Relative efficacies of sticky yellow rectangles against three *Rhagoletis* fly species (Diptera: Tephritidae) in Washington State and possible role of adhesives

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ABSTRACT

Sticky yellow rectangle traps are used to monitor various pest *Rhagoletis* flies (Diptera: Tephritidae), but it is unclear if relative efficacies of these traps differ with fly species. Here, the main objective was to identify the most efficacious of five commercial sticky yellow rectangles baited with ammonium carbonate against western cherry fruit fly, *R. indifferens* Curran, apple maggot fly, *R. pomonella* (Walsh), and walnut husk fly, *R. completa* Cresson, in Washington State, U.S.A. Two plastic yellow sticky strips (PL1 and PL2) supplemented with Tanglefoot adhesive and three sticky yellow cardboards, the Pherocon AM (PA1), Multigard AM (PA2) and Alpha Scents Yellow Card (PA3), were tested. Across all three species, the PL1 and PL2 + Tanglefoot generally caught the most flies, the PA3 sometimes caught more than the PA1, and all caught more than the PA2. Adding Tanglefoot to the PA1 did not make the trap as efficacious as the PL1 + Tanglefoot against *R. indifferens*, but it did against *R. pomonella* and *R. completa*. Results suggest the plastic rectangles tested here are better than standard cardboard rectangles for capturing high numbers of all three *Rhagoletis* species, implying they should be the rectangles of choice for monitoring these flies. Results also suggest that similar trap efficacies against the three species may have different underlying causes.

Key Words: *Rhagoletis indifferens*, *Rhagoletis pomonella*, *Rhagoletis completa*, yellow plastic traps, yellow cardboard traps, Tanglefoot® adhesive

INTRODUCTION

Traps are used to monitor and detect various pest *Rhagoletis* flies (Diptera: Tephritidae) as a first step in a multi-pronged approach for protecting fruit commodities. Of all the different trap types developed, sticky yellow rectangles baited with ammonia compounds, in particular ammonium carbonate, remain the most widely used against these flies in North America (e.g., Riedl *et al*. 1989; Liburd *et al.* 2001; Yee *et al*. 2012). These traps are commercially available, flat, light, easy to store and deploy, and the dark flies are easy to see on and remove from them. Other commercial sticky traps used in North America or Europe are red or green spheres, the Ladd trap (AliNiazee *et al.* 1987; Riedl *et al*. 1989; Jones and Davis 1989), and the Rebell trap (Remund and Boller 1978). Non-commercial, experimental sticky traps include yellow spheres (AliNiazee 1981), a bell trap (Burditt 1988), and cylinder traps (Opp *et al*. 2003).

Efficacies (that is, how well a trap performs in controlled experiments relative to other traps) between rectangle and some other trap types differ among *Rhagoletis* species (e.g., Prokopy and Hauschild 1979; Liburd *et al*., 2001; Lampe *et al*. 2005). For example, against European cherry fruit fly, *R. cerasi* (L.), three-dimensional yellow Rebell traps are more efficacious than Pherocon AM traps, whereas the reverse is true for eastern cherry fruit fly, *R. cingulata* (Loew) (Katsoyannos *et al*. 2000; Lampe *et al*. 2005).

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However, which yellow rectangles are most efficacious and whether efficacies of those rectangles differ among *Rhagoletis* species have not been well studied.

In particular, sticky yellow plastic rectangles that catch more western cherry fruit fly, *R. indifferens* Curran, than conventional sticky yellow cardboard rectangles in Washington State, U.S.A. (Yee 2014), have not been tested against other *Rhagoletis* species. It can be predicted that plastic yellow rectangles are efficacious against them as well, based on similarities in spectral sensitivities in representative species and fly responses to color (Prokopy 1968; Agee *et al*. 1982; Agee 1985). The availability of different commercial yellow rectangles presents an opportunity to test this hypothesis. Rejection of this hypothesis could lead to work identifying factors responsible for trap efficacy and thus more species-specific traps.

In western North America where fruit commodities are of high economic value, trapping is critical for quarantine and control measures against three *Rhagoletis* species. In Washington State and other northwestern U.S. states, as well as in British Columbia, Canada, *R. indifferens* and apple maggot fly, *R. pomonella* (Walsh), are major quarantine pests of cherries (*Prunus* spp.) and apple (*Malus domestica* Borkhausen), respectively. In California, walnut husk fly, *R. completa* Cresson, is a major pest of walnuts (*Juglans* spp.). Annually, in Washington State, cherries are valued at ~$US300–$400 million (National Agricultural Statistics Service 2013a) and apples at ~$US1.5 billion (National Agricultural Statistics Service 2012); in California, walnuts are valued at ~$US1.3 billion (National Agricultural Statistics Service 2013b).

In this study, the main objective was to identify the most efficacious of five commercial sticky yellow rectangles baited with ammonium carbonate against *R. indifferens*, *R. pomonella*, and *R. completa* in Washington State. The hypothesis that relative efficacies of these traps against all three species are similar was tested. A secondary objective was to determine which factors could affect their efficacies. In particular, traps were supplemented with Tanglefoot® adhesive (Contech Enterprises, Inc., Victoria, B.C., Canada) to determine if this can increase the efficacy of a trap, as adhesive type effects on fly captures may vary (Yee 2011).

MATERIALS AND METHODS

Five-trap comparisons. Five commercial sticky yellow rectangles were tested in the first set of experiments (Table 1, Fig. 1). The two plastic traps were the Agri-Sense Yellow Sticky Strip (PL1) and the Olson Yellow Sticky Strip (PL2) (Agri-Sense-BCS, South Wales, U.K., and Olson Products, Medina, OH, U.S.A., respectively), both covered with pressure-sensitive adhesives. These adhesives are thin, solvent-/water-free tacky materials unlike conventional thick, Vaseline-like adhesives. Both traps were 14 × 23 cm. The pressure-sensitive adhesives on the traps were supplemented with Tanglefoot® (Tangle-Trap™ Insect Trap Tropical Formula). Tanglefoot was added, because it is known from previous tests (Yee 2014; W. L.Y., unpublished) that the pressure sensitive adhesives on these traps can lose stickiness within 2–3 weeks. More importantly, the PL1, as received from the manufacturer, had variable amounts of pressure-sensitive adhesive, and occasional lots were not sticky. About 10 g of Tanglefoot (5 g each side) was spread onto each plastic trap.

The three cardboard or paper traps were the Pherocon AM (PA1), used for the last 40 years against *Rhagoletis* flies (e.g., Prokopy and Hauschild 1979; Riedl *et al*. 1989; Liburd *et al*. 2001), the Multigard AM (PA2; it or its variations have been available since at least 1994 [Katsoyannos *et al*. 2000]), and the Alpha Scents Yellow Card (PA3; available within the last six years [Yee 2011]; Table 1, Fig. 1). These three traps were initially tested without adding Tanglefoot to them, because they were assumed to retain their tackiness over test trap durations of $\leq$4 weeks. The sticky adhesives on the PA1 and PA2 were Vaseline-like, but differed from the Tanglefoot (compositions of commercial adhesives are proprietary). About 5.0 g and 5.5 g of sticky adhesives were present on the

Table 1

Five commercial sticky yellow rectangles tested against *Rhagoletis* flies in Washington State, U.S.A.

