Journal of Applied Entomology

WILEY

JOURNAL OF APPLIED ENTOMOLOGY

ORIGINAL ARTICLE OPEN ACCESS

Narrow, Open Canopy Architecture Enables More Effective Management of Mango Scale, *Aulacaspis tubercularis* Newstead in Mango Orchards

Cheesman Jodie[1] | Bennett Dale[1] | Wright Carole[1] | Orr Ryan[1] | De Faveri Stefano[2]

[1]Department of Primary Industries, Mareeba, Queensland, Australia | [2]Department of Primary Industries, Cleveland, Queensland, Australia

Correspondence: Orr Ryan (ryan.orr@daf.qld.gov.au)

Received: 20 February 2025 | **Revised:** 13 June 2025 | **Accepted:** 15 July 2025

Funding: This work was supported by Australian Centre for International Agricultural Research, HORT/2015/042; Hort Innovation, AS18000.

Keywords: canopy management | fruit quality | integrated pest management | pest management | production systems

ABSTRACT

Pest management in horticultural crops must become more efficient, capitalising on non-chemical means of pest reduction. In mango (*Mangifera Indica*), the development of highly productive orchard and canopy management systems offers a potential means to reduce pressure and damage from economically important pests such as mango scale (*Aulacaspis tubercularis* Newstead), but these effects have not previously been examined. High-density narrow hedge and espalier canopy management systems were compared with Australian industry standard low-density wide open-vase canopies. Initially, female scale populations on infested foliage were assessed in three commercial mango varieties for the three canopy systems over three years. Scale fruit damage in the three canopy systems was then assessed in Calypso variety for two following harvests. Narrow canopy management systems had significantly fewer female scale present on foliage, and significantly less fruit damage from scale (64%–84% reduction), resulting in fewer fruit downgrades (58%–89% reduction). This effect may result from changes in the canopy microclimate, with a potential contribution from greater spray penetration in narrow canopies. We suggest that the adoption of highly productive mango canopy designs will provide additional benefit to farmers and consumers by improving pest control and potentially reducing pesticide use.

1 | Introduction

Within food production, two seemingly opposed trends have emerged: the need to produce more high-quality, pest-free food to meet a growing global population, and a reduction in the use of agri-chemicals, particularly pesticides (European Commission 2020). Reducing pesticide use also offers economic benefits including lower farming costs and higher prices for pesticide-free, or organically produced food (Granatstein et al. 2016; Lee et al. 2021; Nitzko et al. 2024). This presents a promising revenue option to farmers, provided alternative means of managing pest-related losses are available (Shaw et al. 2021). Ultimately, to reconcile these trends, pesticide efficiency must be increased to achieve similar or improved pest management while reducing the number, hazardousness, or frequency of pesticide applications.

Plant architecture or canopy structure is a non-chemical strategy to manage pest and disease impacts and can be an important part of an integrated pest management system (Costes et al. 2013). Canopy structure is the size, shape, orientation and positional distributions of various plant organs (Norman and Campbell 1989). While initially genetically dictated, canopy structure exhibits an ability to adapt in response to abiotic drivers such as light, water availability, and wind and biotic drivers such as pest and disease pressure (Sultan 2000). Canopy structure can also be altered through the use of rootstocks, branch bending, pruning, and agronomic management (Costes et al. 2013). In managed canopies, canopy structure is primarily modified to increase productivity (Mahmud, Ibell, Wright, Monks, and Bally 2023; Robinson et al. 1991). Additionally, in some crops, canopy architecture has been used to either reduce pest damage without increasing pesticide use (Simon et al. 2006, 2012; Simon, Miranda, et al. 2007) or use less pesticides but maintain fruit quality (Gil et al. 2021; Xun et al. 2022). Altering canopy architecture through pruning or variety selection can influence the host plant's attractiveness, the suitability of the canopy environment for the pest and their natural predators, and the efficacy of pest control methods (Simon, Sauphanor, and Lauri 2007).

In the tropics, pest management is particularly challenging, as milder winters allow pest populations to persist year-round. In evergreen species such as mango (*Mangifera indica*)—the world's most widely produced tropical fruit (FAOstat 2022)—intensified production systems are becoming more common (Ibell et al. 2024; Menzel and Le Lagadec 2017) and may offer benefits for pest control. Previous studies of these systems have shown that canopy management alters the light distribution and likely associated canopy microclimate (Mahmud, Ibell, Wright, Scobell, et al. 2023; Westling et al. 2020), altering habitat suitability.

Canopy manipulation in apple (*Malus domestica*) (Simon et al. 2006, 2012), pecan (*Carya illinoinensis* (Wangenh.) K. Koch) (Toledo et al. 2024), macadamia (*Macadamia intergrifolia*) (Gutierrez-Coarite et al. 2018) and mango (Bautista-Rosales et al. 2013) has previously been shown to reduce damage from Hemipteran pests, though it was less effective in mandarin (*Citrus clementina* Hort. ex Tan.) (Fonte et al. 2023). While many Hemipteran species are mobile, mango scale *Aulacaspis tubercularis* Newstead is relatively immobile and of significant importance due to the cosmetic damage it causes to fruit skin, reducing marketability (Raza et al. 2023). In severe infestations, leaf loss is high and death of small limbs may occur. This makes it ideal for study in pest management research.

Findings that Hemipteran pests are reduced in narrower or more open canopy management systems have not been tested with mango scale in emerging intensive mango canopy systems. To address this gap, we tested if narrow, highly productive mango canopy management systems reduce the prevalence of, and fruit damage by, mango scale.

2 | Methods

2.1 | Site Management

Leaf scale counts were performed on three mango varieties: NMBP-1243 (Yess!), Calypso and Keitt, with all other trials performed only on the Calypso variety. All mango trees were planted in 2013 on the Department of Primary Industries' Walkamin Research Facility in Walkamin, Queensland, Australia. Walkamin is located on elevated tablelands at 17.13° S, 145.43° E, at approximately 570 m above sea level. Annual average rainfall is 1030 mm, with the majority falling from December to May. Monthly maximum temperatures range from 23°C to 30°C, with minimums between 10°C and 18°C. Site-specific daily weather measurements were sourced from the Australian Bureau of Meteorology (Bureau of Meterology 2024). Soils at the site were Walkamin series, a basaltic brown dermosol (Malcolm and Heiner 1996). Trees were managed according to commercial best practices for pest management, irrigation and nutrition (AMIA 2022). Pest and disease management recommendations were made by an experienced professional, once per month between fruiting seasons and every two weeks between flowering and harvest for all canopy systems and varieties.

