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ORIGINAL PAPER

Inundative release of *Trichogramma dendrolimi* at different developmental stages enhances the control efficacy over *Ostrinia furnacalis*

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Abstract

The Asian corn borer (ACB), *Ostrinia furnacalis*, is a serious maize pest in Southeast Asia, responsible for substantial economic losses to the maize crop every year. To establish insect biocontrol programmes, it is crucial to determine the ideal numbers and developmental stage of natural enemies to release. The purpose of the present study was to assess the parasitism ability of *Trichogramma dendrolimi* and *Trichogramma ostriniae,* which are the most promising biocontrol agents of the ACB, under two different methods of inundative release in maize fields. A total of 10,000 wasps of both species were released using two different methods, i.e. wasps at the same developmental stage (SDS) and wasps at different developmental stages (DDS). The results showed that *T. dendrolimi* wasps exhibited significantly higher parasitism of ACB eggs when they were released with the DDS method than when they were released with the SDS method. In the SDS release method, *T. dendrolimi* parasitized ACB eggs for only 3 days after release, while in the DDS release method, parasitism of ACB eggs occurred for 6 days. However, the two release methods had no significant impact on the performance of *T. ostriniae* in maize fields. In both release methods, *T. ostriniae* parasitized a high percentage of ACB eggs. The results of the present study clearly indicate that the poor field performance of *T. dendrolimi* due to the host-age factor can be improved using the DDS release method.

Keywords *Trichogramma ostriniae* · Asian corn borer · Release strategy · Dispersal · Biological control

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Key messages

- *T. dendrolimi* and *T. ostriniae* are the most promising biocontrol agents of *O. furnacalis*.
- The parasitism of *Trichogramma* released at the SDS and DDS in maize fields was assessed.
- *T. dendrolimi* wasps released with DDS exhibited higher egg parasitism than those released with SDS.
- The field performance of *T. dendrolimi* can be effectively improved using the DDS release method.

Introduction

One of the most destructive pest of corn is the Asian corn borer (ACB) *Ostrinia furnacalis,* Guenée, 1854 (Lepidoptera: Crambidae) (Afidchao et al. 2013; Iqbal et al. 2021). The overuse of chemical pesticides to control the increasing infestation of ACB in maize-producing regions due to environmental and farming practices may lead to various issues such as pest resistance, resurgence and hormesis (Guedes et al. 2016; Gul et al. 2019; Paula et al. 2021; Li et al. 2022). The use of chemical insecticides also has harmful effects on beneficial arthropods and human health (Weisenburger 1993; Desneux et al. 2007; Jiang et al. 2019; Menail et al. 2020; Palma-Onetto et al. 2021). To avoid these issues, the establishment of effective, successful and environmentally sustainable management strategies is needed. Among the available pest management strategies targeting ACB in maize, the use of egg parasitoids belonging to *Trichogramma* genus as biocontrol agents for ACB suppression is promising (Zang et al. 2021).

Trichogramma (Hymenoptera: Trichogrammatidae) is an important genus of egg parasitoid wasps, and several species have been used for the biological control of various lepidopterous pests, yielding significant ecological and economic advantages (Tabone et al. 2010; El-Arnaouty et al. 2014; Li et al. 2019a; Iqbal et al. 2019; Wang et al. 2021b; Zang et al. 2021; Zhang et al. 2021a). The release of these *Trichogramma* parasitoids as biocontrol agents against corn borer pest is considered as the best alternative to pesticides and is a sustainable control measure in many countries of the world (Li 1994; Smith 1996; Zhang et al. 2010). The inundative releases of these parasitoids also have been proven as the most important and successful control measure against corn borers especially in a number of Asian countries, mainly in China (Li 1994; Wang et al. 2005, 2014). Several studies in north-eastern China between 2005 and 2015 have reported that the area of maize fields in which *Trichogramma* parasitoids are applied has increased from 0.6 to 5.5 million ha (Zhang et al. 2014, 2018; Huang et al. 2020; Zang et al. 2021).

