Area-Wide Control Tactics for the False Codling Moth *Thaumatotibia leucotreta* in South Africa: a Potential Invasive Species

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ABSTRACT The false codling moth *Thaumatotibia leucotreta* (Meyrick) is a key pest of citrus, stone fruit, and other crops in many countries throughout continental Africa, including South Africa. There is a growing awareness that this damaging pest could soon be introduced into other countries including the USA as a direct result of increased international trade and daily direct flights from African countries. South Africa currently employs a combination of cultural, chemical, microbial and augmentative biological control to suppress false codling moth. Augmentative biological control makes use of the egg parasitoid *Trichogrammatoidea cryptophlebiae* Nagaraja. However, this integrated programme is not adequate for effective false codling moth control. The sterile insect technique (SIT) is now being developed as an additional method for false codling moth suppression in South Africa, but also as a tactic that could be rapidly integrated in an area-wide integrated pest management strategy if false codling moth were to be introduced or become established as an exotic invasive pest in other countries such as the USA. The SIT is regarded as a host-specific and environment-friendly pest control tactic that is compatible with the application of augmentative biological control. However, fully successful integration of the SIT and parasitoid releases into an effective pest management approach can occur only if the parasitoids do not negatively impact irradiated insects and their progeny more severely than they affect the wild pest population, and if the release of irradiated insects does not negatively impact the efficacy of the parasitoids. Therefore, knowledge of the compatibility of *T. cryptophlebiae* and the release of irradiated false codling moth is crucial to the evaluation of the combined use of these tactics. The development and combination of these off-shore integrated pest management strategies in South Africa will develop and/or enhance scientific expertise and infrastructure in that country, reduce wild populations of false codling moth and lower the risk of its introduction into countries currently free of this pest. In addition, the development of these control tactics and the improved infrastructure (e.g. rearing/irradiation facilities in South Africa) will provide resources, technology, and strategies for eradicating invasive populations of the false codling moth should this pest be introduced into new geographical areas.

KEY WORDS false codling moth, *Thaumatotibia leucotreta*, *Cryptophlebia leucotreta, Trichogrammatoidea cryptophlebiae*, invasive species, South Africa, USA, area-wide, augmentative, SIT

1. Introduction

The false codling moth *Thaumatotibia leucotreta* (Meyrick) is indigenous to southern Africa and the Ethiopian region (Stofberg 1954, Catling and Aschenborn 1974) and has also been recorded from the islands of Madagascar, Mauritius, Reunion and St. Helena (CIBC 1984). It was first reported as a pest of citrus in Natal in 1899 and is now con-

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sidered a key pest of almost all citrus varieties in some parts of South Africa (Stofberg 1954). False codling moth is an increasingly serious pest of cotton and maize in tropical Africa (Angelini and Labonne 1970, Reed 1974). In addition, false codling moth attacks many non-commercial hosts belonging to several different plant families including Anacardiaceae, Gramineae and Euphorbiaceae (Angelini and Labonne 1970). Furthermore, false codling moth has been successfully reared from pomegranate, custard apple, guava, peach, avocado, litchi, apricot, plum, walnut, acorn, pecan, all sweet varieties of citrus (Stofberg 1954), carambola (Angelini and Labonne 1970), okra, sorghum heads (Reed 1974), macadamia (La Croix and Thindwa 1986), and olive (CIBC 1984).

The United States Port Authorities have reported intercepting false codling moth larvae from a wide variety of commercial hosts, including citrus, maize, eggplant, cayenne pepper, cola nuts and cassava in shipments arriving from 16 different African countries including South Africa (United States Department of Agriculture (USDA)-Animal and Plant Inspection Service (APHIS) Port Interception Network records).

In South Africa, false codling moth has developed some resistance against the pesticides used for its control (principally benzylureas) (Hofmeyr and Pringle 1998). Other control tactics, such as orchard sanitation (Stofberg 1954), pathogens, and biological control by parasitoids and predators, have been successful in reducing pest populations, but additional control is needed to further reduce pest populations (Newton 1989).

