Commercial trials of pheromone-mediated mating disruption with Isomate-C® to control codling moth in British Columbia apple and pear orchards

GARY J.R. JUDD, MARK G.T. GARDINER and DON R. THOMSON[1]

AGRICULTURE AND AGRI-FOOD CANADA, PACIFIC AGRI-FOOD RESEARCH CENTRE, SUMMERLAND, B.C. V0H 1Z0

ABSTRACT

Pheromone-mediated mating disruption to control codling moth, *Cydia pomonella* (L.) (Lepidoptera: Tortricidae), was tested in commercial apple and pear orchards in 1991 and 1992 using Isomate-C® dispensers. In 1991, a single treatment of 1000 dispensers/ha released the pheromone, *E,E*-8,10-dodecadien-1-ol (codlemone), at calculated rates of 14.9, 15.2, 16.6 and 17.5 gm/ha from 1 May to 30 September in Kelowna, Summerland, Cawston and Oliver, respectively. At the same four sites, but during the 1-hr dusk flight periods, when most mating occurs, codlemone was released at calculated median rates of 7.6, 8.2, 8.3 and 12.7 mg/ha/h during first brood and 2.4, 2.3, 4.7 and 5.3 mg/ha/h during second brood, respectively. Damage in 22 pheromone-treated apple orchards ranged from 0.02 - 6.75%, with a median of 0.42%, whereas damage in 12 pheromone-treated pear orchards ranged from 0.02 - 6.23%, with a median of 0.87%. Three insecticide-treated apple orchards had a mean of 0.06% damage and one insecticide-treated pear orchard had 4.21% damage. Untreated apple and pear orchards had 56.9 and 2.23% damage, respectively. In pheromone-treated orchards, few male codling moths were caught in Pherocon 1-C wing traps baited with 1 mg of codlemone ($\bar{x}$=2.9 moths/trap/orchard/season) compared with identical traps hung in insecticide-treated orchards ($\bar{x}$=29.2 moths/trap/orchard/season). Traps baited with 10 mg of codlemone caught codling moths in 96% of the pheromone-treated apple orchards and weekly catches showed seasonal flight patterns similar to those in insecticide-treated orchards. A significant linear relationship between mean cumulative catches in traps baited with 10 mg of codlemone during flight of first-brood moths and damage at harvest, can be used to warn growers if mating disruption is failing and that additional treatment may be needed for the second brood. In 1992, treatment of apple orchards in Cawston with 1000 dispensers/ha as a single application on 1 May, released codlemone at calculated median rates of 13.3 and 4.6 mg/ha/h during first and second brood, respectively. A split application of 650 dispensers on 1 May and an additional 350 on 1 July released codlemone at median rates of 8.7 and 7.8 mg/ha/h during first and second broods, respectively. Damage in 5 orchards with a single pheromone treatment ranged from 0 - 1.52%, and 2 orchards with the split application had 0.08 and 0.97% damage. Damage in an untreated control orchard was 43.5%. Used as described here, pheromone-mediated mating disruption using Isomate-C® is commercially viable in British Columbia.

Key words: Codling moth, mating disruption, Isomate-C, codlemone release rates

---

[1] **Current address**: Pacific Biocontrol Corp., Vancouver, WA, U.S.A.

INTRODUCTION

Codling moth, *Cydia pomonella*, (L.), is the key insect pest of pome fruits in the Okanagan and Similkameen Valleys of British Columbia and has been controlled successfully by broad-spectrum organophosphate insecticides for more than thirty years. Reports of resistance to organophosphates (Varela *et al.* 1993) and a desire to market insecticide-free fruit have hastened development and implementation of alternative controls (Dyck and Gardiner 1992). Pheromone-based mating disruption has been studied as an alternative technique for controlling codling moth in Australia (Vickers and Rothschild 1991), Canada (Trimble 1995, Judd *et al.* 1997), France (Audemard 1988), Switzerland (Charmillot 1990), The Netherlands (van Deventer *et al.* 1992), and the United States (Moffitt and Westigard 1984, Barnes *et al.* 1992, Howell *et al.* 1992, Pfeiffer *et al.* 1993, Knight 1995a).

These studies gave varied and sometimes conflicting results, ranging from complete success (Barnes *et al.* 1992), to total failure (Trimble 1995). Most studies reporting failures have involved only a few treated sites (1 - 5), used small plots, which are not applicable to testing pheromone disruption technology, or were conducted at inappropriate population densities. Comparing the efficacy of mating disruption among experiments is also confounded by differences in the voltinism of codling moth in different geographic areas, or the application of supplemental insecticide controls (Knight 1995a). Furthermore, the use of pheromone dispensers with varying and sometimes unknown, or poorly measured release rates, makes comparisons of the efficacy and quantities of pheromone used difficult.

In spite of varied experimental results, disruption of mating in codling moth using pheromones, has been commercialized on every continent where apples are grown (Thomson 1994) and several pheromone formulations and dispensers are now available. Isomate-C® is one pheromone system that has been used extensively in northern Italy, Australia and the Pacific Northwest apple growing areas (Thomson 1994). Yet, apart from a few reports in trade journals (Gut and Brunner 1991, Howell 1992, Judd and Gardiner 1992, Waldner 1996), there is little scientific publication on its successful commercial application (Knight 1995a), leading to the conclusion that routine use against codling moth is not practical (Cardé and Minks 1995). Successful commercial use of mating disruption as a stand-alone technology for control of codling moth in Canada has not been reported, although its use in "organic" apple orchards has been studied (Trimble 1995, Judd *et al.* 1997).

After successful trials with Isomate-C® in organic apple orchards during 1990 (Judd *et al.* 1997), Pacific Biocontrol Corp. expressed interest in registering it in Canada. Unlike the United States and some European countries (Weatherston and Minks 1995), Canadian regulatory policy requires that any new pest control product must be extensively tested and its efficacy demonstrated before it can be registered. Therefore, we undertook a large-scale evaluation in commercial apple and pear orchards to provide data on the efficacy of the Isomate-C® pheromone dispensing system. Our primary objective was to evaluate mating disruption in a few orchards with known histories of codling moth damage, and a majority for which we had no history, but where growers claimed to have had low populations in 1990. Our secondary objective was to relate the observed efficacy of Isomate-C® dispensers to their emission rates (McDonough *et al.* 1992) under British Columbia weather conditions to provide baseline data for comparison with other dispensing systems.

