An Integrated Management System to reduce False Codling Moth, *Thaumatotibia leucotreta* (Meyrick) (Lepidoptera: Tortricidae) infested citrus fruit from being packed for export

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Clint Mac Aleer

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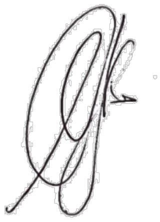
Abstract

False codling moth (FCM), *Thaumatotibia leucotreta* (Meyrick) (Lepidoptera: Tortricidae) is indigenous to southern Africa and is an important pest of citrus in this region. As a result of its endemism to sub-Saharan Africa, several countries to which South Africa exports citrus, regulate it as a phytosanitary pest. Consequently, it is necessary to ship fruit to these markets under cold-disinfestation protocols. This has been possible, as until recently, all of these markets could be considered relatively small niche markets. The South African citrus industry exports approximately 130 million cartons of fruit (15 kg equivalent) annually. During the 2017 season, a total of 48 million cartons were exported to the European Union (EU), which is the equivalent of 41% of South Africa's total export volume, thus making the EU South Africa's most important export market. In 2013 the European and Mediterranean Plant Protection Organisation (EPPO) conducted a pest risk analysis (PRA) on FCM, leading to the EU declaring it an officially regulated pest for this region, effective of 1 January 2018. Citrus is regarded as a preferred non-native host of FCM and South African citrus was identified as a primary focus due to large volumes being exported to Europe. Shipping under cold disinfestation is not possible with such large volumes of fruit. Additionally, several cultivars would suffer high levels of chilling injury under such conditions. In this study, an Integrated Management System was tested with pre- and postharvest controls to test the hypothesis that pre-harvest interventions resulted in lower post-harvest infection. Thirty orchards ranging from soft citrus cultivars such as Nule and Nova Mandarins, to Navel orange cultivars such as Newhall, Palmer and Late Navel and ending with Valencia cultivars such as Midknight and Delta, were identified for this study. This system relies on pre-harvest inspections such as FCM trap counts and fruit infestation on data trees in every orchard, with associated thresholds for action or continued compliance. Inspections were conducted on a weekly basis. There was a significant relationship between the moth catches and FCM infestation for the full monitoring period, using a two-week lag period for infestation. Inspections of harvested fruit were conducted at the packhouse to determine FCM infestation. This included inspection of the fruit on delivery to the packhouse, on the packing line, and a final fruit sample taken from the packed product and inspected for FCM. The highest levels of infestation were recorded on the Navel cultivars, thus confirming that Navels cultivars are a preferred host for FCM. Significant positive relationships were recorded between FCM infestation during the last 4 weeks before harvest and the level of infestation in the fruit delivered to the packhouse and between the fruit delivered to the packhouse and in the fruit packed in a carton for export. There was a substantial reduction in infestation between the fruit delivered to the packhouse and the fruit packed in a carton for export, with certain orchards recording as much as a 93% reduction in the fruit packed in a carton, which indicated that the packhouse could effectively identify and remove FCM infested fruit. The outcome of the study is that a holistic management approach minimizes the risk of FCM in citrus fruit destined for export and therefore mitigate the risk associated with FCM.

Keywords: *Phytosanitary, European Union, Monitoring, Inspection*

Declaration

The following thesis has not been submitted to any other university other than Rhodes University, Grahamstown, South Africa. The work presented here is that of the author.



Clint Mac Aleer   15.12.2018

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Lastly, to my boys, Damian and Kyle, thank you for allowing me to complete this thesis. In life, one has to make certain sacrifices and I look forward to explaining to you why this thesis was so important.

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List of Abbreviations

% - percent

°C - degrees Celsius

ALOP - Appropriate Level of Protection

A&K - Attract and Kill

BASF - Badische Anilin- und Soda-Fabrik

CGA - Citrus Growers Association

CRI - Citrus Research International

CrleGV - Granulovirus

EC - Emulsified Concentrate

EPF - Entomopathogenic Fungi

EPN - Entomopathogenic Nematode

EPPO - European and Mediterranean Plant Protection Organisation

EU - European Union

FAO - Food and Agricultural Organization of the United Nations

FCM - False codling moth

FMS - False Codling Moth Management System

FPEF - Fresh Produce Exporters Forum

g - Grams

GAP - Good Agricultural Practices

GPS - Global Positioning System

ha - Hectare

IGR - Insect growth regulator

IPM - Integrated Pest Management

IPPC - International Plant Protection Convention

ISPM - International Standards for Phytosanitary Measures

kg - kilogram

L - litre

m - Metre

mm - Millimetres

MPL - Maximum Pest Limit

MRL - Maximum Residue Level

PFA - Pest-free Area

PPECB - Perishable Products Export Control Board

PRA - Pest Risk Analysis

PUC - Production Unit Code

RSA - Republic of South Africa

SA-DAFF - South African Department of Agriculture, Forestry and Fisheries

SIT - Sterile Insect Technique

SPLAT - Specialised Pheromone & Lure Application Technology

USA - United States of America

USDA - United States Department of Agriculture

US$ - US Dollar

WTO - World Trade Organisation

ZAR - South African Rand

Chapter 1:

General Introduction

1.1. Problem statement

South Africa is the tenth largest citrus producing country in the world, but the second largest citrus exporting country, after Spain (CGA, 2017). The South African citrus industry exports approximately 130 million cartons (15 kg equivalent) annually. During the 2017 season, 118 million cartons were exported, of which 48 million cartons went to the European Union (which includes Europe and the United Kingdom). This is the equivalent of 41% of South Africa's total export volume, thus making the EU South Africa's most important export market (CGA, 2017).

False codling moth (FCM), *Thaumatotibia leucotreta* (Meyrick) (Lepidoptera: Tortricidae), is a significant pest on citrus, and is considered to be a phytosanitary threat for various countries, including those in the EU, as it is endemic to sub-Saharan Africa (Hill, 1975). The South African citrus industry is currently under threat due to the potential presence of FCM in citrus fruit destined for export. The inability of pre-harvest control measures to eliminate FCM has resulted in this pest being found in citrus fruit destined to be packed for export (Moore & Hattingh, 2012). Europhyt (2016; 2017), reports infestation in fruit that was exported to the EU. Due to the market related pressure enforced by the EU, the South African citrus industry has been forced to adopt a proactive and preventative approach to FCM management, even before the EU regulated FCM as a phytosanitary pest. Although it is difficult to determine the exact financial impact of direct losses due to FCM, it has been estimated that FCM is responsible for annual losses of up to ZAR100 million (US$ 8 million) to the southern African citrus industry (Moore *et al*. 2004); P. Hardman, CGA, personal communication). The value of export citrus fruit has increased over the last 14 years. The control measures for FCM have also intensified over this time, so the current financial implications would be significantly higher. These potential losses, as calculated by Moore *et al*. (2004) and Hardman (pers. comm.), are only due to reduction in yield, with fruit dropping to the ground as a result of FCM infestation prior to harvesting. The costs for pre-harvest control measures for FCM are between US$470 – US$740 per hectare (MJ van der Mescht, Inteligro, pers. comm., 2018). Post-harvest losses are also significant due to decay after infestation. Technology exists that can reduce FCM infestation in fruit at the packhouse, but unfortunately there is no technology that can eliminate it. Fruit from orchards that are considered to have an unacceptably high level of FCM are packed and exported to non-sensitive markets; however, these markets are often less lucrative. It has been estimated that the price difference for exporting fruit to non-sensitive markets can be between US$1.00 – US$2.00 per 15 kg carton (J. Morgan, Corefruit, pers. comm., 2018). In some cases this has financial implications because of market access being restricted due to FCM infestation.

1.2. The South African citrus industry

The first orange and lemon trees arrived in South Africa from St Helena in 1654 and were planted in the gardens of the Dutch East India Company and in 1666 the first lemons were picked (Cartwright, 1977). American growers had great success with exporting citrus fruit under refrigeration by ship to Europe in 1890, which opened new doors for the South African citrus industry to do the same (CGA, 2007). South Africa has been producing, packing and exporting citrus fruit since the early 1900s, with the first record of citrus fruit being exported to England in 1902 (based on a letter from Rudyard Kipling) (Cartwright, 1977). By 1925 South Africa was exporting one million cartons of citrus fruit, and at that stage the government established a Fruit Export Control Board to co-ordinate shipping (Cartwright, 1977). It was decided in 1936 that it was important that the South African citrus industry had a recognisable brand name for marketing purposes (CGA, 2007). The Niven family, (descendants of Sir Percy Fitzpatrick – MP, citrus farmer and author of Jock of the Bushveld in 1907), gave their citrus brand name, Outspan, to the South African Cooperative Citrus Exchange for all its members to use, but members were also still able to use their own brand name (Cartwright, 1977). After de-regulation of citrus fruit exporting took place in 1997, any company was able to register as an export agent. The South African Citrus Growers Association (CGA) was formed in 1998 to manage research projects on behalf of all citrus growers and was funded by voluntary levies paid by growers (CGA, 2007). The Fresh Produce Exporters Forum (FPEF) was formed by export agents to address problems such as agents competing against each other overseas, which resulted in some markets being over-supplied and poorer prices for growers (CGA, 2007). In 2001 the government approved an application from the CGA for a statutory levy on all export citrus, to fund research and market development. The Outspan Citrus Centre was taken over by the CGA and the name changed to Citrus Research International (CRI), (CGA, 2007). Today, citrus is grown in various regions throughout South Africa (Figure 1.1.) and more than 130 million cartons are exported annually (CGA, 2017).

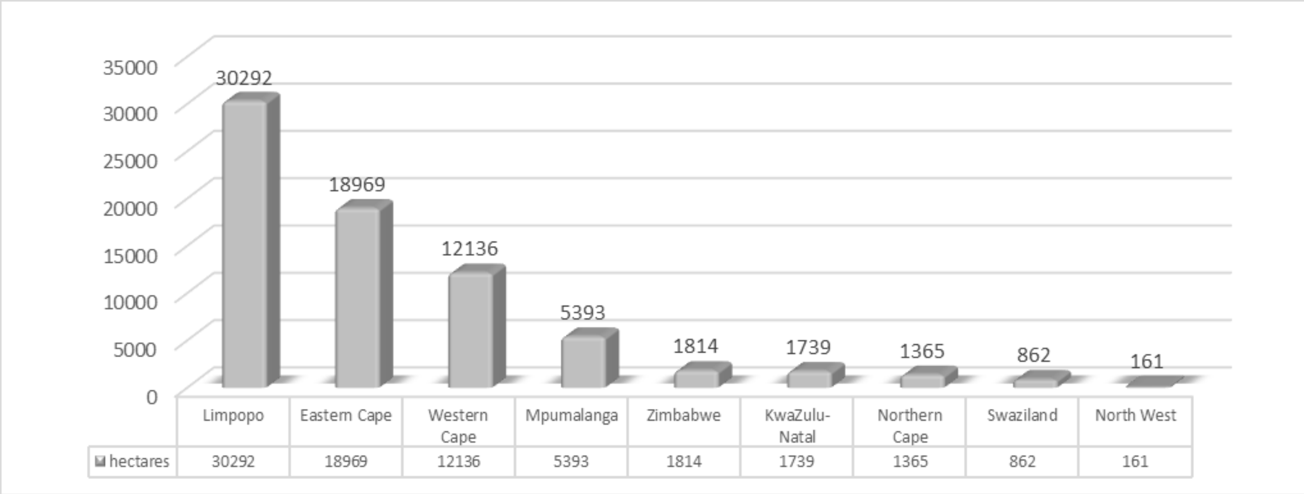


Figure 1.1. The citrus producing regions in southern Africa (CGA, 2017)

1.2.1. Global fresh citrus production

China is the largest citrus producing country in the world, producing 29 500 000 tons during the 2016 season (Figure 1.2.). China is followed by Brazil (19 274 000 tons) and India (8 955 000 tons). These three countries produce approximately 56% of citrus globally, based on the total production of the top 15 citrus producing countries in the world. Spain is the sixth largest producer, producing 5 904 000 tons, which is the equivalent of 20% of China's total volume (CGA, 2017). During the 2016 season South Africa produced 2 488 000 tons, making South Africa the tenth largest citrus producing country in the world. South Africa's total production is relatively low in comparison with the total global citrus production (CGA, 2017). However, South Africa has a significant impact on the global export market.

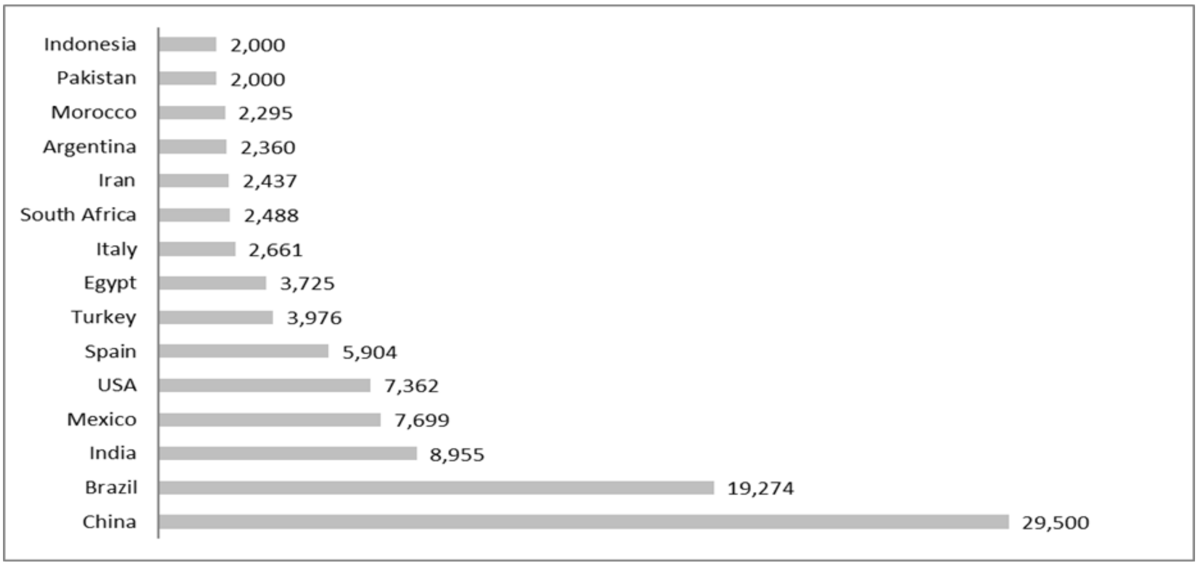


Figure 1.2. Global fresh citrus production volumes (in thousand tons) for 2016 (CGA, 2017).

1.2.2. Global fresh citrus exports

Although China is the largest citrus producing country in the world, it is only the fifth largest citrus exporting country in the world (Figure 1.3.). Countries such as China, Brazil and India have a large local market demand, thus resulting in large volumes being produced for local consumption. These countries also produce large volumes for processing purposes. The citrus is delivered to processing plants or juice factories, where concentrate is made (CGA, 2017). Spain is the largest citrus exporting country in the world, based on the total volume exported during the 2016 season. Although South Africa is only the tenth largest citrus producing country, it is the second largest citrus exporting country in the world. South Africa is the largest shipper of citrus in the world, as Spain mainly exports by land to other European countries. During the 2016 season Spain exported 3 947 000 tons, which is the equivalent of 66% of the total volume produced in Spain (CGA, 2017). South Africa exported 1 702 000 tons, which is the equivalent of 68% of its total volume produced. Spain and South Africa are very dependent on the export market, and it is of utmost importance that good quality fruit is produced and exported to the various markets around the world (CGA, 2017).

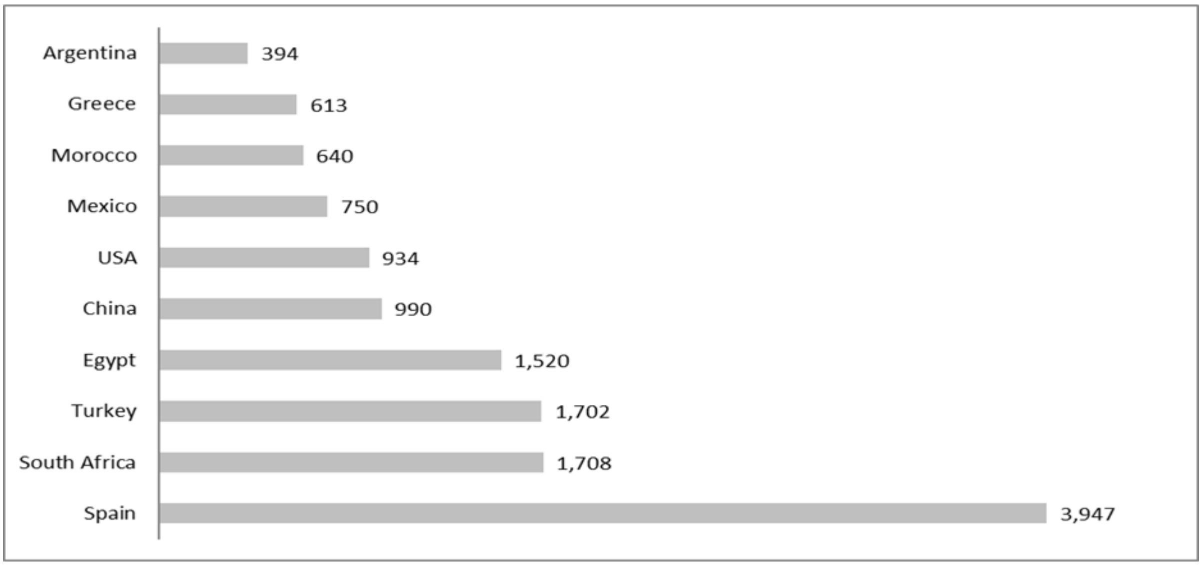


Figure 1.3. Global fresh citrus volumes exported (in thousand tons) for 2016 (CGA, 2017).

1.2.3. South African citrus industry statistics

All fruit destined for export is inspected by the Perishable Products Export Control Board (PPECB), according to the minimum export Standards of South Africa. The minimum export standards include the internal quality standards, also known as the sugar and acid ratios as well as the external standards, also known as blemish standards (SA-DAFF, 2010). In addition, PPECB must also ensure that all fruit packed for export complies with the phytosanitary requirements for the various importing countries (SA-DAFF, 2010). A total of 43% (European Union at 33% and United Kingdom at 10%) of South Africa's total volume was exported to the EU, in the 2016/2017 season (Figure 1.4.) (PPECB, 2018).

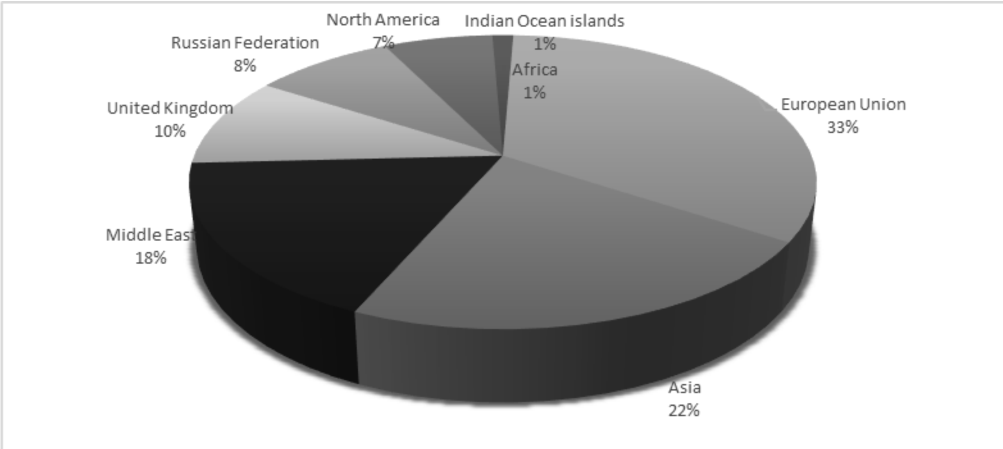


Figure 1.4. Major export destinations for South African citrus, 2017 (PPECB, 2018).

118.1 million cartons were inspected by PPECB during the 2017 season and 1.9 million cartons were rejected, which is the equivalent of 1.67% of the total that was inspected (Figure 1.5.). Although soft citrus (mandarins) is the lowest volume of all the commodities, it obtained the highest rejection rate of 3.14%. Oranges are approximately 61% of the total volume and had the second highest rejection rate of 1.66%. Grapefruit had the lowest rejection rate of 0.62% (PPECB, 2018).

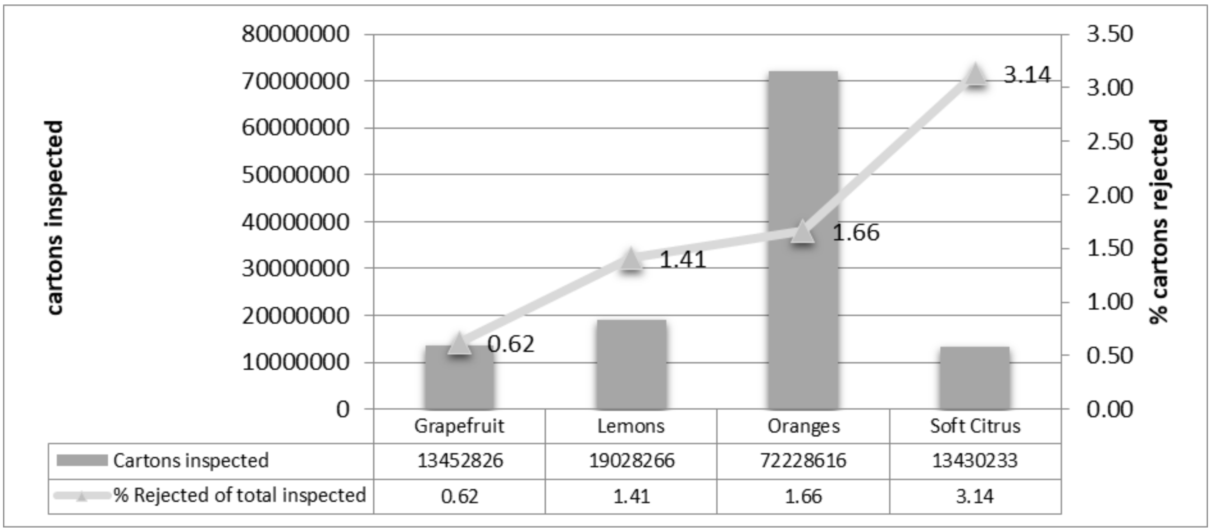


Figure 1.5. The total number of cartons inspected and percentage rejected for export by PPECB in 2017 (PPECB, 2018).

The four main reasons for rejections during the 2017 season (Figure 1.6.) were: 1) FCM: 21%; 2) combined reasons: 26%; 3) blemishes (external damage caused by thrips or wind): 17%; 4) decay: 13%. Combined reasons are rejections that are due to more than one defect. The actual figure for FCM rejections is higher, if lemons (which are not infested by FCM) are excluded (Moore *et al*. 2015b).

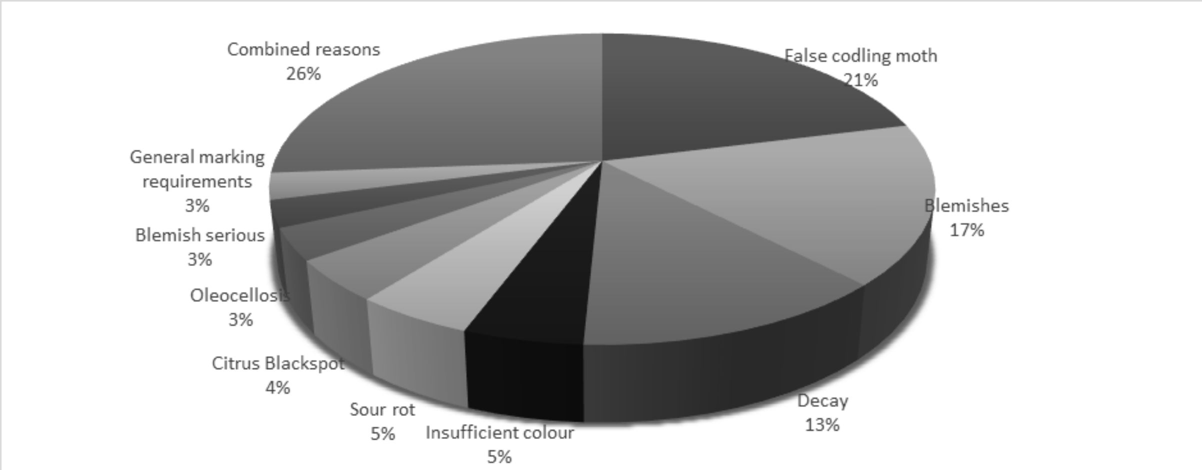


Figure 1.6. The reasons for PPECB rejections, for all citrus cultivars combined during the 2017 season (PPECB, 2018).

1.3. The Pest

1.3.1. Taxonomy and distribution

FCM was first described as the Natal codling moth, *Carpocapsa* sp. by Fuller (1901). The same moth was later renamed as the orange codling moth (Howard, 1909). In 1913 Meyrick classified FCM as *Argyroploce leucotreta*, and it was later transferred to the genus *Cryptophlebia* by Clarke (1958), after which Komai (1999) placed it in *Thaumatotibia*. FCM overlaps in distribution and host range with two close relatives in southern Africa, the macadamia nut borer, *Thaumatotibia batrachopa* (Meyrick) (Prinsloo & Uys, 2015) and the litchi moth, *Cryptophlebia peltastica* (Meyrick). Codling moth (*Cydia pomonella*) (Linnaeus) (Lepidoptera: Tortricidae) can be confused with FCM because of the resemblance in appearance and the damage caused, even though the codling moth mainly attacks apples and pears (Venette *et al*. 2003). FCM, has been recorded from most sub-Saharan areas of Africa and neighbouring islands of the Indian and Atlantic Oceans (Hill, 1975), (Figure 1.7). The moth has been reported as an agricultural pest in Israel, possibly due to accidental introduction of infested macadamia nuts (a crop which is no longer grown commercially in Israel) (Wyoski, 1986).

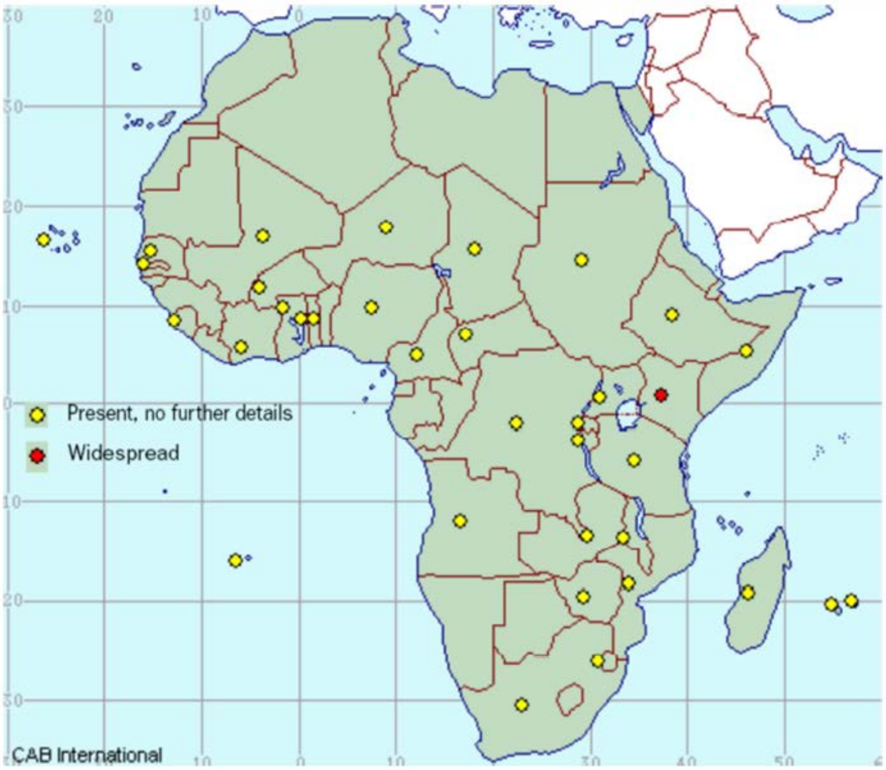


Figure 1.7. The geographical distribution of false codling moth in Africa and neighbouring islands (Stibick, 2008).

1.3.2. Host range for FCM

FCM is a polyphagous pest and can attack a variety of cultivated (Table 1.1.) and wild host plants, as listed during the pest risk Analysis for FCM by EPPO in 2013 (Table 1.2.) (Schwartz, 1981; van den Berg, 2001).

Table 1.1. Cultivated plants which have been recorded as hosts of FCM (Daiber, 1980; Newton, 1998; Pinhey, 1975; Venette *et al*. 2003; Kirkman & Moore, 2007; CABI 2005; EPPO, 2013).

Host plant	Common name	Plant family
Capsicum spp.	Pepper	Solanaceae
Citrus reticulata & hybrids	Mandarin orange	Rutaceae
Citrus sinensis & hybrids	Orange	Rutaceae
Citrus paradisi	Grapefruit	Rutaceae
Gossypium spp.	Cotton	Malvaceae
Litchi chinensis	Litchi, Litchee	Sapindaceae
Macadamia spp.	Macadamia	Proteaceae

Host plant	Common name	Plant family
Mangifera indica	Mango	Anacardiaceae
Prunus persica	Peach	Rosaceae
Prunus persica var. nucipersica	Nectarine	Rosaceae
Persea americana	Avocado	Lauraceae
Psidium guajava	Guava	Myrtaceae
Punica granatum	Pomegranate	Lythraceae
Quercus robur	Oak	Fagaceae
Ricinus communis	Castor oil plant	Euphorbiaceae
Rosa sp.	Rose	Rosaceae
Solanum melongena	Eggplant	Solanaceae
Vitis vinifera	Grape	Viticeaea
Zea mays	Maize	Poaceae

EPPO (2013) conducted a thorough review of the existing host lists and have removed various species. Recently the option of non-hot status for certain species has been adopted (Liquido *et al*. 1995; Aluja *et al*. 2004; Follett & Neven 2006; Follett & Hennessey 2007; Pringle *et al*. 2015). It was indicated that there are no definitions of host status of fruit specifically for tortricid pests (Pringle *et al*. 2015). Aluja & Mangan (2008) described the host status for Tephritidae: a natural host is infested under totally natural field conditions. A non-natural host is not known to be infested under natural field conditions, but there is experimental evidence that it can be infested and produce reproductive adults under laboratory (artificial) conditions. A non-host is a plant in which development cannot be completed (Aluja & Mangan 2008).

Table 1.2. Wild plants which have been recorded as hosts of FCM (Schwartz, 1981; Venette *et al*. 2003; Kirkman & Moore, 2007; EPPO, 2013).

