Use of the sterile insect technique in New Zealand: Benefits and constraints

R.M. Horner¹, J.T.S. Walker², D.J. Rogers², P.L. Lo² and D.M. Suckling^{1,3}

¹*The New Zealand Institute for Plant & Food Research Limited, Private Bag 4704, Christchurch Mail Centre, Christchurch 8140, New Zealand*

²*The New Zealand Institute for Plant & Food Research Limited, Hawke's Bay, Private Bag 1401, Havelock North, New Zealand*

³*School of Biological Sciences, University of Auckland*

Corresponding author: rachael.horner@plantandfood.co.nz

Abstract The sterile insect technique (SIT) is increasingly being evaluated as a potential complementary strategy for pest suppression or elimination. New Zealand's export fruit sector has an imperative to meet strict international phytosanitary requirements, together with increasing market demand for residue-free produce. SIT is a pest-specific method of insect control that can complement current Integrated Pest Management (IPM) strategies. Successful SIT presents significant challenges: the target pest must be a good candidate for suppression, and strong stakeholder and community commitment is required to achieve and maintain suppression until area-wide elimination is achieved. Emerging sterilisation technologies and refinement of existing methods are making this technology progressively more efficient and cost-effective. This study reviewed the advantages of including SIT in an IPM programme and described the first use of codling moth SIT in New Zealand. A pilot programme is currently underway to evaluate its potential to achieve local elimination of codling moth in Central Hawke's Bay apple orchards.

Keywords Sterile Insect Technique, integrated pest management, apples, codling moth, local elimination

INTRODUCTION

For several insect pests worldwide the sterile insect technique (SIT) is being increasingly used as an environmentally-friendly component of area-wide integrated pest management (AW-IPM) programmes (Klassen & Curtis 2005). The sterile insect technique is a biological control method that involves the sterilisation of reared insects using either ionizing radiation, genetic modification or exposure to chemicals. Large numbers of sterile or partially sterile insects when released into

the environment compete with the wild males to mate with wild females, reducing the number of successful matings and offspring (Lance & McInnis 2005). Inducing inherited sterility is the preferred method, as it not only requires a lower dose of radiation than immediate sterility, but also released sterile insects have higher fitness and competitiveness. That way, the radiation-induced deleterious effects are inherited by the F1 generation and penetration into the wild population is far

greater for every sterile male that mates with a wild female, with collapse at F2 (Carpenter et al. 2005).

SIT can help provide a market advantage by locally eradicating or suppressing an insect pest and thereby gaining area freedom. For example, in Thailand, two tephritid fruit fly species, the guava fruit fly *Bactrocera correcta* and the oriental fruit fly *Bactrocera dorsalis*, were considered the most significant horticultural insect pests, causing considerable loss of fruit quality and yield (Orankanok et al. 2007). The flies limited domestic commercialisation and prevented access to international markets. An ongoing AW-IPM programme since 1991 involves combining SIT with other IPM methods such as bait sprays and orchard sanitation. Damage was reduced from 80% before programme implementation to 3.6% over 5 years in Ratchaburi Province, and from 42.9 to 15.5% in Pichit Province over 2 years. This pre-harvest suppression combined with postharvest risk mitigation measures has allowed mangoes to be exported to high value markets that have strict quarantine requirements such as Japan (Orankanok et al. 2007). A benefit: cost ratio of 7.5:1 and a net benefit of US\$7.5 million was estimated for the mango growers in Ratchaburi Province since the beginning of the programme. This compares with a 2:1 benefit: cost ratio and a net benefit of US\$0.17 million using conventional methods (Enkerlin 2001). In Israel, a suppression programme targeting Mediterranean fruit fly (Medfly), *Ceratitis capitata*, resulted in increased fresh vegetable exports from the Avara region that are now valued at almost US\$30 million per year (Cayol et al. 2004).

The only example of the use of SIT in New Zealand was as part of the 1999-2006 area-wide programme to eradicate the Australian painted apple moth, *Teia anartoides* (Suckling et al. 2007). A combination of methods was used. SIT was tested in 2002 and releases started in 2003 when trap catches indicated a population at ~1% of the population in previous years. An estimated overflooding ratio of 100:1 following an aerial *Bacillus thuringiensis kurstaki* (Btk) spray programme drove the wild population to extinction (Suckling et al. 2007). This programme

was a small-scale one, where only a few thousand insects were released per week, targeting small delimited populations. The technology, however, even when used on a small scale has a number of advantages that when deployed can cost-effectively restore biosecurity (Suckling 2003).

