Developing female removal for *Cydia pomonella* (Lepidoptera: Tortricidae) in organic pear in the USA and Italy

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**Abstract**

Seventeen trials were conducted using traps baited with kairomone-based lures to evaluate female removal (FR) as an effective management tactic for codling moth, *Cydia pomonella*, L., in organic pear, *Pyrus communis* L., production in Italy and USA during 2019–2020. Studies included paired plots (0.4–1.4 ha) treated with or without 60 traps ha⁻¹ in cultivars Bartlett and Abate Fétel. Paired plots were also treated together with or without mating disruption (MD) and with similar spray programmes. Three-, four-, and five-component lures were used with several trap types: green, clear or green/white bucket traps and orange delta traps. The three-component lure consisted of \((E,E)-8,10\text{-dodecadien-1-ol}\) (sex pheromone, PH), \((E,Z)-2,4\text{-ethyl decadienoate}\) (pear ester, PE) and acetic acid (AA); the four-component lure was PE, \((E)-4,8\text{-dimethyl-1,3,7-nonatriene}\) (DMNT), 6-ethenyl-2,2,6-trimethyloxan-3-ol (pyranoid linalool oxide, LOX), and AA, and the five-component lure had PH added. Preliminary studies were also conducted to evaluate the trapping efficacy of non-saturating bucket traps. A clear bucket trap baited with PE/DMNT/LOX + AA captured 97-fold more codling moth females than an orange delta trap baited with PH/PE. However, female captures did not differ between traps when both were baited with the four-component lure. Fruit injury from codling moth was significantly reduced with the implementation of FR in both pear production regions. At harvest, mean fruit protection in the USA studies was 65% and 27% in Italy. This difference was likely associated with the four-component lure being less effective in Italy than in the USA. Nevertheless, results demonstrate that FR can be a useful approach to remove females immigrating into orchards and as a new tactic to reduce pest pressure in selected areas of orchards allowing both MD and organic insecticide programmes to be more effective. Further studies should investigate the cost-benefit of matching the intensity of FR to variable pest pressures.

**KEYWORDS**
bucket trap, Codling moth, mass trapping, organic pest management, *Pyrus communis*
1 INTRODUCTION

Insect pest management in pear, *Pyrus communis* L., is structured as a balance between the necessary management of the direct key pest codling moth, *Cydia pomonella* L., with the variable need to suppress pear psylla, *Cacopsylla* spp., a secondary pest harmful only at high population levels. In fact, while for codling moth the action threshold generally matches the pest presence recorded with monitoring traps, for pear psylla according to the pear cultivar and the seasonal period there are different thresholds determined using beat trays and visual inspection of spurs and foliage (Civolani, 2012; Horton, 1999; Jones et al., 2009). Pear psylla is more of a sporadic pest than codling moth due to the variable levels of natural control of its population density imposed from key biological control agents, such as the parasitoid *Trechites insidiosus* Crawford, and several generalist predators, including the hemipterans *Deraeocoris brevis* Knight, and *Campylomma verbasci* Meyer, in North America (DuPont & Strohm, 2019) and *Anthocoris nemoralis* Fabricius, in Europe (Solomon et al., 2000). Unfortunately, insecticide sprays applied for codling moth can disrupt biological control of pear psylla and economic loss can occur due to feeding by pear psylla causing fruit staining and vectoring the phytoplasma ‘pear decline’, as well as, the deposition of honeydew throughout the canopy being a severe nuisance to pickers (DuPont et al., 2021; Solomon et al., 1989; Westigard & Moffitt, 1984).

A trade-off occurs in organic pear production where selective sprays for codling moth are the primary tools used for its management, but where effective measures to suppress pear psylla are also limited (Benuzzi & Ladurner, 2018; Knight et al., 2019). Pear growers have used sex pheromones for mating disruption (MD) of codling moth for more than three decades (Moffitt & Westigard, 1984), in an effort to reduce their use of insecticides and avoid selection for resistance in both codling moth and pear psylla (Jones et al., 2009; Weddle et al., 2009). Organic insecticides for codling moth primarily include the use of granulosis virus, oil and spinosad (Daniel et al., 2018). However, the over-use of spinosad for codling moth can be disruptive of biological control (Daniel et al., 2018), while other studies in pear did not find its limited use disrupted pear psylla (Arthurs et al., 2007).

Successful fruit attack by larval codling moth varies among pear cultivars, and increases later in the season as fruits ripen (Van Steenwyk et al., 2004; Westigard et al., 1976). Thus, effective management programmes for codling moth later in the season in pear, and especially for late-season cultivars are most critical. In particular, the potential for immigration of mated tortricid females into pear orchards late in the season can be a major problem, as reported for oriental fruit moth, *Grapholita molesta* Busck moving from stone fruit, *Prunus* spp. into pear (Il’ichev & Williams, 2006; Il’ichev et al., 2007). Border spray applications to manage codling moth along these more susceptible areas of the orchard have been used by some growers with one of several adulticides, but there are no effective materials available to organic growers (Knight, 2004, 2010; Trimble & Vickers, 2000). Mass trapping or ‘lure and kill’ of adult codling moth especially along orchard borders is another method that can be used to reduce moth populations; however, early experimental trials with male attractants demonstrated that this approach was not robust enough to be adopted by growers (summarized in El-Sayed et al., 2006, 2009).

