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Pest Management

Seasonal activity of plum curculio (Coleoptera: Curculionidae) in small Southeastern peach orchards

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Plum curculio, *Conotrachelus nenuphar* (Herbst) (Coleoptera: Curculionidae), is a key pest in Southeastern peach production by infesting fruit and decreasing yield. In Northeastern apples, plum curculio was found to have an "edge effect," where more plum curculio are present next to a forested border than in the center of an orchard, and their propensity to fly or walk depended on air temperature. We conducted field studies over 3 seasons (2019–2021) to investigate whether plum curculio in small Southeastern peach plots exhibits the edge effect and to determine its primary mode of movement (flying or walking). Our results revealed that plum curculio did not exhibit the edge effect in Southeastern peaches. Thus, unlike Northeastern apples where plum curculio exhibits the edge effect, the reduced-input application program where insecticide sprays mainly target a few perimeter-row trees instead of the whole orchard for plum curculio management is not recommended for Southeastern peaches. Additionally, we observed that plum curculio in Southeastern peaches did not exhibit a primary mode of movement, and in most of the sampling weeks, the numbers of flying and walking plum curculio were not significantly correlated in the field. These results emphasize that using plum curculio sampling tools that only capture flying or walking plum curculio is not ideal for monitoring plum curculio activity in the Southeast. Overall, our findings indicate that plum curculio in Southeastern small peach plots and Northeastern apples does not exhibit the same behavior (i.e., edge effect and propensity to fly or walk).

Key words: behavior, edge effect, movement, monitoring

Introduction

Plum curculio (PC), *Conotrachelus nenuphar* (Herbst) (Coleoptera: Curculionidae), is a key pest of stone and pome fruit east of the Rocky Mountains in North America (Chapman 1938). In Southeastern peaches, the overwintering generation of PC becomes active in early spring, feeding and ovipositing in fruit, followed by more than one summer (field) generation that also attacks peach fruit later in the season. In the fall, adult PC moves to wild hosts or ground litter to overwinter (Racette et al. 1992, Lan et al. 2004). Currently, Southeastern peach growers rely heavily on calendar-based spray programs, conducting weekly or bi-weekly broad-spectrum insecticide applications to manage PC. Up to 12 insecticide applications per season may be required for late-season varieties (Foshee et al. 2008, Akotsen-Mensah et al. 2011). Conversely, in Northeastern apples, researchers have established a reduced-input application program based on PC's natural dispersal behavior for PC management (Chouinard et al. 1992, 2021, Vincent et al. 1997, Prokopy et al. 2004).

In the Northeast, adult PC are known to immigrate to orchards in the spring and emigrate back to overwintering sites in adjacent wooded areas after the season (Lafleur and Hill 1987, Lafleur et al. 1987, Racette et al. 1992, Piñero and Prokopy 2006, Lampasona et al. 2020). During their immigration in the spring, PC arrive at the border apple trees, adjacent to the wooded areas, and subsequently move toward the center of the orchard, resulting in an "edge effect," where more PC are present next to the forested border than in the center of the orchard (Le Blanc et al. 1984, Lafleur and Hill 1987). Based on this dispersal tendency of PC in Northeastern apple orchards, researchers developed a reduced-input application program in which, after an initial full-block spray at pink or petal fall, subsequent insecticide sprays could target just the first few border rows instead of the whole orchard. This approach effectively reduced PC damage while minimizing overall insecticide use (Chouinard et al. 1992, 2021, Vincent et al. 1997, Prokopy et al. 2004).

The northern strain PC, originating from the Northeast, and the southern strain PC, originating from the Southeast, are univoltine and multivoltine, respectively, and are genetically distinct, which means the 2 strains might also exhibit different behaviors (Schoene 1936, McClanan et al. 2004, Zhang et al. 2008, Lampasona et al. 2020). Although Johnson et al. (2002) observed an edge effect in the southeastern strain of PC in Arkansas and Oklahoma peach orchards, no other studies have reported an edge effect by PC in any other Southeastern states. Without a better understanding of PC's dispersal behavior in the Southeast, a spatiotemporal management program targeting PC is likely to remain undeveloped.

Various traps have been evaluated for their effectiveness in capturing and monitoring PC, such as the black pyramid trap, Circle trap, sticky Plexiglas panel, and vertical black cylinder trap (Vincent et al. 1999, Johnson et al. 2002, Prokopy et al. 2003, Leskey and Wright 2004, Leskey 2006, Akotsen-Mensah et al. 2010). These traps can yield different results in PC monitoring due to their capture mechanisms or deployment methods. To design and deploy monitoring traps that can effectively capture PC, understanding the common motility of PC (flying or walking) throughout the season is crucial. Otherwise, a trap might fail to reflect the overall PC abundance or activity in an orchard if the trap's capture mechanism is not congruent with PC's mode of movement.

Previous research in the Northeast demonstrated that PC tend to move from overwintering sites in adjacent wooded habitats to host trees by flight rather than walking, with their propensity to fly or walk depending on air temperatures (Racette et al. 1992, Dixon et al. 1999, Prokopy et al. 1999). Specifically, Prokopy et al. (1999) found that in Massachusetts apples, there were significantly more walking PC than flying PC at air temperatures below 20°C, whereas there were significantly more flying PC than walking PC when air temperatures were 20°C or higher. In Georgia, researchers have reported that ground-deployed pyramid traps failed to detect the summer generation of PC in the field. They suspected that PC might tend to fly rather than walk in the orchard during summer, thereby evading the traps (Jenkins et al. 2006). Despite these findings, there remains a critical gap in understanding the primary mode of movement for PC in Southeastern peach orchards.

In the Southeast, the lack of knowledge of PC dispersal patterns and their propensity to fly or walk in a peach orchard impedes the development of a reduced-input and well-timed management program where growers can spatiotemporally target insecticide sprays on PC infestation hotspots and reduce insecticide use. The goal of our research was to facilitate the development of targeted management approaches against PC by studying PC behavior in Southeastern peaches. The objectives of our research were to investigate whether PC exhibits an edge effect in Southeastern peaches and to determine PC's primary mode of movement (flight or walking) within a peach orchard throughout the season.

Materials and Methods

Study Sites

We conducted field studies over 3 seasons (2019–2021) in 2 experimental peach orchards located at the USDA Southeastern Fruit and Tree Nut Research Laboratory in Byron, GA, United States. Each peach orchard used in our studies consisted of only 1 single peach variety, either "Contender" or "Scarletprince." These 2 orchards are hereafter referred to as the Contender orchard (≈0.64 ha; 32°39′08.4″N, 83°44′06.4″W) and Scarletprince orchard (≈0.46 ha; 32°39′19.7″N, 83°44′21.5″W). Peach trees in these 2 orchards were pruned to ~2.5 m in height at the beginning of the season and

typically grew to ~3.5 m by the end of the season. These 2 peach varieties generally ripen from late June to mid-July in Byron, GA, United States. The peach trees were planted with a row spacing of 6.1 m and a tree spacing of 6.1 m in the Contender orchard, and with a row spacing of 6.1 m and a tree spacing of 4.9 m in the Scarletprince orchard. Both orchards were rectangular, with the southern borders facing woods and the other sides bordered by mixed agricultural crops, including pecans, peaches, and plums. During our research, both orchards regularly received fungicide applications and weed management, but were free of insecticide treatments.

Edge Effect

At each experimental orchard, we installed Circle traps (Great Lakes IPM, Inc., Vestaburg, MI, United States) (Akotsen-Mensah et al. 2010) on peach tree trunks ~30 cm above the ground on the perimeter peach trees and interior peach trees of the orchard. Circle traps intercept and capture PC into clear collection cups as they walk up the tree trunks. In the Scarletprince orchard, we installed Circle traps on 12 perimeter and 12 interior trees in 2019 and 2020; and in 2021, there were 11 perimeter trees and 11 interior trees installed with the Circle traps. In the Contender orchard, we installed Circle traps on 12 trees at each tree location (perimeter and interior) in 2019. In subsequent years, due to tree losses, there were 10 and 6 trees installed with Circle traps at each tree location in 2020 and 2021, respectively. The perimeter traps and interior traps were at least 3 trees apart, ~18.3 m and 14.7 m in the Contender and Scarletprince orchards, respectively. If the circumference of a tree trunk was larger than the length of the bottom of the Circle trap, we deployed more than one Circle trap per tree to surround the trunk.

To account for PC's flying behavior, alongside trapping PC walking up to trees with Circle traps, we also conducted "beat sampling" (Hernandez-Cumplido et al. 2017). For this method, we randomly selected 5 terminal branches from each tree with the Circle traps and also the tree directly adjacent without traps, and gently jarred the terminal branches with a foam bat and collected PC falling from the terminal branches onto a beat sheet (71 cm × 71 cm, Great Lakes IPM, Inc., Vestaburg, MI, United States). Circle traps and beat sampling were chosen in our study to observe PC's natural behavior without cues (e.g., visual or olfactory cues) that could alter their natural behavior. We checked the Circle traps and conducted beat sampling 1–3 times a week and recorded the numbers of PC collected from each sampling tree by each sampling method. In each sampling year, PC sampling began at the pink stage and continued until postharvest in mid to late fall, with all sampling activities conducted between 1000 and 1400 h.

