PUTTING THE STERILE INSECT TECHNIQUE INTO THE MODERN INTEGRATED PEST MANAGEMENT TOOLBOX TO CONTROL THE CODLING MOTH IN CANADA

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SUMMARY

The Okanagan-Kootenay Sterile Insect Release (OKSIR) programme, in southern British Columbia, Canada, has been successfully applying the Sterile Insect Technique (SIT) as part of a sustainable area-wide integrated pest management (AW-IPM) programme to control the codling moth *Cydia pomonella* L. in pome fruits in the region for over 20 years. Chemical, cultural and biological techniques that complement the SIT are also integrated into orchard and regional pest management plans by the programme and/or individual growers. The AW-IPM programme is supported by close monitoring of codling moth populations in orchards and adjacent urban properties; enforcing suppression of codling moth infestations in orchards and urban areas; removing derelict orchards, wild host trees and poorly managed host trees; and increasing public awareness and education. Successful collaboration between the OKSIR programme, the pome fruit industry, area residents and various government organizations has reduced codling moth populations by 94%, relative to pre-programme levels, and codling moth damage to less than 0.2% of fruit, in more than 90% of the orchards in the programme area. Local pesticide sales indicate a 96% reduction in the amount of active ingredient used against the codling moth since 1991. Implementing the SIT through an innovative social approach to local community-centred area-wide pest management has posed many challenges and created many learning opportunities. The codling moth mass-rearing facility in Osoyoos, British Columbia, has the capacity to produce 780 million sterile codling moths annually, but only a portion of that is used seasonally to treat 3400 hectares (ha) of pome fruit made up of small orchards intermixed with residential areas in the Okanagan Valley. As a result of climate change and increasing global trade, destructive insect pests are migrating to new habitats throughout the world. These new threats must be managed in ways that protect both the agrifood industries and the natural environments in which the industries operate. The OKSIR programme is an effective and easily transferred model to meet these challenges, especially as a supplement to other biological control methods. The programme is also a

compelling model of success that can encourage other regions to use the SIT in their pest management toolbox to combat codling moth infestations across multiple local community jurisdictions using environment-friendly, cost-effective methods based on proven technology. The OKSIR programme is exploring the sale of surplus sterile moths, egg sheets or possible virus production as an opportunity to offset costs of incorporating additional area-wide approaches to combat other invasive pests.

Key Words: beneficial insects, biological control, virus, pheromone-mediated, mating disruption, pesticide resistance, area-wide integrated pest management, IPM, SIT, *Cydia pomonella*, British Columbia

1. INTRODUCTION

The codling moth *Cydia pomonella* L., the proverbial “worm in the apple”, damages pome fruit directly, and is a key pest of this crop in most of the areas where it is cultivated (Beers et al. 2003). If left uncontrolled, the codling moth can damage 50 to 90% of an apple crop (Ontario Ministry of Agriculture, Food and Rural Affairs 2011). Though the codling moth originated in Asia Minor, it arrived in the Okanagan region in the early 1900s, making it a pest for nearly as long as apples have been produced commercially in the area (Bloem et al. 2007). The Okanagan region in southern British Columbia, the western-most province of Canada (Fig. 1), is unique in Canada because of its dry, sunny climate (hot, dry summers and mild winters). Tree fruit production has been a hallmark of the region for over 100 years.

In this region, and most other areas where pome fruits are produced, broad-spectrum insecticides were previously used heavily to control codling moth populations (Madsen and Morgan 1970). Codling moth populations in many areas had started developing resistance to some classes of insecticides, and concerns over development of cross-resistance were mounting (Dunley and Welter 2000). The use of broad-spectrum insecticides also had indirect costs related to the loss of natural enemies and pollinators; it was a source of environmental contamination, and consumers were concerned over insecticide residues on food (Vreysen et al. 2010). For these reasons, negative public attitudes towards the use of pesticides stimulated support for codling moth control strategies that did not rely on synthetic pesticides (Madsen and Morgan 1970).