2.2 | Tree Architecture

The trees used in this study formed part of a larger split-split-plot experiment where trees were planted in large replicate blocks with 3 different planting densities at the main block stratum. Each density block was then split into plots representing different canopy training systems and then split at a lower level into 3 cultivar specific sub-plots. These large blocks were replicated 6 times, though not all six block replicates were used in all experiments, as specified. Full details of the larger experimental design can be found in Ibell et al. (2024) or displayed diagrammatically in Figure S1. Of the five canopy management systems (planting density and training system combinations) in the larger experiment, three were investigated in these experiments: a widely spaced open-vase (WO), a closely spaced narrow hedge (NH) and a closely spaced narrow espalier trellis system (NE) (Figure 1). Orchard rows were orientated north–south with suitable guard rows in place to minimise light or spray contamination between treatments. All trees were pruned annually soon after harvest, in approximately February, with mechanical hedgers and hand pruning.

WO trees were planted with 6 m between trees and 8 m between rows for a planting density of 208 trees/ha. Canopies of these trees were maintained between 2.5 and 3 m wide with an approximate height of 2.7 m. The open-vase structure was established through the removal of central structural branches to allow light to enter the centre of the canopy (Figure 1).

NH trees were planted with 2 m between trees and 4 m between rows for 1250 trees/ha. The canopies were maintained at an approximate width of 0.85 m and height of 2.7 m. As the trees grew and reached their allocated space, they were managed as a continuous canopy or hedgerow, rather than as individual trees (Figure 1). Both WO and NH systems had their external dimensions maintained through mechanised hedging, with additional internal pruning to enhance canopy openness and remove dead branches.

NE trees were spaced 2 m between trees and 4 m between rows, with a planting density of 1250 trees/ha. These trees were established along a trellis fence made up of five taut steel wires attached to timber posts, with the wires spaced 0.5 m apart from 0.5 m to 2.5 m above the ground. A single central leader (main trunk) was developed from which the lateral branches grew. Trellised trees were hand pruned to an approximate

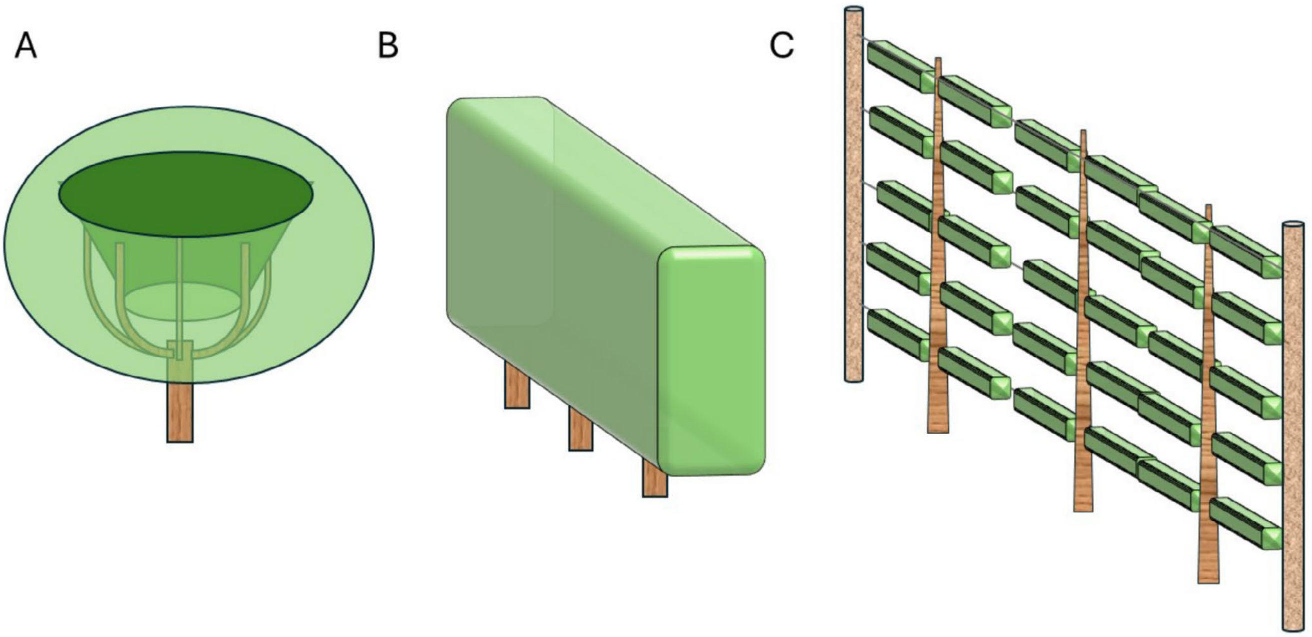

FIGURE 1 | The three canopy management systems used for these experiments. (A) Wide open-vase canopy (WO), (B) Narrow hedge canopy (NH), (C) Narrow espalier canopy (NE). [Colour figure can be viewed at wileyonlinelibrary.com]

width of 0.75 m to maintain shape and structure and to develop future fruiting points. Approximately two months after new vegetative flushes had matured, these branches were bent laterally along the trellising wires to form the espalier structure. Each year, upward or downward facing shoots were removed to allow light penetration between the trellising wire sections. Branches between the wires were also removed to maintain gaps between the espalier levels. This management approach resulted in a uniform, horizontal canopy along the espalier wires with well-spaced gaps between each level (Figure 1).

2.3 | Leaf Scale Count

This study was conducted from February 2018 to November 2021. Leaf samples from four data trees of each combination of variety and canopy management system were assessed approximately monthly. Samples were collected between 08:00 and 10:00, a minimum of one hour after sunrise. From each tree, two mature leaves infested with scale insects were selected at random from different areas of the east side and two from different areas of the west side of the tree between 1 and 2 m height. The initial sampling on August 2, 2018 comprised five leaves, rather than four, but was refined to provide better balance across the canopy. Leaves from the north and south were not sampled, as the NE and NH systems' continuous canopy lacks distinct north and south aspects, unlike the WO systems that have individual tree canopies with defined sides facing all four cardinal directions. In all systems, leaves were selected from within the canopy rather than the canopy edge, to ensure they were representative of the canopy environment.

For all leaves selected, a stereo microscope (Nikon SMZ1500, Nikon Corporation, Japan) was used to count the number of live female scales on each leaf. Live scales were intact and usually purple coloured, whereas dead scales were dried, withered and brown or black (Mahr 2024). Only females were considered in this study as they are responsible for the majority of damage (Ofgaa and Emana 2015). Numbers of female scales parasitised by *Encarsia* sp. and *Aphytis* sp. were recorded. Scales parasitised by *Encarsia* were identified by the characteristic mummification of the female scale and observation of a circular exit hole on the back of the scale (Forster et al. 1995). Scales parasitised by *Aphytis* were identified by the distinctive presence of their pupal cases and meconial pellets on the desiccated scale insect body (Forster et al. 1995).

