Agriculture, Ecosystems and Environment 368 (2024) 109028

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Protective covers impact honey bee colony performance and access to outside resources

Carolyn A. Sonter[a,*], Jeremy Jones[a], Blake M. Dawson[a], Jared N. Reid[a], Karen C.B.S. Santos[a], Steve Fuller[b], Matthew Tighe[a], Susan C. Wilson[a], Romina Rader[a]

[a] *University of New England, Madgwick Drive, Armidale NSW 2351, Australia*
[b] *Bee Services, 70 Washpool Road, South Grafton, NSW 2460, Australia*

ARTICLE INFO

Keywords:
Protective covers
Pollination services
Apis mellifera

ABSTRACT

Protective crop covers are used extensively to protect high-value crops from bird and hail damage, however, these structures may present challenges for honey bees (*Apis mellifera* L.), the main pollinators in these systems. Some studies have indicated that protective covers result in declines in colony size and resource storage, but few replicated field trials exist. To determine the impact of protective cropping structures on honey bee brood production and resource storage, 14 honey bee colonies were placed inside and outside of protective covers on four blueberry (*Vaccinium corymbosum* and *V. virgatum*) farms in northern New South Wales, Australia. We measured changes in brood production, pollen and honey storage, hive weight and ambient hive temperature fortnightly over a 12-week period. Brood production, pollen and honey storage, and hive weight all displayed greater reductions within four weeks of placement under net cover, compared to hives outside of net cover. Although brood and honey metrics gradually increased in all hives during the remainder of the 12-week monitoring period, hives located under protective netting had relatively smaller gains in brood production and pollen storage when compared to hives located outside the protective covering. Hives under protective netting that were in the shade and/or whose entrances were facing south were most impacted by the end of the monitoring period. Our findings highlight the need for protected crop management strategies to consider pollinator health as well as crop pollination needs so that both bee health and pollination services are maintained in these systems.

1. Introduction

High-value crops such as winter and spring fruiting blueberries (Southern highbush (*V. corymbosum*) and rabbiteye (*V. virgatum*) are commonly grown under netting or semi-transparent covers, which in addition to excluding many pests, improves the growing environment for increased crop yield and quality (Candian et al., 2019; Hall et al., 2020). Although blueberries are self-pollinating, greater fruit set and quality is achieved when cross pollinated by insects (Cook et al., 2020; Kendall et al., 2020), and the inclusion of managed pollinating insects within these enclosures is generally required. Protective covers can alter light spectrum and intensity, temperature, air movement, and alter the visual cues that bees use to navigate when foraging (Collett et al., 2013; Evans et al., 2019; Hall et al., 2020). These conditions may influence honey bee foraging behaviour, access to resources and colony viability.

European honey bees (*Apis mellifera*) are the most commonly used insects for pollination in protected agriculture in Australia (AgriFutures Australia, 2020). Several morphological and behavioural characteristics contribute to honey bee pollination efficiency including a hairy body and legs, specialised mouth parts, generalist foraging behaviour and the social practice of colony dwelling, unlike the majority of Australian native bees (Winston, 1987; Heard, 2016). Managed bees and some flies are commonly and effectively used to deliver pollination services to protected crops (Howlett, 2012; Dag, 2015; Strange, 2015; Cutting, 2018; Silva-Neto et al., 2018) however, conditions for optimal foraging activity vary greatly amongst insect species (Kendall et al., 2021). Bumble bees (*Bombus terrestris*) and some fly species (*Calliphora vicina*) perform well in cooler conditions (optimal foraging range of <24 to <20 °C). Activity in cooler conditions may be compatible with some winter flowering crops such as blueberry, but these taxa are either not present (i.e. Bombus) or present in low numbers (many of the candidate fly taxa), in north-eastern Australia (Kendall et al., 2021). Although

* Corresponding author.
E-mail address: csonter@myune.edu.au (C.A. Sonter).

https://doi.org/10.1016/j.agee.2024.109028
Received 16 November 2023; Received in revised form 4 April 2024; Accepted 8 April 2024
Available online 11 April 2024

stingless bees (*Tetragonula carbonaria*) are present in the blueberry growing regions of north-eastern Australia, optimal foraging occurs at 29–31 °C, rendering this species less suitable for winter flowering crops (Greco et al., 2011). As a result, honey bees are relied upon to provide pollination services for winter flowering blueberries, despite foraging conditions being less than ideal (Kendall et al., 2021).

Brood production and resource storage, and consequently colony size, are anecdotally reported to decline under nets on blueberry farms (Bee Aware, 2014). To our knowledge, little replicated research has been reported on colony health under protected cropping conditions on blueberry farms in Australia or globally. Although honey bee health and pollination under protected and enclosed environments has recently been reviewed and recommendations made to improve pollinator efficiency and health, enclosed blueberry crops were not assessed (Hort Innovation Australia Limited, 2022). However, research regarding pollen flow in netted blueberry crops shows a lower diversity of pollen deposition on blueberry stigmas under nets, suggesting a reduced diversity of nutritional resources available to bees in this environment, with potential impacts on bee health (Santos et al., 2023). Bees are already under threat due to numerous stressors including reduced resources from intensive agriculture, and the addition of protective nets may amplify the existing threats (Belsky and Joshi, 2020; Sharma et al., 2020; Willcox et al., 2023).

Here, we assessed the weight, temperature, colony development and resource storage of 14 honey bee colonies on blueberry farms of northern New South Wales, Australia. The aim of this study was to determine the extent to which protective netting (i.e. anti-bird and anti-hail) conditions impact (i) honey bee access to resources, and (ii) honey bee colony performance.