The two *Trichogramma* species, *T. dendrolimi* Matsumura and *T. ostriniae* (Pang & Chen), are considered the best biocontrol agents for the ACB (Wang et al. 2005; Zang et al. 2021). Since 2012, releases of *T. dendrolimi* alone (225,000 parasitoids ha^{-1}) have covered an area of approximately 2.3 million ha in north-eastern China (Zang et al. 2021). Moreover, the application of *T. ostriniae* (75,000–120,000 parasitoids ha^{-1}) in maize fields has also resulted in parasitism of more than 90% of ACB eggs (Wang et al. 2014; Zang et al. 2021). The release of these parasitoid species has continuously increased because they are an effective tool for the suppression of the ACB in maize fields (Wang et al. 2003; Yang et al. 2011). Although these parasitoid species have strong performance as biocontrol agents, it is necessary to optimize their use to reduce variability in their effectiveness (Wang et al. 2022).

Previous studies notably showed that the host age could impact parasitism (Pizzol et al. 2012; Biondi et al. 2013; Wang et al. 2021a) including in the case of ACB eggs parasitized by *T. dendrolimi* (Wang et al. 2022). Recently, we reported the preference of *T. dendrolimi* to parasitize 0–8-h-old ACB eggs, and their parasitism dramatically declined as the age of ACB eggs increased from 8 h under choice and no-choice conditions. In contrast, the age of ACB eggs does not impact the parasitism ability of *T. ostriniae,* and this species is regarded as the most effective ACB biocontrol agent (Zang et al. 2021; Wang et al. 2022). However, we should not overlook the role of *T. dendrolimi* species in the biological control of the ACB due to its potential to achieve parasitization rates of 50–60% or higher among ACB eggs in maize fields under suitable conditions (Liu et al. 1998). Additionally, the mass production of *T. dendrolimi* is carried out using eggs from the Chinese oak silkworm *Antheraea pernyi* (Lepidoptera: Saturniidae) in China (Li et al. 2019; Wang et al. 2005; 2020); the advantages of using the *A. pernyi* host in the mass production of *Trichogramma* have been previously reported in detail (Wang et al. 2014). The other species *T. ostriniae* can only be mass reared on small eggs, such as the rice grain moth, *Corcyra cephalonica*, or angoumois grain moth *Sitotroga cerealella* eggs and not by oak silkworm *A. pernyi* eggs or artificial host eggs (Wang et al. 2014, 2005), due to which the application of *T. ostriniae* is limited in practice (Feng 1996).

Therefore, the objectives of our current study were to evaluate a method of overcoming the host-age limitations faced by *Trichogramma* wasps in maize fields and to enhance their parasitization potential by incorporating this release method. In this study, we released *T. dendrolimi* or *T. ostriniae* wasps under two different strategies in maize fields. In one strategy, *T. dendrolimi* or *T. ostriniae* were released as pharate adults (same developmental stage) inside the factitious rearing host. In the other strategy, *T. dendrolimi* or *T. ostriniae* were released at different developmental stages (i.e. prepupal, pupal and pharate adults) inside the factitious rearing host for continuous emergence of parasitoids. We incorporated these two inundative release methods for *T. dendrolimi* and *T. ostriniae* and evaluated their outcomes under field conditions against ACB eggs.

Materials and methods

Parasitoids

The parasitoids *T. dendrolimi* and *T. ostriniae* were initially collected in 2017 from parasitized ACB eggs in maize fields in Changchun, Jilin Province, China (43.89°N, 125.32°E). Both parasitoid species were identified through scanning electron microscopy of the male genital capsules (Pinto 1992), and their taxonomic identity was further confirmed by rDNA ITS2 sequence analysis (Stouthamer et al. 1999). Voucher specimens were kept at the Institute of Biological Control, Jilin Agricultural University, China. Parasitoid colonies were reared on eggs of the rice moth, *Corcyra cephalonica* (Stainton), under laboratory conditions (25 ± 1 °C, relative humidity (RH): 70 ± 5%, photoperiod of 16:8 (L/D hours)). For rejuvenation, after continuous rearing for five generations on *C. cephalonica* eggs, *T. dendrolimi* and *T. ostriniae* colonies were reared for a generation on their native host (the ACB).

