 mg attractant (85 mg per block) for the open field experiments (for details, see Uefune et al., 2020).

Kugimiya et al. (2017) reported that the attractiveness of one cellulose block covered with film with the same amount (85 mg) of the attractant, as in this study, and that with 0.85 mg attractant were not significantly different under laboratory conditions. Further, the block with 85 mg

attractant emitted more than 10% of the attractant after 42 days. The ratios of the blend showed some changes according to duration. However, these slight changes will not affect the attraction, since Uefune et al. (2013a) reported that not only the real blend (used in this study) but also an artificially made blend (1:1:1:1 blend: similar to the blend after 42 days) attracted *C. vestalis*. Thus, in this study, the dispensers were expected to be attractive during the experimental period.

## Field Experimental Conditions

Field experiments were conducted in an open agricultural field owned by a farmer in a rural area of the northern part of Kyoto City, Japan. We set two plots (10 m × 1 m each) at opposite ends of the field (northwest and southeast). In each plot, we planted 50 cabbage seedlings (*Brassica oleracea* var. *capitata* 'Shikidori') on 12 June 2010 and 19 June 2011. Sweet potato plants were grown by the owner of the fields in the area between the two plots (17 m × 17 m). No pesticides were applied during the experimental period. We switched the control plot with the treated plot in the second year to exclude the effect of space.

One plot (the northwest plot in 2010 and the southeast plot in 2011) was assigned to be the treated plot in which the dispensers and feeder were set. On the planting day, we set three dispensers, each of which was attached to an iron pole 2

m above the ground. Three poles were set every 3 m along the plot, and one sugary-food feeder (5 cm diameter × 7 cm tall yellow glass bottle filled with honey; for details, see Shimoda et al., 2014) was set 50 cm above the ground on the centre pole. Another plot on the opposite side was assigned to be the control plot, in which neither dispensers nor feeders were set. The experimental days were as follows: 25 June, 2 July, 17 July, 22 July, 4 August, 26 August, 3 September, and 10 September 2010, and 8 July, 15 July, 9 August, 18 August, and 31 August 2011. We attached a new dispenser to each pole and renewed the feeder on 2 July, 22 July, and 26 August 2010, and on 15 July and 18 August 2011.