Modes of Movement

To obtain the numbers of flying and walking PC in the orchards, we considered the tree installed with the Circle traps and its adjacent tree together as a sampling unit. In each sampling unit, we obtained the numbers of PC walking to the tree by subtracting the numbers of PC collected by beat sampling from the tree installed with the Circle traps from the numbers of PC collected by beat sampling from the adjacent tree. Thus, the numbers of PC flying to the tree were the numbers of PC collected by beat sampling from the tree installed with the Circle traps. We determined PC's tendency to fly or walk throughout the season by comparing the numbers of PC flying and walking with the peach trees.

Statistical Analysis

For both investigations, counts of collected PC from the same sampling week were pooled together for statistical analyses. During our research, if a sampling week was skipped due to field conditions, the

Circle trap PC counts used for statistical analyses for the next available sampling week were accumulated over the period between the sampling week before and the next available sampling week.

To investigate PC's edge effect, we compared the numbers of PC captured in the perimeter peach trees with those captured in the interior peach trees with *t*-tests in each sampling week and across all sampling weeks in each year. Since different sampling methods used in our study accommodated different modes of PC movement (flying or walking), and thus might yield varying outcomes, we performed *t*-tests using the PC counts collected from the Circle traps, beat sampling conducted on the trees directly adjacent to the trees installed with the trunk traps, and also the 2 sampling methods combined (trunk trap captures and beat samples from the trees with the trunk traps), separately. The above analyses were conducted using R (R Version 4.1.1, Vienna, Austria). We also compared the total numbers of PC captured in the perimeter with those captured in the interior over the course of all sampling years, regardless of the sampling methods, in both orchards using a Generalized Linear Mixed Model (PROC GLIMMIX) with a negative binomial distribution and log-link function in SAS (SAS OnDemand for Academics 2024, SAS Institute, Inc., Cary, NC, United States). The effect of location (perimeter and interior) was a fixed effect, and year (2019, 2020, and 2021), orchard (Contender and Scarletprince), and sampling method (Circle trap, beat sampling, and 2 methods combined) were random effects.

To determine PC's primary mode of movement, we performed paired *t*-tests to compare the numbers of PC flying and walking in each sampling week and across all sampling weeks in each year. The above analyses were conducted using R (R Version 4.1.1). We also compared the total numbers of PC flying and walking over the course of all sampling years in both orchards using a Generalized Linear Mixed Model (PROC GLIMMIX) with a negative binomial distribution and log-link function in SAS (SAS OnDemand for Academics 2024, SAS Institute, Inc.). PC's mode of movement (flying and walking) was a fixed effect, and year (2019, 2020, and 2021) and orchard (Contender and Scarletprince) were random effects. In addition, we performed Pearson's correlation tests to determine the association between the numbers of PC flying and walking in each sampling week and across all sampling weeks in each year. Pearson's correlation tests were conducted in JMP (JMP, Version X, SAS Institute Inc.).

Results

Edge Effect

Using the beat sampling method alone, we found significantly more PC in the perimeter than the interior during the 20th week of the year (*t*-tests, df = 22; *P* = 0.028) in the Scarletprince orchard in 2019, the 18th week of the year (*t*-tests, df = 22; *P* = 0.026) in the Contender orchard in 2019, and the 24th week of the year (*t*-tests, df = 12; *P* = 0.007) in the Contender orchard in 2021 (Figs. 1 and 2). Except for these 3 sampling weeks, we did not detect any other sampling weeks with significantly more PC in the perimeter than the interior in either of the orchards throughout the 3-year study. On the contrary, during the 15th week of the year (*t*-tests, df = 20; *P* = 0.027), the 33rd week of the year (*t*-tests, df = 20; *P* = 0.008), and the 38th week of the year (*t*-tests, df = 20; *P* = 0.022) in 2021, there were more PC in the interior than the perimeter in the Scarletprince orchard (Fig. 1). Across all sampling weeks in each site and year, the Scarletprince orchard in 2021 was the only one that showed significant differences in season-long cumulative PC counts in the interior and the perimeter, where there were significantly more PC in the interior than the perimeter (*t*-tests, df = 20; *P* = 0.017).

When employing the Circle trap alone, we did not observe any sampling weeks with significantly more PC in the perimeter than the interior in either of the orchards throughout the 3-year study (Figs. 3 and 4). However, there were several sampling weeks, where there were significantly more PC in the interior than the perimeter, including the 32nd week of the year (*t*-tests, df = 20; *P* = 0.015), the 33rd week of the year (*t*-tests, df = 20; *P* = 0.021), the 35th week of the year (*t*-tests, df = 20; *P* = 0.023), and the 38th week of the year (*t*-tests, df = 20; *P* = 0.024) in the Scarletprince orchard in 2021 (Fig. 3). Across all sampling weeks in the Scarletprince orchard in 2020 (*t*-tests, df = 22; *P* = 0.039) and 2021 (*t*-tests, df = 20; *P* = 0.006), there were significantly more season-long cumulative PC captures in the interior than the perimeter. In the Contender orchard, across all sampling weeks in each year, no sampling years showed significant differences in season-long cumulative PC counts between the interior and perimeter.

In the combined sampling method, we found significantly more PC in the perimeter than the interior during the 24th week of the year (*t*-tests, df = 12; *P* = 0.028) and the 31st week of the year (*t*-tests, df = 12; *P* = 0.01) in the Contender orchard in 2021 (Fig. 5). Except for these 2 sampling weeks, we did not detect any other sampling weeks with significance based on PC location throughout the 3-year study. Across all sampling weeks in the Contender orchard in each year, the season-long cumulative numbers of PC in the perimeter and interior were not significantly different (*t*-tests, df = 22, *P* = 0.726; df = 18, *P* = 0.128; and df = 12, *P* = 0.177 in 2019, 2020, and 2021, respectively). In the Scarletprince orchard, there were significantly more PC in the interior than the perimeter during the 31st week of the year in 2019 (*t*-tests, df = 22; *P* = 0.026); and the 15th, 32nd, 33rd, and 38th weeks of the year in 2021 (*t*-tests, df = 20, *P* = 0.027; df = 20, *P* = 0.017; df = 20, *P* < 0.006; and df = 20, *P* = 0.007, respectively) (Fig. 6). Across all sampling weeks in the Scarletprince orchard in each year, there were significantly more season-long cumulative PC counts in the interior than the perimeter in 2021 (*t*-tests, df = 20; *P* = 0.008), while in the other 2 sampling years, the season-long cumulative PC counts in the perimeter and interior were not significantly different (*t*-tests, df = 22, *P* = 0.956 and df = 22, *P* = 0.467 in 2019 and 2020, respectively).

Overall, in the majority of the sampling weeks in both orchards in our 3-year study, PC counts in the perimeter and interior were not significantly different, regardless of the sampling methods employed. In the sampling weeks with significant differences between PC counts in the perimeter and interior, most of them had more PC in the interior than the perimeter. We never found any sampling weeks with more PC in the perimeter than the interior when the Circle traps were used alone. The occurrence of significant differences in PC captures between the perimeter and interior varied due to different sampling methods. Over the course of all sampling years in both orchards, we captured a total of 783, 1021, and 1423 PC using Circle trap, beat sampling, and a combination of both methods, respectively, and the effect of location (perimeter and interior) on the numbers of total PC captured was not significant ($F_{1,365} = 2.29$, $P = 0.1313$).