Hosts

Asian corn borer eggs

To obtain ACB host eggs for the experiment, their moths were reared in a large number at the Institute of Biological Control, Jilin Agricultural University, Changchun, China. ACB larvae were fed under laboratory conditions using a climate chamber (26 ± 1 °C, RH: 60 ± 5% and photoperiod of 14:10 (L/D)). After pupation, the insects were collected and placed in a mesh cage (35 cm × 35 cm × 35 cm). After the moths emerged, a 20% honey solution (v/v) was provided on a cotton wick, according to Iqbal et al. (2021). A large piece of wax paper (30 cm × 30 cm) was suspended in the cage as an egg-laying substrate, and the egg masses newly laid (0–4 h old) on the wax paper were cut out with scissors and used in the following field experiments.

Chinese oak silkworm

Cocoons of the Chinese oak silkworm (*A. pernyi*) were collected from Yongji city (Jilin Province, China) and were transferred to the Institute of Biological Control, Jilin Agricultural University, in December 2020. Cocoons were stored until February 2021 (nearly 3 months) at a temperature of 4 °C. Then, the cocoons were hung in emergence rooms for incubation at a temperature of 25 ± 1 °C. Mature and unmated female moths of *A. pernyi* were collected after emergence from cocoons and were kept for 2–3 days at a temperature of 4 °C in a refrigerator. Host eggs for breeding of *T. dendrolimi* were collected by dissecting the abdomen of mature female moths, washed with distilled water and kept at room temperature to dry (Wang et al. 2020).

Parasitoids reared

In this experiment, the *T. dendrolimi* and *T. ostriniae* parasitoids were reared with regular methods, i.e. the former was reared on *A. pernyi* host eggs, while the latter was reared on *C. cephalonica* host eggs. The parasitoids were reared on different hosts because *T. dendrolimi* can be efficiently reared on *A. pernyi* hosts via monoparasitism, but *T. ostriniae* cannot be reared on *A. pernyi* hosts via monoparasitism and can be reared only on *C. cephalonica* or *Sitotroga cerealella* hosts (Wang et al. 2005, 2014; Zang et al. 2021).

Parasitism potential of both *Trichogramma* species on ACB eggs under field conditions using different release strategies

Our previous laboratory study (Wang et al. 2022) showed that the age of ACB eggs has a significant impact on the parasitization of *T. dendrolimi* under both choice and no-choice conditions. *Trichogramma dendrolimi* preferred to parasitize 0–8-h-old ACB eggs, and its parasitization rate dramatically declined on ACB eggs older than 8 h. Therefore, based on Wang et al. (2022), in this experiment, we used 0–4-h-old ACB eggs in maize fields to test the parasitism potential of *T. dendrolimi* and *T. ostriniae* wasps released at different developmental stages.

The experiment was performed in a maize field in Changchun, Jilin Province, China (43.89°N, 125.32°E), in 2021. In the maize field, the parasitoid release point (0 m) was the centre point where parasitoids were released. The sentinel ACB egg masses (0–4 h old) were distributed in all four directions (east, west, north and south) from the central parasitoid release point (0 m) and were equally distributed in the same directions, spaced 5 m apart. A total of five ACB egg distribution points were established in each direction, with the final point 25 m away from the centre parasitoid release point (0 m) in each test plot, in which the area covered approximately 2000 m^2. The sentinel egg masses were provided for *Trichogramma* species to parasitize over 24 h. Each sentinel egg mass contained 50 ACB eggs (the extra eggs were killed by a needle). After 24 h, the sentinel ACB egg masses were replaced with fresh 0–4-h-old sentinel ACB egg masses; this procedure was followed for 6 consecutive days. The sentinel ACB egg masses from each point were separately collected in glass tubes, transferred to the laboratory and kept in an artificial climate chamber (25 ± 1 °C, RH of 60 ± 5% and photoperiod of 14:10 (L:D)) for observation of parasitoid development. The number of eggs parasitized by two *Trichogramma* species at each point was determined by examination under a stereoscopic microscope (LEICA S6E, Germany) in the laboratory, with parasitized eggs characterized by a dark colour.

Release of *Trichogramma* parasitoids at the same developmental stage (SDS), i.e. pharate adult stage

In this release method, *T. dendrolimi* or *T. ostriniae* individuals were released when they were at the pharate adult stage inside the factitious rearing host (i.e. one day after release, wasp emergence started). The *Trichogramma* individuals were released at the pharate adult stage at only the centre point (0 m). Approximately 10,000 wasps of each species were released at the centre point (0 m) in the maize field. The test was replicated three separate times, with a 100-m distance between each replication unit in the field.