			Sticky area	Thickness	Mean color space values ± SE[f]			Light passage[g]
Trap[a]	Form	Size (cm)	(cm^2)[e]	(mm)	L*	a*	b*	
PL1 + Tanglefoot[b]	1 sheet	23 × 14	596	0.33	76.83 ± 0.22	-9.39 ± 0.07	63.22 ± 0.67	4,736
PL2 + Tanglefoot[b]	1 sheet	23 × 14	596	0.30	81.09 ± 0.62	-13.68 ± 0.11	57.55 ± 0.67	2,691
PA1[c]	folded	23 × 14	407	1.22	88.77 ± 0.60	-6.41 ± 0.14	77.56 ± 0.89	54
PA2[c]	folded	23.5 × 14	313	1.23	98.11 ± 0.18	-26.80 ± 0.29	81.22 ± 1.57	43
PA3[d]	1 sheet	20 × 14	478	0.48	92.86 ± 0.57	-15.02 ± 0.13	68.39 ± 0.89	474

[a]PL, plastic; PA, cardboard = paper. [b]Tanglefoot (Contech Enterprises, Inc., Victoria, B.C., Canada) spread over pressure-sensitive adhesive on trap supplied by manufacturer; ~10 g per trap. [c]Adhesives of proprietary formulations different from Tanglefoot: 5 g and 5.5 g on PA1 and PA2, respectively. [d]Hot-melt pressure-sensitive adhesive. [e]From manufacturer: total of two sides of traps; excludes borders without adhesive. [f]Measured over sticky surface; five traps. [g]Lm/m^2, measured with white light of 9,688 lm/m^2 on one side of trap; room light of 1,076 lm/m^2 (Yee 2014). Manufacturers: PL1: Agri-Sense-BCS, South Wales, U.K.; PL2: Olson Products, Medina, OH, U.S.A.; PA1: Trécé, Adair, OK, U.S.A.; PA2: Scentry Biologicals, Billings, MT, U.S.A.; PA3: Alpha Scents, West Linn, OR, U.S.A.

PA1 and PA2, respectively. The sticky material on PA3 was a hot-melt pressure-sensitive adhesive that was tackier than the pressure-sensitive adhesive on the PL1 (Yee 2011).

A vial containing 10 g of ammonium carbonate (Keystone Universal, Melvindale, MI, U.S.A.) with a plastic lid and two 1-mm holes was hung ~1 cm above each trap.

Study sites and experimental types in five-trap comparisons. All sites were located in central or western Washington State (WA). Sites were unmanaged orchards, homeowners' yards, or wild habitats. Twelve tests were conducted between May and September 2014 in sweet cherry (*Prunus avium* (L.) L.), apple, black hawthorn (*Crataegus douglasii* Lindley), and English walnut trees (*Juglans regia* (L.); Table 2). For each fly species, three to five tests were conducted, each using a randomized complete block design with three to five replicate blocks.

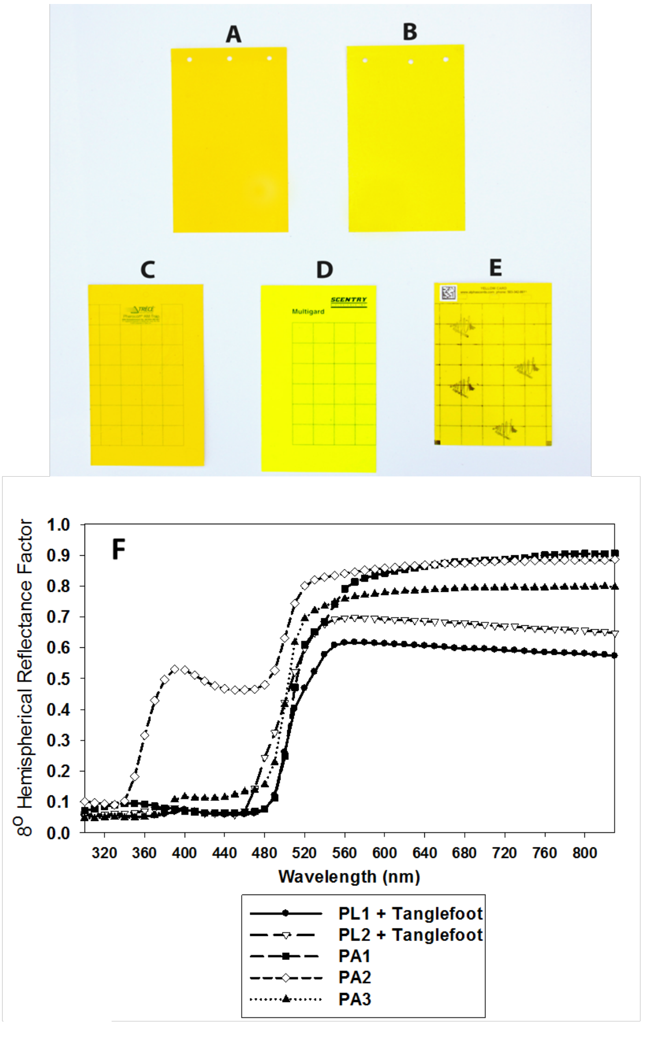

Figure 1. Yellow rectangle traps used in study: (A) PL1 + Tanglefoot, (B) PL2 + Tanglefoot, (C) PA1, (D) PA2; (E) PA3; all to same scale; (F) reflectance curves of the five traps (Perkin-Elmer Lambda 9UV-Vis-NIR Spectrometer Ser. No. 1611; Avian Technologies LLC, Sunapee, NH).

A block was a defined location comprising a set of trees, a single tree, or a sector of a tree containing all five trap types and within which all trap types were rotated to further reduce spatial effects. The number of blocks equaled the number of replicate traps. Availability of trees and layout of trees determined the number of replicates and possible blocking schemes, as no sets of trees in the field are neatly arranged like trees in orchards.

One trap per tree was set up in five-tree blocks when at least 25 trees (five trap types × five replicate trees) were available to use at a site. Here, each trap was spaced 3–5 m apart, depending on inter-tree distances. This scheme was used for *R. indifferens* and *R. pomonella* (Table 2). When only about five large trees were present, all five trap types were placed in one tree; each tree was a block. All traps were placed in the south half of a tree, ~2 m apart. This scheme was used for *R. indifferens*, *R. pomonella*, and *R. completa* (Table 2). Two or three blocks per tree were set up when there were only two large, 15–18 m wide walnut trees at a site. Here each block was a 4–5 m sector of a tree with five traps, each trap 1–2 m apart within the sector (Table 2).

In all tests, traps were hung from branches ~1.5–2 m above ground. Traps within blocks were rotated 2 to 18 times (Table 2). Flies were removed from traps every time positions were changed and were saved in cups and later sexed in the laboratory. Traps were replaced after three weeks if needed, with one to three replacements occurring over the 3–8 week tests. Particulars of each test site and its trees follow.

Four five-tree block tests were conducted (Table 2). Two tests were conducted for *R. indifferens*: one in an unmanaged cherry orchard in Yakima with 145 trees ~4–5 m tall and wide, and the other in an unmanaged cherry grove in Vancouver with 50 trees ~6–8 m tall and ~3–5 m wide. Two tests were conducted for *R. pomonella* in an old homestead in Skamania County with approximately 100 apple and 25 black hawthorn trees ~5–8 m tall and wide.

Six tests using blocks of one tree were conducted (Table 2). One test for *R. indifferens* was conducted in five seedling cherry trees ~5–7 m tall and wide in Roslyn. Three tests for *R. pomonella* were conducted in a contiguous stand of black hawthorn trees ~6–8 m tall and wide in the Nile Valley and in individual black hawthorn and apple trees ~5–7 m tall and wide in Vancouver. Two tests for *R. completa* were conducted in five walnut trees ~3–4 m tall and wide in Zillah, Site 1, and in 12 walnut trees ~8–17 m tall and wide in Naches.

