Seasonal variation in recapture of mass-reared sterile codling moth, *Cydia pomonella* (L.) (Lepidoptera: Tortricidae): implications for control by sterile insect technique in British Columbia

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ABSTRACT

In 1992, the Okanagan-Kootenay Sterile Insect Release (SIR) Programme was initiated to eradicate codling moth, *Cydia pomonella* (L.), from montane, fruit-growing valleys in British Columbia (BC), Canada. Excessive damage in 1994, and failures to maintain sterile:wild (S:W) over- flooding moth ratios at 40:1, a target deemed necessary for eradication, led to concern about activity of sterile moths and recommendations to supplement control in spring. Using pheromone-baited wing traps and passive sticky pane traps we monitored operational S:W ratios to determine if they continued to fall below 40:1 post-1994. Seasonal flight activity and recapture of sterile moths was compared with that of wild moths from 7 May - 1 September, 1995 - 1999, in nine commercial orchards in Cawston, BC. Mean weekly catches of wild males in pheromone traps, reflected first- (May) and second-generation (August) peaks of flight activity in orchards supplemented with pheromone disruption, but only a single period of activity in insecticide-supplemented orchards. Weekly catches of sterile moths in these same orchards were always at their lowest in spring, and activity was correlated with seasonal air temperatures. Yearly average S:W ratios in the insecticide-treated orchards ranged from 24:1 - 203:1 in 1995 - 1997. Examining S:W ratios using data from those weeks when wild moths were actually caught, indicates ratios were frequently (29 - 91%) less than 40:1 in spring but S:W ratios fell below 40:1 less often during summer than spring. Passive pane traps also revealed patterns of fewer sterile moth catches, and lower S:W ratios in spring, compared with summer. Our data suggest low overflooding ratios contributed to slower than predicted population reductions, and increased release of sterile moths, of improved quality, between 1995 and 1997 did not significantly increase mean weekly catches or S:W ratios in individual orchards in spring. Therefore, continued application of supplemental insecticides, or a pheromone disruption treatment that reduced catch of moths, but did not significantly affect S:W ratios in spring, is recommended. We conclude that similar analysis of trap data for the entire SIR Programme (1994 - 2004) and correlations with damage would provide recommendations for the best use of sterile insects as part of any future area-wide codling moth management programme.

Key Words: Codling moth, sterile insect technique, flight activity, sterile:wild ratios

INTRODUCTION

In 1992, the British Columbia Fruit Growers' Association and Regional District governments launched a multimillion dollar Sterile Insect Release (SIR) Programme in the Creston, Okanagan and Similkameen Valleys of British Columbia

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(BC), Canada with an objective to eradicate codling moth, *Cydia pomonella* (L.), from these montane, fruit-growing valleys by 2000 (Dyck and Gardiner 1992). This area-wide programme was the culmination of 30 years of basic research, small implementation trials and much planning (Proverbs 1971, 1982; Proverbs *et al.* 1966, 1977, 1982; Dyck *et al.* 1993).

Originally the programme was divided into three distinct phases: 1) *Pre-release Sanitation*, 2) *Sterile Moth Release*, and 3) *Surveillance Monitoring and Protection.* During Phase 1 growers were required to reduce wild codling moth populations to levels resulting in 0.1 - 0.3 % damage at harvest, considered equivalent to about 100 overwintering larvae per ha (Dyck *et al.* 1993). Operationally, it was anticipated these measures would equate to adult populations of no more than two wild moths per pheromone trap per week during periods of peak emergence (Bloem and Bloem 2000). In Phase 2, the programme would make weekly releases of sterile moths in all commercial orchards in order to maintain sterile:wild (S:W) overflooding moth ratios at 40:1, a target that extensive research demonstrated was necessary to eradicate populations in three years (Proverbs 1971, 1982; Proverbs *et al.* 1982). In Phase 3, an area-wide pheromone trapping programme would be implemented post-2000 to prevent reinfestation of pest-free areas through early detection and targeted controls. These three phases were to be implemented sequentially in each of two zones. Zone 1, which included the Okanagan from Osoyoos to Summerland, Similkameen and Creston Valleys, entered Phase 1 in 1992 and was to recieve sterile moths under Phase 2 from 1994 - 1996. Zone 2 from Peachland to Salmon Arm inclusive, was scheduled to enter Phase 1 in 1995 and receive moths from 1997 - 1999 (Dyck *et al.* 1993).

Following a two-year pre-release sanitation programme in Zone 1, the first sterile moths were released in May 1994. Almost immediately it was noted that weekly S:W ratios from pheromone trap catches in individual orchards were less than the 40:1 target. Unfortunately, in previous sterile insect implementation trials in BC (Proverbs 1982; Proverbs *et al.* 1966, 1977, 1982;), codling moth S:W ratios were almost always presented as averages for regions, generations or seasons. These coarse-grained values made it difficult to know what ratios should be expected on a weekly basis in individual orchards and whether there should be concern for the long-term control effort. In this regard, similar implementation trials in Washington state (White *et al.* 1976) showed that S:W ratios within a single 130-ha orchard ranged from 54:1 to 938:1 when all traps were averaged over the season, but when examined individually, 21 of 38 total traps showed at least one weekly ratio that was less than 20:1. Furthermore, 78% of all codling moth damage was found within 152 m of these 21 traps. Therefore, to achieve area-wide population reduction and suppression of codling moth in a fruit-growing region like BC, where there are numerous, small, noncontiguous orchards, it is important to maintain appropriate S:W ratios in individual orchards and traps, especially during periods of peak emergence of wild moths. Any critical assessment of the annual progress or success of a sterile insect programme in BC should be based on an analysis that reveals the extent to which appropriate S:W ratios are being achieved in individual sites and presented as a proportion of all orchards being treated.

Our original objectives in this study were to document operational S:W ratios in several orchards in an effort to determine whether they were falling below the 40:1 target after 1994, and if so, to determine the extent to which inadequate ratios were resulting from large wild populations, thus justifying need for supplemental controls, or were resulting from poor recapture of sterile moths. A further rationale in publishing these data now, is that these data and analyses of this type are needed to make objective decisions about the design of a sustainable area-wide codling moth control programme post-2005 (Dendy *et al.* 2001). Our analyses may be useful in making decisions on the best uses of sterile codling moths in BC and other parts of the world where application of this technique is currently being considered.