MATERIALS AND METHODS

Description and Selection of Test Orchards. Seventy-five growers, representing 140 ha of apple and pear orchards in the Okanagan, Similkameen and Kootenay Valleys, Vancouver Island and Lilooett participated in this study. Growers were introduced to the technology through local information meetings organized by B.C. Ministry of Agriculture, Fisheries and Food personnel. Growers volunteering to treat their orchards with pheromone were solicited and where possible sites with no more than 3% damage the previous year and no less than 0.5 ha in size were chosen; these are known requirements for successful pheromone-based disruption of codling moth mating (Charmillot 1990).

Of the 75 orchards treated with pheromone in 1991, results from 34 in the Okanagan and Similkameen Valleys, where 99% of B.C.'s fruit production is concentrated and could be supervised adequately, are given here. Twenty-two apple and 12 pear orchards treated with pheromone were monitored and sampled for damage. For comparison, 4 insecticide-treated orchards (3 apple, 1 pear) and 2 untreated orchards (1 apple, 1 pear) were also monitored and sampled. In 1992, 7 of the original 22 pheromone-treated apple orchards and an untreated orchard were monitored and sampled for damage.

The location, physical description, and varieties of each of the 40 orchards are given in Table 1. Location of towns are mapped in Cossentine and Jensen (1992, pg. 19). The median size of apple orchards was 1.12 ha with 646 trees/ha. The 14 pear orchards had a median size of 0.93 ha with 278 trees/ha. Individual tree canopy volumes were calculated by multiplying the height (measured from the first scaffold limb coming off the trunk to the top of the central leader) by the base width at the first scaffold limb. An average for 10 trees in each orchard was multiplied by the area of the orchard to give the canopy volume/orchard. The median canopy volume of pear orchards (42,900 m^3) was slightly larger than apple orchards (34,900 m^3), but because they were smaller in area, pear orchards had greater volume to area ratios to treat with pheromone.

Pheromone Disruption Treatment. Pheromone was released by Shin-etsu rope-type dispensers containing a 155 mg blend of, 58.8% *E,E*-8,10-dodecadien-1-ol (codlemone), 29.5% dodecanol, 5.3% tetradecanol and 3.1% antioxidants including vitamin E. This dispenser was a 20-cm long, sealed, translucent polyethylene tube (1.1 mm ID) containing pheromone and a metal wire running through its length for support. This dispenser was marketed in the United States under the trade name Isomate-C® (Pacific Biocontrol Corp., Davis, California, U.S.A.), but its commercial efficacy had not been demonstrated when this study was conducted.

Pheromone dispensers were usually deployed at a standard rate of 1000/ha, except on the outermost row of trees which had the equivalent of 2000 dispensers/ha. Dispensers were tied to branches in the upper third of the tree canopy about 0.5 - 1.0 m from the top of the central leader on the first lateral branch. Dispensers were usually tied on the north-east side of trees to minimize exposure to direct sunlight. All dispensers were deployed a few days before the first codling moth was expected to emerge, but no later than 1 May. In 1991, 2 orchards (A-22 and P-36) received an additional 1000 dispensers/ha on 1 July and in 1992, 2 orchards (A-13 and A-14) received a split application of 650 dispensers/ha on 1 May (A-13) or 7 May (A-14), and an additional 350 dispensers/ha on 1 July. With the exception of 2 pear orchards (P-37 and P-38) no insecticides were applied to pheromone-treated orchards after the blossom period.

Pheromone Dispenser Emission Rates. Pheromone emission from the Isomate-C® dispenser is complicated and cannot be described accurately by changes in weight or length of the liquid column. Release rates for each of the dispenser's components as a function of temperature, dispenser age and the thickness of polymerized pheromone and dust which accumulates on the dispenser, were described mathematically by McDonough *et al.* (1992). These equations were incorporated into a computer programme (Knight 1995b) that can be used to predict the rate of release of each of the dispenser's components based on ambient temperature and the dispenser's age. Hourly air temperatures, recorded with DP-212 Datapods (Omni Data Int., Logan Utah) housed inside standard Stevenson Screens placed in four representative orchards, were used in Knight's (1995b) model to calculate the release of codlemone in mg/ha/h as a function of

Table 1

Location, physical description and fruit varieties of commercial apple (A) and pear (P) orchards used for evaluating pheromone-based mating disruption of codling moth with Isomate-C in 1991 and 1992.