More recently, the ability to use mass trapping to remove female moths (coined ‘female removal, FR) has offered a new promise for effective codling moth management (Jaffe et al. 2018; Jaffe & Landolt, 2018, 2019). These initial studies were conducted in apple *Malus domestica* Borkhausen, with a three-component kairomone-based experimental lure comprised of (E,Z)-2,4-ethyl decadienoate (pear ester, PE); the tertiary blend comprised PE, (E,E)-4,8-dimethyl-1,3,7-nonatriene (DMNT), 6-ethyl-2,2,6-trimethylxan-3-ol (pyranoid linalool oxide, LOX) and AA was developed and shown to be 3-fold more effective in capturing females in delta traps than the n-butyl sulphide-based lure (Knight et al., 2019b). Also, the addition of the sex pheromone (E,E)-8,10-dodecadien-1-ol (PH) to this four-component blend increased male and total captures (Knight et al., 2019c).

Our FR studies in pear were conducted in 2019 with new multi-component blends in long-lasting lures, including PH/PE + AA and PH/PE/DMNT/LOX + AA, using non-saturating bucket traps in the USA (Preti et al., 2021a). Meanwhile, the effectiveness of these blends to capture codling moth in traps was found to be lower for codling moth in Italian apple and pear orchards than in those in the USA (Preti et al., 2021a). Also, the addition of PH into the same PVC matrix together with three other volatile organic compounds was found to significantly reduce female moth captures (Preti et al., 2021a). Therefore, FR pear studies were conducted in 2020 in both countries with the PE/DMNT/LOX + AA lure to evaluate the comparative use of this novel management tool for codling moth, considering also apple crop for trap-lure comparison studies.

2 MATERIALS AND METHODS

2.1 Lures and traps

Three different multi-component blends formulated in proprietary PVC matrices (Trécé Inc.) were used in traps with a closed membrane acetic acid (AA) co-lure in different moth flights and years. These PVC lures included two, three or four volatile organic compounds loaded into the same matrix to obtain, respectively, a binary, tertiary and quaternary blend. The binary blend comprised (E,E)-8,10-dodecadien-1-ol (sex pheromone, PH) and (E,Z)-2,4-ethyl decadienoate (pear ester, PE); the tertiary blend comprised PE, (E,E)-4,8-dimethyl-1,3,7-nonatriene (DMNT) and 6-ethyl-2,2,6-trimethylxan-3-ol (pyranoid linalool oxide,
LOX); and the quaternary blend comprised PH, PE, DMNT and LOX. Loadings of active ingredients in both the PVC and membrane lures were identical to those reported previously (Knight et al., 2019b, 2019c; Preti et al., 2021a).

Several types of traps were used in FR trials including all green or all clear bucket traps (Unitrap®, Great Lakes IPM, Vestaburg, MI, USA) or a green/white bucket trap (Multipher III®; Distributions Solida Inc.). Bucket traps were partially filled with 250 ml of a 20:80 mix of propylene glycol (Duda Energy) and mineral oil (HI Supreme Spray Oil-NW®; Integrated Agribusiness Professionals) in the USA or 100% mineral oil (VERNOIL®; UPL Europe) in Italy. Orange delta traps (Pheron® Vi; Trécé Inc.) with sticky liners coated with a hot-melt pressure sensitive adhesive were also used in some 2020 FR trials in the USA.

2.2 | Trap type and lure comparison trials

As follow-up of other lure comparison studies run with the same multi-component lures in both the USA and Italy in apple and pear (Preti et al., 2021a), two studies were conducted to evaluate the effectiveness of different trap-lure combinations for codling moth FR. In the first study (trap comparison #1), moth captures in an orange delta trap baited with the PH/PE lure (the standard trap-lure set used for monitoring codling moth) and in a clear bucket trap baited with PE/DMNT/LOX + AA lure were compared. This study was conducted from 7–22 May 2019 in a conventional Red Delicious apple plot located in Warapo, Yakima (WA) (46°24′46.45″N–120°28′25.83″W) prior to the application of insecticides for codling moth. Traps (N = 10 replicates) were randomized and liners were replaced in the delta traps after one week to prevent the liners saturating, while captures in the bucket traps were checked only at the end of the trial.