Twenty years of research and planning culminated in the early 1990s with the implementation of the Okanagan-Kootenay Sterile Insect Release (OKSIR) programme (Dyck et al. 1993). Though the programme was initially more expensive than a conventional insecticide programme, a number of factors contributed to its adoption in the region. Restrictions on pesticide use, particularly those most effective at controlling the codling moth, were increasing. Concern for the impacts of insecticides on beneficial insects, the environment, and surrounding communities was mounting. Finally, reducing pesticides and codling moth populations created marketing advantages for local pome-fruit growers. In weighing these costs and benefits, and taking a long-term view of their implications, the programme was deemed to have a net benefit to the industry and community (Holm 1985, 1986; Jeck and Hansen 1987) and was therefore initiated in 1991.

2. THE STERILE INSECT TECHNIQUE

The concept of the Sterile Insect Technique (SIT) for insect control was conceived by E. F. Knipling in the 1930s, and first developed and applied in the 1950s to successfully control the New World screwworm *Cochliomyia hominivorax* Coquerel (Klassen et al. 2021). The SIT is a biological insect control method in which insects are mass-reared, irradiated to make them sterile, and then released into the environment at regular intervals to mate with wild insects. Wild female insects that mate with the sterilized male insects produce no offspring, thereby reducing the number of insects in the next generation. Continued use of the SIT at appropriate overflooding ratios thus leads to successively smaller generations, and can, if applied correctly on an area-wide basis, result in an area of low pest prevalence or even eradication of the population in that area (Dyck et al. 2021).

Since the 1950s, the SIT has been successfully used around the world to suppress, prevent, contain or eradicate many dipteran insect populations such as the New World screwworm, several tsetse flies *Glossina* spp., and fruit flies such as the melon fly *Zeugodacus cucurbitae* Coquillett, Mediterranean fruit fly *Ceratitis capitata* Wiedemann and Mexican fruit fly *Anastrepha ludens* Loew (Dyck et al. 2021).

The SIT has also been applied with success against various lepidopteran pests such as the cactus moth *Cactoblastis cactorum* Berg, the painted apple moth *Orgyia anartoides* Walker, the false codling moth *Thaumatotibia leucotreta* Meyrick, and the pink bollworm *Pectinophora gossypiella* Saunders (Carpenter et al. 2007; Suckling et al. 2007; Dyck et al. 2021; Bello et al., this volume; Boersma, this volume; Staten and Walters, this volume).

3. OKANAGAN-KOOTENAY STERILE INSECT RELEASE PROGRAMME

At the inception of the OKSIR programme, other non-insecticide-based insect control methods, such as pheromone-mediated mating disruption, were considered in order to reduce codling moth populations in southern British Columbia (Judd et al. 1996). Due to the heterogeneous landscape of orchard and residential areas in most of the region (creating a non-contiguous orchard area (Cardé 2007; Witzgall et al. 2008)), the SIT was considered a more suitable solution to manage the codling moth. The OKSIR programme was initially conceived in 1991 as an eradication programme, and was based on research conducted by Proverbs and colleagues in the 1970s and 1980s (Proverbs et al. 1978, 1982).

The mandate and objectives changed in 1997 when the goal became suppression of the codling moth below economic levels through delivery of an efficient, effective and sustainable AW-IPM programme using the SIT as the main control tool. It was concluded that permanent area-wide suppression rather than eradication was a more realistic goal because of the large programme area, the limited human and financial resources available, and because an expensive quarantine programme that would be necessary during and after eradication for which the Federal Government of Canada, which regulates quarantines, had no plans (Bloem et al. 2007).

A community-based, AW-IPM approach was essential to reduce costs and increase the effectiveness of the programme. Area-wide measures applied over a geographically- or politically-defined area enable control of an entire pest population, a prerequisite to sustainable pest management. Insects do not respect property boundaries, and a field-by-field approach that focusses narrowly on the value loss to individual crops cannot successfully control pest populations because unmanaged cultivated and wild host trees on neighbouring public, private or abandoned land are recurrent sources of reinfestation (Hendrichs et al. 2007).