Crop	Orchard number	Location	Varieties[a]	Area	Tree x row spacing	Tree density	Canopy volume
				ha	m x m	/ha	m^3 x 1000
Apple	A- 1	Oliver	R,G	1.54	2.4 x 4.6	891	39.3
	A- 2	Oliver	R,G	1.43	4.3 x 5.5	643	37.2
	A- 3	Summerland	S,M	0.78	4.3 x 4.6	577	38.5
	A- 4	Summerland	S,M	1.71	2.6 x 4.6	819	38.5
	A- 5	Naramata	S,M	0.61	4.9 x 4.9	418	44.8
	A- 6	Naramata	S,M	0.44	4.9 x 4.9	418	42.6
	A- 7	Westbank	B,E	2.20	1.5 x 3.0	2272	16.0
	A- 8	Westbank	G	1.11	2.0 x 4.0	1257	40.0
	A- 9	Keremeos	R,G	0.61	2.4 x 4.6	907	38.2
	A-10	Keremeos	R,G	0.75	2.4 x 4.6	909	38.2
	A-11	Keremeos	S,M	1.17	2.0 x 4.2	1230	35.1
	A-12	Cawston	R	1.68	6.1 x 6.1	270	42.4
	A-13	Cawston	R,G,S	0.82	3.0 x 5.0	673	40.2
	A-14	Cawston	R,G,S	1.27	3.6 x 4.6	598	39.1
	A-15	Cawston	M,S	1.41	3.0 x 5.5	626	32.9
	A-16	Cawston	R,G,S	1.11	3.6 x 4.6	649	38.7
	A-17	Cawston	R	0.57	3.0 x 6.1	618	42.4
	A-18	Cawston	R	1.28	2.4 x 4.2	1020	27.7
	A-19	Cawston	M,S	2.00	3.6 x 5.5	603	37.0
	A-20	Cawston	S	0.93	3.0 x 5.5	615	47.0
	A-21	Cawston	M	1.12	2.4 x 4.6	938	29.4
	A-22	Cawston	R,G,S,M	2.30	4.6 x 4.6	473	46.2
	A-23	Cawston	S	0.68	4.6 x 4.6	473	41.4
	A-24	Cawston	S	0.97	3.0 x 5.5	615	47.0
	A-25	Cawston	S	0.48	3.6 x 4.6	664	36.0
	A-26	Summerland	R,G,S,M	0.30	2.3 x 4.6	1040	32.8
Pears	P-27	Winfield	A,Bt	1.04	3.3 x 5.9	513	37.7
	P-28	Kelowna	A,Bt	1.72	3.6 x 6.1	456	40.5
	P-29	Kelowna	A,Bt	1.18	6.1 x 6.1	278	35.9
	P-30	Westbank	A,Bt	1.05	5.8 x 5.8	300	47.0
	P-31	Westbank	A,Bt	2.16	6.1 x 6.1	278	46.2
	P-32	Naramata	Bt	0.25	4.9 x 5.1	395	44.0
	P-33	Cawston	A,Bt	0.66	3.0 x 5.4	648	33.1
	P-34	Cawston	A,Bt	4.69	7.5 x 7.5	183	42.2
	P-35	Cawston	A,Bt	0.82	6.1 x 6.1	278	44.8
	P-36	Cawston	A,Bt	0.42	6.1 x 6.1	278	44.6
	P-37	Cawston	A,Bt	0.68	6.1 x 6.1	278	47.1
	P-38	Cawston	A,Bt	0.60	6.1 x 6.1	278	42.6
	P-39	Kelowna	Bt	0.64	6.1 x 6.1	278	35.9
	P-40	Kelowna	A,Bt	1.83	3.6 x 6.1	456	40.5

[a]Abbreviations for apple varieties are: Braeburn (B), Elstar (E), Golden Delicious (G), McIntosh (M), Spartan (S), Red Delicious (R), and pear varieties are Anjou (A) and Bartlett (Bt)

temperature, time of day, dispenser age and number of dispensers applied. The release of other components was not considered because they are not active pheromone components (McDonough *et al.* 1995). A similar approach to modelling pheromone delivery rates was used by Howell *et al.* (1992) and Suckling *et al.* (1994) and has been validated by Knight (1995b).

Monitoring Seasonal Flight of Male Codling Moths. Most orchards were monitored with Pherocon 1-C style wing traps (Phero Tech Inc., Delta, B.C.) baited with commercial codlemone (99% isomeric and chemical purity, Shin-etsu, Fine Chemicals Division, Japan) loaded on to red rubber septa. In 1991, pheromone-treated orchards were monitored with traps baited with 1 or 10 mg of codlemone and in 1992 with 10 mg traps only. All other orchards were monitored with 1 mg traps. Traps were hung 1.5 - 2.0 m above ground in the interior of each block at a density of 1/ha. Trap positions were fixed throughout the season and checked weekly to record numbers of male moths captured. Pheromone baits were changed every three weeks throughout the season.

Fruit Damage. All orchards were sampled for damage during harvest, as fruit maturity and growers dictated. Each sampled tree was completely picked and all fruit were inspected for damage from codling moth. Damage estimates include surface feeding (stings) and deep entries. We sampled a minimum of 5 trees and a maximum of 3% of all the trees in each orchard using a stratified, cluster sampling procedure where the outer border row of trees and interior trees represent 2 strata, and each tree represents a cluster of fruit, respectively. As border trees usually have more damage than interior trees and damage is often aggregated on trees, this division seems logical. The estimated percentage of damage for each whole orchard is a weighted average for both strata, with weighting based on the proportion of total fruit in each stratum and the variability in damage between trees within a stratum. The estimated percentages of damage in each orchard are expressed with ± 2 standard deviations (SD), which provides an approximate 95% confidence interval for the estimates (Mendenhall *et al.* 1971).

Paired Insecticide and Pheromone Treatments. In 1991, 3 conventionally-managed apple orchards and 1 conventionally-managed pear orchard were subdivided and each half received either a standard insecticide programme (B.C. Ministry of Agriculture, Fisheries and Food 1991) or a pheromone treatment. Each orchard was monitored with pheromone traps as described earlier and insecticides were applied when trap catches were above the specified threshold (2 moths/trap/week for 2 consecutive weeks) and degree-day accumulations. The numbers of damaged and undamaged fruit found in samples taken in each of these paired orchard blocks were compared with χ^2 tests.

RESULTS

Dispenser Release Rates. Applying 1000 Isomate-C® dispensers/ha is equivalent to treating each ha with 91 gm of codlemone, but according to McDonough *et al.* (1992) and Knight (1995b), most of it is never released into the air because of photodegradation, isomerization and polymerization. According to Knight's (1995b) model, the total amount of codlemone released in orchards in Kelowna, Summerland, Cawston and Oliver during both the first and second broods of moths was 14.9, 15.3, 16.6 and 17.5 gm/ha, respectively, about 16 - 19% of the total in dispensers (Table 2). The seasonal total amounts of codlemone delivered at dusk (Table 2), during which time most of the mating takes place, represented less than 1% of the 91 gm applied in dispensers. Changes in temperature greatly affected daily pheromone release rates as the ranges at dusk indicate. In 1991, estimated release rates at dusk ranged from 1.3 - 18.4 mg/ha/h in Cawston, 2.4 - 24.7 in Oliver, 0.6 - 17.0 in Summerland, and 0.2 - 20.6 in Kelowna. Average release (means and medians) varied between sites, years and particularly between generations within a year (Table 2). In 1991, codlemone release rates on nights when temperatures were suitable for flight (≥15°C), and presumably mating, never fell below 2 and rarely below 6 mg/ha/h during first brood at any site (Table 2). During the second brood, dusk release rates were frequently below 2 mg/ha/h. As expected, an additional 1000 dispensers in summer released over twice as much pheromone during the second brood, as did a single application of 1000 dispensers (Table 2).

