Final Report

Integrated pest management of longicorn borers and leafhoppers in pecans

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Media Summary

The research from this project indicates that the pecan borer and lucerne leafhopper are unlikely to have any significant impact on pecan production and are no longer considered significant pests to the pecan industry.

The findings from the current research indicate that borer infestations are not the direct cause of mechanical pruning (as previously thought), but are the result of dead or dying timber which was caused by lower limb shading. Lower limb death is caused directly by shading and is not caused by borers or mechanical pruning. Tree collapse is rare and was not caused by borers, but was caused by cutting trees open (with chainsaws to remove borers) and allowing the timber to die and become dry and brittle. Therefore, manual removal of borers from the trunk is likely to cause more damage to the trees than the presence of borers. As the borer is no longer considered a pest, manual removal and further control methods are no longer recommended. This has significantly reduced input costs and increased profits to the pecan industry.

Cultural control practices through improved tree health were investigated. Primarily the limb dieback and borer problem was caused by: pruning lower limbs to short, pruning in a rectangular shaped hedge, growing hedges too tall for their row space and growing some hedges in an east-west direction. Recommended improved canopy management and pruning practices include: pruning hedges into a tapered shape (preserving the lower limbs as wide as possible), pruning in a North-South direction and limiting tree height. By producing a healthy more productive tree, not only will limb death and borer incidence decrease, but yield and nut quality will increase, resulting in increased profits.

IPM options for controlling leafhoppers have been developed. By simply changing mowing practices (to mowing every alternate row, rather than mowing all rows simultaneously) leafhoppers can be reduced whilst beneficial organisms are preserved.

Through the success of this research, the Australian pecan industry has predominantly remained insecticide free, thus retaining a sustainable “clean” industry with significant domestic and export value.

Technical Summary

The pecan borer (*Agrianome spinicolis*) had previously been described as a significant pest which can lead to structural weakness, limb death and debilitation of the tree. Lucerne leafhoppers (*Austroasca alfalfae*) have been observed in pecans and were thought to cause significant damage to the foliage. However, it was not known if this damage affects yields. The aims of this project were to determine the damage done by these pests and seek chemical free integrated pest management solutions.

The research from this project indicates that the pecan borer and lucerne leafhopper are unlikely to have any significant impact on pecan production and are therefore not key pests to the pecan industry.

Previously it was thought that borer incidence was largely attributed to the damage caused by mechanically pruning large limbs. However, the findings from the current research indicate that borer infestations are not the direct cause of mechanical pruning, but are the result of dead or dying timber which was caused by lower limb shading. Lower limb death is caused directly by shading and is not caused by borers or mechanical pruning. Tree collapse is rare and no evidence was found that it is caused by borers, but it is thought to be caused by cutting trees open (with chainsaws to remove borers) and allowing the timber to die and become dry and brittle. Therefore, manual removal of borers from the trunk is likely to cause more damage to the trees than the presence of borers. As the borer is no longer considered a pest manual removal and further control methods are not recommended. This has significantly reduced input costs and increased profits.

Improved cultural control practices through improved tree health were investigated. This included studies in canopy management and canopy modelling. Pruning practices that have led to poor tree health (resulting in lower limb die-back, borer infestation and declining nut yields) have been identified. Primarily the problem was caused by cutting off lower limbs to close to the trunk, in a rectangular shaped hedge. This has essentially cut off the sunlight to the lower limbs (which had previously reached out into the sunlight). The problems were exacerbated by growing hedges too tall for their row space and growing some hedges in an east-west direction. Improved canopy management and pruning practices have been suggested. These include: pruning hedges into a tapered shape (preserving the lower limbs as wide as possible), pruning in a North-South direction and limiting tree height. By producing a healthy more productive tree, not only will limb death and borer incidence decrease, but yield and nut quality will increase, resulting in increased profits.

The fungal biopesticide *Metarhizium anisopliae* failed to control neonate pecan borers as mortality in fungus treated logs (pre-infested with the neonates) was not significantly different than untreated and oil only (the carrier) controls.

The fungus did have an effect on the established larger larvae, as there was a higher mortality in the *M. anisopliae* treated sites. However, it produced less than 10% mortality, which is not a practical level of control. Further investigation of this biopesticide is no longer recommended as the borer is no longer considered an economic pest of pecans.

The role of predatory earwigs in controlling borers was investigated. Predatory earwigs are likely to play a significant role in naturally regulating borers. However, augmentation (by mass rear and release) is not necessary because the earwigs are already well established and borer control is no longer considered necessary.

We have an understanding of leafhopper damage and how it is caused. The effects on yields and alternate bearing are not clear, but with improved orchard management practices it is unlikely to affect yields or require further inputs. IPM options for controlling leafhoppers have been developed. By simply changing mowing practices (to mowing every alternate row, rather than mowing all rows simultaneously) leafhoppers can be reduced whilst beneficial organisms are preserved. Bio-assays indicated that insecticidal soap, surfactants and oils could reduce leafhopper incidence, but are unlikely to be required. A synergist was found, which would allow reduced rates of insecticidal soaps or surfactants to kill leafhoppers. This could potentially reduce phyto-toxicity and application costs for controlling other pests in other industries.

Introduction

The pecan borer (*Agrianome spinicolis*: Cerambycidae) has previously been described as a significant pest which can lead to structural weakness, limb death and debilitation of the tree (Coombs 1999, 2003). After a change in canopy management practices involving heavy pruning (at the Stahmann Farms Trawalla orchard from 1999 to 2001), it was observed that the borer incidence increased. Coombs (2003) hypothesised that an increase in borer incidence was attributed to the use of mechanical pruning equipment when used on large limbs. It was noted at the time that the mechanical pruning caused damage to the larger limbs resulting in shattering and splits in the heartwood. The increase in borer incidence was attributed to this damage. On this advice, the industry undertook a cultural control program, by removing all borers from infested pecan limbs and trunks. These wounds were then dressed with a paint barrier as a borer oviposition barrier (Newton 2006). As part of this program, all dead or damaged timber was removed to prevent further borer infestations. At one stage, this cultural control program costed over $1M per annum to Stahmann Farms alone (Newton 2006). The cost to the entire pecan industry would have been considerably more. Therefore, a solution to the borer problem would save the pecan industry significant input costs and increase the producers' profit margins.

Previous research programs recommended further research be undertaken to find biological and cultural solutions to the borer problem (Coombs 2003, Newton 2006). This included: the further development of fungal based biopesticides, the role of predatory and parasitic insects, and improved cultural control practices. Newton (2006) indicated that shade-out of lower limbs contributed to the borer problem and recommended that pruning practices be reviewed with the aim of reducing shade-out. It was also suggested that research is required into determining the best model for pruning hedgerows.

Lucerne leafhoppers (*Austroasca alfalfae*) have been observed in pecans and were thought to cause significant damage to the foliage. Heavy infestations were thought to cause yellowing, leaf curl, stunted leaves, leaf burn, and leaf necrosis. It is not known if the leafhoppers were having an effect on yields. However, data from the USA has shown that aphids (a somewhat similar pest) feeding on pecan foliage can reduce photosynthesis and thus affect return bloom and yields the following year (Dutcher *et al.* 1984, Tedders and Wood 1985, Wood *et al.* 1987).

Austroasca alfalfae (Evans 1941) is an Australia native insect, found on lucerne and many other plant hosts including: cotton, cowpea, *Crotolaria* sp., jimson weed (*Datura stamonium*), *Erythrina* sp., french bean, macadamia, papaya, peas (*Pisum sativum*), potato, castor oil plant (*Ricinus communis*), sorghum, soybean and tomato (Waite 1973). *Austroasca alfalfae* is known to cause yellowing from the leaf tip, with heavy infestations causing leaf yellowing with burnt tips, plant stunting and even death (Wood *et al.* 2000).

Leafhoppers are attacked by a large number of predators, pathogens, and parasites (Carver *et al.* 1991). These natural enemies may be enhanced by indundative release or through habitat manipulation. In and around Queensland citrus orchards, the micro-parasitoids *Anagrus baeri* and *Stethynium* nr *empoascae* are known to parasitise *A. alfalfae* and other leafhopper species (Freebairn and Smith 2002). Similar parasitoids have been successful at controlling leafhoppers in the USA through habitat manipulation and cultural control practices (English *et al.* 2003, Kido *et al.* 1984, Murphy *et al.* 1996, 1998, Wells *et al.* 1988, Williams 1984).

In Queensland, Freebairn and Smith (2002) found large numbers of *A. alfalfae* in the inter-rows or in close proximity to citrus. When this vegetation was mowed the adults moved onto the citrus trees. Freebairn and Smith (2002) recognised the importance of inter-row vegetation and orchard undergrowth in citrus orchards. They hypothesised that reduced water inputs and mowing the inter-row may be detrimental to the beneficial insects, thus contribute to citrus leafhopper (*Empoasca smithi*) outbreaks. They suggested allowing the undergrowth to grow during the spring to permit beneficials to accumulate. Mowing can have a direct effect on both the leafhopper pest and its natural enemies. In Californian vineyards, Nicholls *et al*. (2000) found that mowing forced Anagrus wasps and leafhopper predators into the adjacent vines to help control the leafhoppers.

In Australian pecans, Coombs (2000) found that mowing assisted in the control the green vegetable bug (GVB) *Nezara viridula*. This was achieved by timing the mowing to occur before the winged adults developed in the understory. This mechanically killed the nymphs and cut off their food supply. The understorey vegetation was thought to harbour important predators and parasites of the pest, so the orchard understorey was allowed to grow as much as possible before the adult GVB developed. However, in recent years this management method was changed and the orchard understorey was now kept permanently short at Trawalla. This method has still retained low numbers of GVB (I. Newton, unpublished data), but may be contributing or causing the leafhopper problem. Leafhopper parasites and predators may no longer have shelter, alternative hosts/prey or a food supply (pollen and nectar). The practice of simultaneously mowing the entire orchard understorey could also result in the vertical migration of the adult leafhoppers into the pecan canopy, as has occurred in citrus (Freebairn and Smith 2002). An alternative strategy may be to utilize strip mowing, by mowing one row and leaving every alternative row long. This strategy has been used to control leafhoppers in lucerne in the USA. Weiser *et al.* (2003), found that leafhoppers (*Empoasca fabae*) were reduced by leaving an uncut strip of lucerne. The uncut strip acted as a trap-crop for leafhoppers and refuge for predatory insects and other natural enemies.

