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RESEARCH ARTICLE

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# The effect of permanent protective netting on insect pest prevalence in citrus orchards in South Africa

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*The use of protective netting is becoming an increasingly popular practice in the citrus industry in South Africa. However, data on its effects on biotic factors, particularly insect pests, are limited. This study focused on the effect nets have on key citrus pests in the Eastern Cape province. Orchards under nets and open orchards, of similar cultivars, ages and management practices, were monitored at several sites over two seasons for pest infestation and damage. Weekly monitoring was conducted for Thaumatotibia leucotreta infestation. Other pests were monitored either monthly or once a season. During the first season, T. leucotreta infestation was higher in orchards under nets, probably because, unlike the open orchards, the nets provided protection for the existing high levels of T. leucotreta. No T. leucotreta infestation was recorded in both orchard types in 2019. This was due to generally lower than usual pest abundance and dramatically improved area-wide management of T. leucotreta. Pheromone traps were used to monitor T. leucotreta males, including sterile moths used in a sterile insect technique programme. Although higher catches of wild T. leucotreta moths were recorded in orchards under nets, so too were there higher numbers of sterile moths and a higher ratio of sterile to wild moths, indicating the potential for better pest suppression for orchards under nets. Various other key pests were monitored during this time, with variable results for each species. Pests that were elevated under nets include Planococcus citri and Aonidiella aurantii. Pests that seemed to be lower under nets were Ceratitis capitata and Scirtothrips aurantii. Nets had no effect on Empoasca distinguenda, Penthimiola bella and Eriophyes sheldoni. These differences in pest levels in netted and open orchards trigger an important debate on whether nets are beneficial for or detrimental to the successful implementation of an integrated pest management programme.*

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## INTRODUCTION

Protective nets or exclusion barriers have been used in agriculture for pest suppression since the 1990s and their use is growing in popularity (Chouinard et al. 2016; Mahmood et al. 2018). The main purpose of the nets is to protect agricultural crops from sunburn, wind, hail and in some instances, insect pests (Shahak et al. 2009; Alaphilippe et al. 2009; Bastias et al. 2012). There are two types of netting methods that can be used to protect crops. The first method is complete exclusion netting, including tunnel and drape netting, where single rows in the orchard are covered with netting and the soil can be omitted from the enclosed area. These nets are then removed at harvest time. Complete exclusion netting has the lowest impact on the environment and covers the soil, preventing the pests from completing their life cycle. The second type of netting is full canopy or incomplete exclusion netting, where permanent structures are erected over the entire orchard. Incomplete exclusion netting requires less attention for maintenance and removal of structures, as they are permanent and are thus more cost effective over the long term. Incomplete exclusion netting also requires less overall labour once installed (Rigden 2008; Chouinard et al. 2016).

The majority of the literature on the use of netting in agriculture focuses on photo-selection, humidity, temperature and microclimate changes within nets (Shahak et al. 2009; Bastias et al. 2012; Mahmood et al. 2018; Marshall and Beers 2021). Limited data are available on the use and effect these nets have on insect dynamics, with much of this literature focused exclusively on *Cydia pomonella* (Linnaeus, 1758) (Lepidoptera: Tortricidae) in apple orchards (Alaphlippe et al. 2009; Sauphanor et al. 2012; Chouinard et al. 2016; Marshall and Beers 2021). Bastias et al. (2012) reported that the use of netting in organic orchards successfully reduced *C. pomonella* infestation. This research raised the question of whether the closely related key citrus pest, *Thaumatotibia leucotreta* (Meyrick, 1913) (Lepidoptera: Tortricidae), could similarly be excluded from citrus orchards through the use of netting, either temporarily or permanently, which was the primary purpose of our study. Furthermore, a sterile insect technique (SIT) programme is being implemented for *T. leucotreta* in citrus orchards in South Africa (Hofmeyr et al. 2005; Hofmeyr et al. 2016), including at our study sites. Consequently, it was considered equally important to determine the impact of netting on the efficacy of the SIT programme.

Citrus is host to a wide range of pests (Grout and Moore 2015). Some of the important pests, other than *T. leucotreta*, that were recorded in this study at our trial sites, included California red scale, *Aonidiella aurantii* (Maskell, 1879) (Hemiptera: Diaspididae), citrus mealybug, *Planococcus citri* (Risso, 1813) (Hemiptera: Pseudococcodae), citrus thrips, *Scirtothrips aurantii* (Faure, 1929) (Thysanoptera: Thripidae), Mediterranean fruit fly, *Ceratitis capitata* (Wiedemann, 1824) (Diptera: Tephritidae), citrus bud mite, *Eriophyes sheldoni* (Ewing, 1937) (Arachnida: Eriophyidae), green citrus leafhopper, *Empoasca distinguenda* (Paoli, 1932) (Hemiptera: Cicadellidae) and brown citrus leafhopper, *Penthimiola bella* (Stål, 1855) (Hemiptera: Cicadellidae) (Bedford et al. 1998). Consequently, in addition to *T. leucotreta*, we took the opportunity to assess the impact of nets on these other important pests.

The southern African citrus industry has a long history of the implementation of biological and integrated control, developing into the more sophisticated integrated pest management (IPM) approach in the 1970s (Bedford 1998; Grout and Moore 2015). Since the early 1990s, IPM has come under increased pressure, with fruit-importing countries becoming increasingly intolerant of infestation levels of pests and diseases posing phytosanitary risk (Grout and Moore 2015). Therefore, despite the simultaneous growth of market intolerance for chemical residues, there has ironically also been increased pressure for growers to use synthetic pesticides to control these organisms. Consequently, the impact of nets on the ability to implement IPM is a very pertinent question. Thus, the overall objective of this study was to determine what effect permanent nets have on various important citrus pests, including the ability to effectively implement an IPM programme, with the main focus on *T. leucotreta*.

