The impact of codling moth (Lepidoptera: Tortricidae) mating disruption on apple pest management in Yakima Valley, Washington

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ABSTRACT

From 1991 to 1993, pheromone-based mating disruption for control of codling moth, *Cydia pomonella* (L.)was evaluated in seven apple orchards. Each pheromone-treated orchard was paired with a similar orchard without pheromone. Populations of codling moth, secondary pests, and selected natural controls were monitored. The cost of using pheromone dropped nearly $100 per ha from 1991-1993 because of reductions in the price of dispensers and improved application. Growers saved $87-147 in insecticides per ha in pheromone-treated orchards, because of an 83% reduction in sprays for codling moth, but savings from reduced labor and machinery costs in treated orchards were minimal. Damage from codling moth was high in one treated orchard in 1991 (7.4%), and increased to 20.8% in 1992. The population density of codling moth was low in the other orchards (fruit injury < 0.4%) in all three years. Insecticide applications after petal-fall for secondary pests were reduced by 18% in treated orchards. Populations of secondary pests were similar between orchard pairs. Among natural controls only parasitism of leafminers differed significantly between treated and untreated orchards. In 1991, leafrollers caused > 3% fruit injury in three of seven treated orchards, but were not a problem thereafter. Substituting mating disruption for insecticides to manage codling moth in apple orchards may therefore be successful, but for the first three years, may not substantially improve biological control of secondary pests.

Key words: *Cydia pomonella*, apple, mating disruption

INTRODUCTION

Apples are identified by the public in the United States as a wholesome food (Washington State Apple Commission 1993), yet they are one of the crops most heavily sprayed with pesticides (Pimental *et al.* 1992). Increased public awareness and changes in social attitudes towards exposure to pesticides (Ott *et al.* 1991) are forcing a reconsideration of existing pest management programs in tree fruits (Prokopy & Croft 1994). In the western U.S., codling moth, *Cydia pomonella* (L.) is the key pest of apples. Conventionally-managed orchards rely on a series of 'cover sprays' during the season (Washington State University Cooperative Extension Service 1992). Organophosphate insecticides have been used almost exclusively for codling moth during the last 35 years, but resistance has recently been documented (Varela *et al.* 1993, Knight *et al.* 1994a).

Much of the effort to transform apple pest management in the western United States from broadspectrum pesticides to more biointensive methods has focused on using sex pheromones to disrupt mating of codling moth. Since the registration of a multicomponent polyethylene tube pheromone dispenser in 1991, successful field trials have been reported by Barnes *et al.* (1992) and Pfeiffer *et al.* (1993). Researchers continue to evaluate mating disruption of codling moth and to optimize its efficacy and cost (Knight 1992). Yet the effect of adopting this technology on the complex of secondary pests and natural enemies in apple orchards is unclear. A three year study was conducted from 1991 to 1993 to evaluate the use of polyethylene tube dispensers in commercial apple orchards in the Yakima Valley. The objectives of this study were to evaluate the effect of mating disruption on: 1) the control of codling moth; 2) growers' spray schedules and cost of pest management; and 3) the population densities of some other pests and their natural enemies compared with similar orchards not treated with pheromone.

MATERIALS AND METHODS

Study Sites. Seven apple growers near Yakima treated a portion of their orchards in 1991 with 1,000 translucent polyethylene tube dispensers (Isomate-C^R, Pacific Biocontrol, Davis, CA) per ha for codling moth. The dispensers were loaded with an average of 171 mg active ingredient of (E,E)-8,10-dodecadien-1-ol, 1-dodecanol, and 1-tetradecanol (63:31:6 blend); plus 13% inert ingredients (UV inhibitors and antioxidants). Each year, a single application of dispensers was applied in orchards before the moths emerged (third week of April to early May).

Each grower's pheromone-treated orchard was paired with another without pheromone (designated as untreated). Paired orchards were matched for similar area, cultivar, tree size, and planting density and represented typical horticultural practices, including the use of insecticides, for this region (Table 1). Borders of paired orchards were usually separated by 100 to 200 m. Pest management advice was provided by farm managers and fieldmen from a local chemical supply company.