The aims of the current research program were to:

- Find biological control (with fungal biopesticides and predatory insects) solutions to the borer problem.
- Find cultural control (through improved tree health and reduced shading) solutions to the borer problem.
- Reduce the reliance (or eliminate) manual borer removal, without using chemical insecticides.
- Understand leafhopper biology and estimate leafhopper damage and effects on yields.
- To provide integrated pest management options for controlling leafhoppers.

Methods

Study Site

The majority of studies and experiments were conducted at the Stahmann Farms "Trawalla" orchard, which is located 35 km east of Moree (29^o 29' S, 149^o 53' E) on the Gwydir Highway in New South Wales, Australia. Trawalla is approximately 700 ha in size and is bordered by the Gwydir River, from which the orchard is irrigated. The orchard contains approximately 70 000 mature pecan trees, most of which were planted in the early 1970's. Most of the orchard is grown with two grafted pecan varieties, Wichita and Western Schley, which are grown in alternative rows for cross pollination. The trees are mechanically hedged in winter. The orchard is divided into 50 irrigation blocks, of approximately 1600 trees per 16 ha. block (see map Appendix 1).

Borers

Biopesticides: Neonate control

Field trials were carried out in Jan/Feb 2008 to control *Agrianome spinicolis* neonate borer larvae using the entomopathogenic fungus *Metarhizium anisopliae* (isolate No. FI-1375, see Coombs 2003). The product was manufactured and supplied by Becker Underwood and was formulated at 45g(spores)/L(oil) with Synertrol Horti Oil™ (Organic Crop Protectants P/L) as the oil carrier to be used as an emulsion.

Sentinel borer neonate larvae were placed in pre-prepared pecan logs and were used to measure the efficacy of the *Metarhizium* biopesticide. The method of preparing the sentinel logs is as follows. Large borer larvae were collected from established borer sites by cutting them out with a chainsaw and a splitting the logs with a steel wedge mounted to a hydraulic press. Larvae were individually kept in kept in 500ml take away food containers with fresh pecan wood shavings, which were changed monthly. Larvae were reared through to adult beetles at 20-25^{o}C. The method of culturing beetles and obtaining fertilized eggs and then neonates is detailed in Coombs (2003). Freshly prepared logs were prepared by cutting down "wild" pecan trees growing along the river banks. Logs were approximately 100-200mm diameter and 500mm long. A split was put into one end of each log using a steel wedge attached to a hydraulic press. The neonate larvae were carefully placed in or on the split and allowed to crawl into the logs over 24 hours. Each log contained 20 neonate larvae.

There were 4 logs used per block per treatment. The treatments and rates are given in Table 1. A few days before spraying, the logs were attached (with pallet straps) to the lower branches of trees (approximately 1.5–3m from the ground). There were delays in receiving the *Metarhizium* product. There were also delays in applying the product because of wet weather. The first spray occurred on the night of 30th Jan 2008, the second application was made on the 19th February. As a positive control, large larvae (n=10) were dipped into a sample taken directly from each spray tank and kept and observed for mortality and sporolation. Each treatment was applied in to two separate random blocks of 80 trees (which included 40 Western Schley and 40 Wichita trees). The sentinel logs were randomly placed within each block. Spray applications were made with a 1900L capacity, fan-forced air-blast orchard speed sprayer.

Table 1. Treatments and Rates of *Metarhizium anisopliae*

Treatment	Number of applications	Rate (g/Ha)	Rate x 10^{12} spores/Ha
L1: low rate	1	50	2.9
L2: low rate	2	50 x 2	2.9
M1: medium rate	1	150	8.7
M2: medium rate	2	150 x 2	8.7
H1: high rate	1	300	17
H2: high rate	2	300 x 2	17
C1: Oil only	1	0	0
C2: Oil only	2	0	0
C0(1): Negative Control	0	0	0
C0(2): Negative Control	0	0	0

The nozzles used were: TeeJet™ Disc-Core type, D10 stainless steel Discs with brass DC56 cores. The final mixed spray applications were made at 1112 L/ha at a ground speed of 6.2 km/hr. The spray applications were made to past the point of run-off, which was tested and confirmed with water sensitive paper. The applications were made on dry warm evenings at approximately 28°C (1st application) and 22 °C (2nd application) at the time of application. Conditions remained clear, dry and hot for at least 72hrs after each application. The sentinel logs were split (with a steel wedge mounted to a hydraulic press) 5-6 weeks after application and mortality was assessed.

Biopesticides: Established Borer Control

A 16Ha block (H1 see appendix 1) of 1600 pecan trees (alternate rows of 40 Western Schley and Wichita) was chosen which had a high incidence of established borers. Estabished borer sites in lower limbs were found by looking for frass at the base of the trees. Established borer infested limbs were marked with fluorescent paint and randomly allocated as either “treated” or “control”.

The “treated” sites were sprayed with an oil emulsion containing 4% Synertrol Horti Oil™. The oil contained 45g of *Metarhizium anisopliae* spores (isolate No.FI-1375) per L of oil, which gave a final suspension concentration of 1.8g of *Metarhizium* spores per L of water. The product was manufactured, formulated and supplied by Becker Underwood. The suspension was sprayed from a hand held spray gun (nozzle type: Spraying systems Co., 5500 adjustable cone jet, 12V electric “Flowjet” pump model 4100-505) pumped from quad-bike mounted 2x70L interconnected tanks, calibrated at 2.5L/min.

The suspension was sprayed to well past the point of run-off and completely covered each borer site. A total of 130L of the suspension was applied to 31 tree sites (4.2L per tree).The *Metarhizium* fungus was applied on the 21st January 2009, from approximately 11:30am to 1:30pm.

The weather conditions at the time of application were dry and overcast at 28-31°C with a relative humidity of 35-49% and a North East wind speed of 15-20km/hr. The temperature dropped after application and remained cool for the remaining 24hrs (20-22°C). Rain started to fall from 5pm on the day of application and continued to fall for the following 24hrs (70mm).

From four to six weeks after application the limbs were removed by chainsaw and carefully split with a steel wedge mounted to a hydraulic press. Mortality and sporolation were recorded. Live larvae were kept in 500ml take away food containers with fresh pecan wood shavings and were monitored for further mortality and sporolation. Dead larvae were also kept and observed for sporolation.

Predatory Earwigs

Ring-legged earwigs *Euborellia annulipes* were found living and nesting inside borer galleries. The earwigs were observed (in the lab and in the field) to attack, kill and consume small longicorn borer larvae (and most other soft bodied insect). Earwigs were collected from borer galleries, under pot plants and in a compost bin.
Earwigs were mass reared in large plastic rectangular boxes (storage containers) 80cm x 50cm x 60cm, obtained from a discount shop (Crazy Clarks P/L). A rectangle ventilation window of approximately 40cm x 5cm was cut out of one end at about 15cm from the bottom. This window was covered with fine nylon gauze which was fixed with contact glue. The containers were filled with sterilized (autoclaved) moistened potting mix and/or soil to about 10cm high. A plastic card (45cm x 10cm x 0.5mm thick) was placed on top of the soil in front of the window. Ground (using a food processor) dry dog food was placed on top of the plastic card. The window provided ventilation to stop the food from going mouldy. Several layers of moistened corrugated cardboard (cut from cartons) were placed on top of the soil. A large plastic card (48cm x 70cm x 0.5mm thick) was placed on top of the cardboard, which covered most of the surface (apart from the food) to retain moisture. About 200 adult earwigs were placed into each container. About once a fortnight the food card was cleaned and food changed. At this time water was also misted onto the soil and cardboard layers. The earwig culture was kept at 23-25 ^{o}C. After 2-3 months the box would contain several thousand earwigs. The earwigs could easily be harvested by placing moistened corrugated cardboard cards (5cm x 5cm, kept together with staples) on top of the large plastic card cover. Another plastic card cover could then be placed on top to retain moisture. Earwigs would collect in the cards which could then be transferred or used by removing the entire cards (with about 10 earwigs per card).

Borer Biology and Tree Health

Position of limb attack, sun exposure, mechanical hedging

Observations

Observations were made throughout the Trawalla orchard on the position of borer attacks within the orchard and within the tree. Observations were also made on sun exposure and the action of mechanical pruning and effects on limb die-back. Some of these general observations were photographed and are shown in the results. Tree maintenance crews and long time farm workers were also consulted as to their experience and observations of borers and limb die-back.

Measurements

A study was also undertaken to measure limb die-back and borer attack in relation to sun exposure and mechanical pruning. Sites were chosen that had one complete face of the hedgerow that had full sun exposure to ground level. These were: F3 (appendix 1) along the edge of an East-West row that faced some houses and had full northern sun exposure and in A1 along the edge of a North-South row that faced a road and had full western sun exposure. Trees were randomly selected from the sun exposed rows and compared to randomly selected trees from within the more shaded interior of the orchard. All the trees were pruned the same way using mechanical pruning equipment, so the only difference between treatments was the exposure to sunlight. The number of borer sites (both old and new), live, dead and removed (dead) limbs were recorded above and below 3m from ground. Missing limbs were recorded as dead, as these were usually removed by tree maintenance crews after they had died.

Position and borer phenology within the tree

Borer infested limbs and trunks were observed and dissected with a chainsaw. Notes and photographs were taken on the borer larval stage and position within the timber and the condition of the timber in which it was found (e.g. live dead, moist, dry, decayed etc.). Tree maintenance crews and long time farm workers were also consulted as to their experience and observations of borers within the trees.

Improved Tree health through better canopy management

Canopy Modelling

A canopy modelling study was conducted by John Palmer of the Horticultural and Food Research Institute of New Zealand (HortResearch). The model examined the light interception and distribution within the canopy and between rows, throughout the growing season. The model calculations are described in Palmer (1977) and Palmer (1989b). The model was run for the Trawalla (Moree) location and inputs were based on the current 10x10m row spacing at Trawalla. The model looked at the effects of row orientation (North-South Vs East-West), canopy width, tree height and hedge shape (rectangular Vs tapered).