This paper focuses on the potential for future use of SIT in pest management and suppression on a larger, area-wide scale in New Zealand. We will illustrate the concept using a pilot codling moth (*Cydia pomonella*) eradication, to be reported more fully elsewhere.

ADVANTAGES OF INCLUDING SIT IN AN IPM PROGRAMME

SIT provides economic benefits and environmental advantages when integrated with other conventional and biological methods. This integration enables the application of totally biological systems for managing insect pests. SIT also exhibits increased efficiency with decreasing pest population density. Therefore, it is the only environmentally-friendly technology that can eradicate insect pests if applied area-wide.

Economic benefits

The financial gain can far outweigh the cost of SIT used for suppression or eradication, which has been demonstrated in a number of cases. Mexico protects a horticultural export market of over US\$3 billion/year with an annual investment of only ~\$25 million (Hendrichs 2000). When implemented on an area-wide basis and when coupled with an insect rearing and sterilisation facility, SIT can be potentially cost-competitive with conventional pest control over time. Pest control can be optimised and there are significant market access benefits (Mumford 2005). The economic benefit of eradicating codling moth from Brazil was valued at US\$100 million (Kovaleski & Mumford 2007). One of the challenges frequently faced by new SIT proposals is the capital cost of building an insect rearing facility. However, sterile

insects can be imported, for example, South Africa imported sterile Canadian insects for local release (Blomefield et al. 2011), thereby overcoming the capital investment challenge.

Legislative framework

The legislative framework allowing SIT to be used for controlling species already present in New Zealand is relatively straightforward compared with that for some other types of pest management technologies. For example, there are no restrictions meeting the stringent requirements of the Hazardous Substances and New Organisms Act (1996), which often restricts the use of other pest management technologies such that they become impractical to consider e.g. those involving insect pathogens not currently in New Zealand, or some pesticides which are subject to reassessment. If the SIT programme is reliant on the importation of sterile insects from overseas, even for organisms not new to New Zealand (such as codling moth), an Import Health Standard and permit to import live animals is still necessary under the Biosecurity Act (1998). No registration is required under the Agricultural Compounds and Veterinary Medicines (ACVM) Act 1997.

Reduced environmental impact

There is a public preference for pest suppression tactics such as SIT that involve lower personal and environmental impact over other interventions, including aerial or ground spraying (Gamble et al. 2010). In British Columbia, a long-running programme was established to mass-rear and release sterile codling moths for suppression, partly because of pressure from peri-urban residential owners concerned with the application of organophosphate insecticides in nearby orchards. Similar concerns also exist in Hawke's Bay, where there is extensive crossover between apple production and residential borders. Under current Integrated Fruit Production (IFP) protocols, apple growers apply insecticides three to eight times a season for codling moth, depending

on their use of mating disruption (Walker et al. 2013). Mating disruption with a multiple species product supports pest suppression and helps to provide market access without insecticide residues for a significant portion of growers (Walker et al. 2015). SIT in conjunction with other insect controls could further reduce the frequency of insecticide use and residential concern.

Insecticide elimination and resistance management

Sterile insect releases could help to manage insecticide resistance by significantly reducing the risk, or delaying its onset. Some insecticides are also being banned by regulatory bodies because they no longer meet environmental and/or human health and safety regulations. SIT could replace banned insecticides. Recent developments in Australia with the loss of organophosphates fenthion and dimethoate for field control of Queensland fruit fly (Qfly) have allowed that pest to expand its overwintering geographic distribution significantly to the south and east. One response has been for the South Australian authorities to build a new sterile insect factory at Port Augusta as part of a larger programme to control this expanding pest that threatens local and export production (SITplus 2016). Current suppression controls are seen as inadequate, so a diverse range of new and supplementary pest control methods are under investigation to support this SIT initiative.

Efficiency at low population densities

SIT is effective even when pest populations are at a very low density and released sterile insects actively seek and mate with rare insects. Other methods fail to achieve cost-effective pest control when the target population is very small. Over time the sterile male to fertile male ratio increases, sterile mating rates increase, and the target population continually diminishes (Knipling 1955).

Reduced surveillance and intervention costs

Successful local eradication of codling moth across production areas has the potential to reduce surveillance and intervention costs for growers. It could also enhance access to high value markets where there is a nil tolerance for codling moth, although area freedom is likely to require regulatory approval and implementation of appropriate monitoring and reporting measures.

A PILOT ERADICATION OF CODLING MOTH IN CENTRAL HAWKE'S BAY

The goal of our evaluation of SIT for codling moth control in New Zealand is to determine if local eradication, or at least a significant reduction in population, can be achieved. Our major fruit importers demand pest-free, low residue or residue-free fruit. Codling moth is a pest of quarantine concern in many of New Zealand's export programmes, as there is a zero codling moth tolerance policy in many of the high value Asian markets. SIT coupled with reduced pesticide use would also be compatible with European demand for low-residue or residue-free fruit.