False codling moth typically has four to six non-discrete generations per year in South Africa (Stofberg 1954, Georgala 1969) and it has no documented true diapause (Angelini and Labonne 1970, Reed 1974). Females lay individual eggs on fruit (Catling and Aschenborn 1974) or foliage (Daiber 1978). Newly emerged larvae penetrate the fruit, where larval development is completed. Mature larvae exit the fruit and spin silken cocoons near the soil or in bark crevices (Stofberg 1954, Georgala 1969). Attack by false codling moth generally causes the fruit to drop prior to harvest (Georgala 1969). However, because larval entries take a few days to become visible, larval entries that occur close to fruit harvest might not be seen by packing house fruit graders and infested fruit can be packaged for export (Georgala 1969).

Adult false codling moths are nocturnal (Stofberg 1954) and females lay between 100-250 eggs in their lifetime (Stofberg 1954, Angelini and Labonne 1970). A sex pheromone has been identified for false codling moth (Read et al. 1968, Henderson and Warren 1970, Read et al. 1974, Persoons et al. 1976), and Hofmeyr and Burger (1995) developed a controlled release dispenser for the pheromone. Several different sticky traps have been tested successfully and are available for monitoring populations of false codling moth (Daiber 1978, Angelini et al. 1980, Newton and Mastro 1989). The adults are also attracted to mercury vapour light traps (Reed 1974).

Mass-rearing of false codling moth was originally described by Theron (1947) and modified by Schwartz (1972). Currently, a vigorous colony (about 2.5 million adults per week or ten million adults per month) is maintained at the Ceder Biocontrol insectary in Citrusdal, South Africa. The artificial diet consists of an autoclaved maize meal paste that is inoculated with *Rhizhopus* sp. fungus. Developing larvae feed on the biproducts of the fungal infection. The rearing system is labour-intensive but effective. The reason for rearing false codling moth at Citrusdal is solely to provide host material (eggs) to rear the egg parasitoid *Trichogrammatoidea cryptophlebiae* Nagaraja for augmentative releases against false codling moth populations in citrus (Newton 1988, 1989, Newton and Odendaal 1990). The current level of parasitoid production at Ceder Biocontrol is sufficient to treat 600-800 hectares of commercial citrus per month.

The development and use of the SIT for suppression of false codling moth was proposed for a number of reasons: (1) as previously mentioned, the basic infrastructure for mass-rearing false codling moth is already in place in South Africa. Apart from the utilization of the false codling moth colony for egg parasitoid rearing, improved utilization of reared false codling moth (i.e. the use of adult moths in a programme involving SIT) would improve the cost efficiency of this insectary; (2) theoretical and experimental evidence suggests that combined use of the SIT and parasitoids can provide pest control that is more effective than when either tactic is employed separately (Knipling 1992, Carpenter 1993, 2000); (3) the SIT is a species-specific environment-friendly pest control tactic that would build infrastructure, improve expertise, provide local jobs, and enhance the range of available control options; (4) the development of the SIT for false codling moth would provide resources and strategies for elimination of invasive populations should this pest be accidentally introduced into the USA, which is a major trading partner of South Africa.

2. Research Gaps and Progress to Date

2.1. Development of the SIT for False Codling Moth Thaumatotibia leucotreta

Myburgh (1963), Schwartz (1978) and Du Toit (1981) conducted preliminary studies on the effects of gamma radiation on false codling moth in South Africa. However, these studies did not address the use of inherited sterility (North 1975, Carpenter 1993, Bloem et al. 1999), which results in more competitive moths for use in programmes that employ the SIT. Additionally, no data were published on the possibility of irradiating adults rather than pupae or on fertility levels when treated males are crossed to treated females.