MATERIALS AND METHODS

Test Sites and Sterile Insect Delivery. Studies were carried out in four conventionally- and five organically-managed apple orchards in Cawston, BC, located in the Similkameen Valley, within Zone 1 of the Okanagan-Kootenay SIR Programme (Dyck *et al.* 1993). Orchards ranged in size from 1 - 3 ha and were composed of mixed 'McIntosh', 'Spartan', 'Delicious' and 'Golden Delicious' apple varieties planted at densities of 600 - 900 trees / ha with tree × row spacings of 2.4 - 4.6 × 4.6 - 5.5 m, respectively. Orchards were chosen because of their known history (Judd *et al.* 1996, 1997) and because they were part of the original sterile insect implementation trials conducted by Proverbs *et al.* (1982).

While our trials were being conducted, conventional growers were asked to apply insecticidal controls during flight of first-generation adult codling moths in May and June, which most growers did in 1995 - 1997 (Bloem and Bloem 2000). Organic growers did not apply insecticides, but they supplemented release of sterile males by applying Isomate-C and Isomate CM/LR (Pacific Biocontrol Corp., Vancouver, Washington, USA) in 1995 - 1996 and 1997 - 1999, respectively, at a rate of 500 - 1000 dispensers / ha, as pheromone treatments to disrupt mating of wild codling moths (Judd *et al.* 1996, 1997; Judd and Gardiner 2004). Pheromone treatment was required because organic growers did not want to lose certification by applying conventional insecticides. This application presented an opportunity to determine what impact a pheromone-based mating-disruption treatment might have on flight activity of sterile moths and S:W ratios.

The original plan was to deliver 1000 mixed-sex sterile codling moths in each ha of orchard two times each week (Dyck *et al.* 1993). However, Bloem and Bloem (2000) stated that on average orchards were receiving 2250 moths / ha / week in 1994, and as many as 3750 moths / ha / week in 1997, although it is not clear whether these numbers refer to mixed-sex moths, or males only. Exactly how many sterile moths reached our study orchards is unknown, but all orchards were visited twice weekly by the same release drivers throughout each year and therefore, should have received similar numbers of moths. Beginning in late April or early May and continuing until mid-September, moths were distributed in every fifth or ninth row of orchard approximately 25 - 30 m apart. Chilled moths irradiated as described by Bloem and Bloem (2000) were dispensed by gently blowing them onto the ground beneath trees from a small hopper and fan unit (McMechan and Proverbs 1972) mounted on the front end of an all-terrain vehicle (Bloem and Bloem 2000).

Monitoring Codling Moth Seasonal Flight Activity. From 1995 through 1999, seasonal flight activity and capture of sterile and wild male codling moths was assessed using pheromone-baited traps. Two to six Pherocon 1-CP style, sticky wing traps (Phero Tech Inc., Delta, BC) baited with the codling moth sex pheromone codlemone, (*E,E*)-8,10-dodecadien-1-ol (99% isomerically pure, Shin-etsu, Fine Chemicals Division, Tokyo, Japan) were used in each orchard. A minimum of two traps and a maximum of two traps per ha were used in each orchard. Traps were hung ca. 1.5 - 2.0 m above ground near the centre of each orchard on 7 or 8 May (Julian Day 128) and were checked weekly until 1 September. Trap positions remained fixed within orchards across seasons. Trap bottoms were replaced weekly and pheromone baits were changed every third week. Sterile codling moths were identified by an internal red dye sequestered from the artificial diet on which they were reared (Brinton *et al.* 1969).

All pheromone lures were prepared by dispensing a 200 µl solution of codlemone dissolved in dichloromethane solvent into wells of red rubber septa (Aldrich Chemical Company Inc., Milwaukee, Wisconsin, USA). After loading, septa were air dried for 18 h at 23 °C in a fume hood and stored at 0 °C until pinned to the inner side of trap lids in the field. Septa used in conventional orchards were loaded with 1 mg of codlemone and septa used in pheromone-treated orchards were loaded with 10 mg of codlemone because the former are less attractive in Isomate-treated orchards (Judd *et al.* 1996).

In 1996, catches of sterile and wild, male and female codling moths were also monitored using passive pane traps (Weissling and Knight 1994) to measure relative activity of sterile and wild moths independent of response to pheromone lures. Pane traps consisted of vertically-oriented, semirigid, clear acetate plastic squares (30 × 30 cm) that were coated with STP oil treatment (First Brands Corporation, Scarborough, Ontario, Canada) to capture alighting insects. Sticky panes were clamped 3 m above ground to an upright iron rod abutting tree trunks. Eight to 30 pane traps were deployed evenly in a grid pattern throughout each orchard. Due to their cumbersome nature and need for frequent maintenance, pane traps were only used in 1996 and were placed in the field every other week, and only for a three-day sampling interval, Tuesday through Thursday.

Orchard Temperatures. Hourly air temperatures throughout this study were recorded at a centrally-located orchard in Cawston, BC from 1 May through 1 September each year. Temperature readings were made using a two-channel DP-212 Datapod (OmniData^{TM}, Logan, Utah, USA) housed in a 1 m high Stevenson screen. Daily degree-day (DD) summations above a 10 °C developmental base temperature and below a 31 °C upper developmental threshold were calculated by fitting a sine wave (Allen 1976; case 4) to daily air temperature minima and maxima using the computer program described by Higley *et al.* (1986).

Data Analyses. Codling moth catches in all traps within an orchard were summed each week. Median catches per trap per orchard in each generation and year were compared using a Kruskal Wallis non-parametric analysis of variance followed by Dunn's multiple comparisons test for ranked data (Zar 1984). Some paired frequency data were analyzed using Fisher's exact test and χ^2 tests where appropriate. Regression analyses was used to relate weekly and seasonal catches to temperature. All statistical tests were performed using SigmaStat® (Version 3.0.1, SYSTAT Software Inc., Richmond, California, USA) and an experimental error rate of $\alpha = 0.05$.