Two tests employing multiple blocks per tree were conducted for *R. completa* (Table 2) in English walnut in homeowners' yards. The first test was at Zillah, Site 2, with two trees, each ~15–18 m tall and wide; the second was at Donald, with two trees, each ~15 m tall and wide.

PL1 + Tanglefoot vs. PA1 and other traps + Tanglefoot. The main purpose of this second set of experiments was to determine if adding or replacing the adhesive already present on a trap with Tanglefoot improves the trap's efficacy. Emphasis was placed on comparing the PL1 + Tanglefoot with the PA1 + Tanglefoot, in most cases with the same sticky surface areas. However, to gain additional information, other yellow traps + Tanglefoot (all baited with ammonium carbonate) were also compared in 2014 and 2015. Blocking schemes and other procedures followed those described for the five-trap comparison tests.

For *R. indifferens*, one test was conducted from 18–29 May 2015 in three sweet cherry trees with one or two blocks per tree for five total blocks in Kennewick, WA. The PL1 + Tanglefoot vs. PA1 + Tanglefoot (each with 596 cm^2 sticky surface) was the major comparison. The adhesive on the PA1 was scraped off and replaced with Tanglefoot (~5 g each side). To obtain additional information, the traps were compared with three non-rectangle traps. The first was a yellow PALz trap, a plastic rectangle with ends tied together (30.5 × 22.9 cm, 614 cm^2 sticky surface; Plant Protection Institute, Budapest, Hungary). This trap was covered with a thick Tanglefoot-like adhesive, so no Tanglefoot was added to it.

Table 2
Tests of five trap types against three *Rhagoletis* species in Washington State, U.S.A. in 2014

Five-Tree Blocks: One Trap in Each Tree

Fly species	Traps in[a]	Site	No. trees	No. traps per type	Trapping dates	No. trap rotations[b]
R. indifferens	Sweet cherry	Yakima	25	5	19 May–25 June	9
	Sweet cherry	Vancouver	25	5	12 June–14 July	5
R. pomonella[c]	Apple, black hawthorn	Skamania	25	5	4 July–7 Aug	5
	Apple	Skamania	25	5	11 Aug–2 Sept	3

Blocks of One Tree Each: All Five Trap Types in Each Tree

Fly species	Traps in[a]	Site	No. trees	No. traps per type	Trapping dates	No. trap rotations[b]
R. indifferens	Sweet cherry	Roslyn	5	5	9 July–18 Aug	11
R. pomonella	Black hawthorn	Vancouver	3	3	23 June–16 July	2
	Black hawthorn	Nile Valley	5	5	9 July–3 Sept	13
	Apple	Vancouver	3	3	3 July–23 July	3
R. completa	English walnut	Zillah, Site 1	5	5	2 July–2 Sept	18
	English walnut	Naches	5	5	16 July–29 Aug	12

Multiple Blocks within a Tree, 2 Trees, Each Tree with 2 Blocks, 5 Trap Types Per Block

Fly species	Traps in[a]	Site	No. trees	No. traps each type	Trapping dates	No. trap rotations[b]
R. completa	English walnut	Zillah, Site 2	2	4	2 July–1 Aug	6
	English walnut	Donald	2	4	30 July–26 Aug	7

[a]Sweet cherry, *Prunus avium* (L.) L.; black hawthorn, *Crataegus douglasii* Lindley; apple, *Malus domestica* Borkhausen; English walnut, *Juglans regia* (L.).
[b]Rotated = traps moved over to next position in trees within blocks.
[c]Three replicates in apple and two in black hawthorn.

The second trap was a yellow 'Fly Trap' with a "modular" design (24.8 cm high × 8.9 cm wide, 482 cm^2 sticky surface; PIC Corporation, Linden, NJ), and the third trap was a 9.0-cm diameter yellow ball (283 cm^2 sticky surface; laboratory made). The Fly Trap had a thin layer of pressure-sensitive adhesive, and the ball had no adhesive; Tanglefoot was added to both. Traps within blocks were rotated four times; due to high fly numbers, traps were replaced each time.

For *R. pomonella* (Table 3), three tests were conducted in 2014 and 2015. All tests used one trap per tree. In Test 1, five blocks of five trees each were set up. In Test 2, five blocks of two trees each were set up. In Test 3, three blocks of two trees each were set up.

For *R. completa* (Table 3), four tests were conducted in 2014 using multiple blocks per tree. In all four *R. completa* tests, five blocks were set up. In Tests 1, 3, and 4, there were two blocks in each of two trees and one block in one. In Test 2, there were two blocks in one tree and three in a second tree.

For both species, traps within blocks were rotated four to seven times, except at Skamania in 2015 (twice; Table 3). In 2014, Tanglefoot was added on top of adhesives already present, but in 2015, the adhesives were scraped off and replaced with Tanglefoot.

Statistics. For each test, fly counts were summed over all collection dates and square-root transformed (Zar 1999; data met normality and homogenous variance assumptions) and then subjected to randomized complete block analysis of variance (ANOVA), followed by Tukey's HSD test for means separation (SAS Institute Inc. 2010). In a second analysis, counts were adjusted for sticky surface area (cm^2) before analysis with ANOVA and Tukey's HSD test. In addition, orthogonal contrasts were conducted after ANOVA, using the contrast statement in SAS for fly counts per cm^2 to identify possible common factors affecting captures. Specifically, for the five trap-comparison tests, three contrasts of plastic vs. paper traps or Tanglefoot vs. other adhesives were made: the means of PL1 + PL2 with Tanglefoot vs. means of PA1 + PA2, PA1 + PA3, and PA2 + PA3. For the PL1 + Tanglefoot vs. PA1 and other traps + Tanglefoot tests against *R. pomonella* and *R. completa*, two or four contrasts of Tanglefoot vs. other adhesives were made (none was made for the *R. indifferens* test). Female- and male-fly data were combined to simplify the results, as catch patterns of the sexes were similar.

RESULTS

Five-trap comparisons. Within fly species, relative trap efficacy patterns using five-tree block, one-tree block, and multiple blocks per tree designs were similar, especially for the best performing traps (Figs. 2–4), so the way blocking was performed made no difference in the conclusions. Across all three *Rhagoletis* species, the PL1 and PL2 + Tanglefoot were generally the most efficacious of the five traps tested. Compared with the PL2 + Tanglefoot, the PL1 + Tanglefoot caught statistically more *R. indifferens* in one (Fig. 3A) of three tests, more *R. pomonella* in one (Fig. 3D) of five tests, and more *R. completa* in one (Fig. 4A) of four tests.

The PA3 was the next most efficacious trap, but the PL1 + Tanglefoot caught statistically more flies than the PA3 in nine of twelve tests across species. The PA3 caught statistically more *R. pomonella* than the PA1 in one (Fig. 3D) of five tests and more *R. completa* than the PA1 in three (Figs. 3E, 3F, and 4B) of four tests. In no case did the PA1 catch statistically more flies than the PA3. The PA2 was the least effective of all five traps.

Combining data from all tests, more females than male flies were caught on all trap types. For *R. indifferens*, 58–60% caught on the five trap types were females. For *R. pomonella*, 65–69% of flies caught were females; for *R. completa*, 55–66% were females.

Table 3

Tests of PL1 + Tanglefoot vs. PA1 + Tanglefoot and other traps against *Rhagoletis pomonella* and *R. completa* in Washington State, U.S.A., in 2014 and 2015. Numbers of traps of each type tested are shown inside the table.