2.4 | Fruit Analysis

This study was conducted over two consecutive Calypso harvests (2022/23 and 2023/24) on the three previously mentioned canopy management systems. Six replicate Calypso trees of each canopy design were evaluated, with individual fruit analysis to determine distributions and avoid potential sampling bias. Assessments were uniform between seasons, with fruit less than 150 g excluded as they were considered not commercially relevant. In total, 3169 fruits were assessed in the 2022/23 season, and 2868 fruits were assessed in the 2023/24 season.

Mango scale blemishes on fruits, known as 'pink spots' were counted for each fruit. Fruits were then graded into classes according to the Mango Industry Quality Standards (Holmes 2009):

- Class 1: Fewer than six spots or an area of 1 cm^2.
- Class 2: Six or more spots but no more than 15 spots or an area of no more than 3 cm^2.
- Reject: Greater than 15 spots or an area larger than 3 cm^2.

2.5 | Spray Penetration

This trial was also conducted solely on the Calypso mango variety with four data trees in each canopy management system.

For data collection, water-sensitive cards (7.6×2.6 cm) were used to assess spray coverage. Six cards were placed on each tree, positioned at three heights (canopy skirt, mid-point and apex) and at two locations (depths) per height: the inner canopy (centre point) and the outer edge of the canopy. The water-sensitive cards were stapled onto the upper surface of leaves to capture spray deposition and distribution. Trees were sprayed with water using a commercial Silvan air-blast sprayer (model unknown) travelling at a constant speed of 7 km/h in a north–south direction down both sides of the marked rows. Each spray wing consisted of 15 nozzles (ATR-80° hollow cone) subdivided into four zones.

After spraying, the water-sensitive cards were collected and analysed using the 'SnapCard' app (version 2.1.1 Department of Agriculture and Food Western Australia) to assess the percentage spray coverage on the cards. Card images were manually cropped to exclude non-card areas.

2.6 | Statistical Analysis

A repeated measures linear mixed model was fitted to the mean female scale count per leaf per tree and the mean total parasitoids per leaf per tree. The main effects of canopy management system and variety, and the two- and three-way interactions of these with time were fitted as fixed effects. Terms representing the replicates and plots within replicate were fitted as the random effects. A simple correlation model was fitted for both variables. For the mean female scale, heterogeneous variance over time was fitted, while for mean total parasitoids, homogeneous variance over time was fitted. A $\log_{10}$ transformation was applied to satisfy the normality and homogeneity of variance assumptions for both variables. To account for any zeros, a small constant of 0.5 and 0.1 was added prior to transforming the mean female scale and mean total parasitoids, respectively.

In 2023/24, three fruit from the low-density conventional treatment had excessive numbers of scale blemishes and an accurate count was not possible. The count of scale ceased at 150 per fruit due to practical limitations with the ability to distinguish individual blemishes and therefore data from these fruit are considered censored. A Tobit hierarchical generalised linear model (HGLM) (Lee and Nelder 1996; Terza 1985) was fitted to the number of scale blemishes on each piece of fruit. The Tobit procedure uses an E-M algorithm to estimate the censored observations and then applies a Poisson-log HGLM to the scale counts with the censored values replaced by the estimates. The upper bound was set at 150 counts. To account for the experimental design, the random effects included terms for replicates and plots within replicates, crossed with a term representing year. The random effects were assumed to follow a gamma distribution with logarithm link. The fixed effects included the main effect and interaction of canopy management system and year and were assumed to follow a Poisson distribution with logarithm link. The dispersion parameter was fixed at one.

The three fruit grades were assumed to be ordinal response categories with no concept of distance between them. A proportional odds model which assumes a multinomial distribution and logit link function was fitted to the ordinal categories (McCullagh 1980). The model terms included replicate and a single factor representing combinations of year and canopy management system.

The percent spray coverage collected from the spray penetration trial was analysed using analysis of variance (ANOVA). The random model comprised terms for replicate, tree and spatial dimensions within each tree (horizontal and vertical levels). This ensured the effects of height and depth positions of the cards were tested at the correct stratum. The main effects and interactions of height, depth and canopy management system were fitted as fixed effects.

For all analyses, model assumptions were checked using appropriate diagnostic plots and transformations applied when necessary to satisfy the assumptions. All significance testing was performed at the 0.05 level. Where a significant effect was found, the 95% least significant difference (lsd) was used to make pairwise comparisons. The leaf scale count data was analysed using the ASReml-R package version 4 (Butler et al. 2017) in R version 4.3.1 (R Core Team 2023). All other analyses were performed in Genstat for Windows 24th edition (VSN International 2024).

3 | Results

3.1 | Leaf Counts

The repeated measures linear mixed model on the count of female scale per infested leaf detected a significant interaction of canopy management system and time ($\chi^2_{(117)} = 1012.37$; $p < 0.001$) and a significant interaction of variety and time ($\chi^2_{(78)} = 107.28$; $p = 0.016$). The 3-way interaction of system, variety and time was not significant ($\chi^2_{(160)} = 184.24$; $p = 0.092$). Figure 2A shows the overall effect of each canopy management system over time and Figure 3 shows the overall effect of each variety over time.

For parasitoids, no terms in the model involving variety were significant. The 3-way interaction of system, variety and time was not significant ($\chi^2_{(160)} = 126.53$; $p = 0.976$). The interaction of system and time was significant ($\chi^2_{(117)} = 180.38$; $p < 0.001$), but the interaction of variety and time was not ($\chi^2_{(78)} = 14.52$; $p = 0.912$). Figure 2B shows the overall effect of each training system over time.

Environmental drivers differed between years of this study, with the greatest difference being the average minimum temperatures in winter (Figure 4). In 2021, average minimum temperatures were considerably higher than for other years, possibly enabling greater scale population growth across the entire orchard. The average minimum temperature for winter in the years where fruit assessments were undertaken (2022 and 2023) was intermediate to temperatures observed in the years used for leaf assessment (2019–2021). This suggests that average macro environmental factors were unlikely to differ between the two assessment periods.