2. Methods

Southern highbush (*V. corymbosum*) and rabbiteye (*V. virgatum*) blueberries are grown on over 300 farms throughout Australia, excluding the Northern Territory, with the majority located on the New South Wales (NSW) north coast. An estimated 23,452 tonnes of blueberries were produced in Australia during 2020/21, valued at $411.2 M (Hort Innovation, 2023). Cultivars grown on the NSW north coast include "cultivars: 'C99–42' (patented, US20100043109), 'Snowchaser' (patented US20080196128), 'Ridley 1111' (patented, US20110185459) and 'OB1' and 'Brightwell', with most farms growing a combination of cultivars to ensure berry production throughout the year (Plant Health Australia, 2020). Blueberry crops are usually grown in blocks under anti-bird or anti-hail netting, or polythene protected tunnels (Hall et al., 2020). Winter and spring fruiting blueberry crops are high value and are usually grown under protective covers, requiring the inclusion of honey bee colonies for pollination from March to October (NSW Department of Primary Industries, 2015). In NSW, honey bee colonies are usually introduced in March with an initial stocking rate of approximately 2 hives per hectare at 5% of peak crop bloom, and increasing to approximately 10 hives per hectare at the peak of the flowering season, from May to September (Goodwin, 2012; Hort Innovation, 2023).

This study was conducted at four commercial blueberry farms situated on the Mid North Coast of New South Wales, Australia: central Coffs Harbour (30°18′08″S 153°07′08″E) (n = 1), Macksville (-30° 42' 28.08'' N and 152° 55' 13.044 E) (n = 1), and Woolgoolga (30°07′S 153°12′E) (n = 2) during the blueberry flowering period from mid May to late August 2020. A total of 14 bee hives were sampled, including seven under and seven outside nets (Table A.1). Sampling occurred prior to hive placement on the farm, then fortnightly from late May to late August 2020, and involved photographing each frame in the brood box, and recording the weight of the hive and the ambient temperature at the hive location. Langstroth bee hives were used in the study with a single brood box containing between 8 and 10 frames, and a honey super (i.e. box for storage of honey). Prior to the commencement of the experiment the bee hives had been on a native forest site for approximately three months. At placement on the farms, all bee colonies were comparable regarding the age of the queen bees, number of bees and frames, health, and the honey supers were empty. No supplementary feeding occurred on the blueberry farms. The weather during the study period was unusually cool (daily mean 20.6 °C) with higher than average winter rainfall (monthly mean 76.4 mm) (Australian Government Bureau of Meteorology, 2020). Floral surveys were conducted of the vegetation under net cover and the vegetation surrounding the farms during the study period.

2.1. Farm and surrounding vegetation

Blueberry varieties grown on the farms in this study are cultivars: 'C99–42' (patented, US20100043109), 'Snowchaser' (patented US20080196128), 'Ridley 1111' (patented, US20110185459), 'OB1' and the Rabbiteye variety "Brightwell". In these systems, blueberry bushes are grown in row formation approximately 3 m apart with approximately 3–4 m at the end of the rows to allow farm machinery to drive through and around the rows. At the time of data collection only the Southern Highbush varieties were flowering. Several exotic herbaceous plants with pollen and nectar known to be attractive to honey bees were also observed under the nets (Table A.2) (Somerville, 2019). Additional floral resources surrounding the farms consisted of native and exotic herbaceous plants, shrubs, vines and trees (Table A.2), the majority of which possess pollen and nectar attractive to honey bees (Somerville, 2019).

2.2. Netted enclosures

Netted enclosures were already established on the farms and were constructed of wooden poles approximately 4–6 m high over which anti-bird netting was stretched to create a taut canopy, extending down the sides (Fig. 1a). Entry into the enclosure was through a removable section of anti-bird netting. The enclosure space varied between 22744 and 318732 m^3 (Table A.3) and was located on sloping ground. Anti-hail netting had been placed on top of three enclosures, in the place of anti-bird netting, which resulted in anti-hail netting on the top of those enclosures and anti-bird netting on the sides (Table A.1). Anti-bird and anti-hail netting was comprised of black or white nylon mesh with 18 $\times$18 mm and $\leq$ 8 $\times$8 mm holes, respectively in a grid pattern (Fig. 1b; 1c).

2.3. Hive location

Bee hives were placed in pairs, one hive inside and the other hive outside the net, with attempts made to match the aspect (i.e. hillside or valley) on each farm as closely as practicable (Table A.3). Due to plant row formation and/or terrain it was not always possible to place the hives close together (i.e. one outside and one under net cover) or to place the hive under net cover with the entrance facing east or north or to receive all day sunlight (Table A.3) (Root, 1978). This resulted in only two hives under net cover being placed with the entrance facing north/north east and the remaining facing south or west (Table A.3). All hives outside net cover were placed with the entrance facing north/north east and in all day sunlight.