Table 1

Apple orchards treated with pheromone dispensers for codling moth from 1991 to 1993. Each was paired with a similar untreated orchard

Orchard	Area treated (ha) 1991-1993[a]	Cultivars	Trees / ha	Mean tree height (m)
Y1	7.3-2.0	Rome & Granny Smith	598	3.5
Y2	7.0-7.0	Red Delicious & Golden Delicious	633	4.1
Y3	2.5-2.5	" " " "	527	3.6
Y4	6.5-6.5	" " " "	269	4.4
Y5	4.0-2.0	" " " "	664	3.8
Y6[b]	8.0	" " " "	332	2.9
Y7[c]	7.3	" " " "	427	3.9

[a] Area treated with pheromone in 1991 and 1993.
[b] Orchard Y6 was in the study from 1991-1992.
[c] Orchard Y7 was in the study only in 1991.

Evaluation of Costs. Costs associated with the pheromone dispensers were assessed by interviewing growers. Besides the growers in this study, 10 others using mating disruption were interviewed. The costs included the dispensers and labor ($6 per hr). Costs of insecticides were obtained from a local chemical supply company. Sprays applied only to orchard borders were counted as 0.2 and alternate-row middle sprays (every other row was sprayed) were treated as 0.5 of a full application.

Sampling Pests and Natural Enemies. Population densities of various pest and beneficial insects were monitored in each orchard. These included: adult codling moth; a complex of green aphids, viz. *Aphis pomi* DeGeer, *Rhopalosiphum fitchii* (Sanderson), and *Aphis spiraecola* Patch; white apple leafhopper, *Typhlocyba pomaria* McAtee and its mymarid parasitoid, the *Anagrus* wasp; western tentiform leafminer, *Phyllonorycter mespilella* (Hübner), and associated parasitoids; and larval populations of the leafroller moth, *Pandemis pyrusana* Kearfott. Sampling dates were chosen to coincide with periods of peak population densities of each pest. Fruit injured by codling moth and *P. pyrusana* was sampled at mid-season and just before harvest.

Sampling protocols varied between years. All orchards were divided into four sections in 1991 and five sections (four edges and the middle of the orchard) in 1992-93. Edges were designated as the outer 20 m of the orchard. Trees, shoots, and leaves were sampled randomly along transects within each section.

Green Aphids. Green aphids were sampled by counting the number of aphids on the most infested leaf per shoot (Hull & Grimm 1983). In 1991 they were counted on five shoots from 10 trees within each section from 14-22 August. During the next two years, they were sampled by counting the number of aphids on the most infested leaf per shoot from five shoots on 12 trees per section. Sample dates were 28-29 July, 1992 and 1-3 July, 1993, respectively. Five density classes were established: **1** = 0 aphids; **2** = 1-25; **3** = 26-100; **4** = 101-250; and **5** = > 250 aphids. The total number of generalist predators per shoot was also recorded.

Leafhoppers. Adult white apple leafhopper and *Anagrus* sp. adults were sampled with sticky yellow cards (22.7 x 27.7 cm) (Trece Inc., Salinas, CA). The traps were placed at 2.0 m height in the tree canopy and were retrieved after 6-10 d. Five traps were placed in each section from 1-8 July, 1991. Five traps were again placed in each orchard during both adult flights 3-5 June and 4 September, 1992 and 17 June and 25-27 August, 1993. Results were recorded as the mean number of adult leafhoppers and parasites caught per day per trap.

Leafminers. The density of immature leafminers was sampled in each orchard in 1991 on 15-19 July and 14-21 August by counting the number of mines on the third leaf down the shoot from the leaf visually selected. In each section, five leaves were sampled per tree from 10 trees. Levels of parasitism were assessed for each generation by dissecting 20 mines per section. Parasitism of first generation mines was assessed on 11-12 June. In 1992, leafminers were sampled on 2-7 July and 23-29 September, by counting the number of recent mines per leaf on 10 leaves per tree on 20 trees. Levels of parasitism were assessed on 21-29 May, 8-9 July and 3 September by dissecting 100 mines per orchard. The number of first generation mines in 1993 was too low to assess percent parasitism. The protocol from 1992 was used to assess leafminer density and parasitism on 3-4 August and 25-26 August, 1993. In all three years, host feeding was included as a part of total parasitism (Barrett & Brunner 1990).