RESULTS

Flight Activity of Wild Moths. Mean weekly catches of wild codling moths in conventional insecticide-treated orchards in 1995 - 1999 peaked at 12, 4.5, 0.75, 0.4 and 0.2 moths / trap / week during the first four weeks of each trapping season, respectively (Fig. 1A). Catches of wild moths in insecticide-treated orchards were always lower in the second half of the season (Fig. 1A) and near zero after 1996. Catches of early-season, first-generation wild moths however continued into 1999 (Fig. 1A). After 1996, catches of wild moths in insecticide-treated orchards never went above the anticipated maximum threshold of 2 wild moths / trap / week, and during the five-year monitoring period they were less than this threshold 97.5% of the time.

In contrast to insecticide-treated orchards, trap-catch curves in pheromone-treated orchards reflected both first- and second-generation peaks of wild moth flight activity in 1995 and 1996 (Fig. 1B). Total catches in the second half of 1995 were even greater than the first half. However, after 1996, catches of wild codling moths were extremely low under pheromone-treatment and no wild moths were caught in any pheromone-treated orchard in 1999 (Fig. 1B).

Flight Activity of Sterile Moths. A plot of mean ± standard error (SE) weekly catches of sterile moths from 1995 - 1999 in conventional insecticide-treated orchards reveals a pattern of low catches during the early season and increasing catches later in the season (Fig. 2). Mean catches of sterile moths in the first two weeks of the season (Fig. 2) were often below the 40 moths / trap / week needed to ensure a 40:1 S:W ratio if only a single wild moth were caught. On average, it was not until week 8 that catches were consistently greater than 80 moths / trap / week needed to ensure a 40:1 S:W ratio if the programme threshold of 2 wild moths / week were reached. There was a significant linear ($r^2 = 0.87$, $P < 0.05$) increase in weekly catches of sterile males in weeks 1 - 8, but catches over the entire season were described more accurately ($R^2 = 0.93$, $P < 0.05$) by a sigmoid curve (Fig. 2). Increasing catches in weeks 1 - 8 were

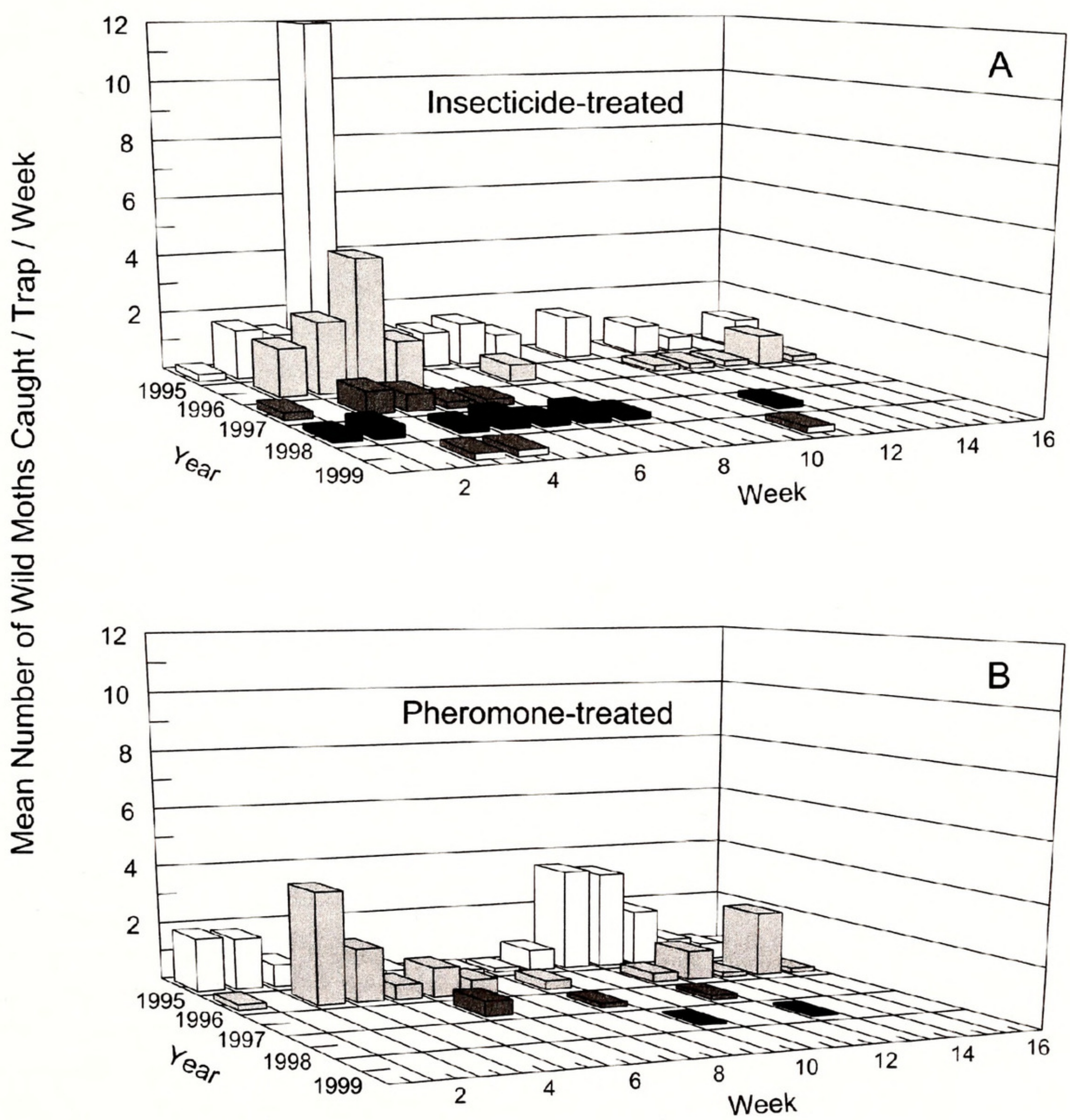

Figure 1. Mean weekly catches of wild male codling moths in pheromone-baited wing traps in insecticide-treated conventional (A) and pheromone-treated organic (B) apple orchards under management of the Okanagan-Kootenay SIR Programme from 1995 - 1999, in Cawston, BC. n = 4 conventional and 5 organic orchards and 2 - 6 traps / orchard.