SIT is being implemented alongside other IPM methods including mating disruption, phenology and threshold-based pheromone trap sprays, and on-orchard alternate host removal. Expansion of the pilot programme to the wider Hawke's Bay area and Nelson will be considered if eradication can be achieved, and the logistics, economics and likelihood of success of a wider SIT programme are considered.

Three large orchards (approximately 200 ha in total) have been included in the SIT pilot programme that began in October 2014. They are located on the Ruataniwha Plains in Central Hawke's Bay (CHB), which has about 450 ha of apple orchards and is geographically isolated by 80 km from the main growing area in Hawke's Bay, the Heretaunga Plains (Figure 1). There are seven orchards in CHB surrounded by pastoral farms. These orchards are therefore relatively isolated, with relatively few sources of codling moth within 5-10 km. They have a history of very low codling moth activity after >15 years of adhering to Pipfruit New Zealand's IFP programme.

Mass-reared codling moth irradiated at ~~200 Gy~~ 150 Gy* have been imported from the Okanagan-Kootenay Sterile Insect Release (OKSIR) facility in Osoyoos,

* Correction
made by authors
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Figure 1 The location of Te Papa, Thornton and Pacific apple orchards on the Ruataniwha Plains, Central Hawke's Bay, New Zealand. The borders of these orchards receiving releases of sterile codling moths release are highlighted in yellow. These apple orchards are isolated from the main orchard district (80 km to the south west).

Table 1 The requirements for the use of a pilot programme based on the sterile insect technique in Central Hawke’s Bay apple orchards for codling moth control. Sterile codling moth is imported from Canada. UAV = Unmanned Aerial Vehicle

Requirement	Codling moth example	Potential Problem
Mass rearing	Insects mass reared in Canada	Transportation costs, flight schedules, weather and flight availability
Sterility	150 Gy* 200-Gy which has been optimised for fitness and sterility	N/A
Releases over pest reproductive period	Weekly imports from Canada by air freight	Interruption in supply from Canada
Isolation	80 km from the major growing area called the Heretaunga Plains	Transport of fruit or bins hosting pupae between treatment zones. Corridors of wilding apples and isolated home garden trees. Low risk of re-invasion by codling moth as apples are exported directly out of Hawke’s Bay, and apples generally do not enter the area. Only a few orchard companies involved (three in the pilot area).
Minimum area	200 ha over three orchards	Gaining support from all growers in a zone
Correct overflooding ratio	To be confirmed for this situation, potentially >100:1	Not enough insects released to overflow wild population, or insects wasted if the overflooding ratio is overestimated
Closed population	450 ha of apple orchards in CHB, of which 200 ha is being SIT treated	Immigration of fertile insects from outside treated areas
Single sex	Both sexes released, as no economic sexing methods available	Not optimised
No pest damage to F1 generation	Inherited sterility	N/A
Delivery system	Mountain bike and UAV	UAV requires suitable weather and landing areas. CAA regulations
Cost effective	Pilot study costs	Shipping and application costs are expensive on small scale
Grower trust and confidence in SIT	Built up by working closely with three participating orchards	Technique does not reduce target pest population to required low level
Targeting of peri-urban areas	Many households have walnuts or apple trees in their backyards.	Lack of public support for removal of trees or fruit; permission to over-fly urban properties; permission to spray insecticide on trees
Stakeholder support	Gained from current participants	Wider industry benefit depends on discussions with regional authorities

*Correction made by authors 08/10/2019

British Columbia, Canada. Some 400,000 sterilised adult moths were imported from November 2014 to March 2015 and about 480,000 more in 2015 and 2016. An import health standard was issued for the import of commercially-packaged insects. The consignments were accompanied by certificates of sterilisation and they were certified as free of from associated organisms or diseases.

The fitness of mass-reared, sterilised insects before and after chilling and airline freight has been extensively tested. No significant reduction in fitness (at 200 Gy) has been found in flight ability (Carpenter et al. 2013), mating ability, fecundity and fertility (Bloem et al. 1999) or longevity (Blomefield et al. 2011) after up to 72 h in transit. Similar fitness performance tests were undertaken on insects imported into New Zealand after 35 hours in transit (unpublished data).

Previous research showed mating compatibility among populations of codling moth from different geographic origins, including mating between populations from Canada and New Zealand (Taret et al. 2010).

Extensive codling moth SIT release programmes in Canada (Bloem et al. 2007) and pilot programmes in South Africa and Washington have greatly improved quality management of the insects, which over time has enhanced the efficacy of SIT for codling moth control.