Release of *Trichogramma* parasitoids at different developmental stages (DDS), i.e. the prepupal, pupal and pharate adult stages

In this release method, *T. dendrolimi* or *T. ostriniae* were released when they were at different developmental stages inside the factitious host eggs (i.e. prepupal, pupal and pharate adults). Approximately 10,000 wasps of each *Trichogramma* species were released separately; these wasps were equally distributed among three developmental stages (i.e. 3330 wasps at the prepupal stage, 3330 wasps at the pupal stage and 3330 wasps at the pharate adult stage). This release method ensured successive wasp emergence over several days. The releases of parasitoid wasps of the two species at different developmental stages were carried out separately at the central release point (0 m). The test was replicated three separate times, with a 100-m distance between each replication unit in the field.

Statistical analysis

The number of eggs parasitized was analysed using a generalized linear mixed models (GLMM) implemented in R (R Development Core Team, version 4.1.1). The fixed effects were the number of days after release, the distance from the centre of release, the *Trichogramma* species and the method used (SDS or DDS) as well as all pairwise interactions. The random effect was the replication number. Model was fitted using a negative binomial distribution to correct for overdispersion in count data, and statistical significance of variables was determined by analysis of variance (ANOVA) with a χ^2 test. The marginal effects of predictors on dependent variable were estimated and visualized using the "ggeffects" package.

Results

The number of days after release (1–6 days), the distance from the centre of release (0 to 25 m), the *Trichogramma* species (*T. dendrolimi* or *T. ostriniae*) and the method used (SDS or DDS) as well as all pairwise interactions had an impact on the number of 0–4-h-old ACB eggs parasitized except the interaction between the method and the distance from the centre of release (Table 1, Figs. 1, 2).

Table 1 Response of the number of 0–4-h-old ACB eggs parasitized to *Trichogramma* species (*T. dendrolimi* or *T. ostriniae),* wasps released method (DDS vs. SDS), distances from the release point in the maize field and number of days after release as well as all the pairwise interactions

Factors	Chisq	Df	Pr (> Chisq)
Days	98.0	5	< 0.001
Method	175.8	1	< 0.001
Distance	698.9	5	< 0.001
Species	2397.9	1	< 0.001
Method/species	408.1	1	< 0.001
Days/species	326.6	5	< 0.001
Distance/species	1048.6	5	< 0.001
Days/method	296.1	5	< 0.001
Method/distance	1.2	5	0.945
Days/distance	65.4	1	< 0.001
(Replication)	12.6	2	0.002

The number of eggs parasitized by *T. ostriniae* was between 2 and 4 times higher for all methods combined (SDS and DDS), for all distances combined (except at 0 m, Fig. 1) and for all days after release compared to the number of eggs parasitized by *T. dendrolimi* (significant interactions: method x species, days x species, distance x species; Fig. 2). The method of release did not vary according to the distance, since in both DDS and SDS, the number of eggs parasitized was lower when the distance from the release point was greater (Fig. 2). Conversely, the number of parasitized eggs was higher in DDS than in SDS method from day 3 to day 6 of sampling (significant interaction between days and method; Fig. 2) and this difference was higher in *T. dendrolimi* than in *T. ostriniae* (Fig. 1; significant interaction between method x species). Finally, the number of parasitized eggs was lower as the days passed by and the distance increased (significant interaction between days x distance; Fig. 2). Again, the reduction in the number of eggs parasitized by *T. dendrolimi* was more drastic, reaching 0, compared with the number of eggs parasitized by *T. ostriniae*, which did not fall below 60% on average (out of 50 eggs offered per day; Fig. 1).