2.4. Sampling method

Honey bee access to outside resources was assessed by visual observation of individual honey bee foragers exiting the hive and immediately attempting to leave the netted area (i.e. nets at the top or the side of the enclosure). Upon the forager arrival at the net, the time of exit for each bee was recorded using a stopwatch. All net rebounds were recorded until the bee was either lost from sight (within the crop or simply lost), successfully passed through the net, or abandoned the exit attempt. This was conducted on nine days between March and June 2020 on a total of 21 hives randomly selected within netted blocks

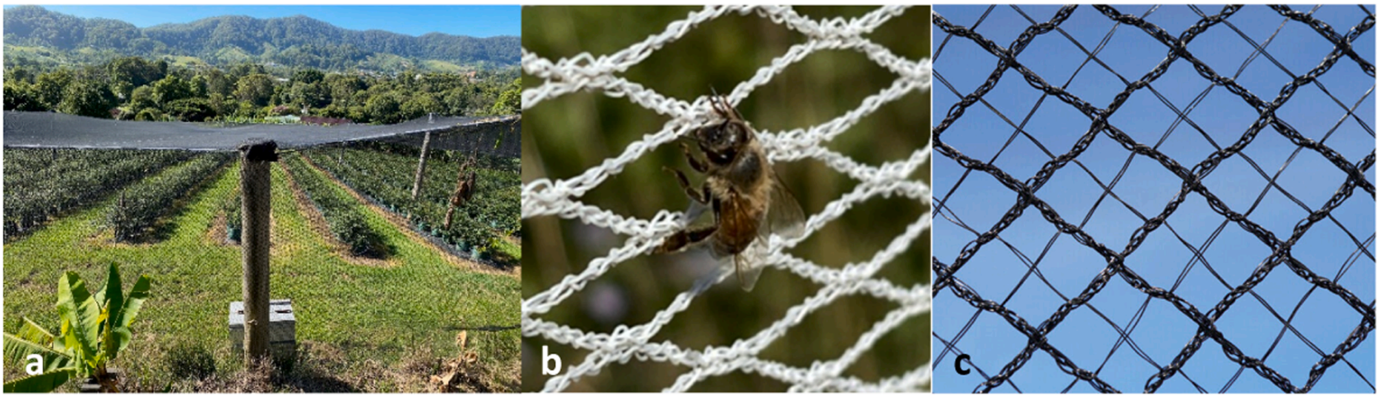

Fig. 1. a. Netted blueberry crop at Coffs Harbour with anti-hail net roof and anti-bird net sides; b. Anti-bird netting with 18 ×18 mm holes; c. Anti-hail netting with ≤ 8 ×8 mm holes.

across the farm sites. A maximum of 20 bees were recorded from a hive, and each hive was assessed once.

To evaluate variations in resource storage and brood development, photographs were taken fortnightly of each side of every frame in the brood box. Each photograph was assessed using a grid divided into 15 equal sections, to allow clear identification of brood area changes (Fig. 2). Larvae and capped pupae (without pierced capping) were considered the best indication of emerging adults and successful brood development (Winston, 1987). Brood data was collected by counting the number of cells containing larvae and pupae in each grid section and adding the grid counts together to obtain a total number for each frame. The total number of cells containing larvae and pupae were divided by the total number of cells to obtain a proportion. Stored honey and pollen were assessed by the same method. BroodMinder™ (Stoughton, USA) weight and temperature sensors were placed under the hive box to record weight and ambient hive temperature on an hourly basis. Hive weight and temperature data was processed using the mean value for each 24-hour period. When analysing hive weight and temperature, brood and resource storage metric data collection days were excluded from analysis owing to the temporary weight and temperature changes associated with the physical manipulation of hives for monitoring purposes.

At the completion of the study period, brood, honey and pollen increase or decline in each hive was calculated by comparison of final and initial data. Hive orientation, i.e. the cardinal direction that the entrance faced, was recorded for each hive. The distance from the closest edge of the net to the hive and the total area under the netted area were also recorded for hives located under crop covers.

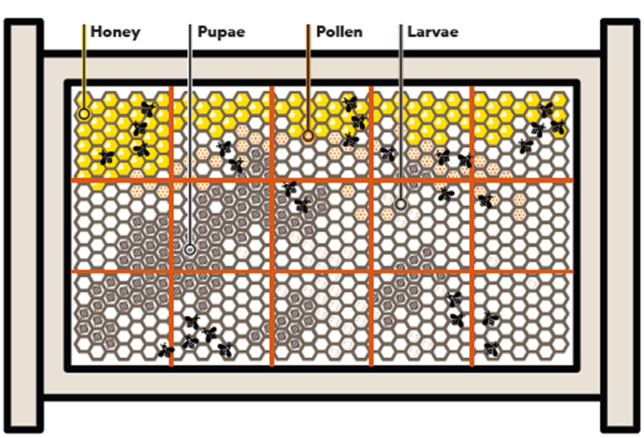

Fig. 2. Illustration of brood frame, with grid used to assess the number of cells containing larvae (light grey-coloured), capped pupae (dark grey-coloured), stored pollen (orange-coloured) and capped honey (yellow-coloured).

2.5. Statistical analysis

We evaluated the effect of protective covers on the ability of bees to manoeuvre through anti-hail and anti-bird netting by measuring the number of times bees rebounded when contacting anti-hail or anti-bird netting. This metric could only be measured under anti-hail or anti-bird netting because the metrics of assessment only applied to the netted environment. The control group, i.e. hives outside the netted environment, would have recorded 0 for all metrics, rendering statistical analysis invalid.

To test the effect of anti-hail or anti-bird netting on the time period and the number of times that the bee rebounded from the net when attempting to exit the protected cover generalised linear mixed effects models (GLMMs) were constructed using the “fitTMB” function in the *glmmTMB* package in R (Brooks et al., 2017; Harrison et al., 2018; R Core Team, 2021). We fitted the GLMMS using a poisson distribution, unless the data was overdispersed, in which case we used a negative binomial distribution.

We examined the effect of netting on bee ability to exit the netted enclosures by conducting three separate GLMMs using the response variables number of rebounds, exit time (seconds), and exit success (yes or no). The same fixed effect (net type) was used for all three models. Variation due to location in the response metrics were accounted for by nesting the farm location as a random effect. Post-hoc comparisons were undertaken using Tukey’s comparisons via the emmeans package (Lenth et al., 2023).