## MATERIALS AND METHODS

Trials were conducted over two citrus growing seasons using 14 orchards located in the Sundays River Valley, Eastern Cape province (Table 1). Nets (Agri-Netting, The Co-op, Humansdorp, South Africa) with a mesh size of 2 × 2 mm on the top and 1 × 1 mm on the side, providing 20% shading on top and 40% shading on the sides (standards according to Agri-Netting) (Figure 1). The mesh size and percentage shading of the nets is not a regulated standard, but an individual choice, based on tree size, cultivar and production needs (Chouinard et al. 2016). Nets were erected over mature orchards at the end of the 2017 citrus harvesting season, after all fruit were removed from the trees, following the incomplete exclusion netting system.

Selection of orchards over which to place permanent netting structures, was made by the growers, pest management aspects did not play a role in these selections. Growers' decisions were based on horticultural factors, such as yield and improvement of fruit quality. As the profitability of Navel oranges is marginal, the erection of nets was considered to potentially improve this. Pest pressure had no effect. Monitoring of trial sites were then initiated in the first week of January 2018. Seven orchards under nets and seven open orchards were randomly selected with the precondition that similar cultivars were used (for this trial, all fruit analysed were navel oranges) (Figure 2). Pest control practices for all orchards were identical, following conventional control programmes, as all orchards used were managed by the same grower, albeit on different farms. These orchards were monitored for key citrus pests at weekly intervals for a 27-week period.

### Temperature and humidity

Temperature and humidity were monitored for orchards under nets and open orchards. In all orchards monitored, a single DS1923L-F5 Maxim Temperature and Humidity iButton (Cold Chain Thermodynamics Software, Fairbridge Technologies, Gauteng, South Africa) was placed in the tenth tree in the fifth row, on a branch under the canopy and close to the trunk. The iButtons recorded the temperature and humidity at hourly intervals for the duration of the study.

Temperature data were converted into effective heat units (EHU) for comparison between orchards under nets and open orchards, using the below formula (Hardy and Khurshid 2007). Effective heat units are used to determine the suitability of the

**Table 1:** Details of the citrus orchards monitored for the study in the Sundays River Valley, Eastern Cape province.

| Cultivar | Net | Orchard number | Co-ordinates | Area (ha) |
|---|---|---|---|---|
| Cambria Navel | Under nets | 18 | 33°37′26.25″S 25°41′21.11″E | 1.17 |
| | | 22 | 33°37′31.75″S 25°41′23.05″E | 1.13 |
| | | 24 | 33°37′33.28″S 25°41′17.85″E | 1.1 |
| | Open | 1 | 33°37′36.17″S 25°41′1.20″E | 5.43 |
| | | 2 | 33°37′41.97″S 25°40′55.46″E | 6.1 |
| | | 3 | 33°37′40.66″S 25°41′9.04″E | 5.22 |
| Washington Navel | Under nets | 54 | 33°26′22.19″S 25°31′38.06″E | 1 |
| | | 52 | 33°26′26.40″S 25°31′41.73″E | 1.13 |
| | Open | 47A | 33°26′22.45″S 25°31′45.33″E | 1 |
| | | 47B | 33°26′22.36″S 25°31′46.86″E | 1 |
| Newhall Navel | Under nets | 23 B | 33°26′32.42″S 25°29′38.45″E | 2 |
| | | 23 A | 33°26′30.42″S 25°29′32.16″E | 2 |
| Fukumoto Navel | Open | 22 B | 33°26′26.77″S 25°29′40.06″E | 1.38 |
| | | 22 A | 33°26′26.03″S 25°29′33.40″E | 1.48 |

**Figure 1:** One of the netted orchards used in this study

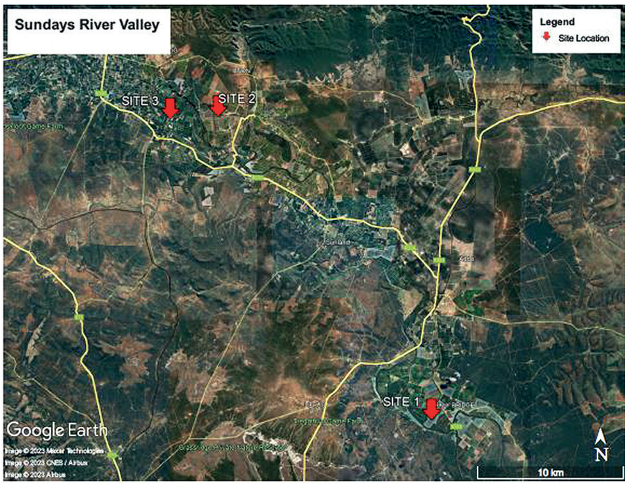


**Figure 2:** Study sites located throughout the Sundays River Valley, Eastern Cape

area for citrus production. The ideal growth range for citrus is between 13 and 35 °C. The number of hours spent within this temperature range is calculated as EHU (Hardy and Khurshid 2021):

- EHU = (Monthly average – 13 °C) × days in the month (13 °C is used as it is the crop threshold for citrus).

The vapour pressure deficit (VPD) was calculated using the following formula (Grossiord et al. 2020; Allen et al. 1998):

- Saturation vapour pressure ($e_{sat}$) = 0.6108 × Exp (17.5028 × Temperature (°C) / (Temperature (°C) + 240.97)
- Actual vapour pressure ($e_a$) = Relative humidity / 100 × $e_{sat}$
- Vapour pressure deficit (kPa) = $e_{sat} - e_a$ ($e_{sat}$: saturation vapour pressure; $e_a$: actual vapour pressure)

## Monitoring of false codling moth

### *Fruit infestation*

*Thaumatotibia leucotreta* infestation of fruit was monitored on 10 data trees in each orchard. Data trees were selected in the middle of each orchard. Fallen fruit were collected separately from each of these data trees weekly until harvest. Each tree's fallen fruit were analysed separately. Infestation was recorded by dissecting fruit with a sharp knife and determining the presence of *T. leucotreta* larvae, or signs of tunnelling and frass within the fruit, indicative of the larva having exited (Moore et al. 2015). This method of monitoring is considered to be highly accurate and unbiased, as all *T. leucotreta* infested fruit do drop from the tree and thus no data are lost (Moore et al. 2015). Monitoring continued until harvest for both seasons.