***R. pomonella*: One Trap per Apple Tree**

Trap Type	Sticky surface area, cm^2	Test 1: Five blocks of five trees each; Skamania, 4 Sept–16 Oct 2014	Test 2: Five blocks of two trees each; Skamania, 3–29 Sept 2015	Test 3: Three blocks of two trees each; Roslyn, 17 Aug–24 Sept 2015
PL1	596	5	—	—
PL1 + Tanglefoot	596	5	5	3
PA1 + Tanglefoot	596	5	5	3
PA2 + Tanglefoot	596	5	—	—
No. trap rotations		7	2	6

***Rhagoletis completa*: Multiple Blocks per Walnut Tree**

Trap Type	Sticky surface area, cm^2	Test 1: Three trees, each with one block or two blocks; Naches, 27 Aug–26 Sept 2014	Test 2: Two trees, one with three blocks and one with two blocks; Donald, 27 Aug–26 Sept 2014	Test 3: Three trees, each with one block or two blocks; Naches, 29 Aug–26 Sept 2014	Test 4: Three trees, each with one block or two blocks; Naches, 29 Aug–26 Sept 2014
PL1	596	5	5	5	—
PL1 + Tanglefoot	596	5	5	5	—
PA1	407	5	—	—	—
PA1 + Tanglefoot	407	5	5	—	—
PA1 + Tanglefoot	596	—	5	—	—
PA2 + Tanglefoot	596	—	—	5	—
PA1	478	—	—	—	5
PA1 + Tanglefoot	478	—	—	—	5
PA3 + Tanglefoot	478	—	—	—	5
No. trap rotations		6	6	5	4

—: trap not tested.

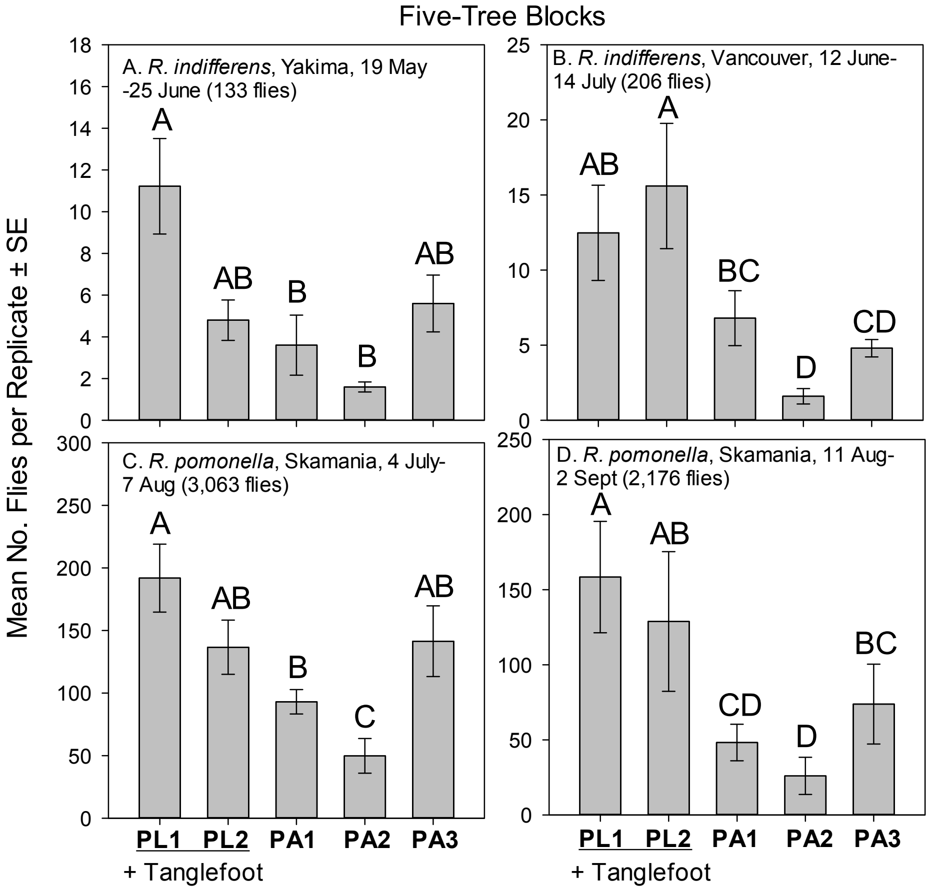

Figure 2. Five-tree block tests: mean numbers of flies (sexes combined) caught per replicate ± SE in 2014: (A) *R. indifferens* in Yakima; (B) *R. indifferens* in Vancouver; (C) *R. pomonella* in Skamania in apple and hawthorn; (D) *R. pomonella* in Skamania in apple. (A) $F = 5.96$; df = 4, 16; $P = 0.0039$; (B) $F = 17.70$; df = 4, 16; $P < 0.0001$; (C) $F = 16.77$; df = 4, 16; $P < 0.0001$; (D) $F = 19.34$; df = 4, 16; $P < 0.0001$. Means within tests with same letters are not significantly different (Tukey's HSD test, $P > 0.05$).

PL1 + Tanglefoot vs. PA1 and other traps + Tanglefoot. The PL1 + Tanglefoot caught statistically more *R. indifferens* than the PA1 + Tanglefoot when both had 596 cm^2 sticky surfaces (Fig. 5). It also caught more flies than two non-rectangle traps with Tanglefoot, although statistically not more than the PALz (Fig. 5), which had a different adhesive. However, unlike for *R. indifferens*, mean catches of *R. pomonella* on the PL1 + Tanglefoot and PA1 + Tanglefoot with 596 cm^2 sticky surfaces did not differ statistically in three tests (Figs. 6A–6C). Similarly to those of *R. pomonella*, mean catches of *R. completa* on the PL1 + Tanglefoot with a 596 cm^2 sticky surface and PA1 + Tanglefoot with 407 and 596 cm^2 sticky surfaces did not differ (Figs. 7A and 7B). However, the PL1 + Tanglefoot caught more *R. pomonella* than the PA2 + Tanglefoot (Fig. 6A) and more *R. completa* than both the PA2 + Tanglefoot (Fig. 7C) and PA3 + Tanglefoot (Fig. 7D) when sticky surface areas were equal.

Fly captures adjusted for sticky surface area. In the first set of the five-trap comparisons, the relative efficacies of traps based on catch numbers not adjusted and adjusted for sticky surface area differed, but the major patterns were the same (Table 4).

Notably, for *R. indifferens*, the PL1 + Tanglefoot was still more efficacious than the PA2 and PA3 in two of three tests; for *R. pomonella*, the PL1 + Tanglefoot was more efficacious than the PA1 in three of five tests, and the PL1 and PL2 + Tanglefoot were more efficacious than the PA2 in all five tests; the PL1 + Tanglefoot was more so than the PA3 in four of five tests. For *R. completa*, the PL1 + Tanglefoot was more efficacious than the PA1 and PA2 in all four tests—more so than the PA3 in two of four tests (Table 4).