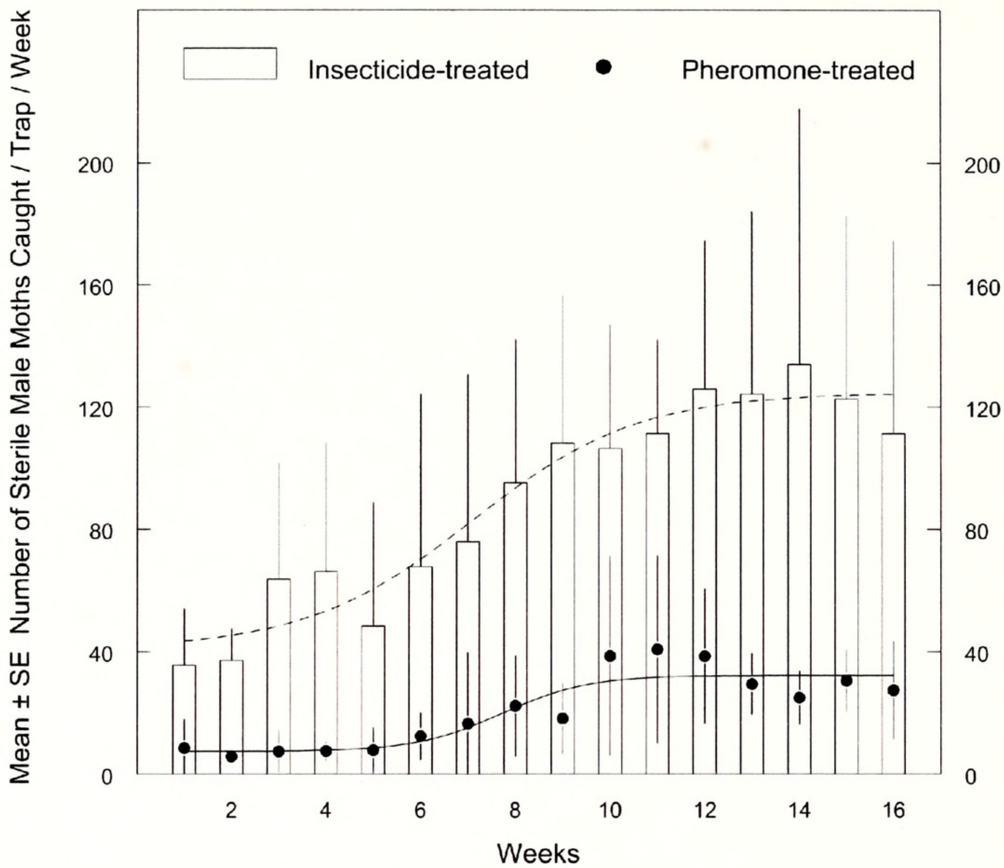

Figure 2. Comparison of mean (± SE) weekly catches of sterile male codling moths in pheromone-baited wing traps in insecticide-treated conventional (bars) and pheromone-treated organic (dots) apple orchards under management of the Okanagan-Kootenay SIR Programme from 1995 - 1999, in Cawston, BC. Curves represent nonlinear regression lines fitted to mean catches in insecticide- ($124.7 / [1 + e^{-(x-7.1)/1.75}]$) and pheromone-treated orchards ($32.2 / [1 + e^{-(x-7.72)/0.9}]$).

correlated ($r = 0.661$, $P < 0.05$) with concurrent seasonal increases in mean weekly temperatures.

Although weekly catches of sterile moths in pheromone-treated orchards were reduced significantly (ca. 78%) over catches in insecticide-treated orchards, they revealed a similar pattern of low early season catches that increased as the season progressed (Fig. 2). Catches of sterile males regularly reached as many as 40 moths / trap / week after week 9. Again, while there was a significant linear ($r^2 = 0.641$, $P < 0.05$) increase in catches of sterile males in pheromone-treated orchards during weeks 1 - 8, catches over the entire season were better described ($R^2 = 0.83$, $P < 0.05$) by a sigmoid curve (Fig. 2).

The median number of sterile moths caught in conventional orchards varied less among years than between generations within years (Table. 1). There was no significant difference (Dunn's test $\alpha = 0.05$) in the median number of sterile moths caught during weeks 1 - 8 in 1995, 1996, 1997 and 1999 (Table. 1). In 1998 however, significantly more sterile moths were caught, mean temperatures were higher, and more $DD_{10\,°C}$ accumulated during the first eight weeks of the season than any other year (Table 1). In each of the five years, median trap catches in weeks 1 - 8 (first generation) were less than median catches in weeks 9 - 16 (second generation). In each year, the ratios of second-generation to first-generation median trap catches were significantly ($P < 0.05$) different than an expected 1:1 ratio under a null hypothesis of equal probabilities of catch (Table 1), and over five years sterile moths were 3.9-fold more likely to be caught in second than in first generation.

Table 1.
Median number of sterile male codling moths caught per trap per week and degree-day (DD) accumulations during first- and second-generation wild moth flight activity and median yearly catches and sterile:wild (S:W) overflooding moth ratios in four insecticide-treated conventional apple orchards receiving sterile codling moths under management of the Okanagan-Kootenay SIR Programme, in Cawston, BC, 1995 - 1999.

Year	Adult generation[1,2]				Generational trap catch ratios[3]	Median yearly total catch	Yearly S:W overflooding ratios
	First (weeks 1 - 8)		Second (weeks 9 - 16)				
	Catch	$DD_{10°C}$	Catch	$DD_{10°C}$	Second / First		
1995	27.4a	463	53.2 a	584	1.9 *	40.3a	24
1996	42.7a	339	175.1 b	674	4.1 *	108.9b	139
1997	37.9a	427	72.0 a	611	1.9 *	56.4a	203
1998	112.9b	512	204.9 b	757	1.8 *	158.9b	794
1999	65.3a	374	168.5 b	653	2.6 *	116.9b	275
1995-1999	42.7	423	168.1	656	3.9 *	108.9	287

[1] Trap-catch medians for a generation within a column followed by different letters are significantly different (Dunn's test $\alpha = 0.05$) following a significant ($P < 0.05$) Kruskal-Wallis Test.
[2] $DD_{10°C}$ totals above 10 °C accumulated for first generation from Julian Day 128 - 184 and for second generation from Julian Day 185 - 241.
[3] Asterisks indicate trap-catch ratios are significantly different ($P < 0.05$) from 1:1 by a χ^2 test on actual trap catches.