To test the effect of anti-hail or anti-bird netting on bee hive metrics, GLMMs in R were also used as above, with a beta distribution and the same approach to dispersion and assumption checking (Brooks et al., 2017; Harrison et al., 2018; R Core Team, 2021). The effect of netting on brood development and pollen and honey storage was determined by the fixed effect of net (i.e. with net or without net) with the response variables of the proportion of larvae, pupae, pollen and honey. Variation due to location in the response metrics were accounted for by nesting individual hives as a random effect. Variability in the responses among weeks were accounted for by nesting the individual hive identifier, hive size (i.e. number of frames in brood box), net, and week as random effects. Post-hoc comparisons were undertaken for pollen storage using Tukey’s comparisons via the emmeans package (Lenth et al., 2023). No post-hoc comparison was undertaken for larvae, pupae and honey due to no significant differences being identified.

Due to variation in the number of frames per hive and the duration of hive placement on farms, we assessed the effect of netting and temperature on final hive weight by comparing the percentage weight change for each hive from the start until the conclusion of monitoring. Percentage weight change was used as the response variable with the net (i.e. with net or without net) and its interaction with mean temperature as the explanatory variables. Where the interaction between net and mean temperature was not significant an additive model was fitted, using two-way analysis of variance (ANOVA). Model assumptions were checked as appropriate, for all metrics analysed. All analyses were carried out in R 4.2.2 (R Core Team, 2021) and RStudio 2022.12.0 (RStudio Team, 2020).

Hive location, i.e. placement on farm regarding aspect and cardinal direction of the entrance, was not analysed because not all paired hives faced the same cardinal direction. The space under the nets and the distance from the edge of the net to the hive location were not analysed due to the great variation that occurred for these measurements.

3. Results

3.1. Access to outside resources

Forager bees attempting to leave the netted area took significantly longer (estimate = 0.43, Standard Error (SE) = 0.11, $p = 0.0001$) to pass through anti-hail net (*Mean (M)* = 12.65, SE = 1.11 sec) than through anti-bird net (*M* = 9.08, SE = 0.56 sec) (Fig. 3; Appendix Output 1). Bees contacted and rebounded from the net on significantly more occasions (estimate = 0.76, SE = 0.16, $p = <0.0001$) when exiting anti-hail netting (*M* = 8.98, SE = 1.31) when compared to anti-bird netting (*M* = 4.60, SE = 0.38) (Fig. 3; Appendix Output 1). Bee success in exiting anti-hail netting (*M* = 31.46, SE = 0.05 %) was significantly less (estimate = 0.35, SE = 0.12, $p = 0.004$) than bee success in exiting the anti-bird netting (*M* = 50.73, SE = 0.03 %) (Fig. 2; Appendix Output 1). These results indicate a trend of increased time and attempts, with decreased exit success with anti-hail netting, when compared to anti-bird netting.

3.2. Brood response metrics

Although a greater mean proportion of larvae and pupae was observed in hives with no net cover when compared to hives with net cover, the difference was not significant, regardless of the week of the study (Fig. 4; Tables A.4; A.5; Fig A; Appendix Output 2).

3.3. Resource storage metrics

From hive establishment in blueberry orchards, the mean change in the proportion of pollen stored in bee hives both under nets and outside of the nets initially decreased. However, by week 9 of the study, the hives with no net cover contained significantly ($p = 0.0019$) greater proportion of stored pollen (*M* = 1.51, SE = 2.09 %) than the hives with net cover (*M* = 0.42, SE = 0.42 %) (Fig A.1; Appendix Output 2). By week 11 of the study period, the proportion of stored pollen in hives with

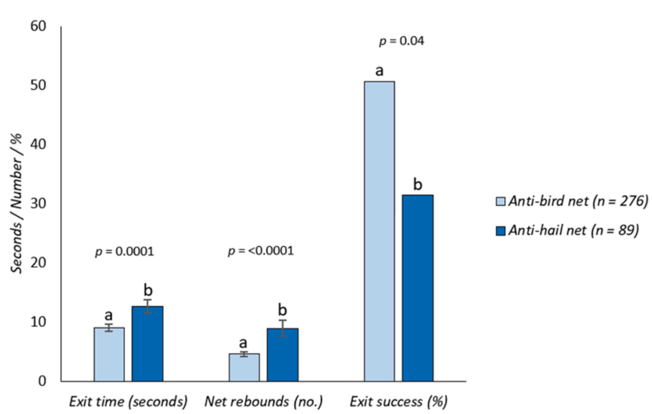

Fig. 3. Bee exit time (mean seconds), rebound incidents (mean number) and percentage of bees that successfully exited the netted environment. The number of bees in sample is shown as *n*. Significance is denoted by different letters (i.e. a and b) and $p < 0.05$. Error bars represent standard error.

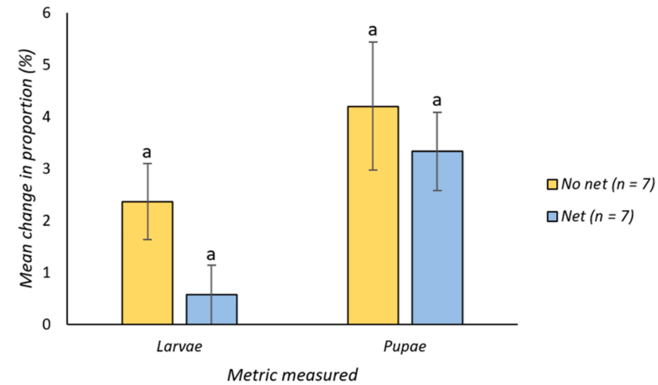

Fig. 4. Total mean change in the proportion (%) of larvae and pupae in bee hives without net cover and under net cover during the study period. Number of hives in sample is shown as *n*. Significance is denoted by different letters and $p < 0.05$. Error bars represent standard error.

no net cover (*M* = 2.33, SE = 4.38 %) was also significantly greater ($p = <0.0001$) than in hives with net cover (*M* = −0.12, SE = 0.90 %) (Fig. 5; Appendix Output 2). Overall, a significant greater (estimate = 0.51, SE = 0.22, $p = 0.02$,) proportion of pollen was stored in hives without net cover than in hives with net cover.