Similar pheromone release rates were calculated for 1992 (Table 2). Splitting an application of 1000 dispensers (650 first brood and 350 second brood) in 1992, produced a lower mean release rate during first brood, but a higher rate during second brood, than did a single application of 1000 dispensers (Table 2). This split application distributed pheromone more evenly throughout the season, and application rates never fell below 2 mg/ha/h during second brood, unlike the standard treatment (Table 2).

Table 2

Summary statistics for the estimated codlemone evaporation rates at different locations during 1991 and 1992.

Year-Brood	Location	Dispenser number /ha	Dusk mean mg/ha/h	Dusk median mg/ha/h	Dusk range mg/ha/h	Seasonal dusk total gm/ha	Seasonal daily total gm/ha	% nights when dusk temp ≥ 15°C and codlemone release ≥ given mg/ha/h thresholds 2	4	6	8	10
1991-1	Oliver	1000	12.3	12.7	2.4-24.7	0.87	12.3	100	100	96.6	89.8	76.3
	Cawston	1000	9.0	8.3	1.3-18.4	0.57	12.1	100	100	96.1	68.6	43.1
	Summerland	1000	8.3	8.2	0.6-17.0	0.65	11.4	100	98.3	90.0	68.3	45.0
	Kelowna	1000	8.4	7.6	0.2-20.6	0.70	11.3	100	96.8	84.1	57.1	47.6
1991-2	Oliver	1000	5.3	5.3	1.5-11.4	0.28	5.2	90.7	66.7	38.9	14.8	3.7
	Cawston	1000	4.1	4.7	0.7-8.3	0.21	4.5	86.2	58.8	13.7	3.9	0
		2000[a]	16.1	18.4	2.9-32.6	0.80	17.5	100	100	88.5	84.6	73.0
	Summerland	1000	3.1	2.3	0.2-7.6	0.20	3.9	56.3	39.0	7.8	0	0
	Kelowna	1000	3.2	2.4	0.3-8.2	0.21	3.6	68.2	40.9	16.7	3.0	0
1992-1	Cawston	1000	13.2	13.3	1.8-37.3	0.66	14.6	100	100	97.7	93.2	86.3
		650	8.6	8.7	1.1-24.2	0.43	9.5	100	97.7	90.9	68.2	36.4
1992-2	Cawston	1000	4.7	4.6	0.9-11.9	0.23	5.3	93.8	60.4	20.8	6.3	4.2
		1000[b]	8.1	7.8	1.8-14.7	0.39	8.8	100	89.6	75.0	47.9	29.2

[a]Isomate-C applied at a rate of 1000 dispensers/ha on May 1 plus an additional 1000/ha on July 1
[b]Isomate-C applied at a rate of 650 dispensers/ha on May 1 plus an additional 350 dispensers/ha on July 1

Pheromone Trap Catches and Seasonal Flight of Male Codling Moths. Catches in each of 23 apple orchards and 11 pear orchards where traps were maintained are shown in Table 3. In pheromone-treated apple orchards, few moths were caught in traps baited with a standard 1 mg load of codlemone ($\bar{x}$= 2.9 moths/trap/orchard/season), compared with identical traps in insecticide-treated apple orchard ($\bar{x}$= 29.2 moths/trap/orchard/season). So few moths were caught in 1 mg traps hung in pheromone-treated orchards in 1991 that their use was discontinued in 1992. Traps with 10 mg baits in pheromone-treated orchards were attractive enough to show seasonal flight patterns of codling moth similar to those seen in insecticide-treated orchards (Fig. 1). Despite the low density of traps used, 10 mg baits attracted codling moths in 96% of the pheromone-treated apple orchards, whereas 1 mg baits attracted moths in only 61% of the pheromone-treated orchards in 1991.

In pheromone-treated apple orchards the $\bar{x}$ ± standard error (SE) cumulative number of first brood moths caught in traps with 10 mg baits (7.15 ± 1.27) was 4.2 times greater than the mean with 1 mg baits (1.7 ± 0.23). During second brood the mean number (5.26 ± 1.53) of moths in 10 mg traps was only 2.7 times greater than the mean number in 1 mg traps (1.93 ± 0.82), suggesting that 10 mg traps were becoming comparatively less attractive later in the season.

Fruit Damage. In 1991, damage to pheromone-treated apples ranged from 0.02 - 6.75 %, with a median level of 0.42% (Table 3). In three paired comparisons (A-16 *vs* A-25, A-17 *vs* A-23 and A-20 *vs* A-24) damage in the pheromone-treated halves of these apple orchards was not significantly different (χ^2 tests, p < 0.05) from the insecticide-treated halves. Damage in an untreated control (A-26) was substantially greater than that in any treated orchard (Table 3), showing there was potential for codling moth damage.