An AW approach requires a strong partnership among all stakeholders to succeed. For OKSIR, a partnership was therefore developed between the region's local governments and the tree-fruit industry. The Province of British Columbia enacted legislation establishing a mandatory community-based, AW-IPM programme (Municipalities Enabling and Validating Act [RSBC 1960] 1989) that required all property owners, including both residential and commercial host-tree owners, to control codling moth infestations and participate in local funding of the programme.

Researchers at Agriculture Canada, local governments and growers selected the SIT to reduce the use of insecticides because of concerns about excessive pesticides in the environment, an attempt to delay insecticide resistance, and to support agritourism opportunities in the area. This collective action, i.e. action taken jointly by the stakeholders in pursuit of their perceived shared interests, made it possible to deliver results in a much larger geographic scale than could be provided or protected by a single farmer (Lefebvre et al. 2015b).

3.1. Programme Area

The programme area covers approximately 600 km², and at its onset serviced approximately 8 900 ha (22 000 acres) of pome fruit; the surface of pome fruit within this area was gradually reduced to 3 440 ha (at the time of writing). The large area to be serviced, and the need for pre-release sanitation (discussed below), required the programme to be implemented sequentially across three zones (Fig. 1). Pre-release sanitation and construction of the rearing facility began in zone 1 in 1992 followed by moth release in 1994. Pre-release sanitation started in 1998 and 2000 in zones 2 and 3, respectively, with moth release occurring after two years of sanitation efforts.

3.2. Rearing Facility

At the heart of the OKSIR programme is a state-of-the art insect mass-rearing facility. Construction of the facility located in Osoyoos, British Columbia was completed in 1993. The facility is capable of producing more than 2 million sterilized moths per day or 780 million sterile codling moths annually. Maintenance and operational costs, as well as capital upgrades, are funded by local property tax requisitions.

3.3. Programme Services

The OKSIR programme services include pre-release sanitation, mandatory SIT application, surveillance, enforcement and education:

Figure 1. Location of the OKSIR programme. The map of Canada (right) indicates where the OKSIR Programme is located in British Columbia, and the inset (left) illustrates how the programme area, covering a linear distance of ca. 175 km, was divided into three zones.

3.3.1. Pre-Release Sanitation

The first phase of the programme was pre-release sanitation. This entailed the removal of thousands of unmanaged/abandoned host trees to reduce refugia for the codling moth. The programme also coordinated and supported the suppression of codling moth populations in orchards through the use of conventional insecticides, cultural practices and pheromone-mediated mating disruption. Wild codling moth populations had to be reduced as much as possible throughout all communities to increase the efficiency of subsequent SIT application. The programme continues to remove unmanaged/abandoned host trees and derelict orchards as needed.

3.3.2. Mandatory SIT Application

The programme delivers a mandatory area-wide control application of sterile codling moths to every orchard property, i.e. 2000 sterile codling moths of mixed sex (1:1)/ha/week for approximately 20 weeks per season. As necessary and practical, additional releases are made to address high pest pressure “hot spots.”

3.3.3. Surveillance

Every orchard property is monitored with pheromone-baited traps (1 trap/ha) that are checked once a week. These spatially explicit trapping data are disseminated in real-time through the programme’s website to allow growers to respond rapidly with supplementary controls if needed (OKSIR 2017).

Other monitoring techniques include: in-season fruit inspections, end-of-season assessment of fruit damage, and banding of host trees (corrugated cardboard strips wrapped around trees to trap mature larvae; later the strips are removed and destroyed). Codling moth host trees are also monitored on non-orchard properties (properties with less than 20 host trees) by visual fruit inspections and banding. It is important to recognize that the monitoring of non-orchard properties is focussed on a 200-m buffer zone around commercial orchards, though other properties are visited as needed.

3.3.4. Enforcement

Codling moth control is enforced throughout the programme area. The programme has the legal authority to enter orchards and residential properties to inspect for codling moth infestation and issue control orders for fruit stripping and tree removal. Dedicated enforcement ensures that all host-tree owners do their part to prevent outbreaks and ensure proper management of the codling moth.

3.3.5. Education

Education is essential to reduce enforcement actions as much as possible. Extensive education and outreach about the programme and codling moth control is done each season with growers and residential tree owners in the region. This is critical, especially during the first stages of programme implementation. Outreach occurs via media advertising, publications, newsletter articles, the programme website, field visits and public meetings.