### *Moth population*

Population levels were monitored by trapping *T. leucotreta* male moths, using yellow Delta traps with a sticky floor and pheromone lure (Chempac FCM lure; Chempac (Pty) Ltd, South Paarl, South Africa). A single trap was placed in each orchard under nets and in the open. Traps were placed in the 10th tree in the fifth row of the orchard on the upwind side of the orchard (Moore 2022). These traps were also used to monitor recaptures of released sterile moths, where SIT was implemented, which was only in two netted and two open orchards. Sterile moths were differentiated from wild moths by squashing the moth abdomen and noting any pink colour, due to the addition of Calco Oil Red® (Royce International, Sarasota, Florida, USA) to the larval artificial diet (Hofmeyr et al. 2015). Trap catches were also used to determine the ratio of sterile to wild catches and compared to the recommended minimum overflooding ratio of 10 sterile to 1 wild moth (Hofmeyr et al. 2005).

## Monitoring of fruit fly

*Ceratitis capitata* populations were only monitored for one season. This was done by placing a single Sensus trap with Capilure® (River Bioscience, Pty Ltd, South Africa) and a Sensus trap with Questlure® (River Bioscience, Pty Ltd, South Africa) in each orchard. Capilure® (trimedlure) is a mixture of isomers used to attract male *Ceratitis* spp., whereas Questlure® is primarily a protein-hydrolysate attractant, particularly for female *Ceratitis* spp. The Sensus traps contained a dichlorvos tablet that killed the adult flies once they entered the trap. The trapping systems and method of monitoring were chosen as they follow the industry guidelines for citrus production in South Africa (Manrakhan 2023). Traps were placed in the same row as the 10 data trees used for the fallen fruit analysis. The Capilure® trap was placed 5 trees before the first data tree and the Questlure® trap was placed 5 trees after the 10th data tree. These traps were placed in the orchard 6 weeks before harvest. Traps were examined and emptied weekly and the numbers of *C. capitata* males and females were counted and recorded.

## Monitoring for other key citrus pests

Monitoring for *A. aurantii*, *P. citri* and *S. aurantii* infestation and/or damage was conducted as a once-off inspection at the end of each season. The same 10 data trees that were used to collect fallen fruit for *T. leucotreta* infestation assessments were used to scout for these three key pests. Ten (10) fruit on either side of each of the data trees were examined for the presence or absence of the pests (Grout 2019).

During the second season, while scouting for the three key pests, an increased level of leafhopper damage was observed as chlorotic yellow marks on the fruit (Moore 2013). Consequently, a once-off scout was conducted for leafhopper damage, again using the same 10 data trees. Ten fruit on either side of each tree were examined for leafhopper damage. Furthermore, adult *E. distinguenda* and *P. bella* were also monitored by placing three Chempac Yellow Sticky Traps (Chempac®, Paarl, South Africa) diagonally across all orchards. Traps were retrieved after 7 days. The number of *E. distinguenda* and *P. bella* were recorded (Moore 2013).

A once-off assessment for *E. sheldoni*-damaged fruit was also conducted during the second season, as symptoms of damage to fruit were observed while conducting the weekly monitoring for other pests. Again, using the same 10 data trees, 10 fruit were selected and examined for the characteristic symptoms of *E. sheldoni* damage, which included ridging from the calyx end of the fruit, flattening and general malformation of fruit and a protruding navel-end (Grout and Moore 2015).

## Monitoring for predatory mites and spiders

*Euseius addoensis*, which is the main predator of *S. aurantii* in the Eastern Cape region (Grout and Richards 1992a), was scouted once at the end of the second season. This was done to determine whether differences in the abundance of *E. addoensis* was the likely cause of the lower level of *S. aurantii* damage recorded under nets. The same 10 data trees were used for scouting. All life stages of *E. addoensis* were counted on 10 horizontally opposed leaves, 30 to 50 cm inside the tree canopy. This was repeated on each of the 10 data trees (Grout and Richards 1992a).

While scouting for the various pests, a higher occurrence of spiders, nesting amongst fruit, was noted under nets than in open orchards. Consequently, a once-off scout for spiders was conducted. Again, the same 10 data trees were used. Ten fruit on either side of the tree were examined for the presence of spiders. Samples of spiders were collected, placed in ethanol and sent for morphological identification by Charles Haddad at the University of the Free State, Bloemfontein, South Africa.

## Statistical analysis

To assess whether pest and predator abundances differed between the netted and open orchards (netted orchards $n = 7$ and open orchards $n = 7$), a series of generalised linear mixed models (GLMM) (Bolker et al. 2009; Brooks et al. 2017) was specified. The same models were used to assess differences between EHU and VPD, however, the log of EHU was used. Pest and predator counts were summed and collected as described above and were modelled as a linear function of the netting treatment applied, which was specified as a categorical fixed effect with two levels (netted versus open). Orchard was modelled as a random intercept term to account for the repeated samples taken in different weeks from each orchard. Where data were available for multiple years, these data were combined and analysed together as we were not interested in differences between years, *per se*, and data were not available for enough years to allow us to model year as a random effect. Models were specified using a Poisson distribution and a log-link distribution, unless overdispersion was encountered, whereby a negative binomial distribution was specified. Overdispersion and model fits were assessed using residual analysis from the R package 'DHARMa' (Hartig 2021). To test whether pest/predator abundances differed between netted and open orchards, Wald's Chi-Square Tests were used for all models, other than the fruit fly model due to the zero counts in one treatment group, which required the use of a Likelihood Ratio Test (LRT) ($p < 0.05$). All GLMMs were specified using the 'lme4' R package (Bates et al. 2015), except for the negative binomial GLMMs, which were specified using the 'glmmTMB' R package (Brooks et al. 2017). All statistical analyses were performed in R ver. 4.2.0 (R Core Team 2022).

# RESULTS

## Temperature and humidity

Effective heat units for each month were calculated from the temperature recordings. The mean temperature measurement from October to May for both seasons under nets was 352.67 ± 35.84 EHU (mean ± SE) and in open orchards was 428.22 ± 47.24 EHU (mean ± SE). The temperatures under nets and in open orchards were not significantly different. (Wald chi-square $\chi^2 = 0.7608$, df = 1, $p > 0.3831$).