Discussion

Several studies have compared the efficacy of *T. dendrolimi* and *T. ostriniae* against ACB eggs in maize fields. For example, Zhang et al. (1979) found that the parasitism rate by *T. dendrolimi* of first-generation ACB eggs was high only during the release period, while the parasitism rate by *T. dendrolimi* decreased to 5% on second-generation ACB eggs. Their study showed that *T. dendrolimi* was replaced by *T. ostriniae* (a naturally established population) during the second generation of ACB eggs, and the parasitism rate by *T. ostriniae* was reported as 95%. A survey was conducted to determine potential *Trichogramma* species for the control of the ACB in 13 provinces of China; the dominant

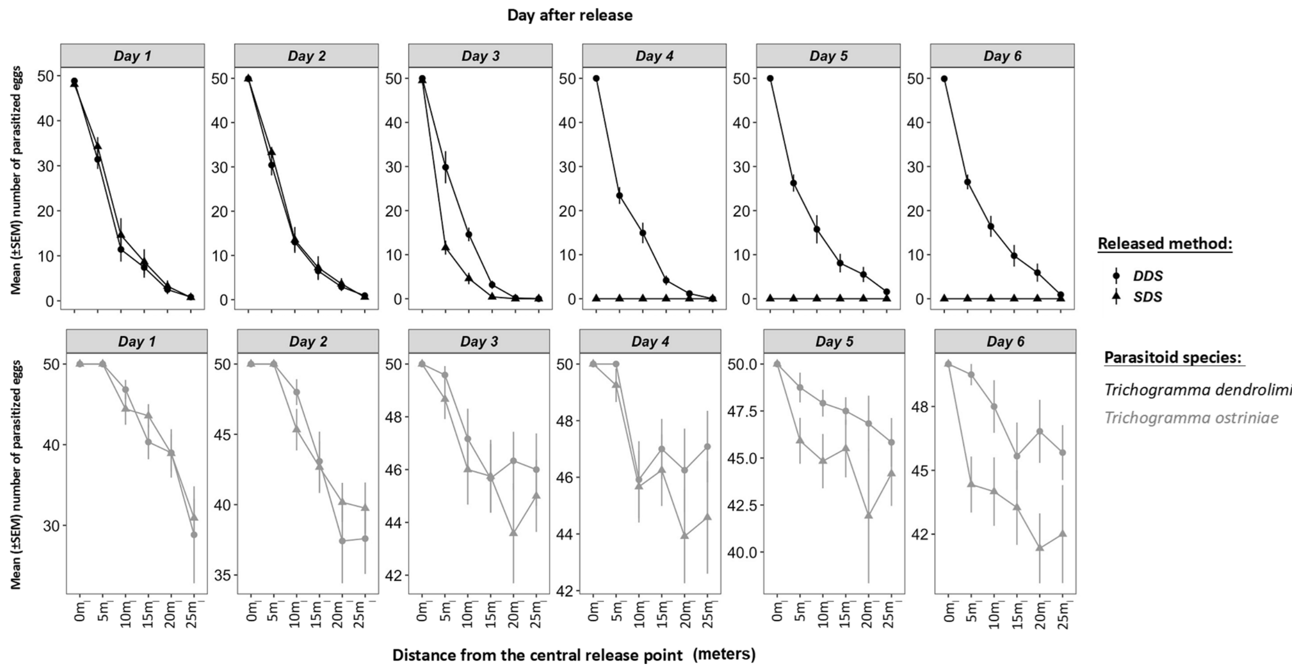

Fig. 1 Mean (±SEM) number of 0–4-h-old ACB eggs parasitized by *T. dendrolimi* or *T. ostriniae* wasps released at different developmental stages (DDS; i.e. prepupal, pupal and pharate adults) or at the same developmental stage (SDS; i.e. pharate adults) at different distances from the release point in the maize field over 6 days

parasitoid species of the ACB pest in some areas was *T. dendrolimi*, while in other areas, it was *T. ostriniae* (Zhang et al. 1990). Similarly, Feng (1996) conducted a survey of maize fields in Shandong Province and found that the two species (*T. dendrolimi* and *T. ostriniae*) both maintained high parasitic potential on ACB eggs during the release period; however, from the perspective of population duration, the *T. dendrolimi* population was quickly replaced by *T. ostriniae*. Zhang et al. (2004) conducted field release experiments to identify *Trichogramma* species with good parasitic potential against ACB. Their results showed that the parasitism rate by *T. ostriniae* of ACB eggs was also significantly higher than that by *T. dendrolimi* in the release area which is consistent with our results. All the above findings raise concerns about the effectiveness of *T. dendrolimi* against ACB in field trials as well as why its initial parasitization rates at release quickly fade in subsequent generations.

