A review of control measures and risk mitigation options for false codling moth (FCM), *Thaumatotibia leucotreta*, and their efficacy

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Citrus Research International
07 December 2016

Introduction

Thaumatotibia leucotreta populations vary extensively as a function of crop production region and host type (Moore et al. 2017). Such variation in host susceptibility exists even within a single crop type. For example, there is a wide range of susceptibility levels among different citrus types. Within citrus, this ranges from non-host status (lemons), through low susceptibility (Valencia cultivars and white grapefruit) and moderate susceptibility (Midseason cultivars, certain mandarin types such as Satsumas, Star Ruby grapefruit and Turkey Valencias), to more susceptible Navel oranges (Grout and Moore, 2015; Moore et al. 2015a). Even within a single citrus type, such as Navel oranges, there is extensive variation in susceptibility between cultivars (Newton, 1990; Love et al., 2014). *Thaumatotibia leucotreta* population pressure also varies greatly between production regions (Grout and Moore, 2015). For example, within citrus production regions of southern Africa, *T. leucotreta* population pressure is generally higher in the southern production regions, but in some northern production regions it seldom causes any damage, especially in less susceptible citrus types and cultivars. Additionally, *T. leucotreta* pressure can differ significantly from season to season, mainly as a factor of climate, but also environmental conditions and management practices. Such extensive variation in pest status across host type, production region, management practices and seasons, is of relevance when considering appropriate potential phytosanitary risk mitigation measures.

Pre-harvest control

Pre-harvest control options for *T. leucotreta* include orchard sanitation, biological control, microbial control, chemical control, semiochemical control and the sterile insect technique (SIT). The efficacy of all of these control measures has been studied in the field and documented. These treatments can be variably combined to provide a highly effective suite of control options which can be selected to align with the pest pressure in each production situation (Moore and Hattingh, 2012; Moore et al., 2015a; Moore et al., 2017).

Moore and Kirkman (2008) demonstrated that weekly orchard sanitation conducted from December to June could reduce fruit infestation by an average of 75%. Sanitation is strongly enhanced by biological control. *Thaumatotibia leucotreta* has a range of natural enemies that suppress it in the field (Grout and Moore, 2015). The most effective biological control agent against *T. leucotreta* is the egg parasitoid, *Trichogrammatoidea cryptophlebiae*, which not only occurs naturally in citrus orchards, but can be augmented commercially from insectary-reared parasitoid cultures (Moore and Hattingh, 2012). Augmentation has been shown to reduce *T. leucotreta* infestation by up to 60% (Newton and Odendaal, 1990; Moore and Hattingh, 2004 & 2012). More importantly, where undisrupted, egg parasitism from naturally occurring parasitoids reached between 80% and 100%, causing from 67% reduction in *T. leucotreta* infestation in Navel oranges from December to harvest to total elimination of *T. leucotreta* infestation by harvest (Moore and Hattingh, 2012).

Moore et al. (2015b) reported that more than 50 trials with granulovirus (CrleGV) products had been conducted against *T. leucotreta* in citrus orchards over a 15-year period, achieving up to 92% reduction in fruit infestation. The entomopathogenic nematode (EPN), *Heterorhabditis bacteriophora*, was recently registered for control of *T. leucotreta* on citrus. Similarly, the entomopathogenic fungi (EPFs), *Beauveria bassiana* and *Metarhizium anisopliae*, are at an advanced stage of development for application to the soil for control of the soil-dwelling life stages of *T. leucotreta*. Both the EPN and the EPFs have been shown to reduce *T. leucotreta* infestation of fruit by 80% or more for the full duration of the season, with a single application in spring (Moore et al., 2013; Coombes et al., 2016).

Chemical control of *T. leucotreta* has also been shown to be effective. In field trials two synthetic pyrethroids, applied two to three months before harvest, reduced fruit drop by an average of 90% (Hofmeyr, 1983). Field trials conducted by Hofmeyr (1984) and Newton (1987) showed a single application of the insect growth regulators, triflumuron (Alsystin) or teflubenzuron (Nomolt), to reduce fruit loss by up to 86%. Although *T. leucotreta* insecticide resistance has been reported for the older chemical control options (Hofmeyr & Pringle, 1998), Moore et al. (2015b) showed that the more recently registered chemicals, such as methoxyfenozide (Runner) and spinetoram (Delegate) are also effective in controlling *T. leucotreta* infestation.

Field trials conducted in Navel orange orchards with the mating disruption product, Isomate, revealed a 55% (in an orchard with high pressure) to 75% (in an orchard with low pressure) reduction in *T. leucotreta* infestation from December to the end of April (Hofmeyr & Hofmeyr, 2002; Moore and Hattingh, 2012). More importantly, these reductions were 86% and 95% respectively in later evaluations shortly before harvest.