Leafrollers. Larval populations densities were estimated by counting the number of rolled leaves per 1 minute of searching 20 trees per section from 12-14 June and 28-30 July, 1991. Sampling during 1992 and 1993 consisted of examining 40 terminal shoot tips (20 from the top and 20 from the bottom of the canopy) from 20 trees on 12-15 May and 9-14 July, 1992 and 20 May, 1993, respectively.

Codling Moth. Two pheromone-baited traps (Scentry Inc., Buckeye, AZ) were placed in each section (separated by > 50 m) to monitor adult codling moth in 1991. One was baited with a red rubber septum loaded with 1 mg and the other with a septum loaded with 10 mg codlemone (Trece Inc., Salinas, CA). The septa were replaced every 4 weeks and type of septum was alternated between traps in each section. Traps at a density of one per 1.0-2.0 ha were placed in each orchard during 1992 and 1993. All traps in pheromone-treated orchards were baited with septa loaded with 10 mg of codlemone; traps in untreated orchards had 1 mg septa. Septa were replaced every 3 weeks. Trap liners were replaced as needed.

Fruit Injury. Percent fruit injured by codling moth in 1991 was assessed on 2-3 July and for both *P. pyrusana* and codling moth prior to harvest (3-10 d) of each major cultivar ('Golden Delicious' from 10-20 September and 'Red Delicious', 'Rome' and 'Granny Smith' from 2-9 October). Fruit injury was sampled in mid-season and at harvest along ten transects (examining 20 fruits from five consecutive trees) per section (or 4,000 fruits per orchard).

Mid-season fruit injury in 1992 was assessed on 19-30 June and injury prior to harvest from 3-17 September. Mid-season injury was sampled by visually inspecting from the ground 30 fruits high and 30 fruits low in the canopy of 100 trees (estimated to be equivalent to 6,000 half-fruits). Injury at harvest was measured by manually examining 15 fruits per height from 10 trees per section (1,500 fruits per orchard).

Injury was sampled in 1993 mid-season from 18-23 June and prior to harvest on 11 September for 'Golden Delicious' and 23 September for late cultivars. On all three sampling dates, 15 fruits were manually examined at both heights from 10 trees per section (1,500 fruits per orchard). Fruit injury was weighted by the percentage of each cultivar in the orchard.

Statistical Analysis. Aphid density classes in pheromone-treated and untreated orchards were compared on each date with Wilcoxon Signed Rank test (Hintze 1987). Means from all other counts were compared between treatments on each date using a paired t-test.

RESULTS

Cost of Using Pheromone. Costs varied among the seventeen growers interviewed depending on the way the dispenser was attached to the tree. The lowest cost (mean ± SE) was for dispensers applied by hand from the ground (n=5, \$27 ± 7 / ha). However, in 1991 most growers (n=9) used ladders to apply dispensers in the upper third of the canopy. This method was the most expensive (\$69 ± 10 / ha) and was disliked by many growers because of the risk to workers. Workers of other growers applied dispensers from trailers pulled through the orchard by a tractor (n=3, \$35 ± 5 / ha). With each method, costs were highest in orchards where growers trained their workers carefully and monitored their work. Beginning in 1992, many growers tied the dispensers onto plastic clips (Series W, No. 6, Kwik Lock Corp., Yakima, WA) and used a telescoping pole to attach dispensers at the recommended height in the canopy. The average cost of this method (\$38 ± 4 / ha) was similar to the use of trailers, but allowed growers greater flexibility in placing dispensers. The cost of the dispensers declined during this study from \$326 / ha in 1991 to \$272 / ha in 1993.

Insecticide Usage. The number of sprays applied for codling moth in orchards treated with pheromone during this three-year study was 83% lower than in the untreated orchards (Table 2). The use of insecticides for codling moth in the pheromone-treated orchards was highest in 1992 as more growers either sprayed borders or supplemented their use of pheromone. In 1993, three growers applied a single insecticide spray to the border of their pheromone-treated orchards.