Bloem et al. (2003) recently published data on the radiation biology and inherited sterility of false codling moth. They examined the effect of increasing doses of gamma irradiation on the fecundity and fertility of this species. Newly emerged adults as well as mature pupae were treated with doses of radiation ranging between 0 and 350 Gy and adults were inbred or outcrossed to fertile counterparts. Results showed that fecundity was not adversely affected by dose of radiation when untreated females were mated to treated males. However, the fecundity of treated females mated to either untreated or treated males declined precipitously as the dose of radiation increased. They also found that the dose at which 100% sterility is achieved for treated false codling moth females is 200 Gy (Fig. 1). In addition, Bloem et al. (2003) examined the inherited effects resulting from treatment of parental (P) males with selected doses of radiation (0, 100, 150, 200 and 250 Gy) on the F_1 generation. Decreased F_1 fecundity (total eggs produced) and fertility (egg hatch), increased F_1 mortality during development, and a significant shift in the F_1 sex ratio in favour of males were recorded.

More recently, Hofmeyr et al. (2005) examined the effect of different release ratios of treated (T) to untreated (U) moths on the incidence of fruit damage and on the competitiveness of treated males in replicated field cage studies in South Africa. Individual navel orange trees were enclosed in large mesh cages and adult moths treated with either 150 or 200 Gy were released into the cages at ratios of 5T:1U and 10T:1U. Results showed that the number of larval entries as well as the number of F_1 progeny per cage decreased significantly as the release ratio of treated moths increased. In addition, the lowest mean number of fertile F_1 adult females and males was obtained from the treatment that combined the lower dose (150 Gy) and 10T:1U release ratio. This treatment also showed the lowest per generation rate of increase (less than 1 from the P to the F_1 generation) suggesting that growth in the wild population would have been prevented if releases of treated moths at this dose and ratio were maintained in the field.

The next step in development of the SIT for false codling moth will be a season-long validation under field conditions. A pilot study is scheduled to begin in August 2005 at the Hexrivier Blikhuis orchard north of Citrusdal, South Africa. The 36-hectare orchard is rela-

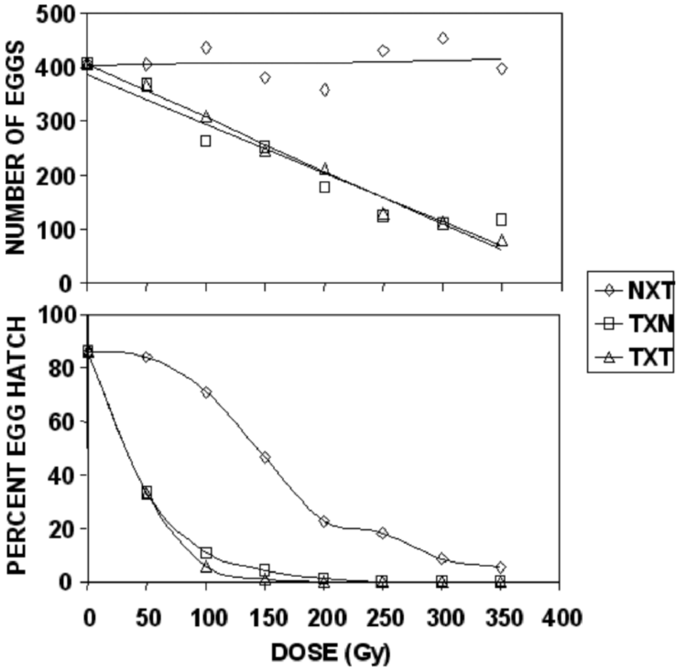

Figure 1. *Effect of radiation dose on false codling moth fecundity (mean number of eggs laid per mated female) and fertility (mean percentage of eggs that hatched). Males and females were treated (T) with 0, 50, 100, 150, 200, 250, 300 and 350 Gy and inbred (T females x T males) or outcrossed (T females x N males, N females x T males) to untreated (N) adults (Bloem et al. 2003).*

tively isolated from other orchards and, in preparation for the SIT pilot, is being managed with an aggressive sanitation programme (that removes all fallen fruit) and with monthly releases of *T. cryptophlebiae* egg parasitoids. The wild false codling moth population is being monitored weekly with pheromone-baited traps. Fruit drop is also monitored each week at 20 stations located in close proximity to trap sites.