The RH data were converted to VPD to compare orchards under nets and in the open. The mean humidity measurement from October to May for both seasons under nets was 0.35 ± 0.05 kPa (mean ± SE) and in open orchards was 0.29 ± 0.06 kPa (mean ± SE). The difference in vapour pressure deficit (VPD) between trees under nets and in open orchards was not significant (Wald chi-square $\chi^2 = 0.5302$, df = 1, $p > 0.4665$).

## Monitoring of *T. leucotreta*

During the first season, *T. leucotreta* infestation of fruit was higher in orchards under nets, with an average of 1.31 ± 0.28 (mean ± SE) infested fruit per week per tree compared to open orchards with an average of 0.20 ± 0.05 (mean ± SE) infested fruit per week per tree (Wald chi-square $\chi^2 = 22.21$, df = 1, $p < 0.001$), when averaged across orchards. Given the extremely low presence of *T. leucotreta* at the trial sites during the second season, no infested fruit was recorded, neither in orchards under nets nor in open orchards.

During the first season, the number of wild moths trapped in orchards under nets was also higher than in open orchards. However, so too were sterile moth recaptures under nets higher than in open orchards. The ratio of sterile to wild moths under nets was 9.5:1 and in open orchards was 6:1 (Figure 3). The higher sterile moth recaptures and hence higher sterile to wild moth ratios under nets would result in a greater efficacy of the SIT programme.

During the second season, a much higher ratio of sterile to wild moths was recorded. It must be noted that the wild moth population during this season was extremely low for the whole

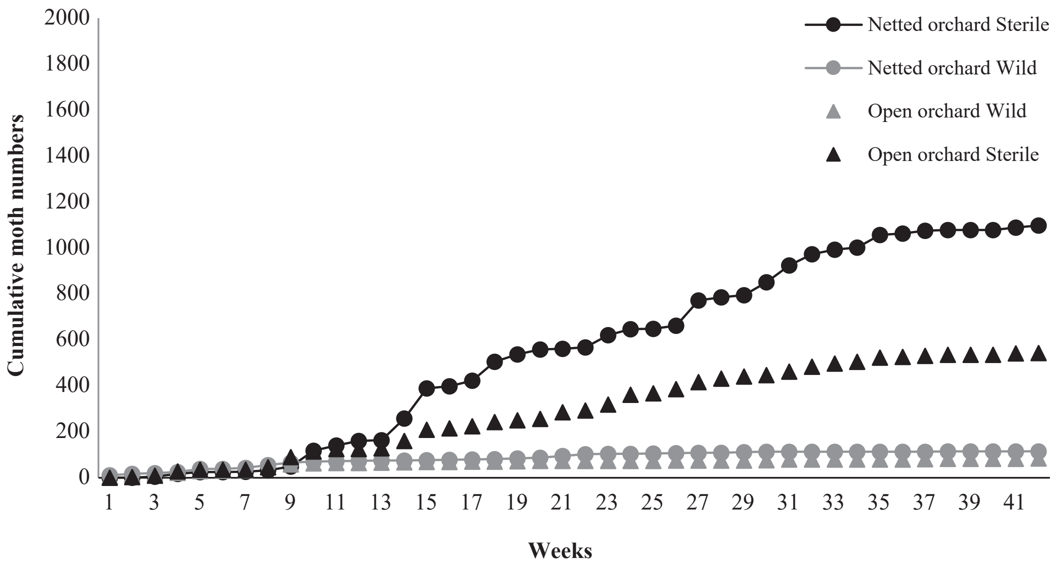


**Figure 3:** Mean cumulative numbers of sterile and wild *Thaumatotibia leucotreta* moth catches in orchards under nets and in open orchards for the two sites in the Sundays River Valley, where SIT was conducted in 2018 (Sterile: *t*-test = 7.98, $p = 0.0001$; Wild: *t*-test = 10.79, $p = 0.0001$).

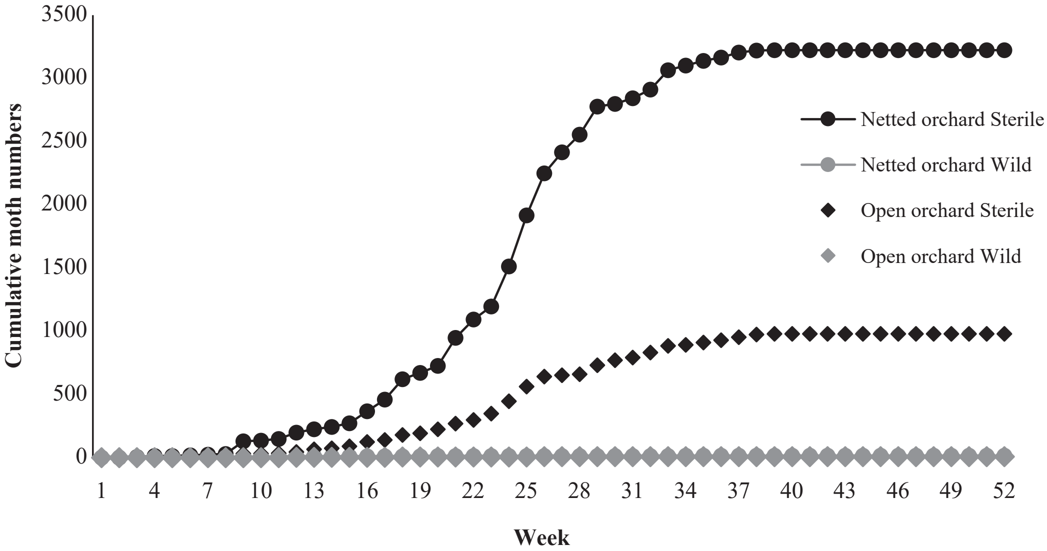


**Figure 4:** Mean cumulative numbers of sterile and wild *Thaumatotibia leucotreta* moth catches under nets and in open orchards for the two sites in the Sundays River Valley where SIT was conducted in 2019 (Sterile: *t*-test = *p* = 0.0001; Wild: *p* = 0.0001).

of Sundays River Valley. The ratio of sterile to wild moths under nets was 215:1 and in open orchards was 140:1 (Figure 4).