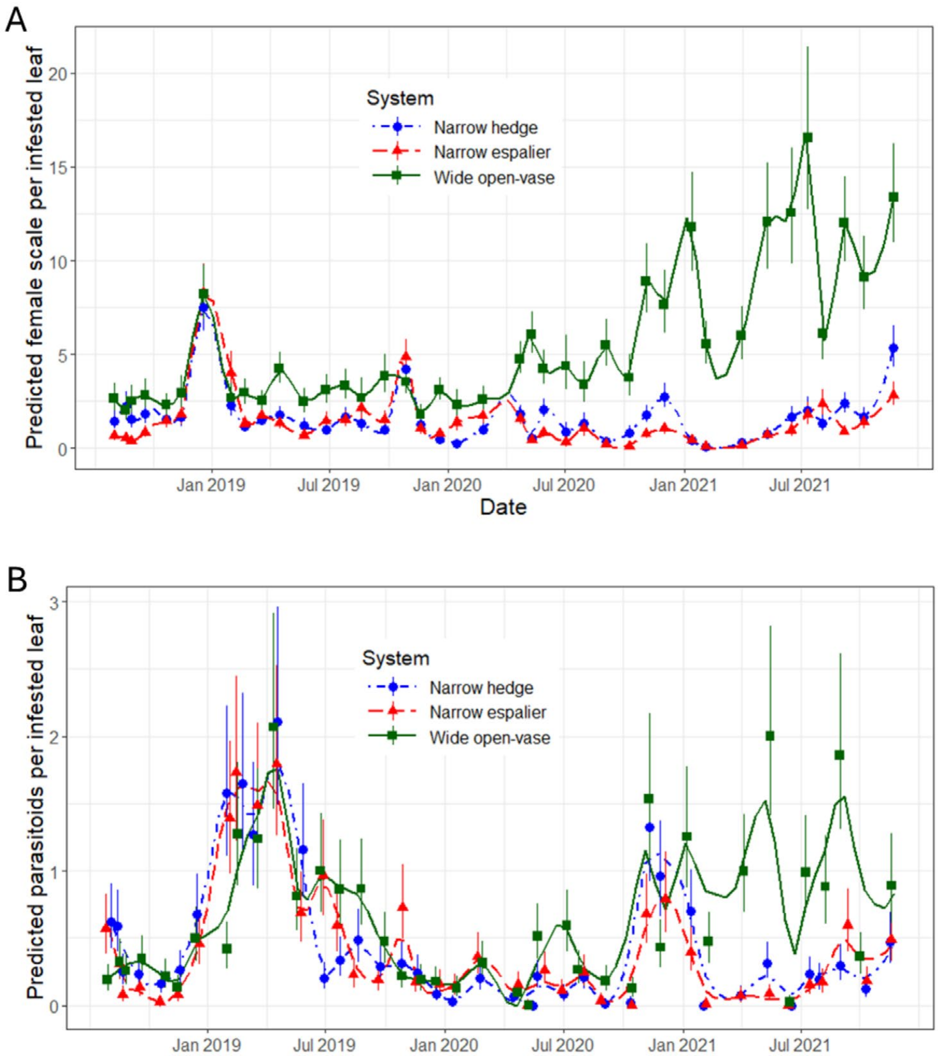

FIGURE 2 | The predicted mean count of (A) live female scale, and (B) parasitoids, on scale infested mango leaves within, narrow hedge canopies, narrow espalier trellised canopies and wide open-vase canopies from 2018 to 2021. The points are the predicted means, and the error bars are +/− one standard error. A jitter has been applied to make overlapping points more visible, and the trend is represented by a loess smooth. [Colour figure can be viewed at wileyonlinelibrary.com]

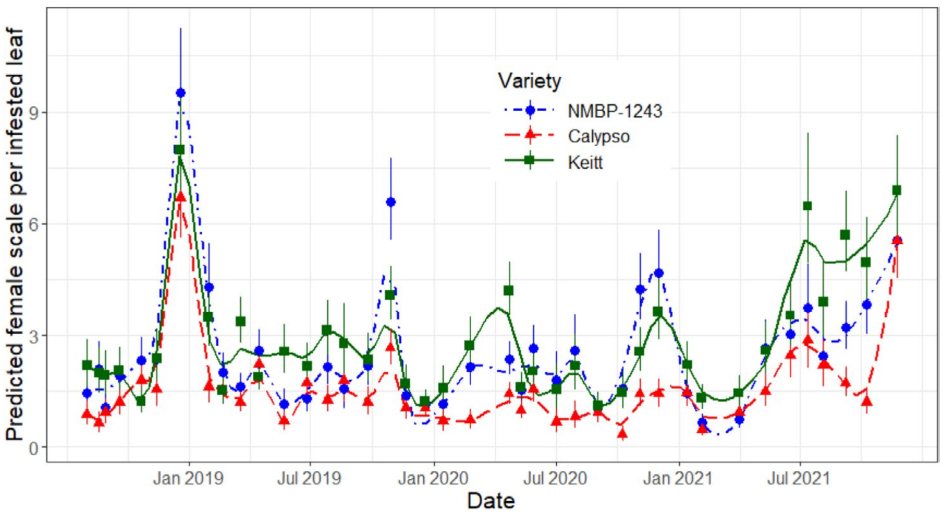

FIGURE 3 | The predicted mean count of live female scale from all three training systems on scale-infested mango leaves for NMBP-1243, Calypso and Keitt from 2018 to 2021. The points are the predicted means, and the error bars are +/− one standard error. A jitter has been applied to make overlapping points more visible, and the trend is represented by a loess smooth. [Colour figure can be viewed at wileyonlinelibrary.com]

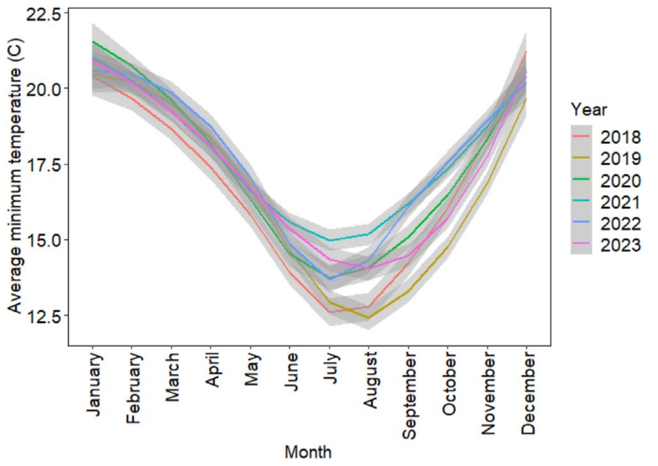

FIGURE 4 | Average minimum temperatures during the research period. Lines indicate the average minimum temperature for each month and shading indicates +/− one standard error. [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 | Mean count of scale blemishes per fruit.