We observed 10 randomly chosen cabbage plants and counted the number of DBM larvae and cocoons of *C. vestalis* in the treated and control plots. DBMs and *C. vestalis* cocoons are commonly found on wild cruciferous weeds, particularly on yellowcress plants (*Rorippa indica*) in the northern part of Kyoto (Abe et al., 2020). In the treated and control plots, we also recorded aphids, *Pieris rapae* larvae, and Plusiinae spp. larvae as pest insects of cabbage crops; the caterpillars are non-hosts of *C. vestalis*. We also observed parasitised aphids (mummies) and clusters of cocoons of *C. glomerata*, a parasitoid wasp of *P. rapae* larvae. The numbers of these arthropods were also recorded. The observed arthropods, except for aphids, were identified based on their morphology. The aphid species observed in the plots were not identified.
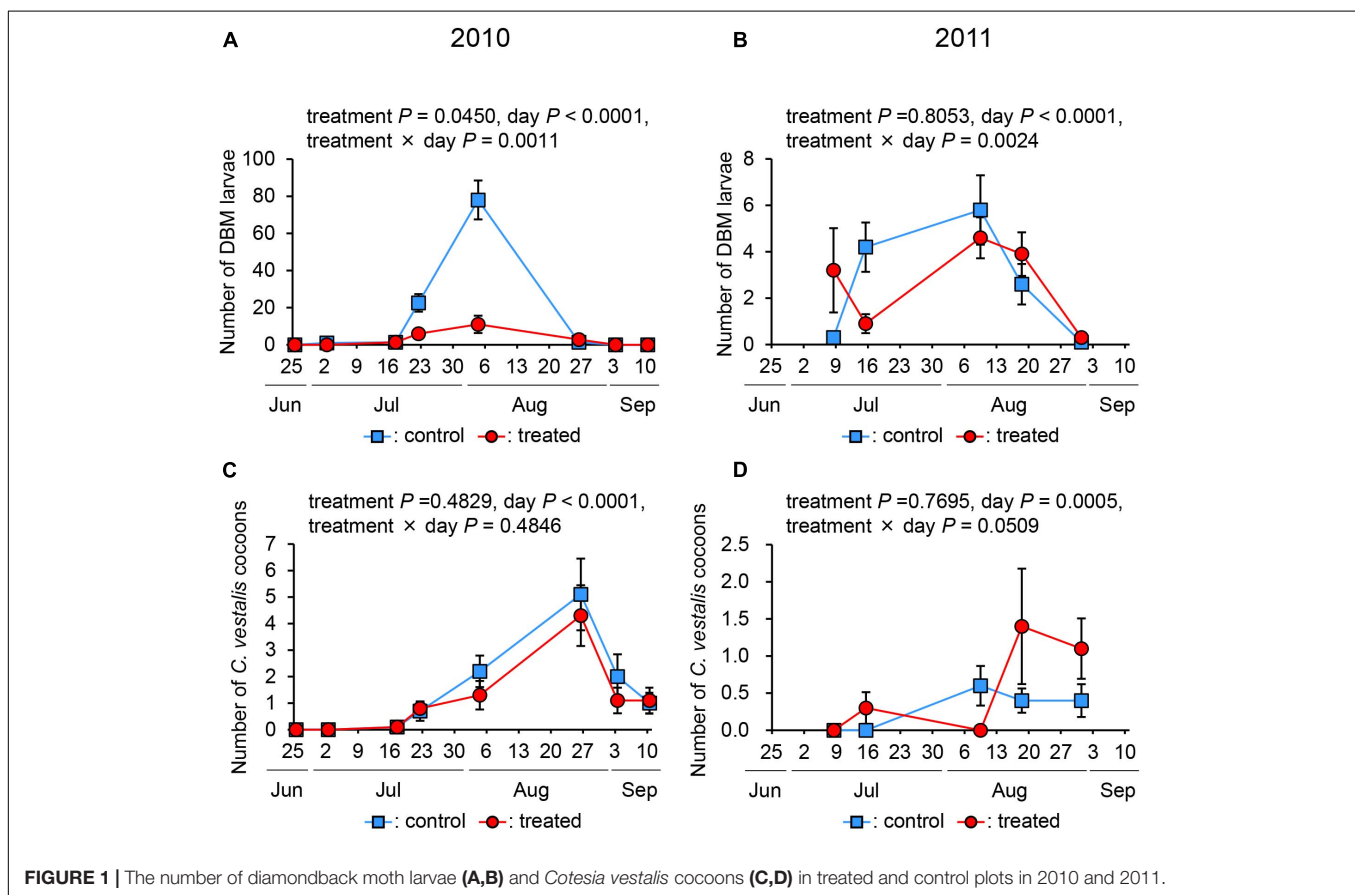


**FIGURE 1 |** The number of diamondback moth larvae **(A,B)** and *Cotesia vestalis* cocoons **(C,D)** in treated and control plots in 2010 and 2011.

## Statistics

### Comparisons Between Treated and Untreated Plots

We analysed the effects of the treatment, day, their interaction on the number of DBM larvae, *C. vestalis* cocoons, and other insect pests and their natural enemies in the treated and control plots. To do so, we used the least square mixed model after Box-Cox transformation in JMP version 14.2.0 (SAS Institute, 2018). When a data set had 0 values, 0.5 was added to all values in the data set before the Box-Cox transformation. The individual cabbage plant was a random effect in all models.