Common Name	Species
Bur weed	*Triumfetta* spp.
Bluebush	*Diospyros lycioides*
Bloubos	*Diospyros pallens*
Boerboon	*Schotia afra*
Buffalo thorn	*Ziziphus mucronata*
Carambola	*Averrhoa carambola*

Common Name	**Species**
Castorbean	*Ricinus communis*
Chayote	*Sechium edule*
Cowpea	*Vigna unguiculata, Vigna* spp.
Custard apple	*Annona reticulata*
Elephant grass	*Pennisetum purpureum*
English Walnut	*Juglans regia*
Governors plum	*Flacourtia indica*
Indian mallow	*Abutilon hybridium*
Jakkalsbessie	*Diospyros mespiliformis*
Jujube	*Ziziphus jujube*
Jute	*Abutilon* spp.
Kapok/copal	*Ceiba pentranda*
Kei apple	*Dovyalis caffra*
Khat	*Catha edulis*
Kudu-berry	*Psuedolachnostylis maprouneifolia*
Lima bean	*Phaseolus lunatus*
Mallow	*Hibiscus* spp.
Mangosteen	*Garcinia mangostana*
Marula	*Sclerocarya birrea*
Monkey pod	*Senna petersiana*
Oak	*Quercus* spp.
Okra	*Abelmoschus esculentus*
Peacock flower	*Caesalpinia pulcherrima*
Port Jackson	*Acacia longifolia*
Pride of De Kaap	*Bauhinia galpinii*
Raasblaar	*Combretum zeyheri*
Red milkwood	*Mimusops zeyheri*
Rooibos / Bushwillow	*Combretum apiculatum*
Sida	*Sida* spp.
Snot apple	*Azanza garckeana*
Stamvrugte	*Englerophytum magalismontanum*
Sodom apple	*Calotropis procera*

Common Name	**Species**
Soursop	*Annona muricata*
Stemfruit	*Englerophytum magaliesmontanum*
Surinum cherry	*Eugenia uniflora*
Suurpruim / large sour plum	*Ximenia caffra*
Water-bessie	*Syzygium cordatum*
Wag 'n bietjie	*Capparis tomentosa*
Weeping boerboon	*Schotia brachypetala*
Wild almond	*Brabejum stellatifolium*
Wild fig	*Ficus capensis*
Wild medlar	*Vangueria infausta*
Wild plum	*Harpephyllum caffrum*
Wing bean	*Xeroderris stuhlmannii*
Yellow-wood berries	*Afrocarpus falcatus*
Yellow-wood, real	*Podocarpus latifolius*

1.3.3. Life history of FCM

Female moths (Figure 1.8) lay their eggs singly and often in large numbers, on the rind of the fruit. The egg is a translucent, hemispherical disc with a granulated surface (Daiber, 1979a). The egg measures at 0.77 mm in length and 0.60 mm in width. The incubation period for the egg is generally dependant on temperature, being between 9 and 14 days in winter-, and 4 to 8 days in summer (Schwartz 1981). The neonate larvae are white with a black head capsule and first thoracic segment, measuring approximately 1.4 mm in length (Annecke & Moran 1982; Stofberg 1948). According to Pinhey (1975), the larvae will bore into the fruit and begin to feed on the inner rind of the fruit. Five larval instars were recorded based on the width of the head capsule (Daiber 1979b). A mature fifth instar larva can measure between 15 and 20 mm in length. Development of larvae from first to fifth instar takes 25 to 67 days, dependant on temperature (Stofberg, 1948). Larval development is also influenced by the available food. The mature larva exits the fruit through a frass-filled hole, either while the fruit is still on the tree, or after the fruit has dropped to the ground (Moore, 2017). At this stage the larva stop feeding and begin to spin a cocoon from silk and soil particles (Stofberg, 1948). In the field, the duration of the pupal stage can vary between 21 and 80 days, depending on the temperature (Daiber 1979c). Stofberg (1948) determined that female moths laid up to 300 eggs each, while Daiber

(1979a) recorded 456 eggs per female moth. The entire life-cycle of FCM takes 45 to 60 days to complete during warm summer months, from August to March, and 68 to 100 days during cooler winter months, April to July (Stofberg, 1954). Conditions such as climate and food quality will cause the number of generations to vary between five and eight per year, but usually six (Newton, 1998).

Figure 1.8. False codling moth (*Thaumatotibia leucotreta*). Georg Goergen/IITA Insect Museum, Cotonou, Benin as published in CABI 2000

1.3.4. Phytosanitary status of FCM

FCM is regarded as a phytosanitary pest and has regularly been intercepted in recent years, particularly in Europe (Europhyt, 2016). An incursion of FCM was detected in the Netherlands in glasshouse grown peppers, *Capsicum chinense* in 2009 and was subsequently eradicated. This introduction of FCM from Ugandan peppers into the Netherlands led to a Dutch Pest Risk Analysis (PRA) for *Thaumatotibia leucotreta* (Potting & van der Straten, 2010).

Another pest risk analysis for FCM was conducted in 2013 (EPPO, 2013), subsequent to the Dutch PRA, by the European and Mediterranean Plant Protection Organisation (EPPO). EPPO is an intergovernmental organization responsible for international cooperation in plant protection in the European and Mediterranean region and consists of 52 member states (Table 1.3.). The membership of 52 states also emphasises the authority level of the organisation with regard to decision making within the EU (EPPO, 2018a). The PRA concluded that citrus is a preferred host of FCM and South African citrus was identified as a primary focus due to large volumes being exported to Europe (Table 1.4.) (PPECB, 2018). FCM was listed as a A2 quarantine pest (A2 pest are locally present in the EPPO region). In June 2018, a single male specimen of *Thaumatotibia leucotreta* was caught in a trap during an official survey carried out in Saxony, Germany. The trap was placed in a glasshouse producing *Capsicum annuum* fruits (EPPO, 2018b)

Table 1.3. EPPO – List of member countries (EPPO, 2018a).

1	Albania	19	Guernsey	37	Norway
2	Algeria	20	Hungary	38	Poland
3	Austria	21	Ireland	39	Portugal
4	Azerbaijan	22	Israel	40	Romania
5	Belarus	23	Italy	41	Russia
6	Belgium	24	Jersey	42	Serbia
7	Bosnia and Herzegovina	25	Jordan	43	Slovakia
8	Bulgaria	26	Kazakhstan	44	Slovenia
9	Croatia	27	Kyrgyzstan	45	Spain
10	Cyprus	28	Latvia	46	Sweden
11	Czech Republic	29	Lithuania	47	Switzerland
12	Denmark	30	Luxembourg	48	Tunisia
13	Estonia	31	Macedonia (FYROM)	49	Turkey
14	Finland	32	Malta	50	Ukraine
15	France	33	Moldova	51	United Kingdom
16	Georgia	34	Montenegro	52	Uzbekistan
17	Germany	35	Morocco		
18	Greece	36	Netherlands		

Table 1.4. Exported fresh fruit volumes from South Africa to Europe per category (PPECB, 2018).

Category	**Volume - thousand tonnes**
Citrus (excluding lemons and limes)	600 - 700
Table grapes	190 - 210
Stone fruit	58 - 63
Avocados	32 - 36
Persimmons	4 - 6
Pomegranates	4 - 5
Mangos	1 - 2

1.4. Management of FCM

It is important that the different life stages of FCM are monitored to determine the potential threat of FCM infestation and to determine FCM population levels in orchards. FCM is controlled by implementing certain pre-and postharvest interventions. There are various options available to control FCM at a preharvest level. They include chemical control, orchard sanitation, mating disruption, attract and kill, augmentative biological control by using egg parasitoids, and the use of pathogens and sterile insect technique (Hofmeyr & Pringle, 1998; Newton, 1998; Bloem *et al.* 2003; Moore *et al.* 2004; Hofmeyer *et al.* 2005; FSQA Subdirectorate: API 2007).

1.4.1. Inspection and monitoring

Although egg surveys can be useful to determine population fluctuations, it remains problematic to inspect citrus fruit for FCM eggs due to the egg size and the fact that the eggs are transparent and therefore easy to miss (Moore, 2017). There is also a relatively poor, and variable relationship between egg numbers and fruit drop as a result of FCM, due to egg parasitism and other natural factors that influence the mortality of the larvae. Although fruit drop surveying is regarded as one of the most important means of monitoring FCM, it is an indication of recent historical FCM levels, as fruit drop occurs a few weeks after an increase in moth activity (Moore, 2017). It is recommended that dropped fruit be inspected from as early as January until harvest to determine FCM activity. These data can be used to determine the extent of FCM activity at an orchard level (Moore, 2017). The pheromone based trapping system is the most common means of monitoring FCM and is also considered the most effective method to monitor FCM population levels (Moore, 2017). Although pheromone traps are very effective for monitoring activity, they cannot be used to control FCM (Moore, 2017). There are currently three pheromone monitoring systems registered for FCM. These are Lorelei, FCM PheroLure and Chempac FCM Lure (Moore, 2017). Trap counts should be evaluated in conjunction with fruit drop to determine infestation levels. The trap consists of a dispenser which contains a female pheromone, which attracts the male moths (Moore, 2017). The distribution should be 1 trap for every 4 to 6 hectares of citrus. Historically it was determined that if 10 or more males were caught per trap within a given week, subsequent fruit infestation would justify a corrective measure or treatment and this level of trap catch was thus set as the intervention threshold (Moore & Hattingh, 2012). However, these economic thresholds should no longer apply, given the phytosanitary status of FCM for most export markets (Moore, *et al*. 2008b).

A yellow delta trap (a PVC pipe trap is an alternative) containing the female pheromone lure and a sticky floor (Figure 1.9.) must be placed at a density of one trap per 4 ha and in accordance with CRI's recommendations (Moore, 2017). The trap should be hung on the shady side of the tree. However, the available space between the trees will determine whether the trap is placed on the southern, south eastern or eastern side of the tree (Moore, 2017).

Figure 1.9. Delta trap with pheromone lure and sticky pad used for monitoring FCM adult males (CRI).

Figure 1.10. A yellow delta trap loaded with a pheromone dispenser, hung in a citrus tree for monitoring FCM adult males (CRI).

The traps must be inspected every week on the same day to determine the number of FCM in the various traps (Moore, *et al*. 2016). Fruit infestation must be monitored and a minimum of 5 data trees for every 3 ha is recommended. All fruit underneath the 5 data trees must be collected and inspected visually and also dissected to determine FCM infestation levels (Moore, *et al.* 2016). Fruit must be considered as infested if any FCM larvae are found or any positive sign is found that the fruit was infested by an FCM larva.

1.4.2. Cultural control

Orchard sanitation is regarded as the cornerstone of FCM control and it has been shown that it is possible to remove as much as 75% of FCM larvae from an orchard by conducting weekly orchard sanitation (Moore & Kirkman, 2008). By removing all fruit showing signs of damage or infestation (both fruit on the tree and fallen fruit), FCM larval numbers are significantly reduced, as is the risk of post-harvest decay (Moore, 2017). Orchard sanitation must be a continuous process prior to harvesting and this practice should therefore continue to be implemented once harvesting in an orchard is completed. It was determined that orchard sanitation should ideally be initiated before December (Schwartz, 1974), as the highest infestation levels were found during mid-December. All fruit that is collected from the orchard must either be buried or destroyed mechanically to ensure that no larvae escape (Hepburn & Bishop, 1954).

1.4.3. Biological control

There are many biological methods to suppress FCM in citrus orchards, including parasitoids and predators. The egg parasitoid *Trichogrammatoidea cryptophlebiae* (Nagaraja) (Hymenoptera: Trichogrammatidae), is considered to be the most effective biological control agent for FCM (Moore, 2017). The parasitoid occurs naturally in all citrus-producing regions and can parasitize more than 80% of FCM eggs (Moore, 2017). It has been shown that releasing a total of 100 000 parasitoids per ha (four monthly releases of 25 000 each) is usually adequate to get control in all areas except the Western Cape (Moore & Hattingh, 2004). An additional 25 000 parasitoids per ha (a total of 125 000 parasitoids per ha) should be released in the Western Cape to obtain the required result. Moore and Hattingh (2012) reported that inundative augmentation of 100 000 parasitiods per ha reduced FCM infestation by 60%. It has been documented that *Orius* beetles prey on FCM eggs, but ants are probably the most effective predators and research has shown that ants can significantly reduce the number of FCM pupae in orchard soils (Bownes *et al.* 2014).

1.4.4. Microbial control

Cryptogran (River Bioscience, South Africa), Cryptex (Andermatt, Switzerland) and Gratham are virus-based products containing the Cryptophlebia leucotreta granulovirus (CrleGV), (Moore, 2017). CrleGV is an indigenous pathogen and is registered as a biological control agent to control FCM (Moore, 2002). These products have no effect on beneficial insects and are therefore fully compatible with an Integrated Pest Management (IPM) programme. The virus is sprayed onto the fruit and ingested by the larvae as they attempt to feed, subsequently infecting the entire body, causing it to die and rupture (Moore, 2017). CrleGV succeeded in reducing FCM damage by between 30% and 92% in 13 field trials that were conducted between 2001 and 2013 (Moore *et al.* 2015a).

Cryptonem, with the entomopathogenic nematode (EPN), *Heterorhabditis bacteriophora*, as the active ingredient, is the only product that is registered to be applied against the soil-dwelling life-stages of FCM (Coombes *et al.* 2017; Goble *et al*. 2010). This registration has subsequently been suspended pending an environmental impact assessment. After penetration of the insect, EPNs release synergistic bacteria, which kill the insect. There are currently two entomopathogenic fungi (EPF) registered to control FCM, Broadband and Eco-Bb, both developed from *Beauveria bassiana* (Moore, 2017). The spores of the fungus germinate, secreting enzymes which weaken the larvas's cuticle. The fungus enters the host by means of the weakened cuticle, feeding on the internal organs and subsequently killing the larva (Coombes *et al.* 2017).

1.4.5. Chemical control

There are two chitin synthesis inhibitors (belonging to the benzoyl urea group), Alsystin (triflumuron) (Bayer, Germany) and Nomolt (teflubenzuron) (BASF, Germany) that are registered for FCM control. The objective of these products is to disrupt embryonic development of the larvae in the eggs. These products are only effective if the eggs are laid on the treatment residue (Moore, 2017). Thorough coverage of fruit during application is thus important (Moore, 2017). Three spray programmes involving Alsystin and Nomolt are recommended. These programmes are based on the length of time before harvest during which protection is required. The use of both Alsystin and Nomolt has been restricted because FCM has developed resistance where these products have been used extensively in the Western Cape (Hofmeyr & Pringle, 1998). Another concern is maximum residue level (MRL), restrictions, which prevent use of these for many important markets. Runner (methoxyfenozide) is an ecdysone agonist, which is also an insect growth regulator (IGR). After ingestion, larvae undergo a developmentally lethal premature moult.

There are two synthetic pyrethroids for FCM control, i.e. cypermethrin, which is manufactured and supplied by various companies, as well as Meothrin (fenpropathrin) (Philagro, South Africa). Both of these products are larvicides and the objective is to kill the FCM larvae after hatching and before penetration of fruit, thus protecting the fruit against FCM infestation shortly before harvest (Moore, 2017). The application of pyrethroids should be considered carefully as they are potentially toxic to a wide range of beneficial insects and could cause repercussions of pests such as red scale, mealybug and soft brown scale (Moore, 2017).

Delegate, whose active ingredient is spinetoram, a member of the group of spinosyns, targets a nicotinic acetylcholine receptor, which causes insect death (Moore, 2017). The novel anthranlic diamide insecticide, Coragen, is a ryanodine receptor activator, that prevents muscle contractions and causes death by paralysis (Lahm, *et al*. 2009). Another chemical insecticide has recently been registered, Warlock, (Adama, Israel). It contains emulsified concentrate (EC) emamectin benzoate (Zhao, *et al.* 2006). The active ingredient disrupts the nerve signals within the targeted pest. Warlock has translaminar activity but is not systemic, therefore thorough coverage is essential.

1.4.6. Mating disruption

Mating disruption is also used as a control method for FCM and relies on the prevention of mating, thus reducing the number of viable eggs. In this technology, a synthetic female sex pheromone is applied in citrus orchards, causing the males to be disorientated and unable to find females for mating (Moore, 2017). There are currently four products registered for FCM control in South Africa. These are Isomate (Sumitomo, Japan), Checkmate (Suterra, USA), Splat (Specialised Pheromone & Lure Application Technology, (ISCA, USA)) and X-mate (Insect Science, South Africa). Isomate consists of dispensers containing liquid sex pheromone. Checkmate is a pheromone containing micro-capsule suspension formulation (Moore, 2017). Splat is an amorphous polymer matrix, containing pheromone. X-Mate consists of cellulose disc dispensers containing liquid sex pheromone (Moore, 2017). Although all four products are considered to effectively control FCM, the effect of these products is temporary, due to the cool autumn temperatures that prevent adequate dispensing of the pheromone for continued control (Moore, 2017).

1.4.7. Attract and kill

The attract and kill (A&K) technique is similar to the mating disruption method, the difference being that instead of disrupting mating, the male is killed. Last Call FCM (Insect Science, South Africa) is a transparent gel, consisting of a synthetic pheromone and a pyrethroid (Moore, 2017). The male is killed soon after making contact with the pyrethroid active ingredient.

1.4.8. Sterile Insect Technique

The objective of this technique is to release large numbers of irradiated sterile male FCM at an overflooding ratio of at least 10 sterile males to 1 wild male, thus reducing the number of FCM that can reproduce, which will ultimately lead to a reduced FCM population (Hofmeyr, *et al*. 2015). The sterile insect technique was initially investigated as a control method for FCM in Citrusdal in the Western Cape. Today, SIT is used in various production regions and is proving to be highly effective (Hofmeyr *et al*. 2015), having reduced moth catches by 99%, fruit infestation by 96% and export rejections by 89% since the start of the programme in Citrusdal, Western Cape Province, in 2007 (Barnes *et al*. 2015). In a semi-commercial trial, SIT as a stand-alone treatment, reduced FCM infestation in 35 ha of Washington Navel oranges by 95.2%, in comparison to the untreated control orchard (Hofmeyr *et al*. 2016). A 35% reduction in FCM infestation was obtained where the SIT programme was implemented in conjunction with a registered spray application (Nepgen *et al*. 2018).

1.4.9. Post-harvest control

Trials showed that treating larvae in artificial diet with -0.5°C for 21 days (also known as cold sterilisation), led to 100% mortality of FCM larvae (Myburgh, 1963). Today, cold sterilisation is the only recognised stand-alone quarantine disinfestation treatment for citrus from South Africa. Certain countries, such as the United States have enforced cold sterilisation as an entry level requirement to ensure market access (USDA, 2016). This treatment is very costly and can only be considered for fruit destined for more lucrative markets such as the United States, China and Japan, to justify the additional costs. There are also certain problems associated with cold sterilisation, the main problem being that certain cultivars cannot be shipped at such low temperatures without developing unacceptable levels of chilling injuries. South Africa also does not have the infrastructure to export large volumes under cold sterilisation. More recently, it was demonstrated that the following treatments caused mortality of FCM at or in excess of the probit 9 level: 16 days at or below -0.1 °C, 18 days at or below -0.3 °C, and 19 days at or below 1.2 °C (Moore, *et al*. 2017). These provide the opportunity for far more favourable cold sterilization export protocols, but have nor yet been commercially accepted.

To effectively manage the risk posed by FCM, integration of the control approaches as described above is required, thus potentially being components within a systems approach.

1.5. A Systems Approach for FCM

A systems approach is defined as the integration of different risk management measures, of which two should act independently, and should cumulatively achieve the appropriate level of protection against regulated pests (FAO, 2002). The reasons why a systems approach for FCM should be considered are, a) FCM is a regulated phytosanitary pest for the EU, and b) cold sterilisation to this market is impossible. There are many challenges associated with the implementation of systems approaches to pest insect control and the efficacy or accuracy of systems approaches across an entire pathway comprising of many complex processes remains the biggest challenge. The World Trade Organisation (WTO) states that measures must be applied to the extent required to achieve an appropriate degree of sanitary/phytosanitary protection and must follow a science-based risk assessment (FAO, 2006a). A systems approach can include both pre- and post-harvest procedures that may contribute to the effective management of the pest. The biological, physical and operational factors that can affect the incidence, viability and reproductive potential of a pest into a system of practices and procedures are integrated by a systems approach (Jamieson *et al*. 2013). A systems approach should in principle comprise a combination of phytosanitary measures that can be implemented in the place of production within the exporting country. An analysis should be conducted to determine the pathway from the country of origin to the destination country and a quantitative and qualitative evaluation should be conducted to determine the probability of entry, establishment and spread of a specific pest (Jamieson *et al*. 2013). The quantitative and qualitative estimate of the economic consequences in case of biosecurity failure should also form part of such an analysis. All importing countries are entitled to an Appropriate Level of Protection (ALOP) as a precautionary method. If the risk of entry and establishment of a pest is determined to be higher than the ALOP, the importing country may enforce certain measures to mitigate the risk. In the past, approaches generally used probit 9 (based on the mortality rate of 99.9968% at a 95% confidence level) as a criterion for treatment efficacy. It was argued (Landolt *et al*. 1984) that probit 9 did not guarantee quarantine security because the probability of introduction depends on the number of pests surviving rather than killed and information such as pre-treatment infestation levels and other biological data are required to calculate the risks. More recently there has been an argument that probit 9 is an excessive requirement, especially for pests that solitarily infest fruit (Moore, *et al.* 2018). The Maximum Pest Limit (MPL) was introduced (Baker *et al*. 1990) and was defined as the smallest number of individuals capable of establishing a colony and therefore the maximum number of pests that may be present in a consignment imported during a specific time to a specific location. Yamamura & Katsumata (1999) focused on the probability of introduction as presented by Landolt *et al*. (1984). Cannon (1998) emphasised that a risk assessment should be focused on the probability of establishment of the pest rather than just probability of introduction. It needs to be determined whether a maximum pest limit for FCM is achievable and more investigation should be done to determine whether the system is effective.

Phytosanitary regulations were imposed for FCM for South Africa's largest export market i.e. the EU (Official Journal of The European Union, 2017). As the old existing acceptable postharvest quarantine disinfestation treatment (i.e. cold sterilization) would be unaffordable to this market, a systems approach for FCM has been proactively developed and implemented by the South African industry (Moore *et al.* 2016). The systems approach is a protocol whereby certain pre-harvest practices and postharvest inspections are used as an alternative method to assist in managing the threat that FCM poses to the South African citrus industry and more importantly to the export market. The components of the systems approach, referred to as the False Codling Moth Risk Management System (FMS) are described below (Moore *et al*. 2016).

- The potential establishment and maintenance of Pest Free Areas, Pest Free Places of Production and Pest Free Production Sites in accordance with the relevant ISPM 4 (FAO, 1995) and 15 (FAO, 2006b) and an agreed FCM Pest Free Zones protocol
- Registration of eligible orchards
- Orchard monitoring – traps and fruit infestation, with associated thresholds for the latter, indicating if additional pre-harvest control measures are required and subsequent handling options within the FMS
- Orchard sanitation
- Use of only registered pre-harvest control measures
- In-orchard fruit culling
- Post-harvest fruit inspections – for FCM infestation on delivery at packhouse, indicating which subsequent handling options are available
- Packhouse grading of fruit
- Phytosanitary inspections of fruit packed for export – by Perishable Products Export Control Board (PPECB)
- South African Department of Agriculture, Forestry & Fisheries (SA-DAFF) phytosanitary certification of compliant consignments

- A limited set of post-harvest shipping options for application to individual export consignments as determined by the level of compliance with other aspects of the FMS.

A pheromone trap must be placed in a 4 ha area to monitor FCM activity. A set of 5 data trees must be placed in every orchard up to 3 ha in size (Moore, *et al.* 2016).

A random fruit sample must be taken from each orchard and inspected for FCM infestation once the fruit is delivered to the packhouse. The sample size may differ depending on the export option selected and complied with. The sample must be taken as evenly as possible and should not be taken only from a single bin. The inspections are conducted superficially and only suspicious fruit are inspected destructively thereafter. The inspections must be performed by a trained person.

The procedure for fruit inspection:

- the fruit are inspected thoroughly for any marks which might indicate a possible point of FCM penetration;
- the rind is then cut away under the mark which will allow observation of even the shallowest penetration of a very small larva;
- the next step is to continue cutting into the flesh to determine infestation;
- the same procedure is followed with all navel ends of Navel oranges (even if no marks are present;
- in the case of non-Navel cultivars, the fruit is cut into quarters and inspected for any signs of infestation;

Infestation thresholds apply at this point. The benefit of implementing the proposed inspection system is to have a more proactive approach by having data with FCM status prior to packing (Moore, *et al*. 2016). The success of such a systems approach is dependent on Good Agricultural Practices (GAP), an adequate inspection system and accurate record keeping.

1.6. Aims of study

The main objective of this thesis was to implement a systems approach for FCM risk mitigation in citrus, on a commercial level, and to determine its effectiveness in reducing the risk of exporting infested fruit, both through control measures and predictive inspections.

Within this, the thesis had three main research aims:

1. To determine whether there is a relationship between pre-harvest orchard practices to reduce FCM and FCM infestation levels in fruit thereafter (Chapter 3).
2. To determine the relationship between levels of FCM in the orchard and in fruit delivered to the packhouse (Chapter 3).
3. To determine the relationship between levels of FCM in fruit delivered to the packhouse and fruit packed in the carton (retention samples) (Chapter 3).

Some of the specific questions to be answered by this study are:

- Will an optimum pre-harvest FCM programme in conjunction with Good Agricultural Practices (GAP) and inspection systems at orchard and packhouse level adequately minimise the risk of FCM infested fruit being exported?
- Are certain citrus types more likely to be infested with FCM on delivery at packhouse and after packhouse processing?
- How effective is the integrated management system that is currently being implemented – both in the field and the packhouse?
- What are the shortcomings with the integrated management system – both in the field and the packhouse?
- Recommendations on how to improve the current integrated management system – both in the field and the packhouse

Chapter 2:

Materials and Methods

Introduction

The overall objective of this study was to determine whether an Integrated Management System or Systems Approach is sufficient to reduce the level of FCM infestation in citrus fruit to a phytosanitarily acceptable level. This system requires that various management steps be followed in order to identify the presence and level of FCM and to minimize infestation to an acceptable level. The Integrated Management System relies on certain pre-harvest and post-harvest practices and inspections. The methods used to investigate the role of pre- and postharvest practices are cited below.

2.1. Pre-harvest

2.1.1. Trial sites

A total of 30 citrus orchards were identified for this study. All the orchards were situated in the Sundays River Valley, near Addo in the Eastern Cape. The trial sites included Tortello Investments (Tortello and Sunset Farms) (GPS coordinates: 33°26’19.34”S; 25°34’44.03”E), Wicklow (GPS coordinates: 33°30’15.99”S; 25°35’58.52”E), Sackville (GPS coordinates: 33°31’30.87”S; 25°38’52.33”E), Rietfontein (GPS coordinates: 33°30’59.14”S; 25°38’21.15”E), Daisy Dell (GPS coordinates: 33°29’5.46”S; 25°39’22.26”E) (Figure 2.1.). Within the Sundays River Valley the study orchards were located in an area extending about 20 km northwest of Addo (33.526519°S, 25.711898°E, 77 m asl) and 10 km wide in a hot semi-arid Köppen-Geiger Bsh climate region with an average annual temperature of 18.5°C and annual average rainfall of 380 mm based on meteorological recorded about 10 km north east of Addo in the Addo Elephant Park. All weather data was obtained from a weather station in the Sundays River Valley.

Figure 2.1. Geographical distribution of the trial sites

2.1.2. Trial layout

The orchards consisted of various citrus cultivars where FCM was monitored and recorded. These included three orchards of Nule Clementine, two orchards of Nova Mandarin, three orchards of Navelina Navel, five orchards of Palmer Navel, one orchard of Washington Navel, five orchards of Cambria Late Navel, two orchards of California Late Navel, two orchards of Autumn Gold Navel, three orchards of Navelate Late Navel, two orchards of Midknight Valencias and two orchards of Delta Valencia. The details of all orchards where FCM was monitored were recorded (Table 2.1). Assessments were undertaken from first week of February when fruit were in 50-60 mm diameter, and those within bunches about to touch, until up to about 31 July (about 29 weeks) in both 2017 and 2018.

Table 2.1. The details of all orchards where FCM was monitored.

Farm Name	Cultivar	Orchard number	Year planted	Ha	Trees	Spacing (rows x tree)	Rootstock	Irrigation type
Sunset Farm	Palmer Navel	8	2006	1.14	1144	5x2	Carrizo Citrange	Drip
		9	2006	1.59	1593	5x2	Carrizo Citrange	Drip
Tortello	Palmer Navel	7	2006	1.38	1377	5x2	Carrizo Citrange	Drip
	Autumn Gold Late Navel	5	2003	1.38	1377	5x2	Carrizo Citrange	Drip
		6	2003	1.14	1144	5x2	Carrizo Citrange	Drip
Daisy Dell	Cambria Late Navel	DD01	2014	3.07	1865	5.5x3	Carrizo Citrange	Drip
		DD02	2014	0.45	609	5.5x3	Carrizo Citrange	Drip
		DD03	2014	0.98	555	5.5x3	Carrizo Citrange	Drip
		DD04	2014	1.44	874	5.5x3	Carrizo Citrange	Drip
		DD05	2014	4.51	2732	5.5x3	Carrizo Citrange	Drip
Rietfontein	Nules Clementine	RF06	1996	1.65	1000	5.5x3	Swingle Citrumelo	Drip
	Nova Mandarin	RF21	1999	1.7	850	5x4	Swingle Citrumelo	Micro
		RF22	1999	1.7	850	5x4	Swingle Citrumelo	Micro
Sackville	Palmer Navel	SV12	1997	1.12	1022	5.5x2	Swingle Citrumelo	Drip
	Navelina Early Navel	SV10	1998	1.22	1113	5.5x2	Swingle Citrumelo	Drip
		SV11	1998	1.27	1155	5.5x2	Swingle Citrumelo	Drip
	Navelate Late Navel	SV13	1998	1.16	1060	5.5x2	Swingle Citrumelo	Drip
		SV14	1998	1.2	1100	5.5x2	Carrizo Citrange	Drip
		SV20	2006	2.5	1522	5.5x3	Carrizo Citrange	Drip
	Washington Navel	SV15	2006	1.59	965	5.5x3	Carrizo Citrange	Drip
	California Late Navel	SV17	2006	1.37	832	5.5x3	Carrizo Citrange	Drip
		SV19B	2006	1.08	652	5.5x3	Carrizo Citrange	Drip
	Nules Clementine	SV31	1999	1.14	1040	5.5x2	Swingle Citrumelo	Drip
		SV32	1999	0.95	860	5.5x2	Swingle Citrumelo	Drip
Wicklow	Midknight Valencia	WK07	1995	1.07	1070	5x2	Troyer Citrange	Micro
		WK08	1995	0.42	415	5x2	Troyer Citrange	Micro
	Delta Valencia	WK25	1995	1.24	750	5.5x3	Swingle Citrumelo	Micro
		WK28	1995	3.96	2400	5.5x3	Swingle Citrumelo	Micro
	Palmer Navel	WK26	1995	0.54	280	5.5x3	Carrizo Citrange	Micro
	Navelina Early Navel	WK27	1995	0.46	280	5.5x3	Carrizo Citrange	Micro

2.1.2.1. Monitoring of FCM infestation of fruit

A set of five data trees was allocated for every orchard. Monitoring of FCM infestation for the 2017 season started in February (summer) and ended when the orchard was harvested. Monitoring of FCM infestation for the 2018 season started in January and ended when the orchard was harvested. The data trees were clearly marked by placing barrier tape around the trees (Figure 2.2.). The data trees had to be clearly visible to ensure that none of the fruit lying underneath the data trees were removed by the farm workers while conducting sanitation. All fruit lying underneath the five data trees were collected every week (on the same day) and the fruit were inspected visually for any signs of infestation. Only suspect fruit were dissected using a knife, to determine whether they had fallen due to FCM infestation, and if so, whether larvae had exited the fruit (where the larvae had entered the fruit and had exited by means of an enlarged hole with frass remains) or if they were still present.

Figure 2.2. A set of five data trees

2.1.2.2. Monitoring of pheromone traps to determine FCM activity

Yellow Delta trap with Chempac pheromone lures were used to monitor the activity of FCM in the citrus orchards described in Table 2.1. Monitoring of the pheromone traps in the 2017 season started in February and ended after the orchard was harvested. Monitoring of the pheromone traps in the 2018 season started in January and ended after the orchard was harvested. The pheromone lures were replaced every three months. The sticky liners were replaced as and when necessary i.e. when they became too dirty or began to lose stickiness. One pheromone trap was placed per every 4 ha of orchards. The pheromone trap was hung in the south eastern side of the tree using a wire at an approximate height of 2 m above the ground. The trap was placed in the sixth row in the sixth tree in the orchard. The trap was placed in the outside leaf canopy. The area around the trap was cleared of all branches and leaves throughout the year. The trap had a sticky liner with the Chempac pheromone.

The isomers within the pheromone blend were (Z)-8-dodecenyl acetate), (E)-8-dodecenyl acetate) 62.5 g/kg, (E)-7-dodecenyl acetate), attracting male moths. Traps were inspected on a weekly basis (on the same day), and all FCM adults on the sticky liner were recorded. The traps were monitored from the first week in February until the orchard was harvested.

Figure 2.3. A yellow Delta trap with pheromone lure for monitoring male FCM adults.

2.1.2.3. Orchard sanitation

Orchard sanitation is considered to be the cornerstone for successfully minimising FCM in citrus orchards. Sanitation was done on a weekly basis by the grower’s farm workers. All the fruit lying underneath all trees were removed from the orchard, except for the fruit underneath the data trees (where the pheromone trap was positioned). The standard of sanitation was evaluated on a weekly basis (on the same day). Figure 2.4. represents an orchard with good orchard sanitation. Figure 2.5 represents an orchard with poor orchard sanitation. The rating was determined by the number of fruit lying underneath the trees. The method of rating was recorded as “1” = Poor (>5 fruit per tree, “2” = Average (3 - 4 fruit per tree), “3” = Good (1 - 2 fruit per tree). A random sample of 10 trees was selected to calculate the rating of the orchard sanitation.