An information technology specialist maintains the website that provides real-time trapping and phenological data to growers. The growers themselves become sources of positive promotion once they are convinced of the benefits that the OKSIR programme is bringing to their economies and the environment (Bloem et al. 2007).

3.4. Governance, Funding and Budget

The OKSIR programme is governed by a Board of Directors, comprising five elected community representatives from each of the four regional municipal governments within the programme's service area, and three grower representatives nominated by the pome fruit industry.

The programme has a central administration and is funded through local taxation. All properties in the region pay a tax based on assessed land value. Currently, the average residential property pays ca. CAD 11/year (USD 9/year), and growers pay a parcel tax of ca. CAD 340/ha. Overall, the programme obtains 60% of its funding from local property owners in the community and 40% from commercial growers. The percentage share of the funding allocation has been arbitrarily determined based on political will. The annual programme budget is ca. CAD 3.2 million. In 2016, CAD 1.7 million was collected from general taxpayers via land value tax and CAD 1.16 million from growers (approximately 3440 ha) via parcel tax (cost/ha). The programme received an additional ca. CAD 350 000 from the sale of excess products, interest income and grants.

Of the total operating budget in 2016, CAD 1.1 million was used for field operations, CAD 1.1 million to operate the mass-rearing facility, and CAD 681 000 to cover administrative costs. The programme services are delivered by 16 full-time staff and up to 75 seasonal staff working in the field and mass-rearing facility. From 2010 to 2017, the programme operated without increase in either land value or parcel taxes.

4. SUCCESS OF THE OKSIR PROGRAMME OVER 20 YEARS

Over the more than 20 years that the OKSIR programme has been operating, it has achieved sustained codling moth suppression (Fig. 2). Overall, there was a 94% reduction in codling moth population, relative to pre-programme levels in the OKSIR programme area as measured by pheromone traps (Fig. 2).

It must be noted that in zones 2 and 3, on recommendation of an operational advisory committee, the OKSIR programme piloted zone-wide use of pheromone-mediated mating disruption in commercial orchards as an alternative to the SIT from 2011-2014. Pheromone trap captures during these years are not directly comparable to other years or zone 1 during these years because a different trapping system was used. For economic and other reasons, in 2015 the OKSIR programme returned to using the SIT in commercial orchards across the entire programme area (Cartier 2014). Since 2000, and in all zones, mean codling moth trap captures remain well below the recommended treatment threshold of two codling moths per trap per week for two consecutive weeks (Vakenti 1972) (Fig. 2).

Figure 2. Mean wild codling moth captures per trap per week from 1995 to 2017 for each zone managed by the OKSIR programme in zone 1 (from 1995), in zone 2 (from 1998), and in zone 3 (from 1999), averaged over each fruit-growing season. The dashed line indicates the recommended threshold (two codling moths per trap/week for two consecutive weeks) at which insecticide controls supplementary to the SIT would be required.

In zone 1, codling moth fruit damage was effectively suppressed after approximately five years, and has remained that way in more than 90% of orchards (Fig. 3).

Codling moth suppression followed similar trends in zones 2 and 3, except that population suppression occurred at a slower rate (Figs. 2 and 3). It is difficult to pinpoint exactly why this was the case, and no single factor alone was likely responsible for this result. Reasons for slower population decline include:

- Larger urban centres in zones 2 and 3 with more infested backyard trees acting as refugia for codling moths.
- Pheromone-mediated mating disruption that was used extensively in zones 2 and 3 during the pre-release sanitation phase, may have been less effective than the extensive initial application of organophosphate insecticides for suppression in zone 1.
- The increased service area created greater demand on the programme's limited expert knowledge and human resources.
- The organic fruit producers reside predominantly in zone 1, meaning there may have been less grower buy-in or more scepticism in zones 2 and 3.

Ultimately, by 2015 more than 90% of orchards had less than 0.2% fruit damage due to codling moth (Fig. 3) in all zones.