Year	Canopy management system	Mean	SE	BT
2022/23	Wide open-vase	1.45a	0.315	4.26
	Narrow Hedge	0.44b	0.313	1.55
	Narrow Espalier	−0.36c	0.316	0.70
2023/24	Wide open-vase	1.94a	0.314	6.96
	Narrow hedge	0.13bc	0.314	1.14
	Narrow espalier	0.26bc	0.314	1.29
$L_{(2)}$	7.00			
p	0.030			

Note: Mean and standard error (SE) are on the $\log_e$ scale. Means with a letter in common are not significantly different using the 95% least significant difference. BT, back-transformed mean expressed as a count of scale blemishes per fruit is italicised.

3.2 | Fruit Assessments

The likelihood test based on the results from the Tobit HGLM on the counts of scale blemishes per fruit shows a significant interaction of treatment and year (Table 1). In both 2022/23 and 2023/24, the WO system had significantly higher mean scale counts per fruit. A significant difference between the two narrow systems (NH and NE) was only observed in 2022/23, where the NE system had a significantly lower mean scale count per fruit. For each individual canopy management system, there was no significant difference between the mean counts per fruit for 2022/23 and 2023/24.

Results from the proportional odds model suggest there is a tendency for NH and NE systems to have fewer fruit in the reject grade ($\chi^2_{(5)} = 681.1$; $p < 0.001$; Figure 5). The NH and NE systems had a significantly lower proportion of fruit in the reject grade compared to WO. In 2023/24, the WO and NE systems had fewer high-quality fruit compared to 2022/23, but there was no significant year effect on the NH system.

3.3 | Spray Penetration

Results for the spray penetration trial detected a significant interaction of canopy management system and depth (Table 2). For all systems, there was higher mean spray coverage in the outer canopy compared to the inner canopy, but it was not significantly higher in the NE system. No significant difference was detected between the mean coverage for each system at each canopy depth. No interactions involving height were significant, but the main effect was significant. The mean spray coverage in the higher canopy was significantly lower than at the low and medium heights.

4 | Discussion

There is a need to reduce pesticide use while maintaining productivity and quality. In this study, we have demonstrated that emerging highly productive mango canopy management systems reduce female mango scale populations on infested foliage (Figure 2) and resulting fruit damage from scale (Table 1).

Scale infestation severity was affected by the interaction of time of year and variety (Figure 3). This suggests the importance of the phenological stage of each variety in scale population dynamics, consistent with previous findings (Ofgaa and Emana 2015; Urías-López et al. 2010). Neither variety alone, nor its interaction with the canopy management system, were significant predictors of scale infestation severity, suggesting that the findings from one variety, while dependent upon phenological differences, are consistent between varieties (Figure 3). The effects of the canopy management system were consistent across foliage populations (Figure 2), fruit populations (Table 1) and fruit quality outcomes (Figure 4). Effective control of scale on foliage supports overall tree health, while reducing infestation on fruit has a more direct impact on fruit quality. Given that just five pink blemish scale spots caused by female mango scale are enough to downgrade fruit in Australia (Holmes 2009), and that infestation begins with mobile first instar crawlers moving from leaves to fruit (del Pino et al. 2020; Labuschagne 1993), it is reasonable to assume that the infestation severity of mango scale populations on foliage will link to fruit infestation and downgrading due to blemish formation (del Pino et al. 2021).

Changing the canopy architecture and structure changes both the microclimate, which alters habitat suitability for pests, and the distribution of pesticides (Simon, Sauphanor, and Lauri 2007). Insects, as ectotherms, are particularly susceptible to temperature, relative humidity and light availability of their surroundings, all of which depend upon canopy architecture. Bautista-Rosales et al. (2013) identified that temperature and relative humidity were key drivers of scale population growth. They further identified environmental conditions that favoured the abundance of scale females (18°C–22°C, 73%–78% relative humidity) or males (25°C–28°C, < 70% relative humidity). In the canopy management systems assessed

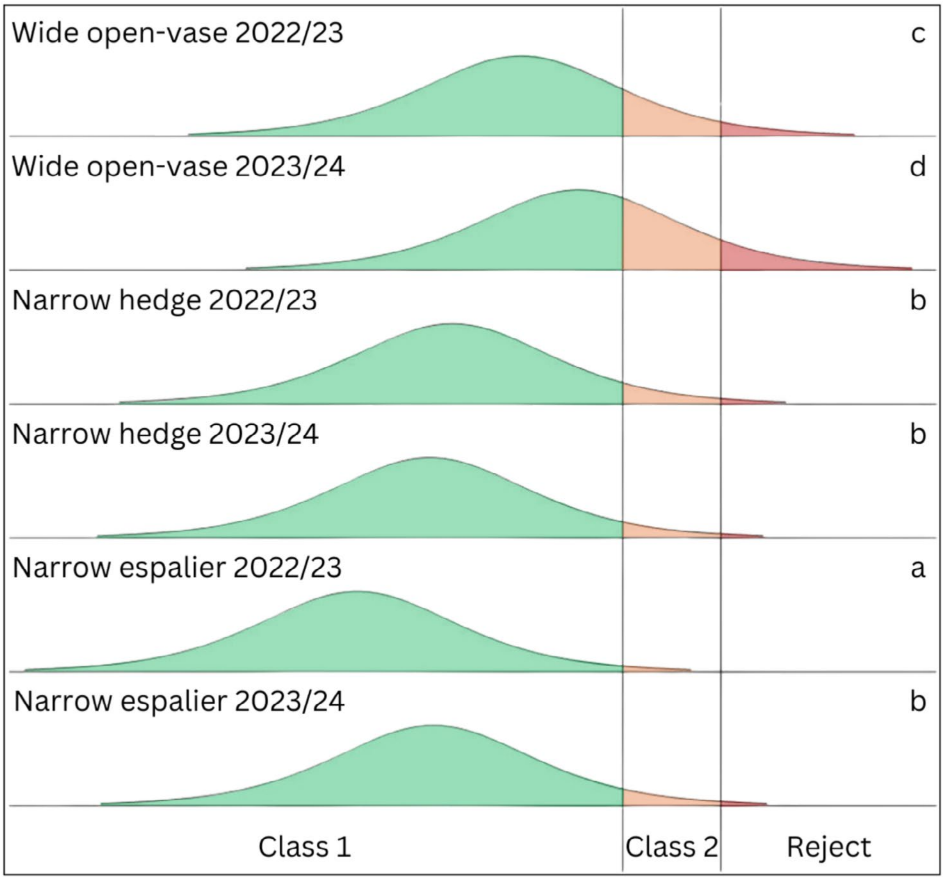

FIGURE 5 | Predicted mean frequency of fruit quality rating for each of the three canopy management systems for the two seasons of study. Classes and colours represent industry relevant cut-offs for sale (Holmes 2009). Letters in the right edge indicate post hoc grouping based on the 95% least significant difference, where distributions with a letter in common are not significantly different. [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 2 | The mean percentage saturation of water-sensitive spray cards sprayed using a commercial insecticide sprayer with equal spray settings across three canopy management systems, at three canopy heights (low = canopy bottom, middle = canopy centre, high = upper canopy) and two canopy depths (inner = canopy centre, outer = canopy edge).