Leafhoppers

Leafhopper biology, damage and hosts

Identification

Specimens of the adult leafhopper were collected off pecan foliage and sent to Dr Murray Fletcher (Principal research scientist, research operations, NSW DPI, Orange NSW) for identification.

Leafhopper culture

Adult leafhoppers were collected (using an aspirator) from pecan foliage flush and cultured on potted castor oil plants *Ricinus communis,* as detailed by Freebairn and Smith (2002). This involved collecting seeds from wild castor oil plants and growing the potted plant outside. The plants were then caged and bagged (with nylon gauze) in the laboratory and adult leafhoppers were added. When new adults were reared through, they where then transferred (by aspirator) onto new plants. Two-spotted mite was often a problem on the caged plants indoors, but could be controlled with a wetter (Wetter 1000™ at 5ml/L) or insecticidal soap (Natrasoap™ at 10ml/L), after removing wanted leafhoppers.

Damage assessment and hosting (leafhopper exclusion/ inclusion experiment)

To test if the perceived damage to pecan foliage (i.e. leaf chlorosis, leaf curl, black pit marks and foliage death) was actually caused by leafhoppers, an exclusion/ inclusion experiment was set up. Pecan foliage flush (Wichita, Western Schley and Cape Fear varieties) was bagged (Figure 1) and either sprayed with Yates™ “ready to use” pyrethrum (exclusion) or approximately 40 leafhoppers were added to the bags (inclusion). Six replicates were bagged for each treatment. The bags were checked every week and removed after 10 weeks. Foliage was assessed for damage and leafhopper eggs and nymphs.

Plant host range for leafhoppers

The foliage in the exclusion inclusion experiments was also examined for leafhopper nymph emergence. Un-bagged foliage was also regularly examined for leafhopper nymph emergence. The orchard floor plants were examined regularly for leafhopper activity. Wild castor oil plant, *Ricinus communis*, growing on the edge of the orchard (generally on the river bank) was examined for leafhopper activity. Leafhopper activity was observed by direct observation of leafhopper adults and nymphs, by looking for leafhopper eggs laid into leaves and the use of emergence traps. Leafhopper eggs can be found by holding the leaves up to a light source and observing the translucent eggs in the leaf veins (Freebairn and Smith 2002). Emergence traps were set up by putting foliage into an enclosed darkened box or container, which contained a funnel leading up to a transparent tube. Insects would fly up towards the light source and get trapped in the transparent tube.

Leafhopper Parasitoids

Pecan foliage was collected regularly and examined for parasitoid emergence. This was done by directly examining leafhopper eggs (dissecting with a needle) and using emergence traps (as previously described). Leafhopper egg sentinel traps were also set up at locations near wild castor oil plants located at the orchard edge. This was done by leaving potted castor oil plants that had previously been infested with leafhopper eggs (as previously described in the “leafhopper culture” section), in the field for a few days.

Figure 1. Bagged exclusion/inclusion experiment. Pecan flush was bagged and sprayed with pyrethrum to exclude leafhoppers or bagged with leafhoppers added.

The castor plants were then placed in emergence traps and parasitoids collected. In an attempt to culture the parasitoids, the emerged adult parasitoids were placed onto fresh leafhopper infested castor oil plants.

Orchard edge and castor oil plants

This study was conducted to investigate the abundance of leafhoppers around castor oil plants in riverside vegetation at the orchard edge. In Jan-Feb 2007, yellow sticky traps (available from Bugs for Bugs, Mundubbera QLD) were placed in the field (Trawalla D1 and D2, Appendix 1). There were three treatments: (1) “River” amongst the riverbank vegetation within stands of castor oil plants, (2) “Edge” immediately adjacent to the riverbank in the pecan trees and (3) “Mid Crop” well within the pecan crop (approximately 30m in). There were four traps per treatment.

Another study was used to compare castor oil dominated vegetation with other riverbank vegetation (in the absence of castor oil plants). The study was conducted at “the point, Trawalla” from the 4th to the 8th of Feb 2007. Here, riverbank site locations could be found with and without castor oil plants. Traps were placed amongst the castor oil plants within the riverbank vegetation and in the tree crop immediately across the road. Traps were also placed in the riverbank vegetation where castor oil plants were absent and in the tree crop (tied to the lower foliage) immediately across the road. There were four traps per treatment.

Surfactants, oils and other additives

Laboratory Bio-assays

Bioassays were undertaken on various soaps, surfactants, oils and various additives. Treatments and concentrations are detailed in the results. Lucerne leafhoppers were cultured on castor oil plants as described above. Large (last instar) leafhopper nymphs were placed onto freshly harvested pecan foliage flush (Western Schley variety). Approximately 15 nymphs were placed onto each leaflet and 3 leaflets were used per treatment (approximately 45 nymphs were used per treatment). The leaflets were then sprayed with a small hand pumped spray-misting bottle (as used for indoor plants etc). The leaflets were sprayed so as to completely cover the entire leaf surface beyond the point of runoff. Controls were sprayed with boiled rainwater alone. The leaflets were then hung from a string with a plastic clothes peg and maintained at 25^{o}C. The leaflets were checked and mortality was assessed at 2hrs (data not shown) and then at 20hrs (the conclusion). Mortality was checked by probing the nymphs with a pin.

Field Trials

Neem

A neem product “Nutri-Neem cold pressed neem oil 85%™” by Nutri-Tech Solutions was applied at the rate of 0.2 ml/L (280ml/ha) “the low rate” and 2 ml/100L (2.8L/ha) “the high rate”, on the night of the 17th of December 2006 on a warm dry night. The product was applied in volumes of 1800 L water per ha. Applications were made with a ground airblast spray rig, with a vertical boom and nozzle type DVP5, 25607 Quick Tee Jet (S.S. Co.), at a ground speed of 5 km/h. Pressure at the nozzle was 7.5 bar. The treatments were made in a random block design (4 blocks per treatment) and leafhopper activity was measured using yellow sticky traps (2 per block, 8 per treatment).

Surfactant and oil trial

This trial used three treatments and a negative control. The treatments were:

- A paraffinic mineral oil (Trump Oil™ Vic chemicals, which is registered in pecans), at the label rate of 14ml/L or 25L(oil)/1,800L(water)/ha,
- A surfactant (Wetter 1000™ a non-ironic 1000g/L alkoxylated alcohol wetter, by Ospray Pty Ltd) only, at a high rate of 5 ml/L or 9 L (surfactant)/1,800 L (water)/ha.
- A low rate of the same surfactant at 0.5 ml/L or 0.9L(surfactant)/1,800L(water)/ha) with Experimental Synergist at 7.14 ml/L(water), which is the equivalent of 0.5% (w/v) final concentration of dry Experimental Synergist /L of water.

To counter the migratory effects of the leafhoppers, the treatments were applied to large blocks (of at least 16 ha/treatment) and the samples were collected from the centre of those blocks. The treatments were applied on the night of the 18th Dec 2007. The applications were made with the same equipment and conditions as described above in the neem trial. It rained towards the end of the spraying program which may have affected the results.

Leafhopper activity and leaf damage was assessed in February 2008, by collecting 3 random terminal leaves from the tops of 10 Western Schley trees (the most affected variety) per treatment. Damage was assessed by counting the number of feeding marks per cm of leaflet midrib. This was done by marking 1cm with a scalpel (measured with digital vernier callipers) and counting the black marks under a dissecting microscope (see Figure 18 of results section). There were 3 leaflets counted from each of the 10 trees accessed.

Orchard Understory Management: Mowing Trials

There were three mowing treatments. They were:

- A full mow, where the understory is grown long, then all rows were mowed at the same time, approximately every 6-8 weeks.
- A short mow, where all rows were mowed regularly, about every 4 weeks.
- An alternate row mowing treatment, where every 2nd row was mowed every 6-8 weeks, alternating 3-4 weeks apart.

There were at least 64 Ha per treatment. Alternative row and short mow treatments commenced on the 11th October 2006. A full mow occurred on the 14-17th Nov 2006. Very little Leafhopper activity was recorded before this date. The mowing was done using large PTO tractor driven slashers.

To monitor leafhopper activity yellow sticky traps (available from Bugs for Bugs, Mundubbera QLD) were hung the in pecan canopy. There were 12 traps per treatment and they were changed at 6 weeks. Traps were replaced and leafhoppers counted on the 24 Nov 2006 (1 week after mowing). Traps were again removed and leafhoppers counted on the 7th January 2007. To monitor leafhopper damage (i.e. direct leaf damage) feeding marks (per cm of midrib) were measured from terminal leaflets harvested in February 2007 (as described above in the surfactant and oil trials).

Predators were monitored with sweep nets through the understorey (at 20 sweeps per 20m transect and 10 –20 transects per treatment).

Results

Borers

Biopesticides: Neonate control

Laboratory Controls (positive controls)
The following mortality rates were recorded for the laboratory controls:
High rate: 9/10 = 90% mortality
Medium rate: 10/10 = 100% mortality
Low rate: 3/10 = 30% mortality.
Oil only 0/10 = 0% mortality
Neg Control 0/10 = 0% mortality
All dead larvae showed typical green *Metarhizium* sporulation.

Field trials
Mortality of borer neonate larvae ranged from 62-90% for the oil only controls and all other treatments were within this range (Figure 2).

The average number of larvae that survived per log, ranged from 2 to 7.5. There was no significant difference between any of the treatments (P=0.73, F=0.669, DF=9,30, ANOVA). The fungus treatments did not kill any more larvae than the controls or oil only treatments. There was also no difference between the various rates applied.