Figure 2.4. An example of good orchard sanitation.

Figure 2.5. An example of poor orchard sanitation**.**

2.1.3. FCM control programmes

The orchards from Wicklow, Daisy Dell, Sackville and Rietfontein followed the same control programme for FCM during the 2017 season. The programme included the application of Broadband, with the active ingredient *Beauveria bassiana.* Broadband was applied at a rate of 1 ml per 100 L of water and was applied in November/December 2016 and again in January 2017. Some of the Navel cultivars received a third application in February 2017. The mating disruptor, Isomate was also used in these orchards. The dispensers with dodecenyl acetate were hung in November at a density of 500 dispensers per ha and again in January at a density of 300 dispensers per ha, as per label instructions. The orchards from Sunset and Tortello farms followed a different programme during the 2017 season. The programme included Cryptex, with the active ingredient Cryptophlebia leucotreta granulovirus. Cryptex was applied at a rate of 3.3 ml per 100 L of water and was applied in November 2016 and again in January 2017. The orchards from these farms were also part of the Sterile Insect Technique

(SIT) programme. Sterile moths were released on a weekly basis between September and April at a density of 2000 moths per ha per week.

The orchards from Wicklow, Daisy Dell, Sackville and Rietfontein followed the same control programme for FCM during the 2018 season. The programme included Cryptex, applied as described above, in November 2017 and again in January 2018. The mating disruptor, Checkmate-FCM was also used in these orchards. Checkmate-FCM was applied at a rate of 110 ml per ha and was applied monthly between October 2017 and March 2018. Eco-Bb (*Beauveria bassiana)* was also applied at a rate of 15 ml per 100 L of water and was applied on certain Navel cultivars in October 2017. The orchards from Sunset and Tortello farms followed a different programme during the 2018 season. The programme included Cryptex, which was applied in November and again December 2017. The orchards from these farms were also part of the Sterile Insect Technique (SIT) programme. Sterile moths were released on a weekly basis between September and April at a density of 2000 moths per ha per week.

2.2. Postharvest

2.2.1. Trial site

All the fruit of the various orchards were delivered to Wicklow Citrus packhouse (GPS coordinates: 33°30’0.40”S; 25°36’11.12”E), near Addo in the Eastern Cape.

2.2.2. Trial layout

The fruit were washed, sorted and treated with postharvest fungicides before they were packed for export. The fruit were inspected for FCM infestation at three points in the postharvest process:

- Packhouse delivery inspection
- Production start-up inspection
- Retention sample

2.2.2.1. Packhouse delivery inspection

The fruit were harvested and placed into a bin, which was manufactured from plastic with the following dimensions: 1.2 m (width) x 1.0 m (length) x 0.75 m (height) (Mpact, Cape Town). Each bin can store an approximate nett weight of 400-440 kg of fruit. Each consignment that was delivered to the packhouse was inspected (Figure 2.6.). A consignment is best described as fruit from the same variety that was harvested from a specific farm or PUC (Production unit code) and from the same orchard. The fruit from the specific farm or PUC were then delivered to the packhouse, where the fruit were inspected, graded and packed for export. During the 2017 season, a 400 fruit sample was taken from each consignment that was delivered to the packhouse on various days. A random 100 fruit sample was taken from four bins. During the 2018 season, a 600 fruit sample was taken only from the first consignment that was delivered to the packhouse. A random 150 fruit sample was taken from four bins. The packhouse delivery sample was inspected visually by a trained person. All suspect fruit were dissected with a knife and all the fruit that were infested with FCM were recorded. The objective of the inspection was to determine the FCM infestation level of the consignment.

Figure 2.6. Quality assurance inspector taking a sample at fruit delivery

2.2.2.2. Production start-up inspection

The production start-up inspection was conducted on the day that the consignment was packed at the packhouse. Each orchard was packed separately. The sample was taken at the bin tipper (Figure 2.7.) when the fruit were placed on the packing line. Trained graders were used at various sorting tables inside the packhouse to grade the fruit. Dedicated containers were placed at the pre- and main sorting table inside the packhouse (Figure 2.8.). All fruit that were suspected to have been potentially infested with FCM, i.e. where the peel around the penetration hole was a yellow colour on green fruit and an orange colour on coloured-up fruit, were removed by sorters and placed into the containers. The fruit in the containers were inspected visually and only the fruit which were suspected to be infested by FCM were inspected destructively by a trained online quality assurance inspector. Only fruit in which an FCM larva was found were recorded as positively infested.

Figure 2.7. Quality assurance inspector conducting a production start-up inspection

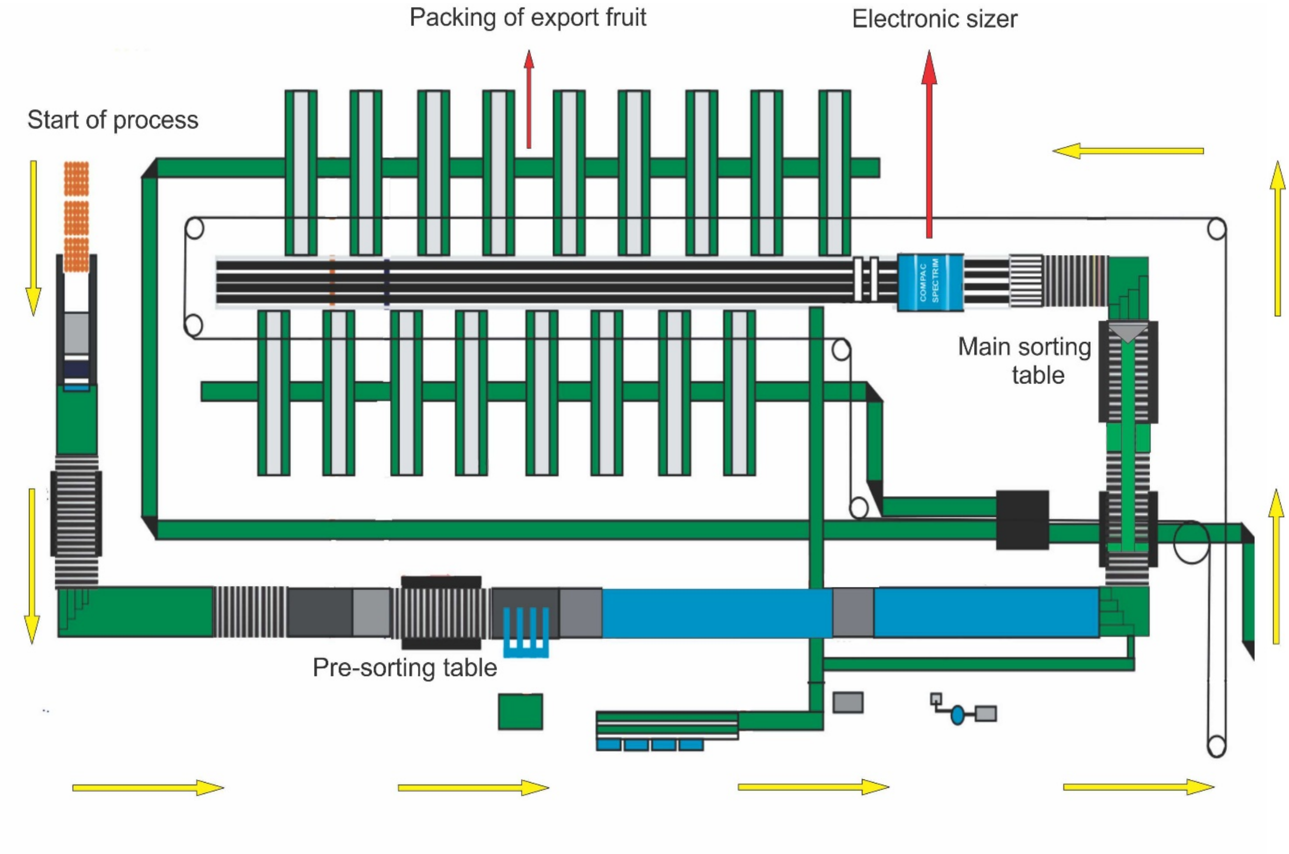


Figure 2.8. Diagram of packhouse

2.2.2.3. Retention sample inspection

The objective of the retention sample was to monitor the quality of the fruit and also to determine whether developing factors such as decay might occur after packing. The most important objective for the purpose of this study, was to determine the level of FCM infestation. A sample of 600 fruit was taken from each consignment that was packed for export and was stored for 21 days under ambient conditions. The sample was inspected every week, over a 3 week period (Figure 2.9.a). Allowing the fruit to stand for 3 weeks at ambient conditions, allowed development of larvae and the development of associated symptoms, such as decay which increased the chance of detecting infestation relative to 3 weeks previously when the consignment had just been packed and exported. All 600 fruit were inspected visually and the suspect fruit were dissected with a knife (Figure 2.9.b). Only fruit with FCM larvae inside the fruit were recorded as being infested (Figure 2.9.c).

a

b

c

Figure 2.9.a: A quality assurance inspector conducting a retention sample inspection, **b:** A quality assurance inspector dissecting a fruit, **c:** A fruit infested with FCM.

2.2.3. Statistical Analysis

Simple regression analyses using the Generalized Linear Model (Firth 1990) were conducted between preharvest levels of fruit infestation, for the full period of monitoring and moth catches, and for the last 4 weeks before harvest, and the level of infestation in fruit delivered to the packhouse; and between the level of infestation of fruit delivered to the packhouse and the level of infestation in fruit packed for export. These analyses were performed using Statistica 12.0 (Statsoft Inc., Tulsa, OK, 2013).

2.3. Discussion

The success of the integrated management system (Figure 2.12.) is determined by many variables in the process. The integrity is determined by harvesting each orchard separately, delivering the fruit to the packhouse and ultimately having full traceability of the fruit which were packed. It is common practice in the citrus industry to combine different orchards at the packhouse when packing commences. All orchards have to comply with the same thresholds on delivery to the packhouse. The proposed Systems Approach has been devised on an orchard basis, then packhouse basis and then consignment / container basis.

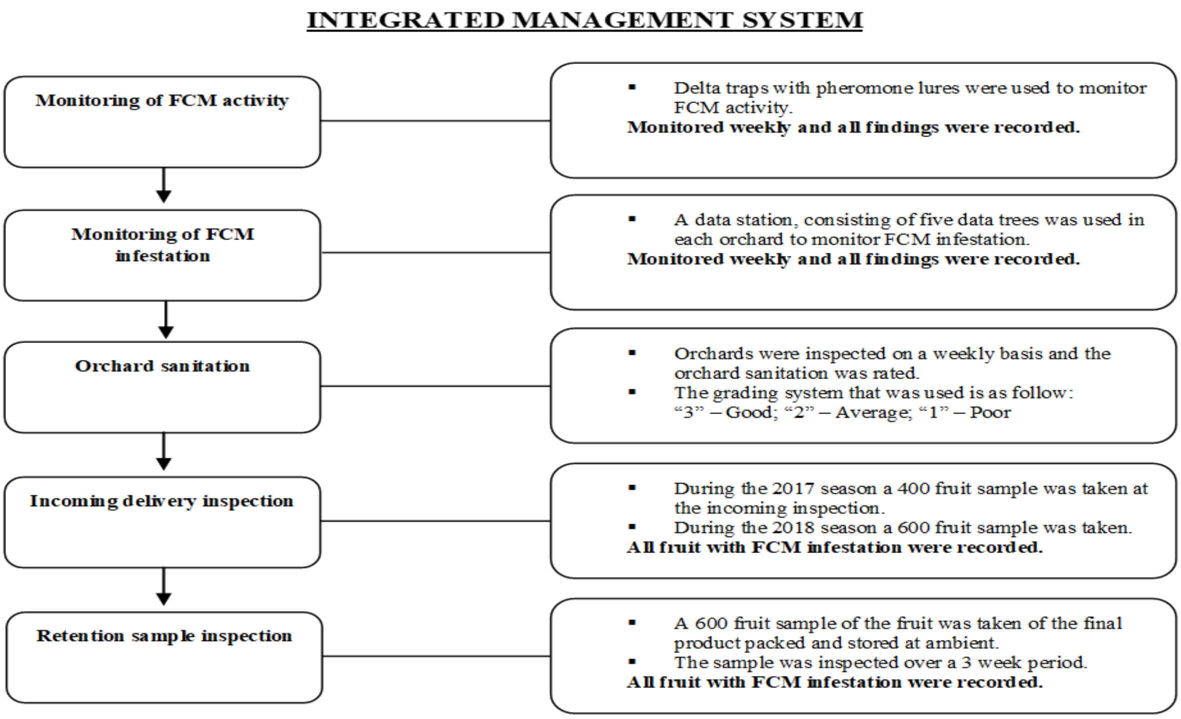


Figure 2.10. Flow diagram of the integrated management system

Chapter 3:

Results of study

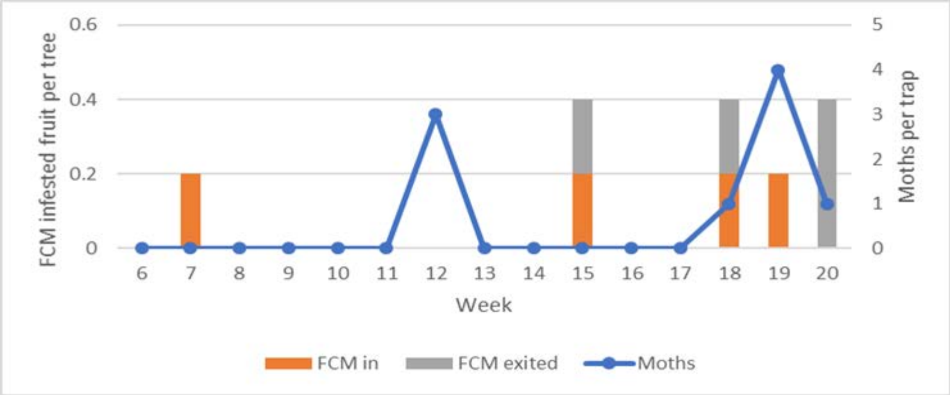
Introduction

It was very important to measure the efficacy of the various steps in the systems approach, in order to assess the overall efficacy of the system. There is sufficient information and analysis that shows real efficacy of the various systems approaches that are reported in the literature e.g. the incidence of codling moth in packed nectarines in California (Curtis *et al.* 1991); a systems approach for *Thaumatotibia leucotreta* on Hass avocado in South Africa (Grove *et al.* 2010); a systems approach for *Thaumatotibia leucotreta* for export citrus from South Africa (Moore *et al.* 2016). All the pre - and postharvest measurements were recorded and the results are presented in this chapter. The thresholds used for this study were stipulated by Moore *et al.* (2016) in the verification of inspection standards of a systems approach for FCM for export citrus, and in the subsequent FCM Risk Management System for export of fresh citrus fruit produced in South Africa, which is not available in the public domain. The moth activity and infestation were monitored by conducting weekly inspections of the pheromone traps and the data trees in each orchard. It was important to determine whether the infestation was due to an FCM larva being in the fruit (recorded as "FCM in"), or whether the fruit was infested by a larva, but had already exited the fruit (recorded as "FCM exited"). The threshold of 0.2 infested fruit per tree was used for the last 4 weeks before harvest to determine the preharvest risk of each orchard. The threshold of 0.33% infested fruit was used for the packhouse delivery inspection. The packhouse delivery inspection was compared to the retention sample, to determine the overall FCM risk of each orchard. The various orchards were separated into the following three groups: Navels, Mandarins and Valencias.

3.1. Navels

3.1.1. Orchard WK27 – 2017 season

FCM trap catches peaked in week 12 and 19 and the FCM infestation was the highest in weeks 15, 18 and 20 (Figure 3.1.A). FCM infestation was recorded in weeks 7, 15, 18, 19 and 20 (Figure 3.1.B.). The FCM infestation exceeded the threshold (0.2 infested fruit per tree), in weeks 15, 18 and 20. Low orchard sanitation rating was scored in weeks 15, 16 and 19 (Figure 3.1.C.).



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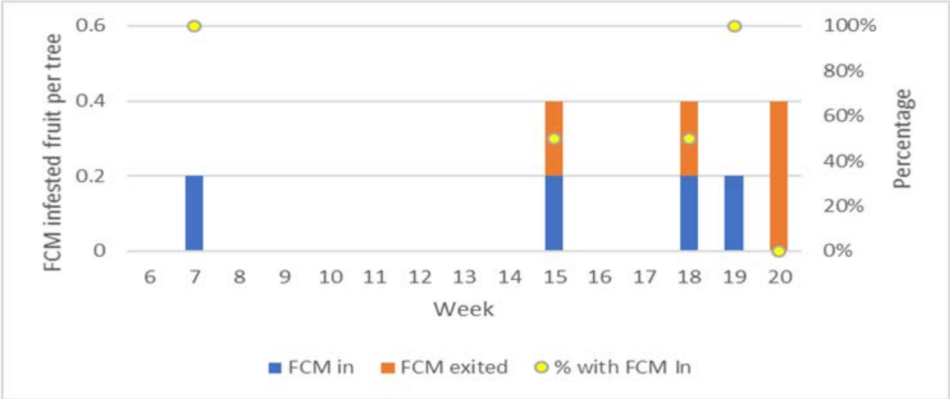

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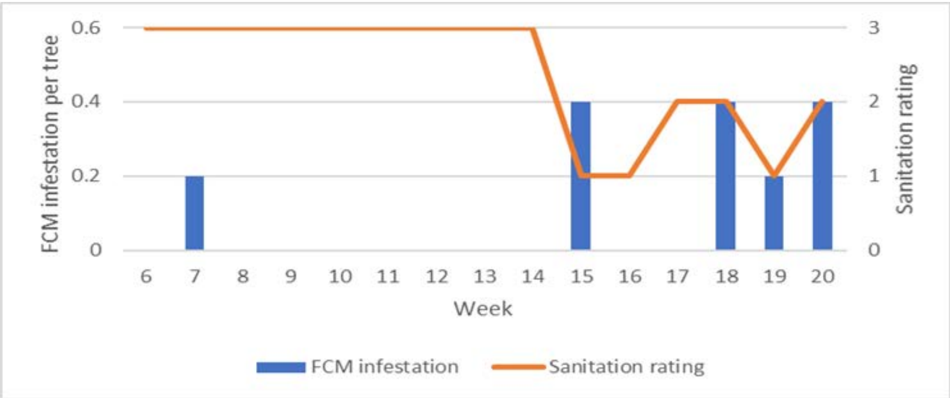


C.

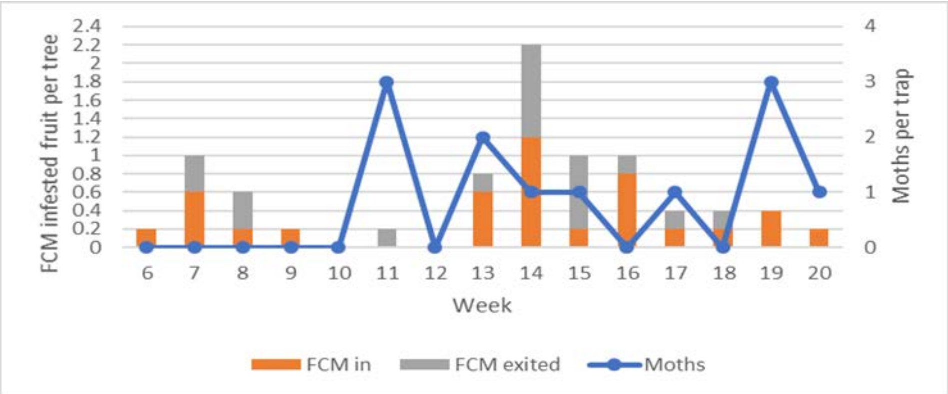
Figure 3.1.A: Weekly FCM moth trap counts and FCM infestation (in and exited). “In” is fruit found with FCM larva in the fruit, whereas “exited” is the fruit where the larva had already exited the fruit, **B:** Percentage of fruit dropped, **C:** FCM infestation and orchard sanitation rating. The orchard sanitation rating is determined by the number of fruit lying underneath the trees. The following grading system was used: ”1” = poor (>5 fruit per tree), “2” = average (3-4 fruit per tree) and “3” = good (1-2 fruit per tree).

3.1.2. Orchard WK27 – 2018 season

Orchard WK27 had no moth trap catches nor any fruit with FCM infestation during the period that the orchard was monitored.

3.1.3. Orchard SV10 – 2017 season

FCM trap catches peaked in weeks 11, 13 and 19 and the FCM infestation was the highest in weeks 7, 14, 15 and 16 (Figure 3.2.A.). FCM infestation was recorded in weeks 6, 7, 8, 9, 11, 13, 14, 15, 16, 17, 18, 19 and 20 (Figure 3.2.B.). The FCM infestation exceeded the threshold (0.2 infested fruit per tree), in weeks 7, 8, 13, 14, 15, 16, 17, 18 and 19. Low orchard sanitation rating was scored in weeks 14 and 15 (Figure 3.2.C.).



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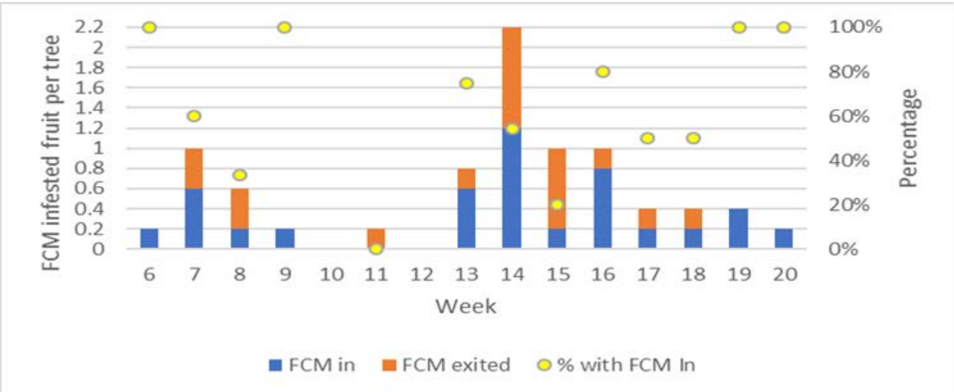

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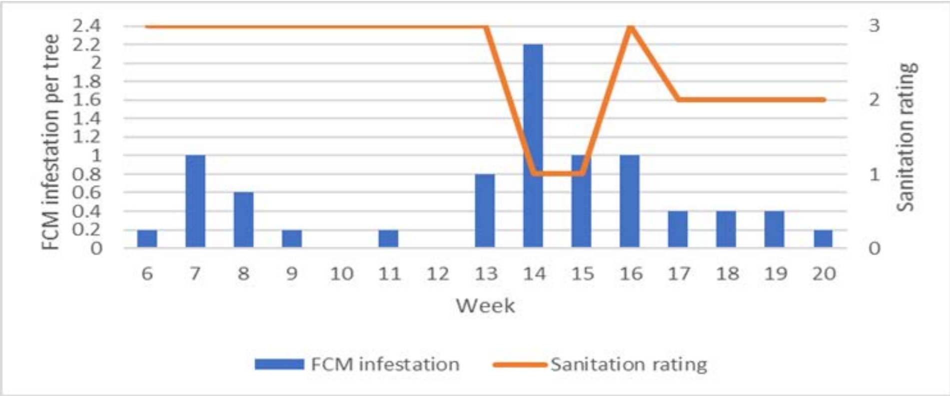
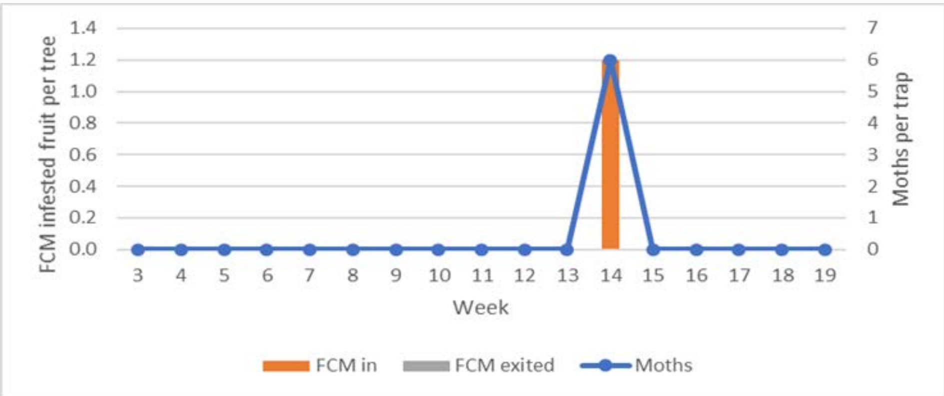


C.

Figure 3.2.A: Weekly FCM moth trap counts and FCM infestation (in and exited). "In" is fruit found with FCM larva in the fruit, whereas "exited" is the fruit where the larva had already exited the fruit, **B:** Percentage of fruit dropped, **C:** FCM infestation and orchard sanitation rating. The orchard sanitation rating is determined by the number of fruit lying underneath the trees. The following grading system was used: "1" = poor (>5 fruit per tree), "2" = average (3-4 fruit per tree) and "3" = good (1-2 fruit per tree).

3.1.4. Orchard SV10 – 2018 season

The only FCM trap catch was recorded in week 14 (Figure 3.3.A.). The only FCM infestation of fruit was recorded in week 14 (Figure 3.3.B.). The FCM infestation exceeded the threshold (0.2 infested fruit per tree), in week 14. Low orchard sanitation rating was scored in week 3 (Figure 3.3.C.).



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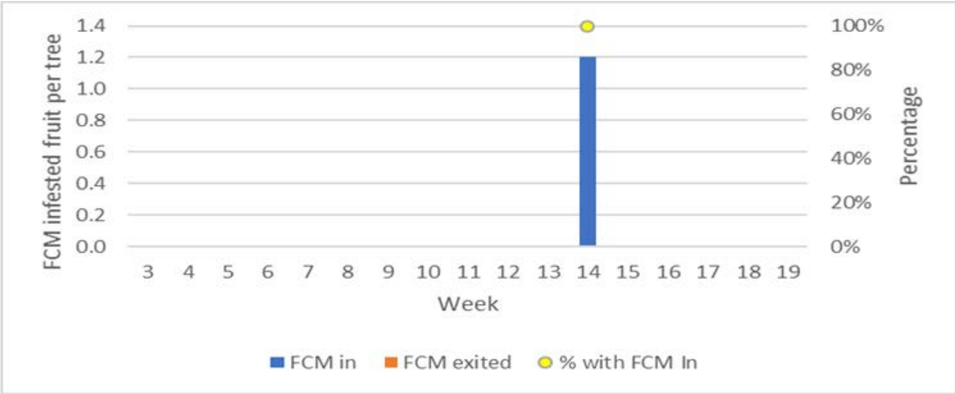

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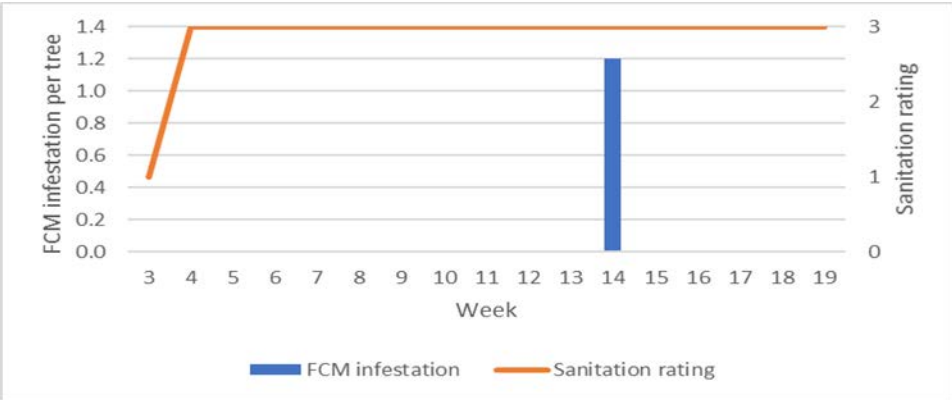
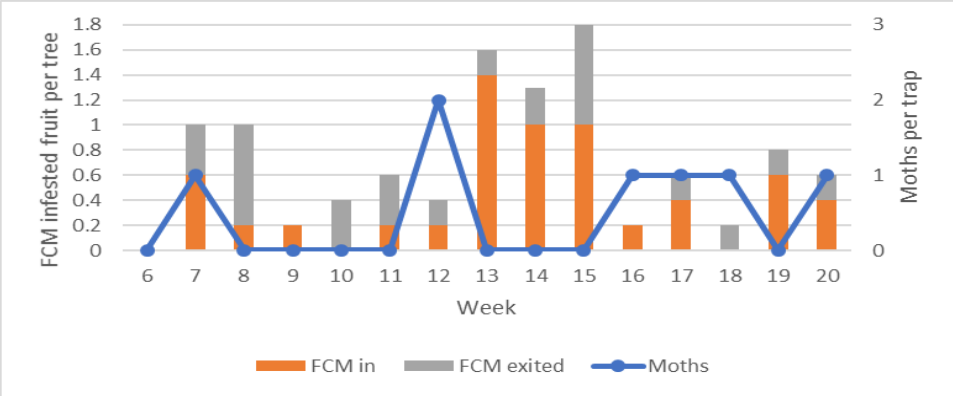


C.

Figure 3.3.A: Weekly FCM moth trap counts and FCM infestation (in and exited). "In" is fruit found with FCM larva in the fruit, whereas "exited" is the fruit where the larva had already exited the fruit, **B:** Percentage of fruit dropped, **C:** FCM infestation and orchard sanitation rating. The orchard sanitation rating is determined by the number of fruit lying underneath the trees. The following grading system was used: "1" = poor (>5 fruit per tree), "2" = average (3-4 fruit per tree) and "3" = good (1-2 fruit per tree).

3.1.5. Orchard SV11 – 2017 season

FCM trap catches peaked in week 12 and the FCM infestation was the highest in weeks 13 – 15 (Figure 3.4.A.). FCM infestation was recorded in weeks 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19 and 20 (Figure 3.4.B.). The FCM infestation exceeded the threshold (0.2 infested fruit per tree), in weeks 7, 8, 10, 11, 12, 13, 14, 15, 17, 19 and 20. Low orchard sanitation rating was scored in weeks 14, 15 and 19 (Figure 3.4.C.).



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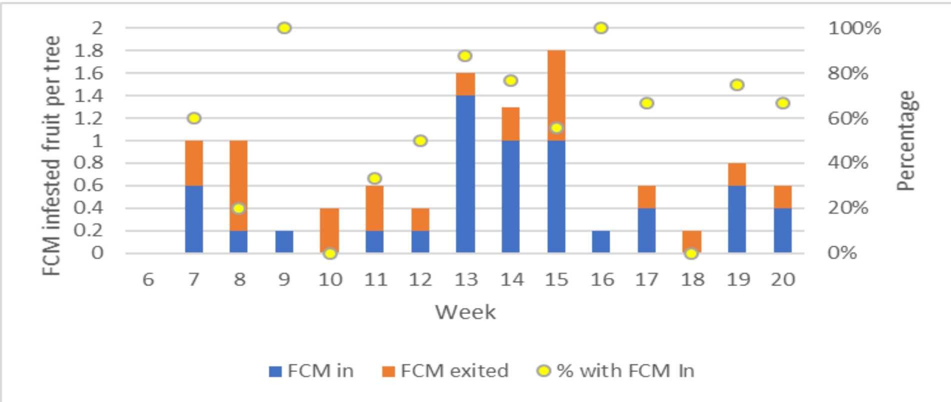

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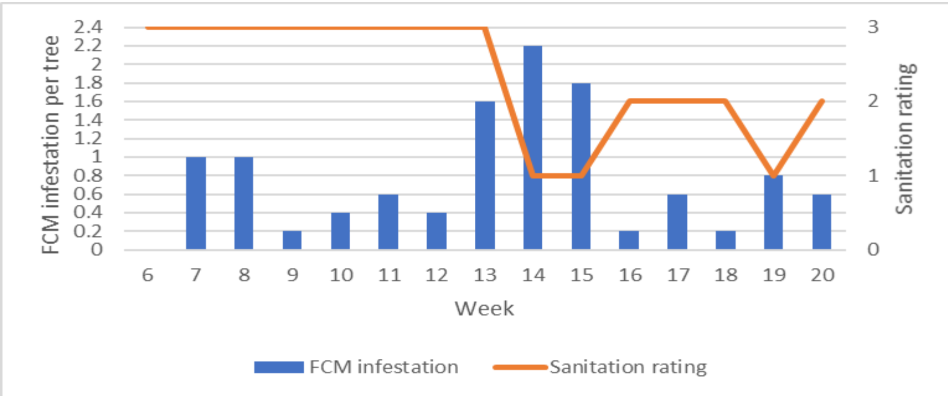


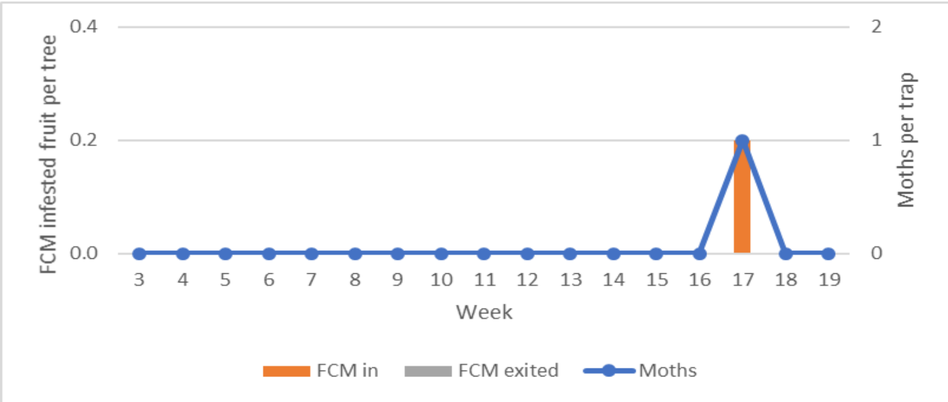
C.

