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Evaluation of drone and ground releases of *Cryptolaemus montrouzieri* for mealybug (*Pseudococcus maritimus*) control in apples☆

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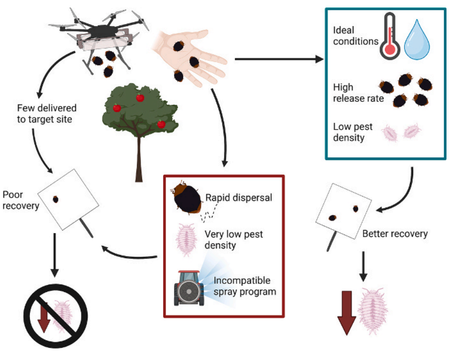
HIGHLIGHTS

- *Cryptolaemus montrouzieri* release for mealybug control in Washington, USA apple.
- This is the first study reporting on drone applications of *C. montrouzieri.*
- High rate, early timing ground releases reduced mealybug densities, but only in one trial.
- *C. montrouzieri* rapidly dispersed from plots, especially in drone releases.

GRAPHICAL ABSTRACT



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ABSTRACT

In apple growing regions of Washington State (USA), mealybug outbreaks are infrequent but can be severe, especially in organic production systems. Because insecticide sprays are ineffective for this pest, management tactics are limited, and alternative approaches that are compatible with organic practices are needed. In four trials (2020–2023), we evaluated releases of mealybug destroyers, *Cryptolaemus montrouzieri* Mulsant (Coleoptera: Coccinellidae), for the control of grape mealybug, *Pseudococcus maritimus* (Ehrhorn) (Hemiptera: Pseudococcidae), in commercial organic apple orchards. Although *C. montrouzieri* are well known for their role in classical biological control of mealybug pests in a variety of cropping systems worldwide, this is the first report of their use as augmentative biocontrol in apple orchards in the US. Different application types (drone vs hand-releases), timings, life stages (adults vs larvae), and rates were tested. In 2020, early season hand releases at high rates (12,355/ha) reduced *P. maritimus* relative to the untreated control, but in subsequent years no efficacy was observed; pest pressure was also lower in these trials. Across all four years of the study, *C. montrouzieri* adults dispersed rapidly from field sites, especially in drone releases. Further research is needed to assess if larval releases in mealybug “hot spots” can be effective. Based on their propensity for dispersal, high host-density dependence, and expense, releases of adult *C. montrouzieri* for *P. maritimus* control in apple are not strongly supported.

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1. Introduction

Grape mealybug (*Pseudococcus maritimus* (Ehrhorn)) is a sporadic but important pest of apple and pear orchards in the Pacific Northwest (USA). In Washington State (WA), outbreaks of mealybugs are rare but can be severe, particularly in organic orchards (Burts and Dunley, 1993). Direct feeding by mealybugs on trees can reduce tree vigor but is not a principal concern. More importantly, like other phloem-feeding pests, honeydew produced by mealybugs drips onto fruit and promotes sooty mold growth, resulting in russeting and eventual fruit downgrading (Burts and Dunley, 1993; Grasswitz and Burts, 1995). At high densities, mealybugs can also infest and feed on fruit, clustering around the calyx and stem, causing direct damage to fruit and becoming a potential export concern (Burts and Dunley, 1993). If mealybugs penetrate the calyx end of the apple and reach the core, they may not be detected at harvest and cause the fruit to rot in storage (Grasswitz and Burts, 1995).

Grape mealybug is a known vector of little cherry virus 2 (LChV2), one of the causal agents of little cherry disease (LCD), which widely threatens cherry production (Mekuria et al., 2013). A five-year survey (2017–2021) of cherries in the Pacific Northwest found 7% of samples were infected with LChV2 (Shires et al., 2024). It is estimated that LCD and X-disease (causative agent, *Candidatus phytoplasma* pruni), which cause indistinguishable symptoms, resulted in a loss of 394 ha of cherries and >$115 million USD in lost revenue and replanting costs from 2015 to 2020 (Molnar et al., 2022). Given the relative proportion of samples testing positive for each causative agent from the years these studies overlapped (2017–2020) (Shires et al., 2024) and the annual reported values in lost sales (Molnar et al., 2022), approximately $14 million USD in lost cherry sales from 2017 to 2020 can potentially be attributed to LChV2. Although there is no evidence that apple is a host of LChV2, there is a concern that increased mealybug pressure can put neighboring cherry orchards at risk (Warner, 2015).

Given their potential for damage in orchards, mealybug management is essential, yet current control options are limited. Mealybug suppression in pome fruit orchards with low populations is often attributed to natural enemies, including parasitoid wasps and generalist orchard predators, such as lacewings, chamaemyiid flies, coccinellids, and predatory hemipterans (Burts and Dunley, 1993; Doutt, 1948; Doutt, 1950; Grasswitz and Burts, 1995; Hill and Burts, 1982). When outbreaks do occur, few insecticides are effective at controlling mealybugs (Bixby-Brosi and Beers, 2015; Washington State University Extension, 2025). Waxy filaments produced by mealybugs form a protective layer, decreasing pesticide efficacy, and inactive adults and late instars seek shelter in protected locations (e.g., shoot and bark crevices, leaf axils, fruit calyx) or high in the canopy where they avoid direct contact with sprays (Burts and Dunley, 1993; Grasswitz and Burts, 1995; Madsen and Westigard, 1962). As a result, most pesticide applications target the motile first instars, known as crawlers. Timing sprays to when crawlers are active can be difficult, and currently, no products for mealybug control are considered highly effective (Washington State University Extension, 2025). The challenge of achieving adequate spray coverage together with a scarcity of effective pesticides makes chemical control largely ineffective for mealybug management, especially for organic growers (Warner, 2005). Washington is currently the top producer of organic apples in the US (>90% annually) (Northwest Hort Council, 2023), so alternative control measures for mealybug management that are compatible with organic growing practices are needed.

One potential management tactic for mealybug control is augmentative biological control with the mealybug specialist, *Cryptolaemus montrouzieri* Mulsant (Coccinellidae: Coleoptera), the mealybug destroyer. Native to Australia, *C. montrouzieri* feed on mealybugs as well as other soft-bodied prey, including scale insects (Kairo, 2013). Since the 1890s, *C. montrouzieri* has been released in over 64 countries as part of one of the most widespread and successful classical biological control programs for various mealybug pests (Kairo, 2013; Michaud, 2012; Moore, 1988). Mass-rearing and commercial availability have facilitated the use of these predators in both outdoor and indoor settings (Daane et al., 1998; Michaud, 2012). Annual releases in California grapes are relatively common, including releases by drone (MacMillan, 2022). *Cryptolaemus montrouzieri* are also released in California citrus (Daane et al., 1998; Grogan and Goodhue, 2014; University of California, 2025), and the first commercial insectary in North America was established in 1916 specifically for these releases (Daane et al., 1998; Smith and Armitage, 1920). However, despite its widespread adoption for classical biological control, few replicated studies have assessed its utility for augmentative releases to control pests (Daane et al., 2012). Augmentative releases of *C. montrouzieri* have shown potential to control various species of mealybugs in vineyards (Italy) (Parrilli, 2021), pomegranate (Turkey) (Öztop and Keçeci̇, 2022), and eggplant (India) (Mishra et al., 2020), but did not control citrus mealybug in trials in Spain (Villalba et al., 2006). Only a single published report has evaluated releases in apple (Australia), but this preliminary study was unreplicated and lacked untreated controls, so the efficacy of the releases cannot be determined (Nimmo, 2016). No studies have evaluated efficacy or developed recommendations for augmentation in regions like central WA, where *C. montrouzieri* is not expected to establish due to cold winter temperatures (Babu et al. 1987, Maes et al. 2014b).