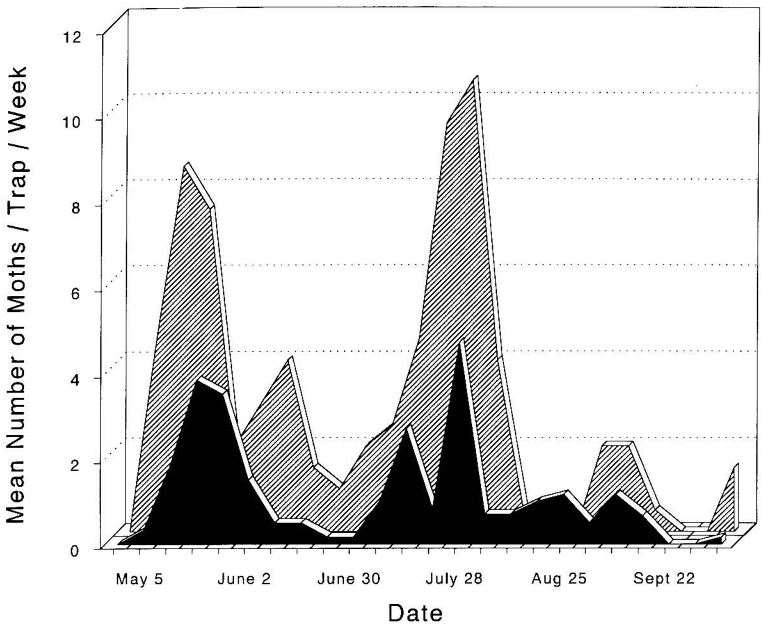

Figure 1. Comparison of weekly catches of male codling moths in traps baited with 10 mg of codlemone and hung in a pheromone-treated apple orchard (black) or with 1 mg in an adjacent insecticide-treated orchard (hatched) during 1992.

Damage to pheromone-treated pears ranged from 0.02 - 6.23% with a median of 0.87%, almost twice that of apples, which is surprising because pears are generally less susceptible to damage from codling moth than apples. Damage in one insecticide-treated pear block (P-39) was significantly higher (χ^2 test, $p < 0.05$) than a paired pheromone-treated block (P-29).

In 1992, damage to apples ranged from 0 - 2.5%, with a median of 0.5%, and in an untreated orchard it was 43.5% (Table 3). Despite a split application, and consequently less pheromone during first brood flight, orchards A-13 and A-14 had damage levels of 0.08% and 0.97%, respectively, i.e. less than the conventional economic threshold.

Trap Catch and Damage Correlation. In pheromone-treated apple orchards damage at harvest was nearly always preceded by catches in 10 mg traps during first brood (Table 3), whereas no first brood moths were caught with 1 mg baits in several pheromone-treated orchards having damage (e.g. orchards A-5, A-6, A-12, A-13, A-14, A-16). Using 18 apple orchards that received one standard pheromone disruption treatment, and for which we also had suitable damage and trap-catch data (orchards A-7, A-8, and A-22 were excluded on this basis; A-21 was excluded as an outlier that appeared to sustain damage due to immigration into the block), damage at harvest in 1991 was regressed against mean cumulative catches of first brood males in traps with 10 mg baits. Although the data were highly variable, the regression was significant

Table 3

Mean cumulative number of male codling moths caught in traps baited with 1 or 10 mg of codlemone during first (1st) and second (2nd) brood flights and % damage at harvest in pheromone-treated, insecticide-treated and untreated apple (A) and pear (P) orchards in 1991 and 1992.

			Mean cumulative number of moths per trap						Number of trees sampled, fruit load and damage at harvest		
			1 mg codlemone			10 mg codlemone					
Year	Orchard	Treatment	No. of traps	1st flt.	2nd flt.	No. of traps	1st flt.	2nd flt.	No. of trees	Fruit/tree $\bar{x} \pm$ SD	Damage % ± 2 SD
1991	A-1	Isomate-C	4	0.8	0.3	4	7.3	0.8	15	434 ± 219	0.01 ± 0.01
	A-2	Isomate-C	2	1.0	0	2	1.5	0	10	308 ± 138	0.61 ± 0.44
	A-3	Isomate-C	2	0	0	2	2.0	1.0	13	249 ± 96	0.06 ± 0.05
	A-4	Isomate-C	2	0	1.0	2	1.0	2.0	16	241 ± 85	0.05 ± 0.03
	A-5	Isomate-C	1	0	0	1	9.0	6.0	6	484 ± 303	0.70 ± 0.69
	A-6	Isomate-C	2	0	0	1	0	1.0	5	392 ± 138	0.18 ± 0.24
	A-7	Isomate-C	0	-	-	0	-	-	70	15 ± 9	6.75 ± 1.94
	A-8	Isomate-C	0	-	-	0	-	-	23	170 ± 122	1.61 ± 0.81
	A-9	Isomate-C	1	2.0	8.0	1	11.0	12.0	10	244 ± 127	0.90 ± 0.54
	A-10	Isomate-C	1	2.0	1.0	1	10.0	15.0	10	348 ± 130	0.92 ± 0.45
	A-11	Isomate-C	1	1.0	3.0	1	0	0	18	237 ± 78	0.37 ± 0.02
	A-12	Isomate-C	2	0	0	2	4.0	1.0	5	376 ± 125	0.10 ± 0.07
	A-13	Isomate-C	1	0	0	1	1.0	0	18	411 ± 275	0.17 ± 0.09
	A-14	Isomate-C	1	0	0	1	3.0	7.0	23	411 ± 275	0.47 ± 0.22
	A-15	Isomate-C	1	3.0	0	1	11.0	5.0	16	133 ± 52	0.67 ± 0.38
	A-16	Isomate-C	1	0	0	1	1.0	5.0	24	298 ± 185	0.15 ± 0.06
	A-17	Isomate-C	1	1.0	0	1	3.0	1.0	12	217 ± 134	0.13 ± 0.12
	A-18	Isomate-C	1	2.0	11.0	1	22.0	21.0	10	178 ± 13	0.94 ± 0.76
	A-19	Isomate-C	3	0.3	0.3	2	1.0	1.0	28	94 ± 63	0.12 ± 0.05
	A-20	Isomate-C	1	3.0	1.0	1	2.0	2.0	14	465 ± 214	0.11 ± 0.06
	A-21	Isomate-C	1	0	1.0	1	1.0	1.0	27	52 ± 39	2.40 ± 1.02
	A-22	Isomate-C	3	7.0	10.2	3	32.3	19.3	23	390 ± 214	2.27 ± 0.98
	A-23	APM x 2[a]	2	16.0	23.5	0	-	-	11	245 ± 147	0.14 ± 0.09
	A-24	APM x 2[a]	1	14.0	17.0	0	-	-	14	379 ± 148	0.04 ± 0.02
	A-25	APM x 3[a]	2	8.5	8.5	0	-	-	12	859 ± 129	0.02 ± 0.02
	A-26	Untreated	0	-	-	0	-	-	12	116 ± 97	56.87 ± 2.65
	P-27	Isomate-C	1	0	0	1	2.0	2.0	14	143 ± 58	0.27 ± 0.16
	P-28	Isomate-C	2	1.0	1.0	2	9.0	2.0	20	127 ± 20	2.28 ± 1.01
	P-29	Isomate-C	2	0	1.0	1	0	1.0	6	346 ± 68	1.09 ± 1.16
	P-30	Isomate-C	0	-	-	0	-	-	14	455 ± 168	6.23 ± 3.64
	P-31	Isomate-C	0	-	-	0	-	-	14	499 ± 110	7.10 ± 4.10
	P-32	Isomate-C	0	-	-	0	-	-	10	265 ± 19	0.66 ± 0.61
	P-33	Isomate-C	1	0	0	1	6.0	11.0	12	103 ± 53	0.17 ± 0.12
	P-34	Isomate-C	4	0.8	0.3	4	14.5	0.8	17	413 ± 200	0.16 ± 0.09
	P-35	Isomate-C	1	0	0	1	0	0	10	360 ± 50	0.02 ± 0.01
	P-36	Isomate-C[b]	0	-	-	1	5.0	2.0	10	278 ± 133	3.31 ± 2.41
	P-37	Isomate-C[c]	1	4.0	0	1	16.0	1.0	6	157 ± 61	1.51 ± 1.51
	P-38	Isomate-C[c]	1	5.0	0	1	12.0	3.0	10	238 ± 135	0.37 ± 0.26
	P-39	Imidan x 2[c]	1	26.0	25.0	0	-	-	9	396 ± 112	4.21 ± 3.15
	P-40	Untreated	2	13.0	9.0	0	-	-	20	117 ± 31	2.23 ± 0.99
1992	A-01	Isomate-C	0	-	-	4	1.0	0.8	15	427 ± 215	0 ± 0
	A-12	Isomate-C	0	-	-	2	0.5	0	5	346 ± 116	0.07 ± 0.03
	A-13	Isomate-C[d]	0	-	-	2	1.5	2.0	18	455 ± 168	0.08 ± 0.05
	A-14	Isomate-C[d]	0	-	-	2	1.0	1.0	23	499 ± 110	0.97 ± 0.42
	A-15	Isomate-C	0	-	-	2	16.0	2.0	16	165 ± 56	0.74 ± 0.38
	A-19	Isomate-C	0	-	-	2	1.0	0	28	101 ± 51	0.11 ± 0.07
	A-21	Isomate-C	0	-	-	2	2.0	1.0	27	62 ± 41	1.52 ± 0.78
	A-26	Untreated	0	-	-	0	-	-	12	64 ± 31	43.5 ± 2.95