Table 2

Spray records and cost of insecticides in paired orchards treated with and without codling moth sex pheromone,1991-1993,YakimaValley,WA

	Mean number of sprays applied per orchard					
	1991		1992		1993	
Pest	Pheromone	None	Pheromone	None	Pheromone	None
Codling moth	0.5	3.0	0.9	2.8	0.1	3.8
Leafrollers[a]	0.9 (0.4)	1.1 (0)	0.4 (0.3)	0.8 (0)	0.6 (1.0)	0.6 (0.7)
Leafminers	0.0	0.1	1.0	1.3	0.0	0.0
Aphids and leafhoppers	1.5	2.4	2.2	2.5	2.6	2.6
Mites	0.1	0.1	0.2	0.3	0.2	0.2
General	1.0	1.0	1.0	1.0	1.0	1.0
Mean cost ($)[b]	194.64	282.30	243.54	345.06	202.79	349.75

Materials used (/ ha) included: Guthion 50W (1.7-2.2 kg) and Imidan 50W (5.6-6.6 kg) for codling moth; Lorsban 50W (3.4 kg) and Penncap-M 2F (7.0-9.3 liter)for leafrollers; Vydate 2L (0.6-2.3 liter) for leafminer; Phosphamidon 8E (0.6-0.9 liter), Sevin XLR (1.2-1.8 liter) Thiodan 50WP (2.2-4.4 kg), Meta-Systox R 2E (3.5 liter), Phosdrin 4E (0.6 liter), Pyrellin (2.3 liter), Lannate 1.8L (0.6 liter), and Methoxychlor 50W (4.7 liter) for aphids and leafhoppers; Omite 30W (6.7-8.4 kg) for mites; and Lorsban 4E (4.7 liter) for general pests. Sprays applied to borders counted as 0.2; sprays applied to alternate row middles counted as 0.5.

[a] Mean number of sprays of Dipel 2X (1.1 kg) / ha for leafrollers in parentheses.

[b] Mean cost is the total retail cost of all insecticides used during the season.

Insecticides were applied for other pests in orchards both with and without pheromone (Table 2). Nearly all orchards in 1991 were sprayed during the summer for leafrollers. During the second year, growers switched from chlorpyrifos to encapsulated methyl-parathion to control leafrollers and fewer orchards were treated (Table 2). Following widespread bee poisoning from summer use of insecticides for leafrollers in 1992 (M. Willett, personal communication) the use of products containing *Bacillus thuringiensis* Berliner increased in 1993. All orchards were treated with 1 or 2 applications of insecticide for leafminer in 1992. Insecticides were widely used to control green aphids and leafhoppers during all three years of this study. Only 2 or 3 orchards were sprayed for mites each year (Table 2).

The mean cost of insecticide materials per ha was higher in the untreated than in the pheromone-treated orchards each year, i.e. $87 more in 1991, $101 in 1992, and $147 in 1993 (Table 2). However, there were minimal savings from reduced operating costs in pheromone-treated versus untreated orchards because of the application of materials other than insecticides during the season (growers commonly mixed several insecticides, mineral supplements, herbicides, or fungicides together). No change was observed in the rates of chemicals used between orchard-pairs.

Aphids. The population density of green aphids varied from year to year and no significant difference was found between orchards with and without pheromone on the selected dates (Table 3). Few generalist predators were found in samples during 1991 and 1992 (< 1.0% of shoots had ≥ 1 predator), and no difference in their population density was found between orchard pairs (Table 4). However, in 1993, 4.3% of the shoots in the pheromone-treated orchards had ≥ 1 predator compared with 0.7% in the untreated orchards ($p = 0.10$). The most abundant predators were immature chrysopids, immature and adult coccinelids, immature syrphids, and adult hemipterans.