Figure 3. Percent of programme area with >0.2% of fruit damaged by the codling moth. Bars show data from 1995 (zone 1) and from 2001 (zones 2 and 3) to 2017 for each zone managed by the SIR programme. The dashed line indicates 10% of the programme area, an economic target set by the Programme's Board; 2012 data not available.

On average, 85% of the planted area was sampled every year for fruit infestation just prior to harvest (though this varied significantly across years due to limited human resources) ranging from 15 to 100%. Orchards that were not sampled were those with no evidence of codling moth populations, as evidenced by trap captures, early-season inspections, and previous sample history, and thus were placed in the $\leq 0.2\%$ damage category.

The programme has contributed to a dramatic decrease in the amount of insecticides applied per ha of pome fruit. From 1991 to 2016, there was an estimated 96% reduction in insecticides used against the codling moth (Fig. 4). Other factors, such as changes in spray application rates in spindle versus traditional planting systems, new product formulations, etc., contributed in part to this reduction. Personal testimonies from growers indicated that many have not needed to spray insecticides to control the codling moth in more than 15 years.

Figure 4. Estimated pesticide active ingredient (kg or L) applied per ha per year for all zones managed by the SIR programme from 1991 to 2016 based on the estimated proportion of sales for the 15 products registered for use against the codling moth (note: a number of these insecticides are also applied for other pests and/or crops). The estimates of active ingredients are divided by the area (ha) of planted pome fruit in the programme area to account for changes in sales due to amount of pome fruit under cultivation.

Anecdotal evidence collected during an external review of the OKSIR programme also suggests that there are collateral pest management benefits occurring (Carpenter et al. 2014). Leafrollers *Spilonota ocellana* Denis and Schiffermüller, *Choristoneura rosaceana* Harris and *Archips* spp., were reported to be on the decline similar to what organic growers have experienced, i.e. when insecticide use is reduced the natural enemy populations are allowed to increase and reduce some pest populations (Leach and Mumford 2008).

5. BENEFITS AND OPPORTUNITIES

The OKSIR programme is an AW-IPM programme that is able to combat insect infestations across multiple local community jurisdictions. It is a programme that requires close collaboration between four different regional governments, growers, urban host-tree owners, fruit packers, industry advisors, tree-fruit retailers and researchers. Therefore, there are benefits and responsibilities at all levels, and the continued commitment of all partners is vital.

Prior to the AW-IPM programme and the release of sterile insects, spraying organochlorine and later organophosphate insecticides was for many years the main method to control the codling moth. Growers had to apply multiple cover sprays each season, and concerns that the codling moth might become resistant to insecticides mounted. In addition, there were growing concerns regarding chemical residues on the crop and the insecticide load in the environment. Residents of the Okanagan Valley have a strong preference for reduced insecticide use on their properties as well as on neighbouring farms, and for reduced insecticide residues on food (Cartier 2014). Insecticide poisoning of farmworkers and groundwater contamination are also serious concerns in many fruit-growing areas (Witzgall et al. 2008), and run-off from farmers' fields may have direct toxic effects on the water supply and aquatic organisms.

Following the introduction of the OKSIR programme, the reduced reliance on insecticides used for codling moth control in the region has significantly minimized the potential risks to the environment, including the local biodiversity and water for both people and crops, and has significantly minimized the risks to workers' safety while maintaining the economic viability of the crop (Tracy 2014). Residents who live near the orchards now have lower exposure to insecticides and access to sustainably produced fruit, and they enjoy the benefits of a thriving local agriculture and the green spaces it provides. Also, the local economy is improved because the agritourism and agricultural industries are supported by the programme.

Currently, a trend towards "social economy" is becoming apparent in Canada, in which individuals and groups take into account the social consequences of economic activity, including the increased attention to social issues. Local non-insecticide control of the codling moth can be seen as a "shared value," which is defined as "policies and operating practices that enhance the competitiveness of a company while simultaneously advancing the economic and social conditions in the communities in which it operates" (European Commission 2013).

This trend is evidenced by the willingness of the vast majority (90.4%) of non-agricultural residents in the area to pay for the programme. Under the current funding structure of the area-wide approach, growers pay 65% less than they would for the same service without the programme (Cartier 2014).