Sterile:Wild Moth Ratios. S:W ratios presented as yearly averages for all orchards suggest overflooding ratios were well above 40:1 in all years except 1995 (Table 1), steadily increasing from 1995 - 1998. However, restricting analysis of S:W ratios in the insecticide-treated orchards to those weeks when wild moths were actually caught (Table 2), indicates ratios during the first eight weeks of the season were less than 40:1, 91% of the time in 1995 (21 of 23 orchard-weeks), 60% in 1996 (9 of 15 orchard-weeks), and 29% in 1997 (2 of 7 orchard-weeks). Closer examination of S:W ratios in these orchards shows that during the first four weeks of the trapping season, when wild catches peaked (Fig. 1A), S:W ratios never reached 40:1 in 1995, did so once in 1996 and only twice in 1997. In one of the three orchards where wild moths were caught in 1998 (Table 2), S:W ratios fell below 40:1 in both weeks this occurred. It was not until 1999, when wild catches were near zero (Fig. 1A), that a 40:1 S:W ratio was achieved in all orchards during the first eight weeks of the season (Table 2). Similar analysis performed in the second half of the season indicates S:W ratios fell below 40:1 about 39% of the time over the five years (9 of 23 orchard weeks), which was significantly less often than during the first eight weeks (Table 2).

S:W ratios in pheromone-treated orchards were only analyzed for 1995 and 1996 because few or no wild moths were caught in these orchards in 1997 - 1999 (Fig. 1B). In spite of yearly reductions (4.5-fold) in catches of sterile moths in pheromone-treated relative to insecticide-treated orchards (Fig. 2), S:W ratios during the first eight weeks of 1995 were similar in both sets of orchards (Fig. 3A-B). This similarity was surprising because in most weeks, wild catches were greater in pheromone- than in insecticide-treated orchards where wild catches went above 2 moths / trap / week only once. While S:W ratios in pheromone-treated orchards never went above 40:1 during flight of first-generation

Table 2.

Frequency of weeks during the first (weeks 1 - 8) and second generation (weeks 9 - 16) of wild codling moths when sterile:wild ratios in pheromone-trap catches were less than 40:1 (numerators) for those weeks when wild moths were caught (denominators) in each of four insecticide-treated conventional orchards receiving sterile codling moths under management of the Okanagan-Kootenay SIR Programme, in Cawston, BC, 1995 - 1999.

Year	Adult generation	Orchards				Yearly frequency totals	Fisher's Exact Test *P*-value[1]
		1	2	3	4		
1995	1st	5 / 5	7 / 8	5 / 5	4 / 5	21 / 23	0.0345
	2nd	1 / 2	3 / 6	1 / 2	3 / 4	8 / 14	
1996	1st	2 / 2	1 / 5	2 / 3	4 / 5	9 / 15	0.0333
	2nd	0 / 1	1 / 4	0 / 0	0 / 4	1 / 9	
1997	1st	0 / 0	2 / 4	0 / 1	0 / 2	2 / 7	ns
	2nd	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	
1998	1st	0 / 0	0 / 3	2 / 2	0 / 2	2 / 7	ns
	2nd	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	
1999	1st	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	ns
	2nd	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	
Orchard totals	1st	7 / 7	10 / 20	9 /11	8 / 14	34 / 52	0.0494
	2nd	1 / 3	4 / 10	1 / 2	3 / 8	9 / 23	

[1]Fisher's Exact Test (2 × 2 contingency table) of the null hypothesis of equal frequencies in each generation during which the sterile:wild ratios are < 40:1 using yearly frequency totals from all orchards. ns = $P > 0.05$

wild moths in 1995 (Fig. 3B), they were only marginally better in the insecticide-treated orchards where ratios reached 40:1 once (Fig. 3A). Note however, this one occurrence was in the week when wild moths were near their lowest, and followed a week when catches of wild moths peaked but catches of sterile moths inexplicably dipped (Fig. 3A). S:W ratios in pheromone-treated orchards fell below 40:1 most of the second half of 1995 (Fig. 3B) because catches of wild moths increased. Late-season increase in wild-moth activity in these orchards may be caused by using more attractive 10 mg lures and waning effects of pheromone disruption dispensers. This apparent increase in activity of second-generation wild moths was a temporary aberration in pheromone-treated orchards. Over five years, total seasonal catches of wild moths declined faster in pheromone-treated orchards than they did in the insecticide-treated orchards (Fig. 1).

Pane Traps *versus* Pheromone Traps. Catches in pane traps from individual orchards were too low to show any significant weekly patterns or conduct any meaningful statistical analyses on catches of either sterile or wild codling moths, so catches were pooled across orchard treatments. S:W ratios on pane traps in weeks 1 - 8 (first generation) are compared to those in weeks 9 - 16 (second generation) and ratios on pane traps are compared with those reflected by pheromone trap catches (Fig. 4). In the insecticide-treated orchards (Fig. 4A) catches in pane traps reflect the same pattern as pheromone traps, low S:W ratios were observed in weeks 1 - 8 and higher S:W ratios in weeks 9 - 16. S:W ratios on pane traps increased 6.2-fold while those in pheromone traps only increased 4.8-fold across generations (Fig. 4A), suggesting activity-driven responses to the former were more important than increased pheromone responses to the latter.

In pheromone-treated orchards (Fig.