During the SIT pilot study, bi-weekly releases of 1000 false codling moth adults per hectare will be made for 40-42 weeks. The moths will be reared at the Ceder Biocontrol insectary in Citrusdal. Newly emerged adults will be packaged, chilled, and transported to Stellenbosch, South Africa, where they will be irradiated at a dose of 150 Gy in a ^{60}Co panoramic irradiator. Treated insects will be returned to Citrusdal and released using a modified codling moth release device (Bloem and Bloem 2000) mounted on an all-terrain vehicle. Release ratios throughout the season will be monitored using pheromone-baited traps and extensive fruit sampling at midseason and at harvest will give an indication of the effectiveness of the SIT.

2.2. Combination of SIT and Parasitoids

Interest is not only in developing the SIT as an area-wide programme to suppress false codling moth in South Africa, but in examining the possibility of combining the SIT with releases of the egg parasitoid *T. cryptophlebiae*. As mentioned above, there is theoretical and experimental evidence that suggests that combined releases of sterile insects and parasitoids can provide pest suppression that is more effective than when either technique is employed separately. In programmes involving sterile insect releases for Lepidoptera pests, both treated males and females are released in the field (Stewart 1984, Bloem and Bloem 2000). Because all matings taking place during SIT operations (including those involving treated moths) result in the production of eggs, a potentially large number of host eggs may be present in areas under the SIT. For control of the codling moth *Cydia pomonella* (L.), the combined release of irradiated insects and *Trichogramma* spp. egg parasitoids was first suggested by Nagy (1973). Field cage experiments conducted by Bloem et al. (1998) showed that an additive suppressive effect can be realized when treated codling moths are released at a 10:1 release ratio (T:U) together with *Trichogramma platneri* Nagarkatti when compared to cages receiving treated moths or egg parasitoids only.

Carpenter et al. (2004) conducted a laboratory study that examined the acceptability and suitability of false codling moth eggs to parasitization by *T. cryptophlebiae* under no choice and choice situations. Male and female false codling moth were treated with 150 or 200 Gy of gamma radiation, inbred or outcrossed to untreated counterparts, and the eggs laid by different crosses offered to *T. cryptophlebiae* as host material. Newly laid (24 hour-old) false codling moth eggs, as well as eggs that were 48 hours and 72 hours old were evaluated.

Results revealed that all treatments in the no-choice experiments were acceptable for oviposition and suitable for the development of *T. cryptophlebiae*. However, significant differences in the number of parasitized eggs were detected in the choice situations when one member of the host cross, particularly the female, was treated with gamma radiation or when the egg age was greater than 24 hours. These results suggest that *T. cryptophlebiae* would accept, successfully develop in, and emerge from false codling moth eggs laid by the different crosses that would theoretically be present in the field under a programme involving the SIT (U females by T males, T females by U males, T females by T males) and indicate that further evaluations combining releases of treated moths and parasitoids are warranted.

Field cage studies to examine the effectiveness of releasing irradiated false codling moth alone or in combination with *T. cryptophlebiae* were conducted in 2005. Four treatments were randomly assigned to 15 large-mesh cages containing individual navel orange trees with 50 fruits per tree. Treatments were: (1) U = control = 10 pairs of untreated moths, (2) U + T = untreated moths plus a 10:1 overflooding ratio of moths treated with 150 Gy = 100 pairs of treated moths, (3) U + P = untreated moths plus two releases of *T. cryptophlebiae* parasitoids (approximately 3000 parasitoids total per cage), and (4) U + T + P = untreated moths plus treated moths plus parasitoids.