Table 3

Mean (± SE) population densities of some secondary pests in pheromone-treated and untreated apple orchards

		1991		1992		1993	
Pest sample	Generation	Pheromone	None	Pheromone	None	Pheromone	None
Mean density class: green aphids / most infested shoot[a]	-	1.22(0.07)	1.23(0.06)	2.45(0.38)	2.50(0.28)	1.93(0.34)	1.76(0.29)
No. leafhopper adults	1st	38.7(11.8)	31.8(7.0)	47.6(7.9)	88.0(30.1)	46.7(18.3)	64.5(40.9)
per sticky trap	2nd	-	-	86.8(33.4)	121.8(42.5)	14.2(17.7)	6.5(8.7)
No. leafminer larvae	2nd	0.19(0.06)	0.19(0.05)	5.44(1.64)	4.74(1.33)	0.22(0.10)	0.21(0.08)
per leaf	3rd	0.48(0.19)	0.33(0.11)	3.23(1.38)	2.50(0.80)	0.57(0.30)	0.96(0.49)
No. leafroller larvae	1st	0.02(0.00)	0.06(0.4)	0.00	0.00	0.00	0.00
per shoot sample	2nd	0.11(0.04)	0.07(0.02)	0.00	0.00	0.00	0.00
% leafroller injury	-	3.00(1.63)	0.8(0.35)	0.14(0.06)	0.09(0.05)	0.08(0.08)	0.04(0.04)

Differences in aphid density ranks ($p > 0.05$, Wilcoxon Signed Ranks test) and other samples ($p > 0.05$, paired t-tests) not significant in any year between orchard types.

[a] Aphid density classes: 0 aphids = 1; 1-25 = 2; 26-100 = 3; 100-250 = 4; and > 250 aphids = 5.

Table 4.

Mean (± SE) population densities of some natural enemies in pheromone-treated and untreated apple orchards

		1991		1992		1993	
Natural enemy sample	Generation	Pheromone	None	Pheromone	None	Pheromone	None
% shoots with aphid predators	-	0.71(0.62)	0.85(0.42)	1.73(0.61)	2.21(0.70)	4.34(1.83)	0.67(0.40)
No. adult *Anagrus*	1st	0.07(0.01)	0.10(0.07)	0.65(0.49)	0.34(0.28)	0.46(0.19)	0.44(0.24)
/ sticky trap	2nd	-	-	0.000.00	1.26(1.04)	0.26(0.21)	
% parasitism of	1st	30.9(3.9)a	17.6(3.9)b	6.2(2.9)	2.8(0.8)	-	-
leafminer larvae	2nd	27.1(10.3)	21.2(9.0)	5.8(3.2)	0.7(0.5)	19.5(6.8)	11.2(3.7)
	3rd	42.9(9.3)	33.8(10.1)	15.0(8.4)	13.8(5.8)	27.5(8.8)a	12.2(5.5)b

Means within year for each generation followed by different letters are significantly different, $p < 0.05$, paired t-test.

Leafhoppers. Population densities of white apple leafhoppers were not significantly different between pheromone-treated and untreated orchards (Table 3). However, there was weak evidence ($p = 0.09$) of a reduced population density of second generation adults in 1992 in the pheromone-treated orchards. In general, there were fewer leafhoppers in pheromone-treated than untreated orchards during 1992 and 1993 (Table 3).

Few *Anagrus* sp. were caught on sticky traps and numbers varied among orchards (Table 4). On two dates (first generation in 1992 and second generation in 1993) the density of this parasitoid was 1.8-4.1 times higher in the pheromone-treated than in untreated orchards, but these differences were not significant (Table 4). The ratio of adult parasites to leafhopper adults on traps on these two dates was also higher (4.2-6.7 times) in the treated than in the untreated orchards, but these differences were not significant ($0.20 < p < 0.30$). During the second generation in 1992, no adult parasites were found on sticky traps (Table 4).

Leafminers. The mean number of mines per leaf was low in all orchards in 1991 and their density only exceeded 1 mine per leaf in two pheromone-treated orchards during the third generation (Table 4). In contrast, populations were high (> 3 mines per leaf during second generation) in all but one pair of orchards 1992, and orchards were sprayed at least once with insecticide (Table 2). Leafminer populations were low in all orchards during 1993.

Levels of parasitism of leafminers were higher in treated than untreated orchards, but the difference was only significant on two dates, first generation in 1991 and the third generation in 1993 (Table 4). Levels of parasitism were low in all orchards during 1992.