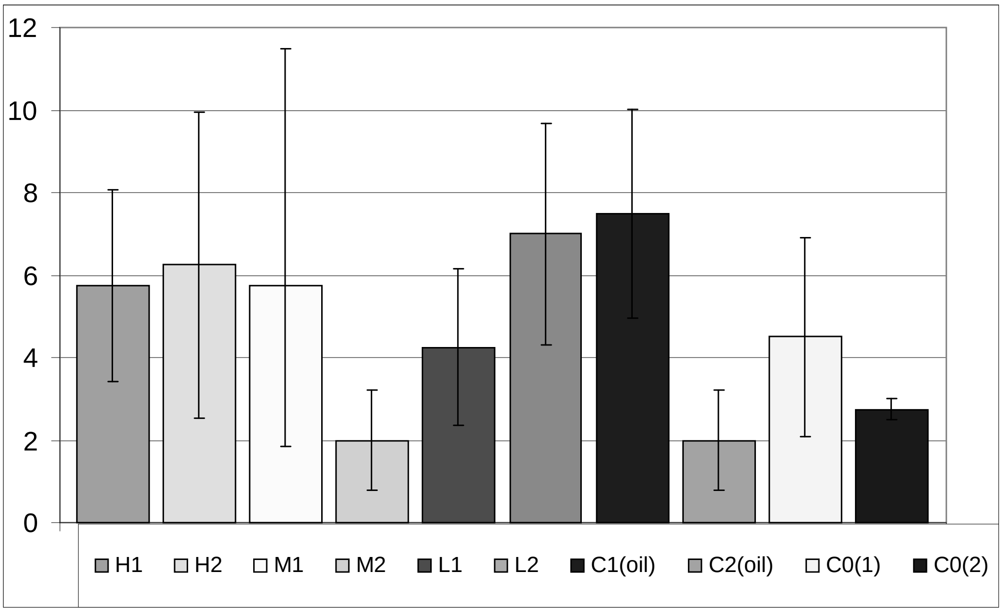


Figure 2. Average number of surviving neonate larvae per log. There was no significant difference between treatments or controls. Bars = standard error. Treatments were: H1 = high rate applied once, H2 = high rate applied twice, M1 = medium rate applied once, M2 = medium rate applied twice, L1 = low rate applied once, L2 = low rate applied twice, C1 = oil only applied once, C2 = oil only applied twice, C0(1) and C0(2) = negative controls with no sprays.

Pooling (combining) the treatments and controls did not make any difference as there was still no significant difference between the treatments and controls (P=0.527, t=2.02, DF=38, students t-test) (Figure 3).

Biopesticides: Established Borer Control

The *Metarhizium* fungus treatment had an effect on established larvae and demonstrated some level of control. Established borer larvae mortality was significantly higher (P=0.007, t=2.00, DF=58, t-test, log10+1 transformation) in the fungus treated sites (9.73% mortality) compared to the unsprayed negative controls (0.785% mortality) (Figure 4).

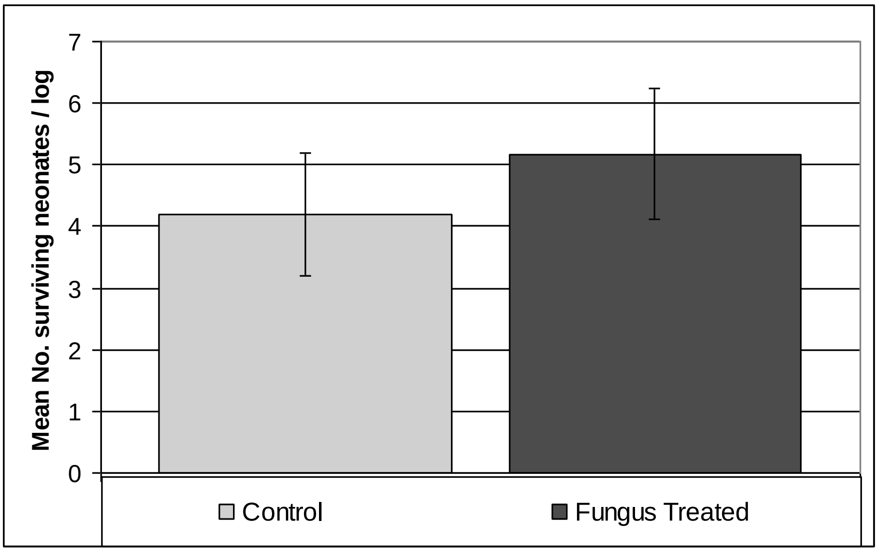


Figure 3. Average number of surviving neonate larvae per billet (log). Bars = standard error, for pooled treatments and pooled controls (including oil only). There was no significant difference between fungal treatments and controls.

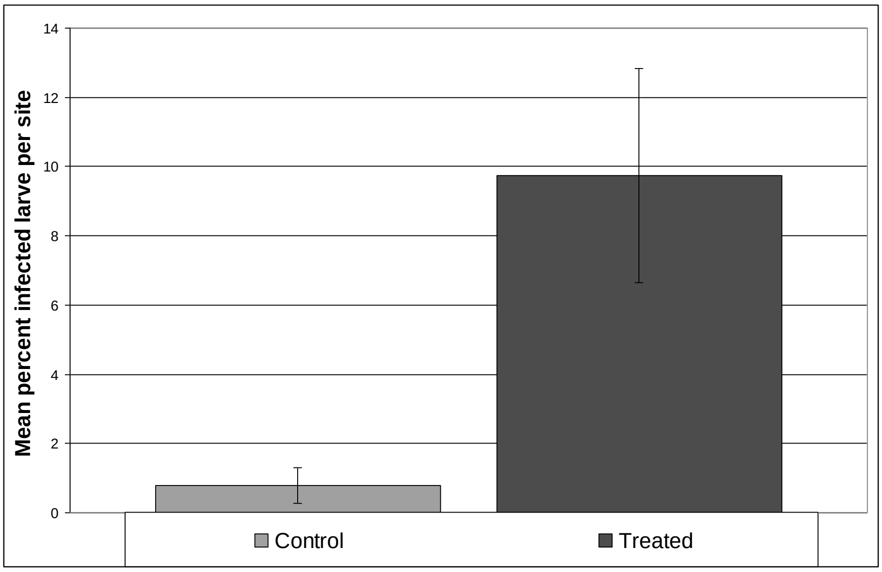


Figure 4. Average larval mortality of established borers in *Metarhizium* fungus treated sites verses untreated controls. There was significantly higher mortality in the fungus treated sites (P=0.007, t=2.00, DF=58, t-test log10+1 transform). Bars = standard error.

Predatory Earwigs

Although the predatory earwigs were found to be ferocious predators of small borer larvae they were not accessed for release in the field. On close observation it was found that the earwigs were abundant throughout the orchard at Trawalla. The earwigs were often observed in great numbers: in most borer galleries (where they were found nesting), in cracks in the pecan bark, in cracks in the timber, in fallen logs and in/on the ground. Therefore, it was concluded that there would be would be no advantage in mass-rearing and releasing them at Trawalla, as it would be impossible to enhance them more than their already high numbers.

Borer Biology and Tree Health

Position of limb attack, sun exposure, mechanical hedging

Observations: Limb death and the effect of hedging and sun exposure
It was observed that where full sun is available to the lower canopy there is very little limb death and borer activity. Limb death could be observed within the lower shaded areas of the canopy where no mechanically hedging has taken place, e.g. within the hedge row (Figure 5). This demonstrates that (in this case) it is not mechanical hedging that is causing the limb death. Throughout the Trawalla orchard there are examples on the edge of blocks where full sun reaches the lower canopy. These faces were mechanically hedged in exactly the same way as within the block, but there is very little limb death and borer activity (Figure 7). Yet within the same block (in the shaded interior) there is a high level of limb death and borer activity (Figure 6). The lower limbs in the full sun have had the same levels of pruning damage as has occurred within the shaded canopy. However, it was observed that where these limbs were exposed to full sunlight, they produced many healthy shoots that rapidly healed over the pruning wounds. The same response was observed in the upper canopy, which also receives more sunlight. Conversely, the shaded lower limbs did not produce many viable shoots (where they did, the shoots often died later in the season), they did not heal over and subsequently died back and were attacked by borers. Mechanical hedging does not appear to be the factor in limb death or borer attack.

Measurements: Full Northern sun exposure to East-West rows
Limb death was caused by shading and not the act of mechanical hedging. In this study, both treatments had the same mechanical hedging treatment, but differed only in the amount of Northern sun exposure to the lower limbs. The lower position of shaded tree rows within the orchard had significantly more dead or dying limbs than the same position from a row of trees with full northern sun exposure (t-test, $P<0.001$, $t=2.04$, $DF=30$) (Figure 8). The lower position of the row of trees with full northern sun exposure also had the highest number of live limbs (Figure 9).

Measurements: Full Western sun exposure to North-South rows
The same pattern was seen in N-S rows (A1), where full western sun exposure was compared to the shaded orchard interior. Again, the lower position of shaded tree rows within the orchard had significantly more dead or dying limbs than trees with full sun exposure (Figure 10). Again, the sun exposed trees had significantly more live lower limbs (Figure 11).

Borer Infestation and the effect of hedging and sun exposure
In A1 there were more trees that had borer infestations in the shaded trees than the sun exposed trees (Figure 12). There were 0.45 borers sites per shaded tree which was significantly more than the 0.048 borers sites per sun exposed tree. Both treatments were exposed to the same mechanical hedging. In F3, 25% of the shaded trees had borer infestations and the sun exposed trees had zero infestations.