The second study (trap comparison #2) was conducted in Italy during 2020 in both apple and pear crops to compare the trapping efficacy of a non-saturating clear bucket trap with the standard delta monitoring trap when both trap types were baited with the PE/DMNT/LOX + AA lure set. Six trap comparison trials were conducted in organic pear plots cultivars Santa Maria (2 trials) and Bartlett (1 trial) and in organic apple plots cultivar Gala (3 trials) located in Ferrara province, Emilia-Romagna Region (44°46′11.12″N–11°18′5.88″E; 44°46′7.49″N–11°19′37.92″E). Trials were conducted over 50–60 days during the first and second codling moth flights (9 April–5 June, 5 June–5 August in pear and 1 May–18 June, and 18 June–5 August in apple). A variable number of trap-lure replicates (N = 7–22) was used in this study and liners in the delta traps were not replaced during these trials. In both countries and in all the trials, traps were placed in the upper third of the canopy (>3.0 m) with a pole, spaced 30 m apart and from the orchard perimeter, and not rotated during the studies. All moth captures were counted and sexed in the laboratory at the end of each trial period. These two studies considered both apple and pear crops focusing primarily to evaluate the bucket trap type for FR.

2.3 | FR field trials

All FR studies (17 trials) were conducted in organic pear plots located either in USA or Italy. During 2019, five orchards were selected in California (3 trials), Oregon (1 trial) and Washington State (1 trial). In 2020, six orchards were selected in Oregon and Washington State (3 trials per State) and in the Emilia-Romagna Region of Italy (6 trials). Trial locations were chosen among organic certified pear farms in these regions where growers reported medium to high levels of codling moth injury in the previous year. Experimental plots in both countries were placed within orchards treated with or without mitigate, MD (see supplemental material, Table S1). Treated orchards received sex pheromone dispensers (PH-MD) including Isomate®-CM Flex (Pacific Biocontrol Corporation), Checkmate® CM-XL (Suterra Europe Biocontrol S.L.), Isomate®-CTT (CBC Europe S.r.l.), and Cidetrak® Meso (Trécé Inc.), or PH/PE-MD dispensers Cidetrak® CMDA Combo™ Meso (Trécé Inc.) loaded with sex pheromone and pear ester. All paired plots were treated with the same growers’ spray programme, according to the organic products authorized in the USA and Italy. A minimum area of 0.4 ha was treated with FR and a similar sized adjacent plot was selected as the control without FR. A trap density of 60 traps ha⁻¹ was installed in the FR plots in April, prior to the start of adult flight of codling moth. Traps were attached to poles and placed in the upper third of the canopy, and evenly distributed 25 m apart.

All traps in the USA study in 2019 were baited with the PH/PE + AA lure in April, and at mid-season these lures were replaced with PH/PE/DMNT/LOX + AA. All traps in both countries during 2020 were baited with the PE/DMNT/LOX + AA lure. Lures were replaced once at mid-season in the pear cultivar Bartlett in both the USA and Italy. However, lures were replaced twice during the season in the pear cultivar Abate Fétel in Italy at ca. 8-week intervals (Table S1). In detail, in Italy the first codling moth flight started in mid-April 2020. Captures check, lures replacement and fruits injury assessment were carried out in mid-June, before the begin of the second codling moth flight that started in late June. The second captures check, lures replacement and fruits injury assessment were carried out in late July and early August, before the begin of the third flight; after these assessments the pear cultivar Bartlett was harvested. The third flight started in the early August and the pre-harvest captures check and fruits injury assessment were carried out in mid-September only for locations with pear cultivar Abate Fétel; after these assessments the pear cultivar Abate Fétel was harvested. Trials across different geographical areas included bucket traps of different colours (green or green/white in the USA and clear in Italy). Three FR trials conducted in Washington State during 2020 were initiated in mid-June with the installation of 40 Cidetrak® CMDA Combo™ Meso dispensers ha⁻¹ for MD and the deployment of FR using orange delta traps (Table S1).

Moth captures (either filtered from the liquid in bucket traps or by removing the trap liners in delta traps) were brought to the laboratory to count and sex all moths. A subsample of codling moth females (typically 100 individuals) were sorted and dissected on
each date to determine their mating status by observing the bursa copulatrix with a stereomicroscope. In addition, non-target species were recorded to evaluate the selectivity of the FR traps. Levels of fruit injury were sampled in each of the paired plots at each lure replacement date and prior to harvest, by inspecting 1,000–2,400 fruits on trees (30–40 fruits per tree from the mid- to upper canopy) in the central area of each plot. Three of the four and two of the four Bartlett and Abate Fétel plots, respectively, were thinned by Italian growers at the end of the first codling moth flight (mid-June) to remove codling moth injured fruits.