Overall, for both seasons, a significantly higher number of *T. leucotreta* moths were captured in netted orchards compared to open orchards (Wald chi-square $\chi^2$ = 112.83, df = 1, $p <$ 0.001). A significantly higher number of sterile moths were also recaptured in netted orchards (Wald chi-square $\chi^2$ = 55.179, df = 1, $p < 0.001$)

### Monitoring of *Ceratitis capitata*

*Ceratitis capitata* abundance was significantly higher in open orchards than in netted orchards (LRT $\chi^2$ = 35.20, df = 1, $p <$ 0.001). No *C. capitata* were captured in Sensus traps in netted orchards, while 2.75 ± 0.68 (mean ± SE) flies were counted per trap in open orchards.

### Monitoring for other citrus pests

*Aonidiella aurantii* infestation was significantly higher under nets over the two-year period (Wald chi-square $\chi^2$ = 24.20, df = 1, $p < 0.001$). The mean percentage of fruit infested per tree with *A. aurantii* was 1.61 % (0.23 ± 0.04 (mean ± SE) fruit infested per tree) in open orchards and 3.72 % (0.84 ± 0.11 (mean ± SE) fruit infested per tree) in orchards under nets. *Planococcus citri* was also significantly higher in netted orchards than open orchards (Wald chi-square $\chi^2$ = 10.04, df = 1, $p$ = 0.002). The mean percentage fruit infested per tree with *P. citri* was 4.11 % (0.31 ± 0.07 (mean ± SE) fruit infested per tree) in open orchards and 6.44% (0.61 ± 0.099 (mean ± SE) fruit infested per tree) in netted orchards (Figure 5).

There was no difference in *S. aurantii* infestation between netted and open orchards (Wald chi-square $\chi^2$ = 3.31, df = 1, $p$ = 0.069). The mean percentage fruit infested per tree by *S. aurantii* was 14.56% (0.01 ± 0.01 (mean ± SE) fruit infested) in open orchards and 2.22% (0.10 ± 0.03 (mean ± SE) fruit infested) in orchards under nets. However, *S. aurantii* damage was significantly higher in open than netted orchards (Wald chi-square $\chi^2$ = 44.53, df = 1, $P < 0.001$). The mean percentage fruit damaged per tree by *S. aurantii* was 10.71% (1.06 ± 0.11 (mean ± SE) damaged fruit per tree) in open orchards and 3.71 % (0.30 ± 0.06 (mean ± SE) damaged fruit per tree) in orchards under nets (Figure 6).

*Eriophyes sheldoni* damage was significantly higher under nets (Wald chi-square $\chi^2$ = 5.14, df = 1, $p$ = 0.023 > 0.01). The mean percentage *E. sheldoni* damaged fruit per tree was 17.51 % (1.76 ±

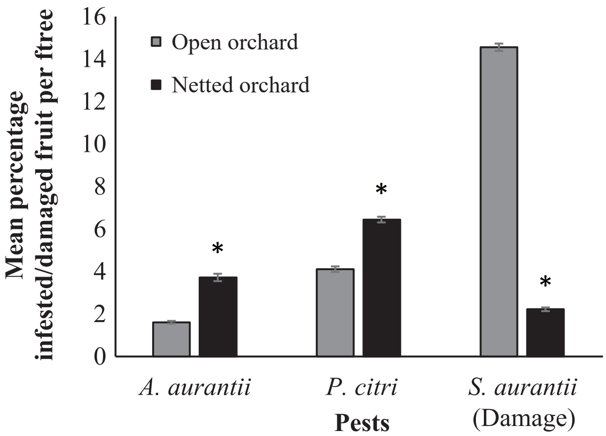


**Figure 5:** Mean percentage fruit per tree infested with *Aonidiella aurantii* (*n* = 200) and *Planococcus citri* (*n* = 100), and damaged by ***Scirtothrips aurantii*** (*n* = 100) for all orchards (netted and open) in the Sundays River Valley, monitored shortly before harvest in 2018. (* indicates a significant difference (*p* < 0.05) between orchards under nets and open orchards).

0.25 (mean ± SE) damaged fruit per tree) in netted orchards and 12.86% (1.29 ± 0.18 (mean ± SE) damaged fruit per tree) in open orchards.

*Empoasca distinguenda* numbers were significantly higher in open orchards (Wald chi-square $\chi^2$ = 32.75, df = 1, $p > 0.001$). The mean number of *E. distinguenda* caught per yellow sticky trap in open orchards was 169.83 ± 78.01 (mean ± SE) and under nets was 435.00 ± 205.73 (mean ± SE). *Penthimiola bella* trap catches did not differ significantly between open orchards and under nets (Wald chi-square $\chi^2$ = 0.93, df = 1, $p$ = 0.336). The mean number of *P. bella* captured on yellow sticky traps in open orchards was 65.17 ± 63.17 (mean ± SE) and under nets were 69.43 ± 50.74 (mean ± SE). No differentiation could be made between damage to fruit caused by *E. distinguenda* and *P. bella*. As such, leafhopper damage was analysed for both leafhopper species combined. The mean percentage of leafhopper-damaged fruit per tree was recorded to be 25% (2.5 ± 0.25 (mean ± SE) damaged fruit per tree) in open orchards and 23.14% (2.31 ± 0.23 (mean ± SE) damaged fruit per tree) under nets. There was no significant difference in the level of leaf hopper damage to fruit between netted and open orchards (Wald chi-square $\chi^2$ = 0.522, df = 1, $p > 0.05$).