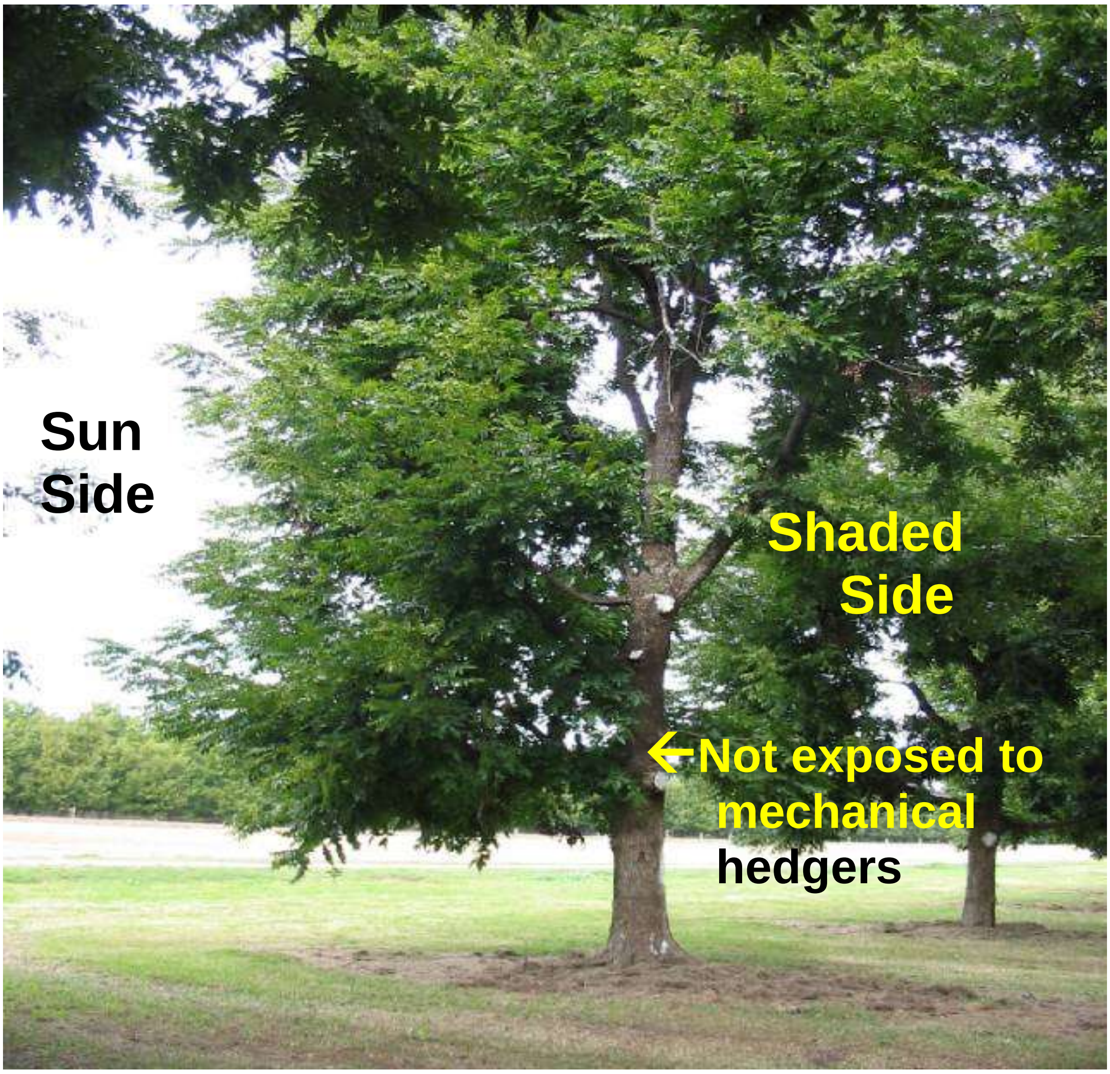


Figure 5. Tall (18m high) Wichita tree rows in F3, showing the full sun exposed position (facing east to the airstrip) with full lower canopy and live lower limbs. The western (shaded) side has lost several limbs (note white paint over wounds) due to shade-out. These limbs were within the hedgerow and therefore, were not exposed to mechanical hedgers.

Figure 6. (Above) within the orchard of a block of tall trees (F3), Showing removed lower limbs (white paint) and a recently dead limb (circled). Note the complete absence of lower canopy and thick upper canopy.

Figure 7. (Left) The same block of trees as above (F3) from the orchard edge. This row receives full northern sun. These trees received the same mechanical hedging as within the block (above), but have had no dieback, very few limbs removed, a full live lower canopy and no borer activity.

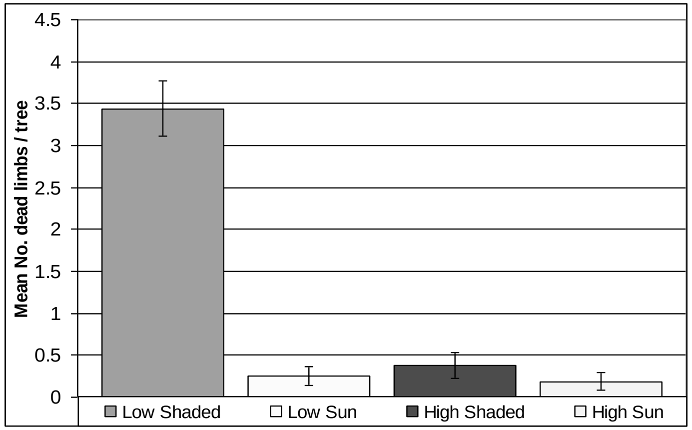


Figure 8. E-W rows (F3). Average number of dead or dying limbs/tree in low (lower than 3m) or high (higher than 3m) positions for full northern sun exposed trees Vs shaded (within orchard) trees.

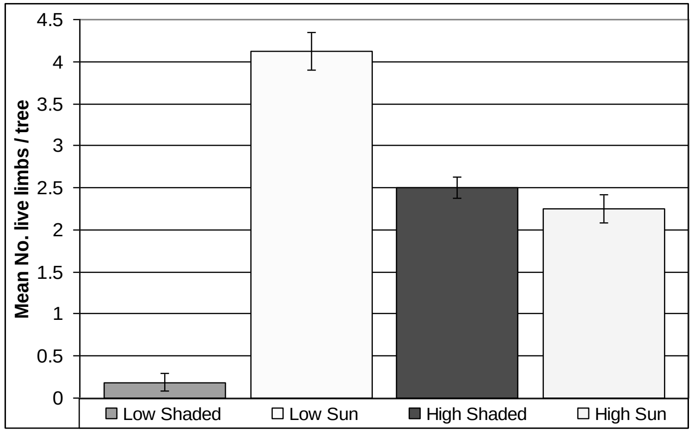


Figure 9. E-W rows (F3). Average number of live limbs in low (lower than 3m) or high (higher than 3m) positions for full northern sun exposed trees Vs shaded (within orchard) trees.

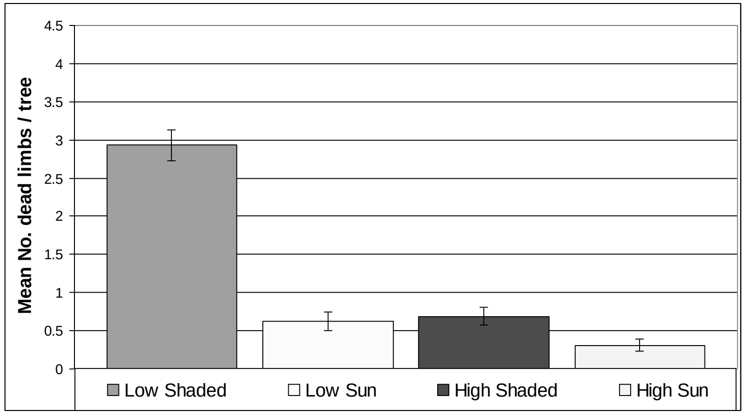


Figure 10. N-S rows (A1). Average number of dead or dying limbs/tree in low (lower than 3m) or high (higher than 3m) positions for full western sun exposed trees Vs shaded (within orchard) trees.

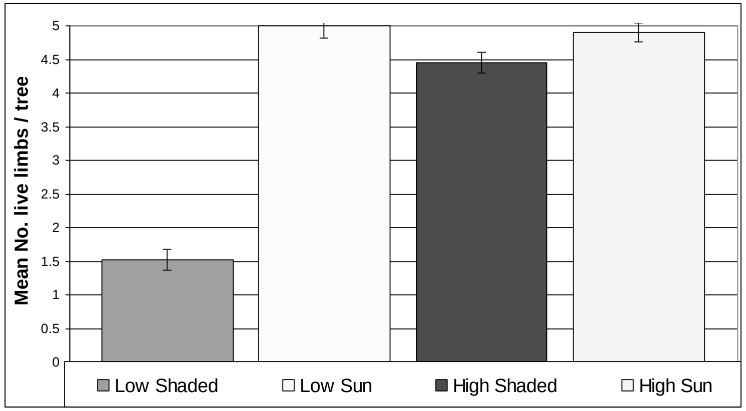


Figure 11. N-S rows (A1). Average number of live limbs in low (lower than 3m) or high (higher than 3m) positions for full northern sun exposed trees Vs shaded (within orchard) trees.