Modes of Movement

In the Contender orchard in 2019, we found more flying PC than walking PC in 5 mid-season sampling weeks: the 21st, 24th, 25th, 26th, and 27th week of the year (*t*-tests, df = 23; *P* < 0.05 in all cases) (Fig. 7). Early in the season, there were more walking PC than flying PC in 2 sampling weeks: the 13th week of the year (*t*-tests, df = 23; *P* = 0.031) and the 14th week of the year (*t*-tests, df = 23; *P* = 0.012) (Fig. 7). Across all sampling weeks in the Contender orchard in 2019, our season-long cumulative data showed that there
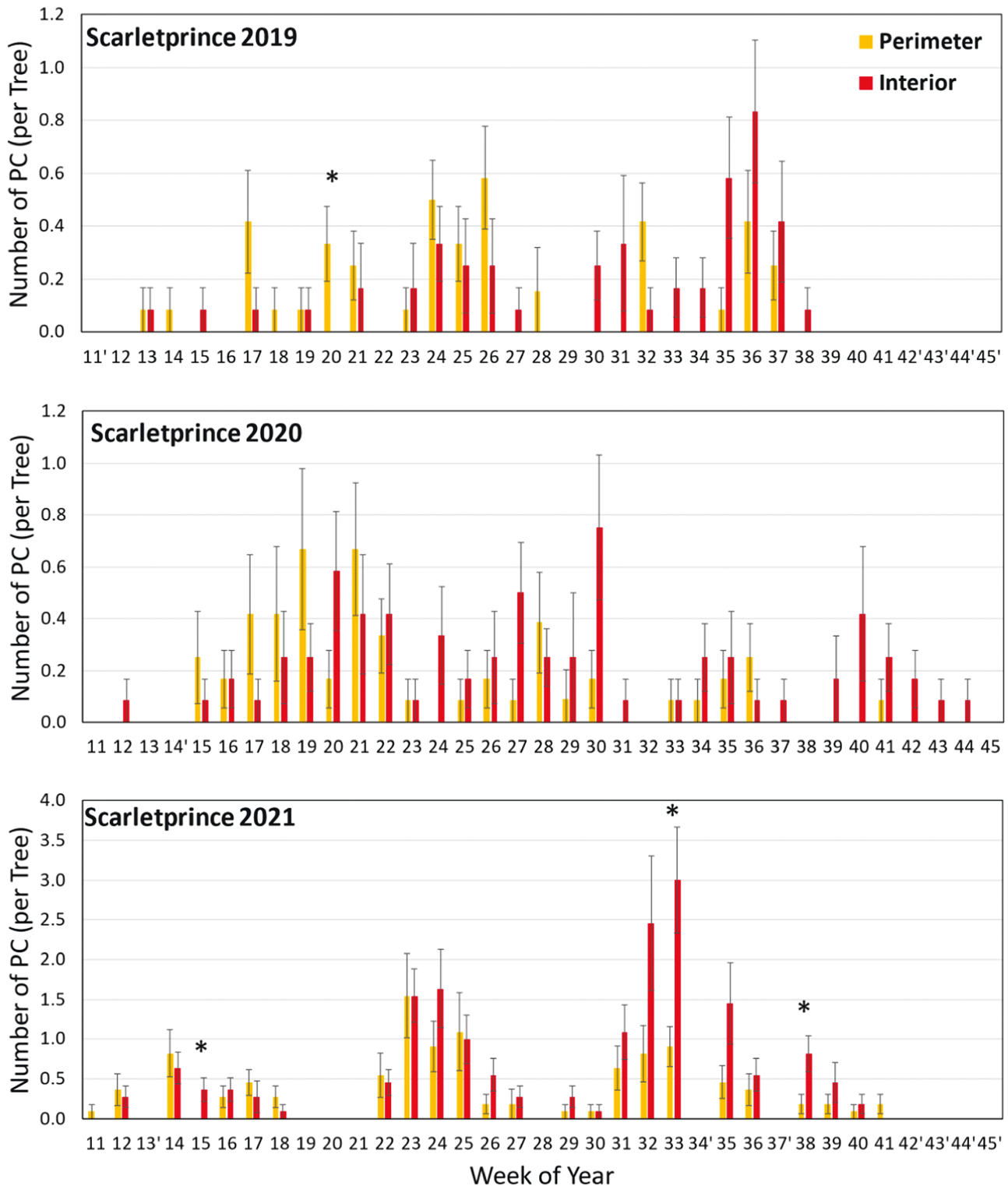
Fig. 1. Number (mean ± SE) of PC adults collected by the beat sampling method alone at different tree locations in each sampling week in 2019, 2020, and 2021 in the Scarletprince orchard. An asterisk (*) indicates significant difference between the 2 tree locations (*t*-tests; *P* < 0.05). A prime (') next to a week number indicates data were not recorded for that week.

were significantly more flying PC than walking PC (*t*-tests, df = 23; *P* = 0.001). However, in 2020 and 2021, the numbers of PC flying and walking were not significantly different in any sampling weeks (Fig. 7), and across all sampling weeks, the season-long cumulative numbers of flying and walking PC were also not significantly different.

In the Scarletprince orchard in 2019, we found 1 sampling week (the 26th week of the year) (*t*-tests, df = 23; *P* = 0.005) with significantly more flying PC than walking PC, while there were no sampling weeks with significantly more walking PC than flying PC (Fig. 8). In the Scarletprince orchard in 2020, there were significantly
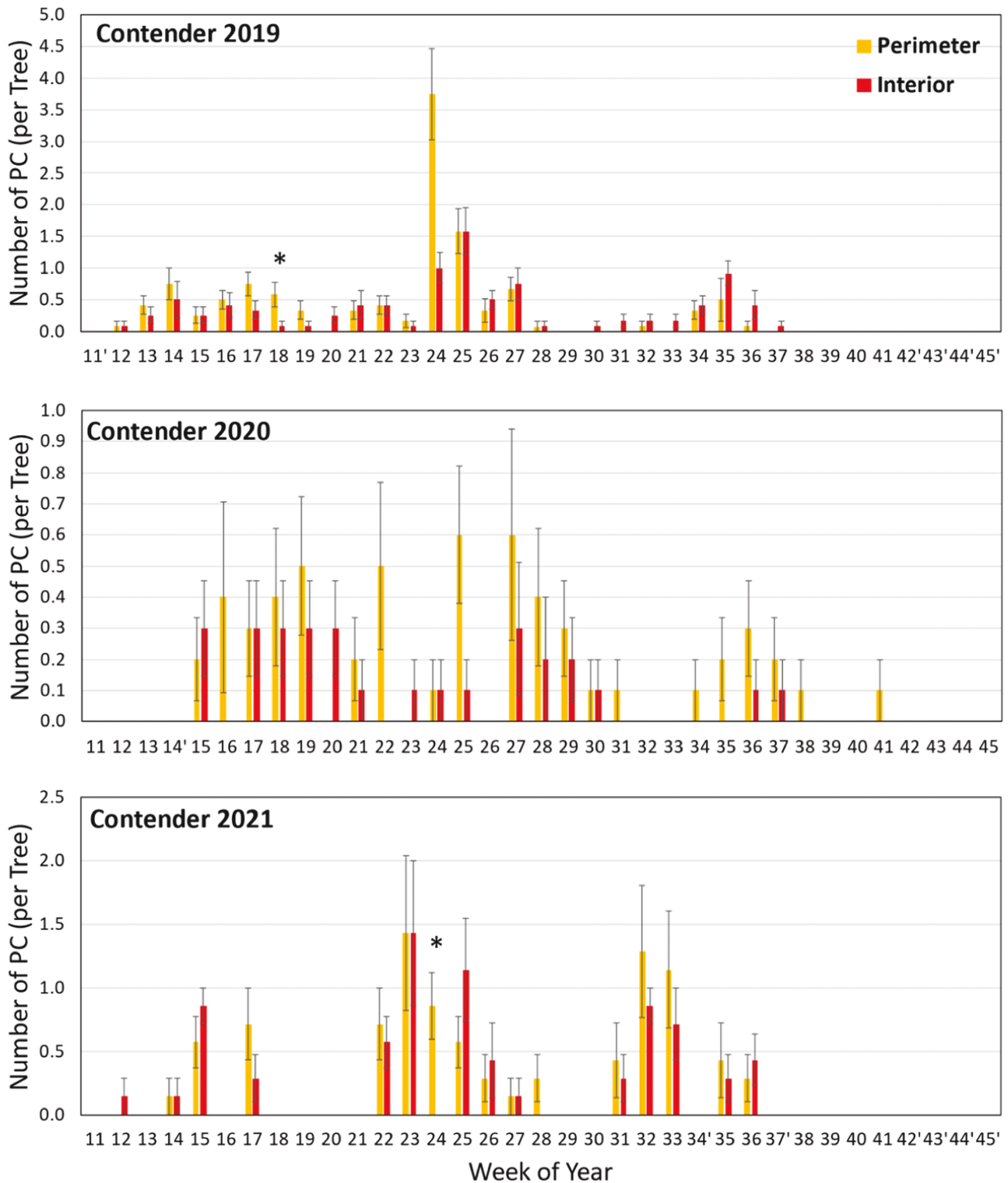
Fig. 2. Number (mean ± SE) of PC adults collected by the beat sampling method alone at different tree locations in each sampling week in 2019, 2020, and 2021 in the Contender orchard. An asterisk (*) indicates significant difference between the 2 tree locations (*t*-tests; *P* < 0.05). A prime (') next to a week number indicates data were not recorded for that week.