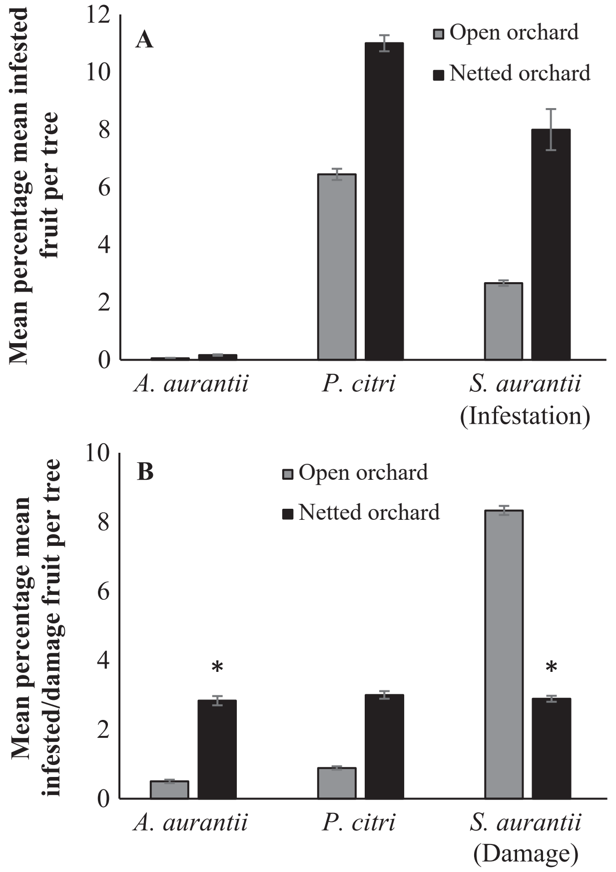


**Figure 6:** A. Mean percentage infested fruit per tree for ***Aonidiella aurantii*** (***n*** = 200), *Planococcus citri* (*n* = 100) and *Scirtothrips aurantii* (*n* = 100) in February 2019. B. Mean percentage infested fruit per tree for ***A. aurantii*** (***n*** = 200) and *P. citri* (*n* = 100) and mean percentage damaged fruit per tree for *S. aurantii* in May 2019. Results combined for all sites monitored in Sundays River Valley. Significant differences between orchards under nets and open orchards are indicated by * (***p*** < 0.05).

### Monitoring for natural enemies

As higher infestation of *S. aurantii* was recorded under nets in the beginning of the season, but higher levels of damage were recorded in open orchards towards the end of the season, it was considered prudent to evaluate the occurrence of its natural enemy, the predatory mite, *Euseius addoensis* (McMurtry) (Acari: Phytoseiidae) and of spiders, which are also considered to be thrips predators (Dippenaar-Schoeman et al. 2013). *Euseius addoensis* occurrence was significantly higher in orchards under nets (Wald chi-square test $\chi^2 = 34.45$, df = 1, $p < 0.001$). The mean number of *E. addoensis* per leaf was 0.70 ± 0.05 (mean ± SE) under nets and 0.37 ± 0.04 (mean ± SE) in open orchards.

The abundance of spiders was significantly higher under nets than in open orchards (Wald chi-square $\chi^2 = 6.5$, df = 1, $p < 0.011$). The mean number of spiders found per tree under nets was 0.46 ± 0.10 (mean ± SE) and in open orchards was 0.03 ± 0.03 (mean ± SE). Specimens were collected and morphologically identified as *Badumna longinqua* (Koch 1867) (Desidae: Araneae) and *Chresiona invalida* (Simon, 1898) (Araneae: Amaurobiidae). *Badumna longinqua* is an introduced species from Australia and *C. invalida* is endemic to South Africa (Simó et al. 2015; Haddad and Vink 2016) (Figure 7).

## DISCUSSION

The use of permanent protective netting in the South African citrus industry is a relatively new practice. Protective nets are used to help shield the trees and their fruit against damage caused by wind, hail and solar radiation (Mupambi et al. 2018). Studies have shown that in warmer regions, nets help to reduce damage to fruit caused by high temperatures and solar radiation, and furthermore improves water usage efficiency. In cooler areas, nets protect against crop loss from wind, hail and torrential rain (Manja and Aoun 2019). Growers in the Sundays River Valley have indeed experienced some of these benefits. Growers have reported an increase in export percentages and income, with more uniform fruit colour and size, making picking and packing easier. The concept of using nets to create a physical barrier, and preventing insect pests from coming into contact with the crop is under investigation (e.g. Chouinard et al. 2016). However, limited data are available on what effect nets have on the citrus pest complex. The main focus of our study was to investigate the effect that nets had on *T. leucotreta*. Simultaneously, we took the opportunity to monitor the occurrence of several other key pests present in the orchards.

The main focus was to determine whether the nets could reduce *T. leucotreta* levels and whether temporary eradication of this pest was possible. Effective control of *T. leucotreta* is imperative, due to its phytosanitary status for certain export markets and potential yield losses (Moore 2021; Moore 2022). Contrary to expectation, *T. leucotreta* infestation was recorded to be higher in orchards under nets than in open orchards, particularly in the first season of monitoring. The higher *T. leucotreta* infestation