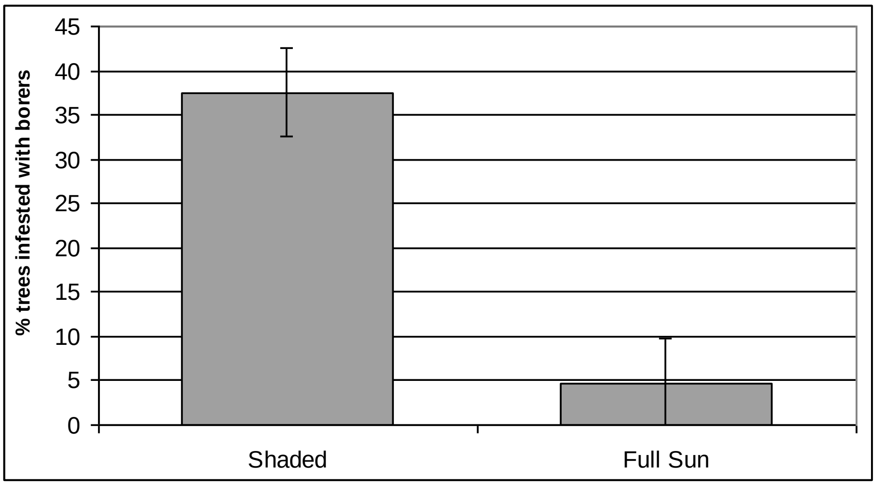
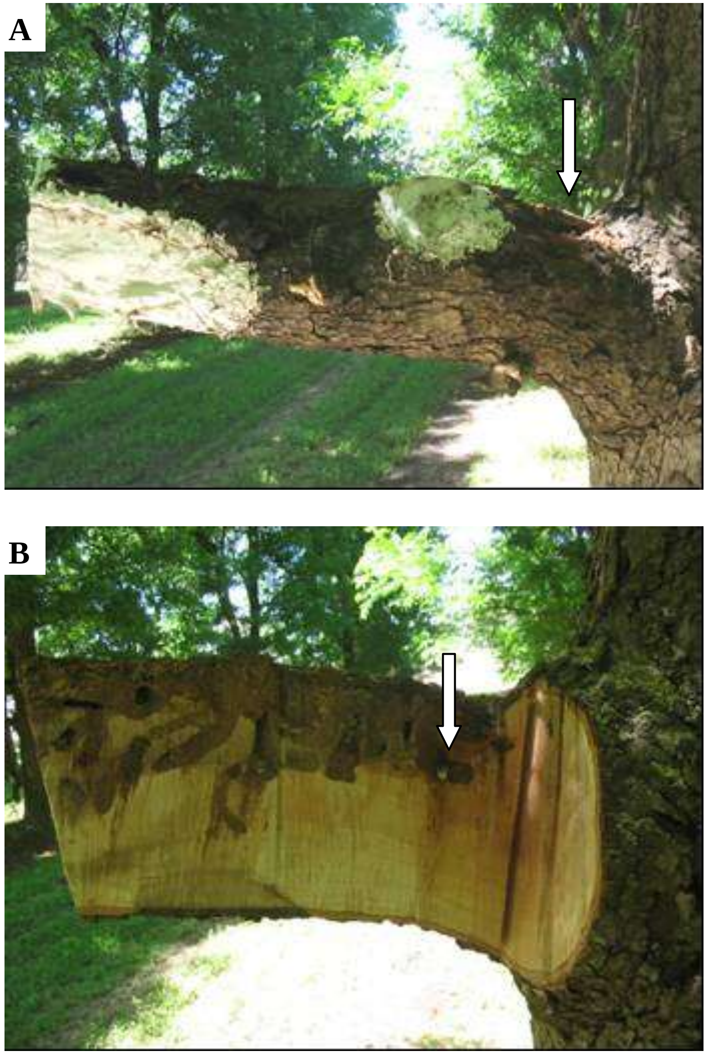


Figure 12. Percentage of trees in block A1 that were infested with borers that were shaded (within the block) and trees that were exposed to full western sun light. There were significantly more borers per tree in the shaded trees.

Position and borer phenology within the tree

The observations (by the author and long term farm workers) were that most borer infestations are nearly always found in the lower limbs or in the trunk region where lower limbs were removed. Borer infestations were rarely observed in the upper canopy. Most borer infestations were observed to be found in limbs that are dying from shade-out (Figure 13A). Dissecting these limbs revealed that the great majority of borers were found in dead timber (Figure 13B). The borers appear to have a preference for dead timber that is close to live timber (Figures 13B and 13C). Borers were rarely observed in live timber. When they were seen in live wood they were usually very large (probably at least 2-3 years old) and their galleries were close to the dead wood, usually with the majority of their galleries occupying the dead wood zone (Figure 13C). They rarely appear to travel very far into the live wood, usually within no more than 20-30mm from the dead open wood. Most small larvae were found within the dead wood, but close to the live wood. Some very small borer larvae (about 5mm long and less than 6 months old) were observed residing in the frass of larger borer galleries.

Most galleries that were found within the trunks were in the lower position of the tree, usually where a lower limb has died back (due to shade-out) and/or was removed by chainsaw (Figure 14A). Some of the worst affected trunks are those that have repeatedly been cut with chainsaws (to remove borers). Observing and dissecting these trunks (Figure 14B), revealed a similar pattern of borer attack as to what was observed in the lower limbs, i.e. most of the borers are found in dead wood that is close to living wood, with an occasional large larvae moving a small distance into live timber (Figure 14C). Borers were not found above or below the open wound, but were restricted to the open dead wood zone (Figure 14A). In trees that have been cut and “opened up” in the trunk region, the timber was observed to dry out, become brittle and crack. It was observed that this process occasionally results in tree collapse (usually after high winds). It is believed that these trees collapse because of the act of opening up and exposing the timber and subsequent dying and drying of the timber Cracks in the dead dry timber are often observed in such trees and these trees have been observed to subsequently fall. Therefore, the collapse is not caused by borers.



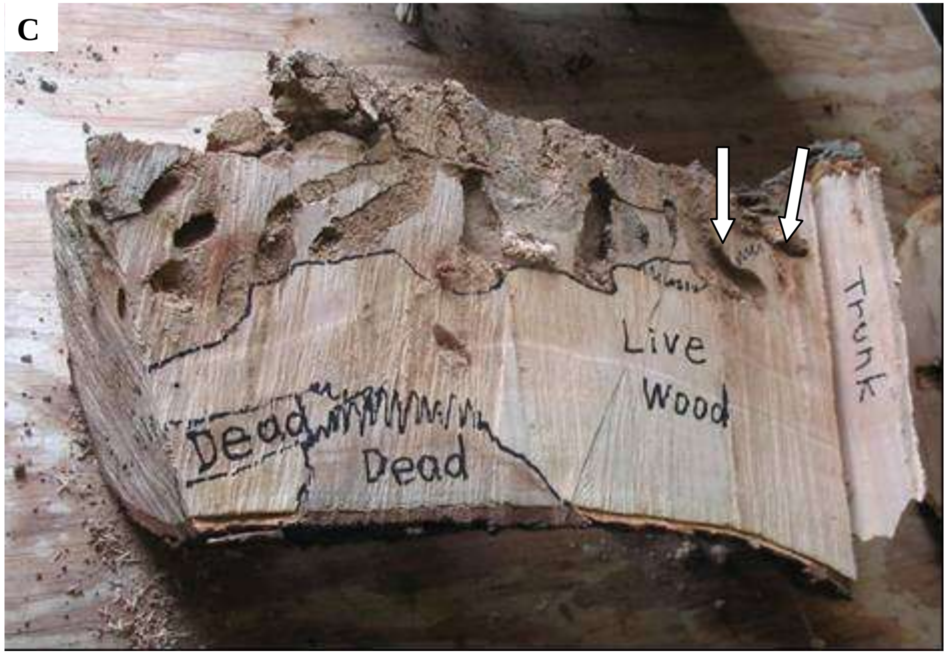


Figure 13. Typical borer infestation from dying lower limb, showing:
(A) in situ before removal, frass is seen exuding from the top (arrow).
(B) longitudinal section removed from limb showing live clean un-infested wood and borer galleries within dead timber. A large borer is shown in the edge of living and dead timber (arrow).
(C) Same limb removed and labelled showing borer galleries absent from most live wood, but occasional found in the living/dead wood zone (arrows).

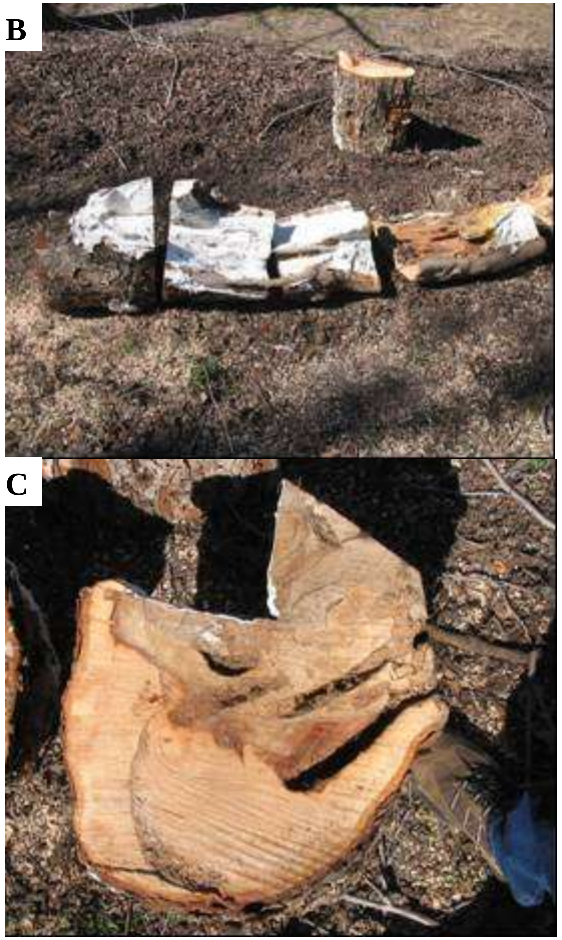


Figure 14. Borer infested trunk: A) before being dissected. B) cross section dissection cuts. C) a cross-section showing borers restricted to dead and edge of living timber.

Figure 15. Showing infested trunk healing up and sealing borers within.

In the authors four years of working at Trawalla no trees were observed to collapse due to borers. Interviews with long term farm workers also revealed that most tree collapses occurred where trees were previously “opened up” with chainsaws.

Trunks that are infested with borers and where chainsaw work was limited appear to heal up and thus seal up the borers (Figure 15). These sites are unlikely to host future borers and may be unsuitable for the existing borers as the moisture content and turger pressure could be too great (see discussion).

Improved tree health through better canopy management

Computer Modelling

Total Light Interception
The computer model predicted the total amount of light intercepted by the trees (verses what light reaches the orchard floor). The model found that interception increases with tree height and canopy width. It found that North-South rows intercept a total of 70-80% of the light (in mid summer), whereas East-West rows only intercept 30-50% of the total light. This means that in E-W rows at least 50% of the sunlight directly hits the orchard floor without reaching the pecan canopy. However, by the end of the season, the light interception increases to over 90% in E-W rows (because of the low angle of the sun), which may be too high and will cause significant inter-row shading. Whereas the N-S rows intercept 70-80% of the light season long.

Light Interception and Tree Height
The relationship between tree height and light interception is curvilinear for N-S rows throughout the season and the model predicts little advantage in increasing tree height beyond about 14m. However, if the trees are truncated (hedged with a sloping side) the relationship becomes more linear (less curvilinear) and there is an advantage in terms of increased light interception for growing N-S trees higher than 14m.
For E-W rows there is a strong linear relationship between total light interception and tree height. Therefore, in mid-summer there is a significant interception advantage in growing these trees up to 18m high. However, at this height between row shading and within canopy shading becomes an issue, particularly late season.