2.4 | Statistical analyses

Statistical analyses of moth captures and fruit injury level were performed with R software version 4.0.3 (R Core Team, 2020), including the packages lme4 (Bates et al., 2015) and multcomp (Hothorn et al., 2008). Figures were created using the package ggplot2 (Wickham, 2016). Akaike’s information criteria (AIC) and residuals distribution were used to select fitted models. To test the effect of the trap/lure type as predictor on the moth counts, captured data were fitted to a negative binomial distribution using the glm.nb function, package MASS (Venables & Ripley, 2002). Proportions of fruit injury were transformed with arcsine(square root(x)) and a paired t-test was used to highlight differences between FR and control plots, using trials as replicates. Results are reported as mean values ± standard error of the mean (SEM).

3 | RESULTS

In the USA trap comparison study #1, total moth captures with the proposed FR trap-lure combination (clear bucket baited with PE/DMNT/LOX + AA) were significantly higher (4.8-fold) than the use of a standard monitoring trap-lure combination (orange delta trap baited with PH/PE) (z = 12.35, theta = 13.42, p < .001) (Figure 1a). In particular, over a 2-week trial period the bucket trap averaged 289.7 female captures or 96.6-fold more than the monitoring trap with its liner replaced after one week (z = 19.28, theta = 8.89, p < .001) (Figure 1b). Also, the number of male captures was significantly higher in the bucket trap baited with the multi-component lure (z = 5.77, theta = 15.95, p < .001) (Figure 1c). In contrast, in 2020 in the Italian trap comparison study #2, total moth captures in the two traps when baited with the same lure (PE/DMNT/LOX + AA) were significantly different (z = 4.21, theta = 3.58, p < .001) only in apple (Figure 2a). No difference in female captures (z = 1.80, theta = 7.29, p = .072) was observed between trap types in either apple or pear in Italy (Figure 2b), while only in apple crop the male captures

**FIGURE 1** Codling moth (*Cydia pomonella* L.) captures in two trap–lure combinations: a standard monitoring orange delta trap was baited with a PVC lure loaded with (E,E)-8,10-dodecadien-1-ol (sex pheromone, PH) and (E,Z)-2,4-ethyl decadienoate (pear ester, PE), while a non-saturating clear bucket trap was baited with a non-pheromone four-component binary lure comprised of a PVC loaded with PE, (E)-4,8-dimethyl-1,3,7-nonatriene (DMNT) and 6-ethenyl-2,2,6-trimethyloxan-3-ol (pyranoid linalool oxide, LOX), and an acetic acid (AA) membrane cup co-lure. Mean (±SEM) results per trap cumulated over a 2-week monitoring period (7 May–22 May 2019) in an apple orchard located in the USA. a = total (males + females) codling moth; b = females codling moth; c = males codling moth.
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in the delta traps were higher than in the bucket traps \((z = 6.87, \theta = 7.00, p < .001)\) (Figure 2c).

The 2019 USA field trials showed that FR significantly reduced levels of fruit injury (Table 1). At mid-season, FR with the PH/PE + AA lure reduced fruit injury ca. 50% and removed 0.2-12.7 codling moth females per trap. At harvest, levels of fruit injury were 40%–80% lower in FR-treated than the untreated plots. Traps baited with the PH/PE/DMNT/LOX + AA lure removed on average 0.3–5.4 females over the second half of the season. The proportion of unmated females captured at mid-season was 0.25–0.28 and few unmated females were captured in the second half of the season. The highest proportion of unmated females (0.51) was observed during the first codling moth flight in trial #5, in the sole orchard treated with PH-MD in the 2019 study (Table 1).

The 2020 results with FR in USA were consistent with those from the previous year, despite the use of different trap types (green/white buckets and orange delta traps) and a different lure (PE/DMNT/LOX + AA) (Table 2). The FR plots had a significantly lower level of fruit injury compared to the control plots both at mid-season, reduced >90% in Oregon, and >50% across all six trials prior to harvest (Table 2). The bucket traps used in Oregon by mid-season removed on average 5.0–18.4 females per trap. In the second half of the season, bucket traps in Oregon removed 2.2–9.9 females per trap and delta traps in Washington State removed on average 2.4–7.7 females.

Fruit damage in the Bartlett orchards in Italy did not differ between FR and untreated plots at the end of the first moth flight (Table 3). However, fruit injury at harvest was significantly lower (reduced 21%) in the FR than the untreated plots. Fruit injury in the FR-treated Abate Fétel cultivar plots was not significantly reduced with FR after either the first or second moth flight (Table 3). However, fruit injury prior to harvest in Abate Fétel was significantly reduced with FR (33% lower) compared with the paired untreated plots. At harvest, in each of the seventeen FR trials carried out in both the USA and Italy the fruit injury level recorded in the FR plot was always reduced in comparison to the damage of the paired control plot, with an average efficacy of 65% in the USA and of 27% in Italy (Figure 3).