Canopy management system	Depth	Mean (%)	Height	Mean (%)
Wide open-vase	Inner	15.8d	Low	46.8a
	Outer	58.7a	Middle	40.3a
Narrow hedge	Inner	27.5cd	High	26.1b
	Outer	45.6ab		
Narrow espalier	Inner	33.7bcd		
	Outer	45.0abc		
$F_{(2,9)}$		5.08	$F_{(2,18)}$	5.11
p		0.033	p	0.017
SE		7.63	SE	4.67
Average 95% LSD		22.67	95% lsd	13.89

Note: Means with a letter in common in the same column are not significantly different using the 95% least significant difference.

in this study, differences in light distribution have been identified (Mahmud, Ibell, Wright, Scobell, et al. 2023; Westling et al. 2020), which would likely also lead to changes in air temperature and relative humidity within the canopy. The canopy systems not only differed in width but in canopy continuity between trees, with the NE and NH systems having a contiguous canopy while the WO canopy was distinct for each tree, likely causing additional differences in light and microclimate. As we only monitored female scale, it is possible that when females declined, males increased with increasing temperature and reduced relative humidity in the narrow canopies. As females contribute more to new infestations through reproduction and are responsible for the majority of damage, the males were not of interest in this investigation. Therefore, it is possible that the development of a microclimate suppressive to the damage-causing female scale population contributed to the observed reduction in pest damage.

In addition to changes to habitat suitability, narrower and more open canopy structures typically allow greater light and air penetration, as well as greater penetration of pesticides (Simon, Sauphanor, and Lauri 2007). We found that while the mean spray penetration to the centre of the canopy was much greater in narrow canopies, the effect was not significant (Table 2). This may be due to the large variability both within and between individual tree canopies. Alternatively, the similarity in the density of the canopy outer wall between canopy management styles may be the determinant of spray penetration, as found by Yeary et al. (2018), rather than canopy width. In the WO and NH systems there was significantly higher spray coverage on the external wall of the canopy than in the interior, unlike the NE system where no significant difference in the interior and exterior was detected. Therefore, while the penetration to the centre of the canopy did not differ significantly between the systems, the volume of the canopy interior, which received less spray in the WO and NH systems and was more conducive to pest development, was less. In the NE system the mean inner spray coverage was higher than in the other systems, though not significantly, potentially due to the more open structure from the espalier canopy management. Finally, spray coverage differed significantly with height in the canopy across all systems suggesting that optimisation of the sprayer would be beneficial. Optimisation of sprayer settings based on tree size and structure in digital twin orchards has previously been explored as a way to improve spray efficiency (Han et al. 2024). The relationship between canopy shape, size and spray optimisation is rapidly advancing and warrants further exploration.

Canopy alterations affect the entirety of the biotic canopy community, not pest populations alone, and may alter the balance between pests and their parasitoids (Pangga et al. 2013; Simon, Sauphanor, and Lauri 2007). The frequency of parasitism across the three canopy management systems closely mirrored the severity of scale infestation (Figure 2), with higher populations observed in early 2019 and 2021. Parasitoid populations displayed a typical host-parasitoid lag, peaking shortly after the scale insect populations reached their maximum levels. De Faveri (2018) found similar parasitoid lag effects on the same scale species, and this aligns with more general host-parasitoid theory (Hassell 2000). Canopy management systems had a significant influence on parasitoid populations over time, suggesting that, as with scale insects, certain years saw increases in populations under specific management regimes. This may be attributed to macro-environmental conditions—and the corresponding microclimates within the canopies—becoming more favourable for parasitoid development or that canopy manipulation improved foraging capability by the parasitoids. Alternatively, higher parasitoid numbers may simply reflect increased availability of scale hosts for parasitism during those periods.

Our findings demonstrate that suitability within the canopy for pests such as mango scale can be altered by changes to canopy architecture. Despite this, the magnitude of change from canopy management is likely to be less than from changes in the external climate (Saudreau et al. 2013). We also recommend further research to better understand the interactions between spray penetration, light penetration, canopy temperature, and relative humidity and better isolate the drivers of pest population dynamics, as these interactions are unclear (Schöneberg et al. 2021). Incorporating changes in canopy microclimate from canopy management may improve predictions of future pest range and habitat suitability (Azrag et al. 2023, 2022; van Klinken et al. 2019). Our findings may also help improve mechanistic modelling of insect-plant interactions (Wang et al. 2016) and enable *in silico* testing of canopy designs for pest minimisation and productivity.

Our findings offer an additional tool to be incorporated in an integrated pest management system. Canopy management to reduce pest populations cannot wholly replace pesticide use but provides an additional environmentally friendly means to improve pest management. The effectiveness of equal spray rates can only be improved so far, potentially limiting the benefits of canopy management in our study. In future, it may be possible to implement spray regimes tailored to canopy management systems to reduce unnecessary spraying. This approach may provide further insight into the spray requirements of emerging canopy management systems. In addition, testing must be done on other pests and diseases of concern, as well as the effects on beneficial and predatory insects. Effects of canopy microclimate on mobile pests such as fruit flies (*Drosophila suzukii*) have been performed (Inskeep et al. 2021; Park 2020) but field testing of differing tree architectures would require large replicate blocks to minimise pest transfer between treatments.

Author Contributions

Jodie Cheesman: conceptualisation (equal), data curation, investigation (lead), methodology, writing – original draft preparation, writing – review and editing. Dale Bennett: conceptualisation (equal), data curation, investigation, methodology, visualisation, writing – original draft preparation, writing – review and editing. Carole Wright: data curation, formal analysis (lead), methodology, validation, visualisation, writing – original draft preparation, writing – review and editing. Ryan Orr: conceptualisation, formal analysis, investigation, methodology, project administration, resources, supervision, visualisation, writing – original draft preparation (lead), writing – review and editing (lead). Stefano De Faveri: conceptualisation (lead), funding acquisition (lead), project administration, resources, supervision, writing – review and editing.