Between Row Shading
East-West rows are not affected by between row shading during most of the summer growing season, but they are affected in Autumn in the lower part of the canopy. This problem is exacerbated by the taller (18m) Wichita trees that will completely shade out the lowest 8-10m of the Western Schely trees at this time.

North-South rows are affected by neighbour row shading throughout the season. The top 4m (from the top of the neighbouring row) is not affected and receives about 90% of the daily photosynthetic active radiation (PAR, the trees usable light). However, at 10m down (from the top of the neighbouring row) the canopy only receives about 70% of the daily PAR.

Shading Within the Canopy (within the hedgerow)
The canopy width only makes a small difference to within canopy shading (if disregarding between row shading). There was very little difference between the 2.4m (8ft) or 3.6m (12ft) wide hedge (2% difference in daily PAR). The light generally penetrates 1m or less into the canopy.

Tree height affects E-W rows (4-5m from top), but not so much N-S rows. At 4m down from the top, E-W trees receive less than 17% of daily PAR (when compared to 100% daily PAR on top of the tree). Whereas, in N-S rows 17% of daily PAR is found at 12m down from the top. From observations, this is about the point at which the canopy finishes before it is shaded out.

Row orientation (N-S verses E-W rows) appears to make significant differences in within canopy shading. The N-S rows receive about twice as much light as the E-W rows at 4m from top. The N-S rows receive consistent sunlight (on both sides of the hedge) throughout the season, whereas the E-W rows are heavily shaded (worse on the south side) and variable throughout season.

Hedge Shape: Tapered Vs Rectangular
Using a tapered or triangular shaped hedge improved within-row shading in both E-W and N-S rows. In EW rows there was a large improvement at the periphery of the canopy (but not within the canopy interior). In tapered N-S rows there is more light at the periphery and within the canopy interior compared to a rectangular hedge.

Converting the trees by truncating and changing to North-South
If the rectangular E-W hedgerows were converted to tapered N-S hedgerows then the trees would intercept more of the light and have less within row shading.
Tapered N-S hedge rows intercept 70-80% of total orchard light, whereas rectangular E-W rows only intercept 30-50% of total orchard light. Within the hedgerow, a tapered N-S hedgerow (compared to a rectangular E-W hedge) receives approximately three times as much light at the canopy periphery (4-12m down from top) and six times as much light inside the canopy (0.5m within the canopy, 4-12m down from top).

Leafhoppers

Leafhopper biology, damage and hosts

Identification
Specimens of the adult leafhopper that were collected off pecan foliage were identified by Dr Murray Fletcher as *Austroasca alfalfae* (Evens) Cicadellidae (Figure 16).

Damage assessment and hosting (leafhopper exclusion/ inclusion experiment)
Where leafhoppers had been “included”, the pecan foliage was damaged (Figure 17). The damage symptoms included black/brown pit marks (feeding marks) along the leaf midribs, leaf veins and new stems (Figure 18). Other symptoms included leaf curling, leaf chlorosis (yellowing), stunted leaf growth and eventual leaf death. The symptoms were identical to the damage observed externally in un-bagged fresh pecan flush,

which was previously observed in pecans and was attributed to leafhoppers. Where leafhoppers were "excluded" the foliage was healthy and showed none of the symptoms (Figure 17).

Figure 16. Adult leafhopper, identified as *Austroasca alfalfae.*

Figure 17. Bagged exclusion experiment, showing undamaged pecan foliage from the leafhopper excluded treatment (left) and damaged foliage from the leafhopper included treatment (right). Note the leaf curling and black feeding marks.

Plant host range for leafhoppers

Leafhopper eggs and emerging nymphs were found in the pecan foliage flush in the bagged "inclusion" treatment and pecan un-bagged foliage (Figure 19). Leafhopper nymphs emerged from Wichita, Western Schley and Cape Fear pecan varieties. No leafhoppers emerged from the bagged "exclusion" treatment. Leafhoppers were restricted to the tender new foliage flush of pecans and did not feed on or lay eggs in mature foliage. The leafhoppers were observed to attack most pecan varieties, but the most severe attack was observed on the tops of Western Schley after they had been machine top-pruned the previous winter.

When the Western Schley trees were not top-pruned leafhopper damage was observed to be very minor. The leafhopper damage was also generally minor in the Wichita cultivar, but this variety had not been top-pruned during the course of this research. During the new spring flush (bud-burst to November) in the pecans, the leafhoppers were usually only observed in very low numbers. Although leafhoppers could be found during most of the pecan season it was only observed in high abundance during mid summer (December-January, see mowing results below). After December leafhoppers were still abundant, but there was very little pecan flush available for them.

In the orchard understory, leafhopper adults were found in Common Sowthistle *Sonchus oleraceus* and White clover, *Trifolium repens*. Leafhopper adults were also found in wild castor oil plants *Ricinus communis* located at the orchard edge. The castor oil plants were heavily attacked by the leafhoppers (usually observed late in the season around February), which appeared to cause a significant amount of damage to them, including: yellowing, leaf-curl and leaf death (similar to pecan damage). Leafhoppers collected from pecan foliage were cultured on castor oil and white clover, but fewer nymphs emerged from clover (not quantified). When the leafhoppers were cultured on castor oil plants the foliage would become damaged, with the same symptoms observed in natural heavy infestations.

Leafhopper parasitoids

Two species of leafhopper egg parasitoid were found in the leafhopper eggs in pecan foliage and castor oil sentinel traps. One species was identified as *Stethynium sp*. probably *Stethynium* nr *empoascae* (Figure 20) The other parasitoid was *Anagrus sp.* (species not identified). The *Stethynium sp*. was subsequently cultured in lucerne leafhoppers on castor oil, but only in low numbers (two spotted mite was a problem in the caged indoor castor oil plants).

Orchard edge study

There were significantly more leafhoppers on the riverbank amongst the castor oil plants than there were in the pecan trees (ANOVA, $P<0.0001$, $F=4.25$, $DF=2,9$), but no difference between the leafhoppers in the pecan trees (edge Vs mid crop) (Figure 21). The presence of castor oil plants influenced the number of leafhoppers, with significantly more leafhoppers being trapped where castor oil plants were present (ANOVA, $P<0.02$, $F=5.90$, $DF=3,7$) (Figure 22).

Figure 18. Feeding marks from leafhoppers showing damage to leaf midrib and veins.

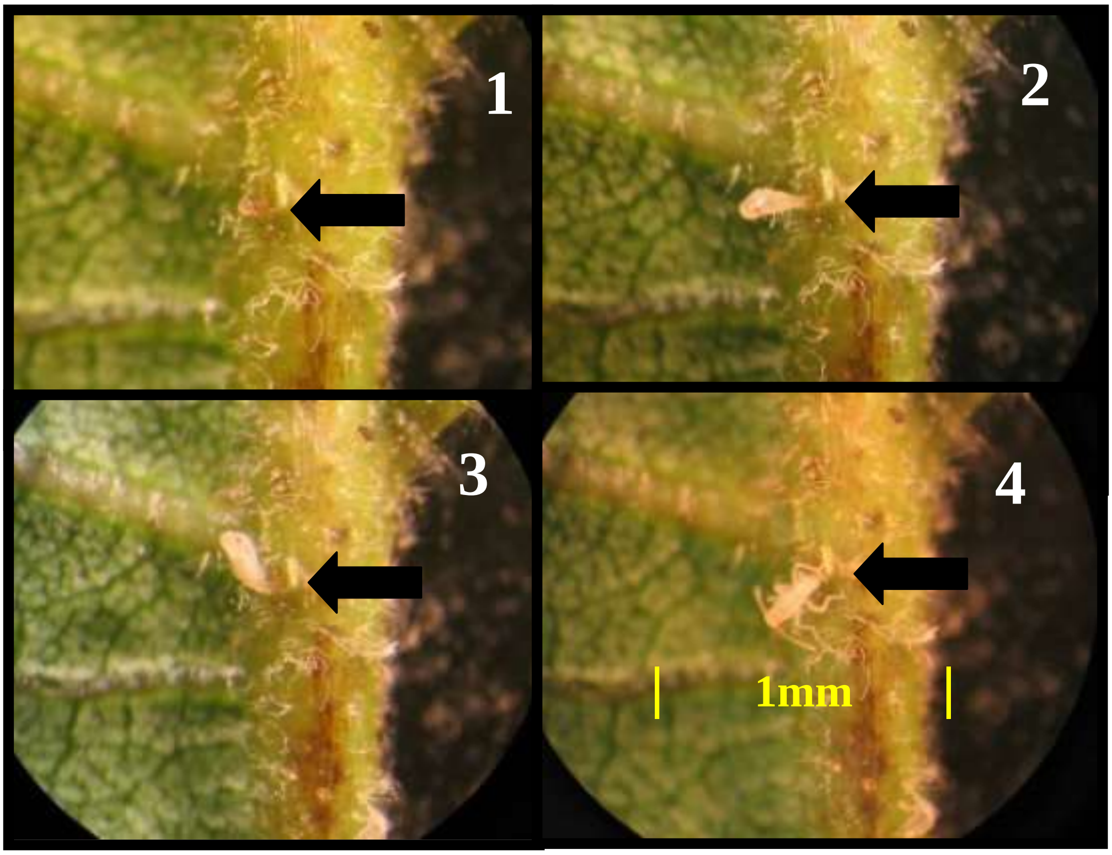


Figure 19. Pecan leaf (Western Schley variety), showing *A. alfalfae* leafhopper nymph emerging from the midrib.

Figure 20. *Stethynium sp*. parasitoid found in leafhopper (*Austroasca alfalfae*) egg in sentinel castor oil leaf vein.