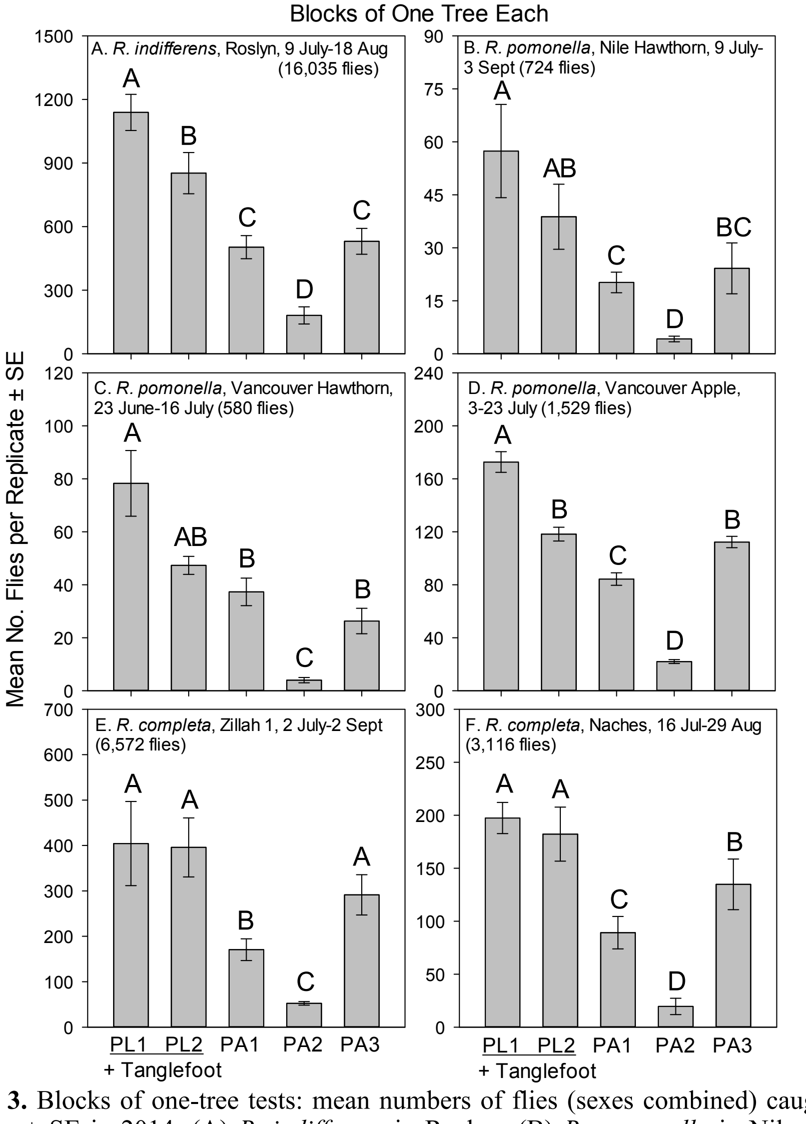

Figure 3. Blocks of one-tree tests: mean numbers of flies (sexes combined) caught per replicate ± SE in 2014: (A) *R. indifferens* in Roslyn; (B) *R. pomonella* in Nile; (C) *R. pomonella* in Vancouver in hawthorn; (D) *R. pomonella* in Vancouver in apple; (E) *R. completa* in Zillah, Site 1; (F) *R. completa* in Naches. (A) $F = 116.27$; df = 4, 16; $P < 0.0001$; (B) $F = 33.51$; df = 4, 16; $P < 0.0001$; (C) $F = 1{,}631.26$; df = 4, 8; $P < 0.0001$; (D) $F = 47.77$; df = 4, 16; $P < 0.0001$; (E) $F = 90.56$; df = 4, 16; $P < 0.0001$; (F) $F = 90.56$; df = 4, 16; $P < 0.0001$. Means within tests with same letters are not significantly different (Tukey's HSD test, $P > 0.05$).

Orthogonal contrasts. For the first set of the five-trap comparisons, contrasts between the means of PL1 + PL2 with Tanglefoot vs. means of PA1 + PA2, PA1 + PA3, and PA2 + PA3 differed regardless of fly species (Table 5). This suggests plastic material or Tanglefoot contributed to higher fly catches. In the PL1 + Tanglefoot and other traps + Tanglefoot comparisons for *R. pomonella*, results suggested Tanglefoot increased captures on PL1, PA2, and PA3, but not on PA1 (Table 5); for *R. completa*, results suggest Tanglefoot increased captures on PL1 and PA1 (Table 5).

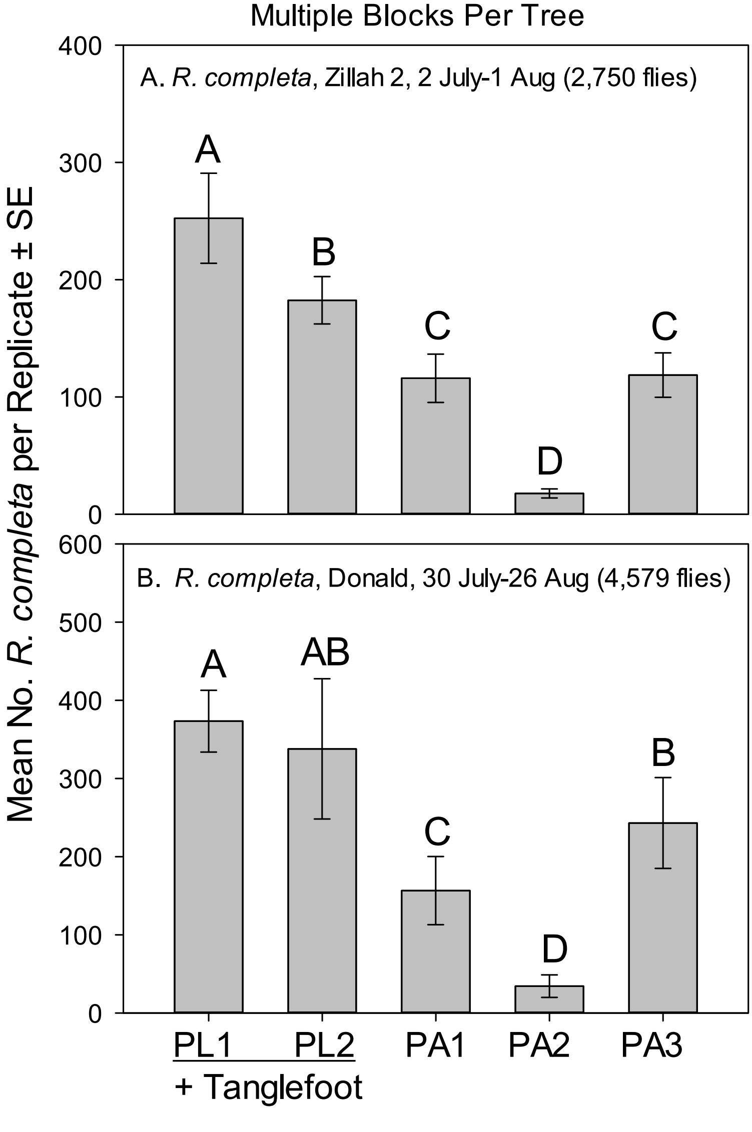

Figure 4. Multiple blocks per tree tests: mean numbers of flies (sexes combined) caught per replicate ± SE in 2014: (A) *R. completa* in Zillah, Site 2; (B) *R. completa* in Donald. (A) $F = 88.45$; df = 4, 12; $P < 0.0001$; (B) $F = 80.80$; df = 4, 12; $P < 0.0001$. Means within tests with the same letters are not significantly different (Tukey's HSD test, $P > 0.05$).