Drone, or unmanned aerial vehicle (UAV), releases are gaining traction as a useful tool for augmentative releases, which can substantially reduce labor costs associated with releases at large scales (Iost Filho et al., 2020; van Lenteren et al., 2017). In tree fruit production, where practitioners must contend with large acreage, inaccessible canopies, and complex trellising, consistent coverage with hand releases can be challenging and labor-intensive. Using drones for releasing beneficials has been best represented with releases of predatory mites and parasitoids, but more recently, private companies are working to optimize drone systems for predatory insect releases, including lacewings and ladybeetles (Iost Filho et al., 2020; Jean and Martel, 2024; Martel et al., 2021). Very few peer-reviewed assessments of drone efficacy with predatory insects are currently available (Del Pozo-Valdivia et al., 2021; Iost Filho et al., 2020) and to our knowledge, there are no published studies assessing drone releases of *C. montrouzieri*.

To assess the viability of *C. montrouzieri* for mealybug control in apple, we evaluated releases in commercial organic apple orchards in WA state for control of *P. maritimus*. Field trials conducted over four years (2020–2023) compared release rates, timings, methods (hand releases versus drone applications), and life stages (adults versus larvae) to create research-based recommendations for their use.

2. Materials and methods

2.1. Study orchards

The experiments were conducted in three commercial, certified organic apple orchards from 2020 to 2023. The orchards were located in Washington State near Pateros (2020 and 2021), Desert Aire (2022), and Rock Island (2023). All orchards were selected due to high *P. maritimus* pest pressure in previous years. Information about the orchard blocks used in each trial, including cultivar, age, and tree spacing is listed in Supp. Table 1. Pesticides applied in the orchard prior to and during each trial are indicated in Supp. Table 2.

In 2020, plots were 450 m^2, with a minimum of three rows (across rows) or 20 m (down a row) between adjacent plots. To better test the performance of drone releases at field-scale, in 2021, plots were 0.40 ha and spaced at least 60 m apart. In 2022 only a limited amount of space was available in the study orchard, resulting in 929 m^2 plots with a minimum of three rows (across rows) or 15 m (down a row) between each plot. In the 2023 trial, plots were 0.10 ha and spaced at least 45 m apart.

2.2. Experimental design

Each year, a set of release treatments (Table 1) was compared to a no-release control using a randomized complete block design. Release treatments were applied to an entire plot and sampling occurred in plot centers. In 2020, plots were blocked into replicates by pre-counts of mealybugs (*2.4 Mealybug sampling*). In all other years, plots were blocked by location within the orchard.

2.3. Ladybeetle releases

Adult *C. montrouzieri* were obtained from BioBee (Sde Eliyahu, Israel) in 2020–2022 and Beneficial Insectary (Redding, CA) in 2023. *Cryptolaemus montrouzieri* larvae (2022) were from Koppert (Howell, MI), and *Hippodamia convergens* (Coleoptera: Coccinellidae) were from NW Beneficials (Bend, OR). Insects were released upon arrival or stored at 10 °C (per insectary recommendations) and released the following day.

In 2020, we tested both the recommended insectary rate for orchards (4,942/ha) and a high release rate recommended for a "hot spot" treatment (5,000/acre or 12,355/ha), hereafter referred to as "low rate" and "high rate" for this trial. We also examined an early timing (14 May) versus a later timing (17 June). The early timing was chosen to avoid sub-freezing evening temperatures. The late timing corresponded to shortly before peak oviposition by *P. maritimus*; adult *C. montrouzieri* are attracted to mealybug ovisacs and will oviposit their own eggs near them (Heidari and Copland, 1992; Merlin et al., 1996; Urbina et al., 2018). In addition to the three ground releases, we also tested a drone release. Ground treatments were applied by walking through the plots and sprinkling approximately the same amount of *C. montrouzieri* onto every tree within the plot. The *C. montrouzieri* were distributed roughly 1.2–1.5 m from the ground, aiming for sections of the tree where there was a "platform" to catch the insects, such as the tree crotch or a large limb. Only the high rate by ground was tested at the early timing, whereas all other treatments were tested at the late timing.

In 2021, the grower chose the release rate and conducted the ground releases by driving an all-terrain vehicle through the orchard while sprinkling the *C. montrouzieri* onto the trees. The trial was planned with an early season timing, but releases were delayed until 25 May to wait for *P. maritimus* populations to build. However, pest pressure remained low throughout sampling (*3.1 Mealybug abundance*). We compared a drone and a ground release to a no-release control.

In 2022, the trial was relocated to an orchard with *P. maritimus* populations that were noted by the grower as exceptionally high in previous years. We tested *C. montrouzieri* adults released by ground or drone as well as a release of larvae. We hypothesized that because larvae cannot fly, they might be retained in plots for a longer period and result in improved efficacy. All ground treatments were applied by sprinkling the insects onto the trees while walking through the orchard.

Table 1
Natural enemy augmentation treatments tested in each trial for mealybug control. All releases were adults except the 18 May 2022 release testing larvae (*) and all treatments were releases of *C. montrouzieri* except for the *H. convergens* release on 23 June 2023 (**).

	Release Date	Rate/ha	Method
2020	14 May	12,355	ground
	17 June	12,355	ground
	17 June	4,942	ground
	17 June	12,355	drone
2021	25 May	2,471	ground
	25 May	2,471	drone
2022	18 May*	4,942	ground
	20 May	4,942	ground
	20 May	4,942	drone
2023	22 June	4,942	ground
	23 June**	49,421	ground

Finally, in 2023, we compared a release of *C. montrouzieri* adults to a release of *H. convergens* adults. The grower had previously used *H. convergens* releases in the orchard and wanted to compare them to *C. montrouzieri*. The grower applied the *H. convergens* by driving an all-terrain vehicle through the orchard while sprinkling and chose the release rate. The research team applied the *C. montrouzieri* by sprinkling while walking.