In this context, the results of our previous study (Wang et al. 2022) confirmed that ACB egg age is one of the key factors influencing the parasitoid's host-seeking behaviour. We showed that the age of ACB eggs had a significant impact on the parasitic ability of *T. dendrolimi* under both choice and no-choice conditions. *Trichogramma dendrolimi* preferred to parasitize newly laid ACB eggs, and its parasitization dramatically declined on ACB eggs older than 8 h under choice and no-choice conditions. After laboratory inspection, in this study, we quantified the dispersal ability and parasitic potential of both *T. dendrolimi* and *T. ostriniae* after modifying their inundative release in the maize field against ACB eggs.

The results of the present study showed that the *T. ostriniae* species released with either the DDS or SDS method and the significant higher number of ACB eggs was parasitized by *T. ostriniae* for all distances combined (except at 0 m) and for all days after release (Fig. 1). These results suggested that the dispersal of *T. ostriniae* was rapid, with individuals achieving a distance of 25 m after release on all days. Similar results were reported by Gardnera et al. (2012) for *T. ostriniae* in maize fields. They found no significant differences among the spatial distributions of sticky trap captured and parasitism rate of egg masses of the European corn borer (*Ostrinia nubilalis)* by *T. ostriniae*. The distances from the release point that encompassed 98% of recaptured *T. ostriniae* increased over time. Chapman et al. (2009) evaluated the dispersal of *T. ostriniae* in potato fields. Their results indicated that the movement of *T. ostriniae* adults from the release point was rapid, with individuals captured at 45 m within 1 d after emergence. High rates of parasitization were also observed at that distance. Similarly, Wright et al. (2001) reported the dispersal behaviour of *T. ostriniae* in sweet maize fields and concluded that the wasps dispersed rapidly, reaching up to 180 m in 6 days and 230 m in 21 days; uniform parasitism of sentinel egg masses was achieved in areas of 1–2 ha surrounding the central release points. Moreover, *Trichogramma ostriniae* is a synovigenic parasitoid; such parasites have only a portion of their egg complement at