Both the provincial and federal governments contributed toward the cost of constructing the codling moth mass-rearing facility (CAD 7.4 million), which is a major seasonal employer in the region. Total employment associated with the programme contributes CAD 2.2 million, or CAD 620 per ha, to the regional gross domestic product (Cartier 2014). Cartier's (2014) benefit-cost analysis revealed that, for every CAD 1 in cost there was CAD 2.5 in benefit, for both producers and society as a whole.

As the mass-rearing facility has the capacity to produce 780 million sterile codling moths annually, of which only a portion is used seasonally to treat the areas in the Okanagan Valley, this has opened opportunities to serve other regions or countries through sales of sterile moths or egg sheets, and offers options for codling moth virus production. As an example, the OKSIR programme currently sells excess production of sterile moths to researchers in the USA working on pheromone research. The New Zealand Institute for Plant and Food Research is conducting a pilot project for codling moth control using sterile codling moth shipped from Canada (Horner et al. 2016). The OKSIR programme also sells egg sheets for commercial virus production.

There are examples of for-profit operations selling sterile insects and related services commercially, such as the onion fly *Delia antiqua* (Meigen) in the Netherlands (Vreysen et al. 2006), Mediterranean fruit fly in Israel and South Africa (Bassi et al. 2007; Barnes et al. 2015), and the false codling moth in South Africa (Boersma, this volume).

As costs of controlling the codling moth decrease because of the success of area-wide application of the SIT, other resources can be redirected to address threats of other/new invasive insect pests. Due to climate change and increasing global trade, invasive insect pests are migrating to new habitats throughout the world.

Subsequent to the successful suppression of the codling moth to below economic levels, the local fruit industry has requested the programme to use its surveillance infrastructure to monitor other existing pests, e.g. leafrollers, and new invasive pests, such as apple clearwing moth *Synanthedon myopaeformis* Borkhausen, apple maggot *Rhagoletis pomonella* Walsh, and brown marmorated stink bug *Halyomorpha halys* Stål. Since programme staff visit the pome orchard properties weekly for codling moth management purposes, there is an opportunity to incrementally add monitoring services for other pests and take advantage of economies of scale.

Insecticide resistance is also increasing. The SIT reduces insecticide use and, therefore, reduces the likelihood of insecticide resistance. There is an opportunity to use codling moth SIT to supplement the use of other biocontrol techniques, such as pheromone-mediated mating disruption or biological insecticides, e.g. *Cydia pomonella* granulosis virus (CpGV) (Judd and Gardiner 2005; Eberle and Jehle 2006; Cardé 2007; Witzgall et al. 2008). The SIT is very efficacious and sustainable, and hence is the ideal tool to supplement other methods as needed (Dyck et al. 2021).

A further benefit to a region of an AW-IPM programme with an SIT component is the provision of employment opportunities for area residents. A major challenge can be the availability and recruitment of sufficient staff for the planned facility and field operations when choosing the physical location of the programme. Central administration of the programme is important because it ensures continuity between areas and allows for the consistent provision of full IPM support services, including monitoring, education and enforcement, at a lower cost. The commitment of staff to the outcome is also critically important; experienced staff is the programme's most valuable resource.

Looking globally, apples and cherries from the area can now be exported into high-value restricted markets, such as Taiwan, China and Japan (the presence of the codling moth restricts the movement of cherries and apples in some high-value Asian markets). The SIT promotes areas of low pest prevalence, which can allow for the biosecurity of the product to be almost guaranteed, while the cost for a rejected

shipment of fruit in such restricted markets and the closure of such markets can be very costly to the exporting nation.

The OKSIR programme is also working with leaders worldwide in addressing invasive pests in a changing climate by developing projects that transfer knowledge using AW-IPM approaches and the SIT. In addition, the programme has successfully exported quality sterile moths to New Zealand, South Africa and the USA for use in IPM pilot projects and research (Blomefield et al. 2011; Carpenter et al. 2012; Horner et al. 2016; Adams et al. 2017).

In recent years, the visibility of the OKSIR programme on the international scene has increased; in 2015 at the 8th International IPM Symposium the programme received the International IPM Award of Excellence for a regional integrated pest management programme (IPM 2015). Also, a panel of international experts recommended the OKSIR programme as a role model for AW-IPM using the SIT (Carpenter et al. 2014).