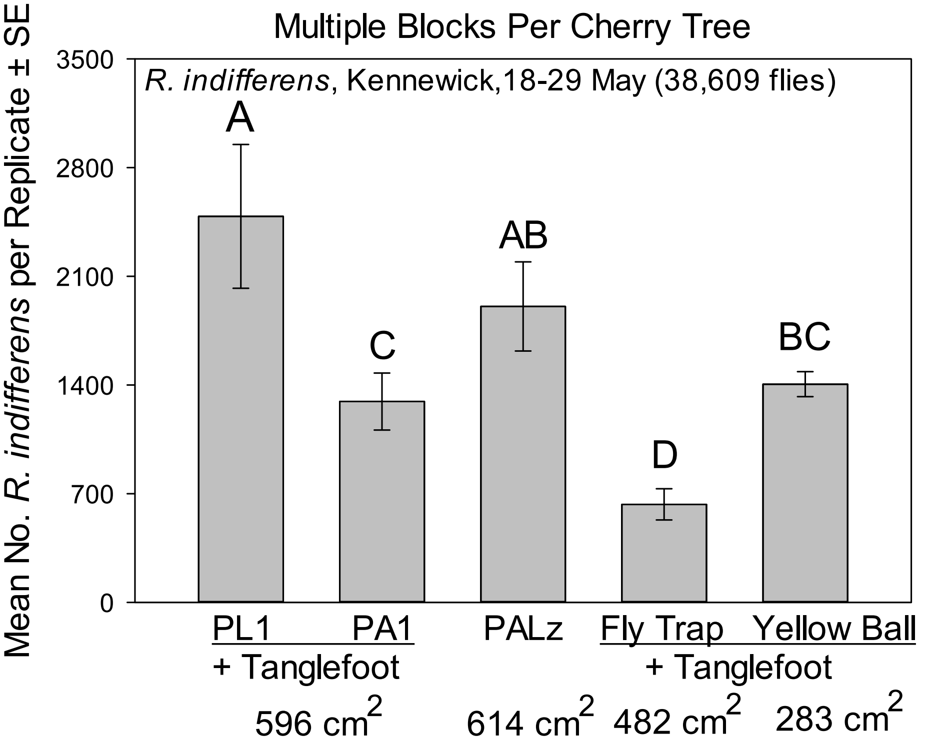

Figure 5. Mean captures of *Rhagoletis indifferens* (sexes combined) ± SE per replicate on PL1 + Tanglefoot vs. PA1 + Tanglefoot and other traps in Kennewick in 2015. Sticky surface areas are shown below trap types. $F = 31.27$; df = 4, 16; $P < 0.001$. Means with same letters are not significantly different (Tukey's HSD test, $P > 0.05$).

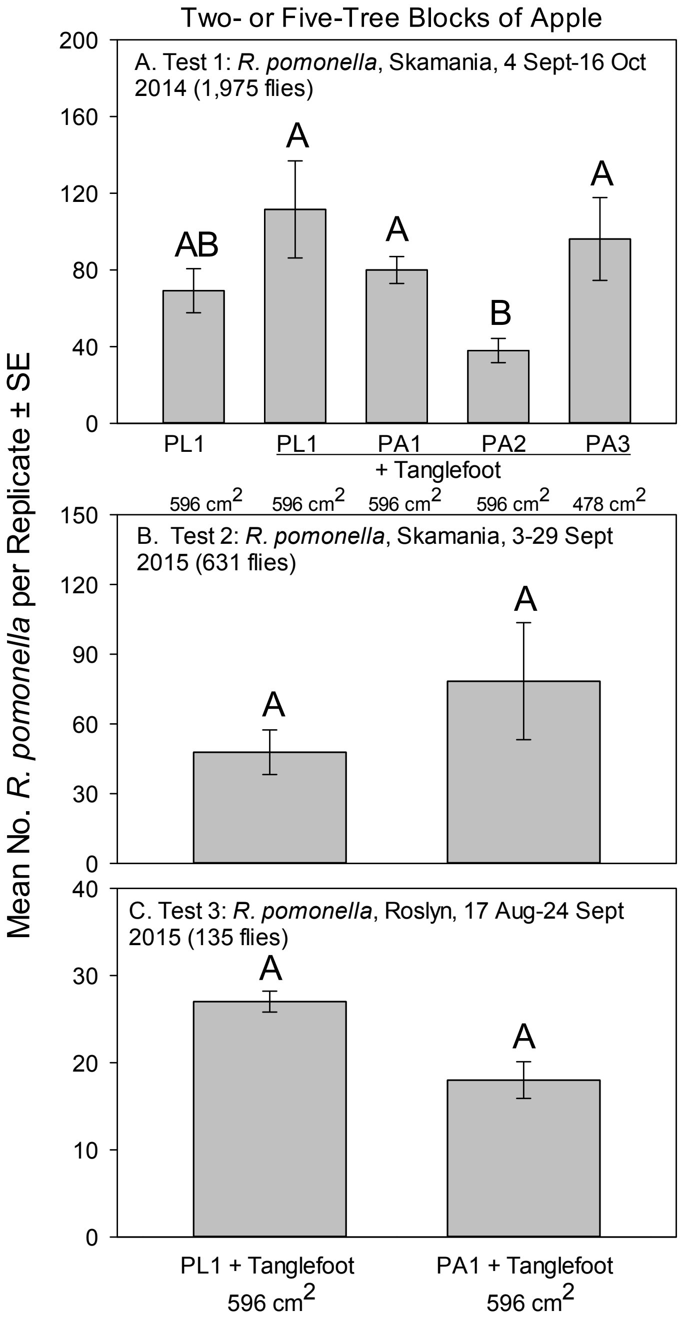

Figure 6. Mean captures of *Rhagoletis pomonella* (sexes combined) ± SE per replicate in 2014 and 2015 on (A) PL1 and PL1 + Tanglefoot vs. PA1 + Tanglefoot, PA2 + Tanglefoot, and PA3 + Tanglefoot; PL1 + Tanglefoot vs. PA1 + Tanglefoot in (B) Skamania and in (C) Roslyn. Sticky surface areas are shown below trap types. (A) $F = 7.10$; df = 4, 16; $P = 0.0017$; (B) $F = 1.66$; df = 1, 4; $P = 0.2669$; (C) $F = 8.13$; df = 1, 2; $P = 0.1041$. Means within tests with same letters are not significantly different (Tukey's HSD test, $P > 0.05$).