Although the mean proportion of stored honey decreased in all hives regardless of net cover, the greatest mean decrease occurred in the hives with no net cover, but this change was not significant (Tables A.4; A.5).

3.4. Weight and temperature metrics

Placement of bee hives under net cover resulted in a significant decrease in bee hive weight (F(1, 8) = 26.92, estimate = −30.48, SE = 6.18, $p = 0.0008$; Fig. 6, Fig A.2; Table A.6; Appendix Output 3). The decrease occurred from week 3 and the overall mean hive weight decreased by −17.1 (SE = 5.21) %. However, hives without net cover increased mean weight by 13.4 (SE = 2.49) % by week 11 (hive observation event 5) of the study period (Fig A.2; Table A.6). By week 11 of the study, there was a mean difference of 30.5 (SE = 6.18) % between the weight of hives under and outside of net cover. No significant effect was found for mean ambient temperature in explaining hive weight changes (F(1, 8) = 1.95, estimate = −0.59, SE = 0.61, $p = 0.34$; Fig A.3; Appendix Output 4), even though mean daily ambient hive temperature was lower for hives with net cover (*M* = 16.56, SE = 0.61 °C) than for hives without net cover (*M* = 17.15, SE = 0.45 °C). No significant

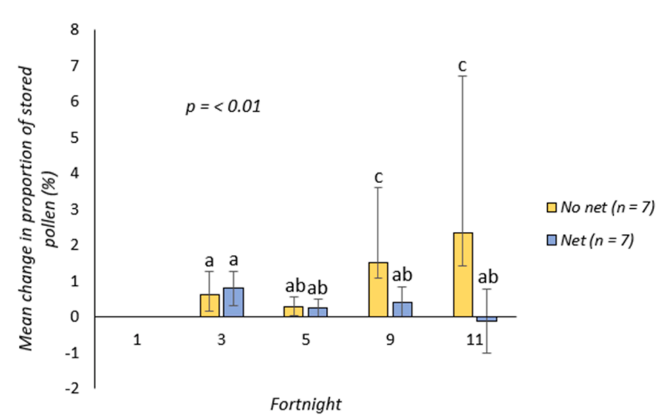

Fig. 5. Mean change in the proportion of stored pollen in bee hives located without net cover and under net cover during each observation period of the study period. The number of hives in sample is shown as *n*. Significance is denoted by different letters (i.e. a, b and c) and $p < 0.05$. Error bars represent standard error.

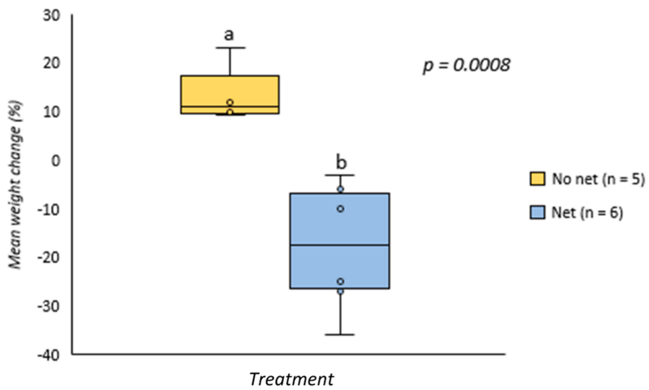

Fig. 6. Mean weight change (%) in bee hives with net ($n = 6$) and no net cover ($n = 5$) on blueberry farms. Mean weight change for individual hives are displayed as an unfilled circle on the plot (not all individual hives appear on plot due to overlapping of some recorded weights). Weight for one hive under and two hives outside net cover were excluded due to technical issues with the BroodMinder™ sensors. The number of hives in sample is shown as *n*. Significance is denoted by different letters (i.e. a and b) and $p < 0.05$. Error bars represent standard error.

interactions were found for hive weight change between net and ambient mean temperature explanatory variables.

4. Discussion

In this study, we found that anti-hail and anti-bird netting adversely impacted honey bee access to outside resources, was detrimental to colony performance, and reduced hive weight, thereby filling a knowledge gap regarding the long term viability of colonies in this environment. Although floral resources were available under the nets, some forager bees sought resources outside nets. The process of trying to exit the net cover resulted in bees contacting the net and rebounding. This behaviour, particularly in response to anti-hail netting, was time consuming as it took bees longer to exit anti-hail net relative to anti-bird netting and some bees were unable to exit the nets, likely due to the smaller hole size. This extra activity is likely energy consuming, and potentially damages the bee's wings (Visscher and Dukas, 1997; Dukas and Dukas, 2011). Further, as honey bee workers undergo a range of physiological changes to switch from hive duties to foraging at approximately 25 days of age (Seeley, 1982; Winston, 1987; Page and Fondrk, 1995), the longer time away and/or failure to return by a large proportion of forager bees will result in underage bees taking on the activity, depleting the hive of bees available for brood care, hive maintenance and temperature control activities (Winston, 1987; Eckert et al., 1994). Forager bees that remained in the netted enclosure are required to forage in challenging conditions due to the height of the blueberry plants (i.e. touching the roof in some enclosures), which limits the space available for the bees to fly over the rows for flower detection and navigation (Burnett et al., 2022). Additionally, anti-bird and anti-hail netting can alter visual cues such as the quality of sunlight and transmission of ultraviolet light that bees require for foraging (do Amarante et al., 2011; Evans et al., 2019).