### The Relationship Between DBM Larvae and *Cotesia vestalis* Cocoons in the Treated and Control Plots

To analyse the relationship between DBM larvae and *C. vestalis* in the treated and control plots, we focussed on the number of *C. vestalis* relative to the increased number of DBM. To do this, we used Poisson regression analysis in JMP version 14.2.0 (SAS Institute, 2018).
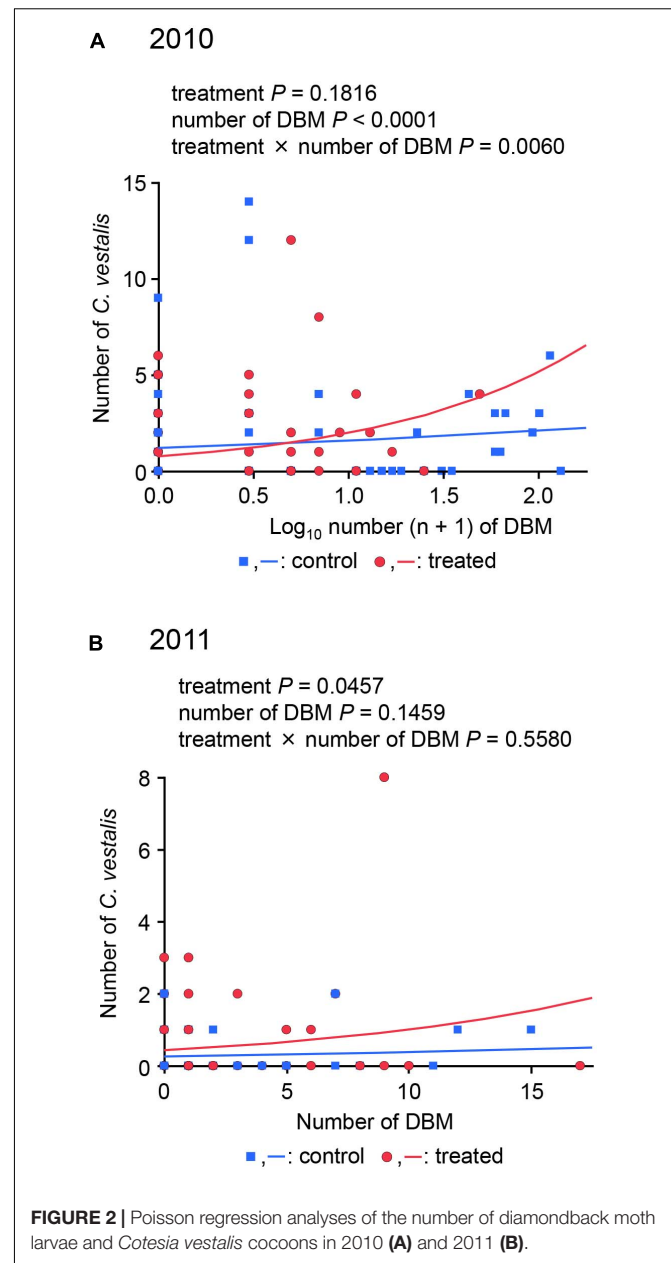
## RESULTS

## Number of DBM Larvae and *Cotesia vestalis* Cocoons

Regarding the number of DBM larvae, the effect of day in both years was significant ($P < 0.0001$). In 2010, the effects of treatment and interaction between the treatment and day were significant (treatment: $P = 0.0450$, and interaction: $P = 0.0011$) (**Figure 1A**), indicating that the treatment suppressed the number of DBM larvae and that this effect varied on individual days. In 2011, the effect of treatment was not significant ($P = 0.8053$), while that of the interaction between treatment and day was significant ($P = 0.0024$) (**Figure 1B**), indicating that the treatment did not suppress the number of DBM larvae.

Regarding the number of *C. vestalis*, the effect of day in both years was significant (in 2010, $P < 0.0001$; in 2011, $P = 0.0005$). The treatment and interaction between the treatment and day in both years were not significant (in 2010, treatment: $P = 0.4829$, and interaction: $P = 0.4846$; in 2011, treatment: $P = 0.7695$, and interaction: $P = 0.0509$), indicating that the number of *C. vestalis* in the treated plot was not significantly different from that in the control plot in both years (**Figures 1C,D**).