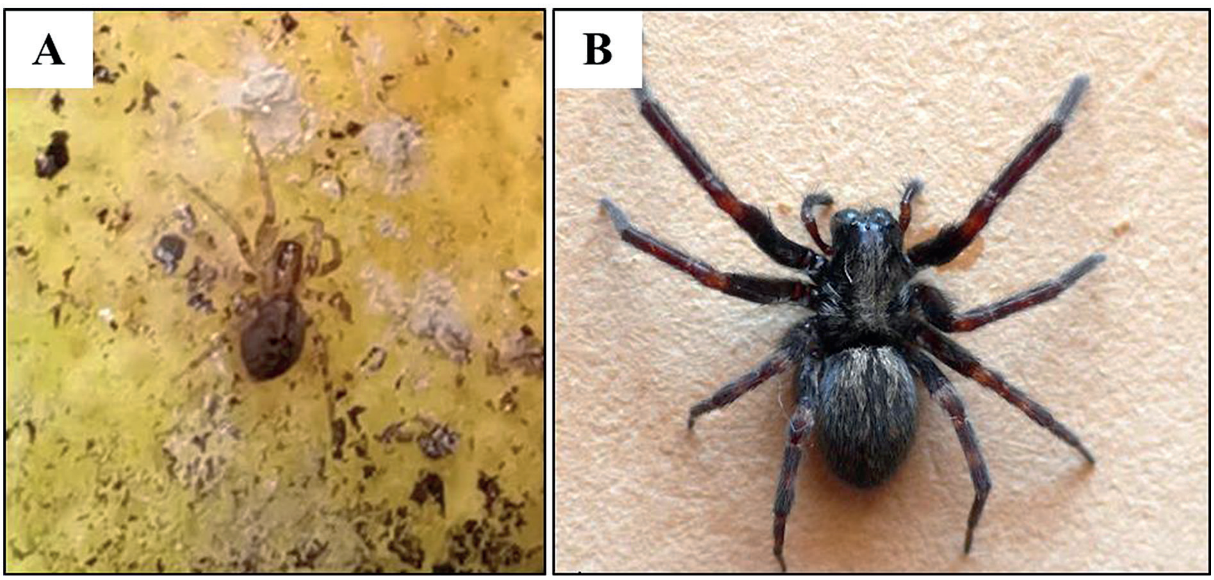


**Figure 7:** The two species of spider recorded in orchards under nets and in open orchards. (A): *Chresiona invalida* and (B): *Badumna longinqua.*

under nets during that season was likely due to the nets having been erected over mature orchards which had experienced high *T. leucotreta* population levels during the previous season, before netting, as reported to us by the grower. Another possibility is that the nets created a more favourable environment, preventing moths from dispersing and protecting them from predators. Even though there was no significant difference in temperature and humidity data, thus little abiotic differences, the effects on *T. leucotreta* could have been biotic. This situation may be reversed in the future, as moths under the nets are effectively controlled and wild moths are restricted from entering netted orchards. This might also mean that if nets are erected over newly planted orchards, *T. leucotreta* levels may well be lower under nets. No literature is available on the effect nets have on *T. leucotreta*, as this is the first study reporting such findings. Several studies have been conducted with *C. pomonella*, however, the opposite effect was observed, whereby *C. pomonella* levels were reduced inside nets compared to open orchards (Alaphlippe et al. 2009; Marshall and Beers 2021).

Furthermore, early indications, from both seasons, are that SIT may be more effective under nets than in open orchards. Recaptures of sterile moths were higher under nets, indicating that the ratio of sterile to wild moth ratios was higher under nets. During the first season of the study, sterile to wild ratios were well below the targeted minimum overflooding ratio of 10:1 (Hofmeyr et al. 2015) in open orchards, but very close to 10:1 in orchards under nets. During the second season, the ratio of sterile to wild moths increased dramatically, with a ratio of over 200 sterile moths to 1 wild moth for both orchards under nets and open orchards. Consequently, if this trend of higher sterile moth activity under nets continues, SIT is likely to prove more effective under nets over time, eventually reducing fruit infestation to a lower level under nets.

It was not possible to confirm this during the second season, as *T. leucotreta* levels were dramatically reduced, due largely to improvement in management practices in the region as a whole, in response to the regulation of *T. leucotreta* as a phytosanitary pest by the European Union (Moore 2021), and thus no fruit infestation was recorded in either environment.

Pests that were significantly elevated under nets were *A. aurantii* and *P. citri*. Various studies have reported an increase in population numbers of small insects under nets for apple and pear crops. These insects include rosy apple aphid, *Dysaphis plantaginea* (Passerini, 1860) (Hemiptera: Aphidae), woolly apple aphid, *Eriosoma lanigerum* (Hausmann, 1802) (Hemiptera: Aphidae), summer fruit tortrix, *Adoxophyes orana* (Fischer von Röslerstamm, 1834) (Lepidoptera: Tortricidae) and apple aphid, *Aphis pomi* (de Geer, 1773) (Hemiptera: Aphidae) (Alaphilippe et al. 2016; Manja and Aoun 2019). It was speculated that the increase in the population numbers of these species could be due to the increased temperature and humidity under nets, albeit a statistically insignificant increase, and the exclusion of natural enemies (Manja & Aoun 2019).

Pests that appeared to not be significantly affected by nets include *E. sheldoni, E. distinguenda* and *P. bella*. The factors associated with netting that led to the elevation or suppression of other pests did not have the same effect on these three-pest species.

Nets were recorded to effectively reduce *C. capitata* levels, as no flies were captured under nets. This is in accordance with other studies where netting was found to be highly effective against *Bactrocera* spp. for stone fruit (Lloyd et al. 2005). A study by Candian et al. (2020) found that nets successfully excluded spotted wing drosophila, *Drosophila suzukii* (Matsumura, 1931) (Diptera: Drosophilidae) and that this may not necessarily be due to the physical barrier created by the net, but because of photo selection, causing optical disruption and preventing the flies from finding the host crop (Candian et al. 2020).

Nets also seemed to have a positive effect on *S. aurantii* management. In two successive seasons, fruit damage caused by *S. aurantii* was significantly lower in orchards under nets. The significantly reduced damage under nets could have been due to the higher incidence of the predatory mite, *E. addoensis*, under nets, and possibly also the greater abundance of spiders under nets. It would be necessary to monitor both pest and natural enemy levels at frequent intervals throughout the season in order to establish whether this relationship was indeed the cause of the reduced damage under nets. *Euseius addoensis* has been shown to be an extremely effective predator of *S. aurantii*. Grout and Richards (1992a) demonstrated that *E. addoensis* was particularly effective in reducing *S. aurantii* damage to fruit to less than 1% cull for export, when there was an average of more than one predatory mite per leaf. In this study, we recorded an average of 0.7 mites per leaf under nets, which although lower than the levels previously reported by Grout and Richards (1992a), was significantly higher than levels recorded in open orchards and highly likely to have resulted in at least some reduction in *S. aurantii* damage. However, reduced damage may not be solely explained by the direct effects of predation but potentially also indirectly, as a result of a non-consumptive effect (NCE).