more flying PC than walking PC in the 20th week of the year (*t*-tests, df = 23; *P* = 0.049) and the 36th week of the year (*t*-tests, df = 23; *P* = 0.043), while there were significantly more walking PC than flying PC in the 30th week of the year (*t*-tests, df = 23; *P* = 0.008). In the Scarletprince orchard in 2021, there were 5 sampling weeks with

significantly more walking PC than flying PC, including the 16th, 18th, 25th, 26th, and the 36th week of the year (*t*-tests, df = 21; *P* < 0.05 in all cases), while there were significantly more flying PC than walking PC in the 33rd week of the year (*t*-tests, df = 21; *P* = 0.01) (Fig. 8). Across all sampling weeks in the Scarletprince
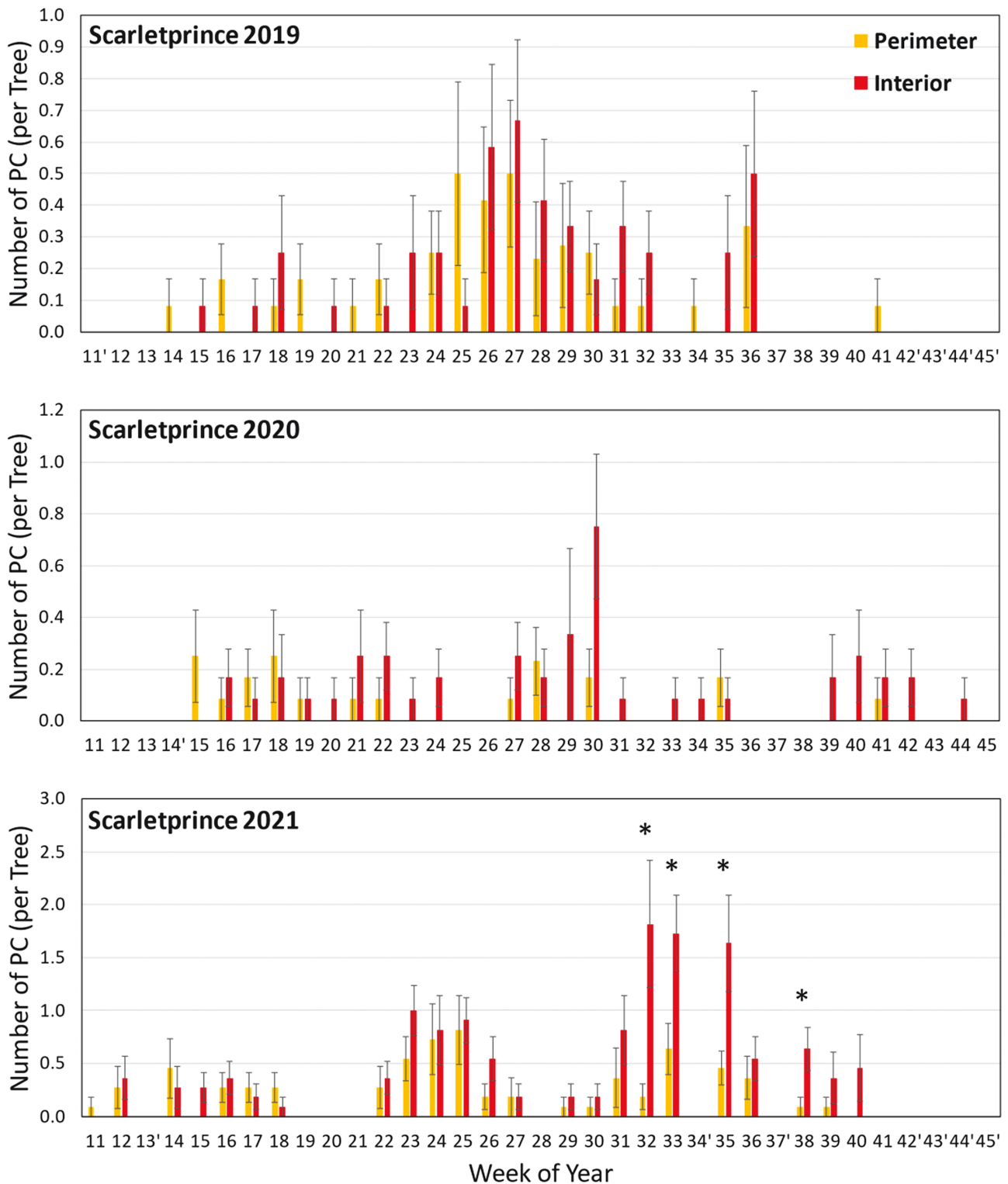
Fig. 3. Number (mean ± SE) of PC adults collected by the Circle traps alone at different tree locations in each sampling week in 2019, 2020, and 2021 in the Scarletprince orchard. An asterisk (*) indicates significant difference between the 2 tree locations (*t*-tests; *P* < 0.05). A prime (') next to a week number indicates data were not recorded for that week.

orchard in each year, the season-long cumulative numbers of flying PC and walking PC were not significantly different.

Overall, throughout 3 seasons in both orchards, in most of the sampling weeks, the numbers of PC flying and walking were not significantly different. There were only 9 sampling weeks in total with significantly more flying PC than walking PC, and 8 sampling weeks in total with significantly more walking PC than flying PC throughout the 3-year study in these 2 orchards (Figs 7 and 8). Over the course of all sampling years in both orchards, there were significantly more flying PC than walking PC ($F_{1,249} = 6.83$, $P = 0.0095$).
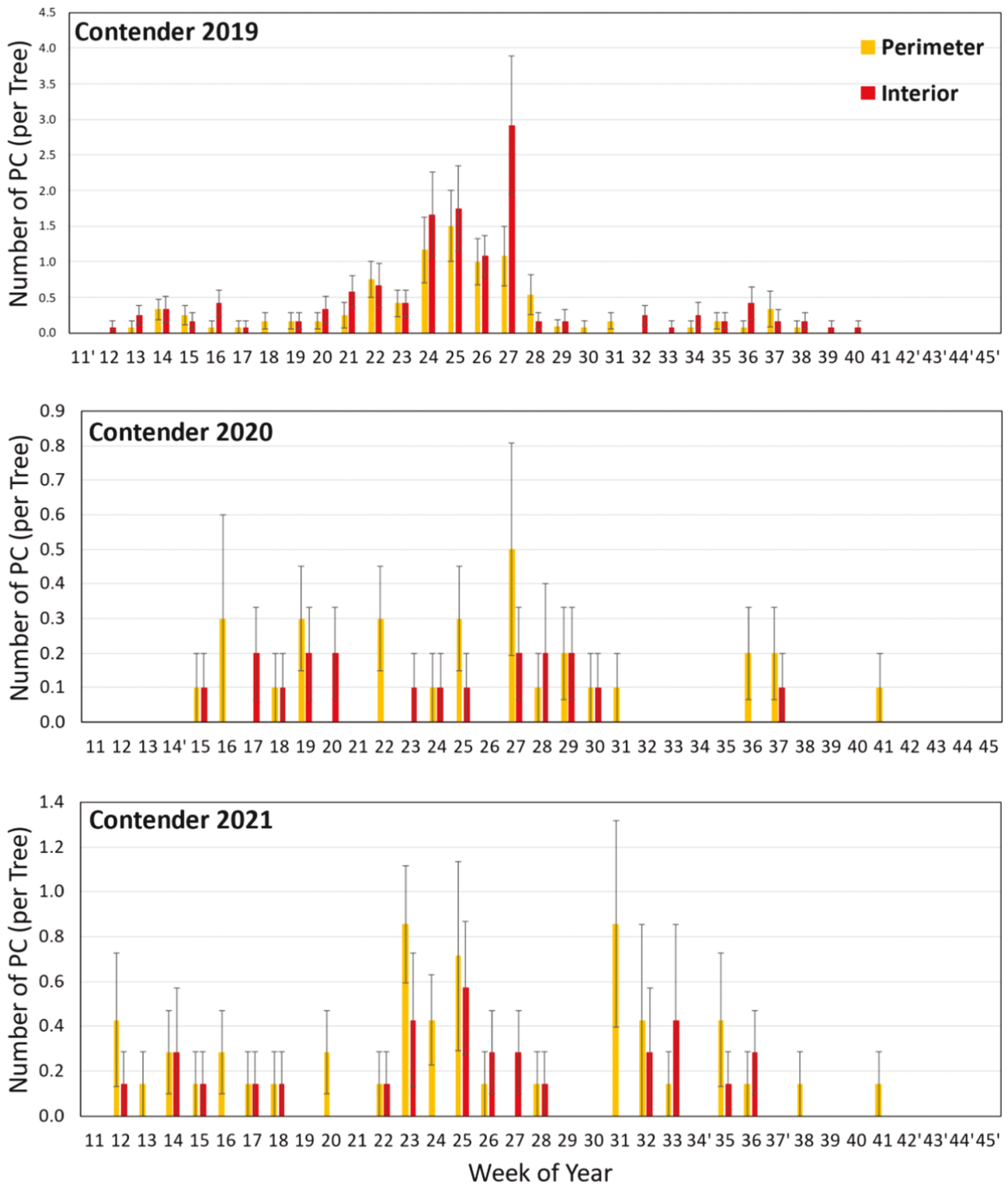
Fig. 4. Number (mean ± SE) of PC adults collected by the Circle traps alone at different tree locations in each sampling week in 2019, 2020, and 2021 in the Contender orchard. No significant differences between the 2 tree locations were found (*t*-tests; *P* > 0.05). A prime (') next to a week number indicates data were not recorded for that week.