Table 5

Catches of codling moths and fruit injury at harvest in-pheromone-treated and untreated orchards

		Mean moths / trap / season			% fruit injury		
Orchard	Treatment[a]	1991	1992	1993	1991	1992	1993
Y1	pheromone	1.0	4.0	0.0	0.00	0.16	0.00
	none	16.0	6.5	0.0	0.25	0.08	0.10
Y2	pheromone	0.0	0.0	0.0	0.10	0.00	0.00
	none	0.0	1.0	0.0	0.15	0.00	0.00
Y3	pheromone	3.0	5.5	0.0	0.25	0.17	0.05
	none	20.3	76.0	17.5	0.20	0.00	0.00
Y4	pheromone	1.0	0.5	0.0	0.0	0.00	0.00
	none	1.0	2.0	0.0	0.0	0.00	0.00
Y5	pheromone	0.3	1.0	1.0	0.40	0.00	0.33
	none	1.8	6.0	7.5	0.15	0.00	0.00
Y6	pheromone	0.9	68.5	-	7.43	20.82	-
	none	14.5	150.0	-	0.42	0.17	-
Y7	pheromone	0.3	-	-	0.00	-	-
	none	5.0	-	-	0.00	-	-

[a] Traps in pheromone-treated and untreated orchards were baited with 10 mg and 1 mg lures, respectively.

Leafrollers. Leafroller larvae were found overwintering in nearly all orchards in 1991 after the application of the delayed-dormant insecticide (Table 3). Fruit injury at harvest was greater than 3% in three orchards. No larvae were found in shoot terminal samples in 1992 and 1993, and fruit injury at harvest was low and restricted to two orchards during these two years (Table 3).

Codling Moth. Traps baited with 10 mg codlemone in 1991 caught 2.1 times more moths than those baited with 1 mg in treated orchards. In contrast, traps baited with 1 mg in the untreated orchards caught 1.4 times more moths than traps baited with the 10 mg lure. Cumulative trap counts were low in all orchards in 1991, but increased in the untreated Y3 and both Y6 orchards in the second year (Table 5). Catches were low in all orchards in 1993.

Levels of codling moth injury to fruit after the first generation in 1991 were low (<0.1%) in all orchards except in the pheromone-treated Y6 orchard. At harvest, injury in Y6 increased to 7.4% (Table 5). Cumulative moth catches per trap did not reflect this high level of injury (Table 5). Levels of injury were ≤0.4% at harvest in all other pheromone-treated and untreated orchards. Injury increased nearly three-fold in the pheromone-treated Y6 orchard in 1992. Damage in this orchard, as in 1991, was primarily restricted to one edge of the orchard reaching about 65%. In 1992 and 1993, injury was low in all other orchards, <0.35% at harvest (Table 5).

DISCUSSION

Use of pheromones to disrupt mating of codling moth was effective in six of the seven apple orchards monitored from 1991 to 1993. In these orchards, the densities of codling moth remained low and use of insecticides for this pest was significantly reduced. The poor control of codling moth in orchard Y6 can be explained. This orchard had a previous history of codling moth injury and the density of the overwintering population in 1991 was unknown. In 1991, the pheromone was applied at a half rate (500 dispensers per ha) along the northeastern edge of the orchard by mistake. A number of physical characteristics found in this area of the orchard also reduced the effectiveness of mating disruption: a large number of missing trees (no pheromone was applied in areas with missing trees), an uneven canopy with tree heights ranging from 2.5 - 5.0 m, and a 6% slope.

The adoption of mating disruption of codling moth by growers is currently limited by its high material cost relative to the use of insecticides (Williamson *et al.* 1994). Further adoption will be enhanced by factors that can lower the cost of application, the cost of the dispensers, and/or the cost of supplementary insecticides applied for codling moth and other secondary pests. Dispenser application costs are likely to be high for any tie-on technique, and the need for applying dispensers in the upper canopy (Weissling & Knight, in press) will add to this cost. However, use of the telescoping pole and plastic clip has lowered the cost of application and improved placement. Nevertheless, alternative methods for using pheromones in tree fruits should be investigated. Broadcast application of dispensers has been tested previously for codling moth (Moffitt & Westigard 1984), and is used commercially for pink bollworm, *Pectinophora gossypiella* (Saunders) where labor costs are high (Brooks *et al.* 1979). Expectations of growers (Alway 1991) and researchers (Barnes *et al.* 1992) that the adoption of mating disruption for codling moth will reduce insecticide use for other pests and enhance the role of biological control in tree fruits, were not met in this study. Less use of insecticides for secondary pests would add to the benefits of adopting mating disruption. For example, elimination of a single spray in a 'Delicious' orchard would save on average $71 per ha (Hinman *et al.* 1992). Results from this study, however, showed that growers in the Yakima Valley continued to spray for secondary pests in pheromone-treated orchards, especially for aphids and leafrollers. Moreover, the potential saving from fewer spray applications for codling moth was reduced by the continued need to apply other farm chemicals on the same dates.