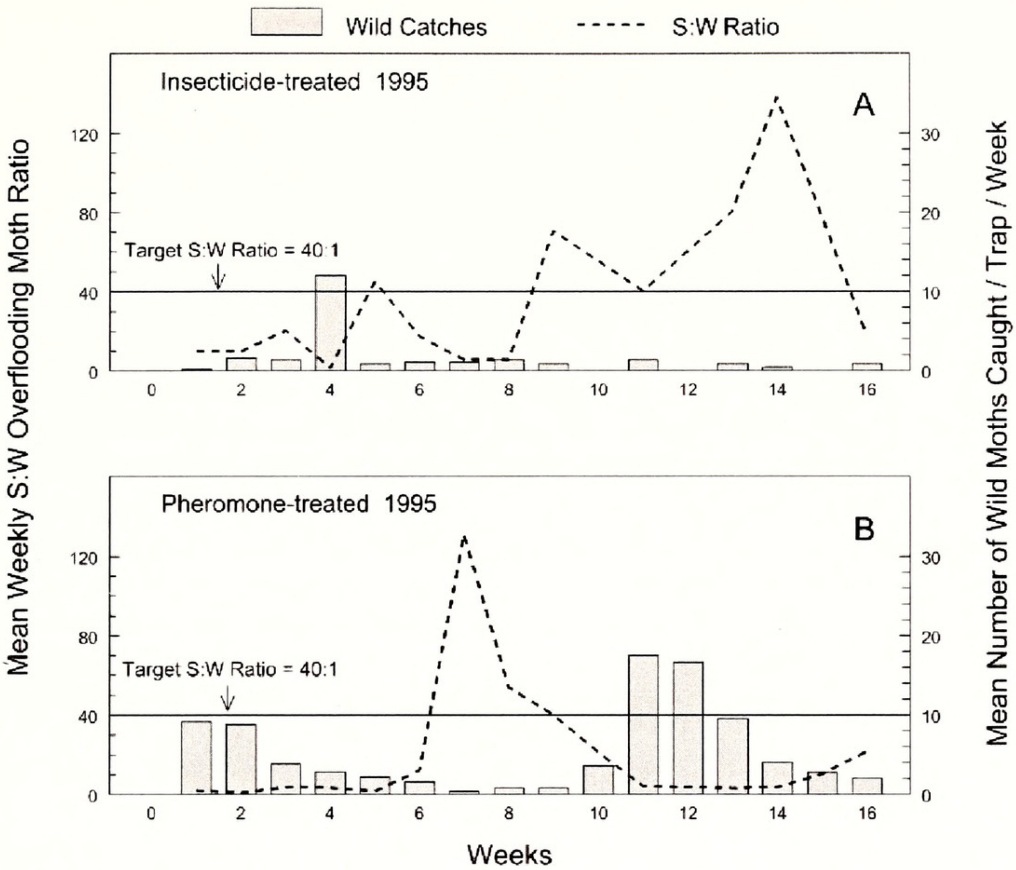

Figure 3. 1995 mean weekly catches of wild male codling moths and sterile:wild moth ratios in pheromone-baited wing traps in insecticide-treated conventional (A) and pheromone-treated (B) organic apple orchards under management of the Okanagan-Kootenay SIR Programme, in Cawston, BC. n = 4 conventional and 5 organic orchards and 2 - 6 traps / orchard.

4B) catches with both pane traps and pheromone traps once again reflect the established pattern of low S:W ratios in weeks 1 - 8 and higher ratios in weeks 9 - 16. However, in pheromone-treated orchards S:W ratios on pane traps showed the same cross-generation increase (2.1-fold) as pheromone traps (2.3-fold), reflecting suppression of sterile male response to pheromone-baited traps in orchards under pheromone-based mating disruption (Fig. 2), which artificially limits ratios.

Catches of females on pane traps were too low to ascribe any specific seasonal pattern in their response.

DISCUSSION

Decades of research examining use of sterile insect technique to control codling moth have identified the need to maintain 40:1 S:W overflooding moth ratios in order to achieve population reduction, and have further emphasized the importance of doing this during the first generation because the reproductive potential of the species is lowest at this time of year. Our detailed examination of seasonal flight activity and recapture of male codling moths in nine commercial orchards under management by sterile insect release showed significant within-season variation over five years, often resulting in S:W ratios less than 40:1. Low S:W ratios were most pronounced in, but not restricted to, the first eight weeks of the trapping season from May through June (Fig. 3; Table 2), the period of wild-moth activity referred to as first generation (Madsen and Procter 1985).

In this study, catches of first-generation wild moths generally peaked during the first four weeks of the season in late May

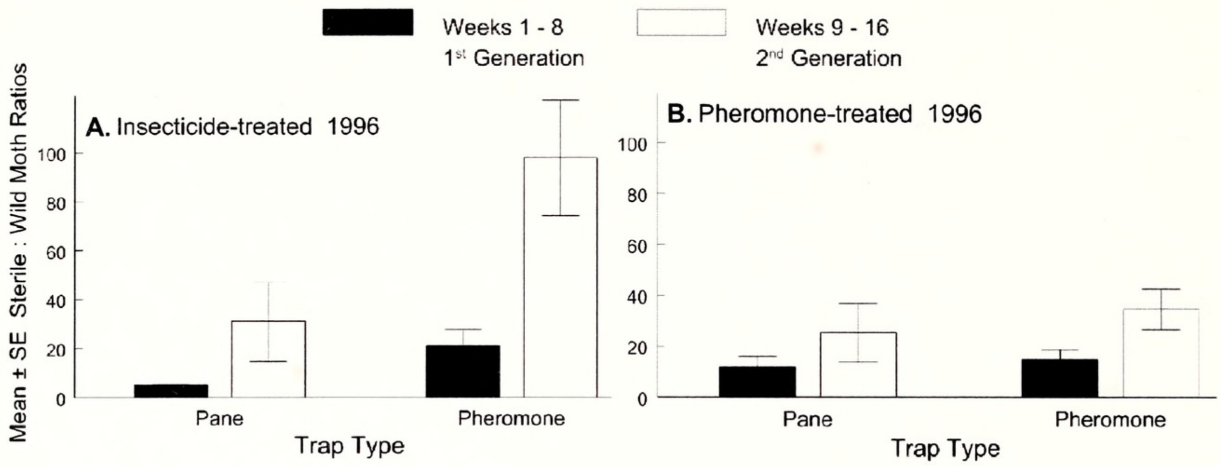

Figure 4. 1996 mean (± SE) sterile:wild moth ratios from catches in pheromone-baited wing traps and sticky pane traps during first- (weeks 1 - 8) and second-generation (weeks 9 - 16) flight-activity periods for wild moths in insecticide-treated conventional (A) and pheromone-treated organic (B) apple orchards under management of the Okanagan-Kootenay SIR Programme, in Cawston, BC. n = 4 conventional and 5 organic orchards and 2 - 6 pheromone traps and 8 - 30 pane traps / orchard.