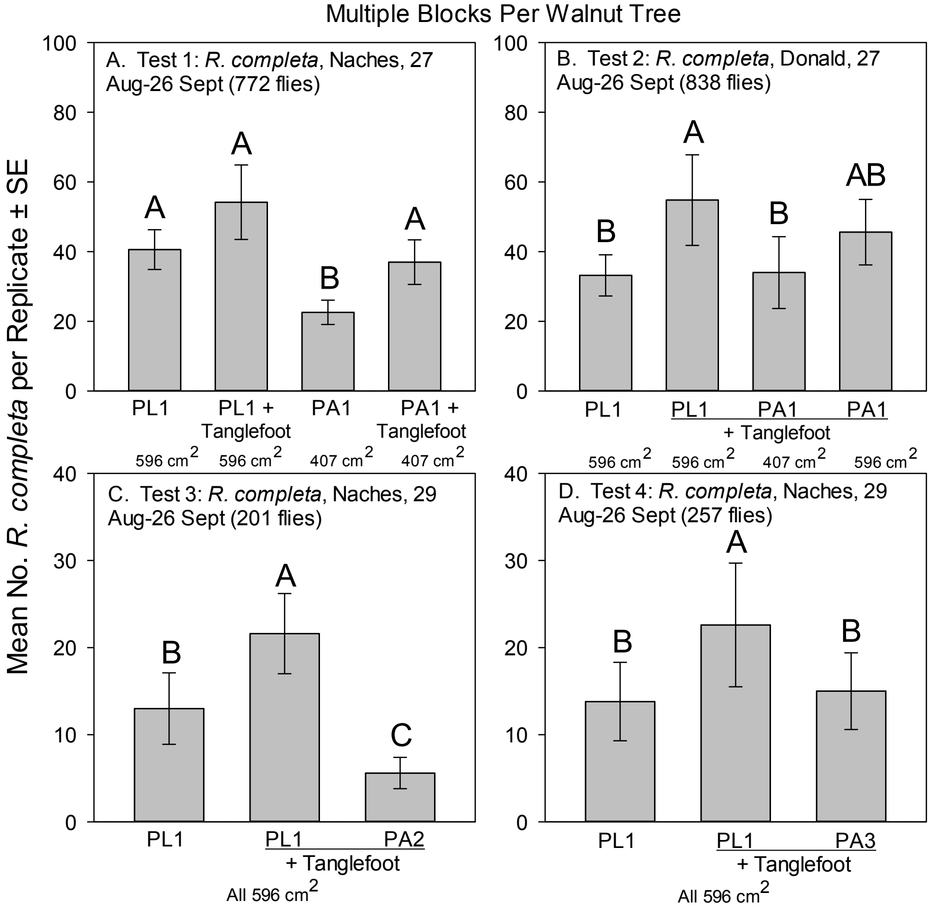

Figure 7. Mean captures of *Rhagoletis completa* (sexes combined) ± SE per replicate in 2014 on PL1 and PL1 + Tanglefoot vs. (A, B) PA1 and PA1 + Tanglefoot; (C) PA2 + Tanglefoot; and (D) PA3 + Tanglefoot. Sticky surface areas are shown below trap types. (A) $F = 12.35$; df = 3, 12; $P = 0.0006$; (B) $F = 8.64$; df = 3, 12; $P = 0.0025$; (C) $F = 19.34$; df = 2, 8; $P = 0.0009$; (D) $F = 7.63$; df = 2, 8; $P = 0.0140$. Means within tests with same letters are not significantly different (Tukey's HSD test, $P > 0.05$).

Table 4

Comparisons of results of Tukey's HSD tests on mean numbers of *Rhagoletis* flies caught on traps unadjusted vs. adjusted for sticky surface area. Letters in front of species indicate different tests. Values in front of adjusted letters are mean flies/cm^2. Means for unadjusted catches are shown in Figs. 2–7. Same letters within columns indicate means of trap treatments are not significantly different ($P > 0.05$).

Five-Trap Comparisons: Five-Tree Blocks

	A. *R. indifferens*		B. *R. indifferens*		C. *R. pomonella*		D. *R. pomonella*	
Trap Type	Unadjusted	Adjusted	Unadjusted	Adjusted	Unadjusted	Adjusted	Unadjusted	Adjusted
PL1 + Tanglefoot	A	0.018A	AB	0.021A	A	0.322A	A	0.266A
PL2 + Tanglefoot	AB	0.008A	A	0.026A	AB	0.229A	AB	0.216AB
PA1	B	0.009A	BC	0.017AB	B	0.228A	CD	0.199CD
PA2	B	0.005A	D	0.005C	C	0.159B	D	0.083D
PA3	AB	0.012A	CD	0.010B	AB	0.296A	BC	0.154BC

Five-Trap Comparisons: Blocks of One Tree Each

	A. *R. indifferens*		B. *R. pomonella*		C. *R. pomonella*	
Trap	Unadjusted	Adjusted	Unadjusted	Adjusted	Unadjusted	Adjusted
PL1 + Tanglefoot	A	1.911A	A	0.096A	A	0.131A
PL2 + Tanglefoot	B	1.430B	AB	0.065B	AB	0.080BC
PA1	C	1.236B	C	0.050B	B	0.091AB
PA2	D	0.580C	D	0.013C	C	0.013D
PA3	C	1.110B	BC	0.051B	B	0.055C

	D. *R. pomonella*		E. *R. completa*		F. *R. completa*	
Trap	Unadjusted	Adjusted	Unadjusted	Adjusted	Unadjusted	Adjusted
PL1 + Tanglefoot	A	0.289A	A	0.678A	A	0.331A
PL2 + Tanglefoot	B	0.199C	A	0.664A	A	0.306A
PA1	C	0.207C	B	0.419B	C	0.219B

Table 4 continued on next page…

Table 4 continued from previous page

PA2	D	0.070D	C	0.167C	D	0.063C
PA3	B	0.235B	A	0.610A	B	0.282A

Five-Trap Comparisons: Multiple Blocks Per Tree

	A. *R. completa*		B. *R. completa*	
Trap	Unadjusted	Adjusted	Unadjusted	Adjusted
PL1 + Tanglefoot	A	0.215A	A	0.626A
PL2 + Tanglefoot	B	0.134AB	AB	0.567AB
PA1	C	0.130B	C	0.385C
PA2	D	0.026C	D	0.110D
PA3	C	0.100B	B	0.508B

PL1 + Tanglefoot vs. PA1 and other traps + Tanglefoot comparisons

A. *R. indifferens*			B. *R. pomonella*		
Trap	Unadjusted	Adjusted	Trap	Unadjusted	Adjusted
PL1 + Tanglefoot	A	4.172AB	PL1	AB	0.116B
PA1 + Tanglefoot	C	2.170C	PL1 + Tanglefoot	A	0.187A
PALz	AB	3.105B	PA1 + Tanglefoot	A	0.134AB
Fly Trap + Tanglefoot	D	1.309D	PA2 + Tanglefoot	B	0.064C
Yellow Ball + Tanglefoot	BC	4.965A	PA3 + Tanglefoot	A	0.201A

PL1 + Tanglefoot vs. PA1 and other traps + Tanglefoot comparisons

C. *R. completa*			D. *R. completa*		
PL1	A	0.068AB	PL1	B	0.056B
PL1 + Tanglefoot	A	0.091A	PL1 + Tanglefoot	A	0.092A
PA1	B	0.055B	PA1 + Tanglefoot	B	0.083A
PA1 + Tanglefoot	A	0.091A	PA1 + Tanglefoot	AB	0.077A

Table 5

Orthogonal contrasts of *Rhagoletis* fly catches adjusted for sticky surface area on traps in a randomized block ANOVA. Letters before the species indicate different tests. **Traps with higher fly catches are in bold.**

Five-Trap Comparisons: Five-Tree Blocks

	A. *R. indifferens*		B. *R. indifferens*		C. *R. pomonella*		D. *R. pomonella*	
Contrasts	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*
PL1 + PL2 + Tanglefoot vs. PA1 + PA2	5.77	0.0288	25.85	0.0001	8.48	0.0102	36.14	<0.0001
PL1 + PL2 + Tanglefoot vs. PA1 + PA3	1.41	0.2531	11.14	0.0042	0.14	0.7092	15.60	0.0011
PL1 + PL2 + Tanglefoot vs. PA2 + PA3[a]	2.41	0.1401	39.44	<0.0001	3.77	0.0698	28.51	<0.0001

Five-Trap Comparisons: Blocks of One Tree Each

	A. *R. indifferens*		B. *R. pomonella*		C. *R. pomonella*	
Contrasts	*F*	*P*	*F*	*P*	*F*	*P*
PL1 + PL2 + Tanglefoot vs. PA1 + PA2	112.40	<0.0001	56.25	<0.0001	35.85	0.0003
PL1 + PL2 + Tanglefoot vs. PA1 + PA3	37.61	<0.0001	15.66	0.0011	8.07	0.0218
PL1 + PL2 + Tanglefoot vs. PA2 + PA3	131.68	<0.0001	58.60	<0.0001	60.38	<0.0001
	D. *R. pomonella*		E. *R. completa*		F. *R. completa*	
Contrasts	*F*	*P*	*F*	*P*	*F*	*P*
PL1 + PL2 + Tanglefoot vs. PA1 + PA2	1,790.44	<0.0001	73.89	<0.0001	117.84	<0.0001
PL1 + PL2 + Tanglefoot vs. PA1 + PA3	49.02	0.0001	3.03	0.1009	12.19	0.0030
PL1 + PL2 + Tanglefoot vs. PA2 + PA3	1,410.31	<0.0001	62.78	<0.0001	86.57	<0.0001