[a] APM is azinphosmethyl applied at 0.84 kg a.i./ha indicated number of times

[b] Isomate-C applied at a rate of 1000 dispensers/ha on May 1 and 1000/ha on July 1

[c] Imidan applied as a single supplemental or indicated number of primary treatments at 0.8 kg a.i./ha

[d] Isomate-C applied as a split application of 650 dispensers/ha on May 1 and 350 dispensers July 1

(%Damage = 0.154 +0.043[Catch]), r^2= 0.55, $p < 0.05$). A similar regression analysis for pears was not significant ($p > 0.05$).

DISCUSSION

During 1991 and 1992 pheromone-mediated mating disruption using 1000 Isomate-C® dispensers/ha controlled codling moth as well as conventional insecticides, under British Columbia conditions. The large number of commercial orchards involved in this study with more successes than failures, leads us to conclude that this is a commercially viable technology for British Columbia's Interior apple and pear industry.

The wide range of damage we observed makes it easy to understand why studies using one (Barnes *et al.* 1992) or two pheromone-treated sites (Trimble 1995), have resulted in contradictory conclusions about the efficacy of Isomate-C®. Intentional or possibly random selection of 1 or 2 orchards at either extreme of the damage range seen (Table 3), could have led us to two completely opposite conclusions about the effectiveness of Isomate-C® depending which extreme we chose. Our selection of orchards was not entirely random, so it is difficult to know whether mating disruption in a completely random sample of orchards would be as successful as shown here. However, in our experience, growers volunteering to use mating-disruption technology have usually experienced difficulty controlling codling moth by other means. This observation has held true for both conventional and organic growers (Judd *et al.* 1997), so if applied industry wide, the proportion of orchards where mating disruption is successful might actually be greater than shown here, as most growers keep codling moth populations low with conventional insecticides.

Pheromone-based mating disruption is a more complex pest control technology than are insecticides and growers will require clear instructions and strict guidelines. Based on our analysis of 34 orchards, failure of the disruption technique could be attributed to three main factors: 1) high population densities, 2) incomplete or uneven tree canopy structure, and 3) immigration of mated females into treated areas. Charmillot (1990) developed a set of criteria necessary for effective control of codling moth by pheromone-based mating disruption. Population density was high on his list. Unlike pesticides, the efficacy of mating disruption as a control for codling moth appears to be lower at higher densities. For this reason we specifically chose orchards with low population densities, because failure to control high population densities is not a failure of the technique, but merely a restriction for its use that is sometimes not considered (Trimble 1995). It is not known at this time whether this density effect results from a greater percentage of mating at higher population densities, or simply, that a greater number of larvae, and consequently damage, arise from a greater number of adults.

With few exceptions, orchards with less than 3% damage the year before pheromone treatment, usually had similar or lesser amounts of damage after it (Table 3), indicating there is probably a relationship between past and potential damage using pheromone treatment. However, percent damage is such a variable factor and not always correlated with population density (Judd *et al.* 1997), that its use as a predictor is often unreliable. Trimble (1995) found that Isomate-C® failed to control codling moth in organic apple orchards with damage ranging from as low as 1.1 - 3.3% after the first year of treatment, indicating population densities were probably much higher than the damage indicated.