Figure 3.4.A: Weekly FCM moth trap counts and FCM infestation (in and exited). "In" is fruit found with FCM larva in the fruit, whereas "exited" is the fruit where the larva had already exited the fruit, **B:** Percentage of fruit dropped, **C:** FCM infestation and orchard sanitation rating. The orchard sanitation rating is determined by the number of fruit lying underneath the trees. The following

grading system was used: ”1” = poor (>5 fruit per tree), “2” = average (3-4 fruit per tree) and “3” = good (1-2 fruit per tree).

3.1.6. Orchard SV11 – 2018 season

The only FCM trap catch was recorded in week 17 (Figure 3.5.A.). The only FCM infestation was recorded in week 17 (Figure 3.5.B.). The FCM infestation did not exceed the threshold (0.2 infested fruit per tree), in any of the weeks. Low orchard sanitation rating was scored in week 3 (Figure 3.5.C.).



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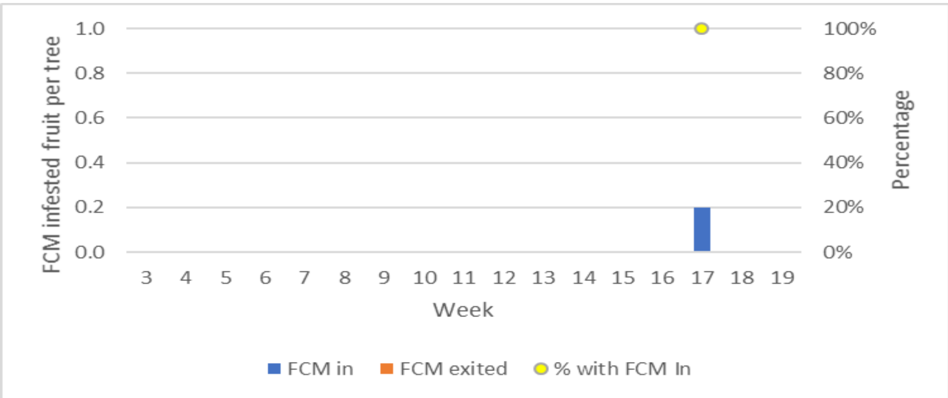

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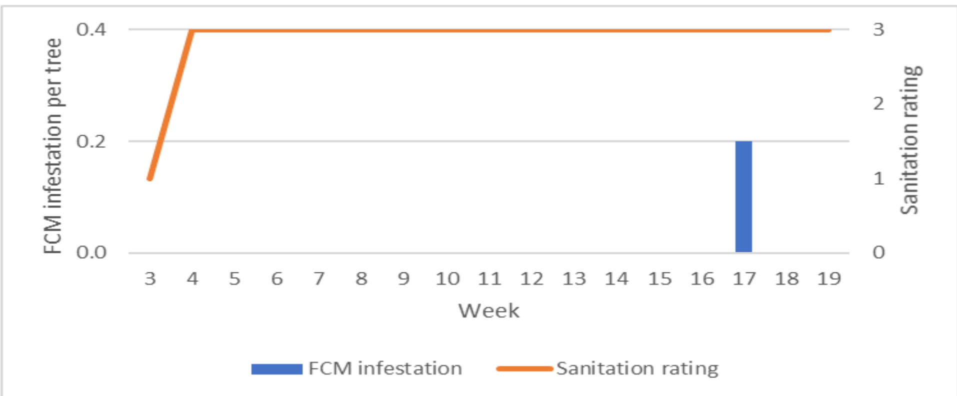
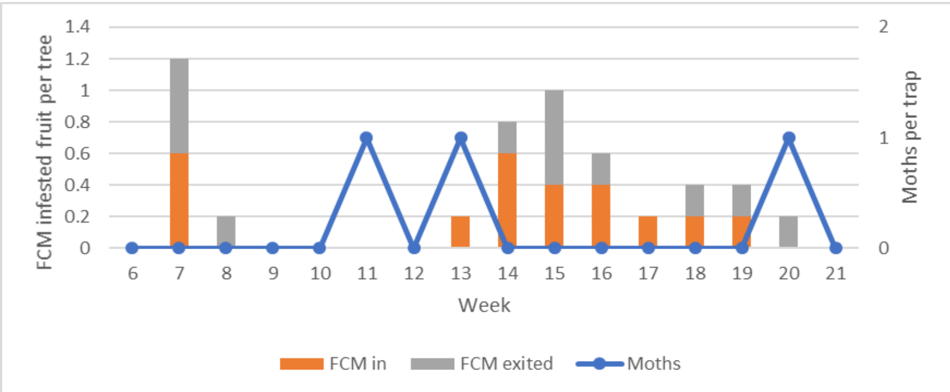


C.

Figure 3.5.A: Weekly FCM moth trap counts and FCM infestation (in and exited). “In” is fruit found with FCM larva in the fruit, whereas “exited” is the fruit where the larva had already exited the fruit, **B:** Percentage of fruit dropped, **C:** FCM infestation and orchard sanitation rating. The orchard sanitation rating is determined by the number of fruit lying underneath the trees. The following grading system was used: ”1” = poor (>5 fruit per tree), “2” = average (3-4 fruit per tree) and “3” = good (1-2 fruit per tree).

3.1.7. Orchard SV12 – 2017 season

FCM trap catches peaked in weeks 11, 13 and 20 and the FCM infestation was the highest in weeks 7, 14, 15 and 16 (Figure 3.6.A.). FCM infestation was recorded in weeks 7, 8, 13, 14, 15, 16, 17, 18, 19 and 20 (Figure 3.6.B.). The FCM infestation exceeded the threshold (0.2 infested fruit per tree), in weeks 7, 14, 15, 16, 18 and 19. Low orchard sanitation rating was scored in weeks 14 and 15 (Figure 3.6.C.).



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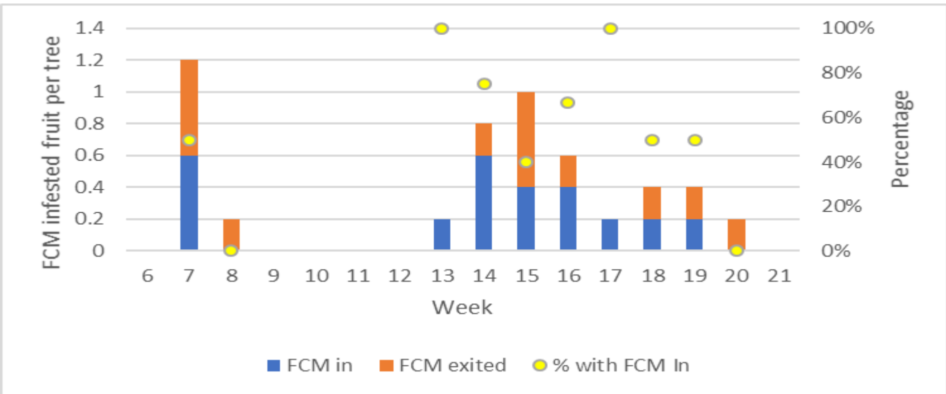

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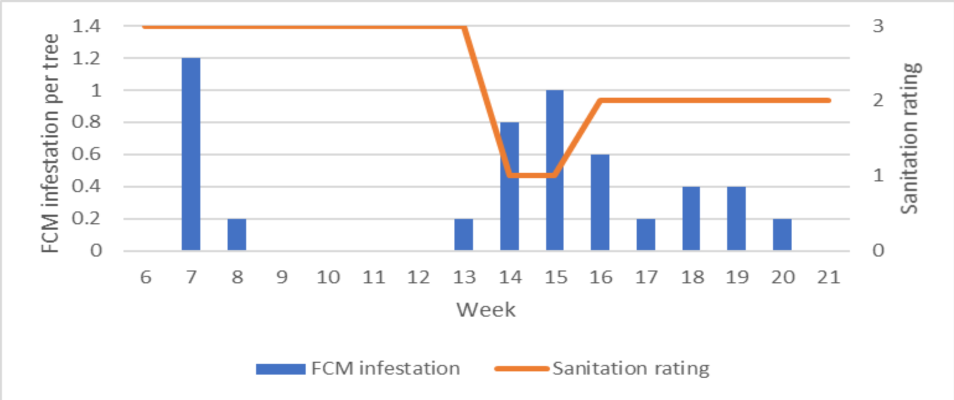
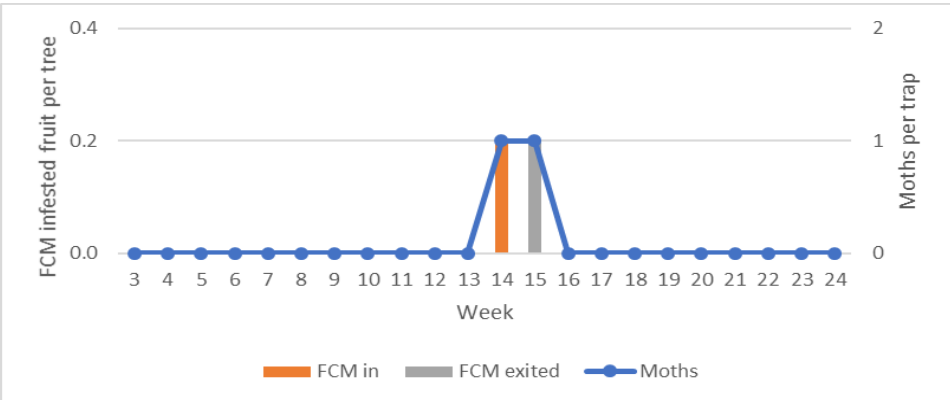


C.

Figure 3.6.A: Weekly FCM moth trap counts and FCM infestation (in and exited). "In" is fruit found with FCM larva in the fruit, whereas "exited" is the fruit where the larva had already exited the fruit, **B:** Percentage of fruit dropped, **C:** FCM infestation and orchard sanitation rating. The orchard sanitation rating is determined by the number of fruit lying underneath the trees. The following grading system was used: "1" = poor (>5 fruit per tree), "2" = average (3-4 fruit per tree) and "3" = good (1-2 fruit per tree).

3.1.8. Orchard SV12 – 2018 season

The only FCM trap catches was recorded in weeks 14 and 15 (Figure 3.7.A.). The only FCM infestation was recorded in weeks 14 and 15 (Figure 3.7.B.). The FCM infestation did not exceed the threshold (0.2 infested fruit per tree), in any of the weeks. Low orchard sanitation rating was scored in week 3 (Figure 3.7.C.).



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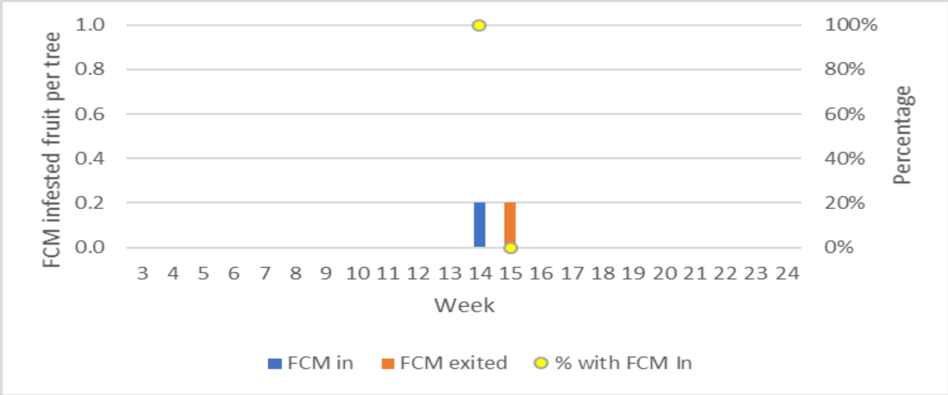

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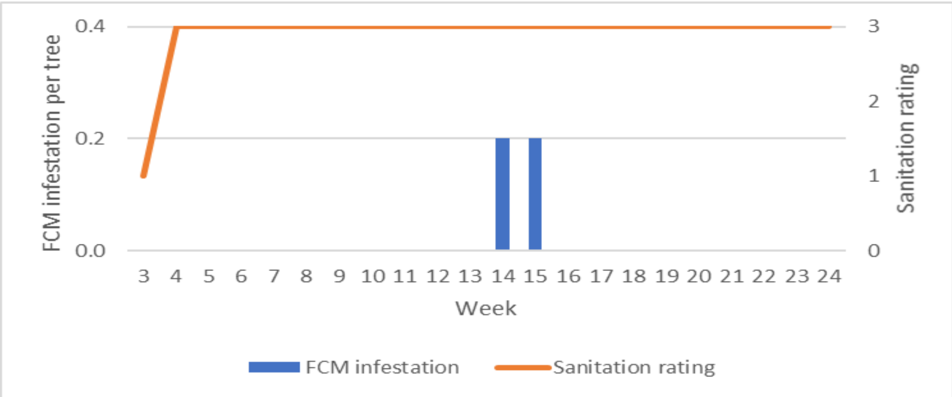
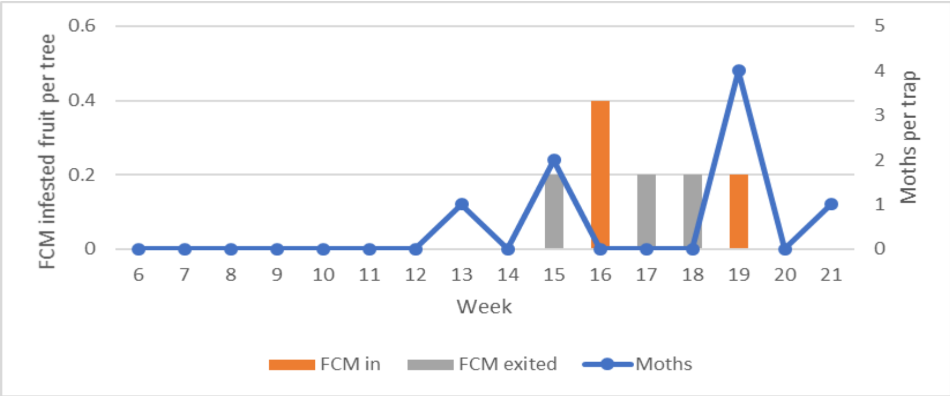


C.

Figure 3.7.A: Weekly FCM moth trap counts and FCM infestation (in and exited). "In" is fruit found with FCM larva in the fruit, whereas "exited" is the fruit where the larva had already exited the fruit, **B:** Percentage of fruit dropped, **C:** FCM infestation and orchard sanitation rating. The orchard sanitation rating is determined by the number of fruit lying underneath the trees. The following grading system was used: "1" = poor (>5 fruit per tree), "2" = average (3-4 fruit per tree) and "3" = good (1-2 fruit per tree).

3.1.9. Orchard WK26 – 2017 season

FCM trap catches peaked in weeks 15 and 19 and the FCM infestation was the highest in week 16 (Figure 3.8.A.). FCM infestation was recorded in weeks 15, 16, 17, 18 and 19 (Figure 3.8.B.). The FCM infestation exceeded the threshold (0.2 infested fruit per tree), in week 16. Low orchard sanitation rating was scored in weeks 14 and 15 (Figure 3.8.C.).



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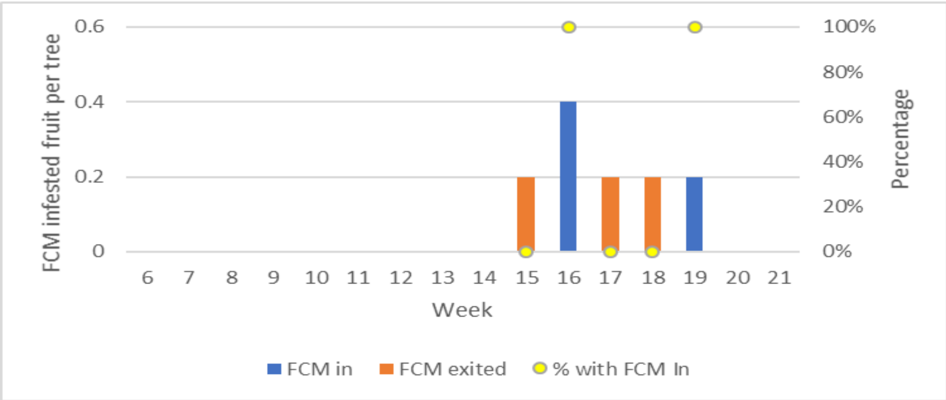

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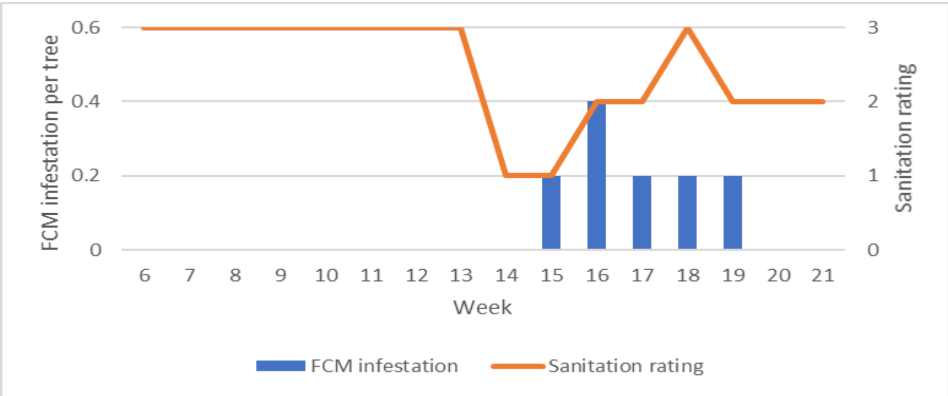
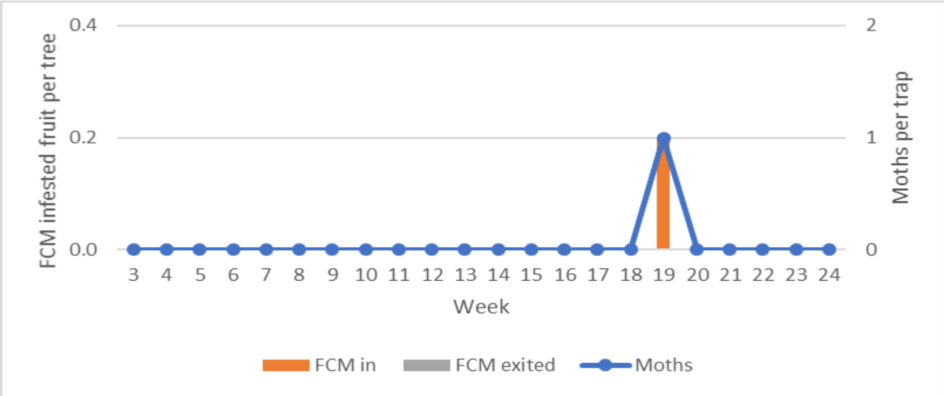


C.

Figure 3.8.A: Weekly FCM moth trap counts and FCM infestation (in and exited). "In" is fruit found with FCM larva in the fruit, whereas "exited" is the fruit where the larva had already exited the fruit, **B:** Percentage of fruit dropped, **C:** FCM infestation and orchard sanitation rating. The orchard sanitation rating is determined by the number of fruit lying underneath the trees. The following grading system was used: "1" = poor (>5 fruit per tree), "2" = average (3-4 fruit per tree) and "3" = good (1-2 fruit per tree).

3.1.10. Orchard WK26 – 2018 season

The only FCM trap catch was recorded in week 19 (Figure 3.9.A.). The only FCM infestation was recorded in week 19 (Figure 3.9.B.). The FCM infestation did not exceed the threshold (0.2 infested fruit per tree), in any of the weeks. The orchard sanitation rating was good in all of the weeks (Figure 3.9.C.).



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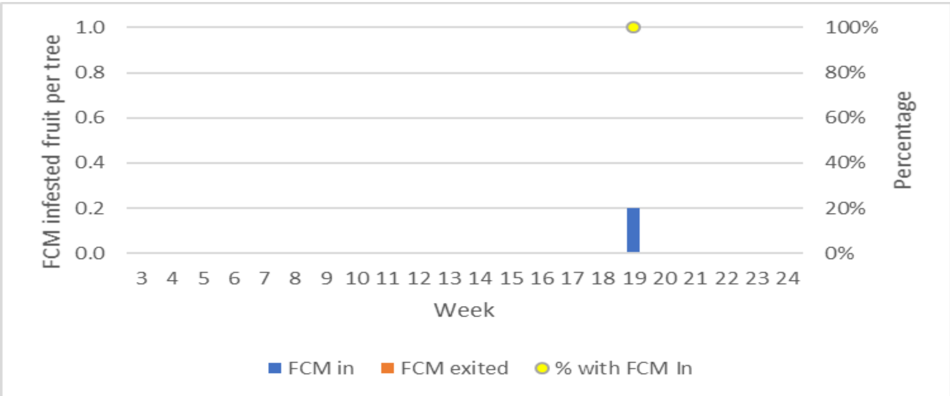

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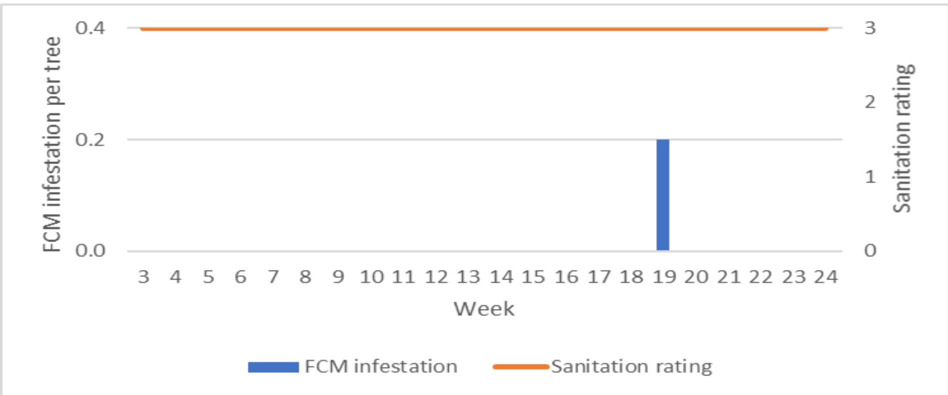
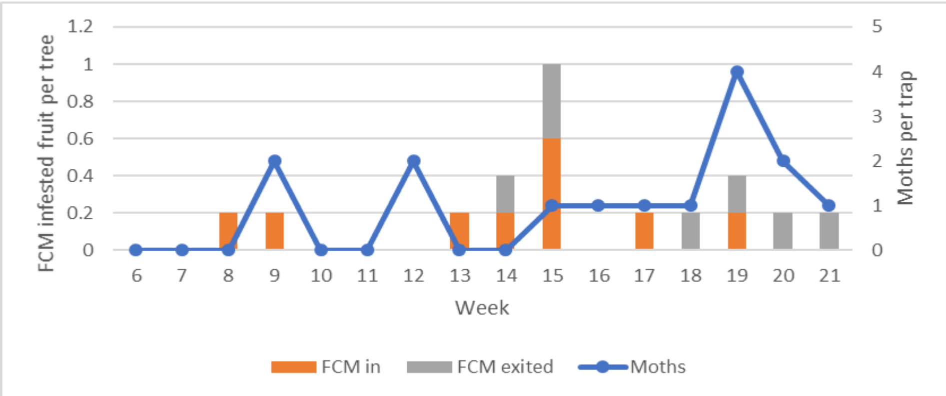


C.

Figure 3.9.A: Weekly FCM moth trap counts and FCM infestation (in and exited). "In" is fruit found with FCM larva in the fruit, whereas "exited" is the fruit where the larva had already exited the fruit, **B:** Percentage of fruit dropped, **C:** FCM infestation and orchard sanitation rating. The orchard sanitation rating is determined by the number of fruit lying underneath the trees. The following grading system was used: "1" = poor (>5 fruit per tree), "2" = average (3-4 fruit per tree) and "3" = good (1-2 fruit per tree).

3.1.11. Orchard 7 – 2017 season

FCM trap catches peaked in weeks 9, 12, 19 and 20 and the FCM infestation was the highest in week 15 (Figure 3.10.A.). FCM infestation was recorded in weeks 8, 9, 13, 14, 15, 17, 18, 19, 20 and 21 (Figure 3.10.B.). The FCM infestation exceeded the threshold (0.2 infested fruit per tree), in weeks 14, 15 and 19. Low orchard sanitation rating was scored in weeks 14 and 15 (Figure 3.10.C.).



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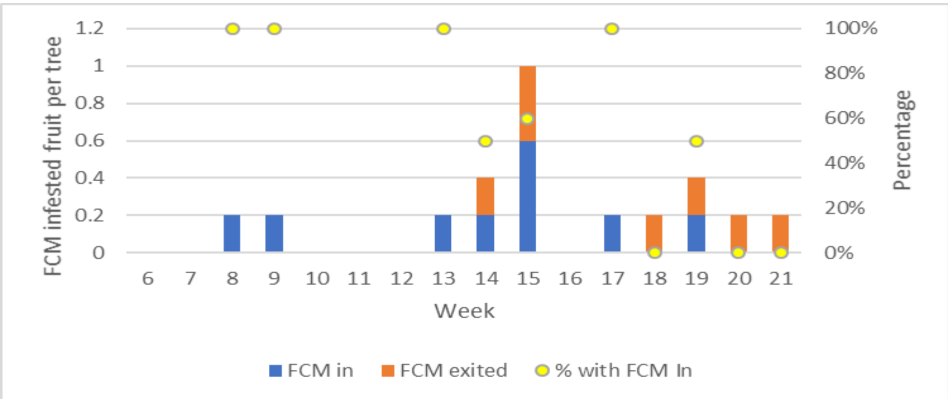

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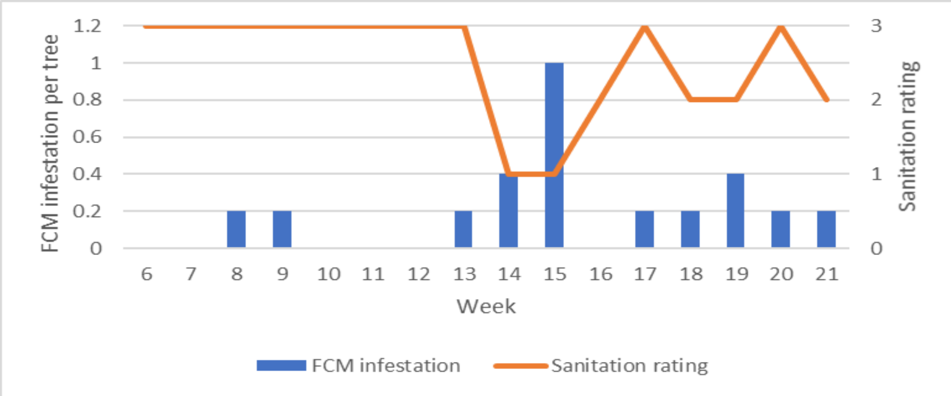


C.

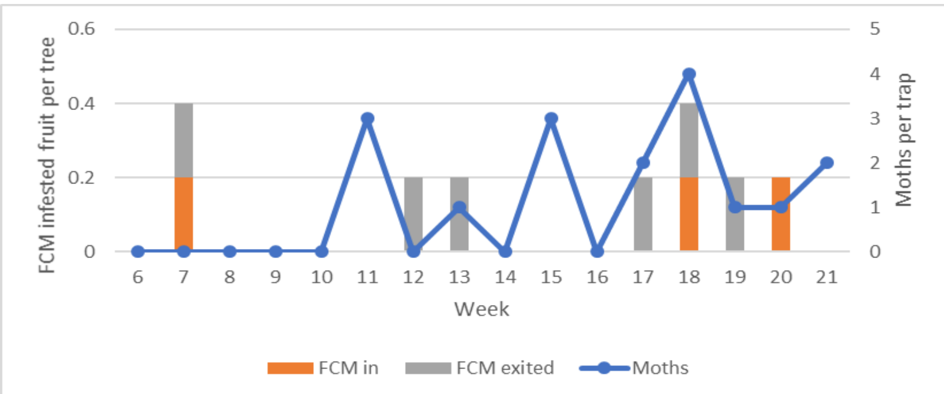
Figure 3.10.A: Weekly FCM moth trap counts and FCM infestation (in and exited). "In" is fruit found with FCM larva in the fruit, whereas "exited" is the fruit where the larva had already exited the fruit, **B:** Percentage of fruit dropped, **C:** FCM infestation and orchard sanitation rating. The orchard sanitation rating is determined by the number of fruit lying underneath the trees. The following grading system was used: "1" = poor (>5 fruit per tree), "2" = average (3-4 fruit per tree) and "3" = good (1-2 fruit per tree).

3.1.12. Orchard 7 – 2018 season

Orchard 7 had no moth trap catches nor any fruit with FCM infestation during the period that the orchard was monitored.

3.1.13. Orchard 8 – 2017 season

FCM trap catches peaked in weeks 11, 15 and 18 and the FCM infestation was the highest in weeks 7 and 18 (Figure 3.11.A.). FCM infestation was recorded in weeks 7, 12, 13, 17, 18, 19 and 20 (Figure 3.11.B.). The FCM infestation exceeded the threshold (0.2 infested fruit per tree), in weeks 7 and 18. Low orchard sanitation rating was scored in week 14 (Figure 3.11.C.).



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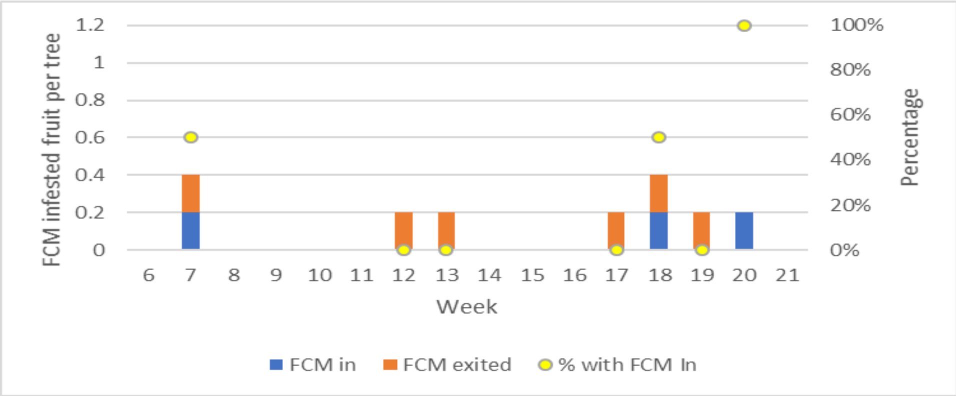

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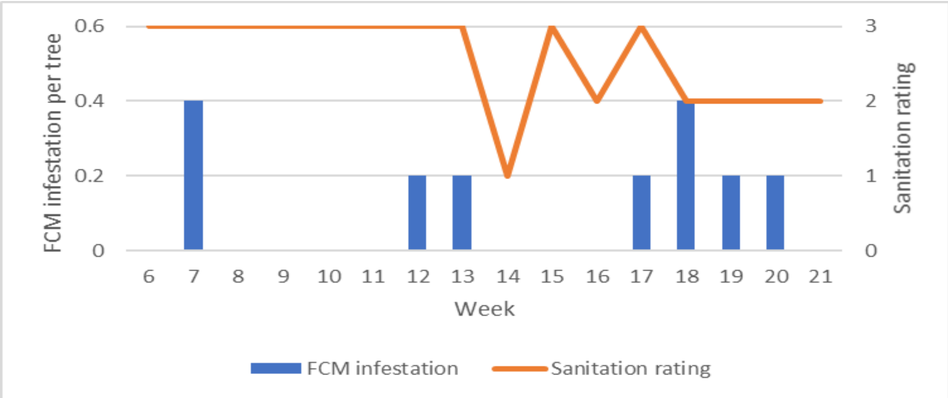


C.