In all trials testing drone deployment, releases were conducted by a licensed, commercial pilot operating a Matrice 600 Pro (DJI; Nanshan, Shenzhen, China) equipped with a rotating cylinder dispenser (Parabug; Salinas, CA). The pilot was provided the *C. montrouzieri* for release and added them to the cylinder after partially filling it with carrier material (organic rice hulls; Riceland, Stuttgart, AR). The carrier and the *C. montrouzieri* were mixed prior to dispensing. The drone was flown directly above each row (5–6 m above the trees) at 14.5 kph. Flights began at 11:00 AM in 2020, 6:00 AM in 2021, and 5:30 AM in 2022.

2.4. Mealybug sampling

Sampling occurred once per week in 2020 from 14 May to 28 July, then on alternating weeks (11 and 25 Aug), and a final sample was collected on 24 September. In this trial, pre-counts were conducted by the grower on 14 May prior to releases. Orchard staff examined ten trees per plot and counted the number of mealybugs on five spurs and five vegetative shoots per tree *in situ*. From 20 May – 10 June, post-release samples were only collected from the plots where *C. montrouzieri* were released ("Early High Rate") and control plots. Starting on 17 June, all plots were sampled. Post-release samples collected by the research team involved picking 30 spurs and 30 vegetative shoots per plot (two each from 15 trees). On five trees in plot centers, a piece of 10 cm wide burlap (Uline, Pleasant Prairie, WI) was tied onto a main limb. Burlap strip traps are attractive to mealybugs seeking shelter in bark crevices (Grasswitz and Burts, 1995). Burlap strips were replaced after each collected sample. Spurs, shoots, and burlap strips were examined under a dissecting microscope to count *P. maritimus.* On 25 August, the number of burlap strips was increased to 15 per plot (these strips were collected on 24 September, the final sampling date). On this date, we also examined 10 fruit *in situ* from five trees (50 total) per plot for the presence of mealybugs in the calyx and stem ends.

Sampling was similar in subsequent years, except that spurs were not sampled because this method caught the fewest mealybugs and appeared to be the poorest at tracking mealybug phenology (*3.1 Mealybug abundance*). We also did not sample fruit at harvest after 2020, as very few mealybugs were detected with this method. All 2021–2023 insect counts were conducted by the research team. Each plot received 20 (2021) or 10 (2022–2023) burlap strips, with one strip per tree in trees from plot centers. Either 20, 15, or 10 shoots were collected from plot centers (1–2 per tree) in 2021, 2022, and 2023, respectively. In some cases, sampling using a particular method was discontinued if mealybug counts were consistently low (*3.1 Mealybug abundance*). Samples were collected once weekly for at least the first three weeks post-release, with subsequent sampling frequency reduced to every 2–3 weeks in some trials. The post-release sampling period was six (2021), eight (2022), or four (2023) weeks. Exact dates of sample collection are shown in the results tables.

2.5. Ladybeetle sampling

In all trials, released ladybeetle adults (*C. montrouzieri* and *H. convergens*) were sampled using beat trays. Beat tray samples were collected at the same time as mealybug samples and from the same trees. A beat tray sample consisted of placing a 0.5 × 0.5 m canvas-covered frame under a tree limb and striking the limb three times with a piece of thick rubber hose. The number of *C. montrouzieri* (all years) and *H. convergens* (2023 only) jarred from the limb onto the tray were counted *in situ*. In 2020, five beat tray samples were collected per plot. In

2021, five beat tray samples were collected per plot on 26 May (first post-release sample date), but this was increased to ten per plot for all subsequent samples. Ten beat trays were also collected per plot in 2022 and 2023. In all trials, only one limb was used per tree and trees were randomly selected from plot centers. If released ladybeetle larvae were observed with any sampling method (shoot/spur, beat tray, or burlap strip traps), their abundance was recorded. Adults were only found in beat tray samples. We examined the mealybug burlap strip traps for ladybeetle eggs, but did not find any *C. montrouzieri* (all years) or *H. convergens* (2023 only) eggs. In 2020, we deployed five double-sided yellow sticky cards (20.3 × 14.0 cm; Alpha Scents, Canby, OR) per plot on 20 May and 27 May, but no *C. montrouzieri* adults were observed on the cards (despite being found in beat tray samples, *3.2 Released ladybeetle recovery*), therefore we discontinued using this sampling method.

2.6. Statistical analysis

All statistical analyses were performed using SAS 9.4 (Cary, NC). Statistical differences in counts of mealybugs (motiles or ovisacs) per shoot and per burlap strip were compared for each year using a generalized linear mixed model (PROC GLIMMIX) with treatment and date as fixed effects, specifying the negative binomial distribution for count data. Date (with subject = plot) and replicate were specified as G-side random effects within the model, with a spatial power model (type=SP (POW)) specified as the covariance model for the “date” random effect due to repeated measurements with unequally spaced observations (Stroup, 2013). When the effect of treatment was statistically significant ($P < 0.05$), pairwise comparisons between treatments were made using a Tukey-Kramer adjustment. Only post-treatment dates were included in the analysis. In the case of the 2020 data, two separate analyses were conducted for each response variable. The first analysis only included the “early release at the high rate” treatment and the no-release control, for all dates after the early release. The second analysis included all five treatments but excluded dates prior to the second release.

3. Results

3.1. Mealybug abundance

Although the selection of random shoots and spurs was specified, the higher values obtained by the orchard staff in pre-counts versus all subsequent samples collected by the research team (Fig. 1) may indicate that samples were targeted rather than random. In the 2020 trial, shoot counts and burlap strip traps showed two population peaks of mealybug motiles within the orchard, although this trend was easier to observe in the burlap strip traps which generally collected more mealybugs than the other two methods (Fig. 1). Population trends were difficult to discern using spur counts, so this sampling method was discontinued. We observed one peak on 17 June and another on 28 July. Ovisacs were first observed on 3 June, with oviposition from the first generation peaking at 24 June with a second, smaller peak on 25 August (Fig. 1).

Numerically, there was a trend for post-release counts of mealybugs (either shoot counts or burlap strip traps) to be higher in the control and the drone release treatment versus the three ground treatments in 2020 (Fig. 1). When we compared just the early release (high rate) versus the control (for the entire season of monitoring), mealybug counts were statistically different in the burlap traps, but not in the shoot samples (Table 2). The seasonal average mealybugs/burlap strip was 55% lower in the early release (high rate) versus the control (Fig. 2). In the analysis using only dates after the second release, comparing all treatments, there were no statistical differences between any of the treatments (Table 2). However, the ground release treatments were numerically similar in their seasonal means, whereas the drone release was numerically similar to the control (Fig. 2). We found 0.02 ± 0.01 mealybugs/fruit at harvest (averaged across all treatments) and concluded that fruit assessments were not suitable for monitoring differences between treatments due to low frequency and high variability between plots.