The insects were initially released in Hawke's Bay from containers transported on mountain bikes at weekly or two-weekly intervals. In the near future, the mountain bike method will be replaced by a remotely-controlled Unmanned Aerial Vehicle (UAV) equipped with a precision guidance system and controlled moth-release mechanism. The UAV was developed in New Zealand in conjunction with M3 Consulting Group (Phoenix, Arizona, USA). The UAV will significantly improve the frequency and accuracy of SIT, compared with ground-based releases of sterile insects.

REQUIREMENTS FOR THE SUCCESSFUL INTEGRATION OF SIT INTO AN IPM PROGRAMME

Suppressing highly mobile pests on an area-wide

basis is more effective, profitable and environmentally-friendly than on an individual orchard basis because of economies of scale. In particular, coordinated pest suppression offers theoretical advantages from farmers in a region facing pest movement (Byers & Castle 2005). However, the practical success of an area-wide IPM programme including SIT relies upon an holistic and multidisciplinary approach and effective management. It also requires significant funding from a diverse range of financial supporters (Klassen 2005). The requirements of successful integration of codling moth SIT into the existing pipfruit IPM programme are discussed in Table 1.

Area freedom from codling moth that will enhance market access will require widespread uptake of the SIT. This may not always be possible. Since 1981 a private firm has applied SIT for onion fly *Delia obliqua* in The Netherlands. Individual farmers contract for SIT independently of their neighbours, many of whom rely on insecticidal control. Because an area-wide approach has not been established, and sterile flies are not released in a contiguous block, the programme has not expanded beyond 16% of the onion production area. It is therefore not as effective as it could be if the SIT was more widespread (Loosjes & Tan 2000). This example illustrates the difficulty of maintaining area freedom, which results in SIT being used mainly for pest suppression rather than eradication. In order for an area-wide codling moth SIT programme to be successful, consultation and collaboration between growers, regional councils and the wider public will be essential.

THE FUTURE OF SIT IN NEW ZEALAND

The current pilot programme involving weekly importation and release of sterile moths from Canada is being undertaken to determine the feasibility of eradication in a relatively small area in Hawke's Bay, with potential to expand to wider pipfruit-growing areas. The pilot programme is important for developing and testing the logistics of transport and release, the costs and feasibility

of success, as well as identifying key components of future success. The data will be used as part of a cost: benefit analysis of any programme expansion.

While there are no other sterile insect programmes as advanced as the codling moth example in New Zealand at the present time, the increasing cost of incursions of exotic insects into New Zealand warrants investigation and development of all potential methods of control and eventually eradication. Emerging sterilisation technologies are making SIT progressively more efficient and cost-effective. The Trojan female technique is a new approach on the traditional SIT model, using naturally occurring maternally inherited mitochondrial (mtDNA) mutations that affect male, but not female, reproductive fitness. Adult “Trojan females” carrying mutant mtDNA would be introduced into the wild population as either single large releases or relatively few small repeat releases. ‘Trojan females’ and their female descendants carrying these mutations would produce sterile male equivalents over multiple generations. This means fewer, larger releases will provide effective and persistent control, more quickly. mtDNA is greatly conserved among eukaryotes, suggesting this approach would have broad application in pest control (Gemmell et al. 2013). Sex-specific sterility may be achieved by developing transgene-based sterile insect technology. Current somatic TALEN and CRISPR technologies provide a future in the area of insect functional genetics (Xu et al. 2014). There is also potential for lure and sterilise technologies (El-Sayed et al. 2009).

There are several other insect orders besides Lepidoptera and Diptera that can be targeted with SIT for potential suppression or eradication. SIT programmes involving eradication of the boll weevil in the United States, *Anthonomus grandis grandis* (Klassen & Earle 1970), and an eradication of sweet potato weevil, *Cylas formicarius*, in Japan, provide examples of SIT within Coleoptera (Kohama et al. 2003). The mass rearing and sterilisation of Qfly in Australia provides the option of eradication by SIT in the case of an incursion into New Zealand. In such a case, SIT is

a suitable technology for small-scale eradications. In a number of countries the surveillance for an incursion of Medfly is coupled with a capacity for sterile insect releases on this scale, but in those cases the technology is already developed.

Early experiments into SIT for the eradication of brown marmorated stink bug are also being carried out by our laboratory using model species e.g. green vegetable bug *Nezara viridula* and USDA ARS co-operators (Carpenter et al. unpublished data). It is likely that the scope of orders, and the number of species targeted with SIT will increase as countries realise the potential of SIT for eradication, and pest management, where eradication is not possible.

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