Figure 3.11.A: Weekly FCM moth trap counts and FCM infestation (in and exited). "In" is fruit found with FCM larva in the fruit, whereas "exited" is the fruit where the larva had already exited the fruit, **B:** Percentage of fruit dropped, **C:** FCM infestation and orchard sanitation rating. The orchard sanitation rating is determined by the number of fruit lying underneath the trees. The following grading system was used: "1" = poor (>5 fruit per tree), "2" = average (3-4 fruit per tree) and "3" = good (1-2 fruit per tree).

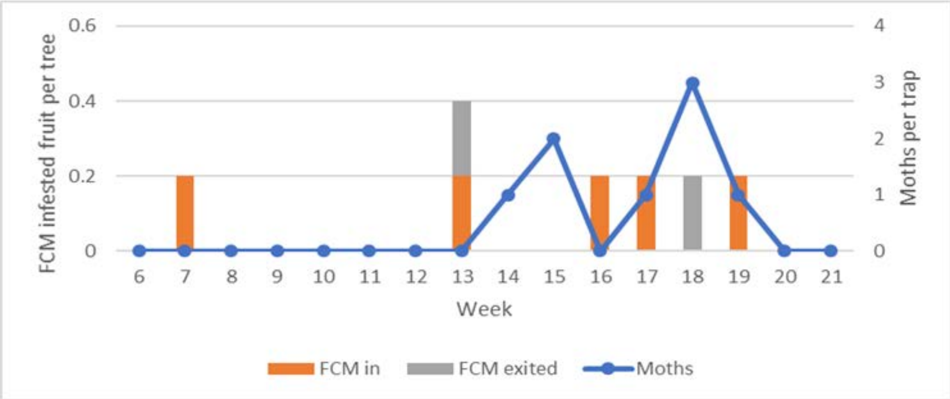
3.1.14. Orchard 8 – 2018 season

Orchard 8 had no moth trap catches nor any fruit with FCM infestation during the period that the orchard was monitored.

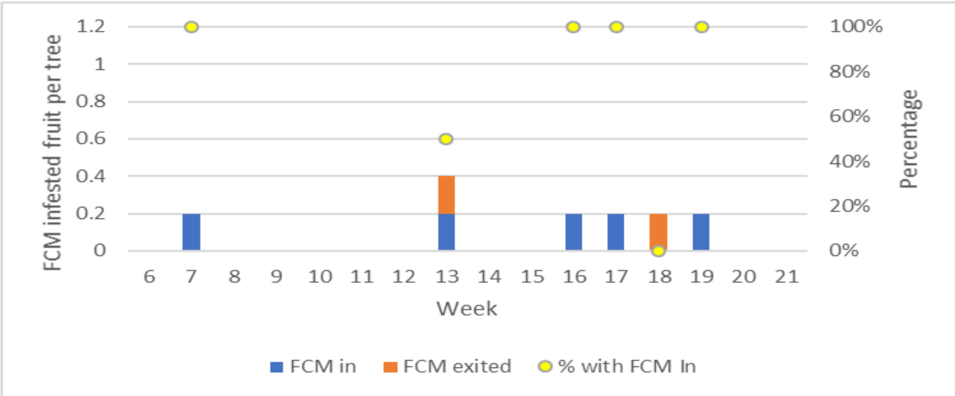
3.1.15. Orchard 9 – 2017 season

FCM trap catches peaked in weeks 15 and 18 and the FCM infestation was the highest in week 13 (Figure 3.12.A.). FCM infestation was recorded in weeks 7, 13, 16, 17, 18 and 19 (Figure 3.12.B.).

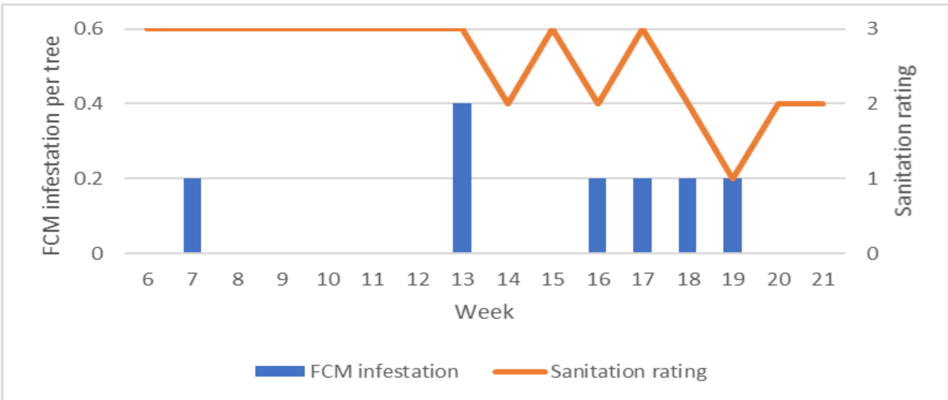
The FCM infestation exceeded the threshold (0.2 infested fruit per tree), in week 13. Low orchard sanitation rating was scored in week 19 (Figure 3.12.C.).



A.



B.



C.

Figure 3.12.A: Weekly FCM moth trap counts and FCM infestation (in and exited). “In” is fruit found with FCM larva in the fruit, whereas “exited” is the fruit where the larva had already exited the fruit, **B:** Percentage of fruit dropped, **C:** FCM infestation and orchard sanitation rating. The orchard

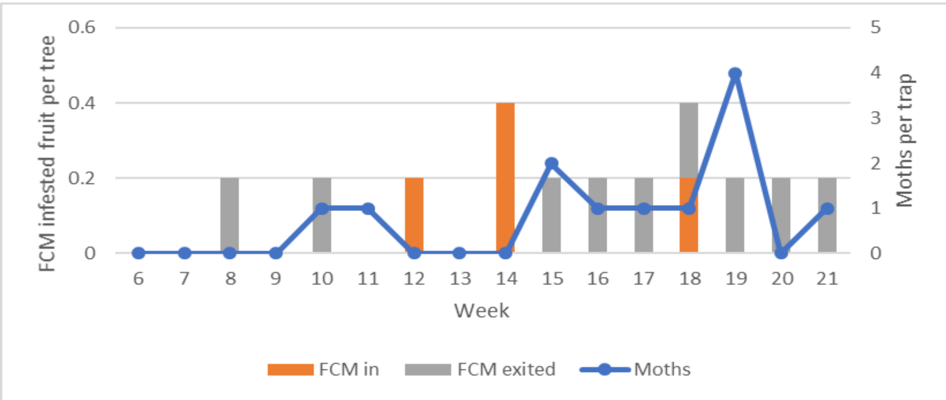
sanitation rating is determined by the number of fruit lying underneath the trees. The following grading system was used: ”1” = poor (>5 fruit per tree), “2” = average (3-4 fruit per tree) and “3” = good (1-2 fruit per tree).

3.1.16. Orchard 9 – 2018 season

Orchard 9 had no moth trap catches nor any fruit with FCM infestation during the period that the orchard was monitored.

3.1.17. Orchard SV15 – 2017 season

FCM trap catches peaked in weeks 15 and 19 and the FCM infestation was the highest in weeks 14 and 18 (Figure 3.13.A.). FCM infestation was recorded in weeks 8, 10, 12, 14, 15, 16, 17, 18, 19, 20 and 21 (Figure 3.13.B.). The FCM infestation exceeded the threshold (0.2 infested fruit per tree), in weeks 14 and 18. Lower orchard sanitation rating was scored in weeks 14, 16, 17, 19 and 21 (Figure 3.13.C.).



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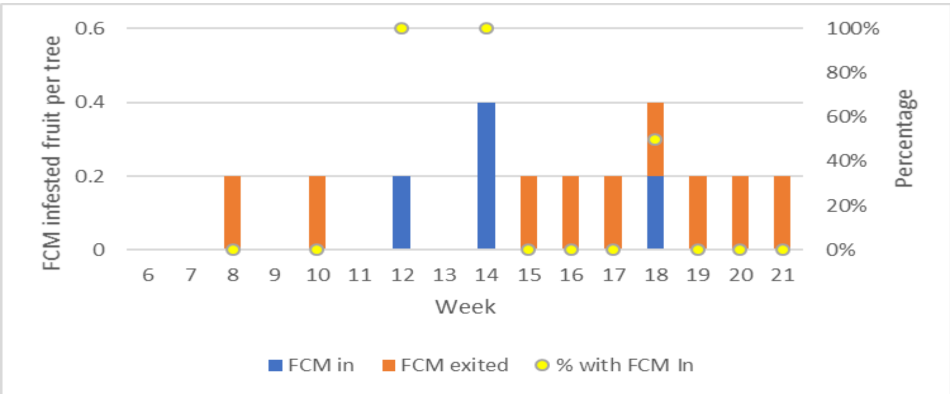

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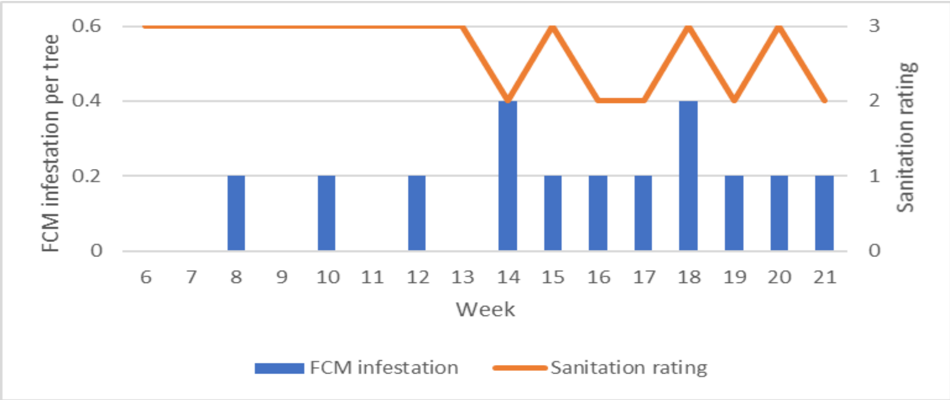


C.

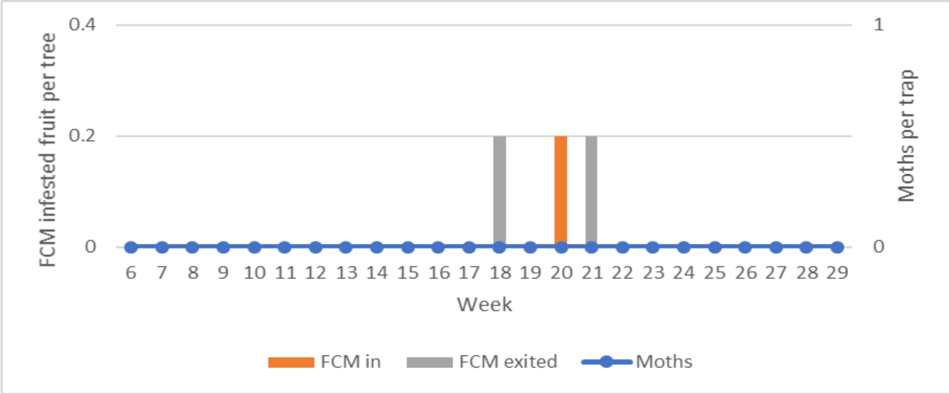
Figure 3.13.A: Weekly FCM moth trap counts and FCM infestation (in and exited). “In” is fruit found with FCM larva in the fruit, whereas “exited” is the fruit where the larva had already exited the fruit, **B:** Percentage of fruit dropped, **C:** FCM infestation and orchard sanitation rating. The orchard sanitation rating is determined by the number of fruit lying underneath the trees. The following grading system was used: ”1” = poor (>5 fruit per tree), “2” = average (3-4 fruit per tree) and “3” = good (1-2 fruit per tree).

3.1.18. Orchard SV15 – 2018 season

Orchard SV15 had no moth trap catches nor any fruit with FCM infestation during the period that the orchard was monitored.

3.1.19. Orchard SV13 – 2017 season

No FCM trap catches were recorded in any of the weeks (Figure 3.14.A.). FCM infestation was recorded in weeks 18, 20 and 21 (Figure 3.14.B.). The FCM infestation did not exceed the threshold (0.2 infested fruit per tree), in any of the weeks. Lower orchard sanitation rating was scored in weeks 14, 15, 16, 17, 18, 20, 21 and 23 (Figure 3.14.C.), which could be related to FCM, as some of these were the only weeks where FCM was recorded.



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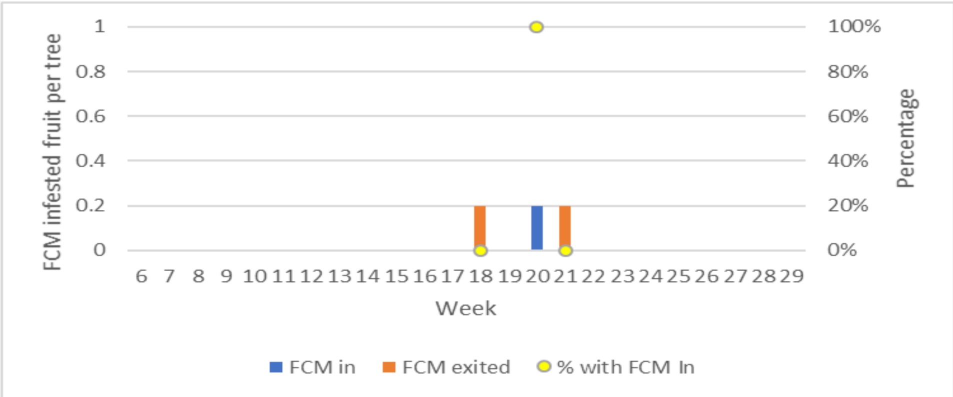

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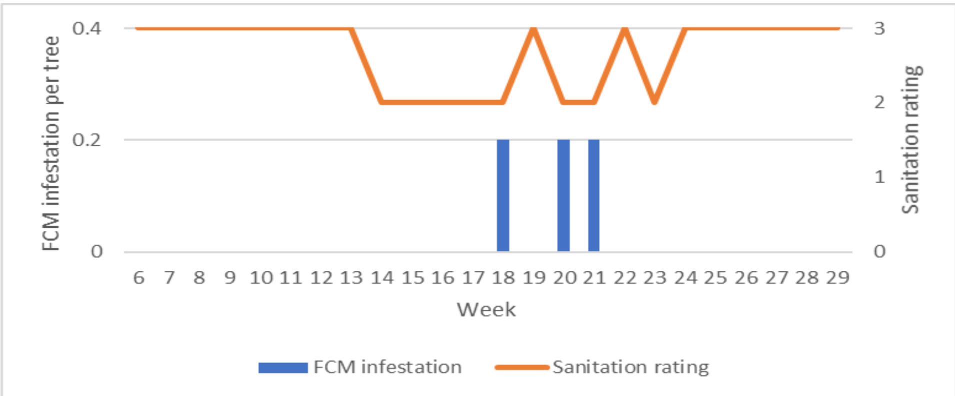
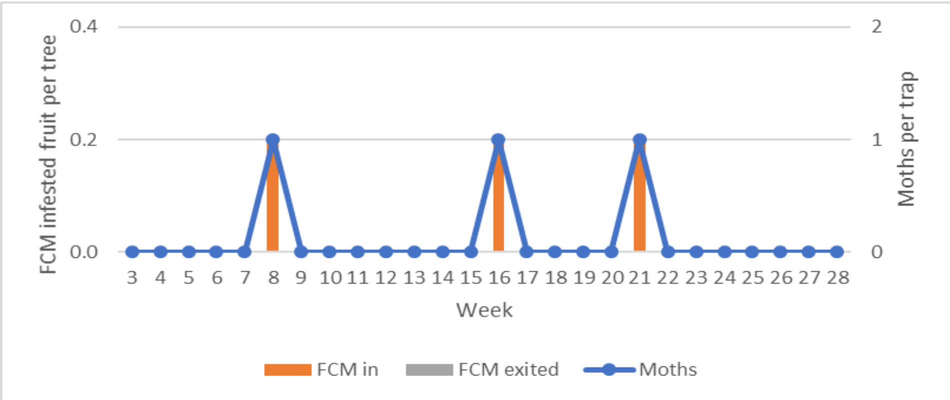


C.

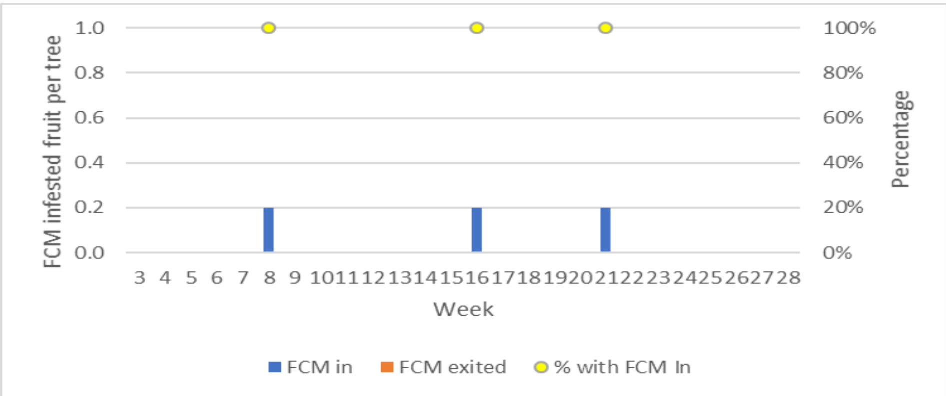
Figure 3.14.A: Weekly FCM moth trap counts and FCM infestation (in and exited). “In” is fruit found with FCM larva in the fruit, whereas “exited” is the fruit where the larva had already exited the fruit, **B:** Percentage of fruit dropped, **C:** FCM infestation and orchard sanitation rating. The orchard sanitation rating is determined by the number of fruit lying underneath the trees. The following grading system was used: ”1” = poor (>5 fruit per tree), “2” = average (3-4 fruit per tree) and “3” = good (1-2 fruit per tree).

3.1.20. Orchard SV13 – 2018 season

The only FCM trap catches were recorded in weeks 8, 16 and 21 (Figure 3.15.A.). FCM infestation was recorded in weeks 8, 16 and 21 (Figure 3.15.B.). The FCM infestation did not exceed the threshold (0.2 infested fruit per tree), in any of the weeks. Low orchard sanitation rating was scored in week 3 (Figure 3.15.C.).



A.



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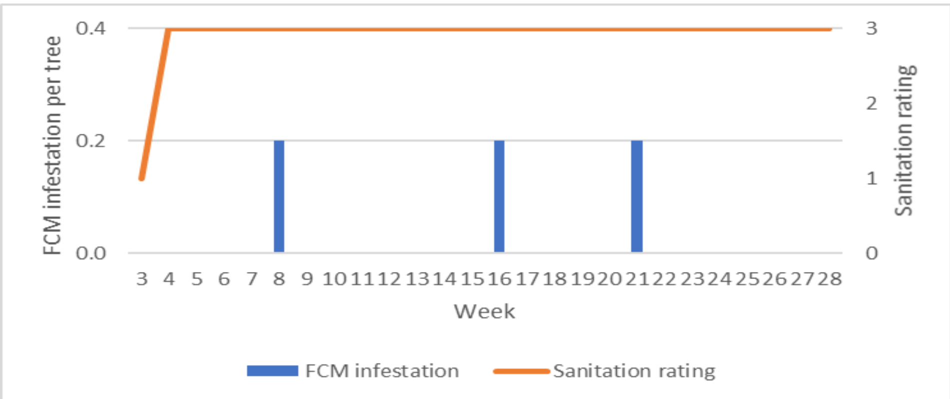
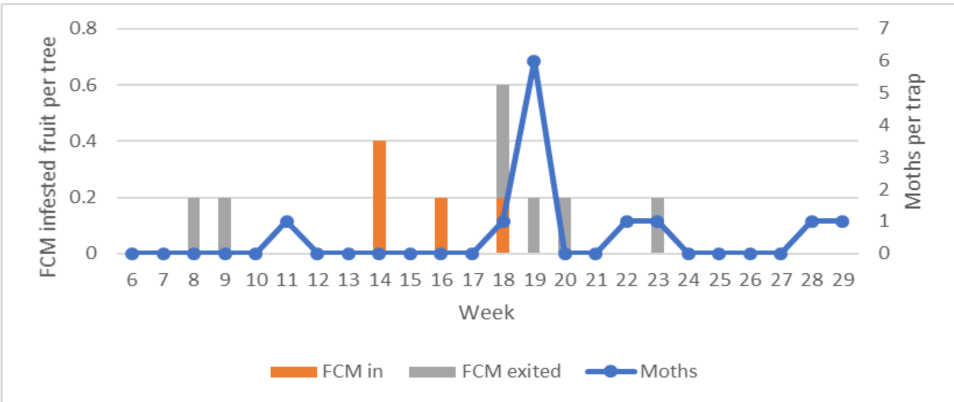


C.

Figure 3.15.A: Weekly FCM moth trap counts and FCM infestation (in and exited). "In" is fruit found with FCM larva in the fruit, whereas "exited" is the fruit where the larva had already exited the fruit, **B:** Percentage of fruit dropped, **C:** FCM infestation and orchard sanitation rating. The orchard sanitation rating is determined by the number of fruit lying underneath the trees. The following grading system was used: "1" = poor (>5 fruit per tree), "2" = average (3-4 fruit per tree) and "3" = good (1-2 fruit per tree).

3.1.21. Orchard SV14 – 2017 season

FCM trap catches peaked in week 19 and the FCM infestation was the highest in weeks 14 and 18 (Figure 3.16.A.). FCM infestation was recorded in weeks 8, 9, 14, 16, 18, 19, 20 and 23 (Figure 3.16.B.). The FCM infestation exceeded the threshold (0.2 infested fruit per tree), in weeks 14 and 18. Lower orchard sanitation rating was scored in weeks 14, 15, 17, 19, 20, 21and 23 (Figure 3.16.C.), which could be related to FCM, as some of these were the only weeks where FCM was recorded.



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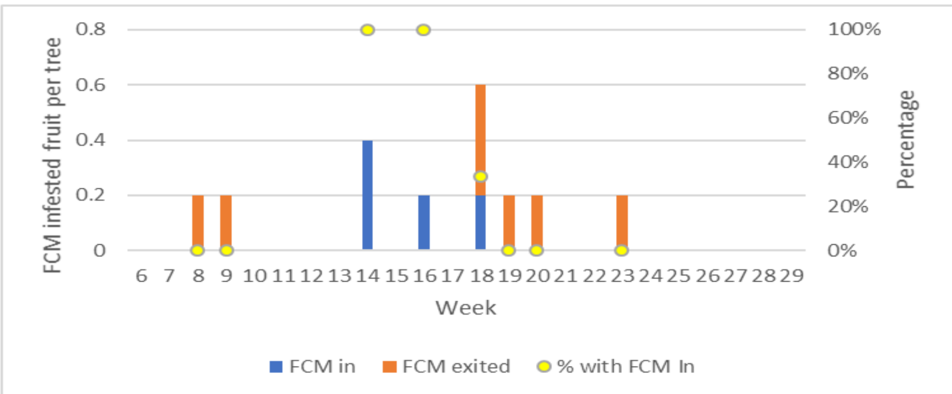

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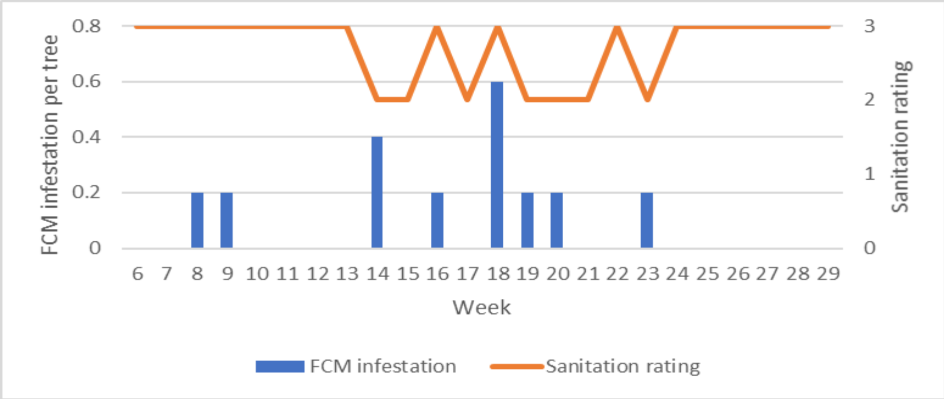


C.

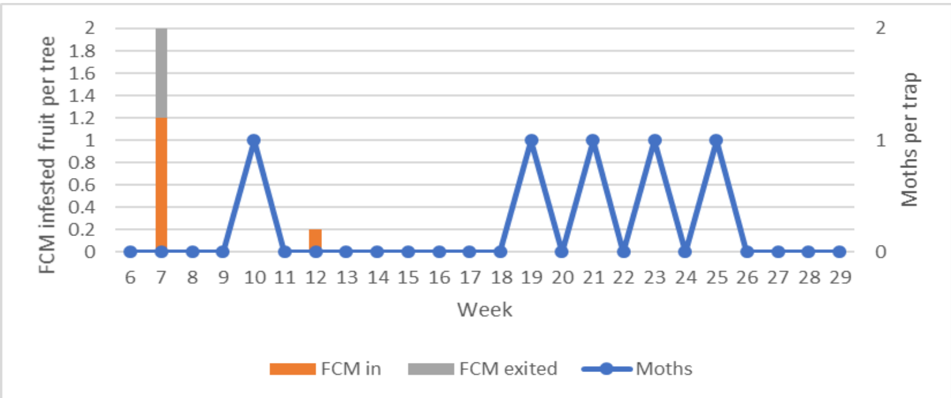
Figure 3.16.A: Weekly FCM moth trap counts and FCM infestation (in and exited). "In" is fruit found with FCM larva in the fruit, whereas "exited" is the fruit where the larva had already exited the fruit, **B:** Percentage of fruit dropped, **C:** FCM infestation and orchard sanitation rating. The orchard sanitation rating is determined by the number of fruit lying underneath the trees. The following grading system was used: "1" = poor (>5 fruit per tree), "2" = average (3-4 fruit per tree) and "3" = good (1-2 fruit per tree).

3.1.22. Orchard SV14 – 2018 season

Orchard SV14 had no moth trap catches nor any fruit with FCM infestation during the period that the orchard was monitored.

3.1.23. Orchard SV17 – 2017 season

FCM trap catches peaked in weeks 10, 19, 21, 23 and 25 (Figure 3.17.A.). FCM infestation was recorded in weeks 7 and 12 (Figure 3.17.B.). The FCM infestation exceeded the threshold (0.2 infested fruit per tree), in week 7. Low orchard sanitation rating was scored in week 19 (Figure 3.17.C.).



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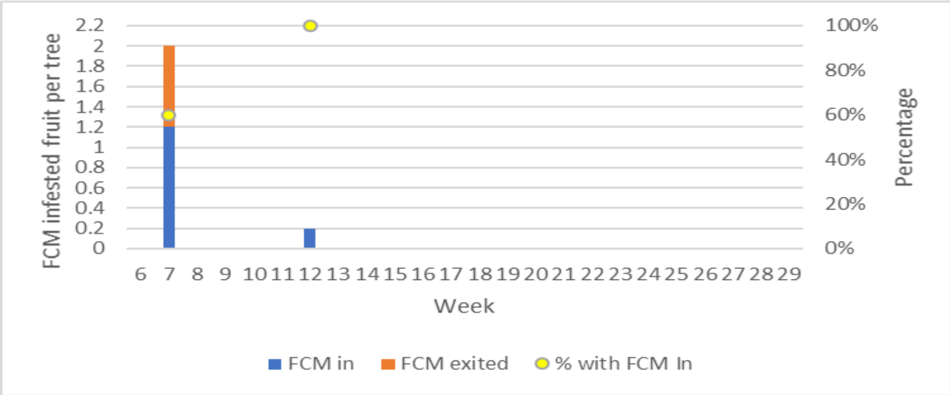

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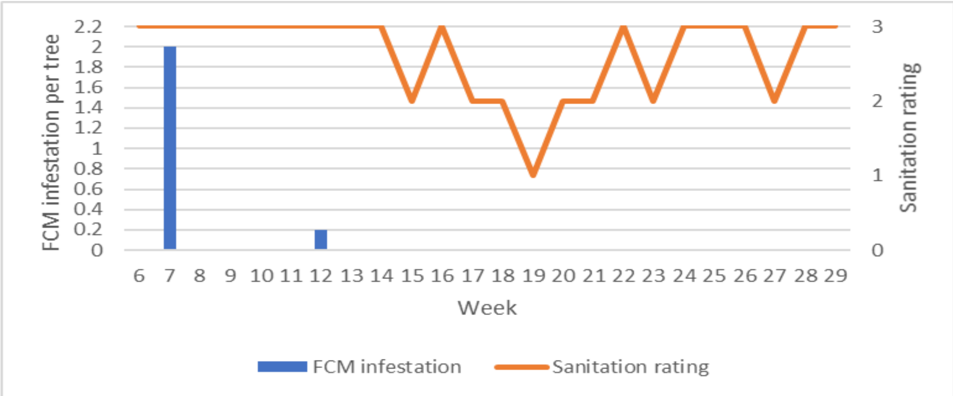
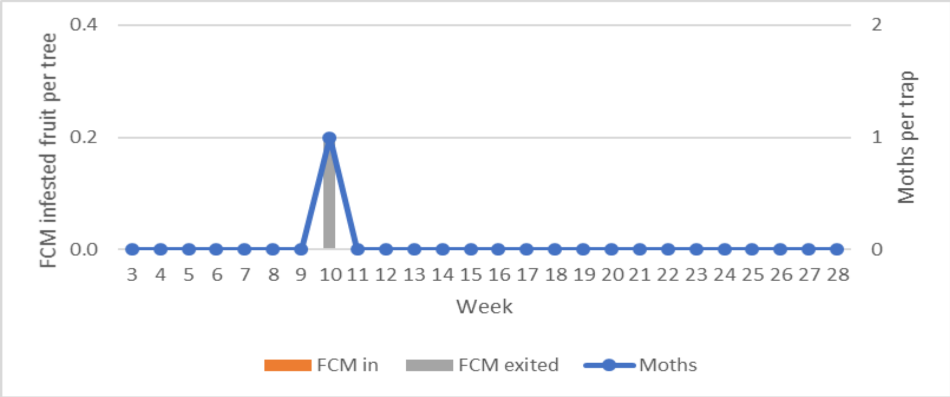


C.

Figure 3.17.A: Weekly FCM moth trap counts and FCM infestation (in and exited). “In” is fruit found with FCM larva in the fruit, whereas “exited” is the fruit where the larva had already exited the fruit, **B:** Percentage of fruit dropped, **C:** FCM infestation and orchard sanitation rating. The orchard sanitation rating is determined by the number of fruit lying underneath the trees. The following grading system was used: ”1” = poor (>5 fruit per tree), “2” = average (3-4 fruit per tree) and “3” = good (1-2 fruit per tree).

3.1.24. Orchard SV17 – 2018 season

The only FCM trap catch was recorded in week 10 (Figure 3.18.A.). The only FCM infestation was recorded in week 10 (Figure 3.18.B.). The FCM infestation did not exceed the threshold (0.2 infested fruit per tree), in any of the weeks. Low orchard sanitation rating was scored in week 3 (Figure 3.18.C.).