Mealybug pest pressure was lower in the 2021 trial compared to 2020, with few mealybugs observed using either sampling method (Table 3). Burlap strips captured more mealybugs than shoot samples. Due to low mealybug abundance, no distinct population peaks were observed using either sampling method (Table 3). Mealybug shoot counts and mealybug ovisac counts in the burlap strip traps were too low for statistical analysis and there were no statistical differences between treatments in mealybug motile counts per burlap strip (Table 2).

Mealybug abundance was higher in the 2022 trial compared to 2021, but lower than the 2020 trial (Table 4). Releases appear to have been conducted later in the mealybug life cycle in 2022 (0.13 mealybugs/strip) than in 2020 (0 mealybugs/strip). Mealybug motiles in the shoot samples were low and variable, so that sampling technique was

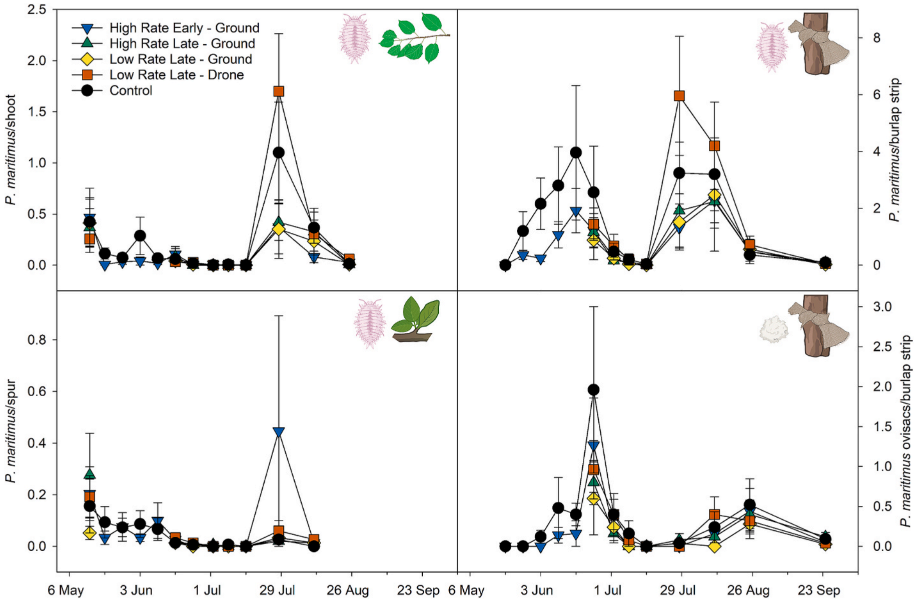

Fig. 1. Mean ± SE of *P. maritimus* motiles collected in the 2020 trial on each date in shoot, spur, and burlap strip samples and *P. maritimus* ovisacs collected in burlap strip samples.

Table 2
Results of statistical models analyzing the effects of treatment and date on mealybug counts in each trial. "Early" 2020 provides the results for the model comparing just the early release and the control for the whole monitoring period, whereas "All" 2020 compares all treatments, but only for the sampling period after the second release.

			Per shoot				**Per burlap strip**			
			Motiles		**Ovisacs**		**Motiles**		**Ovisacs**	
			Treatment	**Date**	**Treatment**	**Date**	**Treatment**	**Date**	**Treatment**	**Date**
Early	**2020**	*F*	2.85	2.65	–		6.74	2.30	1.69	0.26
		df	1,93	1, 9			1, 104	1, 9	1, 104	1, 9
		P	0.0947	0.1382			0.0108	0.1633	0.1962	0.6218
All	**2020**	*F*	1.60	7.80	–		1.92	0.00	1.28	10.16
		df	4, 141	1, 24			4, 166	1, 24	4, 166	1, 24
		P	0.1778	0.0101			0.1095	0.9501	0.2797	0.0040
	2021	*F*	*		–		0.03	0.21	*	
		df					2, 38	1, 14		
		P					0.9675	0.6561		
	2022	*F*	*		–		0.28	0.92	*	
		df					3, 92	1, 19		
		P					0.8378	0.3487		
	2023	*F*	0.62	4.62	0.22	0.32	*		0.05	0.87
		df	2, 38	1, 14	2, 38	1, 14			2, 53	1, 14
		P	0.5422	0.0496	0.8060	0.5811			0.9528	0.3856

– Data not collected.
*Counts too low for analysis.

discontinued after two post-release samples (Table 4). No distinct population peaks were observed in the burlap strip samples, although there was a decrease in mealybug abundance on the last sampling date (eight weeks post-release). Mealybug ovisacs were not found in the burlap strip traps during this trial. There were no statistical differences between treatments in mealybug motile abundance per burlap strip trap and counts were too low for analysis for the other sampling methods (Table 2).

Mealybug counts in the shoot samples started high in the 2023 trial and then rapidly declined 20 days post-release (Table 5). Ovisacs were observed in the shoot samples, which did not occur in the prior trials. Also, shoot samples collected in 2023 had more mealybug motiles and ovisacs than the burlap strip traps, unlike the previous three trials (Table 5). There were no statistical differences between treatments for mealybug motiles per shoot, mealybug ovisacs per shoot, or mealybug ovisacs per burlap strip trap, and there were too few mealybug motiles captured in the burlap strip traps for analysis (Table 2).

3.2. Released ladybeetle recovery

In 2020, we recovered the most *C. montrouzieri* adults in the week immediately following the first release (Fig. 3). After the first release, *C. montrouzieri* adults were observed in plots where adults were released for two weeks, but they were not found in the no-release control plots. On 10 and 17 June (prior to the second release), *C. montrouzieri* adults were collected in early release and control plots, indicating that dispersal out of the release plots had occurred (Fig. 3). In samples following the second release, we found fewer *C. montrouzieri* adults (two per plot or 0.08/beat tray sample at most). After the later release, adults rapidly emigrated from plots; one individual was found in a control plot the week following this release (Fig. 3). No adult *C. montrouzieri* were found on most later season sampling dates (15 July – 24 September), with the exception of 25 August, when four individuals were collected.

Cryptolaemus montrouzieri larvae were only observed in the 2020 trial. They were most commonly collected in burlap strip traps ($n = 6$), but one individual each was also collected in shoot and beat tray samples (Table 6). Two larvae were observed following the first release (41 and 55 d post-release) and six larvae (all 55 d post-release) and one pupae (69 d post-release) were observed following the second release.

In 2021, 15 total *C. montrouzieri* adults were captured in beat tray samples from ground release plots on 26 May (one day post-release) and one additional individual was found in a burlap strip trap (Table 3). Only two individuals were found in drone release plots. The following week (2 June), only three *C. montrouzieri* adults were recaptured in ground release plots and none were found in drone release plots. At all subsequent sampling dates (15, 22, and 43 days post-release), no *C. montrouzieri* were collected (Table 3).

No *C. montrouzieri* of any life stage were recovered at any date post-release in 2022.