Our findings build upon research by Evans et al. (2019) who assessed the performance of honey bee colonies in kiwifruit (*Actinidia chinensis* var. *chinensis* "Zesy002"; commonly known as Gold kiwifruit) orchards, under and outside of protective nets. An acute loss of forager bees and changes in forager behaviour occurred under net cover and bees were roughly three times less likely to return after their first trip outside the hive. Consequently, the number of adult bees in hives under nets rapidly declined, with colonies losing on average 1057, SE = 274 of their bees in under two weeks, compared to an average gain of 117, SE = 422 bees in uncovered orchards over the same period (Evans et al., 2019). Kiwifruit flowers are recognised as unattractive to bees and lack nectar, unlike blueberry flowers which contain nectar attractive to bees (Małgorzata, 2021), but do contain comparable crude pollen of 14 % to blueberry 13.9 %, with both lacking an essential amino acid (Clark and Lintas, 1992; Somerville, 2005; Goodwin et al., 2013).

Honey bee colony brood production is influenced by numerous factors including feedback from foragers regarding the abundance and diversity of resources (Di Pasquale et al., 2016). Limited diversity of resources under the nets and the potential loss of forager bees, may diminish the hive population through a combination of perceived dearth of resources, starvation and brood death (Winston, 1987; Evans et al., 2019). Nutritionally stressed honey bees produce less royal jelly of poorer quality, which further diminishes the colony through reduced larval and pupal survival (Winston, 1987; Meikle et al., 2020). All of these factors may explain the decrease, although not significant, in the proportion of larvae produced, and survival of that larvae to the pupae stage, in the hives established under nets on blueberry orchards. Significant increases or decreases in brood production may have occurred with a larger sample size and over a long study period, and the trend we observed suggests that a decline would occur. The production and survival of fewer larvae under nets would result in fewer nurse bees emerging, and over time further reduce colony size.

We also found a trend of reduced storage of pollen in the bee hives under net cover, particularly in the later weeks of the study, and surprisingly, a trend, although not significant, of greater honey storage in the hives under net cover. The primary floral resource available to the bee under nets were Southern Highbush (*V. corymbosum*) varieties which provide nectar and low-protein pollen (Somerville, 2019). Previous research indicates that honey bees will predominantly forage for nectar on highbush blueberry and collect minimal pollen (Dogterom and Winston, 1999; Bobiwash et al., 2018). Although not confirmed, our finding of reduced pollen and increased honey storage in hives under nets was potentially due to the bees preferentially foraging for nectar, rather than pollen, when provided primarily with blueberry flowers. However, the hives outside of the net cover had limited access to blueberry but unrestricted access to a wide range of floral resources, particularly later in the study when more plants were flowering, including high-quality pollen sources (Table A.2) and this may explain the increased pollen storage (Dogterom and Winston, 1999; Bobiwash et al., 2018).

Hive weight was negatively impacted by net cover despite an increase in honey storage observed by the end of the study period. In contrast, hives with no net cover gained weight through the study period even though honey stores decreased. The reduced honey storage in hives with no net cover is surprising, but it is important to consider the simultaneous increase in brood production and larval survival that consequently increased colony mass, requiring resources during the unusually cool and wet winter period (Huang, 2010; van der Zee et al., 2015; Stabentheiner et al., 2021).

Limitations to our study included variation regarding hive size (i.e. number of frames), and farm size, aspect and topography, vegetation abundance and density both on and off the farm, and climate, despite close geographic location. Hive location regarding the cardinal direction of the hive entrance, the number of hours of sunlight on each hive and hive aspect (i.e. whether the hive was located in a gully or on the top or side of a hill), also varied due to farm management circumstances outside of our control. Although no discernible pattern was observed regarding any correlation to the metrics previously described, 3 (out of 7) hives under net cover were either partially shaded or fully shaded by plants for periods throughout the day and 2 of these hives displayed the greatest decline in all metrics. While we aimed to standardize the management conditions on each farm, the study was conducted on different, commercial farms, hence plant size and planting formation under the nets varied considerably. For example, the farms varied in the distance between blueberry plant height and net cover. Although such variations are representative of real conditions under which pollination by managed honey bees commonly occurs, maintaining uniform conditions outside and under net cover would enhance accuracy of results.

5. Conclusion

This study shows that the performance and long term viability of bee colonies is compromised by protective netting environments. Bees take more time to exit netting and hence have less time to forage and this is impacting brood metrics. Additionally, the protected cropping environment can exacerbate the effect of challenging weather conditions on brood production, and the anticipated increase of extreme weather events due to climate change may emphasise this vulnerability. Our findings highlight the need for crop management strategies to consider pollinator resilience and ensure that colony strength and pollination services can be maintained in these systems. Stronger bee colonies will provide more effective pollination services which is an asset for growers and consumers and in the longer term, supports food security.

Funding

This work was funded by Horticulture Innovation Australia under the “Novel Technologies and Practices for the Optimisation of Pollination Within Protected Cropping Environments” grant (ST19000).