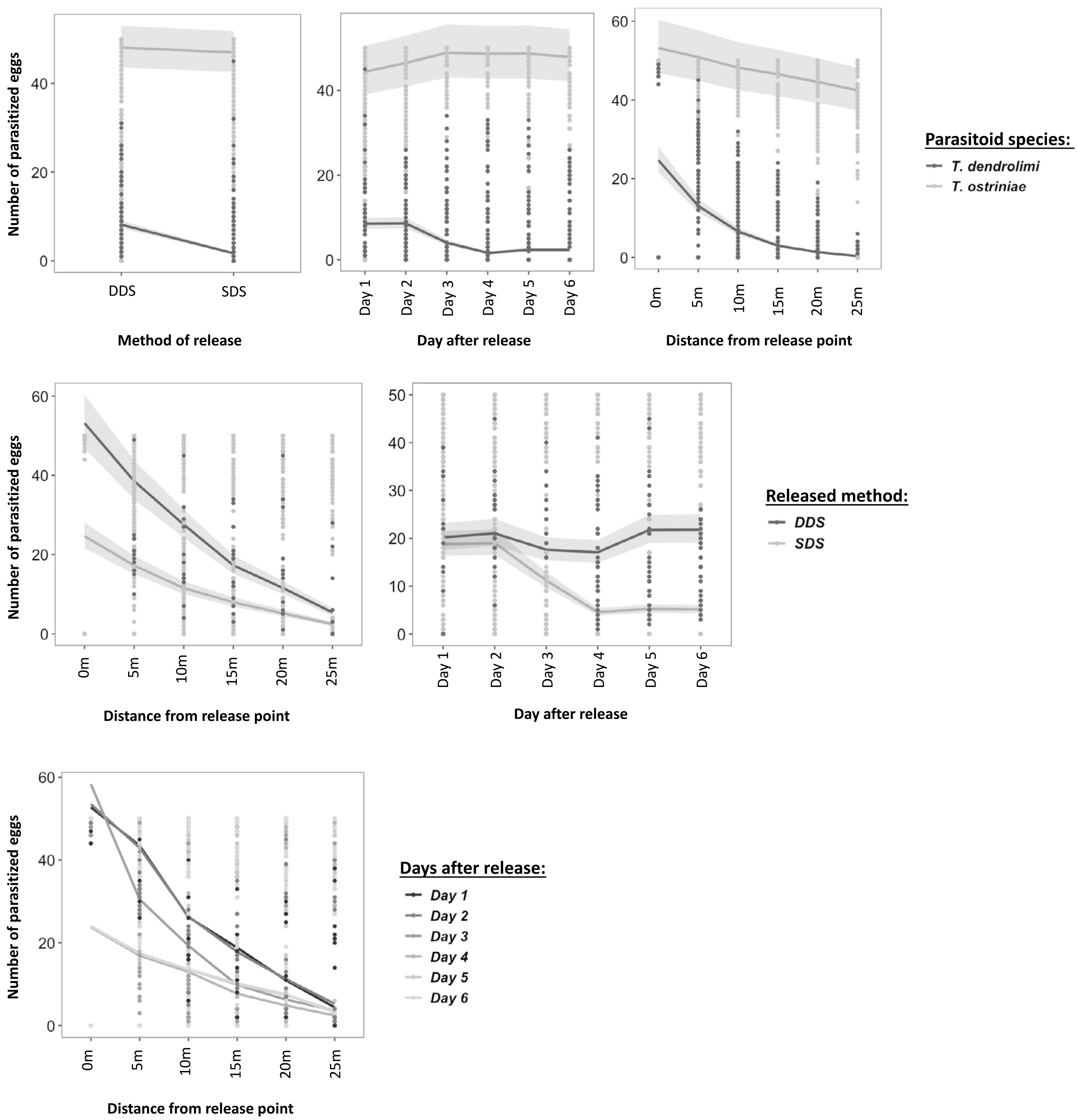

Fig. 2 Number of 0–4-h-old ACB eggs parasitized response to **a** method (SDS vs. DDS) x species (*T. dendrolimi* or *T. ostriniae)*, **b** days after release x species, **c** distance from the release point x species, **d** days after release x method, **e** method x distance from the release point and **f** days after release x distance from the release point. Points are raw data and lines the predicted marginal effects estimated from GLMM following negative binomial distribution. Shaded area = 95% confidence interval

eclosion, and egg maturation tends to increase over adult life (Chen et al. 2005). Synovigenic species also live longer than proovigenic species (Jervis et al. 2001). Thus, we speculated that the synovigenic nature and longer lifespan of *T. ostriniae* are the characteristics responsible for the higher dispersal and parasitism of ACB eggs in maize fields, regardless of the release method.

The present results also concluded that when *T. dendrolimi* wasps were released with the DDS method, they did not disperse rapidly over a large area in the maize field. The freshly provided sentinel ACB eggs significantly differed in rates of parasitism (i.e. in blackish eggs, a sign of being parasitized) by newly emerged wasps on all 6 days (Fig. 1). Significantly high rates of parasitism by *T. dendrolimi* were recorded at the release point (0 m), followed by those at 5 m, 10 m, 15 m, 20 m and 25 m, on the same day for all 6 days (Fig. 1). These results show that the parasitism rate of *T. dendrolimi* was affected by distance. Similar results were reported by Zhang et al. (2021b) for *T. dendrolimi* released against the oriental fruit moth *Grapholita molesta* (Busck) (Lepidoptera: Tortricidae) in a pear orchard. Female *T. dendrolimi* dispersed only up to 12 m from the release point, and parasitism rates of eggs showed a declining tendency with increasing distance from the release point. Bueno et al. (2012) reported the parasitism and dispersal ability of *Trichogramma pretiosum* (Hym.: Trichogrammatidae) against soybean caterpillars. Similarly, the parasitism ability of *T. pretiosum* on *Pseudoplusia includens* (Lepidoptera: Noctuidae) eggs decreased linearly with increasing distance of the pest eggs from the parasitoid release point.