Table 5 continued on next page …

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Five-Trap Comparisons: Multiple Blocks Per Tree

	A. *R. completa*		B. *R. completa*	
Contrasts	*F*	*P*	*F*	*P*
PL1 + PL2 + Tanglefoot vs. PA1 + PA2	24.88	0.0003	148.62	<0.0001
PL1 + PL2 + Tanglefoot vs. PA1 + PA3	7.86	0.0160	19.62	0.0008
PL1 + PL2 + Tanglefoot vs. PA2 + PA3	35.30	<0.0001	105.78	<0.0001

PL1 + Tanglefoot vs. PA1 and other traps + Tanglefoot comparisons

	A. *R. pomonella*		B. *R. completa*		C. *R. completa*	
Contrasts	*F*	*P*	*F*	*P*	*F*	*P*
PL1 vs. **PL1 + Tanglefoot**[b]	5.53	0.0318	4.46	0.0563	12.90	0.0037
PL1 vs. **PA1 + Tanglefoot**[c]	0.65	0.4314	5.03	0.0446	5.01	0.0449
PL1 vs. **PA2 + Tanglefoot**	5.66	0.0302	----	----	----	----
PL1 vs. **PA3 + Tanglefoot**	8.02	0.0120	----	----	----	----

[a]Except for A. *R. indifferens*. [b]Except for B. *R. completa*. [c]Except for A. *R. pomonella*.

DISCUSSION

The plastic rectangles supplemented with Tanglefoot were the most efficacious of the five sticky yellow rectangle traps tested against *R. indifferens*, *R. pomonella*, and *R. completa*. Until recently (Yee 2011, 2014), the PA1 (Pherocon AM) could be assumed to be the most efficacious yellow rectangle against most *Rhagoletis* flies in North America. However, the PA1 had usually been compared with spheres and Ladd traps and not with other yellow rectangles against *R. pomonella* and *R. completa,* as well as the blueberry maggot, *R. mendax* Curran (e.g., Prokopy and Hauschild 1979; AliNiazee *et al*. 1987; Riedl *et al*. 1989; Liburd *et al*. 2001; Teixeira and Polavarapu 2001). In the current study, the PA1 was only more efficacious than the PA2, as it was against *R. cerasi* (Katsoyannos *et al*. 2000). It is unclear whether traits of the PA1 have changed over the years. For this reason, the trap traits documented in Fig. 1 and Table 1 can be useful for future comparisons of traps tested here with other, newer traps.

Based on their superior performance against high *Rhagoletis* populations, the plastic traps + Tanglefoot may be able to detect lower fly populations than all the cardboard traps tested here, perhaps making them better options for monitoring. Plastic and cardboard traps cost about the same (~U.S.$1.10 per trap; cost of 10 g TF per trap is ~9 cents), but have the advantage of not fading over the season, as can the PA2 and PA3 (W. L. Y., personal observations). There are, however, several disadvantages to the plastic traps. One is that they are thinner and lighter, so are more prone to flap in heavy winds. This sometimes causes them to tear loose from branches; however, this can be prevented by securing the traps to branches using three ties instead of one. Another disadvantage is that, as currently manufactured, plastic traps would need to be supplemented with Tanglefoot. Thus, caution should be taken when deciding which traps to use, because overall trap catch is not always necessarily the deciding factor in selecting an 'optimal' trap for monitoring purposes. Traps need only be effective enough to provide a consistent, reliable 'sample' or estimate of a population, with minimal cost and time in servicing.

All traps generally caught more females than males, consistent with findings for *R. mendax* (e.g., Liburd *et al*. 2001; Teixeira and Polavarapu 2001). Other studies showed that 46%, 57%, and 50% of *R. indifferens*, *R. pomonella*, and *R. completa* that emerged from soil under cages, respectively, were females (Frick *et al*. 1954; Dean and Chapman 1973; Boyce 1934). Because females comprised 55–69% of trap catches here, the traps may be slightly biased towards females, suggesting males may be less attracted to yellow rectangles than females.

The major objective here was to identify the most efficacious of five commercial sticky yellow rectangles against flies, but a secondary objective was to determine which factors might affect their efficacies. Differences in sticky surface areas, color, translucence, and adhesive type make identifying factors responsible for the greater efficacies of the PL1 and PL2 + Tanglefoot vs. the PA1, PA2, and PA3 (Figs. 2–4) difficult, but there are at least three possible factors. One is that the sticky surface areas of the plastic traps were larger; however, analyses of catches per sticky area suggest this was of minimal importance for all three species. A second possible factor is that all three fly species were most stimulated visually by color and other cues in the plastic traps. The third possible factor is that supplementing the plastic traps with Tanglefoot increased their efficacy either by making them tackier due to composition or amount or by altering their visual properties.

Results comparing the PL1 and PA1 both with Tanglefoot and with equal sticky surface areas against *R. indifferens* in 2015 suggest that Tanglefoot did not cause the greater efficacy of the PL1 + Tanglefoot vs. the PA1 against *R. indifferens* in 2014 tests. More likely, the yellow color and translucence of the PL1 caused this (Yee 2014). The PL1 + Tanglefoot was also better than two non-rectangle traps with Tanglefoot for catching high numbers of *R. indifferens*, further suggesting traits of the PL1 itself independent of Tanglefoot were responsible for its high efficacy. Perhaps not coincidentally, the PaLz trap was plastic and also performed well.

In contrast to results for *R. indifferens*, Tanglefoot on the PL1 appeared responsible for the higher efficacy of the PL1 + Tanglefoot vs. the PA1 against *R. pomonella* and *R. completa*, based on tests where sticky surface areas were equal. Tanglefoot may be tackier and/or had a lower viscosity than the adhesive on the PA1, making flies stick faster. Less likely, it increased the visual attractiveness of the trap. Polybutene is the active ingredient in Tanglefoot (Contech 2014) and presumably also in the adhesive on the PA1 (exact chemical compositions of the adhesives are unpublished). Even though both adhesives are clear or slightly cloudy, particular polymers, grade, or amount of polybutene in Tanglefoot and other adhesives probably differ.

Supplementing the PA2 and PA3 with Tanglefoot resulted in variable outcomes for *R. pomonella* and *R. completa*. For both flies, Tanglefoot was not a factor in why the PL1 + Tanglefoot performed better than the PA2. The distinct reflectance/color of the PA2 (Fig. 1F) may simply have been less attractive. In contrast, for *R. pomonella*, the PL1 + Tanglefoot appeared better than the PA3 solely because of the Tanglefoot. Traits of the PA3, PL1, and PA1 thus may be similarly attractive to *R. pomonella*. However, for *R. completa*, the PL1 + Tanglefoot caught more flies than the PA3 + Tanglefoot, so traits of the PL1 may have been more attractive for this species, although more tests are needed to confirm this.

In summary, results suggest the plastic rectangles + Tanglefoot tested here are better than standard cardboard rectangles for capturing high numbers of all three *Rhagoletis* species. This implies these should be the rectangles of choice for monitoring these species. The efficacy of some cardboard rectangles tested against *R. pomonella* and *R. completa* but not against *R. indifferens* may be increased simply by using an alternative or more adhesive. This suggests similar trap efficacies against the three species may have different underlying causes, which if true has implications for the development of more species-specific and efficacious traps.

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