Acknowledgements

The authors would like to acknowledge the technical assistance with trial maintenance and scale counts, particularly from Bruno Tamelini, Zac Scobell and Charlee MacDonald. Open access publishing facilitated by Queensland Department of Primary Industries, as part of the Wiley - Queensland Department of Primary Industries agreement via the Council of Australian University Librarians.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are openly available in the Queensland Government eResearch Archive at https://doi.org/10.60699/djjt-sa02, reference number 9161.

References

AMIA. 2022. "Growing Resources." https://www.industry.mangoes.net.au/resources/growing.

Azrag, A. G. A., S. A. Mohamed, S. Ndlela, and S. Ekesi. 2022. "Predicting the Habitat Suitability of the Invasive White Mango Scale, *Aulacaspis tubercularis*; Newstead, 1906 (Hemiptera: Diaspididae) Using Bioclimatic Variables." *Pest Management Science* 78: 4114–4126.

Azrag, A. G. A., S. A. Mohamed, S. Ndlela, and S. Ekesi. 2023. "Invasion Risk by Fruit Trees Mealybug *Rastrococcus invadens* (Williams) (Homoptera: Pseudococcidae) Under Climate Warming." *Frontiers in Ecology and Evolution* 11: 1182370.

Bautista-Rosales, P. U., J. A. Ragazzo-Sánchez, M. Calderón-Santoyo, E. Cortéz-Mondaca, and R. Servín-Villegas. 2013. "*Aulacaspis tubercularis* Newstead in Mango Orchards of Nayarit, Mexico, and Relationship With Environmental and Agronomic Factors." *Southwestern Entomologist* 38: 221–230.

Bureau of Meterology. 2024. "Climate Data Online." http://www.bom.gov.au/climate/data/index.shtml.

Butler, D., B. Cullis, A. Gilmour, B. Gogel, and R. Thompson. 2017. *Asreml-r Reference Manual Version 4*. VSN International Ltd.

Costes, E., P. E. Lauri, S. Simon, and B. Andrieu. 2013. "Plant Architecture, Its Diversity and Manipulation in Agronomic Conditions, in Relation With Pest and Pathogen Attacks." *European Journal of Plant Pathology* 135: 455–470.

De Faveri, S. 2018. "Integrated Pest Management and Biological Pest Control Strategies in Mango Cultivation." In *Achieving Sustainable Cultivation of Mangoes*, edited by P. L. V. Galán, 511–541. Burleigh Dodds Science Publishing Limited.

del Pino, M., C. Bienvenido, J. R. Boyero, and J. M. Vela. 2020. "Biology, Ecology and Integrated Pest Management of the White Mango Scale, *Aulacaspis tubercularis* Newstead, a New Pest in Southern Spain—A Review." *Crop Protection* 133: 105160.

del Pino, M., J. M. Vela, J. R. Boyero, and C. Bienvenido. 2021. "Phenology and Management of the White Mango Scale, *Aulacaspis tubercularis* Newstead (Hemiptera: Diaspididae), in Southern Spain." *Phytoparasitica* 49: 459–477.

European Commission. 2020. "Communication From the Commision to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. A Farm to Fork Strategy for a Fair, Healthy and Environmentally-Friendly Food System."

FAOstat. 2022. "Crops and Livestock Products." https://www.fao.org/faostat/en/#data.

Fonte, A., C. Garcerá, and P. Chueca. 2023. "Influence of Mechanical and Manual Pruning on the Incidence of Pests in 'Clemenules' Mandarins." *Pest Management Science* 79: 4390–4402.

Forster, L. D., R. F. Luck, and E. E. Grafton-Cardwell. 1995. *Life Stages of California Red Scale and Its Parasitoids*. Publications, Division of Agriculture and Natural Resources, University of California.

Gil, E., R. Salcedo, A. Soler, et al. 2021. "Relative Efficiencies of Experimental and Conventional Foliar Sprayers and Assessment of Optimal Lwa Spray Volumes in Trellised Wine Grapes." *Pest Management Science* 77: 2462–2476.

Granatstein, D., E. Kirby, H. Ostenson, and H. Willer. 2016. "Global Situation for Organic Tree Fruits." *Scientia Horticulturae* 208: 3–12.

Gutierrez-Coarite, R., J. Mollinedo, A. Cho, and M. G. Wright. 2018. "Canopy Management of Macadamia Trees and Understory Plant Diversification to Reduce Macadamia Felted Coccid (*Eriococcus ironsidei*) Populations." *Crop Protection* 113: 75–83.

Han, L., J. Cao, P. Ibell, et al. 2024. "Digital Twins for Mitigation of Orchard Spray Drift." *Acta Horticulturae* 1395: 67–78.

Hassell, M. P. 2000. "Host–Parasitoid Population Dynamics." *Journal of Animal Ecology* 69: 543–566.

Holmes, R. 2009. *Mango Quality Assessment Manual: A Guide to Assessing the Post-Harvest Quality of Australian Mangoes*, edited by R. Holmes, P. Hofman, and L. Barker. Dept. of Employment, Economic Development and Innovation.

Ibell, P. T., F. Normand, C. L. Wright, K. Mahmud, and I. S. E. Bally. 2024. "The Effects of Planting Density, Training System and Cultivar on Vegetative Growth and Fruit Production in Young Mango (*Mangifera indica* l.) Trees." *Horticulturae* 10: 937.

Inskeep, J. R., A. P. Allen, P. W. Taylor, P. Rempoulakis, and C. W. Weldon. 2021. "Canopy Distribution and Microclimate Preferences of Sterile and Wild Queensland Fruit Flies." *Scientific Reports* 11: 13010.

Labuschagne, T. I. 1993. "Aspects of the Biology and Population Dynamics for the Integrated Control of the Mango Scale *Aulacaspis tubercularis* Newstead in South Africa."

Lee, M., T. von der Heidt, J. Bradbury, and S. Grace. 2021. "How Much More to Pay? A Study of Retail Prices of Organic Versus Conventional Vegetarian Foods in an Australian Regional Area." *Journal of Food Distribution Research* 52: 46–62.

Lee, Y., and J. A. Nelder. 1996. "Hierarchical Generalized Linear Models." *Journal of the Royal Statistical Society, Series B: Statistical Methodology* 58: 619–656.

Mahmud, K., P. Ibell, C. Wright, Z. Scobell, I. Bally, and D. Monks. 2023. "The Effect of Different Mango Training Systems on Light Transmission Within the Canopy." *Acta Horticulturae* 1366: 345–352.

Mahmud, K. P., P. T. Ibell, C. L. Wright, D. Monks, and I. Bally. 2023. "High-Density Espalier Trained Mangoes Make Better Use of Light." *Agronomy* 13: 2557.