In Italy, data from trial #16 in Abate Fétel were of note as the grower deliberately placed the FR plot in the portion of the orchard where codling moth pest pressure had been the highest in 2019. This biased placement was visible early in the season when the
**TABLE 1** Field trials with codling moth (*Cydia pomonella* L.) conducted in five paired Bartlett pear plots during 2019 in the USA to compare the effectiveness of deploying 60 bucket traps ha⁻¹ (female removal, FR) baited with multi-component lures versus no traps (control) to reduce fruit injury.

| Trial# | Treatment | Mid-season |          |          |          | Pre-harvest |          |          |          |          |
|--------|-----------|------------|----------|----------|----------|-------------|----------|----------|----------|----------|
|        |           | Number of moths per trap | Proportion of females | Proportion of unmated females | Proportion of fruit injury | Number of moths per trap | Proportion of females | Proportion of unmated females | Proportion of fruit injury |
| 1      | FR        | 3.7        | 0.41     | 0.26     | 0.020    | 8.3         | 0.65     | 0.08     | 0.030b   | 0.050    |
|        | Control   | —          | —        | —        | 0.036    | —           | —        | —        | —        | 0.250    |
| 2      | FR        | 1.5        | 0.11     | 0.25     | 0.025    | 1.0         | 0.70     | 0.00     | 0.048    | 0.016    |
|        | Control   | —          | —        | —        | 0.048    | —           | —        | —        | —        | 0.051    |
| 3      | FR        | 6.5        | 0.48     | 0.28     | 0.105    | 8.3         | 0.57     | 0.07     | 0.054    | 0.112    |
|        | Control   | —          | —        | —        | 0.219    | —           | —        | —        | —        | 0.197    |
| 4      | FR        | 20.5       | 0.62     | 0.28     | 0.000    | 3.9         | 0.73     | 0.28     | 0.006    | 0.015    |
|        | Control   | —          | —        | —        | 0.006    | —           | —        | —        | —        | 0.054    |
| 5      | FR        | 4.0        | 0.42     | 0.51     | 0.001    | 1.1         | 0.27     | 0.00     | 0.003    | 0.005    |
|        | Control   | —          | —        | —        | 0.003    | —           | —        | —        | —        | 0.005    |
|        |           | **Means (SEM)** |         |          |          | **Means (SEM)** |         |          |          |          |
| 1–5    | FR        | 7.2 (3.4)  | 0.41 (0.08) | 0.32 (0.05) | 0.030b (0.019) | 4.5 (1.6)  | 0.58 (0.08) | 0.09 (0.05) | 0.039b (0.020) |
|        | Control   | —          | —        | —        | —        | —           | —        | —        | —        | 0.111a (0.047) |

**Note:** Multi-component lures were comprised of [(E,E)-8,10-dodecadien-1-ol (codlemone, PH)], [(E,Z)-2,4-ethyl decadienoate (pear ester, PE)], [(E)-4,8-dimethyl-1,3,7-nonatriene (DMNT)], 6-ethenyl-2,2,6-trimethyloxan-3-ol (pyranoid linalool oxide, LOX) and acetic acid (AA). Traps were initially baited with PH/PE + AA. Lures were replaced at mid-season with PH/PE/DMNT/LOX + AA.
**TABLE 2** Field trials with codling moth (*Cydia pomonella* L.) conducted in six paired Bartlett pear plots during 2020 in the USA to compare the effectiveness of deploying 60 bucket or delta traps ha⁻¹ (female removal, FR) baited with a multi-component lure versus no traps (control) to reduce fruit injury.

| Trial # | Treatment | Mid-season | Pre-harvest |
|---------|-----------|------------|-------------|
|         |           | Number of moths per trap | Proportion of females | Proportion of unmated females | Proportion of fruit injury | Number of moths per trap | Proportion of females | Proportion of unmated females | Proportion of fruit injury |
| 6       | FR        | 34.0       | 0.54        | 0.20        | 0.008                    | 16.3       | 0.61       | 0.21       | 0.070                    |
|         | Control   | —          | —           | —           | 0.034                    | —          | —          | —          | —                        |
| 7       | FR        | 17.4       | 0.48        | 0.29        | 0.000                    | 5.0        | 0.67       | 0.40       | 0.003                    |
|         | Control   | —          | —           | —           | 0.005                    | —          | —          | —          | —                        |
| 8       | FR        | 9.4        | 0.53        | 0.20        | 0.000                    | 3.3        | 0.66       | 0.40       | 0.002                    |
|         | Control   | —          | —           | —           | 0.005                    | —          | —          | —          | —                        |
| 9       | FR        | —          | —           | —           | —                       | 16.5       | 0.44       | 0.37       | 0.021                    |
|         | Control   | —          | —           | —           | —                       | —          | —          | —          | —                        |
| 10      | FR        | —          | —           | —           | —                       | 16.8       | 0.46       | 0.31       | 0.213                    |
|         | Control   | —          | —           | —           | —                       | —          | —          | —          | —                        |
| 11      | FR        | —          | —           | —           | —                       | 5.6        | 0.43       | 0.38       | 0.005                    |
|         | Control   | —          | —           | —           | —                       | —          | —          | —          | —                        |
| Means (SEM) 6-11 | FR | 20.3 (7.2) | 0.52 (0.02) | 0.23 (0.03) | 0.003b (0.003) | 10.6 (2.7) | 0.55 (0.05) | 0.35 (0.03) | 0.052b (0.034) |
|         | Control   | —          | —           | —           | —                       | —          | —          | —          | —                        |