## The Relationship Between the Number of DBM Larvae and *Cotesia vestalis* Cocoons

In 2010, Poisson regression analyses showed that the factors of DBM larvae number and interaction (treatment × DBM larvae number) had a significant effect on the number of *C. vestalis* cocoons, while the factor treatment had no effect (treatment: $P = 0.1816$, day: $P < 0.0001$, interaction: $P = 0.0060$) (**Figure 2A**). In contrast, in 2011 the treatment had a significant effect on the number of *C. vestalis* cocoons, while the number of DBM and the day × treatment



**FIGURE 2 |** Poisson regression analyses of the number of diamondback moth larvae and *Cotesia vestalis* cocoons in 2010 **(A)** and 2011 **(B)**.

interaction had no significant effect (treatment: $P = 0.0457$, day: $P = 0.1459$, interaction: $P = 0.5580$) (**Figure 2B**). As interaction (2010) or treatment (2011) was significant, it is concluded that the treatment results in a significantly higher number of *C. vestalis* in the treated plot than in the control plot in both years.

## Number of Aphids and Aphid Mummies

Regarding the number of aphids, the day was significant in both years ($P < 0.0001$). In 2010, treatment was significant ($P = 0.0038$), while the interaction between treatment and day was not ($P = 0.2264$) (**Figure 3A**), indicating that the treatment results in the suppression of the number of aphids. In 2011, the effects of treatment and interaction between day
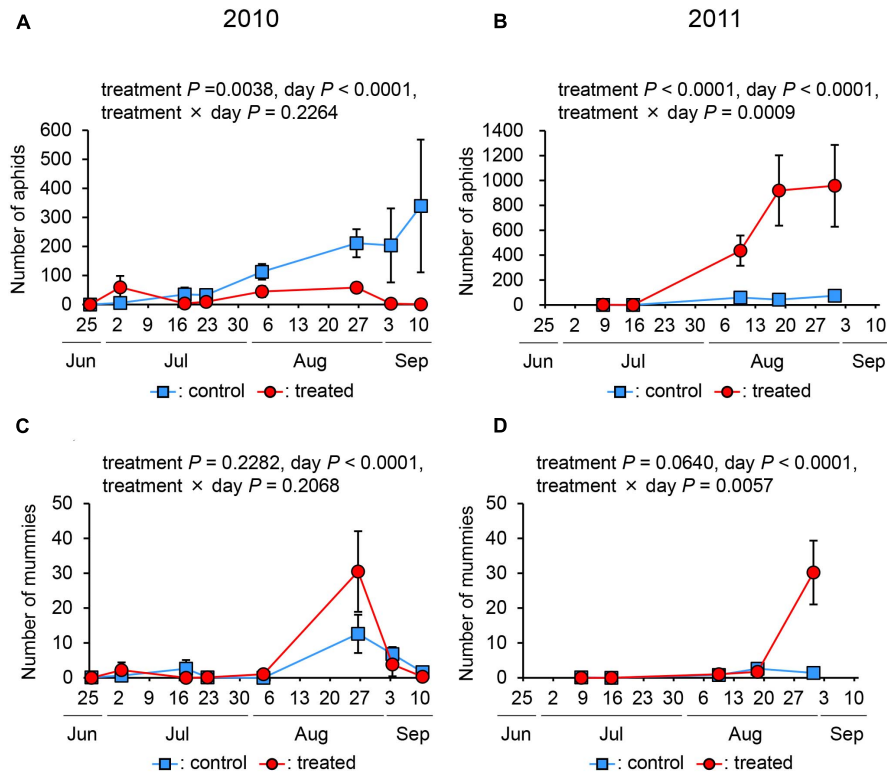
**FIGURE 3** | The number of aphids **(A,B)** and parasitised aphids (mummies) **(C,D)** in treated and control plots in 2010 and 2011.
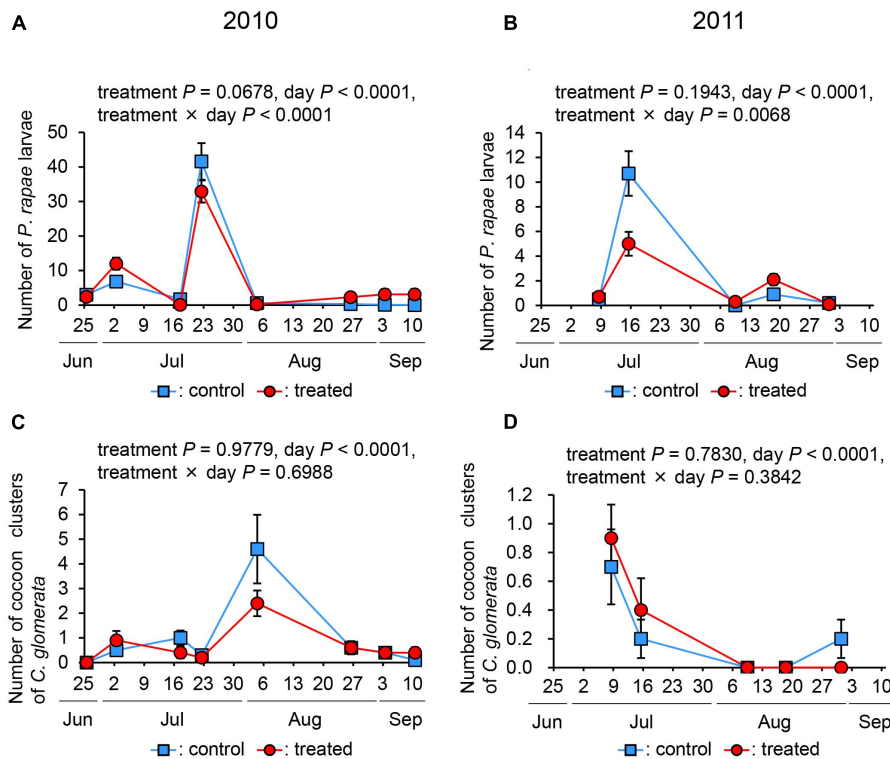