Conversely, the balance between pests and natural enemies expected in apple orchards not sprayed with insecticides for codling moth was not found in this study. The outbreak of leafminers in all orchards in 1992 demonstrated the cyclic failure of biological control for this pest and forced the growers to spray an insecticide disrupting the natural enemies of leafminers and leafhoppers (Table 4). Severe injury to fruit by leafrollers in 1991 caused growers to treat orchards with summer applications of organophosphates in subsequent years, even when pest populations were low. It is unlikely that natural enemies can control pest populations in orchards sprayed with broadspectrum insecticides nor can they respond quickly to pest outbreaks in small, isolated pheromone-treated orchards surrounded by sprayed orchards. Sustained biological control in tree fruit pest management evidently depends on the registration of non-disruptive tools for these sporadic and secondary pests.

The level of biological control possible in apple orchards in the Yakima Valley can probably be seen best in certified organic orchards. Organic orchards cannot be treated with organophosphate, carbamate, pyrethroid, or other synthetic insecticides (Washington State Department of Agriculture 1992). During 1990, pest and natural enemy populations were surveyed in five paired organic and conventional orchards (Knight 1994). Organic orchards had significantly lower populations of aphids and leafminers than conventional orchards, and significantly higher populations of natural enemies of green aphids, leafminers, and leafhoppers. In 1990, leafrollers were not a problem in any of these orchards. However, fruit injury from codling moth was much higher at harvest in organic (0.3-32.0%) than in conventional orchards (0.1-0.9%). Mating disruption was not available in 1990 and organic growers used a seasonal average of 14 botanical and microbial insecticide sprays for codling moth (Knight 1994).

Empirical analysis of these data from 1990-1993 from organic and conventional apple orchards indicates that a combination of these programs could be adopted to reduce the use of broad-spectrum insecticides and enhance the role of biological control. Mating disruption could be used to manage codling moth, and other pests could be managed either early in the season or growers could use biological control and a limited number of selective insecticides. Development, demonstration, and validation of this approach are needed in representative orchards in the Yakima Valley, as well as in each of the other major fruit producing regions in the western United States.

ACKNOWLEDGEMENTS

I thank John Turner and numerous summer field assistants at the USDA-ARS Laboratory, Yakima, WA, who conducted these studies and collected the data. I also thank the growers for their cooperation. This work was conducted with frequent and useful consultation with Larry Gut and Jay Brunner, Washington State University, Wenatchee, WA. Mike Willet, Washington State University, Yakima, WA contributed many useful ideas to this project. I also acknowledge the critical comments of an earlier draft by Bruce Barrett, University of Missouri, Columbia, MO, Larry Hull, Penn State University, Biglerville, PA, and Gary Judd, Agriculture Canada, Summerland, British Columbia. This work was conducted with support from the Washington Tree Fruit Research Commission.

REFERENCES

Alway, T. 1991. A grower's perspective. Proc. WA Hort. Assoc. 87: 204.

Barnes, M. M., J. G. Millar, P. A. Kirsch & D. C. Hawks. 1992. Codling moth (Lepidoptera: Tortricidae) control by dissemination of synthetic female sex pheromone. J. Econ. Entomol. 85: 1274-1277.

Barrett, B. A. & J. F. Brunner. 1990. Types of parasitoid-induced mortality host stage preferences, and sex ratios exhibited by *Pnigalio flavipes* (Hymenoptera: Eulophidae) using *Phyllonorycter elmaella* (Lepidoptera: Gracillariidae) as a host. Environ. Entomol. 19: 803-807.