The Food and Agriculture Organization of the United Nations, the World Bank and other international organizations promote the deployment of biological control agents to suppress pests and replace chemical controls (IAASTD 2009). The Stockholm Convention on Persistent Organic Pollutants, a global environmental treaty effective from 2004, aims to eliminate or restrict persistent organic pollutants (Stockholm Convention 2009). These actions epitomize the global need for environment-friendly pest management programmes like the OKSIR programme. Following improved technology and research, the SIT could play an important role in this area, particularly as a supplement to other biocontrol techniques applied on an area-wide basis (Cardé and Minks 1995; Hendrichs et al. 2007).

6. CHALLENGES

According to Tracy (2014), common obstacles to adopting a programme like the OKSIR are:

1. Low levels of investment in research and development.
2. Lack of coordination among growers in adopting the different methods.
3. Weak or conflicting regulatory framework.
4. Absence of market incentives and consumer awareness.

The OKSIR programme's experience of more than 20 years has revealed vital lessons. The goal in sharing these lessons is to assist other regions and pome fruit growers who want to incorporate the SIT for codling moth control into their pest management system and start their programmes as efficiently and smoothly as possible (Carpenter et al. 2014).

Support from political partners (policy/regulatory) and the public is critically important for establishing and sustaining an AW-IPM programme like OKSIR. The impact of the pest and the techniques used to manage it can be influenced by both politics and emotions. It is vital that all stakeholders share common values, and that their expectations are identified from the beginning and managed along the way. This is crucial for building trust in the programme, especially in its initial phases before the programme results can provide convincing proof.

Champions for the programme outside the administration who represent the interests of each of the stakeholder groups are extremely useful to move the initiative forward and maintain ongoing support for an AW-IPM programme.

Committed partners in the programme are critical to its success. It may be easy to identify and join forces with potential partners, but what happens if this collaboration fails or is unproductive? It is crucial to define how the partnership is constituted. The responsibilities of each partner must be mutually agreeable, such that the integrity and efficacy of the programme can be maintained. Not doing so can jeopardize the success of the entire programme. Defining procedures to allow exit and entry of partners is invaluable.

In the initial phase of the OKSIR programme, many growers resented having the programme “imposed” on them. In addition, it was difficult to convince growers, whose livelihoods depend on their crops, to trust the SIT component of the AW-IPM approach and to apply supplemental chemical control only when needed. However, trust grew over time, in large part due to the real-time trapping and monitoring data made available to growers on the website, and especially with the obvious decline in codling moth populations and crop damage. Growers are now very supportive of the AW-IPM approach because it protects them from potential infestation coming from their neighbours’ poor management practices (both commercial and residential). In addition, the high number of hits on the website’s real-time data pages shows that growers are checking their monitoring data and scrutinizing moth thresholds before spraying, rather than simply applying “comfort sprays” (Lefebvre et al. 2015a).

This was the first area-wide use of the SIT for controlling the codling moth in commercial orchard plantings. Challenges in the early years of the programme included overcoming public resistance to the mandatory requirement to control the pest on all properties, and for the growers to receive a mandatory applied control measure. This was caused in part by ineffective communication with the public and philosophical disagreements between the programme and individual property owners. However, over time, due to improved communication, the roles and responsibilities of all stakeholder groups were better understood, resulting in better cooperative actions and more effective codling moth control. Furthermore, the legal authority for programme staff to enter properties to conduct activities was initially met with resistance from growers and the public. This authority is vitally important for the success of the programme.

Convincing consumers to embrace AW-IPM practices has also been a challenge. Compared with the sale price of fruit produced by conventional production systems, it has been shown that consumers are willing to pay significantly more for certified organic fruit, and moderately more for fruit produced through IPM practices (Lefebvre et al. 2015a). The OKSIR programme supports a relatively small organic pome fruit industry, i.e. less than 10% of British Columbia’s pome fruit production (Macey 2013). These growers enjoy the economic benefits of marketing their fruit as certified organic. However, the remaining conventional growers have not yet taken steps to capitalize on market opportunities afforded by agroecological and socially responsible practices in the same way that growers in the USA have benefited from the “Responsible Choice” label (Tracy 2014).