SIT, as a stand-alone treatment in a semi-commercial trial, reduced *T. leucotreta* infestation in 35 ha of Washington Navel orange orchards by 95.2%, relative to an untreated control orchard (Hofmeyr et al., 2016a). These initial findings led to commercial implementation for control of *T. leucotreta* within an integrated programme, initially in the Western Cape Province (since 2007) and more recently in various other production regions as well, and is proving extremely effective (Hofmeyr et al., 2015), having reduced moth catches by 99%, fruit infestation by 96% and export rejections by 89% since the inception of the programme (Barnes et al., 2015).

As a consequence of the development and successful commercial implementation of a wide range of additional and improved pre-harvest control options, the overall level of *T. leucotreta* control in the southern African citrus industry has improved greatly, especially over the past decade (Moore et al., 2016a; Moore et al., 2017). The availability of a wide range of effective pre-harvest control options, combined with the efficacy of naturally occurring biological control agents, variation in cultivar susceptibility and naturally occurring low population pressure in certain production regions, provides for effective systems approach risk mitigation of *T. leucotreta* (FAO, 2002), as a greatly improved alternative to standalone post-harvest disinfestation treatments (Moore et al., 2016b).

Postharvest control

It has recently been indicated that the EU will in the future adopt measures specific to *T. leucotreta* risk mitigation and that a compulsory cold treatment for citrus fruit may be considered. However, a blanket application of compulsory cold treatment of citrus exports from South Africa to the EU would not be appropriate or feasible. It would not be appropriate since infestation levels in fruit would often not warrant such an extreme measure. Infestation levels, influenced by factors such as fruit type and cultivar, production region, seasonal effects and efficacy of pre-harvest treatments, may at times be zero. Additionally, it would not be feasible since firstly, cold temperatures for a protracted duration are known to be damaging to fruit quality, particularly certain Mandarin, orange and grapefruit cultivars (Lafuente et al. 2003; Cronjé 2007). In addition to the variable intensity of chilling injury effects on all citrus types, the heightened sensitivity of some citrus types completely precludes their potential for export under such conditions. Secondly, it would be logistically impossible to apply cold treatment to the large volumes of citrus fruit that are traditionally exported to the EU. The lack of potential feasibility of such a measure was indicated in an impact analysis within a *T. leucotreta* pest risk analysis conducted by EPPO (EPPO, 2013).

The high levels of control with improved pre-harvest control techniques as discussed in the previous section are a relatively recent development. Consequently, some export protocols that South Africa entered into with trading partners in the past, for example United States in 1997, required a post-harvest cold treatment. However, such export programmes provide for relatively small volumes of fruit exports and applicability to only a limited range of citrus types, unlike the export of citrus fruit from southern Africa to the EU.

The USDA *T. leucotreta* cold treatment has been described as 22 d at −0.55 °C, but consideration of the detail indicates that the following is specified: once treatment has commenced (i.e. an initial temperature of -0.55 °C has been attained), the fruit must be kept at or below −0.27 °C for 22 d and if it rises above this temperature the treatment duration is extended, provided the temperature does not exceed 1.11 °C (USDA, 2016). However, this treatment was based on trials conducted more than 50 years ago. Cottier (1952) was the first to demonstrate the efficacy of *T. leucotreta* postharvest cold treatment for fruit by shipping infested fruit from South Africa to New Zealand at a pulp temperature of -0.55 °C for 21 days, with no survival of *T. leucotreta* larvae and eggs. However, he did not explain the origin of the time-temperature combination. Myburgh (1963; 1965), conducted further trials and concluded that 21 to 22 days at -0.55 °C would provide at least a Probit 9 level of control.

More recently Moore et al. (2017) investigated a range of improved postharvest cold treatments for *T. leucotreta*, justified for the following reasons: Cottier (1952) acknowledged difficulty in maintaining the required temperature (-0.55 °C); Myburgh's (1965) study, conducted half a century ago, reported no evidence for the reliability of temperature recordings; Myburgh (1963; 1965) and Hofmeyr et al. (1998) reported results that indicated that shorter duration sub-zero temperature treatments may also be effective. Consequently, Moore et al. (2017) demonstrated that the following treatments caused mortality at or in excess of the probit 9 level: 16 d at or below -0.1 ℃, 18 d at or below -0.3 ℃, 20 d at or below -0.3 ℃ and 19 d at or below 1.2 ℃.

Moore et al. (2016a & c), recently reported the results of cold treatments for *T. leucotreta* at shipping temperatures of 1, 2, 3 and 4℃ for varying durations. Moore et al. (2016b) reported that the combination of such treatments with various pre-harvest treatments, within a systems approach, ensured that the proportion of fruit potentially infested is less than the level associated with probit 9.