Across all sampling weeks in each orchard in each year, according to Pearson's correlation coefficient tests, the season-long cumulative numbers of flying PC and walking PC were significantly correlated only in the Scarletprince orchard in 2021 (*r* = 0.192, *P* < 0.001) (Table 1). However, the correlation was low. Throughout the 3-year study in 2 orchards, there were only 7 out of 181 sampling weeks in total with significant correlations between the numbers of flying and walking PC (Table 1).

Discussion

Throughout our 3-year research, in either of the 2 experimental orchards, we observed only none, 1, or 2 sampling weeks with significantly more PC at the perimeter than the interior each season, depending on the sampling methods used. Our findings suggest that PC does not exhibit the edge effect in Southeastern peach orchards.
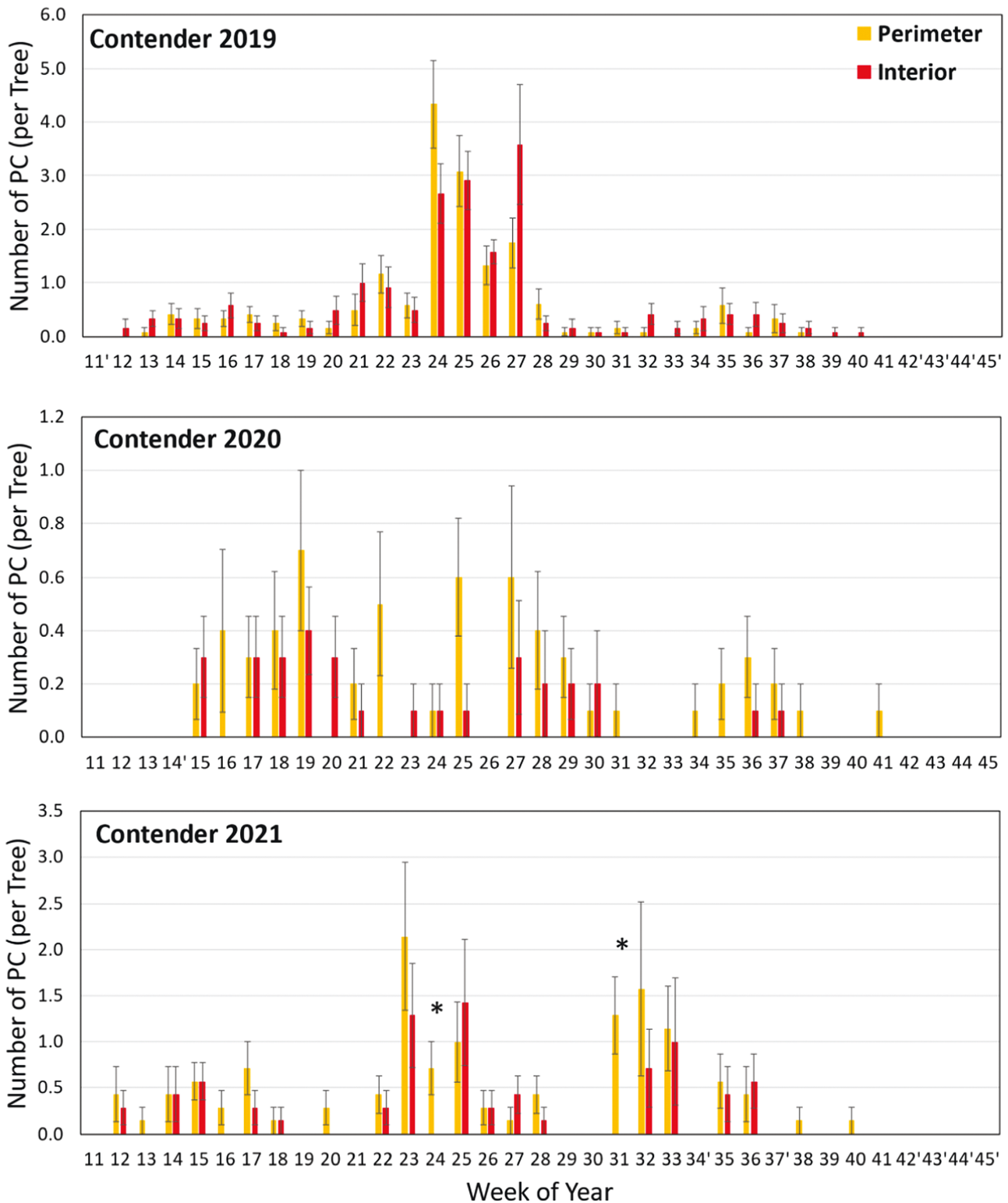
Fig. 5. Number (mean ± SE) of PC adults collected by the Circle traps and beat sampling method combined at different tree locations in each sampling week in 2019, 2020, and 2021 in the Contender orchard. An asterisk (*) indicates significant difference between the 2 tree locations (*t*-tests; *P* < 0.05). A prime (') next to a week number indicates data were not recorded for that week.

The lack of an obvious edge effect from PC in our studies could be attributed to their overwintering behavior. Because previous research has reported that PC could overwinter both within the orchard and in the surrounding wooded habitats (Racette et al. 1992, Piñero et al. 2004, Piñero and Prokopy 2006, Akotsen-Mensah et al. 2010), the edge effect might be undetectable if PC tends to overwinter within the orchard. As a result, this overwintering behavior might be the reason why in the Scarletprince orchard in 2021, there were several
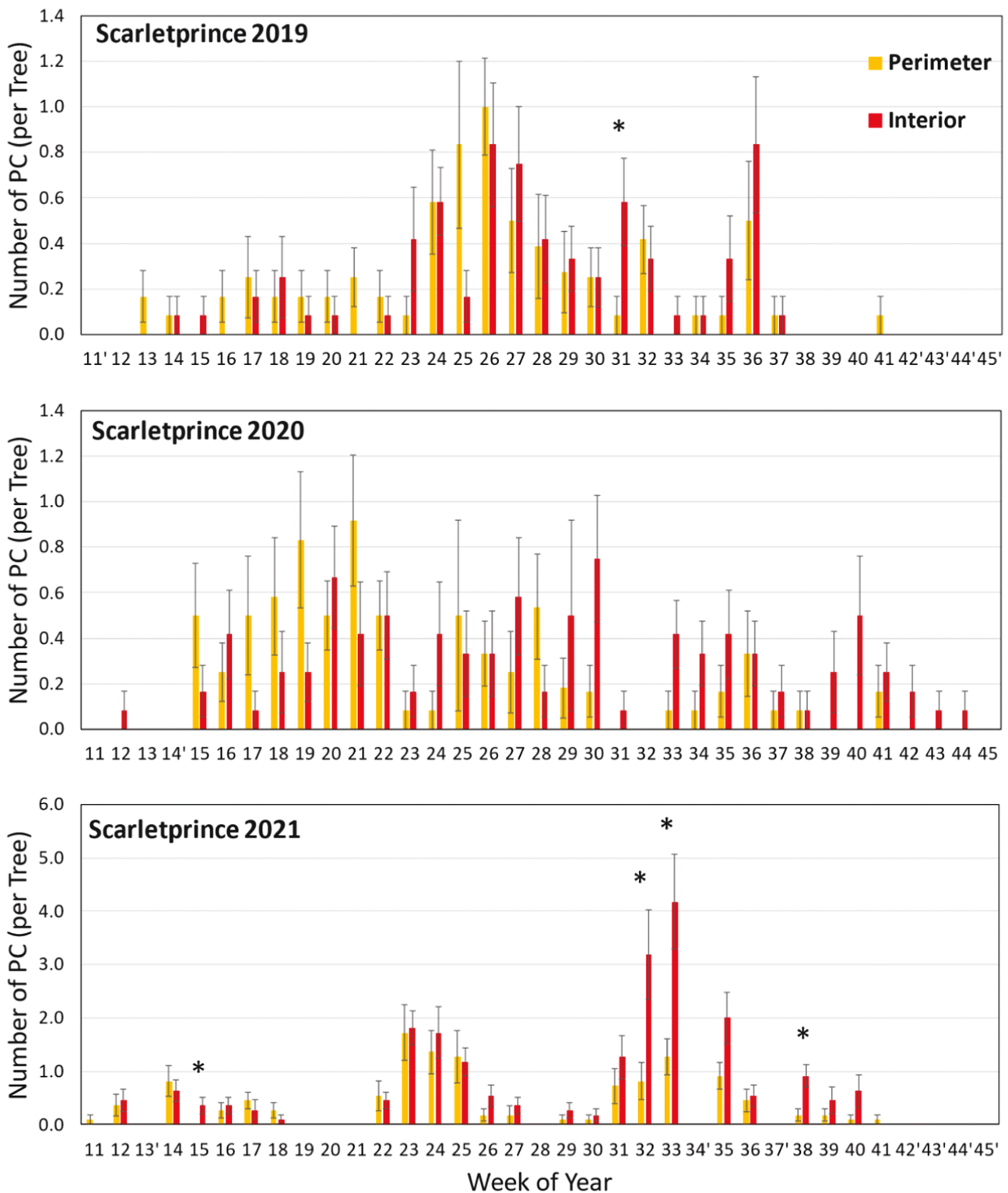
Fig. 6. Number (mean ± SE) of PC adults collected by the Circle traps and beat sampling method combined at different tree locations in each sampling week in 2019, 2020, and 2021 in the Scarletprince orchard. An asterisk (*) indicates significant difference between the 2 tree locations (*t*-tests; *P* < 0.05). A prime (') next to a week number indicates data were not recorded for that week.

sampling weeks with more PC in the interior than the perimeter later in the season when peach fruits were no longer available and also why there were significantly more season-long cumulative PC captures in the interior than the perimeter in the Scarletprince orchard in some sampling years.