or early June (Fig. 1A-B) and when it occurred, second-generation catches peaked in weeks 11 - 12 during early August (Fig. 1B). In contrast, catches of sterile moths (Fig. 2) were at their lowest in the first four weeks of the season, increasing thereafter and reaching a plateau around week 10 in July. The observed sigmoid pattern (Fig. 2) in recaptures of sterile moths might be explained by a combination of factors: (1) released moths that live longer than a week may accumulate with subsequent weekly releases, (2) there may be greater mortality of sterile moths in spring perhaps because of more frequent application of insecticides or cooler temperatures, (3) sterile moths may be less responsive to pheromone traps in spring than summer, (4) sterile moths may be less active under cool spring temperatures than they are in summer, or (5) trap catches may be limited in summer because trap bottoms become saturated with moths reducing apparent late season activity. Whatever the cause(s) it seems likely this seasonal pattern is inherent to activity of sterile moths because a similar pattern was observed in both insecticide- and pheromone-treated orchards, where the latter received no pesticides and where traps never became saturated in moths (Fig. 2).

Response to temperature likely explains much of this seasonal variation because the greatest number of sterile moths was caught in 1998 (Table 1), the warmest spring in this five-year study, and a significant linear correlation was found between mean weekly catches and mean temperatures. S:W ratios in catches on passive pane traps were also greater during weeks 9 - 16 compared with weeks 1 - 8 (Fig. 4A), lending support to the idea that sterile moths are simply less active than wild moths in cool spring weather (Bloem and Bloem 1996; Bloem *et al.* 1998). The lack of any significant difference in spring-time S:W ratios in pheromone- and insecticide-supplemented orchards when measured by pheromone traps (compare Fig. 4A and 4B), is further indication of a seasonal difference in activity. Catches of sterile moths are suppressed by pheromone treatment in summer (Fig. 2) and this reduces S:W ratios relative to insecticide-treated orchards when measured using pheromone traps during weeks 9 - 16 (compare Fig. 4A and 4B). In spring the opposite occurs. Activity of sterile moths as evidenced by catches in the insecticide-treated orchards (Fig. 2) is already low in spring. Therefore, full expression of disruption is not seen in spring and S:W ratios are more similar in pheromone- and insecticide-treated orchards when measured using pheromone traps (compare Fig. 4A and 4B).

Inactivity of sterile moths may be an artifact of laboratory-rearing conditions. Proverbs (1971) stated, although no data were presented, that moths reared at high constant temperatures, as they are in the current SIR Programme (Bloem and Bloem 2000), are less active in spring than wild moths, and males reared at constant temperatures are apparently less responsive to synthetic pheromone than males reared under fluctuating temperatures, especially in spring (Proverbs 1982). Hutt (1979) confirmed that recapture of sterile codling moths in pheromone traps increased after insects were reared at fluctuating temperatures. However, Bloem *et al.* (1998) did not see an affect of fluctuating rearing conditions on pane-trap catches in spring and they saw greater catches in pheromone traps in fall than in summer, even though dusk temperatures were cooler in fall. These apparent contradictions suggest additional factors may be at work. Whether temperature impacts flight activity of sterile moths directly, or indirectly through rearing, or somehow modulates their response to pheromone sources remains to be determined. It should be noted that mass-rearing of sterile moths under fluctuating temperature regimes was tested but deemed impractical in the current Osoyoos rearing facility (Bloem *et al.* 1998).

When the SIR Programme was designed and production capabilities of the rearing facility were considered (Dyck *et al.* 1993), it was calculated that production and release should be able to ensure 40:1 overflooding ratios if the *Pre-release Sanitation* phase could reduce populations of wild codling moth to levels resulting in no more than 0.1- 0.3% harvest damage. It was assumed this level of damage would result in no more than 2 wild moths / trap / week / orchard and initial release numbers were generated around this threshold (Bloem and Bloem 2000). Assuming catches in pheromone traps reflect operational ratios of sterile and wild moth populations, traps need to show catches of 80 sterile males / trap / week, if the SIR Programme is going to maintain 40:1 ratios when wild populations are this large. Our data show that during the first eight weeks of the season this target was only achieved in 1998. These data strongly suggest populations of wild moths should be reduced to levels resulting in no more than 1 wild moth / trap / week at peak flight to ensure S:W ratios are consistently at or above the 40:1 target during spring.

Alternatively, if wild populations are not reduced, 40:1 S:W ratios might be maintained by releasing more sterile moths when wild populations are reaching 2 moths / trap / week. Intuitively, this sounds like a reasonable approach but our analysis suggests it may be questionable in spring. For example, recaptures of sterile moths released in 1995 and 1997 were not significantly different in either generation (Table 1). This is surprising because the SIR Programme reportedly released 1.7 times more sterile moths in 1997 than 1995, and fewer insecticides were applied against codling moth in 1997 than in 1995. With catches of sterile moths averaging 37.9 / trap / week during first generation in 1997, the best that might have been achieved was a 19:1 S:W ratio if 2 wilds / trap / week were caught. At this level of wilds even median catches in summer 1997 (Table 1) would not have produced an overflooding ratio of 40:1. These observations strongly suggest that increasing production and release of sterile moths in 1997 had no demonstrable impact on recapture of sterile moths in our study orchards, particularly in spring, and these increases would rarely have resulted in adequate S:W ratios in individual orchards unless wild populations were reduced well below 2 moths / trap / week.

As a caveat, it should be noted that more sterile moths were produced and released in 1997 than in 1995, but there are no records to verify the number of moths release drivers delivered to any particular orchard. It can also be argued that operational S:W ratios might have appeared larger in this study had we used a trap which was less susceptible to saturation with sterile moths than small wing traps.

However, while trap saturation may play a role in the plateau seen on catch curves in summer (Fig. 2), which conceivably places upper limits on S:W ratios, trap saturation was never an issue in spring, nor on pane traps, nor in pheromone-treated orchards showing the same trends. One of the reasons we used wing traps was because these traps were the standard for the operational programme being assessed.