Ionizing radiation has also recently been investigated as a postharvest phytosanitary disinfestation treatment for *T. leucotreta* larvae and eggs (Hofmeyr et al., 2016b & c). It was demonstrated at the probit 9 level that efficacy was achieved with 100 Gy ionizing radiation. To overcome constraints on ionizing radiation and cold treatments as stand-alone disinfestation treatments for *T. leucotreta*, the efficacy of a range of combination treatments of the two at reduced doses was tested (Hofmeyr et al., 2016d, e). They demonstrated that 60 Gy followed by 16 days at 2.5℃ was effective at the Probit 9 level.

Fumigation is another category of post-harvest disinfestation treatments which has been available for many years. Myburgh (1963) reported on trials conducted with methyl bromide fumigation of *T. leucotreta* in citrus fruit, demonstrating its efficacy at certain doses and temperatures and concluding that fumigation with methyl bromide was an option for disinfestation of fruit for *T. leucotreta*. When ethylene dibromide fumigation was followed by exposure to 4.4℃ for 18 days or 11.1℃ for 21 days, complete disinfestation of fruit from larvae was achieved (Schwartz and Milne, 1972; Schwartz and Kok, 1976).

Systems Approach

In line with the recommendations from the *T. leucotreta* pest risk analysis conducted by the European and Mediterranean Plant Protection Organisation (EPPO) (EPPO, 2013), Moore et al. (2016b) have developed a variable intensity intervention systems approach for management of *T. leucotreta*. This entails orchard monitoring, orchard sanitation, use of registered pre-harvest control options (as listed above), pre-sorting of fruit at harvesting, inspection of fruit on delivery to the packhouse, grading of fruit on the packing line, inspection of fruit within the packed cartons and consequent specification of a range of shipping temperature options. The application of inspection standards to the steps within the systems approach determines the subsequent actions required. A study was undertaken to assess the efficacy of this systems approach (Moore et al., 2016b). They demonstrated that the proportion of fruit potentially infested was a 6 to 38 times improvement on the probit 9 standard, thereby validating the systems approach as an alternative to standalone postharvest disinfestation treatments.

Conclusion

There is a wide range of effective pre- and postharvest treatments available for *T. leucotreta* that may be used singly or in varying combinations. This provides for a range of options for achieving internationally accepted levels of phytosanitary risk mitigation. Many factors determine the selection of the appropriate treatments for each consignment of fruit. These include citrus type, cultivar, region, season, other environmental factors, orchard history, past and present management practices and real time monitoring and inspection. Although some countries importing South African citrus currently require postharvest cold treatment, it must be noted that this inappropriately precludes selection of a treatment option that is relevant to the risk mitigation required. Furthermore, such requirements were put in place before most of the treatments outlined above were available and their efficacy had been quantified and documented. Additionally, such export programmes are limited to small volumes of fruit and a narrow range of citrus cultivars, since it is not logistically feasible to apply to much larger volumes of fruit exports and certain citrus cultivars are excessively sensitive to chilling injury.

Recently EPPO conducted a pest risk analysis for *T. leucotreta* (EPPO, 2013) including an impact assessment report from the southern African citrus industry, which concluded that cold sterilisation is not a feasible option for three main reasons: cold sensitive citrus cultivars would be excluded, there is insufficient precooling capacity and human resources to handle the volumes that are annually exported to the EU, and the additional operational costs associated with cold sterilisation would be immense. Losses and costs combined would preclude continued profitable export of citrus fruit from South Africa to the EU. A systems approach and market segregation were listed as potential options for adequately mitigating the *T. leucotreta* phytosanitary risk, with the latter being the most viable option. The report also remarked that South Africa had a long history (100 years) of citrus exports to Europe, without establishment of the pest in Europe.

The International Standard for Phytosanitary Methods, ISPM 1 (FAO, 2006), provides the following principle for minimal impact of phytosanitary measures: “Contracting parties should apply phytosanitary measures with minimal impact. In this regard, the IPPC provides that they “shall institute only phytosanitary measures that ... represent the least restrictive measures available, and result in the minimum impediment to the international movement of people, commodities and conveyances.” (Article VII.2(g))”. The enforcement of a compulsory cold treatment would have devastating trade consequences and would preclude South Africa from applying risk-aligned, consignment-based flexibility in the choice of appropriate risk mitigation treatments. Consequently, it would be inappropriate in terms of IPPC guidelines to prescribe a compulsory cold treatment when there are less trade restrictive, effective alternatives available that are better aligned with the pest risk.

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