However, in the present study, the modified release method (DDS) significantly and strongly enhanced parasitism of ACB eggs by *T. dendrolimi* in the field (Fig. 1). The release of *T. dendrolimi* with DDS method staggered the emergence of young wasps, such that some emerged each day in the field, which was very important for the parasitization of freshly laid ACB eggs. This approach ensured a constant supply of wasp females actively searching for ACB eggs in the field. The continuous presence of newly emerged female *T. dendrolimi* throughout the oviposition period of the ACB in the field is critical for control (Liu et al. 1998). Bigler and Brunetti (1986) evaluated the biological control of *O. nubilalis* by *Trichogramma maidis* Pint. et Voeg in maize fields in southern Switzerland. They reported that one release at the very beginning of each generation of *O. nubilalis* was sufficient if *T. maidis* individuals at three different developmental stages (late pupal, prepupal and young larvae) were released together to provide full protection for approximately three weeks. The progeny of released trichogrammatids parasitized continuously until the end of each oviposition period of *O. nubilalis*. Similarly, a higher parasitism rate by *T. brassicae* of *O. nubilalis* was recorded in a maize field in a study in 1993 when *T. brassicae* individuals were released at different developmental stages (larvae and pupae), and the percentage of *O. nubilalis* egg masses parasitized by *T. brassicae* decreased with increasing distance from the release point (Greatti and Zandigiacomo 1995). In another study, the variability in the quality of *T. brassicae* individuals from commercial suppliers in Germany was examined over two years (1998–1999) by Hassan and Zhang (2001). They reported that release units contained *T. brassicae* at different development stages to prolong the period of adult emergence and thereby extend the duration of treatment. In both test years, parasitoid release produced strongly overlapping periods of adult emergence that coincided with the egg-laying peak of the pest in the field. Hassan (1980) reported that with an optimal mixture of development stages of *T. evanescens*, the effect of an application was prolonged, and the number of releases needed to control *O. nubilalis* could be reduced to one application per season. Therefore, based on our present results, we strongly recommend the inundative release of *T. dendrolimi* at different developmental stages to control the ACB in maize fields. This practice will ensure the emergence of new *T. dendrolimi* wasps every day, and the emergence of female wasps will coincide with fresh ACB egg masses in the field.

The possible reason for the lower rates and shorter duration of parasitism (only 3 days) is that *T. dendrolimi* is a typical proovigenic parasitoid species (Hegazi and Khafagi 2001). Proovigenic parasitoid species have a full complement of eggs by eclosion. Therefore, it is expected that proovigenic parasitoids (with increased egg loads at emergence) will have decreased dispersal capacities and reduced longevity (Jervis et al. 2001). Additionally, proovigenic parasitoids are less able to adjust their reproductive output to variation in host encounters (Ellers et al. 2000; van Baalen 2000). Notably, Wang et al. (2022) explored the reduced efficacy of *T. dendrolimi* for parasitization of ACB eggs and concluded that the age of the ACB egg mass offers only a narrow window of time for parasitization. *Trichogramma dendrolimi* individuals have to locate ACB egg masses shortly after they are laid to achieve high rates of parasitization in the field. However, despite this temporal limitation on parasitization, our present study emphasizes the importance of this species for augmenting biological control programmes. In maize fields, the parasitism ability of *T. dendrolimi* can be assisted/enhanced by modifying the release method, such as by using the DDS release method. Under this method, *T. dendrolimi* individuals are released at different developmental stages, which ensure the emergence of new wasps every day and the coincidence of female wasp emergence with fresh ACB egg masses in the field. The inundative release of *T. dendrolimi* at different developmental stages will increase the duration of *T. dendrolimi* presence during the ACB oviposition period. This modified release method not only enhances the parasitism potential of *T. dendrolimi*, but also saves the cost due to changing multiple releases to one time release. However, the results further showed that the release methods tested had no significant effects on the performance of *T. ostriniae* in maize fields. Thus, *T. ostriniae* can be released normally to control the ACB with SDS strategy.

Author contributions

LSZ, SW and ND scoped and designed research. YW and YYH conducted experiments and collected the data. LSZ provided parasitoid resources. LSM and YW performed data analysis. YW, AI, SW, LSM and LSZ wrote the paper. All authors read and approved the manuscript.

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Availability of data and materials The datasets generated during and/or analysed during the current study are available from the corresponding author upon reasonable request.

Declarations

Competing interests All authors declare no conflicts of interest. Author ND is Editor-in-Chief of Journal of Pest Science and was not involved in the review process and decisions related to this manuscript.

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