Charmillot (1990) concluded that if a threshold of 2 - 3 overwintering larvae/tree was exceeded, mating disruption would not keep codling moth damage below economic levels. Our studies (Judd *et al.* 1997) support this conclusion, but we think this threshold should be flexible to accommodate the effects of tree density, crop load and varietal susceptibility that will raise or lower the probability of damage at similar population densities. If a larval threshold is to be used it may be better to express it as larvae/hectare than larvae/tree (Judd *et al.* 1997).

Providing growers with a definitive larval threshold and measuring that threshold are so difficult, especially in pears, that traps containing 10 mg of pheromone may be the most convenient way to determine whether an orchard is above threshold during the first year of disruption. We detected males in all but 1 apple orchard where 10 mg baits were used. Apple orchards with mean cumulative catches of >10 males during first brood had damage above the 1.0% economic threshold. Therefore, this number and our regression model showing a relationship between catches of first-brood moths in 10 mg traps and damage, can be used as a rough guide for effective control. When population densities are above this threshold and if growers wish to keep damage below 1%, then other management tactics may be needed to complement pheromone disruption (Judd *et al.* 1997). We now advise growers to use additional controls before or during the first year of disruption if their orchard is above a given threshold.

Monitoring male codling moths does not always guarantee that damage will be detectable. Orchard A-21 had a mean cumulative catch less than 10 males and had 2.4% damage. Damage in this orchard was concentrated along a southern border adjacent (20 m) to an untreated orchard with about 20% damage. Damage decreased with distance into the pheromone-treated orchard, suggesting that immigrant mated females caused the damage. Immigration of mated females will remain a threat to disruption programmes unless larger areas can be treated or supplemental controls can be applied to borders.

The greatest amount of damage was seen in some pear orchards that had been managed with a minimum of pesticides for the previous 2 - 3 years as part of a soft approach to pear psylla management. These orchards probably had more damage or greater populations of codling moth than the growers realized. It also seems reasonable that larger canopy volumes in pears compared with apples (Table 1), may have decreased the average concentration of pheromone per volume of air in the canopy. Also, recent measurements of pheromone concentrations within treated crops (Bengtsson *et al.* 1994, Karg *et al.* 1994) showed that leaves function as secondary pheromone dispensers by adsorbing and re-releasing pheromones. Differences in pear and apple leaf structure may affect the amounts of pheromone adsorbed on to leaves (Karg *et al.* 1994). It remains to be seen whether the efficacy of pheromone disruption can be improved in these pear orchards by distributing the 1000 dispensers/ha more evenly throughout the canopy at varying heights, or whether more dispensers will be required. Other controls may be needed before pheromone disruption is successful in these orchards. Pear trees have extremely rough bark which provides many overwintering sites for codling moth larvae, therefore tree banding (Judd *et al.* 1997) is not likely to be successful.

Small narrow plantings with a high edge to area ratio, young high-density plantings, and widely spaced mature plantings with missing trees were also among the mostly highly damaged orchards. Concentrations of pheromones might be lower in orchards with less dense canopies because wind velocities are greater and may carry pheromones away before leaves can take them up, and areas of orchards with missing trees (broken canopy effect) may provide spaces where insects can escape constant exposure to pheromone, allowing their sensory system to regain sensitivity. Any reduction in pheromone levels or increase in pheromone-free space could increase mating chances. Where possible, pheromone-treatment beyond crop borders could help eliminate edge effects, but there is no simple solution for orchards with many missing trees.

Our work raises questions about the amount of pheromone needed to control codling moth. Previous research has shown that effective mating disruption requires from 2 (Cardé *et al.* 1977) to 10 or 40 mg of codlemone/ha/h (Charmillot 1990). This wide range of doses is due in part to the different ways that dispenser release rates have been measured (Knight 1995b). We controlled codling moth with 2 complete generations a year using a calculated codlemone release of about 6 mg/ha/h, albeit from 1000 dispensers. Charmillot and Pasquier (1992) tested many commercial pheromone formulations against codling moth and demonstrated efficacy with a wide range of release rates and with dispenser densities much lower than those we used. An improved understanding of the relationship between the level of mating disruption, dispenser release rates, their density and potential interplay with canopy structure might make large-scale efficacy testing of different release systems unnecessary if the release rates of dispensers were known. However, pheromone companies seem reluctant to disclose the release-rates of their dispensers, especially under variable temperatures found in the field. This lack of information forces researchers to determine these values themselves (McDonough *et al.* 1992) and slows the development of the technology.

This study also shows that there is a need to improve dispenser efficiency, because 80% of the codlemone in the Isomate-C® dispenser never reaches the orchard air. Codlemone is the most expensive component of these pheromone dispensers and a more efficient release of codlemone could greatly reduce the costs of mating disruption of codling moth. Until this research is completed however, the Isomate® pheromone system is suitable for commercial use in the British Columbia fruit industry, particularly for organic production (Judd *et al.* 1997). Furthermore, pheromone-based mating disruption should provide an alternative approach to area-wide control of codling moth should the SIR programme fail to meet its objective.

ACKNOWLEDGEMENTS

We thank the Similkameen-Okanagan Organic Producers' Association and its cooperating members for allowing us to conduct trials in their orchards. We also thank N. Verpaelst, R. Dickison, B. Whiting, K. White, J. Brooks, J.-P. Deland, and H.L. McBrien for technical assistance. This research was partially funded by the B.C. Ministry of Agriculture, Fisheries and Food D.A.T.E. Grant #292. This article is contribution no. 968 of the Agriculture and Agri-Food Canada, Pacific Agri-Food Research Centre, Summerland.

REFERENCES

Audemard, H. 1988. Confusion sexuelle avec des phéromones en Europe de l'ouest. Agric. Ecosyst. Environ. 21: 101-110.

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

Bengtsson, M., G. Karg, P.A. Kirsch, J. Löfqvist, A. Sauer, and P. Witzgall. 1994. Mating disruption of pea moth *Cydia nigricana* F. (Lepidoptera: Tortricidae) by a repellent blend of sex pheromone and attraction inhibitors. J. Chem. Ecol. 20: 871-887.