In 2023, one adult *C. montrouzieri* was found on 28 June (six days post-release) (Table 5). No additional individuals were found in the three following weekly samples. One *H. convergens* adult was captured on a beat tray prior to the 2023 release, indicating the presence of a resident population (Table 5). Very few individuals were collected post-release ($n = 3$) and were found in both *H. convergens* release plots and other plots. *Hippodamia convergens* larvae were not observed post-release during the trial.

3.3. Pesticide use in study orchards

Pesticides applied to the study orchards before and during our trials are listed in Supp. Table 2. Sulfurs were used for fruit thinning in all orchards in March-April. Summer oil, granulovirus, and *Bacillus thuringiensis* products were applied to manage codling moth (*Cydia pomonella* (L.)). A variety of organic fungicide/bactericide products were used for fire blight control, including the active ingredients *Bacillus pumilus*, *Bacillus subtilis*, potassium bicarbonate, polyoxin D zinc salt, banda de lupinus albus doce, and copper hydroxide. The orchard used in the 2022 trial had the highest fire blight pressure, which is reflected in repeated, multi-product bactericide/fungicide applications and the regular use of a copper hydroxide product. Azadirachtin and pyrethrins were applied multiple times in the 2020 orchard prior to our releases but were discontinued before the first release. Only one application of azadirachtin was made in the 2021 orchard blocks, three weeks prior to releases. No additional insecticides, beyond those for codling moth control, were used in 2022. Spinosad was applied once in the 2023 orchard, but this occurred over a month prior to releases. Post-release, no sprays were applied for at least two days in all orchards except for the 2022 orchard. In that trial, bactericide/fungicides were applied one day after the *C. montrouzieri* larvae release and immediately after the adult release.

4. Discussion

In the first trial (2020), in which mealybug pre-counts were the

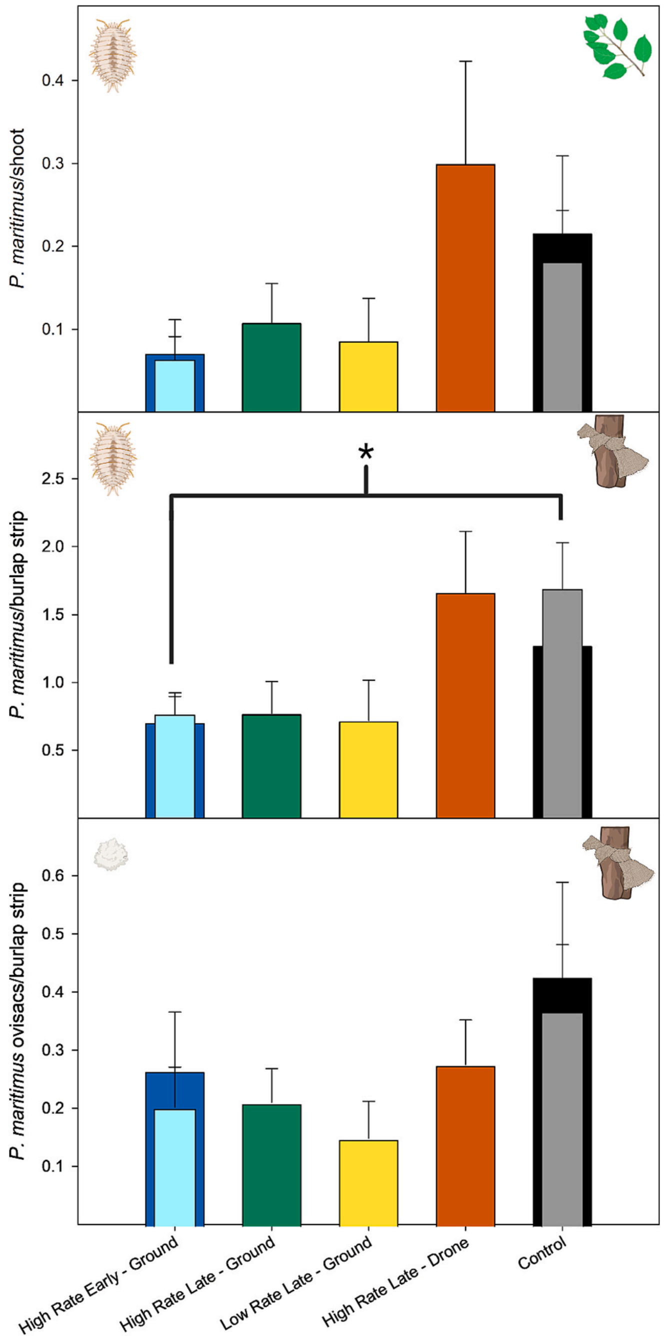

Fig. 2. Seasonal mean ± SE of *P. maritimus* motiles collected in the 2020 trial in shoot and burlap strip samples and *P. maritimus* ovisacs collected in burlap strip samples. The narrower, lighter colored bars in the “high rate early – ground” and “control” treatments indicate the seasonal means for the sampling period after the first release. All other (wider) error bars are the seasonal means for the sampling period after the second release. * indicates statistical significance at $P < 0.05$.

Table 3
Mean ± SE *C. montrouzieri* and *P. maritimus* collected in the 2021 trial comparing drone and ground releases of *C. montrouzieri.*

			P. maritimus		
		C. montrouzieri	**Per shoot**	**Per burlap strip**	
Date	**Treatment**	**per beat tray**	**Motiles**	**Motiles**	**Ovisacs**
19 May (Pre)	Ground	–	0.01 ± 0.01	0 ± 0	0 ± 0
	Drone	–	0.04 ± 0.04	0.03 ± 0.02	0 ± 0
	Control	–	0.01 ± 0.01	0 ± 0	0 ± 0
26 May	Ground	0.60 ± 0.30	0.02 ± 0.01	0 ± 0	0 ± 0
	Drone	0.08 ± 0.05	0.02 ± 0.01	0 ± 0	0.02 ± 0.02
	Control	0 ± 0	0 ± 0	0 ± 0	0.02 ± 0.02
2 June	Ground	0.06 ± 0.04	0 ± 0	0.01 ± 0.01	0.04 ± 0.02
	Drone	0 ± 0	0 ± 0	0 ± 0	0.02 ± 0.01
	Control	0 ± 0	0 ± 0	0 ± 0	0.01 ± 0.01
9 June	Ground	0 ± 0	0 ± 0	0 ± 0	0.01 ± 0.01
	Drone	0 ± 0	0 ± 0	0.04 ± 0.03	0.03 ± 0.01
	Control	0 ± 0	0 ± 0	0 ± 0	0.03 ± 0.01
16 June	Ground	0 ± 0	–	0 ± 0	0.03 ± 0.02
	Drone	0 ± 0	–	0.01 ± 0.01	0.01 ± 0.01
	Control	0 ± 0	–	0 ± 0	0.01 ± 0.01
7 July	Ground	–	–	0 ± 0	0.01 ± 0.01
	Drone	–	–	0 ± 0	0 ± 0
	Control	–	–	0 ± 0	0 ± 0
Seasonal means	Ground	0.02 ± 0.01	0 ± 0	0.02 ± 0.01	0 ± 0
	Drone	0 ± 0	0 ± 0	0.02 ± 0.01	0.01 ± 0.01
	Control	0 ± 0	0 ± 0	0.01 ± 0.01	0 ± 0