**FIGURE 4** | The number of *Pieris rapae* larvae **(A,B)** and *Cotesia glomerata* clusters of cocoons **(C,D)** in treated and control plots in 2010 and 2011.

and treatment were both significant (treatment, $P < 0.0001$; interaction, $P = 0.0009$) (**Figure 3B**). However, in 2011, the number of aphids in the treated plot was higher than that in the control plot.

Regarding the number of mummies, the day was significant in both years ($P < 0.0001$). In 2010, the effect of treatment and day × treatment interaction was not significant (treatment: $P = 0.2282$, and interaction: $P = 0.2068$), indicating that the treatment did not affect the number of mummies. In 2011, the effect of the treatment was not significant ($P < 0.0640$), and that of the interaction was significant ($P = 0.0057$) (**Figures 3C,D**). This indicates that the number of mummies in the treated plot was higher than that in the control plot.

## Number of *Pieris rapae* Larvae and *Cotesia glomerata*

Regarding the number of *P. rapae* larvae, in both years, the effects of treatment were not significant (in 2010, $P = 0.0678$; in 2011, $P = 0.1943$), while those of day and day × treatment interaction were significant (in 2010, day: $P < 0.0001$, interaction: $P < 0.0001$; in 2011, day: $P < 0.0001$, and interaction: $P < 0.0068$) (**Figures 4A,B**).

Regarding the number of *C. glomerata*, the effects of treatment and day × treatment interaction in both years were not significant (in 2010, treatment: $P = 0.9779$, and interaction: $P = 0.6988$; in 2011, treatment: $P = 07830$, and interaction: $P = 0.3842$), while that of day was significant ($P < 0.0001$) (**Figures 4C,D**). These data indicate that the treatment did not affect the number of *P. rapae* larvae and *C. glomerata*.

## Number of Plusiinae spp. Larvae

In both years, the effect of treatment was not significant (in 2010, $P = 0.4056$; in 2011, $P = 0.0962$), while that of day was significant ($P < 0.0001$ in both years). The effect of interaction in 2010 was significant ($P = 0.0170$), while that in 2011 was not ($P = 0.1441$) (**Figure 5**). We did not observe any natural enemies of Plusiinae

spp. larvae. These data indicate that the treatment did not affect the number of Plusiinae spp. larvae.