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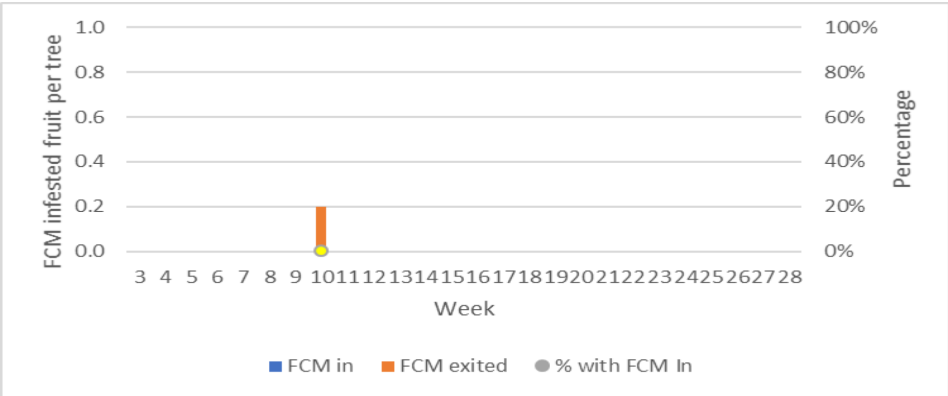

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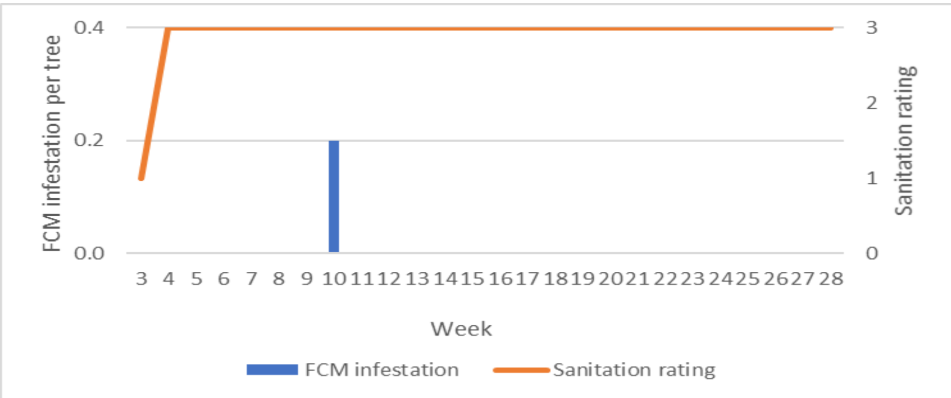
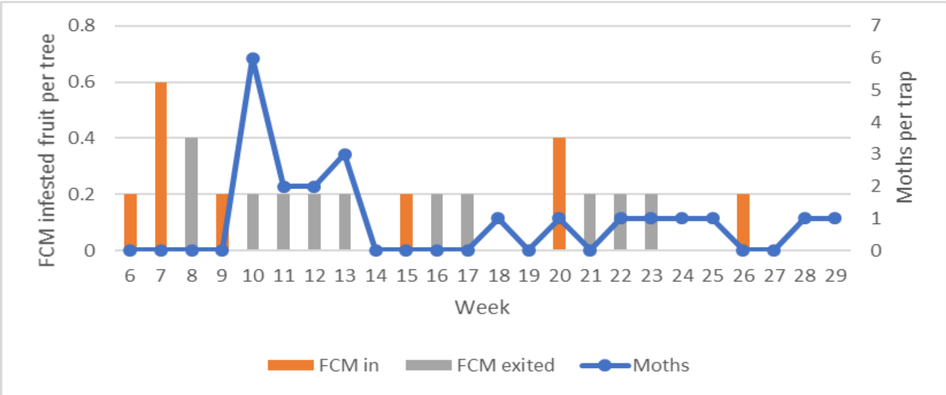


C.

Figure 3.18.A: Weekly FCM moth trap counts and FCM infestation (in and exited). “In” is fruit found with FCM larva in the fruit, whereas “exited” is the fruit where the larva had already exited the fruit, **B:** Percentage of fruit dropped, **C:** FCM infestation and orchard sanitation rating. The orchard sanitation rating is determined by the number of fruit lying underneath the trees. The following grading system was used: ”1” = poor (>5 fruit per tree), “2” = average (3-4 fruit per tree) and “3” = good (1-2 fruit per tree).

3.1.25. Orchard SV19B – 2017 season

FCM trap catches peaked in weeks 10 and 13 and the FCM infestation was the highest in weeks 7, 8 and 20 (Figure 3.19.A.). FCM infestation was recorded in weeks 6, 7, 8, 9, 10, 11, 12, 13, 15, 16, 17, 20, 21, 22, 23 and 26 (Figure 3.19.B.). The FCM infestation exceeded the threshold (0.2 infested fruit per tree), in weeks 7, 8 and 20. Low orchard sanitation rating was scored in weeks 15 and 19 (Figure 3.19.C.).



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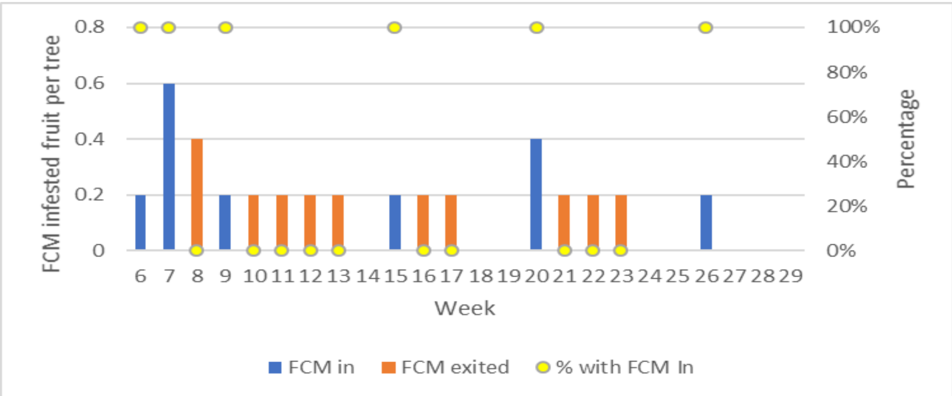

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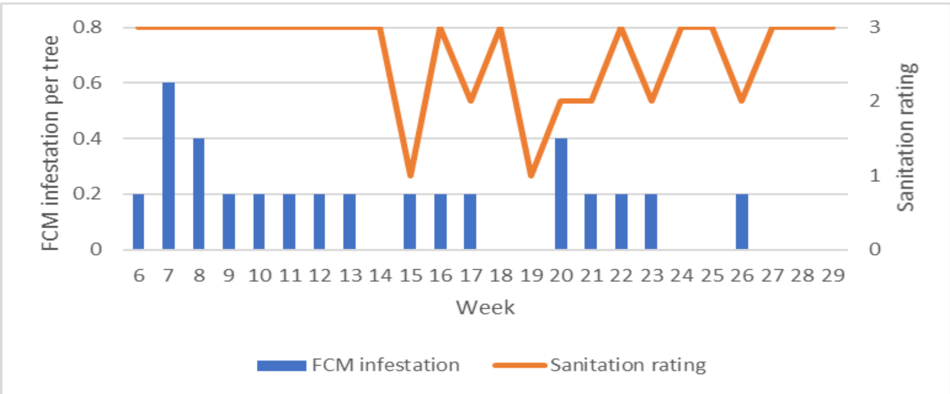
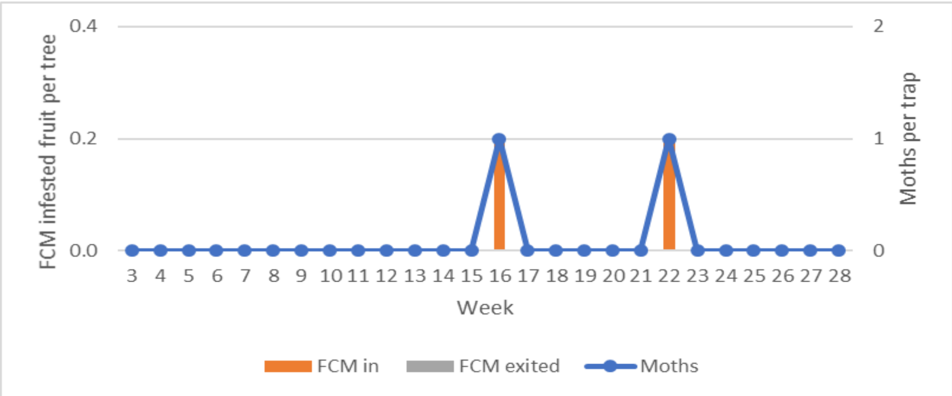


C.

Figure 3.19.A: Weekly FCM moth trap counts and FCM infestation (in and exited). “In” is fruit found with FCM larva in the fruit, whereas “exited” is the fruit where the larva had already exited the fruit, **B:** Percentage of fruit dropped, **C:** FCM infestation and orchard sanitation rating. The orchard sanitation rating is determined by the number of fruit lying underneath the trees. The following grading system was used: ”1” = poor (>5 fruit per tree), “2” = average (3-4 fruit per tree) and “3” = good (1-2 fruit per tree).

3.1.26. Orchard SV19B – 2018 season

The only FCM trap catches were recorded in weeks 16 and 22 (Figure 3.20.A.). The only FCM infestation was recorded in weeks 16 and 22 (Figure 3.20.B.). The FCM infestation did not exceed the threshold (0.2 infested fruit per tree), in any of the weeks. Low orchard sanitation rating was scored in week 3 (Figure 3.20.C.).



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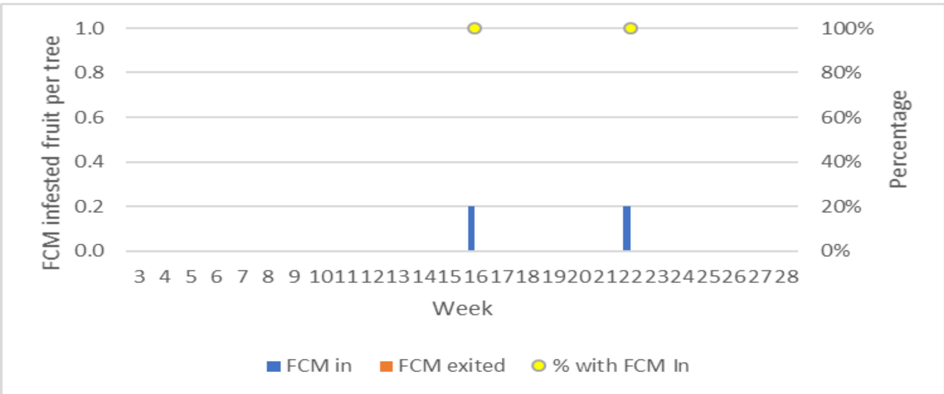

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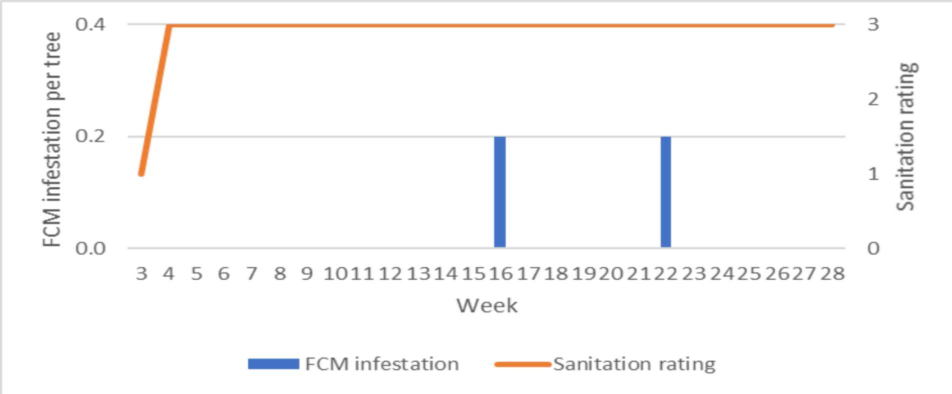
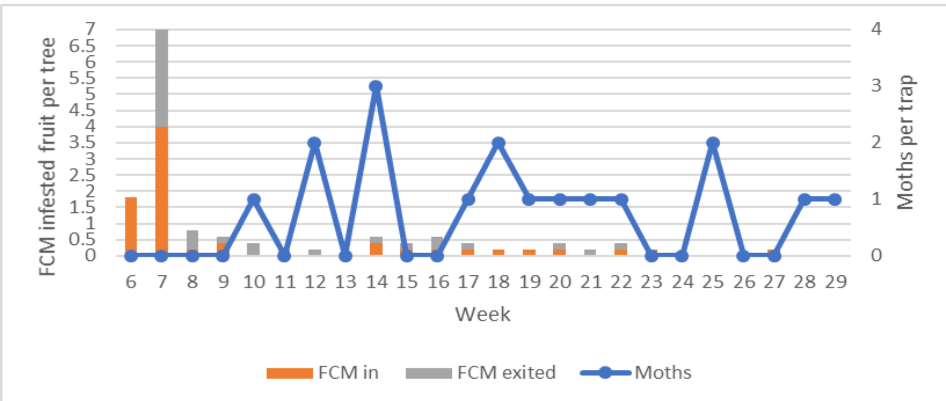


C.

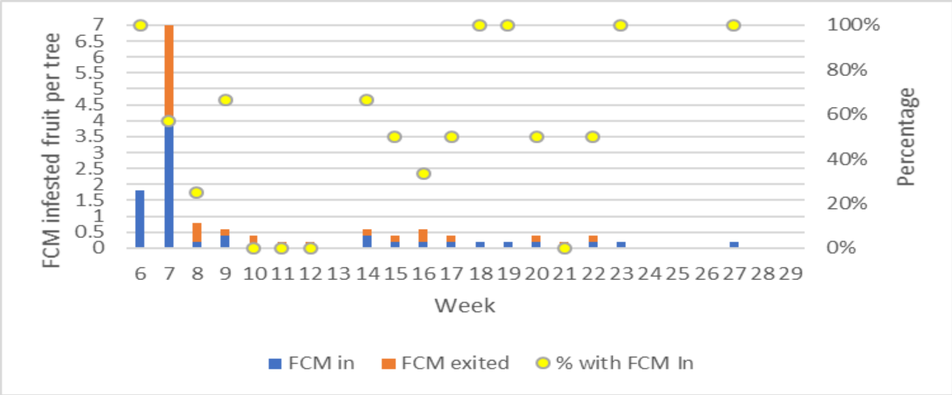
Figure 3.20.A: Weekly FCM moth trap counts and FCM infestation (in and exited). "In" is fruit found with FCM larva in the fruit, whereas "exited" is the fruit where the larva had already exited the fruit, **B:** Percentage of fruit dropped, **C:** FCM infestation and orchard sanitation rating. The orchard sanitation rating is determined by the number of fruit lying underneath the trees. The following grading system was used: "1" = poor (>5 fruit per tree), "2" = average (3-4 fruit per tree) and "3" = good (1-2 fruit per tree).

3.1.27. Orchard SV20 – 2017 season

FCM trap catches peaked in weeks 12, 14, 18 and 25 and the FCM infestation was the highest in week 7 (Figure 3.21.A.). FCM infestation was recorded in weeks 6, 7, 8, 9, 10, 12, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23 and 27 (Figure 3.21.B.). The FCM infestation exceeded the threshold (0.2 infested fruit per tree), in weeks 6, 7, 8, 9, 10, 14, 15, 16, 17, 20 and 22. Lower orchard sanitation rating was scored in weeks 14, 16, 17, 18, 19, 20, 21 and 23 (Figure 3.21.C.), which could be related to FCM, as some of these were the only weeks where FCM was recorded.



A.



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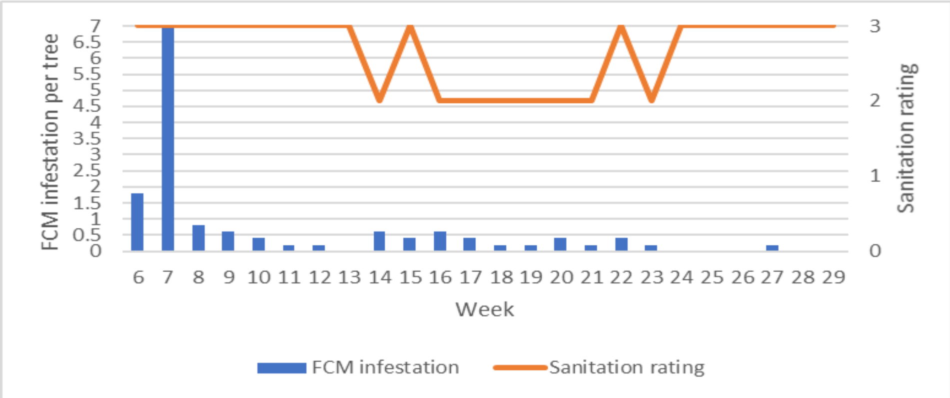


C.

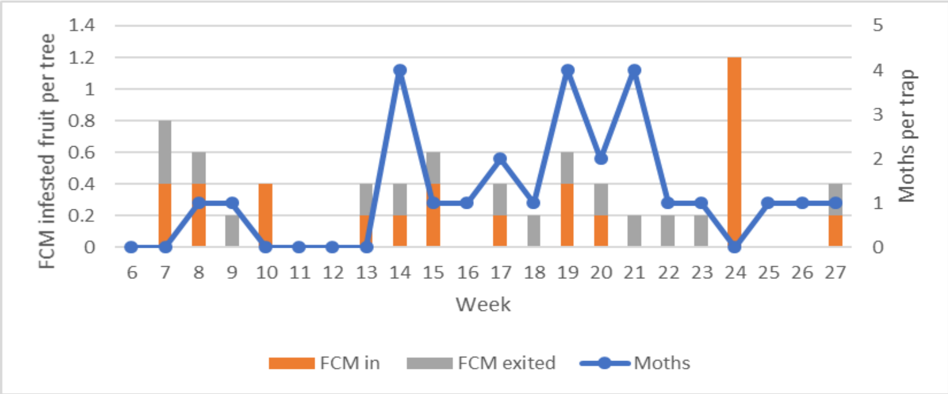
Figure 3.21.A: Weekly FCM moth trap counts and FCM infestation (in and exited). "In" is fruit found with FCM larva in the fruit, whereas "exited" is the fruit where the larva had already exited the fruit, **B:** Percentage of fruit dropped, **C:** FCM infestation and orchard sanitation rating. The orchard sanitation rating is determined by the number of fruit lying underneath the trees. The following grading system was used: "1" = poor (>5 fruit per tree), "2" = average (3-4 fruit per tree) and "3" = good (1-2 fruit per tree).

3.1.28. Orchard SV20 – 2018 season

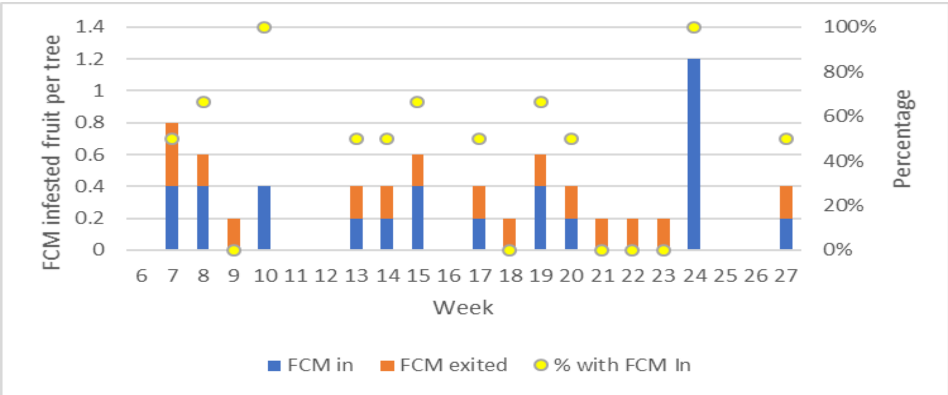
Orchard SV20 had no moth trap catches nor any fruit with FCM infestation during the period that the orchard was monitored.

3.1.29. Orchard 5 – 2017 season

FCM trap catches peaked in weeks 14, 19 and 21 and the FCM infestation was the highest in week 24 (Figure 3.22.A.). FCM infestation was recorded in weeks 7, 8, 9, 10, 13, 14, 15, 17, 18, 19, 20, 21, 22, 23, 24 and 27 (Figure 3.22.B.). The FCM infestation exceeded the threshold (0.2 infested fruit per tree), in weeks 7, 8, 10, 13, 14, 15, 17, 19, 20, 24 and 27. Low orchard sanitation rating was scored in weeks 15, 19, 24 and 27 (Figure 3.22.C.).



A.



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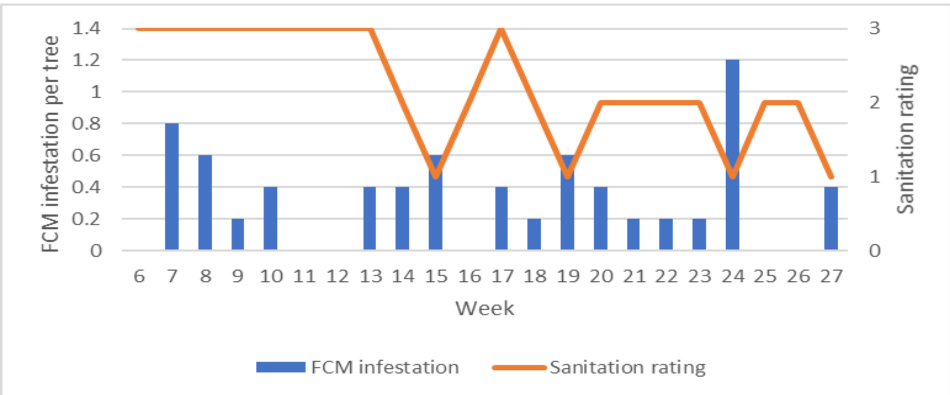


C.

Figure 3.22.A: Weekly FCM moth trap counts and FCM infestation (in and exited). "In" is fruit found with FCM larva in the fruit, whereas "exited" is the fruit where the larva had already exited the fruit, **B:** Percentage of fruit dropped, **C:** FCM infestation and orchard sanitation rating. The orchard

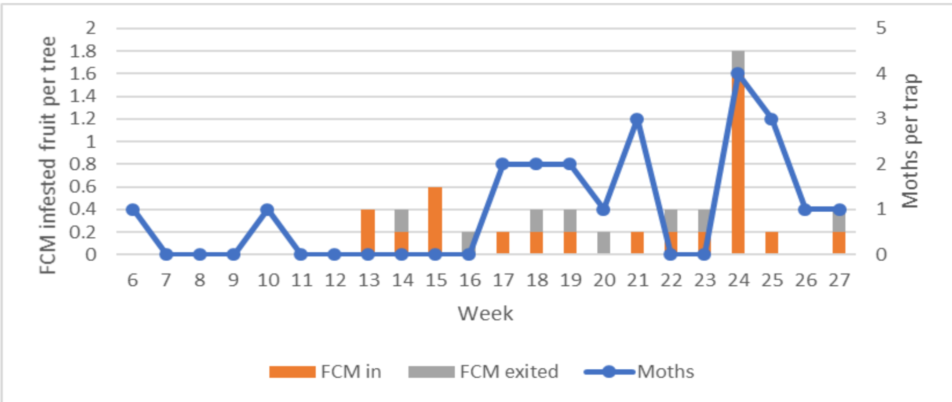
sanitation rating is determined by the number of fruit lying underneath the trees. The following grading system was used: ”1” = poor (>5 fruit per tree), “2” = average (3-4 fruit per tree) and “3” = good (1-2 fruit per tree).

3.1.30. Orchard 5 – 2018 season

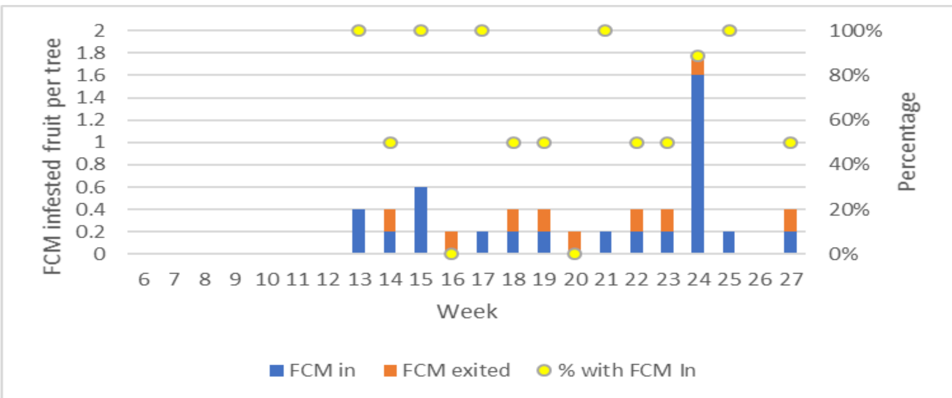
Orchard 5 had no moth trap catches nor any fruit with FCM infestation during the period that the orchard was monitored.

3.1.31. Orchard 6 – 2017 season

FCM trap catches peaked in weeks 21, 24 and 25 and the FCM infestation was the highest in week 24 (Figure 3.23.A.). FCM infestation was recorded in weeks 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25 and 27 (Figure 3.23.B.). The FCM infestation exceeded the threshold (0.2 infested fruit per tree), in weeks 13, 14, 15, 18, 19, 22, 23, 24 and 27. Low orchard sanitation rating was scored in weeks 15, 24 and 27 (Figure 3.23.C.).



A.



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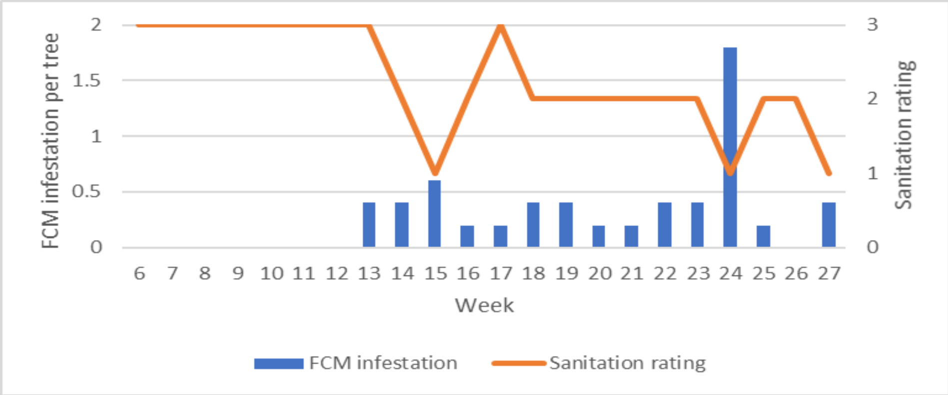


C.

Figure 3.23.A: Weekly FCM moth trap counts and FCM infestation (in and exited). "In" is fruit found with FCM larva in the fruit, whereas "exited" is the fruit where the larva had already exited the fruit, **B:** Percentage of fruit dropped, **C:** FCM infestation and orchard sanitation rating. The orchard sanitation rating is determined by the number of fruit lying underneath the trees. The following grading system was used: "1" = poor (>5 fruit per tree), "2" = average (3-4 fruit per tree) and "3" = good (1-2 fruit per tree).

3.1.32. Orchard 6 – 2018 season

Orchard 6 had no moth trap catches nor any fruit with FCM infestation during the period that the orchard was monitored.

3.1.33. Orchard DD01 – 2017 and 2018 seasons

Orchard DD01 had no moth trap catches nor any fruit with FCM infestation during the period that the orchard was monitored.

3.1.34. Orchard DD02 – 2017 and 2018 seasons

Orchard DD02 had no moth trap catches nor any fruit with FCM infestation during the period that the orchard was monitored.

3.1.35. Orchard DD03 – 2017 and 2018 seasons

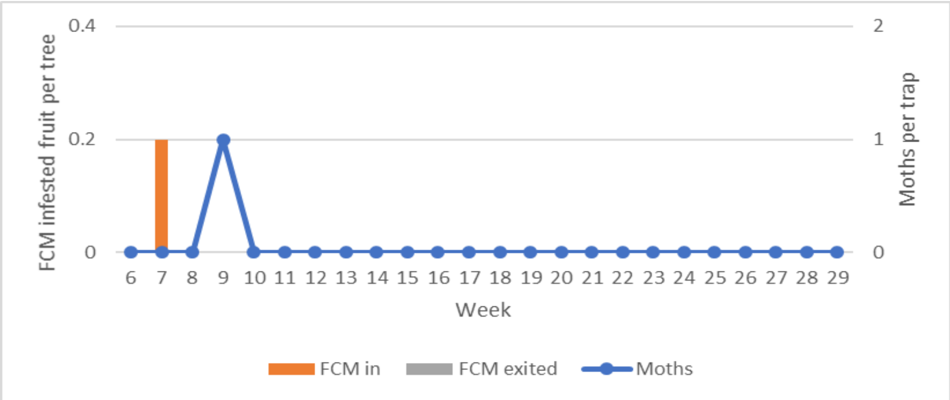
Orchard DD03 had no moth trap catches nor any fruit with FCM infestation during the period that the orchard was monitored.

3.1.36. Orchard DD04 – 2017 and 2018 seasons

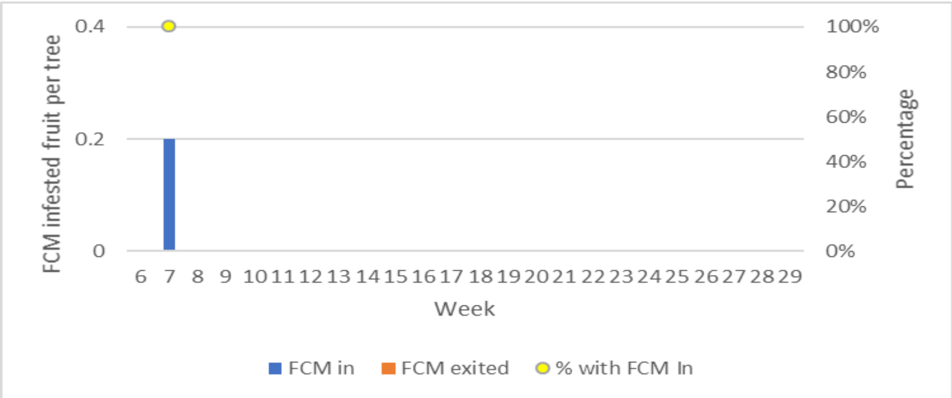
Orchard DD04 had no moth trap catches nor any fruit with FCM infestation during the period that the orchard was monitored.

3.1.37. Orchard DD05 – 2017 season

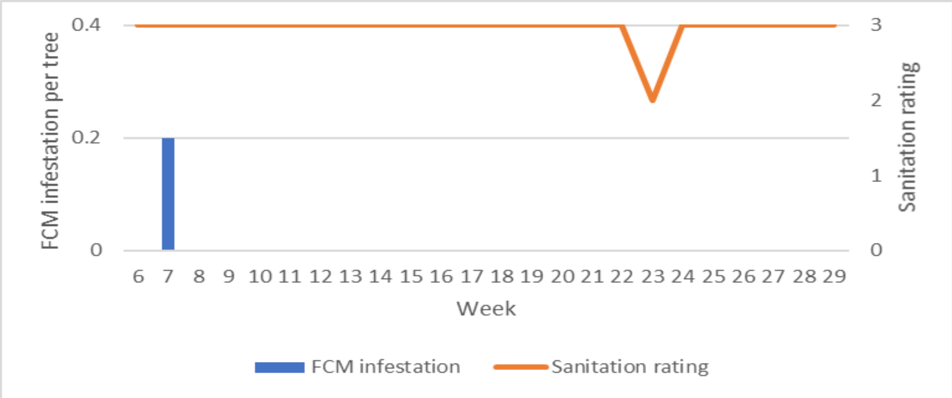
The only FCM trap catch was recorded in week 9 (Figure 3.24.A.). The only FCM infestation was recorded in week 7 (Figure 3.24.B.). The FCM infestation did not exceed the threshold (0.2 infested fruit per tree), in any of the weeks. Lower orchard sanitation rating was scored in week 23 (Figure 3.24.C.).



A.



B.



C.