Non-consumptive effects are often observed between generalist pests, such as mites and spiders and their potential prey (Jandricic et al. 2016). The presence of generalist predators may cause a shift in life history traits, morphology and behaviour of the prey. This, in return, may result in reduced damage (Rypstra and Buddle 2013; Jandricic et al. 2016). Jandricic et al. (2016) showed that the mere presence of predatory mites in a greenhouse reduced the survival of thrips larvae, thereby reducing damage caused to the various plant species by 37–50%. A similar outcome was observed by Walzer and Schausberger, (2009), where the sole presence of predatory mite eggs increased mortality and decreased oviposition of thrips. Similar observations were observed between the presence of spider silks or webs. Rypstra and Buddle (2013) tested various combinations of silkworm silk and spider silk against two beetle species causing severe damage to green bean plants. Herbivory and subsequently plant damage were reduced most effectively in treatments where spider silk was used as an indicator of spider presence (Rypstra and Buddle 2013). This phenomenon has been investigated for *S. aurantii* and *E. addoensis* in a preliminary study, indicating increased movement by *S. aurantii* in the presence of *E. addoensis*, live or squashed (Ben Miller, unpublished data). An expansion of the study is thus warranted.

Other natural enemies that were shown to occur in higher numbers under nets were the two-spider species, *B. longinqua* and *C. invalida*. Both species belong to the family Araneidae. This is the first record of *B. longinqua*, introduced from Australia, being associated with an agricultural ecosystem in South Africa (Charles Haddad, pers. comm). Spiders are known to be very common in agroecosystems in South Africa and can be incorporated into the natural enemy complex as generalist predators. Although spiders may not control major outbreaks of pests, they can regulate low density pest populations, potentially keeping them below economic threshold levels (Dippenaar-Schoeman et al. 2013). Numerous spider species have been recorded in citrus in South Africa and other countries. A two-year study completed in Mpumalanga found 3 054 spiders, consisting of 21 families and 18 species. Several of these spider species were recorded preying on another citrus pest, *Trioza erytreae* (Del Guercio, 1918) (Hemiptera: Triozidae), and were thus considered to be important natural enemies of this pest. As generalist predators, they could well also be playing a role in suppressing *S. aurantii* populations under nets (Carroll 1980; Haddad 2003; Dippenaar-Schoeman et al. 2013; Marsberg et al. 2021).

Although temperature and humidity did not differ significantly under nets, relative to open orchards, the changes recorded could perhaps be biologically significant, leading to a shorter generation time and more rapid build-up of insect species under nets. As these pest species are generally more fecund than their natural enemies, particularly parasitoids, it would take these natural enemies longer to build up to a level where they begin to suppress the pest population, than is the case in open orchards. However, the exact impact of temperature under nets is not yet known, especially on pests and their natural enemies. Various studies report an increase in temperature, others a decrease in temperature and some studies show nets have no effect on temperature. The varying results obtained from these various studies on the effect nets have on temperature can be narrowed down to the diverse microclimates that are created under the versatile nets and different regional climates (Manja and Aoun 2019). Prins (2018) reported that netting of orchards, in particular Mandarin orchards, had an effect on the microclimate. The main findings of the latter study were that the air temperatures within the canopies were higher, solar radiation levels were reduced by approximately 17% and there was a higher relative humidity due to decreased wind. These factors increased stomatal conductance and in return increased photosynthesis, thus having a positive impact on the Mandarins (Prins 2018).

In summary, in our study, protective netting increased the levels of certain key pests, most notably *A. aurantii* and *P. citri* and possibly also *T. leucotreta*, but decreased the levels of other key pests, namely *S. aurantii* and *C. capitata*. Although levels of both *A. aurantii* and *P. citri* were significantly higher under nets than in open orchards during both two successive seasons, infestation levels were nonetheless still low and could not be considered as problematic. Further studies are required with higher levels of these pests in order to be able to observe the trends and efficacy of their respective biocontrol complexes under nets, relative to open orchards. Conversely, any increase in the levels of the phytosanitary pest, *T. leucotreta* cannot be tolerated. However, in mitigation, it appears that SIT may be more effective under nets than in open orchards, potentially leading to greater suppression of *T. leucotreta* under nets over time. Furthermore, the comparative efficacy of other technologies targeted against *T. leucotreta* must be determined under netting, relative to open orchards. This includes mating disruption, which could be enhanced or hindered by netting, parasitoid augmentation and granulovirus sprays (Moore et al. 2015). The efficacy of the last-mentioned may well be enhanced, due to the reduction in levels of harmful UV-irradiation as a result of the shade netting (Manja and Aoun 2019), as baculoviruses degrade rapidly under direct UV-irradiation (Wilson et al. 2020).

What then is the net result of using protective netting over citrus orchards? Are nets detrimental or beneficial to an IPM programme? A few decades ago, the key IPM pest in South African citrus orchards was *A. aurantii* (Bedford 1998). However, since the introduction of pyriproxyfen and imidacloprid in the 1990s, control of *A. aurantii* has become much easier and considerably improved. Currently, *S. aurantii* is the key IPM pest in South African citrus orchards, with a notably elevated pest status in recent years (Grout and Moore 2015). This is due to several factors: erosion of its effective biocontrol complex (particularly *Euseius* spp. predatory mites) by fungicide sprays, particularly mancozeb, targeted against citrus black spot (Grout and Richards 1992b; Grout et al. 1996), *Phyllosticta citricarpa* (Kiely 1948) (Botryosphaeriales: Botryophaeriaceae), incorrectly regulated by the European Union as a phytosanitary threat (CBS Expert Panel 2013); a consequent need to apply even more treatments to control *S. aurantii*; and the non-target effects of these treatments on the natural enemies of other citrus pests, leading to secondary pest outbreaks and consequently, the risk of landing in a chemical treadmill (Grafton-Cardwell et al. 1995). In conclusion, if *S. aurantii* levels, or at least *S. aurantii* damage, are significantly reduced under nets, and consequently, fewer and less harmful insecticides can be used for their control, then the netting of citrus orchards in South Africa must surely provide a boost to the successful implementation of an IPM programme.

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## AUTHOR CONTRIBUTION

Author 1 and 2 conducted the field trials, with assistance from author 3. Author 1 conducted the statistical analyses and wrote the manuscript with author 4. Author 4 secured funding and initiated the project. Author 5 completed statistical analysis. All authors read and approved the manuscript.

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