CRediT authorship contribution statement

Steve Fuller: Methodology, Conceptualization. **Karen C. B. S. Santos:** Writing – review & editing, Data curation. **Jared Nicholas Reid:** Writing – review & editing, Investigation, Data curation. **Blake M Dawson:** Writing – review & editing, Formal analysis. **Jeremy Jones:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Carolyn Anne Sonter:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Romina Rader:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Data curation, Conceptualization. **Susan Caroline Wilson:** Writing – review & editing. **Matthew Tighe:** Writing – review & editing.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Romina Rader reports financial support was provided by Horticulture Innovation Australia Ltd. . If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

Acknowledgements

Acknowledgement and appreciation is given to Kashmir Jhag, Rachpaal Singh, Amrit Atwal and Armadeep Bagri for providing the blueberry orchards used in this study. The University of New England acknowledges the traditional custodians of the land on which this research was conducted and pay respect to their Elders past, present and emerging.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2024.109028.

References

AgriFutures Australia, 2020. Honey Bee and Pollination Program. In: RIRDC (Ed.). ⟨https://www.agrifutures.com.au/rural-industries/honey-bee-pollination/⟩.
do Amarante, C.V.T., Steffens, C.A., Argenta, L.C., 2011. Yield and fruit quality of ‘Gala’ and ‘Fuji’ apple trees protected by white anti-hail net. Sci. Hortic. 129, 79–85.
Australian Government Bureau of Meteorology, 2020. Climate Statistics for Australian Locations.
Bee Aware, 2014. Improving Pollination Outcomes under Netting. Media Releases.
Belsky, J., Joshi, N.K., 2020. Effects of Fungicide and Herbicide Chemical Exposure on Apis and Non-Apis Bees in Agricultural Landscape. Front. Environ. Sci. 8.
Bobiwash, K., Uriel, Y., Elle, E., 2018. Pollen Foraging differences among three managed pollinators in the highbush blueberry (Vaccinium corymbosum) agroecosystem. J. Econ. Entomol. 111, 26–32.
Brooks, M.E., Kristensen, K., Benthem, K.Jv, Magnusson, A., Berg, C.W., Nielsen, A., Skaug, H.J., Mächler, M., Bolker, B.M., 2017. glmmTMB balances speed and flexibility among packages for zero-inflated generalized linear mixed modeling. R. J. 9, 378.
Burnett, N.P., Badger, M.A., Combes, S.A., 2022. Wind and route choice affect performance of bees flying above versus within a cluttered obstacle field. PLoS One 17, e0265911.
Candian, V., Pansa, M.G., Santoro, K., Spadaro, D., Tavella, L., Tedeschi, R., 2019. Photoselective exclusion netting in apple orchards: effectiveness against pests and impact on beneficial arthropods, fungal diseases and fruit quality. Pest Manag Sci. Chichester. UK: Wiley, Chichester, UK, pp. 179–187.
Clark, C.J., Lintas, C., 1992. Chemical composition of pollen from kiwifruit vines. N. Z. J. Crop Hortic. Sci. 20, 337–344.
Collett, M., Chittka, L., Collett, T.S., 2013. Spatial memory in insect navigation. Curr. Biol. 23, R789–R800.
Cook, D.F., Deyl, R.A., Mickan, B.S., Howse, E.T., 2020. Yield of southern highbush blueberry (Vaccinium corymbosum) using the fly Calliphora albifrontalis (Diptera: Calliphoridae) as a pollinator. Aust. J. Entomol. 59 (2), 345–352. https://doi.org/10.1111/aen.12455.
Core Team, R., 2021. Vienna: R foundation for statistical computing, Vienna, Austria. R: A Lang. Environ. Stat. Comput.
Cutting, B.T., 2018. Managed bumble bees are viable as pollinators in netted kiwifruit orchards. N. Z. Plant Prot. 71, 214–220.
Dag, A., 2015. Bee pollination of crop plants under environmental conditions unique to enclosures. J. Apic. Res. 47, 162–165.
van der Zee, R., Gray, A., Pisa, L., de Rijk, T., 2015. An observational study of honey bee colony winter losses and their association with varroa destructor, neonicotinoids and other risk factors. PLoS One 10, e0131611.
Di Pasquale, G., Alaux, C., Le Conte, Y., Odoux, J.-F., Pioz, M., Vaissière, B.E., Belzunces, L.P., decourtye, A., 2016. Variations in the availability of pollen resources affect honey bee health. PloS One 11 e0162818-e0162818.
Dogterom, M.H., Winston, M.L., 1999. Pollen storage and foraging by honey bees (Hymenoptera:Apidae) in Highbush Blueberries (*Ericaceae*), cultivar "Bluecrop". Can. Èntomol. 131, 757–768.
Dukas, R., Dukas, L., 2011. Coping with nonrepairable body damage: effects of wing damage on foraging performance in bees. Anim. Behav. 81, 635–638.
Eckert, C.D., Winston, M.L., Ydenberg, R.C., 1994. The relationship between population size, amount of brood, and individual foraging behaviour in the honey bee, *Apis mellifera* L. Oecologia 97, 248–255.
Evans, L.J., Cutting, B.T., Jochym, M., Janke, M.A., Felman, C., Cross, S., Jacob, M., Goodwin, M., 2019. Netted crop covers reduce honeybee foraging activity and colony strength in a mass flowering crop. Ecol. Evol. 9, 5708–5719.
Goodwin, M., 2012. Pollination of Crops in Australia and New Zealand. In: Corporation, R.I.R.a.D. (Ed.).
Goodwin, R.M., McBrydie, H.M., Taylor, M.A., 2013. Wind and honey bee pollination of kiwifruit (Actinidia chinensis ‘HORT16A’). N. Z. J. Bot. 51, 229–240.
Greco, M.K., Spooner-Hart, R.N., Beattie, A.G.A.C., Barchia, I., Holford, P., 2011. Australian stingless bees improve greenhouse Capsicum production. J. Apic. Res. 50, 102–115.
Hall, M.A., Jones, J., Rocchetti, M., Wright, D., Rader, R., 2020. Bee visitation and fruit quality in berries under protected cropping vary along the length of polytunnels. J. Econ. Entomol. 1337–1346.
Harrison, X.A., Donaldson, L., Correa-Cano, M.E., Evans, J., Fisher, D.N., Goodwin, C.E. D., Robinson, B.S., Hodgson, D.J., Inger, R., 2018. A brief introduction to mixed effects modelling and multi-model inference in ecology. PeerJ 6, e4794.
Heard, T., 2016. The Australian Native Bee Book. Sugarbag Bees, Maroochydore, Australia.
Hort Innovation, 2023. Australian Pollination Service Statistics (HA21005). Hort Innovation, North Sydney.
Hort Innovation Australia Limited, 2022. Honey bee health and pollination under protected and contained environments. LP15007.
Howlett, B.G., 2012. Hybrid carrot seed crop pollination by the fly Calliphora vicina (Diptera: Calliphoridae). J. Appl. Entomol. 136, 421–430.
Huang, Z., 2010. Honey bee nutrition. Am. Bee J. 1–6.
Kendall, L.K., Evans, L.J., Gee, M., Smith, T.J., Gagic, V., Lobaton, J.D., Hall, M.A., Jones, J., Kirkland, L., Saunders, M.E., Sonter, C., Cutting, B.T., Parks, S., Hogendoorn, K., Spurr, C., Gracie, A., Simpson, M., Rader, R., 2021. The effect of protective covers on pollinator health and pollination service delivery. Agric., Ecosyst. Environ. 319.
Lenth, R.V., Buerkner, P., Giné-Vázquez, L., Herve, M., Jung, M., Love, J., Miguez, F., Riebl, H., Singmann, H., 2023. emmeans: Estimated Marginal Means, aka Least-Squares Means. R. Package Version 1. 8. 4-1.