Figure 3.24.A: Weekly FCM moth trap counts and FCM infestation (in and exited). "In" is fruit found with FCM larva in the fruit, whereas "exited" is the fruit where the larva had already exited the fruit, **B:** Percentage of fruit dropped, **C:** FCM infestation and orchard sanitation rating. The orchard sanitation rating is determined by the number of fruit lying underneath the trees. The following grading system was used: "1" = poor (>5 fruit per tree), "2" = average (3-4 fruit per tree) and "3" = good (1-2 fruit per tree).

3.1.38. Orchard DD05 – 2018 season

Orchard DD05 had no moth trap catches nor any fruit with FCM infestation during the period that the orchard was monitored.

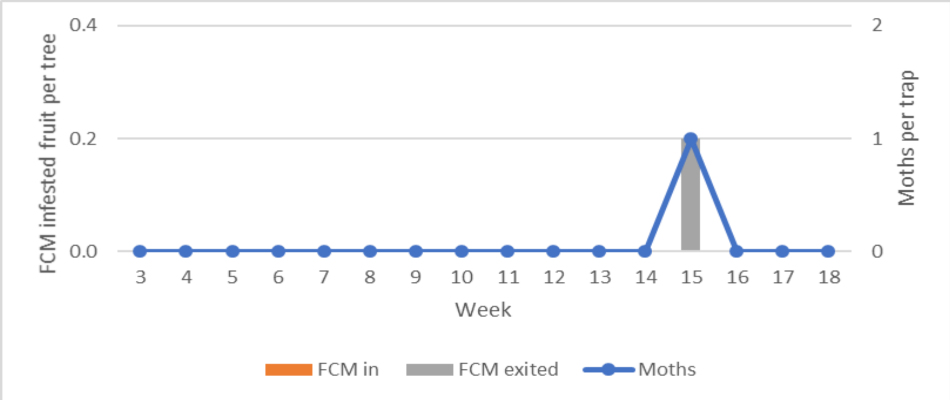
3.2. Mandarins

3.2.1. Orchard RF06 – 2017 season

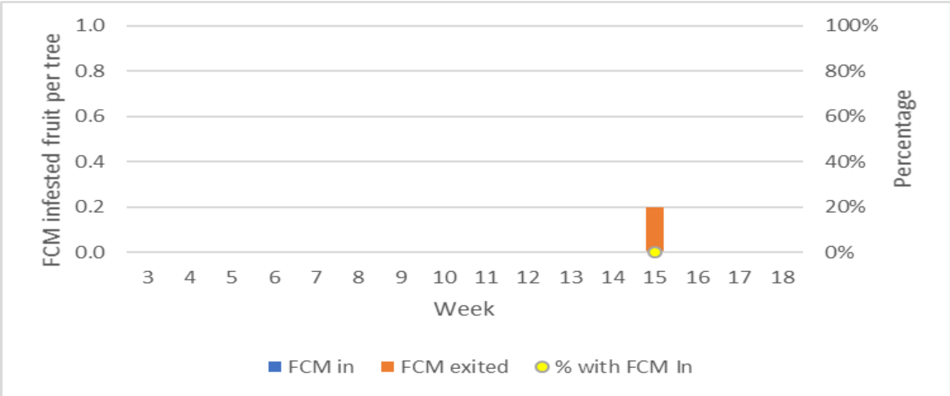
Orchard RF06 had no moth trap catches nor any fruit with FCM infestation during the period that the orchard was monitored.

3.2.2. Orchard RF06 – 2018 season

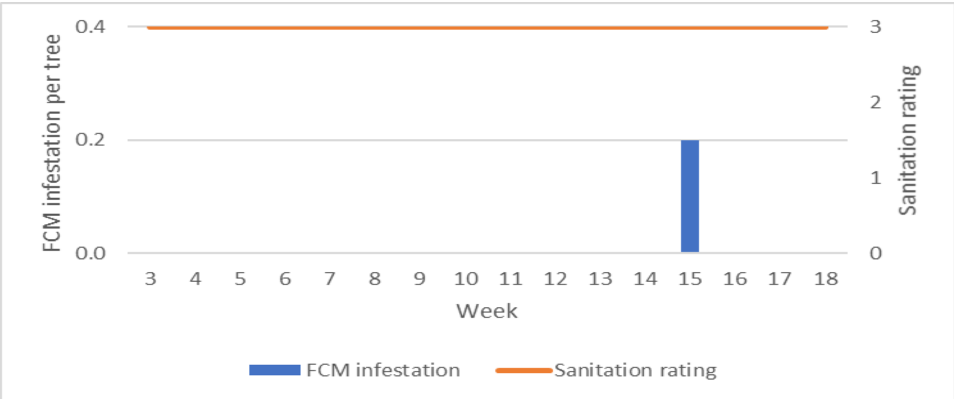
The only FCM trap catch was recorded in week 15 (Figure 3.25.A). The only FCM infestation was recorded in week 15 (Figure 3.25.B.). The FCM infestation did not exceed the threshold (0.2 infested fruit per tree), in any of the weeks. The orchard sanitation rating was very good for all of the weeks (Figure 3.25.C.).



A.



B.



C.

Figure 3.25.A: Weekly FCM moth trap counts and FCM infestation (in and exited). “In” is fruit found with FCM larva in the fruit, whereas “exited” is the fruit where the larva had already exited the fruit, **B:** Percentage of fruit dropped, **C:** FCM infestation and orchard sanitation rating. The orchard sanitation rating is determined by the number of fruit lying underneath the trees. The following

grading system was used: ”1” = poor (>5 fruit per tree), “2” = average (3-4 fruit per tree) and “3” = good (1-2 fruit per tree).

3.2.3. Orchard SV31 – 2017 and 2018 seasons

Orchard SV31 had no moth trap catches nor any fruit with FCM infestation during the period that the orchard was monitored.

3.2.4. Orchard SV32 – 2017 and 2018 seasons

Orchard SV31 had no moth trap catches nor any fruit with FCM infestation during the period that the orchard was monitored.

3.2.5. Orchard RF21 – 2017 and 2018 seasons

Orchard RF21 had no moth trap catches nor any fruit with FCM infestation during the period that the orchard was monitored.

3.2.6. Orchard RF22 – 2017 and 2018 seasons

Orchard RF22 had no moth trap catches nor any fruit with FCM infestation during the period that the orchard was monitored.

3.3. Valencias

3.3.1. Orchard WK07 – 2017 and 2018 seasons

Orchard WK07 had no moth trap catches nor any fruit with FCM infestation during the period that the orchard was monitored.

3.3.2. Orchard WK08 – 2017 and 2018 seasons

Orchard WK08 had no moth trap catches nor any fruit with FCM infestation during the period that the orchard was monitored.

3.3.3. Orchard WK25 – 2017 and 2018 seasons

Orchard WK25 had no moth trap catches nor any fruit with FCM infestation during the period that the orchard was monitored.

3.3.4. Orchard WK28 – 2017 and 2018 seasons

Orchard WK28 had no moth trap catches nor any fruit with FCM infestation during the period that the orchard was monitored.

3.4. Pre-harvest data combined

The FCM infestation (in and exited) and moth trap catches for all of the orchards for the 2017 season were grouped together in Figure 3.26. The highest level of infestation was recorded in week 7, where the average number of fruit infested by FCM exceeded 2.4 fruit per tree. This peak in infestation may have been preceded by a peak in trap catches, but monitoring was only initiated in week 6 and this could therefore not be established. There was a significant drop in the level of infestation from week 8 onwards. The infestation levels peaked again in weeks 14 and 15. The moth catches peaked in week 19, where the average number of moths recorded per trap exceeded 1.20. The moth catches decreased after week 19, with peaks in weeks 21 and 25. These peaks and dips in moth catches and fruit infestation are in all likelihood FCM generations, of which there are usually 6 per year (Stofberg, 1954). It is important to note that the 2017 season was considered an exceptionally high-pressure year for FCM in the Sundays River Valley, due to the extreme fruit drop that was experienced on the Navel cultivars (O.P.J. Stander, unpublished report, 2017).

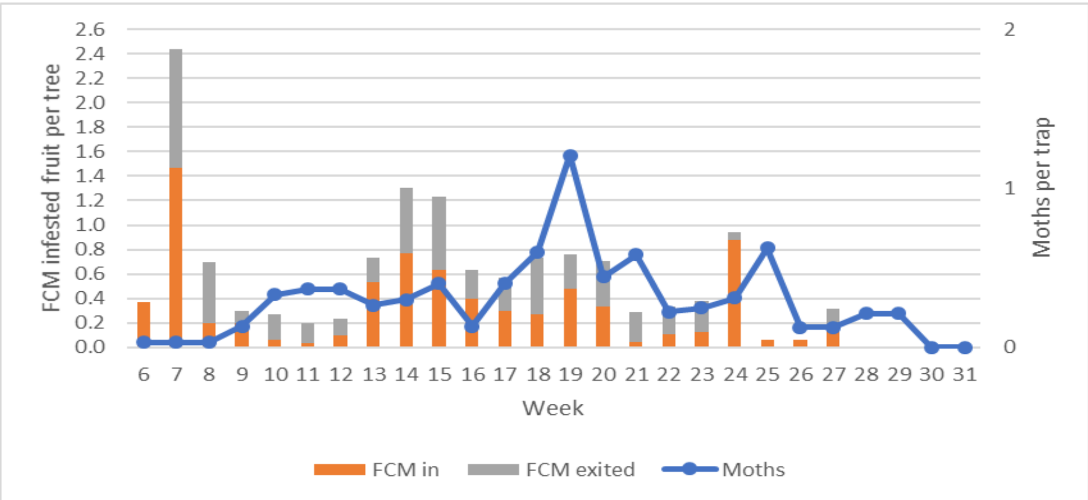


Figure 3.26. Weekly FCM moth trap counts and FCM infestation (in and exited). All the orchards for the 2017 season combined. Monitoring continued up to week 37, but no moths were caught or infestation recorded after week 29.

The FCM infestation (in and exited) and moth trap catches for all of the orchards for the 2018 season were grouped together in Figure 3.27. The highest level of infestation was recorded in weeks 12 and 14, where the average number of fruit infested by FCM were below 0.2 fruit per tree. The moth catches peaked in week 5 and week 31, where the average number of moths recorded exceeded 1.0

moth per trap. The levels of FCM infestation and moth activity were substantially lower in 2018 than in 2017. The 2018 season was considered a low-pressure year for FCM in the Sundays River Valley.

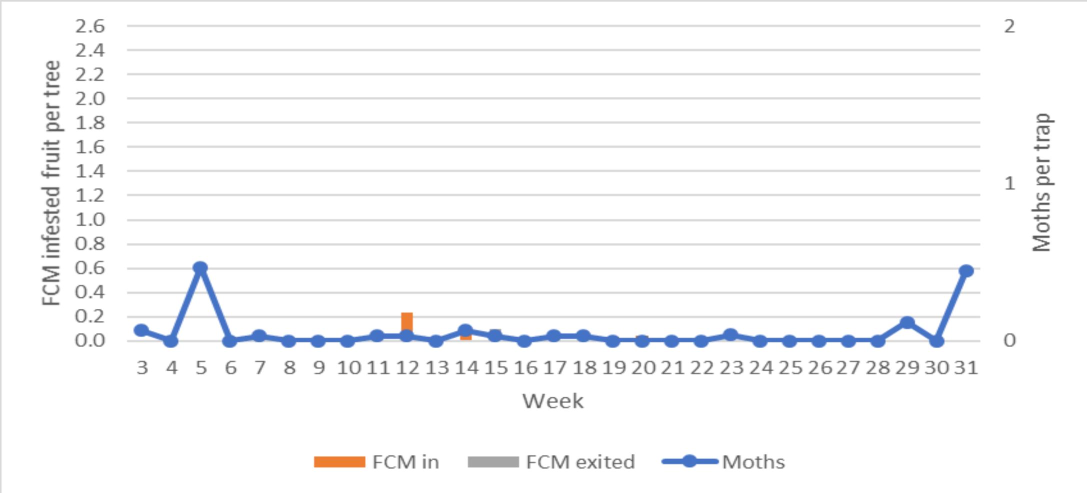


Figure 3.27. Weekly FCM moth trap counts and FCM infestation (in and exited). All the orchards for the 2018 season combined. The same Y-axis was used as for the pervious graph (Figure 3.76), in order to illustrate a comparison of levels between the two seasons better.

A regression analyses was conducted for all orchards and both seasons for trap catches and infestation (FCM in and exited combined), for all lag periods 0 to 5 weeks (Table 3.1.). A two-week lag between infestation and moth catches showed the strongest regression (Figure 3.28). Typically, infestation of fruit would relate to a flight that occurred a couple or a few weeks previously i.e., moths would need to lay eggs, eggs would need to hatch, larvae would need to penetrate fruit and fruit would need to respond physiologically and drop off the tree, which would take a period of time. The lag is due to life cycle for FCM that needs to be completed, i.e., laying of the eggs on the rind of the fruit, and the penetration of the larvae into the fruit. A two-week lag was applied to each orchard for each season to determine whether traps could indicate impending infestation on an orchard basis, not just farm or area basis (Table 3.2). However, there was no significant regression between the pre-harvest FCM infestation of fruit by FCM and moth catches for the full period, using a two-week lag between infestation and moth catches for all except one of the orchards (Table 3.2.). Orchard number 19B recorded a significant positive regression (F = 6.055522; P = 0.021794) in 2018. Additionally, there was nearly a significant positive regression (F = 3.863636; P = 0.063383) for orchard number SV17 in 2017. Simple regression analyses conducted using a Generalized Linear Model.

Table 3.1. Relationship between pre-harvest FCM infestation of fruit by FCM and moth catches for all of the orchards and both seasons for all lag periods 0 to 5 weeks, determined by regression analyses.

Lag between moth catches and infestation	R^2	*F*	Y	*P*
0	0.012360	0.312874	0.1542	0.580899
1 week	0.007855	0.190006	0.1546	0.666807
2 week	**0.301451**	**9.925410**	**0.0345**	**0.004478**
3 week	0.007830	0.173617	0.1667	0.680955
4 week	0.023157	0.497827	0.1837	0.488210
5 week	0.003760	0.075480	0.1127	0.786337

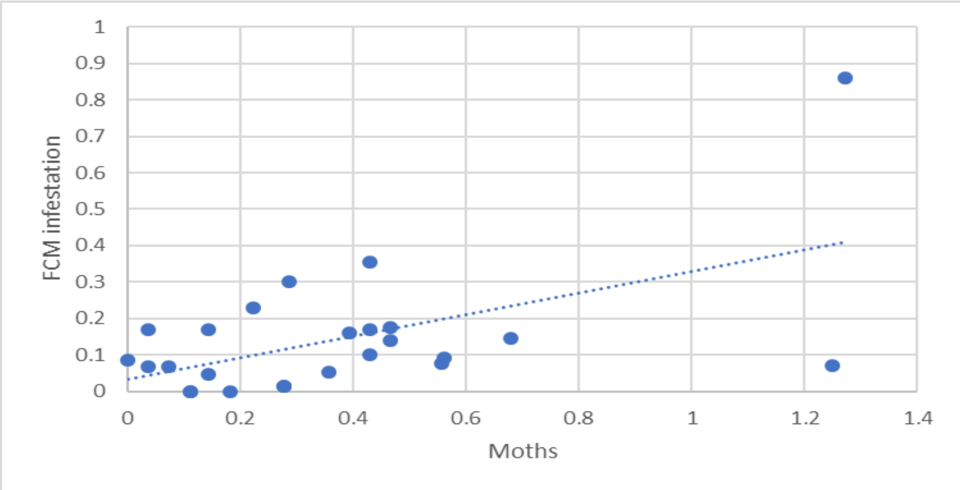


Figure 3.28. Relationship between FCM infestation (using a two-week lag) and moth catches, for all orchards and both seasons.

Table 3.2. Relationship between pre-harvest infestation of fruit by FCM (using a two-week lag) and moth catches for the full monitoring period, determined by regression analyses, for each individual orchard and season for which there were sufficient data.

Year	Orchard number	Cultivar	R^2	*F*	Y	*P*
2017	5	Autumn Gold Late Navel	0.038129	0.713537	0.3705	0.409360
	6	Autumn Gold Late Navel	0.023927	0.441235	0.3557	0.514947
	7	Palmer Navel	0.001326	0.015938	0.2355	0.901628
	8	Palmer Navel	0.174825	2.542373	0.0615	0.136812
	9	Palmer Navel	0.005263	0.063492	0.08	0.805323
	WK27	Navelina Navel	0.000292	0.003217	0.1088	0.955784
	WK26	Palmer Navel	0.00	0.00	0.0857	1.000000
	SV20	Navelate Late Navel	0.087805	1.925134	0.2195	0.180559
	SV19B	California Late Navel	0.003921	0.078727	0.1407	0.781911
	SV17	California Late Navel	0.161905	3.863636	0.00	0.063383
	SV15	Washington Navel	0.007658	0.092602	0.1782	0.766107
	SV14	Navelate Late Navel	0.033428	0.691688	0.1103	0.415411

	SV12	Palmer Navel	0.172365	2.499139	0.2333	0.139893
	SV11	Navelina Navel	0.063395	0.744545	0.7	0.406628
	SV10	Navelina Navel	0.057865	0.675613	0.4778	0.428558
2018	SV19B	California Late Navel	0.208412	6.055522	0.0087	**0.021794**
	SV10	Navelina Navel	0.003906	0.058824	0.075	0.811650

There was no significant regression between FCM infestation per week and the average weekly temperature (°C) (Figure 3.29a and b.). There were very low levels of infestation recorded in weeks 9-11 in most of the orchards during the 2017 season, due to lower fruit drop, which did weaken the data and potentially compromise the detection of a significant relationship.

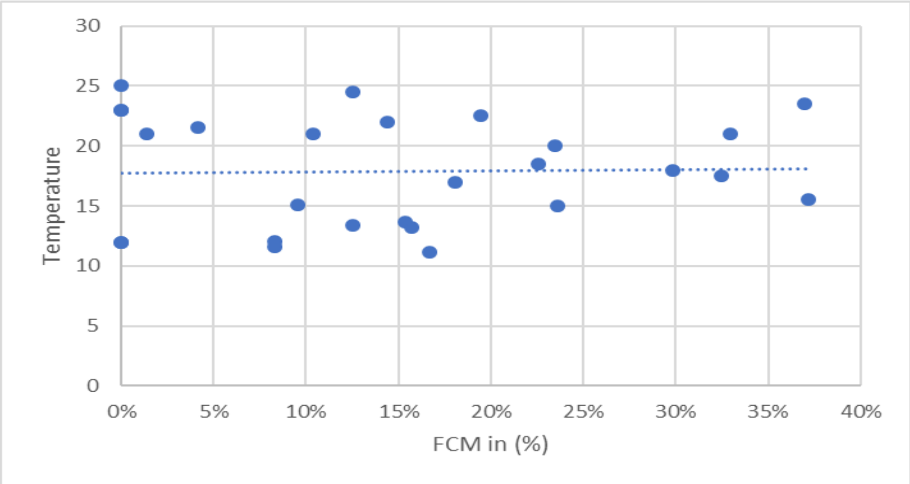


Figure 3.29a. Percentage of fruit dropped due to FCM, with the larva still in the fruit, and average weekly temperature (°C); data for all orchards and both seasons combined.

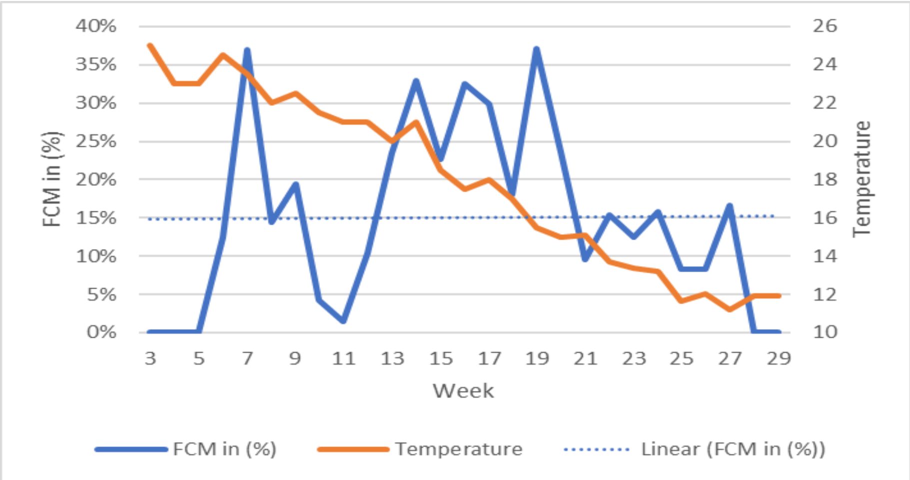


Figure 3.29b. FCM infestation in percentage and average temperature (°C); data for all orchards and both seasons combined.

3.5. FCM infestation: 4 weeks before harvest and packhouse delivery inspection

The threshold as stipulated in the guidelines for the systems approach for FCM (Moore *et al.* 2016), of 0.2 infested fruit per tree per week for the last 4 weeks before harvest was used to determine the preharvest risk of each orchard (Table 3.3.), during the 2017 season. FCM "In", where a larva was found in the fruit, and FCM "exited", where the fruit was infested but the larva had exited, were combined as FCM "total". The Navelina, Palmer, Washington and Autumn Gold (all Navel cultivars) orchards recorded the highest infested fruit per tree per week for the last 4 weeks before harvest. Orchards SV10, SV11, 5 and 6 exceeded the threshold based only on fruit which were still infested (larva in). Orchards WK27, SV12, SV15 and 7 only exceeded the threshold based on total FCM (larva in and exited). Infestation was recorded in orchards WK26, SV20, 19B, 9 and 8, but these levels were lower than the threshold. No FCM infestation was recorded in all of the other Navelate orchards, as well as the Nule, Nova (both Mandarins), Midknight, Delta (both Valencias), and Cambria Navel orchards during the last 4 weeks before harvest. The fruit from all the orchards were delivered to the packhouse after being harvested. The packhouse delivery inspection was conducted on every consignment that was delivered to the packhouse. A random 400 fruit sample was taken from various crates (Table 3.3.). The fruit were inspected by a trained quality inspector. The fruit were inspected visually and all suspect fruit were dissected with a knife to determine whether a fruit was infested with FCM. Only fruit in which a larva was found were recorded as infested. The total number of fruit infested with FCM was divided by the number of fruit in the sample to calculate the percentage infestation. Again, the threshold according to the guidelines for the FCM packhouse delivery inspection of 0.33% was used to determine the postharvest risk for each orchard. The Navelina, Palmer, Washington and Autumn Gold Navel orchards recorded the highest infestation during the packhouse delivery inspection. The same orchards in which high infestation was recorded 4 weeks before harvest exceeded the threshold during the packhouse delivery inspection. It was interesting that orchards SV17, SV14, SV13, DD01, DD03, DD04 and DD05 also exceeded the threshold during the packhouse delivery inspection, although these orchards recorded no infestation during the last 4 weeks before harvest. No FCM infestation was recorded in the Nule, Nova, Midknight and Delta orchards during the packhouse delivery inspection. No fruit were harvested from orchards WK25 and DD02 during the 2017 season.

Table 3.3. Preharvest FCM infestation and packhouse delivery inspection – 2017 season

Orchard	Cultivar	Harvest date	Infested fruit / tree / week Ave. last 4 weeks before harvest		Packhouse delivery inspection FCM infestation		
			FCM In [1]	FCM Total [2]	n	Total FCM	% Infestation
SV10	Navelina	15/05/2017	0.25	0.35	400	37	9.25%
SV11	Navelina	16/05/2017	0.35	0.55	800	38	4.75%
WK27	Navelina	16/05/2017	0.10	0.25	400	5	1.25%
SV12	Palmer	22/05/2017	0.10	0.25	400	9	2.25%
WK26	Palmer	22/05/2017	0.05	0.10	400	21	5.25%
SV15	Washington	22/05/2017	0.05	0.25	1200	8	0.67%
RF06	Nules	01/05/2017	0	0	1200	0	0.00%
SV31	Nules	08/05/2017	0	0	800	0	0.00%
SV32	Nules	08/05/2017	0	0	400	0	0.00%
RF21	Novas	29/05/2017	0	0	2400	0	0.00%
RF22	Novas	29/05/2017	0	0	2800	0	0.00%
WK07	Midknight	12/09/2017	0	0	800	0	0.00%
WK08	Midknight	13/09/2017	0	0	400	0	0.00%
WK28	Delta	07/09/2017	0	0	1200	0	0.00%
WK25	Delta	[3]	0	0	0	0	0.00%
SV17	Navelate	18/07/2017	0	0	1200	13	1.08%
SV20	Navelate	17/07/2017	0.05	0.05	2000	31	1.55%
SV14	Navelate	18/07/2017	0	0	800	9	1.13%
SV13	Navelate	18/07/2017	0	0	800	7	0.88%
SV19B	Navelate	18/07/2017	0.05	0.05	1600	14	0.88%
DD01	Cambria	20/07/2017	0	0	800	11	1.38%
DD02	Cambria	[3]	0	0	0	0	0.00%
DD03	Cambria	21/07/2017	0	0	400	9	2.25%
DD04	Cambria	20/07/2017	0	0	400	10	2.50%
DD05	Cambria	21/07/2017	0	0	400	7	1.75%
5	Autumn Gold	06/07/2017	0.35	0.40	1200	6	0.50%
6	Autumn Gold	07/07/2017	0.50	0.60	800	11	1.38%
7	Palmer	25/05/2017	0.05	0.25	800	18	2.25%
9	Palmer	23/05/2017	0.05	0.10	1200	36	3.00%
8	Palmer	24/05/2017	0.10	0.20	1200	17	1.42%

Notes:

FCM In [1]: Fruit that were infested with FCM where the larva was found in the fruit.

FCM Total [2]: Fruit that were infested with FCM where the larva was found in the fruit and also where the larva had exited the fruit.

[3]: Orchards where no fruit were harvested during the 2017 season.

FCM infestation per tree per week for the last 4 weeks before harvest was again recorded during the 2018 season. As with the previous season, FCM "in" (larva still in fruit), and FCM "exited", were again combined (Table 3.4.). The threshold of 0.2 infested fruit per tree per week was used to determine the preharvest risk of each orchard. The infestation for the last 4 weeks before harvest was substantially lower than in 2017. Only for orchards SV11 and RF06 was any infestation recorded, both being 0.05 infested fruit per tree per week, still well under the threshold. The FCM infestation was recorded in the other 28 orchards in the last 4 weeks before harvest. The fruit were delivered to the same packhouse after harvesting during the 2018 season. The sampling method that was used for the packhouse delivery inspection during the 2018 season was the same as in 2017. However, the sample size was increased to a 600 fruit sample during the 2018 season, and the sample was taken from the first consignment that was delivered to the packhouse from each orchard. The change in sample size was stipulated by Moore *et al.* (2016) in the verification standards for the systems approach for FCM. Although FCM infestation was recorded in fruit from orchards SV11 and RF06 before harvest, no infestation was recorded at the packhouse delivery inspection. This could be as a result of the growers presorting in the orchards, and removing any potentially infested fruit prior to the fruit being delivered to the packhouse. However, infestation during the packhouse delivery inspection was recorded for the following orchards: SV12, SV31, SV32, SV17, DD01, but none of these orchards exceeded the threshold of 0.33%. Orchards SV14 and 7 exceeded the threshold and recorded levels of 0.67% infestation. No infestation was recorded in the packhouse delivery sample for the other 23 orchards.

Table 3.4. Preharvest FCM infestation and packhouse delivery inspection – 2018 season

Orchard	Cultivar	Harvest date	Infested fruit / tree / week		Packhouse delivery inspection		
			Ave. last 4 weeks before harvest		FCM infestation		
			FCM In [1]	FCM Total [2]	n	Total FCM	% Infestation
SV10	Navelina	07/05/2018	0	0	600	0	0.00%
SV11	Navelina	07/05/2018	0.05	0.05	600	0	0.00%
WK27	Navelina	10/05/2018	0	0	600	0	0.00%
SV12	Palmer	11/06/2018	0	0	600	1	0.17%
WK26	Palmer	11/06/2018	0	0	600	0	0.00%
SV15	Washington	11/06/2018	0	0	600	0	0.00%
RF06	Nules	30/04/2018	0	0.05	600	0	0.00%
SV31	Nules	04/05/2018	0	0	600	2	0.33%
SV32	Nules	04/05/2018	0	0	600	1	0.17%
RF21	Novas	13/06/2018	0	0	600	0	0.00%
RF22	Novas	15/06/2018	0	0	600	0	0.00%
WK07	Midknight	15/09/2018	0	0	600	0	0.00%
WK08	Midknight	18/09/2018	0	0	600	0	0.00%
WK28	Delta	19/09/2018	0	0	600	0	0.00%
WK25	Delta	18/09/2018	0	0	600	0	0.00%

Orchard	Cultivar	Harvest date	Infested fruit / tree / week Ave. last 4 weeks before harvest		Packhouse delivery inspection FCM infestation		
			FCM In [1]	FCM Total [2]	n	Total FCM	% Infestation
SV17	Navelate	10/07/2018	0	0	600	2	0.33%
SV20	Navelate	10/07/2018	0	0	600	0	0.00%
SV14	Navelate	10/07/2018	0	0	600	4	0.67%
SV13	Navelate	11/07/2018	0	0	600	0	0.00%
SV19B	Navelate	10/07/2018	0	0	600	0	0.00%
DD01	Cambria	01/08/2018	0	0	600	1	0.17%
DD02	Cambria	01/08/2018	0	0	600	0	0.00%
DD03	Cambria	01/08/2018	0	0	600	0	0.00%
DD04	Cambria	01/08/2018	0	0	600	0	0.00%
DD05	Cambria	01/08/2018	0	0	600	0	0.00%
5	Autumn Gold	27/06/2018	0	0	600	0	0.00%
6	Autumn Gold	28/06/2018	0	0	600	0	0.00%
7	Palmer	17/05/2018	0	0	600	4	0.67%
9	Palmer	21/05/2018	0	0	600	0	0.00%
8	Palmer	21/05/2018	0	0	600	0	0.00%

Notes:

FCM In [1]: Fruit that were infested with FCM where the larva was found in the fruit.

FCM Total [2]: Fruit that were infested with FCM where the larva was found in the fruit and also where the larva had exited the fruit.

A significant positive regression was recorded between the infested fruit per tree per week for the last 4 weeks before harvest and the percentage infestation in the packhouse delivery inspection (F = 25.76961; P = 0.000004) (Figure 3.30), thus confirming that preharvest infestation is a good indication of the risk of postharvest infestation.