Mahr, S. 2024. "Scale Insects." https://hort.extension.wisc.edu/articles/scale-insects/.

Malcolm, D. T., and I. J. Heiner. 1996. *The Soils of Walkamin Research Station*. Department of primary industries Queensland.

McCullagh, P. 1980. "Regression Models for Ordinal Data." *Journal of the Royal Statistical Society: Series B: Methodological* 42: 109–127.

Menzel, C. M., and M. D. Le Lagadec. 2017. "Can the Productivity of Mango Orchards be Increased by Using High-Density Plantings?" *Scientia Horticulturae* 219: 222–263.

Nitzko, S., E. Bahrs, and A. Spiller. 2024. "Consumer Willingness to Pay for Pesticide-Free Food Products With Different Processing Degrees: Does Additional Information on Cultivation Have an Influence?" *Farming System* 2: 100059.

Norman, J. M., and G. S. Campbell. 1989. "Canopy Structure." In *Plant Physiological Ecology: Field Methods and Instrumentation*, edited by R. W. Pearcy, J. R. Ehleringer, H. A. Mooney, and P. W. Rundel, 301–325. Springer.

Ofgaa, D. D., and G. D. Emana. 2015. "Infestation of *Aulacaspis tubercularis* (Homoptera: Diaspididae) on Mango Fruits at Different

Stages of Fruit Development, in Western Ethiopia." *Journal of Biology, Agriculture and Healthcare* 5: 34–38.

Pangga, I. B., J. Hanan, and S. Chakraborty. 2013. "Climate Change Impacts on Plant Canopy Architecture: Implications for Pest and Pathogen Management." *European Journal of Plant Pathology* 135: 595–610.

Park, K. R. 2020. "Behavior of *Drosophila suzukii* in Relation to Abiotic, Biotic, and Nutrient Factors, Oregon State University."

R Core Team. 2023. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing.

Raza, S. T., A. H. Khan, A. Hameed, et al. 2023. "A Review on White Mango Scale Biology, Ecology, Distribution and Management." *Agriculture* 13: 1770.

Robinson, T. L., A. N. Lakso, and Z. Ren. 1991. "Modifying Apple Tree Canopies for Improved Production Efficiency." *HortScience* 26: 1005–1012.

Saudreau, M., S. Pincebourde, M. Dassot, B. Adam, H. D. Loxdale, and D. G. Biron. 2013. "On the Canopy Structure Manipulation to Buffer Climate Change Effects on Insect Herbivore Development." *Trees* 27: 239–248.

Schöneberg, T., M. T. Lewis, H. J. Burrack, et al. 2021. "Cultural Control of *Drosophila suzukii* in Small Fruit—Current and Pending Tactics in the U.S." *Insects* 12: 172.

Shaw, B., C. Nagy, and M. T. Fountain. 2021. "Organic Control Strategies for Use in Ipm of Invertebrate Pests in Apple and Pear Orchards." *Insects* 12: 1106.

Simon, S., P. E. Lauri, L. Brun, H. Defrance, and B. Sauphanor. 2006. "Does Manipulation of Fruit-Tree Architecture Affect the Development of Pests and Pathogens? A Case Study in an Organic Apple Orchard." *Journal of Horticultural Science and Biotechnology* 81: 765–773.

Simon, S., C. Miranda, L. Brun, H. Defrance, P.-E. Lauri, and B. Sauphanor. 2007. "Effect of Centrifugal Tree Training on Pests and Pathogens in Apple Orchards. International Workshop on Arthropod Pest Problems in Pome Fruit Production." *IOBC WPRS BULLETIN* 3: 237.

Simon, S., K. Morel, E. Durand, G. Brevalle, T. Girard, and P.-É. Lauri. 2012. "Aphids at Crossroads: When Branch Architecture Alters Aphid Infestation Patterns in the Apple Tree." *Trees* 26: 273–282.

Simon, S., B. Sauphanor, and P.-E. Lauri. 2007. "Control of Fruit Tree Pests Through Manipulation of Tree Architecture." *Pest Technology* 1: 33–37.

Sultan, S. E. 2000. "Phenotypic Plasticity for Plant Development, Function and Life History." *Trends in Plant Science* 5: 537–542.

Terza, J. V. 1985. "A Tobit-Type Estimator for the Censored Poisson Regression Model." *Economics Letters* 18: 361–365.

Toledo, P. F. S., K. Phillips, J. M. Schmidt, et al. 2024. "Canopy Hedge Pruning in Pecan Production Differentially Affects Groups of Arthropod Pests and Associated Natural Enemies." *Crop Protection* 176: 106521.

Urías-López, M., J. Osuna-García, V. Vázquez-Valdivia, and M. Pérez-Barraza. 2010. "Population Dynamics and Distribution of the White Mango Scale (*Aulacaspis tubercularis* Newstead) in Nayarit, Mexico." *Revista Chapingo. Serie Horticultura* 16: 77–82.

van Klinken, R. D., J. V. Murray, J. N. Garcia, and A. R. Clarke. 2019. "Scale-Appropriate Spatial Modelling to Support Area-Wide Management of a Polyphagous Fruit Fly (Diptera: Tephritidae)." *Annals of Applied Biology* 175: 350–362.

VSN International. 2024. *Genstat for Windows*. VSN International.

Wang, M., B. Cribb, A. R. Clarke, and J. Hanan. 2016. "A Generic Individual-Based Spatially Explicit Model as a Novel Tool for Investigating Insect-Plant Interactions: A Case Study of the Behavioural Ecology of Frugivorous Tephritidae." *PLoS One* 11: e0151777.

Westling, F., K. Mahmud, J. Underwood, and I. Bally. 2020. "Replacing Traditional Light Measurement With Lidar Based Methods in Orchards." *Computers and Electronics in Agriculture* 179: 105798.

Xun, L., F. Garcia-Ruiz, F. X. Fabregas, and E. Gil. 2022. "Pesticide Dose Based on Canopy Characteristics in Apple Trees: Reducing Environmental Risk by Reducing the Amount of Pesticide While Maintaining Pest and Disease Control Efficacy." *Science of the Total Environment* 826: 154204.

Yeary, W., A. Fulcher, H. Zhu, W. Klingeman, and J. Grant. 2018. "Spray Penetration and Natural Enemy Survival in Dense and Sparse Plant Canopies Treated With Carbaryl: Implications for Chemical and Biological Control." *Journal of Environmental Horticulture* 36: 21–29.

Supporting Information

Additional supporting information can be found online in the Supporting Information section.