British Columbia Ministry of Agriculture, Fisheries, and Food. 1991. Tree Fruit Production Guide for Interior Districts. British Columbia Ministry of Agriculture and Fisheries, Victoria, B.C. 88 pp.

Cardé, R.T., T.C. Baker, and P.J. Castrovillo. 1977. Disruption of sexual communication in *Laspeyresia pomonella* (codling moth), *Grapholitha molesta* (oriental fruit moth) and *G. prunivora* (lesser appleworm) with hollow fiber attractant sources. Entomol. Exp. Appl. 22: 280-288.

Cardé, R.T. and A.K. Minks. 1995. Control of moth pests by mating disruption: successes and constraints. Annu. Rev. Entomol. 40: 559-585.

Charmillot, P.-J. 1990. Mating disruption technique to control Codling Moth in Western Switzerland, pp. 165-182. In.: Behavior-Modifying Chemicals for Insect Management:Aapplications of Pheromones and Other Attractants. R.L. Ridgway, R.M. Silverstein and M.N. Inscoe (Eds.). Marcel Dekker, Inc. New York and Basel.. 761 pp.

Charmillot, P.-J. and D. Pasquier. 1992. Lutte par confusion contre le carpocapse *Cydia pomonella* L.: experimentation de longue durée en Suisse romande. Revue Suisse Vitic. Arboric. Hortic. 24: 213-220.

Cossentine, J.E. and L.B. Jensen. 1992. Establishment of *Phyllonorycter mespilella* (Hübner) (Lepidoptera: Gracillaridae) and its parasitoid, *Pnigalio flavipes* (Hymenoptera: Eulophidae), in fruit orchards in the Okanagan and Similkameen Valleys of British Columbia. J. Entomol. Soc. Brit. Columbia. 89: 18-24.

Dyck, V.A. and M.G.T. Gardiner. 1992. Sterile-insect release programme to control the codling moth *Cydia pomonella* (L.) (Lepidoptera: Olethreutidae) in British Columbia, Canada. Acta Phytopath. Entomol. Hung. 27: 219-222.

Gut, L.J. and J.F. Brunner. 1991. Mating disruption as a control for codling moth in Washington. Proc. WA Hort. Assoc. 87: 199-201.

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.

Howell, J.F., A.L. Knight, T.R. Unruh, D.F. Brown, J.L. Krysan, C.R. Sell, and P.A. Kirsch. 1992. Control of codling moth in apple and pear with sex pheromone-mediated mating disruption. J. Econ. Entomol. 85: 918-925.

Judd, G.J.R. and M.G.T. Gardiner. 1992. Management of codling moth with pheromones: a new twist in insect control. British Columbia Orchardist 15: 12-15.

Judd, G.J.R., M.G.T. Gardiner, and D.R. Thomson. 1997. Control of codling moth in organically-managed apple orchards by combining pheromone-mediated mating disruption, post-harvest and tree-fruit removal. Entomol. Exp. Appl. *in press*

Karg, G., D.M. Suckling, and S.J. Bradley. 1994. Absorption and release of pheromone of *Epiphyas postvittana* (Lepidoptera: Tortricidae) by apple leaves. J. Chem. Ecol. 20: 1825-1841.

Knight, A. 1995a. The impact of codling moth (Lepidoptera: Tortricidae) mating disruption on apple pest management in Yakima Valley, Washington. J. Entomol. Soc. Brit. Columbia. 92: 29-38.

Knight, A.L. 1995b. Evaluating pheromone emission rate and blend in disrupting sexual communication of codling moth (Lepidoptera: Tortricidae). Environ. Entomol. 24: 1396-1403.

McDonough, L.M., W.C. Aller, and A.L. Knight. 1992. Performance characteristics of a commercial controlled-release dispenser of sex pheromone for control of codling moth *(Cydia pomonella)* by mating disruption. J. Chem. Ecol. 18: 2177-2189.

McDonough, L.M., H.G. Davis, P.S. Chapman, and C.L. Smithhisler. 1995. Codling moth, *Cydia pomonella* (Lepidoptera: Tortricidae): Is its sex pheromone multicomponent? J. Chem. Ecol. 21: 1065-1071.

Mendenhall, W., L. Ott, and R.L. Scheaffer. 1971. Elementary Survey Sampling. Duxbury Press, Belmont, California, U.S. 247 pp.

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

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

Suckling, D.M., G. Karg, S.J. Bradley, and C.R. Howard. 1994. Field electroantennogram and behavioral responses of *Epiphyas postvittana* (Lepidoptera: Tortricidae) under low pheromone and inhibitor concentrations. J. Econ. Entomol. 87: 1477-1487.

Thomson, D. 1994. The commercialization and implementation of pheromone-based IPM in pome fruits. pp. 77-81 In.: Proceedings of The Entomological Societies of Manitoba and Canada, Workshop. Research, Development and Commercialization of Semiochemicals in Insect Pest Management in Canada. Winnipeg, Manitoba. 102 pp.

Trimble, R.M. 1995. Mating disruption for controlling the codling moth, *Cydia pomonella* (L.) (Lepidoptera: Tortricidae), in organic apple production in southwestern Ontario. Can. Entomol. 127: 493-505.

van Deventer, P., A.K. Minks, L.H.M. Blommers, U. Neuman, and K. Jilderda. 1992. Mating disruption utilizing lepidopterous sex pheromones: three years of testing in apple orchards in The Netherlands. Brighton Crop Protection Conference - Pests and Diseases. 3: 1193-1198.

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

Vickers, R.A. and G.H.L. Rothschild. 1991. Use of sex pheromones for control of codling moth, pp. 339-354. In: L.P.S. van der Geest and H.H. Evenhuis (Eds.), World Crop Pests, vol 5. Tortricid Pests: Their Biology, Natural Enemies and Control. Elsevier, New York.. 808 pp.

Waldner, W. 1996. Ein Viertel der Obstbaufläche verwirrt. Obstbau-Weinbau 33(2):39-40

Weatherston, I. and A.K. Minks. 1995. Regulation of semiochemicals - global aspects. Integr. Pest Man. Rev. 1: 1-13.