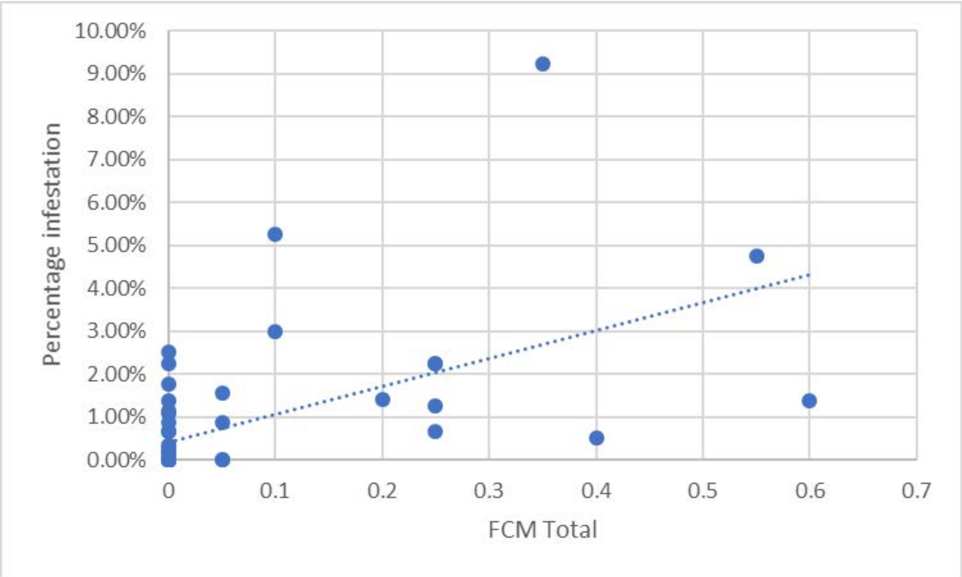


Figure 3.30. FCM infested fruit total per tree per week for the last 4 weeks before harvest and the percentage infestation in the packhouse delivery inspection. R^2 = 0.307625; F = 25.76961; Y = 0.0042; P = 0.000004

3.6. FCM Infestation: Packhouse delivery inspection and retention sample

The packhouse delivery inspection infestation records were used to determine the risk associated with each orchard. A retention sample of each consignment was taken on the day of packing during the 2017 season. The retention sample was a random 600 fruit sample of the final product packed for export. The retention sample was kept at ambient temperature for a three-week period (Table 3.5.). The 600 fruit sample was inspected on the day of packing and the same sample was inspected every week thereafter over the three weeks. The following orchards were packed separately and FCM infestation was recorded in the retention sample: SV10, SV11, WK27, SV12, WK26, SV15 and 7. These were the same orchards for which FCM infestation was recorded at the packhouse delivery inspection. It is common practice for different orchards to be packed together, if of the same farm, cultivar and harvested on the same day, so not all of the orchards were packed separately. The following orchards were grouped together and packed as one consignment and infestation was also recorded in the retention sample: SV17, SV20, SV14, SV13 and SV19B. Orchards 5 and 6 were also packed as one consignment and infestation was also recorded in their fruit. Orchards 9 and 8 were also grouped together and infestation was also recorded. It is important to note that the levels of infestation were substantially lower in the retention sample than in the packhouse delivery sample, with certain orchards showing as much as a 93% reduction. This is an indication that the packhouse was able to sort quite effectively for FCM infested fruit. A very high level of infestation was recorded in Orchard SV15 (Table 3.5.). It is important to note that 29 of the 35 fruit that were found with FCM infestation in the retention sample were only identified in the third week of inspection. It is possible that the fruit was infested by FCM just before packing and that infestation was not clearly visible at the time of packing. The infestation became more visible after three weeks, thus, confirming the importance of retaining the retention sample for a three-week period. However, under commercial conditions, such recently infested fruit would very soon be exposed to cold shipping temperatures (albeit not cold sterilisation temperatures), which would impede any further development of larvae, and certainly kill a high percentage of them, making it similarly unlikely that they would be intercepted during inspections conducted by the importing country. No infestation was recorded in the retention sample for the other 13 orchards.

Table 3.5. Packhouse delivery inspection and retention sample – 2017 season

Orchard	Cultivar	Packhouse delivery inspection			Retention sample inspection		
		FCM infestation			FCM infestation		
		n	Total FCM	% Infestation	n	Total FCM	% Infestation
SV10	Navelina	400	37	9.25%	600	12	2.00%
SV11	Navelina	800	38	4.75%	600	2	0.33%
WK27	Navelina	400	5	1.25%	600	4	0.67%
SV12	Palmer	400	9	2.25%	600	1	0.17%
WK26	Palmer	400	21	5.25%	600	7	1.17%
SV15	Washington	1200	8	0.67%	600	35	5.83%
RF06	Nules	1200	0	0.00%	600	0	0.00%
SV31	Nules	800	0	0.00%	600	0	0.00%
SV32	Nules	400	0	0.00%	600	0	0.00%
RF21	Novas	2400	0	0.00%	600	0	0.00%
RF22	Novas	2800	0	0.00%	600	0	0.00%
WK07, WK08	Midknight	1200	0	0.00%	600	0	0.00%
WK28	Delta	1200	0	0.00%	600	0	0.00%
WK25	Delta	0	0	0.00%	0	0	0.00%
SV17, SV20, SV14, SV13, SV19B	Navelate	6400	74	1.16%	600	6	1.00%
DD01, DD03, DD04, DD05	Cambria	2000	37	1.85%	600	0	0.00%
DD02	Cambria	0	0	0.00%	0	0	0.00%
5, 6	Autumn Gold	2000	17	0.85%	600	4	0.67%
7	Palmer	800	18	2.25%	600	10	1.67%
9, 8	Palmer	2400	53	2.21%	1200	21	1.75%

In 2018, the retention sample was again kept at ambient temperature for a three-week period (Table 3.6.), and inspected on the day of packing and every week thereafter over the three weeks. The following orchards were packed separately and recorded FCM infestation in the retention sample: SV11, WK27 and SV15. Again, not all of the orchards were packed separately. The following orchards were grouped together and packed as one consignment and also recorded infestation in the retention sample: SV17, SV20, SV14, SV13 and SV19B. Orchards: DD01, DD02, DD03, DD04, DD05 were also grouped together and packed as one consignment and recorded infestation. Orchards 5 and 6 were also packed as one consignment and also recorded infestation, as were orchards 9 and 8 again. The infestation levels in the retention samples were extremely low, with the highest infestation of 0.67% recorded. No infestation was recorded in the retention sample for the other 13 orchards.

Table 3.6. Packhouse delivery inspection and retention sample – 2018 season

Orchard	Cultivar	Packhouse delivery inspection			Retention sample inspection		
		FCM infestation			FCM infestation		
		n	Total FCM	% Infestation	n	Total FCM	% Infestation
SV10	Navelina	600	0	0.00%	600	0	0.00%
SV11	Navelina	600	0	0.00%	600	1	0.17%
WK27	Navelina	600	0	0.00%	600	1	0.17%
SV12	Palmer	600	1	0.17%	600	0	0.00%
WK26	Palmer	600	0	0.00%	600	0	0.00%
SV15	Washington	600	0	0.00%	600	4	0.67%
RF06	Nules	600	0	0.00%	600	0	0.00%
SV31	Nules	600	2	0.33%	600	0	0.00%
SV32	Nules	600	1	0.17%	600	0	0.00%
RF21	Novas	600	0	0.00%	600	0	0.00%
RF22	Novas	600	0	0.00%	600	0	0.00%
WK07, WK08, WK25, WK28	Midknight / Delta	2400	0	0.00%	2400	0	0.00%
SV17, SV20, SV14, SV13, SV19B	Navelate	3000	6	0.20%	1200	6	0.50%
DD01, DD02, DD03, DD04, DD05	Cambria	3000	1	0.03%	600	3	0.50%
5, 6	Autumn Gold	1200	0	0.00%	600	1	0.17%
7	Palmer	600	4	0.67%	600	0	0.00%
9, 8	Palmer	1200	0	0.00%	600	1	0.17%

A significant positive regression was recorded between the percentage infestation in the packhouse delivery inspection and the percentage infestation in the retention sample (Figure 3.31).

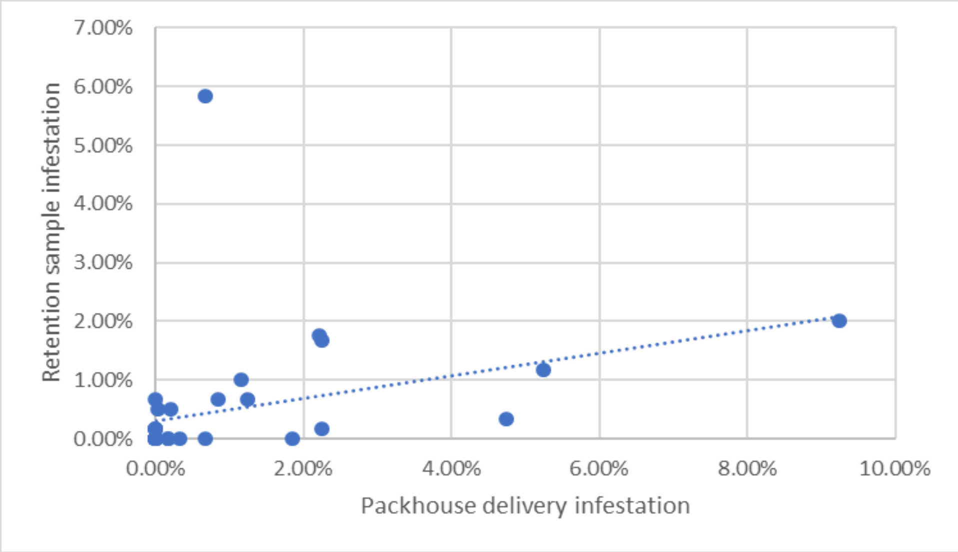


Figure 3.31. Percentage FCM infestation in packhouse delivery inspection and the percentage infestation in the retention sample. R^2 = 0.120760; F = 4.807127; Y = 0.003; P = 0.035081.

3.7. Discussion

The highest trap catches and levels of FCM infestation were recorded on the Navel cultivars, thus confirming that Navels are a preferred host for FCM. Almost no FCM catches and infestation were recorded in the Mandarins and Valencia orchards. Although a two-week lag between FCM infestation and trap catches in the orchard showed a significant regression, using data from all orchards, when conducted with individual orchards, only a single orchard recorded a significant positive regression. There was no significant regression between FCM infestation per week and the average weekly temperatures (°C), supporting Moore and Kirkman (2008). Unfortunately, no relationship could be established between FCM infestation and the orchard sanitation rating. This raises the question whether the orchard sanitation was poor in certain weeks due to FCM infestation or whether FCM infestation was high in certain weeks due to poor orchard sanitation. Sanitation is considered to be the cornerstone for successfully minimising the risk of FCM in orchards and should be seen as an integral step to manage FCM. A significant positive regression was recorded between the infested fruit per tree per week for the last 4 weeks before harvest and the percentage infestation in the packhouse delivery inspection (R^2 = 0.307625; F = 25.76961; Y = 0.0042; P = 0.000004). This confirms that preharvest infestation is a good indication of the risk of postharvest infestation. A significant positive regression was recorded between the percentage infestation in the packhouse delivery inspection and the percentage infestation in the retention sample (R^2 = 0.120760; F = 4.807127; Y = 0.003; P = 0.035081). The results showed that the infestation 4 weeks before harvest was a very good indicator for identifying high risk orchards or consignments at a preharvest level.

The orchards that recorded infestation during the last 4 weeks before harvest also recorded infestation at the packhouse delivery inspection. The packhouse delivery inspection infestation levels were a good indicator for identifying high risk orchards or consignments at a postharvest level. The level of infestation was reduced by as much as 93% in the retention sample. This proves that the packhouse could effectively identify and remove FCM infested fruit.

Chapter 4:

General Discussion

4.1. Introduction

The objective of this study was to determine whether an integrated management system or systems approach could reduce the risk of FCM infested citrus fruit from being packed for export, as the South African citrus industry is dependent on export of fresh fruit to various countries around the world (CGA, 2013). False codling moth, is recorded as a pest of citrus in southern Africa (Newton 1998; Grout & Moore 2015), and as a result of its endemism to sub-Saharan Africa (Moore, 2002), certain export markets of importance for the South African citrus industry, such as United States, People's Republic of China, and South Korea, regulate it as a quarantine pest (SA-DAFF, 2015). There are many export markets that require post-harvest treatment of fresh commodities for the control of phytosanitary organisms (Follett & Neven, 2006). The most commonly used phytosanitary risk mitigation measure is a stand-alone post-harvest treatment such as cold treatment (Paull & Armstrong 1994). There are however alternative options such as, multiple or combination treatments, non-host status, pest-free areas (PFAs), systems approaches, specially designed inspection schemes, and eradication programmes, that can also be used to prevent pest introductions (Follett & Neven 2006).

All of the alternative options can be (or have been or are being) considered for implementation, however, there are challenges associated with their use, which may even be prohibitive in nature. The non-host status for FCM can possibly be considered as a phytosanitary measure. NAPPO (2008) provided the following definitions: a conditional host may be a host or non-host depending on suitability of conditions (e.g. stage of maturity, other physiological conditions or physical conditions), whereas a natural non-host does not become infested in nature. NAPPO (2008) also determined host status from natural infestation by evaluating the infestation during the export harvest season should be a mandatory requirement in determining host status for phytosanitary purposes. Oranges, mandarins and grapefruit are considered hosts for FCM (Schwartz 1981; Van Den Berg 2001). However, it was established that different citrus types have different levels of susceptibility to FCM attack and infestation (Love *et al.* 2014). Certain cultivars of Navel oranges, have been reported to be highly susceptible to FCM infestation (Newton 1990; Love *et al.* 2014). Lemons have been demonstrated to be a non-host (Moore *et al.* 2015b), and although certain cultivars have been shown to be less susceptible than others, all citrus types other than lemons and limes are indeed hosts. Therefore, the use of non-host status as a phytosanitary measure is only useful for lemons and not other citrus types. Consequently, lemons have been considered non-hosts by the EU (EU regulation of 2017) and by China.

Pest Free Areas are officially established areas in which a target pest does not occur and the status is aimed at designated commodities from geographic areas on the basis of the absence of a specific pest (FAO, 1995). Citrus is produced in various regions in South Africa and FCM is present throughout the various areas, so there are no Pest Free Areas for FCM in South Africa. However, there are areas with low pest prevalence, and with the use of area-wide control strategies, such as Sterile Insect Technique and Mating Disruption, the declaration of pest free areas might be possible in future.

Mangan *et al.* (1998) suggested that a minimum pulp temperature of 44°C sustained for 100 minutes was sufficient to provide probit 9 mortality at 95% confidence levels of *Anastrepha ludens* in various citrus types. Unfortunately, this type of heat treatment would only be possible on heat tolerant cultivars such as grapefruit and Valencias. Myburgh (1965) did a study on a cold treatment for FCM where fruit had to be kept at a temperature below 0°C for 22 days. This treatment was found to be expensive, required extensive pre-shipping cooling infrastructure, and could potentially be detrimental to fruit quality due to certain citrus cultivars being highly susceptible to developing chilling injury (Lafuente *et al.* 2003; Lafuente & Zacarias, 2006; Cronje, 2007). However, stand-alone cold treatment is used very successfully to certain niche phytosanitary markets such as USA, China and South Korea, but it is impossible to implement it for the larger markets, such as the EU (which imports more than 40% of South Africa's citrus production), even if the more favourable time-temperature regimes demonstrated by Moore *et al.* (2017) to also be effective, were to be used instead. Due to the challenges associated with a stand-alone cold treatment, alternatives such as systems approaches had to be investigated (Follett & Neven 2006).

A systems approach is defined as the integration of pre- and post-harvest practices used in the production, harvesting, packing and distribution of a commodity, which cumulatively meet predetermined requirements for quarantine security (Jang & Moffitt, 1994). A systems approach should demonstrate that each step in the system reduces the risk of the pest in the commodity that will eventually be shipped. Factors such as host suitability and resistance to infestation (Greany, 1989), along with treatments which are designed to kill remaining pests that may be in the fruit, as well as the distribution of survivors and the likelihood of effective colonization in the receiving area should be considered. Various examples of systems approaches to achieving quarantine security have been published (e.g. Moffitt 1990; Curtis *et al*. 1991; Yokoyama *et al.* 1992; Hata *et al.* 1992; Vail *et al.* 1993; Grove *et al.* 2010; Moore *et al*. 2016).

A study was conducted between 1984 and 1986, to determine the incidence of codling moth in nectarines (Curtis *et al.* 1991). The study included the monitoring of traps in three orchards, the inspection of culled fruit and the inspection of fruit packed in cartons at various packhouses. Pheromone traps were placed in three nectarine orchards and were monitored for 1392 trap-nights. Only 22 codling moth males were trapped during this period (Curtis *et al.* 1991). Culled nectarine fruits were taken from five different packhouses and were examined for the presence of codling moth. Only one live, third instar was found in 37 908 culled nectarines (Curtis *et al.* 1991). Samples of the packed cartons were taken from three different packhouses and were also inspected for the presence of codling moth. Three live fourth instars were found in 326 625 packed nectarines. It was established that nectarine was not a significant host of codling moth (Curtis *et al.* 1991).

Hata *et al.* (1992) conducted a study where pest management before harvest and insecticidal dip after harvest was used as a systems approach to quarantine security for red ginger. Treatment plots were arranged, with four replicates. Each replicate contained 10 plots with approximately 75 plant stalks per plot (Hata *et al.* 1992). The study was divided into three groups: 1) insecticides only applied before harvest, 2) insecticidal dip after harvest and 3) insecticidal treatment before harvest and insecticidal dip after harvest. The flowers were treated and inspected for various quarantine pests. The flowers where insecticides were only applied before harvest, showed that the application of chlorpyrifos (50 DF and 20 MEC), could reduce the level of infested flowers, but not provide quarantine security. Insecticidal dip after harvest as a stand-alone treatment could also not provide quarantine security for all of the pests (Hata *et al.* 1992). The flowers, where insecticidal treatment before harvest and insecticidal dip after harvest were combined, demonstrated that 100% of all insect pest on red ginger were eliminated. It was found that the foliar application of an effective insecticide such as chlorpyrifos in combination with a 5-min + 20-stroke insecticide dip of fluvalinate and insecticidal soap after harvest should be used as a quarantine security for red ginger (Hata *et al.* 1992).

Grove *et al.* (2010) conducted a study to develop a systems approach for FCM on Hass avocado. Two orchards were identified in the Kiepersol area (Mpumalanga Province) and 11 orchards in the Tzaneen area (Limpopo Province) and one orchard in the Deerpark area (Limpopo Province). The FCM population levels in the orchards situated in the Kiepersol and Tzaneen areas were very low and there was a nonsignificant linear relationship between number of FCM captured and the infestation rate in fruit (Grove *et al.* 2010). The population levels in the Deerpark area were higher as well as the infestation levels. Although the majority of the eggs were laid in January, a very small percentage of the eggs were laid close to harvest (Grove *et al.* 2010). Only 0.029 lesions produced live larvae and fifth instars were only present in soft fruit. Fenpropathrin and a granulovirus were used as a control measure, and were effective in reducing infestation levels (Grove *et al.* 2010). The lesions caused by FCM were visible 2 weeks after infestation and these fruit was identified and remove 70-100% effectively. It was determined that Hass avacoado was a poor host of FCM and low infestation levels were recorded, making a systems approach a practical option. It was also established that a cold treatment for FCM should also form part of the systems approach (Grove *et al.* 2010).

More recently, Moore *et al.* (2016) conducted a study where 33 orchards (distributed in the Eastern Cape and Limpopo provinces), were monitored for FCM infestation during the course of the growing season, until harvesting and packing. The orchards in the Eastern Cape were Navel oranges and the orchards in Limpopo were Valencia oranges. The minimum compliance used in the system were: 1) a 4 week average of 0.2 infested fruit per tree per week up to 4 week prior to harvest, requiring additional controls if exceeded; 2) not more than a 4 week average of 0.2 infested fruit per tree per week during the last 4 weeks prior to or during harvest, resulting in disqualification of the orchard from the systems approach; 3) not more than 0.5% fruit infested on delivery to the packhouse if inspections were destructive (if fruit were cut) or 0.33% if inspections were non-destructive (superficial); 4) no infested fruit detected in a 2% sample taken from each pallet o fruit packed for export (Moore *et al.* 2016). A significant regression was recorded between FCM larval infestation of fruit preharvest during the full monitoring period and infestation during the final 4 weeks before harvest. Although there was no significant regression between FCM infestation of fruit during the full period of pre-harvest monitoring and infestation of harvested fruit on delivery to the packhouse, there was however a significant positive regression between pre-harvest infestation during the last 4 weeks before harvesting and infestation of fruit on delivery to the packhouse (Moore *et al.* 2016). There was a moderately strong significant positive regression between infestation of fruit on delivery to the packhouse and infestation of fruit packed for export. (Moore *et al.* 2016). Moore *et al.* (2016) determined that preharvest for the full period, 51.51% (17 out of 33) of orchards would have been noncompliant and would have required a mandatory control measure. During the last 4 weeks before harvest, 33.33% (11 out of 33) of the orchards were not compliant and would have been withdrawn from the systems approach. Of the remaining 22 orchards, 18.18% (4 out of 22) were noncompliant on delivery to the packhouse and would have been prohibited from being packed for export within the systems approach. Only, 16.67% (3 out of 18) of orchards were noncompliant when packed for export and would have been excluded from being exported under the systems approach. The improvement in the level of compliance with each successive step demonstrated the effectiveness of the system. The study reported in this thesis was based on commercial assessment of such a systems approach.

A systems approach is more difficult to manage than a post-harvest cold treatment or a pest free area seeing that the various components need to be monitored to ensure compliance (Liquido *et al*. 1995).

4.2. The relationship between preharvest orchard practices and FCM population levels

Tsuda and Hara (1990) established that field pest control was essential for the management of quarantine pests of red ginger such as mealy-bugs and cardamom thrips. In the current study, 25 orchards from Wicklow, Daisy Dell, Sackville, and Rietfontein followed the same preharvest control programme for FCM in 2017. Broadband (*Beauveria bassiana)* was applied in November/December 2016 and again in January 2017. The mating disruption product, Isomate (dodecenyl acetate) was applied in November 2016 at a density of 500 dispensers per ha and again in January 2017 at a density of 300 dispensers per ha, as per label instructions. The five orchards from Tortello and Sunset Farms followed a different preharvest control programme for FCM. Cryptex (Cryptophlebia leucotreta granulovirus), was applied in November 2016 and again in January 2017. Sterile moths were also released in these five orchards, at a density of 2000 moths per ha per week. Although the various orchards followed two completely different programmes for FCM, it was evident that the preharvest FCM infestation was highest on the Navel orange cultivars, regardless of the programme that was followed. The results from this study recorded negligible to no FCM infestation and FCM moth catches for the Mandarins and Valencias oranges in 2017. This is not unique to the cultivar, as Newton (1990) showed that Navel cultivars are a preferred host for FCM. The weekly FCM moth trap counts and FCM infestation, both fruit where a larva was found in the fruit (FCM “in”) and fruit where the larva had already exited the fruit (FCM “exited”), were recorded for both years. The results showed extremely high FCM infestation and moth catches during the 2017 season. These levels were the highest on the Navel cultivars, with certain orchards realizing infestation levels between 0.2 – 2.0 infested fruit per tree per week for the full period that the orchards were monitored. The Navel cultivars also recorded the highest moth catches, with certain orchards realizing catches between 0.5 – 4.0 moths per trap per week.

The orchards from Wicklow, Daisy Dell, Sackville, and Rietfontein followed a different preharvest control programme in 2018. Cryptex (Cryptophlebia leucotreta granulovirus), was applied in November 2017 and again in January 2018. The mating disruptor, Checkmate-FCM (dodecenyl acetate), was applied once a month between October 2017 and March 2018. Eco-Bb (*Beauveria bassiana)* was also applied on certain Navel cultivars in October 2017. The orchards from Tortello and Sunset Farms applied Cryptex (Cryptophlebia leucotreta granulovirus), in November 2017 and again in December 2017. Sterile moths were also released in these five orchards, at a density of 2000 moths per ha per week. The preharvest FCM infestation and moth catches were negligible for all 30 orchards in 2018, thus, indicating very low FCM presence in 2018. Both the infestation levels for the full period and the moth catches were extremely low in 2018. Only seven (six orchards of Navel cultivars and one orchard of Mandarins), of the 30 orchards recorded sporadic low levels of infestation and moth catches in 2018. The percentage of fruit with FCM in and the average temperatures were also monitored. FCM activity increases in the warmer months and decreases in autumn and the winter months, due to the colder temperatures (Catung *et al.* 1974). Although there were certain outliers, no relationship could be established between FCM infestation and average weekly temperatures. This confirms the research findings reported by Moore and Kirkman (2008). FCM infestation levels and orchard sanitation were also compared. Although the overall orchard sanitation was worse in 2017, due to higher levels of FCM activity, no relationship could be established between the level of sanitation in the orchards and the FCM infestation levels. The level of sanitation was much better in 2018, due to lower FCM activity. The question remains whether poor orchard sanitation led to higher FCM infestation or higher FCM infestation led to poor orchard sanitation. Regardless of which, it has been demonstrated that orchard sanitation is extremely effective in reducing FCM levels in an orchard (Moore & Kirkman, 2008).

4.3. The relationship between preharvest levels of FCM and infestation of fruit delivered to the packhouse

Curtis *et al.* (1991), identified that a sampling inspection procedure at the packhouse was necessary to determine codling moth infestation in nectarines which were destined for export. A packhouse survey which was conducted in 1990 showed that FCM caused 0.65% damage in avocado fruit (Dennill & Erasmus, 1991). Another survey which was conducted in the Nelspruit/Hazyview region during 1991 indicated that FCM was responsible for 1.32% damage of avocado (Erichsen & Schoeman, 1992). These levels are quite similar to the damage caused by FCM in citrus, as 0.42% damage was recorded (all citrus types, excluding lemons) by PPECB during the 2017 citrus season, which was also the main reason for rejections on packed fruit for export (PPECB, 2018). The pre-harvest FCM infestation for the last 4 weeks before harvest was used to determine the preharvest risk of each orchard. The level of FCM infestation in the packhouse delivery inspection was used to determine the risk of each orchard prior to packing. During the 2017 season, extremely high levels were recorded, especially on the Navel cultivars. Fourteen (all Navel cultivars), of the 30 orchards recorded preharvest infestation, of which eight orchards exceeded the threshold of 0.2 infested fruit per tree per week. Certain orchards realized levels as high as 0.6 infested fruit per tree per week. None of the Mandarins or Valencias recorded any infestation during the last 4 weeks before harvest. Again, the level of the pre-harvest infestation and the infestation in the packhouse delivery were negligible during the 2018 season. This study showed that there was a clear relationship between the pre-harvest infestation levels for the last 4 weeks before harvest and the infestation levels detected in the packhouse delivery inspection, as all of the orchards where FCM infestation was recorded prior to harvesting also had FCM infestation in the packhouse delivery inspection. The pre-harvest infestation levels could definitely be used as a method to predict high risk consignments before the fruit are delivered to the packhouse.

4.4. The relationship between FCM infestation of fruit delivered to the packhouse and fruit packed for export

There are numerous steps that citrus fruit are exposed to during packing, such as washing, grading, waxing and placement into cartons, which could have an impact on the external quality of the fruit. Washing, which requires a set of brushes combined with low or high-pressure water spray can cause enhanced water loss in the peel (Hagenmaier & Baker, 1993). Dropping of citrus fruit onto conveyors, which occurs on a packing line, can cause wounds and have an impact on the overall quality of the fruit (Eaks, 1961; Vines *et al.* 1968). Researchers have proposed using CO^2 emission as a physiological test to detect damage to citrus fruit following packing (Eaks, 1961; Parker *et al.* 1984). It is very important to monitor the quality of each consignment after the fruit have been packed. This sample is also referred to as a retention sample. The retention sample is also used to monitor any development of progressive and phytosanitary defects. The level of FCM infestation in the retention sample was compared with that in the packhouse delivery inspection. The highest FCM infestation was recorded in the Navel cultivar retention samples. All of the orchards in which infestation was recorded in the packhouse delivery inspection, also had infestation recorded in the retention sample. However, the infestation levels were substantially lower in the retention samples, thus showing that the packhouse could effectively identify and remove FCM infested fruit. Packhouses rely on people (referred to as graders or sorters), to remove phytosanitary defects such as FCM. Moore *et al.* (2016), demonstrated that 77.8% of infested fruit were externally detectable, currently far better than any electronic device can do. The majority of packhouses use electronic graders to do the final grading of the fruit. Until a few years ago, electronic graders could only grade fruit according to diameter, colour and shape. The technology has advanced over the last 5 years, which has resulted in electronic graders being able to grade fruit into various quality groups based on the external blemishes such as wind and thrips damage as well as internal quality such as the brix and acid levels. Although there is currently no technology available to effectively sort for FCM infestation in the packhouse, the level of technology has advanced dramatically over the last 10 years. The manufacturers of electronic graders are allocating a lot of time and money into research and development, in an attempt to successfully identify and remove phytosanitary defects such as FCM in the near future. Packhouses must however dedicate more time to pre-packing training for FCM for the graders working in the packhouse. Graders should also be trained and evaluated regularly throughout the packing season to ensure compliance. This study showed that high-risk consignments based on pre-harvest infestation levels could be identified prior to the fruit being delivered to the packhouse. The level of infestation in the packhouse delivery inspection could also be used as a method to determine whether such a consignment should be packed for a less sensitive market or whether it should be packed at a slower production speed in the packhouse, thus allowing the graders more time to sort more effectively for FCM infested fruit. This study showed that Navel cultivars are much more susceptible to FCM infestation than any other citrus cultivar, supporting the study of Love *et al.* (2014). With the highest infestation recorded on the early and mid-season Navels. This causes a major challenge for the South African industry, as Navel cultivars represent as much as 25 - 30% of the total volume exported from South Africa (CGA, 2017). This study showed that the preharvest infestation levels could be used as a method to predict infestation levels on consignments before being delivered to the packhouse. The packhouse delivery infestation levels could be used as a method to predict high-risk consignments at packing. These high-risk consignments should be considered for shipment at lower temperatures and possibly less sensitive export markets.

4.5. The way forward

FCM is such a complex pest and its presence in citrus orchards and fruit could have a devastating impact on the sustainability of the South African citrus industry. Various steps are required to successfully mitigate the risk associated with FCM. The source of the pest is in the orchard and good agricultural practices such as preharvest control measures should be adhered to. There are a number of registered products available to manage FCM in citrus orchards. These control programmes include inspection and monitoring, where pheromone lures are used to trap adult FCM, to determine FCM activity. It is of utmost importance that traps are placed in the correct position in the orchard and tree and at the right density of 1 trap per ha. The FCM infestation should also be monitored, which requires a set of five data trees in an orchard. The fruit lying underneath the trees should be removed on a weekly basis, and all fruit infested with FCM should be recorded. Any orchard that exceeds the threshold of 0.2 infested fruit per tree during the last 4 weeks before harvest, should receive an additional control measure. This study showed that these data were crucial in establishing the pre-harvest risk of orchards. Cultural control or orchard sanitation is considered the cornerstone for reducing FCM levels in orchards. Orchard sanitation should be conducted at least once per week, but ideally twice a week. Microbial control methods could be used in conjunction with other control measures to manage FCM levels in orchards. Mating disruption products could also be used to manage FCM population levels in orchards. The use of Sterile Insect Technique has grown over the last couple of years in the citrus industry and growers have achieved good results. The purpose of this study is not to be prescriptive regarding preharvest control measures. Citrus Research International has done a lot of research over the years and has setup guidelines to effectively manage FCM (Moore, 2017). These guidelines should be studied by growers and the optimal pre-harvest control programme should be implemented.

This study showed that the level of infestation 4 weeks before harvest was a very good indicator of the pre-harvest risk of fruit delivered to the packhouse. The pre-sorting of orchards during harvesting is also a very effective method to remove FCM infested fruit and should be considered a mandatory requirement. Orchards that exceeded the threshold of 0.2 infested fruit per tree per week during the last 4 weeks, also exceeded the threshold of 0.33% infested fruit in the packhouse delivery inspection. The infestation in the packhouse delivery inspection confirmed the risk status of the orchard. Some levels recorded were as high as 9.25% infested fruit in the packhouse delivery inspection. The fruit were packed and 600 fruit sample was taken of the fruit packed for export (referred to as the retention sample). The retention sample was stored at ambient temperature and was inspected on the day of packing and every week over a three-week period. All fruit infested with FCM during the four inspections were recorded. The levels of infestation were substantially lower in the retention sample in comparison with the packhouse delivery inspection, with certain levels being reduced by as much as 93%. The graders in the packhouse were able to effectively identify and remove FCM infested fruit. However, continuous training of graders must be considered a mandatory requirement to ensure compliance. The manufacturers of electronic sizers should continue to pursue various levels of technology to detect FCM infested fruit in the packhouse. *Agathis bishopi* (Nixon) (Hymenoptera: Braconidae), which is koinobiont larval endoparasoit of FCM (Ulyett, 1939), has recorded to parasitize up to 34% of larvae in fruit, and is considered a biocontrol potential for FCM (Gendall, 2007). However, Zimba *et al.* (2015), also indicated that *A. bishopi* female parasitoids were attracted to FCM induced volatiles, which could provide the basis for potential development of a chemical detection system using *Agathis bishopi* parasitoids for screening FCM infested fruit in the packhouse (Zimba *et al.* 2015), as could sniffer dogs.

In conclusion, this study demonstrates that the proposed integrated management system for FCM can be used to identify high-risk orchards prior to harvest, it can identify problem orchards once the fruit have been delivered to the packhouse and can also identify high-risk consignments after the fruit have been packed. High-risk consignments should be considered for lower shipping temperatures, based on the FCM infestation levels 4 weeks before harvest and the infestation in fruit delivered to the packhouse, to ultimately minimize the risk of FCM in citrus fruit exported and any live FCM larvae arriving in the market place. It is very important that all the components or control points in the integrated management system are implemented and managed properly to ensure the effectiveness and accuracy of the system.

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