The lack of an edge effect in our results could also be due to the small size of our study sites; however, Johnson et al. (2002) were able to observe significantly higher PC captures from pyramid traps deployed in the first peach row directly adjacent to a woodlot than those from pyramid traps placed in the fifth peach row in a
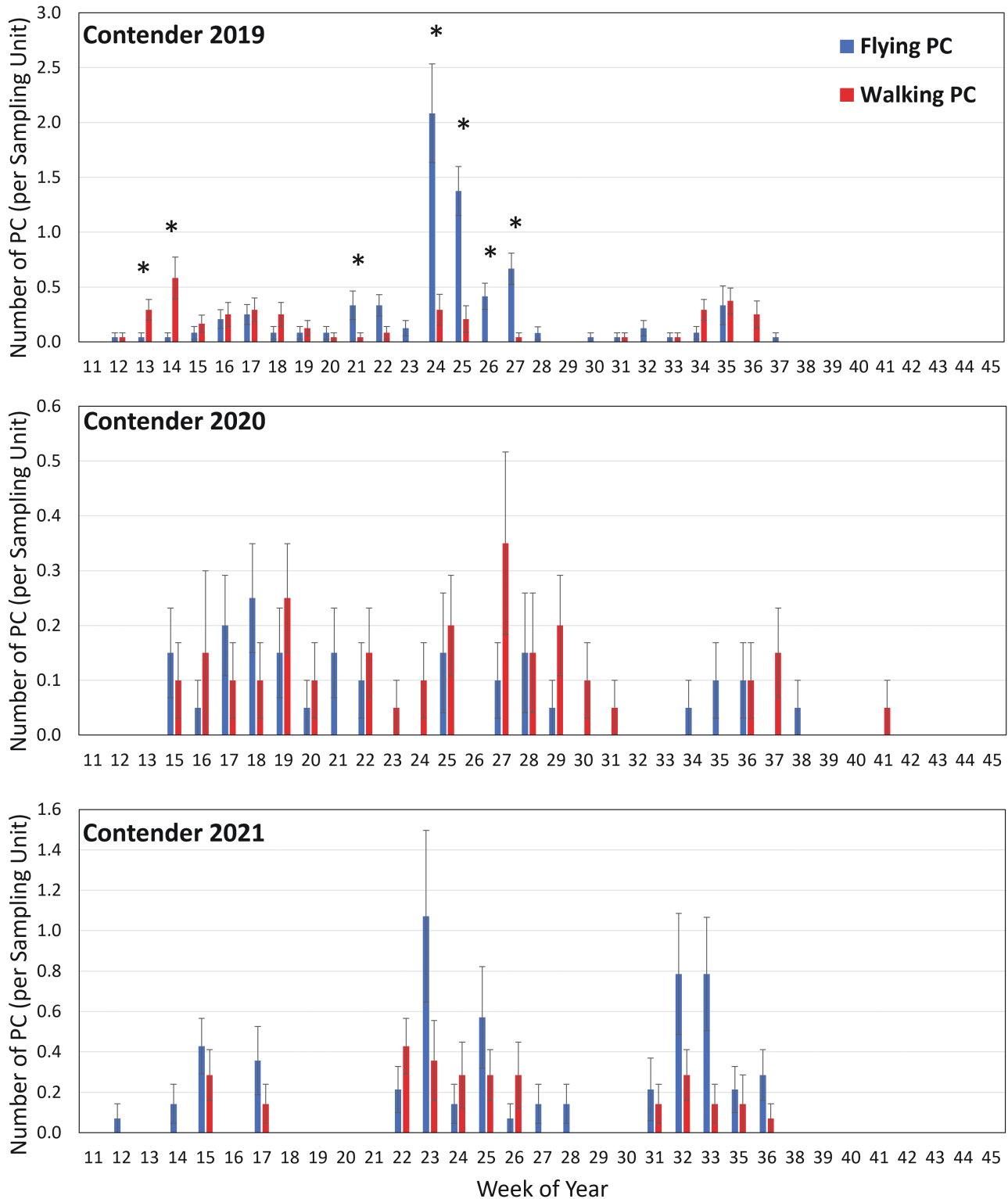
Fig. 7. Number (mean ± SE) of flying and walking PC adults per sampling unit and the average air temperature in each sampling week in 2019, 2020, and 2021 in the Contender orchard. An asterisk (*) indicates significant difference between the 2 modes of movement (*t*-tests; $P < 0.05$).

commercial peach orchard in Forrest City, AR, United States. In addition, based on the findings from Lafleur and Hill (1987), who observed that PC in Quebec apples moved 1.3 m, 1.6 m, 1.4 m, 2.0 m, and 4.4 m per day at the tight cluster, pink, bloom, and petal fall stages, respectively, our intensive sampling (2–3 times per week) early in the season (except for 2021) should have been sufficient to detect PC's edge effect despite the small orchard size. However, under laboratory conditions (Chen et al. 2006), PC were found to travel much further, with a median distance of 122.2 m per day. Whether PC's edge effect is associated with orchard size, and
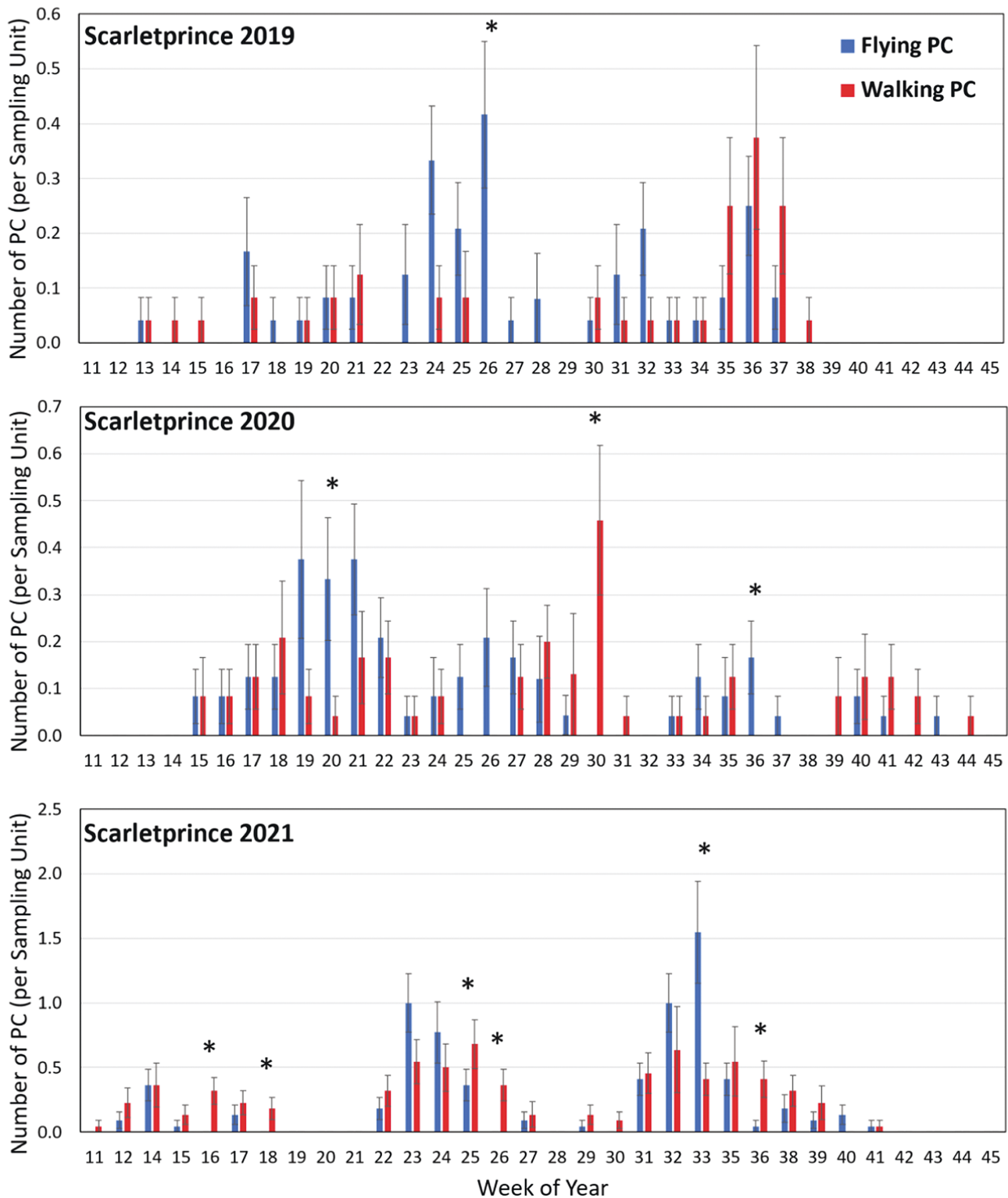
Fig. 8. Number (mean ± SE) of flying and walking PC adults per sampling unit and the average air temperature in each sampling week in 2019, 2020, and 2021 in the Scarletprince orchard. An asterisk (*) indicates significant difference between the 2 modes of movement (*t*-tests; *P* < 0.05).