Results showed that all treatments significantly reduced the number of larval entries when compared to cages receiving only untreated moths. In addition, when treated moths and parasitoids were released together, significantly more parasitoids were produced per cage than when cages received only untreated moths plus parasitoids. These results suggest that combined field releases of irradiated false codling moth and *T. cryptophlebiae* would result in rapid parasitoid population increase, which would have a positive impact on false codling moth population suppression.

3. Benefits of Developing Integrated Pest Management Strategies for South Africa and the USA

3.1. South Africa

The South African Citrus Growers Association has identified false codling moth as a top research priority. South African researchers are involved in a multi-faceted false codling moth research programme that includes the evaluation of new insecticides and improved mating disruption products, optimization of biological control using egg parasitoids, development of a long-lasting pheromone dispenser for trap monitoring, as well as improvements in the potency and shelf-life of false codling moth granuloviruses. Because the SIT can be easily combined with all of the control tactics listed above, there is interest in integrating the SIT as an additional tactic to suppress false codling moth.

As a result of this research, co-funded by the International Atomic Energy Agency (IAEA) under project SAF5007, it is hoped that the ongoing biological control with egg parasitoids can be optimized through the synergism of combining it with the SIT as well as through the increased efficiency in false codling moth/parasitoid rearing operations at the Ceder Biocontrol insectary. It is also hoped that through the combined use of both tactics populations of false codling moth will be reduced both inside and outside citrus orchards, thereby reducing pre- and postharvest crop losses, and losses due to rejection of false codling moth infested shipment consignments.

3.2. United States of America

A significant proportion of the mission of the USDA-Agricultural Research Service (ARS) and USDA-APHIS is directed toward dealing with invasive species and potential emerging pests. USDA-APHIS research and development activities are concentrated on preventing the entry of pests into the USA. However, despite the success of these efforts, many pest species still manage to gain entry and many will become established. While early detection of an invading pest is critical, it is equally important to have a suppression/eradication plan in place before the pest becomes established and well before the geographical range of the pest begins to expand. Proactive research programmes are necessary to quickly respond to any breach in our exclusion mechanisms.

Many federal and state agencies in the USA have expressed concern that the false codling moth may soon be introduced into the USA as a direct result of increased international trade and daily direct flights from African countries. The USDA-APHIS Port Interception Network records indicate that these concerns are well founded. Since 1985, false codling moth has been intercepted more than 122 times at 19 different ports of entry from 22 host plants originating from 15 different African countries. Because false codling moth attacks so many different host plants including citrus, stone fruits, corn, cotton, and vegetables, and because it would be a quarantine issue for some crops, establishment of this pest in the USA could result in considerable economic losses.

The development of "offshore" IPM strategies (i.e. programmes in South Africa), that combine augmentative biological control with genetic control tactics (such as the SIT), would reduce pest populations in South Africa and thereby reduce the risk that false codling moth would arrive in South African shipments to the USA. Also, this project will develop an eradication tool for use against introduced false codling moth populations and improve infrastructure (e.g. rearing/irradiation facilities) and expertise in South Africa. As a result, irradiated false codling moth would be readily available for shipment to the USA for eradication purposes in the event that the pest invaded and became established in this country.

4. Conclusions

In this project it is hoped to demonstrate that this approach can serve as a model on how to prepare for other potentially invasive lepidopteran pests. A general outline of this approach would be: (1) obtain knowledge on the radiation biology of the exotic lepidopteran pest of concern, (2) assist source countries to develop integrated pest management strategies that combine augmentative biological control with genetic control tactics (which would include the ability to mass-rear the pest insect), and (3) develop partnerships between source countries and pest free countries so that irradiated lepidopteran pests would be available for shipment and use in a programme using the SIT in the event that the pest invaded the pest free country.

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