During the planning stages of an AW-IPM programme, it is important to understand what the benefits and costs of the programme are, and to understand the long-term expectations of the stakeholders once the programme achieves its goals. A major challenge to maintain a sustainable programme is to obtain continued funding when the pest is no longer deemed a problem. The success of an AW-IPM approach means that the reason for its existence appears to diminish. However, removing the AW-IPM measures will create a resurgence of the pest to levels existing prior to the programme. For example, once success has been achieved, keeping the population levels below treatment thresholds requires a risk management approach.

The local governments in the community-based OKSIR programme are also under pressure to allocate tax revenue to other uses, and they must justify the continued area-wide service to their constituents (who are also benefactors of the programme). In addition, there has been an overall decrease in pome-fruit area in the region because of low market returns. Because of their northern location, growers in British Columbia are faced with higher production costs than growers in the nearby USA. Also, higher profit margins can be made growing alternative crops such as sweet cherries and wine grapes. Even though a decreasing pome-fruit area equates to reduced parcel-tax revenue, the OKSIR programme has remained financially strong, and in the past seven years there has been no tax increase.

Expansion of the programme also presents challenges. There are challenges for a public-sector regulatory service when considering diversifying the revenue model to include expansion of scale and scope, such as producing a commercial supply for sales of sterile moths or other by-products, and in assisting the setting up of programmes in other regions/countries. There can be complications due to the governance/business model, as well as different languages and cultures when providing technical support to those areas purchasing sterile insects. There are regulatory, shipping and logistics timing issues involved in selling a product internationally (Blomefield et al. 2011; Adams et al. 2017; Suckling et al. 2017). Biological control agents and beneficial insects are still a developing sector. Unfamiliarity with import regulations of these new products by the many customs officials and private companies along the transport chain can impede movement over international borders (FAO 2017).

A small, locally funded programme cannot afford large-scale investment in research to improve the technology, and generally it can afford to focus only on critical operational improvements as situations arise. The OKSIR programme is currently working with collaborators in New Zealand and the USA on advancing the use of unmanned aerial systems for more efficient release of the sterile codling moth in field implementation trials using the SIT to control the codling moth.

The OKSIR programme has relied on the senior government and international research community for technical assistance, and for advancing AW-IPM and the SIT for the codling moth. Due to the increasing public pressure to reduce the use of chemical insecticides around the world, a global investment in SIT research is needed to advance the technology. A few areas worthy of investigation include if or how released sterile female codling moths could create an effect similar to commercially applied pheromone-mediated mating disruption, how SIT affects parasitoid populations, what are effective sterile: wild ratios for extremely low wild populations, and methods to monitor extremely low wild densities (Judd and Gardiner 2005; Witzgall et al. 2008; Bau and Cardé 2016).

7. CONCLUSIONS

The OKSIR programme is a highly effective and easily transferrable model to control orchard pest infestations. There is greater demand for biological control methods to meet mounting pressures of climate change, increasing insect pest populations, impacts of global trade, and concerns over affordability and availability of methods. Concerns are mounting that the codling moth is becoming resistant to the insecticides used commonly for control, with few replacement chemical options being developed. Biological control options also face pressure because they are not stand-alone technologies, often relying on compatible, supplemental control products and crop management practices.

The OKSIR programme clearly illustrates that area-wide integration of the SIT can successfully manage codling moth populations in an environmentally sound way. In addition, it can easily be integrated with other biological control methods such as pheromone-mediated mating disruption and CpGV. Most importantly, the SIT can replace control products that are no longer environmentally or economically viable, and hence provide an excellent biologically sustainable solution for controlling insect pests.

Despite its proven success, the SIT is often considered a curiosity rather than an effective, environment-friendly technology that dovetails into many modern IPM programmes. When considering the success of the OKSIR programme, other regions and pome fruit growers around the world will be compelled positively to consider AW-IPM with a SIT component as a viable management strategy for the codling moth.

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