whether this association varies by orchard location requires further investigation.

Similar to our findings, Akotsen-Mensah et al. (2010) discovered that PC did not exhibit an edge effect in Southeastern peaches in Alabama. In contrast, Johnson et al. (2002) reported the presence of an edge effect with the southeastern PC strain in Arkansas and

Oklahoma. These 2 studies were conducted in different locations and time, and different sampling methods were used. In the research by Akotsen-Mensah et al. (2010), pyramid and Circle trunk traps were the sampling tools, while in the research by Johnson et al. (2002), pyramid traps and beat sampling were used. Alongside our data, these differences suggest that the presence of an edge effect for

Table 1. Pearson's correlation coefficients (*r*) between the numbers of flying PC and walking PC in different sampling weeks and across all sampling weeks (all-season) in the Scarletprince and Contender orchards in 2019, 2020, and 2021

Week of year	Scarletprince			Contender		
	2019	2020	2021	2019	2020	2021
11	–	–	0.000	–	–	0.000
12	0.000	–	–0.139	–0.043	0.000	0.000
13	–0.043	–	–	–0.134	0.000	0.000
14	0.000	–	–0.302	–0.134	–	0.000
15	0.000	–0.063	–0.087	–0.135	–0.140	**–0.548**
16	0.000	–0.091	0.000	–0.246	–0.053	0.000
17	–0.107	**0.619**	0.101	–0.159	–0.167	–0.239
18	0.000	0.301	0.000	–0.145	0.192	0.000
19	–0.043	–0.140	0.000	–0.114	0.081	0.000
20	–0.091	–0.111	0.000	–0.063	–0.076	0.000
21	–0.086	0.235	0.000	–0.111	0.000	0.000
22	0.000	0.046	0.154	–0.213	**0.793**	–0.101
23	0.000	–0.043	0.167	0.000	0.000	–0.348
24	–0.213	–0.063	–0.025	–0.017	0.000	–0.198
25	–0.107	0.000	**0.600**	0.008	–0.157	–0.400
26	0.000	0.000	0.000	0.000	0.000	–0.135
27	0.000	0.169	–0.094	0.101	0.298	0.000
28	0.000	–0.139	0.000	0.000	–0.099	0.000
29	0.000	–0.045	–0.087	0.000	–0.115	0.000
30	–0.063	0.000	0.000	0.000	0.000	0.000
31	**0.891**	0.000	0.209	–0.043	0.000	–0.157
32	–0.107	0.000	**0.457**	0.000	0.000	–0.460
33	–0.043	–0.043	0.004	–0.043	0.000	–0.317
34	–0.043	–0.079	–	–0.193	0.000	–
35	–0.127	–0.079	–0.058	–0.174	0.000	–0.145
36	–0.268	0.000	–0.137	0.000	–0.111	–0.175
37	–0.127	0.000	–	0.000	0.000	–
38	0.000	0.000	–0.213	0.000	0.000	0.000
39	0.000	0.000	–0.120	0.000	0.000	0.000
40	0.000	**0.601**	0.000	0.000	0.000	0.000
41	0.000	–0.079	–0.048	0.000	0.000	0.000
42	–	0.000	–	–	0.000	–
43	–	0.000	–	–	0.000	–
44	–	0.000	–	–	0.000	–
45	–	0.000	–	–	0.000	–
All-season	–0.042	0.050	**0.192**	0.016	0.068	–0.086

Bold indicates significant correlation (Pearson's correlation tests; *P* < 0.05).

the southeastern PC strain might vary by sampling year, site, and method.

Currently, the most common monitoring tools for PC are the ground-deployed black pyramid trap that mimics a tree trunk and attracts both flying and walking PC, and the trunk-deployed Circle trap, which passively captures PC walking up to the tree (Akotsen-Mensah et al. 2010). While the black pyramid trap and the Circle trap collect PC cumulatively, another commonly used monitoring method for capturing PC, beat sampling, samples PC in the tree canopies in real time. Different trapping mechanisms of different sampling methods might explain why in our edge effect study, different sampling methods led to different outcomes. Previous research has reported variations in collected abundances of PC using different trapping methods. For example, Johnson et al. (2002) reported that pyramid traps captured adult PC in 114 sampling visits, while the beat sampling method only captured adult PC in 29 visits to the peach orchard in Arkansas. However, Hernandez-Cumplido et al. (2017) discovered that the numbers of PC collected in pyramid traps were correlated with PC captures obtained from beat sampling in New Jersey blueberries. When the numbers of PC captured in pyramid traps and Circle traps were compared, Johnson et al. (2002) reported that pyramid traps and Circle traps tended to capture similar numbers of PC; on the contrary, Akotsen-Mensah et al. (2010) noted that pyramid traps tended to capture more PC than Circle traps, especially for the overwintering PC generation. These discrepancies in PC numbers captured in different and even same trapping systems in both our current research and previous studies emphasize the importance of finding and implementing the proper trapping methods for PC that best represent PC abundance in an orchard, and also suggest that the best sampling methods might vary from location to location.

In the PC modes of movement study, there were 32–35 sampling weeks in total in each orchard, whereas there were only 0–7 weeks with significant differences in PC's modes of movement. Overall, we did not observe that PC exhibited a primary mode of movement. The inconsistency between our results and the findings from Prokopy et al. (1999) may be explained by the fact that, in addition to air temperature, other environmental factors could also affect PC's movement. Racette et al. (1991) reported that at night, PC were active when wind speed was low and relative humidity was high. McGiffen

and Meyer (1986) found that on a warm day, PC's propensity to take flight was low when humidity was low. However, Chouinard et al. (1993) reported that PC's tendency to fly was not related to relative humidity but was significantly positively related to air temperature, whereas their tendency to walk was not significantly related to either air temperature or relative humidity. Another potential reason causing the inconsistent results between our study and the work by Prokopy et al. (1999) could be different sampling and observation techniques used. Prokopy et al. (1999) observed and recorded PC's propensity to fly or walk after tapping PC from tree branches and catching them on a white sheet (1 m × 1 m). Although dropping, along with walking and flying are all important means of PC's dispersal (Chouinard et al. 1993), we did not specifically focus on studying PC's behavior after they dropped from the trees; instead, we studied and reported PC's natural behavior without interfering with PC's movement before collecting data.

The ultimate goal of our research was to facilitate the development of spatiotemporally targeted management approaches against PC in Southeastern peaches. In summary, our studies indicate that (i) because we did not find the edge effect in Southeastern peaches, the reduced-input application program, where insecticide sprays mainly target a few perimeter-row trees for PC management, is not recommended for small Southeastern peach plots, and (ii) PC in Southeastern peaches did not exhibit a primary mode of movement because most of the time, the numbers of flying and walking PC were not significantly correlated in the field. Hence using PC monitoring tools that only capture either flying or walking PC might not be ideal for PC sampling.

Given that the lack of an edge effect in our study could potentially be attributed to PC overwintering in the orchard, future research should focus on investigating where in an orchard PC overwinter in Southeastern peaches for new potential management tactics targeting PC prior to the following season. Our conclusions were drawn from studies conducted in orchards with small acreage. Future studies could further investigate whether PC's edge effect is associated with orchard size, and thus can further develop PC management practices that accommodate different orchard conditions. The lack of correlations between the numbers of flying and walking PC suggests that future research may need to investigate the correlations between numbers of PC captured from different trap types that utilize different capture mechanisms and peach fruit injury, and determine what trap types and trap deployment strategies can best predict fruit injury caused by PC or correspond with overall PC abundance in an orchard, and thus can be used to determine the timing for insecticide applications.