In spite of suboptimal S:W ratios, mean seasonal catches of wild moths declined from 1995 - 1999 in orchards receiving sterile moths and supplemental insecticides in spring. After three years, second-generation moths were almost undetectable (Fig. 1A). Ignoring the few late-season catches of moths in 1998 and 1999 as resulting from outside sources like wooden apple bins (SIR Programme, unpublished data), an apparent disappearance of second-generation codling moths by 1997 (Fig. 1A), combined with maintenance of S:W moth ratios greater than 40:1 during weeks 9 - 16 throughout 1996 - 1997 (Table 2), supports the view that it is possible to eliminate summer populations of codling moths within three years in localized areas. The difficulty comes in separating the cause(s) of this population decline. It seems likely that intensive insecticide application during first generation (Bloem and Bloem 2000) was critical in achieving this result. Insecticides applied against first-generation larvae will undoubtedly reduce resulting adult populations in second generation, especially when this is done on an area-wide basis as it was during this study. The potential for immigration of background wild populations was probably greatly reduced by this area-wide approach to spraying and other clean-up procedures. The effect of these insecticides is probably the reason why traps in conventional insecticide-treated orchards revealed little or no second-generation wild moth flight activity in 1995 and 1996, but in pheromone-treated orchards there was a relatively large second-generation catch in 1995 (Fig. 1A-B). It seems difficult to argue that observed reductions in second-generation wild moths (Fig. 1A) would have more to do with suboptimal S:W ratios in spring, than with insecticide applications. Likewise, providing evidence that large S:W ratios during summers of 1997 - 1999 had more to do with increasing catches of sterile moths (Fig. 2), than it did with the absence of a second-generation of wild moths (Fig. 1A), is difficult. This being the case, it may make more economic sense to apply insecticides during first generation and only release moths during the second generation.

In spite of extensive spraying, five years of moth release (1994 - 1998), and S:W ratios during second-generation that were always above 40:1 in 1997 and 1998 (Table 2), first-generation moths persisted into 1999 in the insecticide-treated orchards. These data are similar to results reported for Zone 1 as a whole, where average trap captures for all orchards showed great reductions in the second generation in 1995, and persistence of a small first generation through 1997 (Bloem and Bloem 2000). Further evidence of this persistence came from 1500 Zone-1 orchards sampled in 1999 using cardboard tree bands (Judd *et al.* 1997), which found that 15% still had overwintering codling moth larval populations going into 2000 (HMAT, unpublished SIR Programme data). It appears a small portion of the larval population arising from first-generation mating can escape control by insecticides in spring and sterile insect technique in summer. We hypothesize that early-emerging univoltine larvae not killed by insecticides in spring, and diapausing in summer because they are univoltine, could potentially escape both controls. Studies of the degree to which diapause and voltinism may affect predictions of eradication or long-term management of codling moth populations are warranted, especially as efforts to release sterile insects move further north in BC where a greater degree of early diapause is anticipated.

Predictions of eradication of codling moth from Zone 1 by 1996 (Dyck *et al.* 1993) and subsequent predictions by 1999

(Bloem and Bloem 2000) were not realized. Our data suggest that low S:W overflooding ratios during spring may have contributed to a slow rate of population decline. Several studies have emphasized the point that sterile males have their greatest impact on reproduction of codling moth in first generation (Proverbs *et al.* 1966; Proverbs 1971). In studies where codling moth population reduction has clearly been demonstrated using sterile insect technique (Proverbs *et al.* 1966, 1977; Proverbs *et al.* 1982), the authors report it was rare for S:W ratios to fall below 40:1, at anytime during the season. Inadequate spring-time ratios in the BC SIR Programme, means control is largely exerted against one generation each year. Controlling three generations instead of six over a three-year period, likely doubles the time required for eradication from 3 - 6 years, which seems consistent with reported progress (Bloem and Bloem 2000). Within-season and between-orchard variation in S:W ratios was not revealed by average yearly overflooding ratios (Table 1), a coarse-grained statistic often used in sterile insect programmes. These summary type ratios are artificially inflated by summing catches of sterile moths during periods of the season when there are no wilds, thus giving a misleading impression of the control effort being achieved. This type of reporting may not be applicable in an area-wide programme where there are many, small, non-contiguous orchards and wild populations to be eliminated.

If eradication were to be a goal of any SIR programme against codling moth, then efforts must include continued use of insecticides in spring, or reduction of early-season reproduction by means other than sterile moths. In choosing supplemental controls it must be noted that while applying insecticides during first generation obviously increases larval mortality, it also kills sterile moths, or potentially impairs their pheromone response (Linn and Roelofs 1984; Haynes and Baker 1985). Biological insecticides like Virosoft-CP4®, a commercial granulovirus product may be useful because they act on larvae and not adult moths. Our results suggest application of pheromone-disruption treatments against first-generation moths may also be very useful in augmenting control by sterile insects, especially in organic orchards.

Although codling moth was not eradicated in BC and progress was slower and more costly than anticipated, it was reduced to sub-economic levels in most Zone-1 orchards by 2001. Reliance on sterile insect technology seems capable of keeping damage below economic levels but there is some question about financial sustainability (Dendy *et al.* 2001). When much of the expenditure in a typical SIR programme is on rearing and releasing moths, the moths must be used effectively. In our analysis, we have focussed on a ratio of 40:1, because all previous work suggested this was necessary for eradication. However, it appears that ratios less than 40:1 can stabilize but not eliminate populations, and provide some suppression rather than eradication. The key question for management then becomes what ratios are acceptable in that new context.

An analysis of the SIR Programme trapping data from 1994 - 2004, on an individual orchard basis, within a spatial context, may provide insight on the S:W ratios providing suppression. If historic operational S:W overflooding ratios were correlated with damage data, analysis may reveal why the programme has worked in some orchards and areas, and not in others. Such analysis may also provide a more realistic appraisal of any codling moth SIR programme and would compliment the detailed observations we have made on a subset of orchards. This type of analysis will also be useful in planning the best use of sterile codling moths in BC, and other parts of the world where this technique is currently being considered.

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