Brooks, T. W., C. C. Doane & R. T. Staten. 1979. Experience with the first commercial pheromone communication disruptive for suppression of an agricultural pest, pp. 375-388. *In* F. J. Ritter (ed.), Chemical ecology: odour communication in animals. Elsevier, Amsterdam.

Brunner, J. F., L. J. Gut & A. L. Knight. 1992. Transition of apple and pear orchards to a pheromone-based pest management system. Proc. WA Hort. Assoc. 88: 169-175.

Hinman, H. R., P. Tvergyak, B. Peterson & M. Clements. 1992. 1992 estimated cost of producing Red Delicious apples in central Washington. Washington State Univ. Publ. EB1720. 12 pp.

Hintze, J. L. 1987. Number cruncher statistical system. V. 5.01. Kaysville, UT. 286 pp.

Howell, J. F. 1992. Two years of commercial use of Isomate-C to disrupt mating for control of codling moth. Proc. WA Hort. Assoc. 88: 176-181.

Hull, L. A. & J. W. Grimm. 1983. Sampling schemes for estimating populations of the apple aphid, *Aphis pomi* (Homoptera: Aphididae) on apple. Environ. Entomol. 12: 1581-1586.

Knight, A. L. 1992. New dimensions in mating disruption of codling moth. Proc. WA Hort. Assoc. 88: 166-168.

Knight, A. L. 1994. Population densities of pests and natural enemies in paired organic and conventional apple orchards in the Yakima Valley, Washington. J. Entomol. Soc. Brit. Columbia 91: 27-36.

Knight, A. L., J. F. Brunner & D. Alston. 1994. Survey of azinphosmethyl resistance in codling moth in Washington and Utah. J. Econ. Entomol. 87: 285-292.

Moffitt, H. R. & P. H. Westigard. 1984. Suppression of the codling moth (Lepidoptera: Tortricidae) population on pear in southern Oregon through mating disruption with sex pheromone. J. Econ. Entomol. 77: 1513-1519.

Ott, S. L., C. L. Huang & S. K. Misra. 1991. Consumers' perception of risk from pesticide residues and demands for certification of residue-free produce. pp. 175-188. *In* J. A. Caswell (ed.) Economics of food safety. Elsevier, New York.

Pfeiffer, D. G., W. Kaakeh, J. C. Killian, M. W. Lachance & P. Kirsch. 1993. Mating disruption for control of damage by codling moth in Virginia apple orchards. Entomol. Exp. Appl. 67: 57-64.

Pimental, D., H. Acquay, M. Bittonen, P. Rice, M. Silva, J. Nelson, V. Lipner, S. Giordano, A. Horowitz & M. D'Amore. 1992. Environmental and economic costs of pesticide use. BioScience 28: 778-784.

Prokopy, R. J. & B. A. Croft. 1994. Tree fruit pest management, pp. 214-231. *In* R. L. Metcalf & W. H. Luckman (eds.) Introduction to pest management. John Wiley & Sons, NY.

Varela, L. G., S. C. Welter, V. P. Jones, J. F. Brunner & H. Riedl. 1993. Monitoring and characterization of insecticide resistance in codling moth (Lepidoptera: Tortricidae) in four western states. J. Econ. Entomol. 86: 1-10.

Washington State Apple Commission. 1993. Gallup poll on consumer attitudes toward Washington State apples. Wenatchee, WA. 18 pp.

Washington State Department of Agriculture. 1992. Certification of organic foods. RCW 15.86.060.

Washington State University Cooperative Extension Service. 1992. Spray guide for tree fruits in eastern Washington. Washington State Univ. Ext. Bull. 0419. 156 pp.

Williamson, E. R., R. J. Follwell, A. Knight & J. F. Howell. 1994. Economic analysis of codling moth control alternatives in apple orchards. WA State Coop. Ext. EB 1789. 12 pp.

Weissling, T. J. & A. L. Knight. 1995. Vertical distribution of codling moth adults in pheromone-treated and untreated plots. Entomol. Exp. Appl., in press.