Note: In all trials and during all the season, all traps were baited with a binary lure comprised of (E,Z)-2,4-ethyl decadienoate (pear ester, PE), (E)-4,8-dimethyl-1,3,7-nonatriene (DMNT), 6-ethenyl-2,2,6-trimethyloxan-3-ol (pyranoid linalool oxide, LOX) and acetic acid (AA). PE/DMNT/LOX were loaded together in a PVC matrix, while AA was loaded in a membrane cup. Multipher traps were used in trials #6, #7 and #8 during all the season, while delta-shaped traps were used in trials #9, #10, and #11 only in the second half of the season.
level of damage in the FR-treated plot was found to be twice as high as the level sampled in the untreated plot. However, following the thinning of injured fruits in both of the paired plots this was reversed with 2.6- and 1.3-fold higher levels of injury in the untreated than the FR plot in the second and third assessments, respectively (Table 3). In Italy, the proportion of unmated females captured was low throughout the season (0.15–0.18 during the first flight and 0.05 later in the season) regardless of the use of MD (Table 3).

| Trial # | Codling moth flight | Number of moths per trap | Proportion of females | Proportion of unmated females | Pear cv Bartlett | Pear cv Abate Fétel |
|---------|---------------------|--------------------------|----------------------|-------------------------------|----------------|-------------------|
|         |                     |                          |                      |                               | FR | Control | FR | Control |
| 12      | First               | 4.0                      | 0.48                 | 0.17                          | 0.022 | 0.023 | 0.017 | 0.020 |
|         | Second              | 2.4                      | 0.42                 | 0.03                          | 0.007 | 0.008 | 0.010 | 0.010 |
|         | Third               | 2.5                      | 0.87                 | 0.09                          | —    | —     | 0.052 | 0.097 |
| 13      | First               | 3.0                      | 0.41                 | 0.27                          | 0.004 | 0.003 | 0.009 | 0.009 |
|         | Second              | 4.2                      | 0.55                 | 0.06                          | 0.034 | 0.045 | 0.013 | 0.026 |
|         | Third               | 7.4                      | 0.69                 | 0.01                          | —    | —     | 0.058 | 0.085 |
| 14      | First               | 4.4                      | 0.43                 | 0.18                          | —    | —     | 0.013 | 0.019 |
|         | Second              | 3.4                      | 0.64                 | 0.00                          | —    | —     | 0.020 | 0.036 |
|         | Third               | 6.2                      | 0.70                 | 0.04                          | —    | —     | 0.106 | 0.148 |
| 15      | First               | 4.7                      | 0.49                 | 0.03                          | 0.035 | 0.037 | —    | —     |
|         | Second              | 3.9                      | 0.47                 | 0.04                          | 0.009 | 0.013 | —    | —     |
| 16      | First               | 2.2                      | 0.45                 | 0.09                          | —    | —     | 0.043 | 0.021 |
|         | Second              | 5.3                      | 0.45                 | 0.11                          | —    | —     | 0.007 | 0.018 |
|         | Third               | 4.6                      | 0.81                 | 0.04                          | —    | —     | 0.036 | 0.047 |
| 17      | First               | 1.0                      | 0.28                 | 0.13                          | 0.003 | 0.007 | —    | —     |
|         | Second              | 3.5                      | 0.37                 | 0.08                          | 0.008 | 0.010 | —    | —     |
| Means (SEM) 12,13,15,17 | First               | 3.2 (0.8)                | 0.42 (0.05)          | 0.15 (0.05)                   | 0.016a (0.008) | 0.018a (0.008) | — | — |
|         |                     |                          |                      |                               | Paired t-test $t_3 = -0.96$, $p = .416$ | Paired t-test $t_3 = -3.30$, $p = .046$ |
|         | Second              | 3.5 (0.4)                | 0.45 (0.04)          | 0.05 (0.01)                   | 0.015b (0.007) | 0.019a (0.009) | — | — |
|         |                     |                          |                      |                               | Paired t-test $t_3 = -3.30$, $p = .046$ | Paired t-test $t_3 = -4.65$, $p = .019$ |
| Means (SEM) 12,13,14,16 | First               | 3.4 (0.5)                | 0.44 (0.01)          | 0.18 (0.04)                   | —    | —     | 0.021a (0.008) | 0.017a (0.003) |
|         |                     |                          |                      |                               | Paired t-test $t_3 = 0.36$, $p = .740$ | Paired t-test $t_3 = -4.65$, $p = .019$ |
|         | Second              | 3.8 (0.6)                | 0.52 (0.05)          | 0.05 (0.02)                   | —    | —     | 0.013a (0.003) | 0.023a (0.006) |
|         |                     |                          |                      |                               | Paired t-test $t_3 = -2.97$, $p = .059$ | Paired t-test $t_3 = -4.65$, $p = .019$ |
|         | Third               | 5.2 (1.1)                | 0.77 (0.04)          | 0.05 (0.02)                   | —    | —     | 0.063b (0.015) | 0.094a (0.021) |