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Data availability

The data underlying this article will be shared on reasonable request to the corresponding author.

References

Akotsen-Mensah C, Boozer R, Fadamiro HY. 2010. Field evaluation of traps and lures for monitoring plum curculio (Coleoptera: Curculionidae) in Alabama peaches. J. Econ. Entomol. 103(3):744–753. https://doi.org/10.1603/ec09405

Akotsen-Mensah C, Boozer RT, Fadamiro HY. 2011. Field evaluation of reduced insecticide spray programs for managing plum curculio, *Conotrachelus nenuphar* (Coleoptera: Curculionidae), in Alabama peaches. Pest Manag. Sci. 67(6):626–632. https://doi.org/10.1002/ps.2095

Chapman PJ. 1938. The plum curculio as an apple pest. N.Y.S. Agric. Exp. Stn. Bull. 684(1):1–75.

Chen H, Kaufmann C, Scherm H. 2006. Laboratory evaluation of flight performance of the plum curculio (Coleoptera: Curculionidae). J. Econ. Entomol. 99(6):2065–2071. https://doi.org/10.1603/0022-0493-99.6.2065

Chouinard G, Hill SB, Vincent C, et al. 1992. Border-row sprays for control of the plum curculio in apple orchards: behavioral study. J. Econ. Entomol. 85(4):1307–1317. https://doi.org/10.1093/jee/85.4.1307

Chouinard G, Hill SB, Vincent C. 1993. Spring behavior of the plum curculio (Coleoptera: Curculionidae) within caged dwarf apple trees. Ann. Entomol. Soc. Am. 86(3):333–340. https://doi.org/10.1093/aesa/86.3.333

Chouinard G, Pelletier F, Vincent C. 2021. Pest activity and protection practices: four decades of transformation in Quebec apple orchards. Insects 12(3):197. https://doi.org/10.3390/insects12030197

Dixon BM, Prokopy RJ, Schultz BB. 1999. Influence of weather and time of day on plum curculio (Coleoptera: Curculionidae) tree canopy entry behaviors and evaluation of traps for predicting fruit injury. J. Entomol. Sci. 34(2):191–202. https://doi.org/10.18474/0749-8004-34.2.191

Foshee WG, Boozer RT, Blythe EK, et al. 2008. Management of plum curculio and catfacing insects on peaches in central Alabama: standard crop stage-based vs. integrated pest management-based approaches. Int. J. Fruit Sci. 8(3):188–199. https://doi.org/10.1080/15538360802529765

Hernandez-Cumplido J, Leskey TC, Holdcraft R, et al. 2017. Tempo-spatial dynamics of adult plum curculio (Coleoptera: Curculionidae) based on semiochemical-baited trap captures in blueberries. Environ. Entomol. 46(3):674–684. https://doi.org/10.1093/ee/nvx047

Jenkins D, Cottrell T, Horton D, et al. 2006. Hosts of plum curculio, *Conotrachelus nenuphar* (Coleoptera: Curculionidae), in central Georgia. Environ. Entomol. 35(1):48–55. https://doi.org/10.1603/0046-225x-35.1.48

Johnson DT, Mulder PG, McCraw BD, et al. 2002. Trapping plum curculio *Conotrachelus nenuphar* (Herbst) (Coleoptera: Curculionidae) in the Southern United States. Environ. Entomol. 31(6):1259–1267. https://doi.org/10.1603/0046-225x-31.6.1259

Lafleur G, Hill SB. 1987. Spring migration, within-orchard dispersal, and apple-tree preference of plum curculio (Coleoptera: Curculionidae) in Southern Quebec. J. Econ. Entomol. 80(6):1173–1187. https://doi.org/10.1093/jee/80.6.1173

Lafleur G, Hill SB, Vincent C. 1987. Fall migration, hibernation site selection, and associated winter mortality of plum curculio (Coleoptera: Curculionidae) in a Quebec apple orchard. J. Econ. Entomol. 80(6):1152–1172. https://doi.org/10.1093/jee/80.6.1152

Lampasona TP, Rodriguez-Saona C, Leskey TC, et al. 2020. A review of the biology, ecology, and management of plum curculio (Coleoptera: Curculionidae). J Integr Pest Manag 11(1):1–12. https://doi.org/10.1093/jipm/pmaa018

Lan Z, Scherm H, Horton D. 2004. Temperature-dependent development and prediction of emergence of the summer generation of plum curculio (Coleoptera: Curculionidae) in the southeastern United States. Environ. Entomol. 33(2):174–181. https://doi.org/10.1603/0046-225X-33.2.174

Le Blanc J-PR, Hill SB, Paradis RO. 1984. Oviposition in scout-apples by plum curculio, *Conotrachelus nenuphar* (Herbst) (Coleoptera: Curculionidae), and its relationship to subsequent damage. Environ. Entomol. 13(1):286–291. https://doi.org/10.1093/ee/13.1.286

Leskey TC. 2006. Visual cues and capture mechanisms associated with traps for plum curculio (Coleoptera: Curculionidae). J. Entomol. Sci. 41(2):97–106. https://doi.org/10.18474/0749-8004-41.2.97

Leskey TC, Wright SE. 2004. Influence of host tree proximity on adult plum curculio (Coleoptera: Curculionidae) responses to monitoring traps. Environ. Entomol. 33(2):389–396. https://doi.org/10.1603/0046-225x-33.2.389

McClanan ME, Luckhart S, Pfeiffer DG. 2004. *Wolbachia* strains associated with univoltine and multivoltine plum curculios (Coleoptera: Curculionidae). J. Entomol. Sci. 39(1):132–135. https://doi.org/10.18474/0749-8004-39.1.132

McGiffen ME Jr, Meyer JR. 1986. Effect of environmental factors on overwintering phenomena and spring migration of the plum curculio, *Conotrachelus nenuphar* (Coleoptera: Curculionidae). Environ. Entomol. 15(4):884–888. https://doi.org/10.1093/ee/15.4.884

Piñero JC, Prokopy RJ. 2006. Temporal dynamics of plum curculio, *Conotrachelus nenuphar* (Herbst.) (Coleoptera: Curculionidae), immigration into an apple orchard in Massachusetts. Environ. Entomol. 35(2):413–422. https://doi.org/10.1603/0046-225x-35.2.413

Piñero J, Bigurra E, Jácome I, et al. 2004. Are adult plum curculios capable of overwintering within apple orchards. Fruit Notes 69(1):3–5.

Prokopy RJ, Wirth CB, Leskey TC. 1999. Movement of plum curculio adults toward host trees and traps: flight versus walking. Entomol. Exp. Appl. 91(3):385–392. https://doi.org/10.1046/j.1570-7458.1999.00506.x

Prokopy RJ, Chandler BW, Dynok SA, et al. 2003. Odor-baited trap trees: a new approach to monitoring plum curculio (Coleoptera: Curculionidae). J. Econ. Entomol. 96(3):826–834. https://doi.org/10.1093/jee/96.3.826

Prokopy RJ, Jacome I, Gray E, et al. 2004. Using odor-baited trap trees as sentinels to monitor plum curculio (Coleoptera: Curculionidae) in apple orchards. J. Econ. Entomol. 97(2):511–517. https://doi.org/10.1093/jee/97.2.511

Racette G, Chouinard G, Hill SB, et al. 1991. Activity of adult plum curculio (Coleoptera: Curculionidae) on apple trees in spring. J. Econ. Entomol. 84(6):1827–1832. https://doi.org/10.1093/jee/84.6.1827

Racette G, Chouinard G, Vincent C, et al. 1992. Ecology and management of plum curculio, *Conotrachelus nenuphar* (Coleoptera: Curculionidae), in apple orchards. Phytoprotection 73(3):85–100. https://doi.org/10.7202/706025ar

Schoene WJ. 1936. Partial second brood of plum curculio in Virginia. J. Econ. Entomol. 29(3):571–573. https://doi.org/10.1093/jee/29.3.571

Vincent C, Chouinard G, Bostanian NJ, et al. 1997. Peripheral-zone treatments for plum curculio management: validation in commercial apple orchards. Entomol. Exp. Appl. 84(1):1–8. https://doi.org/10.1046/j.1570-7458.1997.00191.x

Vincent C, Chouinard G, Hill SB. 1999. Progress in plum curculio management: a review. Agric. Ecosyst. Environ. 73(2):167–175. https://doi.org/10.1016/s0167-8809(99)00025-0

Zhang X, Tu Z, Luckhart S, et al. 2008. Genetic diversity of plum curculio (Coleoptera: Curculionidae) among geographical populations in the eastern United States. Ann. Entomol. Soc. Am. 101(5):824–832. https://doi.org/10.1603/0013-8746(2008)101[824:GDOPCC]2.0.CO;2