Małgorzata, B., 2021. Nectar Production and Spectrum of Insect Visitors in Six Varieties of Highbush Blueberry (Vaccinium corymbosum L.) in SE Poland. Acta Agrobot. 74.
Meikle, W.G., Weiss, M., Beren, E., 2020. Landscape factors influencing honey bee colony behavior in Southern California commercial apiaries. Sci. Rep. (Nat. Publ. Group) 10.
NSW Department of Primary Industries, 2015. Blueberry establishment and production costs. Primefract 133, 10.
Page Jr., R.E., Fondrk, M.K., 1995. effects of colony-level selection on the social organization of honey bee (Apis mellifera L.) colonies: colony-level components of pollen hoarding. Behav. Ecol. Sociobiol. 36, 135–144.
Plant Health Australia, 2020. Blueberries. 〈https://www.planthealthaustralia.com.au/industries/blueberries〉.
Root, A.I., 1978. The ABC and XYZ of Bee Culture. The A. I. Root Company, Medina, Ohio.
RStudio Team, 2020. RStudio: Integrated Development for R. RStudio. PBC, Boston.
Santos, K.C.B.S., Saunders, M.E., Samnegård, U., Rocchetti, M., Scalzo, J., Rader, R., 2023. Protective nets reduce pollen flow in blueberry orchards. Agric., Ecosyst. Environ. 353, 108544.
Seeley, T.D., 1982. Adaptive Significance of the Age Polyethism Schedule of Honeybee Colonies. Behav. Ecol. Sociobiol. 287–293.
Sharma, A., Shukla, A., Attri, K., Kumar, M., Kumar, P., Suttee, A., Singh, G., Barnwal, R. P., Singla, N., 2020. Global trends in pesticides: A looming threat and viable alternatives, 110812-110812 Ecotoxicol. Environ. Saf. 201. https://doi.org/10.1016/j.ecoenv.2020.110812.
Silva-Neto, Cd.Me, Ribeiro, A.C.C., Gomes, F.L., Melo, A.P.Cd, Oliveira, G.Md, Faquinello, P., Franceschinelli, E.V., Nascimento, Ad.R., 2018. The stingless bee mandaçaia (Melipona quadrifasciata Lepeletier) increases the quality of greenhouse tomatoes. J. Apic. Res. 58, 9–15.
Somerville, D., 2005. Fat Bees Skinny Bees: A Manual on Honey Bee Nutrition for Beekeepers. Rural Industries Research and Development Corporation, Australia.
Somerville, D., 2019. Honey and Pollen Flora of South-Eastern Australia. NSW Government, Department of Primary Industries, Condobolin, Australia.
Stabentheiner, A., Kovac, H., Mandl, M., Käfer, H., 2021. Coping with the cold and fighting the heat: thermal homeostasis of a superorganism, the honeybee colony. J. Comp. Physiol. A Neuroethol. Sens Neural Behav. Physiol. 207, 337–351.
Strange, J.P., 2015. Bombus huntii, Bombus impatiens, and Bombus vosnesenskii (Hymenoptera: Apidae) Pollinate Greenhouse-Grown Tomatoes in Western North America. J. Econ. Entomol. 108, 873–879.
Visscher, P.K., Dukas, R., 1997. Survivorship of foraging honey bees. Insectes Sociaux 44, 1–5.
Winston, M.L., 1987. The Biology of the Honey Bee. Harvard University Press, Cambridge, Mass.