Note: In all trials and during all the season, all traps were baited with a binary lure comprised of (E,Z)-2,4-ethyl decadienoate (pear ester, PE), (E)-4,8-dimethyl-1,3,7-nonatriene (DMNT), 6-ethenyl-2,2,6-trimethyloxan-3-ol (pyranoid linalool oxide, LOX) and acetic acid (AA). PE/DMNT/LOX were loaded together in a PVC matrix, while AA was loaded in a membrane cup. In trials #12, #15, #16 and #17, after the first fruit injury assessment carried out in mid-June, growers removed an unknown number of fruit injured by codling moth in both FR and control plots.
Bucket traps in Italy baited with the PE/DMNT/LOX/AA lure were selective for codling moth as the target pest accounted for 77% of all insects captured. Non-targets (overall mean values ± SEM per trap) captured in bucket traps included beneficial insects, such as pollinators (*Apis mellifera* L., 0.42 ± 0.06) and natural enemies (coccinellids: 1.18 ± 0.10, dermapterans: 0.13 ± 0.03, and syrphids: 0.30 ± 0.05), accounting for 16% of all insect captures. In addition, a few important pome fruit pest species, such as *G. molesta* (0.08 ± 0.02) and the sesiid apple clearwing moth *Synanthedon myopaeformis* Borkhausen (0.55 ± 0.05) were captured (5% of all insect captures). Finally, some hymenopterans including vespid wasps (0.28 ± 0.04) were captured (2% of all insect captures). Similar levels and diversity of non-targets were captured in the USA studies with bucket traps, however, muscid flies and vespid wasps were the most prevalent non-target groups trapped. Delta traps in both countries baited with the multi-component lures captured few non-targets and these data were not summarized. No outbreaks of secondary pests were noted in any of the 17 trial locations.

**4 | DISCUSSION**

The implementation of FR in pear for codling moth significantly reduced levels of fruit injury in both Italy and the USA. Closer examination of the data revealed several interesting results. For example, in Italy the relative effectiveness of FR increased later in the season, especially with the cultivar Abate Fétel. Second, the results from trial #16 where FR was placed in the known ‘pest hot-spot’ in the orchard demonstrated the effectiveness of FR in reducing localized pest problems to a baseline level. Third, the relatively greater effectiveness of FR in the USA than in Italy is consistent with our recent report of geographical differences in the attractiveness of these multi-component lures for codling moth (Preti et al., 2021a). While in the USA the four-component lure PE/DMNT/LOX + AA outperformed other kairomone-based lures for the highest capture of female moths, in Italy the multi-component lures tested (PH/PE/DMNT/LOX + AA) had an overall similar attractiveness for females (Preti et al., 2021a). Further efforts to increase the effectiveness of lures for female codling moth in Italy and perhaps in some other key pear production regions are likely needed to develop the full potential of FR. Meanwhile, these data suggest that a higher trap density may be required to achieve successful levels of FR in pear production regions outside the western USA.

A certain variability in the FR results can be observed across the seventeen locations where the FR studies were carried out. The major factor affecting FR efficacy is likely the actual level of pest pressure, which is very difficult to properly estimate in each pear orchard under study. Other factors that could also explain the different results achieved in the various trials are the total fruit load...
amount and the grower spray programme, which were constant within each trial location for both the treated and control plots, but may vary across locations. Nevertheless, given these uncontrollable field variability sources and using these locations as replicates, a significant fruit injury reduction was overall demonstrated in the FR-treated plots.

Our results with FR in pear largely agree with recent trials in apple using the less attractive lure (PE + n-butyl sulphide + AA) but with twice the density of traps (Jaffe et al., 2018). The use of 60 traps ha$^{-1}$ in pear was based on initial studies of a pear ester septum lure in 2000 (Knight et al., 2001). This trap density was also selected with some consideration of the comparative cost of using MD 25 years ago (Williamson et al., 1994). However, today the value of organic pears is much greater than in the past and growers are more willing to use an expensive management programme for key pests (Granatstein et al., 2016). For example, some growers in Washington State are spending $>1,000 US per hectare for seasonal releases of sterile codling moths (Beers et al., 2020). A benefit-cost analysis of FR as a new control tactic for codling moth in organic pears should be conducted after establishing the correlation of trap density and potential reductions of fruit injury across different cultivars. FR should be one tactic within an integrated management programme and not a stand-alone control method. Thus, the cost of FR needs to be competitive with other available control tactics, including insecticides, but reducing insecticide use can also avoid external costs imposed by international residue tolerances, and the potential for disruption of secondary pests, such as pear psylla and rust mites (family Eriophyidae). The integration of FR with both mating disruption and banding trees with cardboard to remove overwintering larvae could be a very effective programme for organic pear growers (Judd et al., 1997).