highest, releases of *C. montrouzieri* showed promise as an effective treatment, with an early release at a high rate significantly reducing the number of *P. maritimus* sampled from burlap strip traps (but not shoot samples) relative to the no-release control (Fig. 2). However, in subsequent years, trials experienced lower pest pressure, and *C. montrouzieri* failed to remain within orchards after release. Additionally, the effective rate used in 2020 was 2.5 × the highest rate recommended by insectaries (Beneficial Insectary, 2024) and 10 × the rate recommended for citrus mealybug control in California (University of California, 2025). Given the high cost of *C. montrouzieri*, consistent, strong mealybug suppression is needed to justify the expense. Prices for *C. montrouzieri* range from $0.17–0.63 USD per adult, based on our experiences with various vendors; this is consistent with an older survey of natural enemy pricing, where they were one of the most expensive natural enemies available (Cranshaw et al., 1996). The poor retention, rapid dispersal, and prey-density dependence of adult *C. montrouzieri* observed across trials indicate that this predator may not be a cost-effective tool for suppressing *P. maritimus* populations in the region’s apple orchards to an acceptable level.

Rapid dispersal and poor recovery of *C. montrouzieri* were consistently observed across all four trials. Poor retention is a common challenge associated with augmentative releases of predators and is one reason that practitioners are dissuaded from using highly dispersive stages or species (Daane et al., 1998; Obrycki et al., 2009; Shandilya et al., 2024; Sigsgaard, 2005; Sivinski, 2014). Propensity for dispersal has been identified as an important limitation for augmentative biological control using *C. montrouzieri*, even in its native range (Finlay-Doney and Walter, 2012; Villalba et al., 2006) and regardless of prey-density (Heidari and Copland, 1992; Villegas-Mendoza et al., 2012). In the current study, dispersal was observed across the field trials, reflected in recovery of released predators from no-release control plots and overall low adult recapture rates, especially in years with the lowest

Table 4
Mean ± SE *P. maritimus* collected in the 2022 trial comparing *C. montrouzieri* released at different life stages and by drone versus ground.

		P. maritimus	
Date	**Treatment**	**Per shoot**	**Per burlap strip**
10 May (Pre)	Larvae – Ground	0.04 ± 0.03	–
	Adults – Ground	0.09 ± 0.02	–
	Adults – Drone	0.12 ± 0.06	–
	Control	0.03 ± 0.02	–
18 May	Larvae – Ground	0.15 ± 0.11	0.24 ± 0.14
	Adults – Ground	0.04 ± 0.03	0.18 ± 0.10
	Adults – Drone	0.16 ± 0.08	0.16 ± 0.06
	Control	0.11 ± 0.06	0.18 ± 0.07
25 May	Larvae – Ground	0 ± 0	0.18 ± 0.08
	Adults – Ground	0.03 ± 0.02	0.28 ± 0.10
	Adults – Drone	0 ± 0	0.1 ± 0.06
	Control	0 ± 0	0.22 ± 0.12
31 May	Larvae – Ground	–	0.16 ± 0.08
	Adults – Ground	–	0.14 ± 0.10
	Adults – Drone	–	0.1 ± 0.04
	Control	–	0.24 ± 0.15
8 June	Larvae – Ground	–	0.16 ± 0.07
	Adults – Ground	–	0.08 ± 0.06
	Adults – Drone	–	0.08 ± 0.04
	Control	–	0.24 ± 0.10
15 June	Larvae – Ground	–	0.26 ± 0.08
	Adults – Ground	–	0.14 ± 0.07
	Adults – Drone	–	0.1 ± 0.04
	Control	–	0.16 ± 0.07
29 June	Larvae – Ground	–	0.32 ± 0.17
	Adults – Ground	–	0.32 ± 0.10
	Adults – Drone	–	0.10 ± 0.10
	Control	–	0.14 ± 0.05
14 July	Larvae – Ground	–	0 ± 0
	Adults – Ground	–	0.04 ± 0.04
	Adults – Drone	–	0.08 ± 0.04
	Control	–	0 ± 0
Seasonal means	Larvae – Ground	0 ± 0	0.18 ± 0.04
	Adults – Ground	0.03 ± 0.02	0.17 ± 0.04
	Adults – Drone	0 ± 0	0.09 ± 0.02
	Control	0 ± 0	0.17 ± 0.04

pest pressure (2021–2022). Even in 2020, when adult recapture rates were the highest, recovery declined rapidly after the early release date (Fig. 3). In 2023, which compared *C. montrouzieri* to *H. convergens*, both species had poor recovery. This issue is also well-known for *H. convergens*, which is considered unsuitable for augmentation programs (Daane et al., 1998). This species is even more prone to dispersal because it is collected from overwintering sites, and released adults behave as if they are dispersing out of their overwintering location (Daane et al., 1998). Depending on the duration of storage after collection, *H. convergens* individuals can also be in poor condition, with significantly depleted fat bodies (Unruh et al., 2013). However, because of its low cost (Cranshaw et al., 1996), *H. convergens* remains the most common natural enemy released in WA apples, in addition to lacewings (Schmidt-Jeffris, unpublished).

Releases by drone appeared to exacerbate dispersal. In drone and ground releases of *C. montrouzieri*, which were compared in trials in 2020–2022, drone releases had lower *C. montrouzieri* recovery than ground releases. Notably, in 2020, we observed beetles flying out of the drone towards the sun during releases, which corresponded to lower adult recovery and higher mealybug pressure compared to ground releases (Figs. 2-3). Other coccinellids display positive phototaxis (Chen et al., 2020; Jiuxuan et al., 2013; Jiuxuan et al., 2015) and early morning has been speculated to be the best timing for releasing insects by drone (Jean and Martel, 2024). Therefore, in the following trials, we conducted drone releases early in the morning. However, this did not improve retention. In grape production in California, *C. montrouzieri* have similarly been observed flying out of drones when released for vine mealybug (*Planococcus ficus* (Signoret)) control (Skernivitz, 2024). Given the strong propensity of *C. montrouzieri* to fly, drone releases at

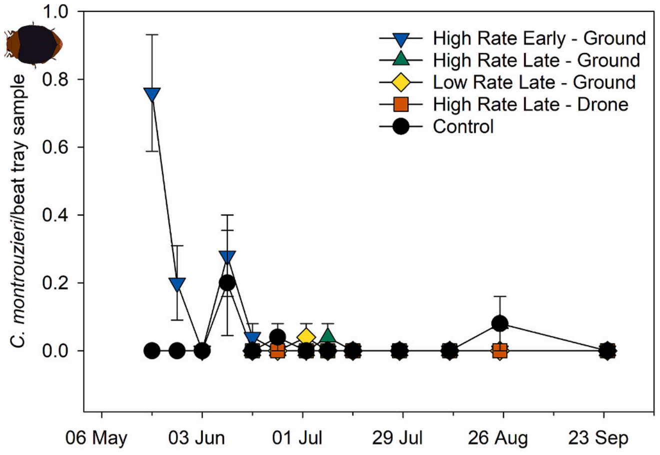

Fig. 3. Mean ± SE of *C. montrouzieri* adults collected per beat tray sample in the 2020 trial on each date post-release.