## DISCUSSION

We set one yellow-coloured sugary-food feeder (Shimoda et al., 2014) in the treated plot in case there were insufficient sugary food sources (i.e., flowers) for adult *C. vestalis* in the surrounding environments during the experiments. In both years, however, sugary food sources in the surroundings were abundant throughout the experimental periods, and *C. vestalis* females visiting either the treated or control plots were, therefore, likely to be satiated. As satiated *C. vestalis* adults are not attracted to yellow colour (Kugimiya et al., 2010; Mitsunaga et al., 2012; Uefune et al., 2013b), it is unlikely that the presence or absence of the yellow-coloured feeder affected the number of *C. vestalis* recorded.

The number of DBM larvae in the control plot in 2011 was consistently low (approximately five larvae per plant), while in the control plot in 2010, an outbreak of DBM larvae was observed. It should be noted that insecticides were not used in either year. The difference in the number of DBM larvae in the control plots in 2010 and 2011 revealed the following two aspects of the treatment.

In 2010, we observed a high number of DBM larvae in the control plot, whereas in the treated plot, the number was consistently low, with a significant difference between the two plots. In the Poisson regression analyses, the effect of DBM number and the interaction of DBM with treatment (treatment × DBM number) were significant. This means that in the treated plot, the increase in the number of *C. vestalis* cocoons, along with an increase in the number of DBM larvae in the treated plot, was significantly higher compared to the control plot. *C. vestalis* females are attracted to the attractant under field conditions, and this attraction increases the incidence of parasitism by *C. vestalis* (Uefune et al., 2012). Thus, it is likely that more *C. vestalis* females are attracted from the surrounding



**FIGURE 5 |** The number of Plusiinae larvae in treated and control plots in 2010 and 2011.
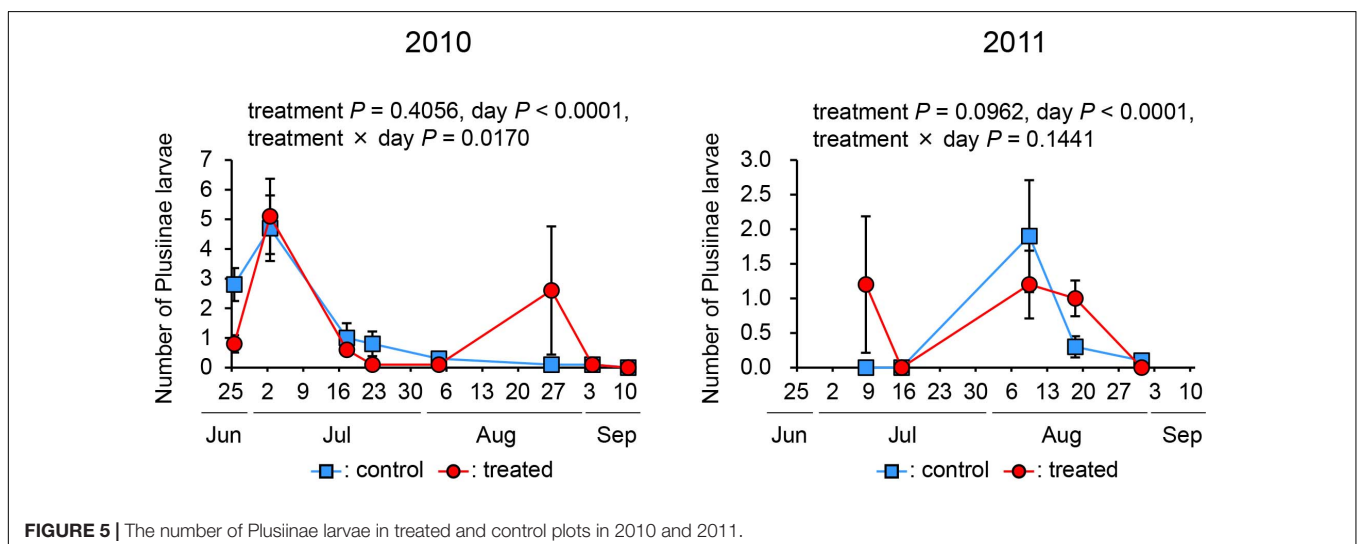
area to the treated plot than to the control plot in a DBM-larvae density-dependent manner. This was also supported by the fact that the incidences of *C. vestalis* cocoons were the same between the control and treated plots, even though the incidence of DBM larvae was significantly different between the two plots. Taken together, in 2010, it is indicated that the attraction of *C. vestalis* to the dispensers in the treated plot contributed to the significant reduction in DBM larvae infestation in the plot.