Immigration of codling moth into orchards whether males or mated or unmated females is of great concern to pear growers (Higbee et al., 2001; Prokopy, 1994; Westigard & Graves, 1976). Jaffe et al. (2018) suggested that their comparative results achieved with FR in apple might have been reduced by their use of 120 lures ha$^{-1}$ drawing codling moth disproportionately into the treated plots, but the drawing range of these non-sex pheromone lures has not been measured. Plot size is always an important parameter impacting the results of semiochemical-based trials due to the dispersal capacity of tortricid moths (Knight, Judd, et al., 2019). It remains unclear from our studies how effective FR would be in protecting orchard borders versus reducing injury towards the centre of plots. Immigration likely impacted the effectiveness of reducing fruit injury in these small FR plots as paired treatments were adjacent, and trial sites were often surrounded by apple/pear blocks with moderate to high codling moth densities.

Modelling studies clearly demonstrate the greater importance in removing female than male codling moth (Knight et al., 2001). Nevertheless, studies conducted with sex pheromone-baited traps capturing only males have in the past demonstrated some level of efficacy in suppressing codling moth (El-Sayed et al., 2006). Most likely, the high rates of male removal achieved with our bisexual lures would be useful when the population density is low due to reduced male polygamy in disrupted orchards (Knight, 2007a). Unfortunately, adding PH to the multi-component PE/DMNT/LOX + AA lure was shown to reduce female captures, and its use would not be justified (Preti et al., 2021a).

The effectiveness of FR is impacted by several factors, including mating behaviours, moth dispersal, population densities and orchard isolation (El-Sayed et al., 2006). Codling moth is a polyphagous pest that can lay a full complement of eggs (>100) following a single mating and begins to oviposit as early as the day after eclosion (Geier, 1963; Howell, 1991). The percent of unmated moths captured in our studies were relatively low and similar in orchards treated with or without MD. The effectiveness of MD in reducing levels of fruit injury from codling moth is due to both disruption of and a delay in mating (Jones et al., 2014; Knight, 1997; Vickers, 1997). The ability of baited traps to remove females before they mate is a key factor impacting the level of population reduction achieved across later generations (Ferro et al., 1975). Dissections of field-collected mating codling moth females found 72% fewer ovarioles than in unmated moths (Knight, 2000). Thus, the greater proportion of unmated females found in the USA than Italy could explain the relatively greater effectiveness of FR despite fewer numbers of females removed. Unfortunately, the immigration of mated females into orchards would still remain a serious limiting factor for MD-FR. Likely, more effective strategies to protect borders of orchards through supplemental tactics including tree banding and removal of extra-orchard hosts of codling moth are critical components of an integrated programme (Basaolto et al., 2010; Judd et al., 1997; Margaritopoulos et al., 2012).

Future adoption of FR to assist the management of codling moth depends on several factors, including the refinement of the strategy across geographical regions with its validation in other countries, evaluations in other host crops such as apple and walnut (Juglans regia L.), and perhaps the identification of new more efficacious attractants (Preti et al., 2021b). Both optimum trap density and distribution per unit of space needs to be investigated for codling moth FR (Knight, 2007b; Suckling et al., 2015). The trap type is also a crucial factor to be considered in further studies, considering that non-saturating bucket traps need to be serviced with a lower frequency than the delta traps and given that in this and other related works both trap designs captured similar numbers of codling moth females regardless apple or pear crop and outperforming the standard trap/lure combination (Jaffe et al., 2018; Landolt et al., 2014). In addition, the combination of FR with other synergistic control techniques such as MD should be further investigated, to evaluate whether the removal of a higher proportion of virgin females may impact positively on the fruit injury reduction, such as studies are required to verify the proportion of mated females trapped prior and after the oviposition. Finally, the use of FR as a key tactic in the integrated organic management of codling moth needs to be assessed over several seasons to fully measure its ability to suppress and maintain codling moth at low levels.
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CONFLICT OF INTEREST
None of the authors have any conflict of interest.

AUTHOR CONTRIBUTIONS
Authors 1, 2, 3 and 4 conceived research and conducted experiments in USA. Author 1 conducted experiments in Italy. Authors 1, 2 and 5 analysed data and conducted statistical analyses. Authors 1, 2 and 6 wrote the manuscript. Author 2 secured funding. All authors read and approved the manuscript.

DATA AVAILABILITY STATEMENT
Data supporting the results are openly available in a public repository at: https://doi.org/10.5281/zenodo.4529030

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SUPPORTING INFORMATION
Additional supporting information may be found online in the Supporting Information section.

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