Table 5
Mean ± SE *C. montrouzieri*, *H. convergens*, and *P. maritimus* collected in the 2023 trial.

				P. maritimus			
		Per beat tray		**Per shoot**		**Per burlap strip**	
Date	**Treatment**	***C. montrouzieri***	***H. convergens***	**Motiles**	**Ovisacs**	**Motiles**	**Ovisacs**
22 June (Pre)	*C. montrouzieri*	0 ± 0	0.02 ± 0.02	–	–	0.04 ± 0.02	0.02 ± 0.02
	H. convergens	0 ± 0	0 ± 0	–	–	0.02 ± 0.02	0.06 ± 0.04
	Control	0 ± 0	0 ± 0	–	–	0.02 ± 0.02	0.08 ± 0.04
28 June	*C. montrouzieri*	0.02 ± 0.02	0.02 ± 0.02	0.67 ± 0.48	0.05 ± 0.04	0 ± 0	0.06 ± 0.04
	H. convergens	0 ± 0	0 ± 0	0.19 ± 0.17	0.09 ± 0.03	0 ± 0	0 ± 0
	Control	0 ± 0	0 ± 0	0.08 ± 0.06	0.04 ± 0.03	0 ± 0	0 ± 0
5 July	*C. montrouzieri*	0 ± 0	0 ± 0	0.04 ± 0.04	0.08 ± 0.04	0 ± 0	0.04 ± 0.02
	H. convergens	0 ± 0	0 ± 0	0.16 ± 0.14	0.12 ± 0.07	0 ± 0	0 ± 0
	Control	0 ± 0	0 ± 0	0.14 ± 0.09	0.10 ± 0.05	0 ± 0	0 ± 0
12 July	*C. montrouzieri*	0 ± 0	0 ± 0	0 ± 0	0.02 ± 0.02	0 ± 0	0 ± 0
	H. convergens	0 ± 0	0.02 ± 0.02	0 ± 0	0.06 ± 0.04	0 ± 0	0 ± 0
	Control	0 ± 0	0.02 ± 0.02	0 ± 0	0.06 ± 0.04	0 ± 0	0.02 ± 0.02
19 July	*C. montrouzieri*	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
	H. convergens	0 ± 0	0 ± 0	0 ± 0	0.08 ± 0.08	0 ± 0	0 ± 0
	Control	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
Seasonal means	*C. montrouzieri*	0.00 ± 0.00	0.01 ± 0.01	0.18 ± 0.13	0.04 ± 0.02	0.01 ± 0.01	0.02 ± 0.01
	H. convergens	0 ± 0	0.00 ± 0.00	0.09 ± 0.05	0.09 ± 0.03	0.00 ± 0.00	0.01 ± 0.01
	Control	0 ± 0	0.00 ± 0.00	0.06 ± 0.03	0.05 ± 0.02	0.00 ± 0.00	0.02 ± 0.01

Table 6

Instances where *C. montrouzieri* immatures were found in the 2020 trial, including the date, the treatment the individual was found in, days since each release, and the total number found per sample type.

	Treatment found in			Days since		*C. montrouzieri* immatures		
Date	Rate	Timing	Method	1st Release	2nd Release	burlap	shoot	beat tray
24 Jun	5,000	14 May	Ground	41	7	1	0	0
8 Jul	5,000	14 May	Ground	55	21	1	0	0
11 Aug	5,000	17 June	Ground	89	55	0	0	1
11 Aug	2,000	17 June	Ground	89	55	1	0	0
11 Aug	5,000	17 June	Drone	89	55	3	0	0
11 Aug	Control (no release)			89	55	0	1	0
25 Aug	Control (no release)			103	69	1*	0	0

*Pupa, all other individuals were larvae.

any time of day may be a poor choice for adults.

In addition to dispersing rapidly, *C. montrouzieri* did not reproduce in orchards with low mealybug pressure. Despite being considered specialists of mealybugs, *C. montrouzieri* may not be proficient at locating prey at low densities (Heidari and Copland, 1992). At close range, *C. montrouzieri* use visual and odor cues to locate prey (Finlay-Doney and Walter, 2012; Heidari and Copland, 1992; Urbina et al., 2018). Adults rely on cues from waxy filaments produced by mealybugs on their bodies and ovisacs to initiate oviposition and will delay egg laying in the absence of those cues (Merlin et al., 1996). The extent to which these cues prompt host-searching at greater distances has not been investigated, but insectaries recommend that *C. montrouzieri* be released close to colonies or ovisacs, suggesting that they are inefficient at long-distance host searching. In field releases of *C. montrouzieri* in covered citrus systems, Middleton et al. (2024) observed fewer attacks on single hibiscus mealybug (*Nipaecoccus viridis* (Newstead)) ovisacs compared with larger clusters, indicating that individual mealybugs or ovisacs may be difficult to locate or are less attractive. This suggests that mealybug density must be both high and concentrated to prompt host-finding and predation by *C. montrouzieri*.

Having adequate prey densities to sustain and retain predators in areas where they are released is a unique challenge for augmentative releases because allowing pest populations to build can diminish efficacy of releases and lead to undesirable crop damage (Daane, 2001; Schmidt et al., 2013). Deploying adequate numbers of predators to suppress high pest densities can be logistically and economically unfeasible (Olivero et al., 2003), so targeting releases early in the growing season when pest densities are lowest may be key to pest suppression (Daane, 2001). However, given that *C. montrouzieri* rely on higher pest densities for host finding, this strategy may be poorly suited to this system and predator. In classical biological control applications, releases of *C. montrouzieri* are frequently paired with releases of a parasitoid wasp for more well-rounded control (Erkilic et al., 2015; Kairo et al., 2000; Öztop and Keçecİ, 2022; Parrilli, 2021; Villalba et al., 2006). This combination accommodates different pest densities: predators for high densities of pests, and parasitoids, which are better adapted for host-searching at lower densities, for when pest pressure is minimal (Moore, 1988). Grape mealybug parasitoids have been identified from tree fruit surveys in WA (Grasswitz and Burts, 1995; Hill and Burts, 1982), but little is known about their distribution and rates of parasitism. Additionally, despite commercial availability of some mealybug parasitoids, to our knowledge, none are recommended for use against *P. maritimus* and so were not pursued in the current study.