In 2011, the number of DBM in both the control and treated plots was consistently low, with the effect of treatment not being significant. This finding is consistent with a previous report, which revealed the economic injury level of DBM larvae to be 5.0 per plant in cabbage production in Japan (Morishita, 1988). In the Poisson regression analysis, only the treatment factor was significant. This means that the number of *C. vestalis* cocoons in the treated plot was significantly higher than that in the control plot, irrespective of the number of DBM larvae. The results in 2011 indicate that a significantly higher number of *C. vestalis* is attracted to the treated plot by the dispensers. The results further indicate that when the densities of DBM larvae are around the economic injury level, the presence of the dispensers in the plot are unlikely to sufficiently reduce the number of DBM larvae to eliminate the risk of economic damage.

In both years, we also observed other arthropods such as aphids, mummies of aphids, *P. rapae* larvae, cocoons of *C. glomerata*, and Plusiinae spp. larvae. The incidence of aphids was not consistent in the 2 years. The incidences of other arthropods were not affected by the treatments. These results indicate that the treatment did not affect the presence of these herbivores and their respective natural enemies. Interestingly, segregation was observed between herbivore species in 2 years. In 2010, an increase in Plusiinae spp. larvae was observed; afterward, an increase in the number of the other herbivore species was observed for *P. rapae* larvae, DBM larvae, and aphids, in that order. In 2011, similar segregation was observed except in Plusiinae spp. larvae, the small number of which was constantly noticed during the observation period.

The attractant used in this study did not affect the oviposition behaviour and performance (pupation rate and pupal weight) of DBM adults/larvae when we set the dispenser next to two crucifer crops: mizuna plants, *Brassica rapa* var. *laciniifolia* (Uefune et al., 2017) and komatsuna plants, *Brassica rapa* var. *perviridis* (M. Uefune, unpublished data). However, in Cruciferae, *Arabidopsis* plants that have been exposed to either (E)-2-hexenal, (Z)-3-hexenal, (Z)-3-hexenol, *n*-octanol, or *allo*-ocimene induce several genes related to defence against herbivores and pathogens (Kishimoto et al., 2005). Yamauchi et al. (2018) reported that (Z)-3-hexenal, (Z)-3-hexenol, and (Z)-3-hexenyl acetate triggered the expression of defence-related genes in *Arabidopsis*. Green leaf volatiles and/or volatile terpenoids have also been shown to induce defence responses in maize, lima bean, citrus, tomato, poplar, and wild tobacco (*Nicotiana attenuate*) (Arimura et al., 2000; Gomi et al., 2003; Choh et al., 2004; Engelberth et al., 2004;

Farag et al., 2005; Paschold et al., 2006; Frost et al., 2008; Sugimoto et al., 2014). Thus, the possibility that setting dispensers in the field affected the physiology of cruciferous crops remained.

This 2-year field study suggests that the dispensers recruited native *C. vestalis* from the surrounding environment to the treated plot. We also found that the dispensers controlled the number of DBM larvae in 2010 when the density of DBM larvae exceeded the economic injury levels for the cabbage crop. Although this study shows the possibility of the use the attractants for DBM control under open field conditions, additional research on the use of the attractant is needed to propose a general use to control DBM in cases where the surrounding landscape structure harbours both DBMs and *C. vestalis* (source), considering the size of cabbage fields (sink). Since DBM is one of the pests of cabbage and other cruciferous crops worldwide, applying the attractant in other areas is our future goal.

## DATA AVAILABILITY STATEMENT

The datasets for this study are included in the article/**Supplementary Material**.

## AUTHOR CONTRIBUTIONS

MU designed the experiments, conducted the experiments, analysed the data, and wrote the manuscript. KY conducted the experiments and analysed the data. MY conducted the experiments. JT analysed the data and wrote the manuscript. All authors have approved the final manuscript for publication.

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## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fevo.2021.702314/full#supplementary-material

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