Releases of *C. montrouzieri* larvae when prey densities are low are likely to perform similarly to adult releases. While larvae, like the adults, are known to be voracious mealybug predators, larval *C. montrouzieri* do not respond to visual or chemical stimuli from mealybugs (Heidari and Copland, 1992). They are far less motile than the adults, so insectaries recommend their application directly to pest “hot spots” (Koppert, 2024). While they are unlikely to disperse from where they are released, they are also likely less proficient at finding diffuse mealybug populations. Releases of larval *C. montrouzieri* were only tested once across the four trials (2022) in an orchard with low pest pressure (although it had historically been very high) and an intense fire-blight management program consisting of repeated applications of bactericide/fungicides. Immediately after releases, the grower applied multiple, tank-mixed bactericide/fungicide products, including copper hydroxide. It is unclear if the poor recovery of any life stage post-release was caused by direct mortality from the pesticides, which have not been assessed against *C. montrouzieri*, or if disturbance by the airblast sprayer dislodged larvae and dispersed adults that did not have sufficient time to settle into the trees. Several studies have assessed the non-target effects of insecticides on *C. montrouzieri* (Kairo, 2013). However, the effects of fungicides are poorly described (Babu and Azam, 1987b). Some conventional fungicides were toxic to *C. montrouzieri* adults in lab assays (Babu and Azam, 1987b; Mani and Krishnamoorthy, 1990), but copper oxychloride exposure was harmless (Mani et al., 1997; Mani and Thontadarya, 1988). There appear to be no published studies on modern, organic fungicide/bactericide formulated products. Larvae releases should be re-evaluated in an orchard with a pesticide program that is more compatible with biological control. Additionally, the effects of organic fire blight spray programs on commonly released natural enemies should be determined in order to design integrated management programs for apples where fire blight can be suppressed without reducing efficacy of releases.

Another key aspect of developing a management program is the establishment of scientifically-validated monitoring methods. There are no established mealybug thresholds for apple and therefore no recommended sampling schemes (Burts and Dunley, 1993). To check for the presence of mealybugs in pears, growers are instructed to examine bark scales for ovisacs and crawlers during the dormant season, developing buds for crawlers at delayed dormant/clusterbud, large limbs for females in June-July, and damaged fruit at harvest (Burts and Dunley, 1993). We have also observed orchard staff using beat tray samples to note the presence of mealybugs in orchards. Researchers have used shoot, spur/cluster, leaf (crawlers only), and fruit samples and burlap strip traps to monitor mealybug populations and make comparisons between treatments (Beers and Browne, 1989; Bixby-Brosi and Beers, 2015; Eisner et al., 1989; Grasswitz and Burts, 1995; Kahn, 1992). In our 2020 trial, we used spur and shoot samples and burlap strip traps. We found very few mealybugs in the spur samples and discontinued using this method. Similarly, counting mealybugs infesting fruits prior to harvest in 2020 resulted in low, highly variable abundance estimates per plot. Based on our results, shoot and burlap samples should always be paired to adequately monitor all stages of mealybug phenology, especially if the monitoring period overlaps movement of crawlers out of ovisacs onto foliage or the return of adults to main limbs and bark crevices as they begin to lay second generation ovisacs (Grasswitz and Burts, 1995). Burlap strip traps have the additional advantage of being able to monitor ovisacs (Grasswitz and Burts, 1995), unlike the other sampling methods, and appear to generally capture more mealybugs. However, their efficacy may decrease if alternative, preferred refuge sites are available. We speculate that the presence of alternative refuge sites in the 2023 trial orchard may have caused low mealybug capture in burlap strip traps compared to the shoot samples; at this orchard, tape was used to hold tree branches in place along the trellis wire and mealybugs were frequently observed within the tape. Burlap strip traps may be less effective in trees with more highly textured bark, numerous graft wounds, or other crevices. Ideally, future research should determine which methods of quantifying mealybugs best correlate to fruit damage levels at harvest and during storage.

The efficacy observed in the first year of the study with a high rate at an early release date was likely the result of ideal climate conditions paired with adequate pest pressure. Insectaries recommend misting target plants with water prior to releasing *C. montrouzieri* (Beneficial Insectary, 2024), and a rain event preceded releases, wetting the canopy of the field site. Temperatures were cool and remained temperate during the trial. Although *C. montrouzieri* are adapted to warmer climates and unable to overwinter in cold conditions (Maes et al., 2015), they are similarly intolerant of excessive heat (Babu and Azam, 1987a; Solangi et al., 2013). The period during which we recovered *C. montrouzieri* larvae post-release corresponds with their development time at cooler temperatures (18–21 °C) (Babu and Azam, 1987a; Fisher, 1963; Maes et al., 2015; Patil et al., 2015). Recovery of *C. montrouzieri* larvae in 2020 also indicates that *P. maritimus* pressure was sufficient to support survival and reproduction of released adults. Despite this success, a low rate release was not compared to the high rate at the early timing, so it is unknown whether the efficacy observed would have been replicated with a lower release rate. Nevertheless, achieving these precise conditions for predator establishment and pest control was challenging for subsequent trials. Based on our experience with *C. montrouzieri,* WA apple growers may face unrealistic obstacles to achieving control with releases of this predator.

Other tactics may be better suited for organic management of *C. montrouzieri* in apples. In pears, releases of *Chrysoperla plorabunda* s.l. (=*Chrysopa californica*) eggs reduced *P. maritimus* fruit infestation by ~ 80% (Doutt, 1950). Another lacewing, *C. rufilabris* (Burmeister), and the European earwig (*Forficula auricularia* L. s.l.) were also promising in preliminary cage studies and single-tree mass releases (Miller and Dunley, 1996). Similarly, we have found that releases of *C. rufilabris* larvae (49,421/ha) reduced *P. maritimus* per shoot by ~ 90% (Schmidt-Jeffris, unpublished). New viticulture research has also shown that mating disruption of *P. maritimus* using pheromone dispensers substantially reduces trap catch, and at the correct rates, results in in complete trap shutdown (Onayemi, 2024). Because of the high uptake of mating disruption for codling moth, Washington apple growers are likely to be receptive to this technology if it can be adapted for their cropping system. Due to its cryptic habits, *P. maritimus* remains a challenging pest to manage in apples, especially under organic production systems, and a multi-pronged approach may be needed for adequate suppression.

CRediT authorship contribution statement

Erica Moretti: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Data curation. **Rebecca A. Schmidt-Jeffris:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Rebecca Schmidt-Jeffris reports that for some trials, released mealybug destroyers were provided by BioBee. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocontrol.2025.105805.

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