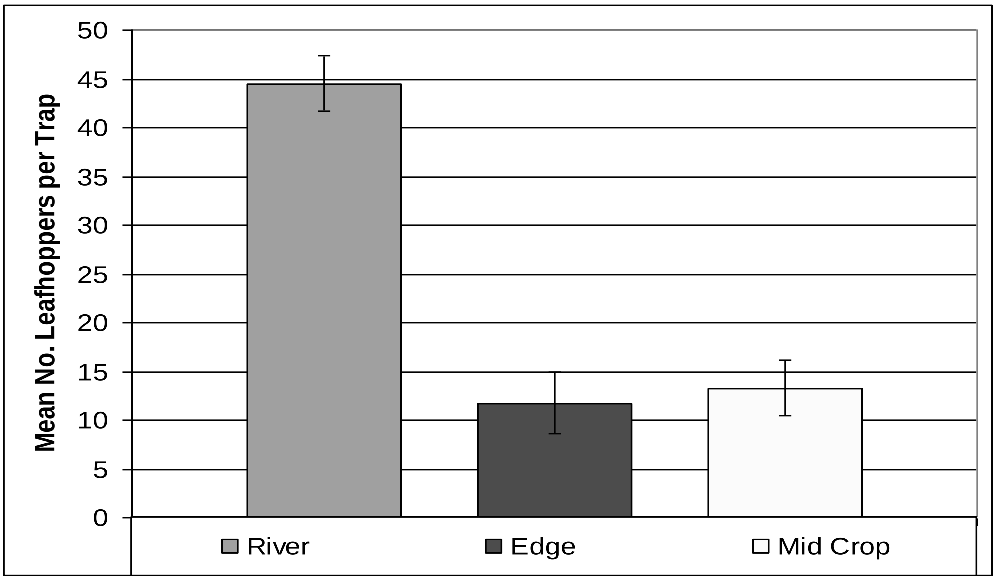


Figure 21. Orchard edge study, showing average number of leafhoppers per yellow sticky trap, on the riverbank (amongst castor oil plants), on the pecan trees at the "edge" of the orchard and within the pecan tree crop (Mid Crop).

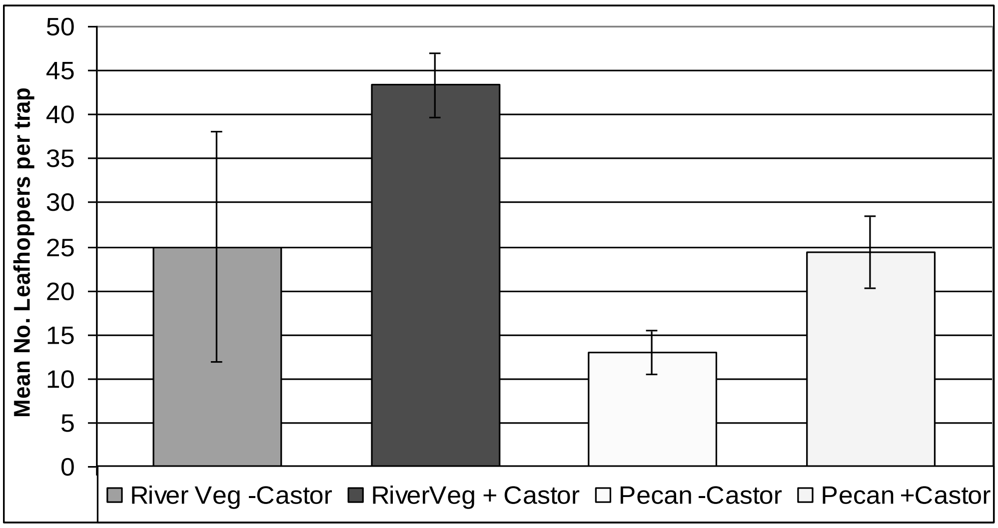


Figure 22. Orchard edge study, showing average number of leafhoppers per yellow sticky trap, in riverbank vegetation amongst castor oil plants (River Veg +Castor), in riverbank vegetation without castor oil plants (River Veg –Castor), on the pecan trees at the edge of the orchard and with castor oil plants (Pecan +Castor) and without castor oil plants (Pecan –Castor). It can be seen that there were more leafhoppers where castor oil plants were present.

Surfactants, oils and other additives

Laboratory Bio-assays

Insecticidal Soap Dose-Response

An insecticidal soap (Natrasoap™ by AgroBest Australia Pty Ltd) was bioassayed using leafhopper nymphs on pecan leaves at concentrations of 1, 5, 10 and 20ml/L of water. It was found that at soap concentrations of 5ml/L or less, mortality was less than 10% (Figure 23). However, at 10 ml/L there was over 90% mortality. At 20ml/L mortality was not much higher than it was at 10ml/L.

Insecticidal Soap and Additives

The soap manufacturer recommended adding a vegetable based horticultural oil. Adding different horticultural oils (Synertrol Horti Oil™-Organic Crop Protectants, Eco Oil™ -Organic Crop Protectants and Spraytech Oil™-AgroBest) at 2ml/L to the insecticidal soap (Natrasoap™) did not increase mortality more than using the soap alone (Figure 24). However, the addition of an Experimental Synergist (E.S.) at 10g/L (1% W/V) did increase mortality.

Insecticidal Soap and a Synergist.

A bioassay was undertaken at various rates of E.S., to determine if lower concentrations of E.S. will still synergise with insecticidal soap. One concentration of soap (Natrasoap™) was tested at 7.5ml/L, against 0.25, 0.5 and 1% E.S. (Figure 25). All E.S. additions increased mortality, but concentrations above 0.5% did not increase mortality. E.S. alone did not increase mortality more than the control.

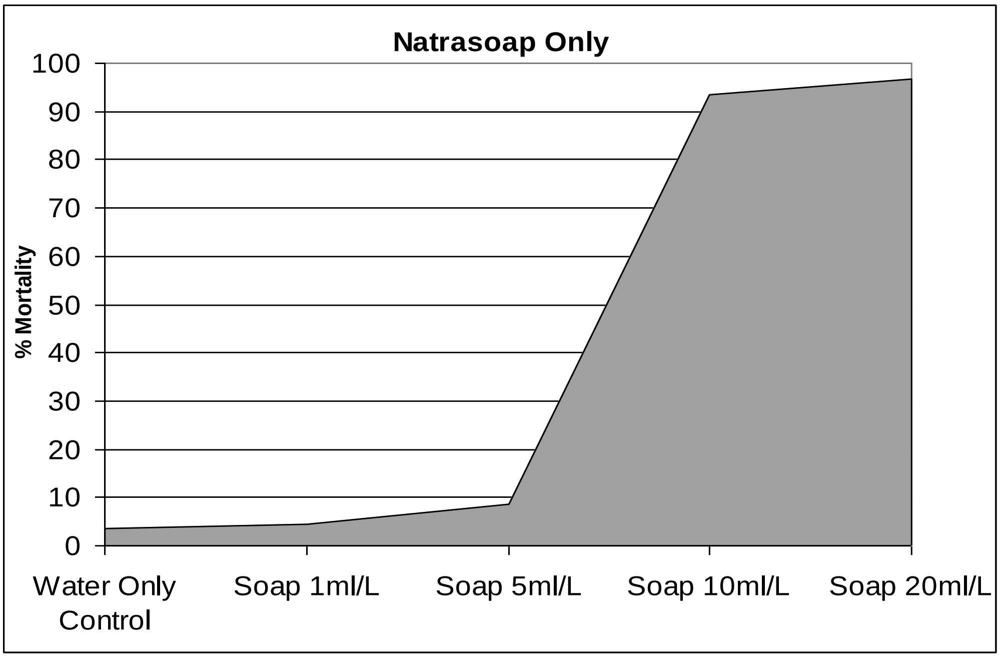


Figure 23. Insecticidal soap (Natrasoap™) bioassay using leafhopper nymphs on pecan leaves, showing mortality (%) at 20hrs post treatment. At concentrations of 10ml/L, mortality was over 90%.

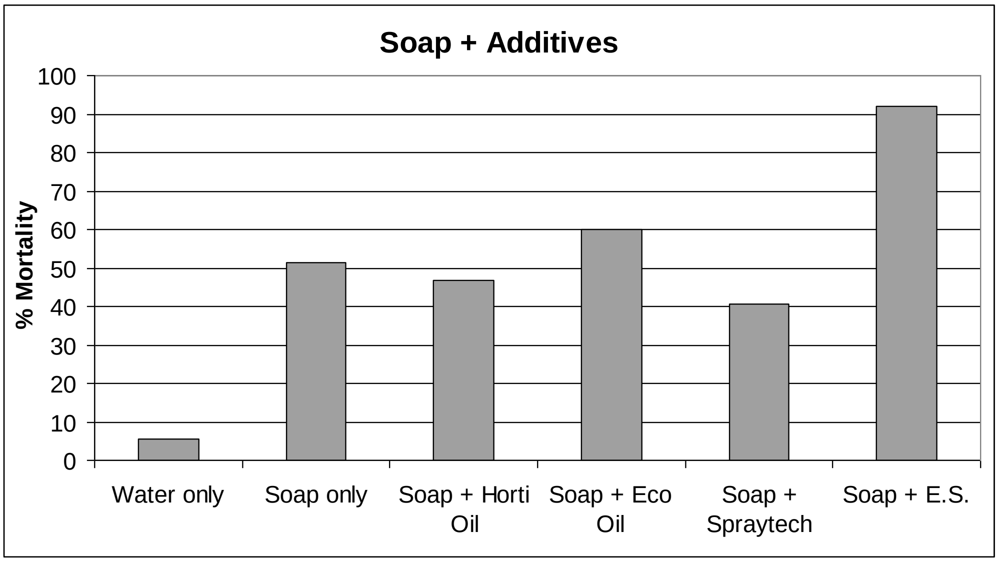


Figure 24. Insecticidal soap (Natrasoap™) bioassay using leafhopper nymphs on pecan leaves, showing mortality (%) at 20hrs post treatment. Soap was at 7.5ml/L, oils (Synertrol Horti Oil™, Eco Oil™ and Spraytech Oil™) were at 2ml/L and E.S. was at 10g/L (1% W/V).

Surfactants and a Synergist

Another bioassay showed that a surfactant (Wetter 1000™ a non-ironic 1000g/L alkoxylated alcohol wetter, by Ospray Pty Ltd) was more affective than the insecticidal soap (Natrasoap™) (Figure 26). Leafhopper mortality also increased with the addition of E.S. (0.5%) to the surfactant. Over 90% mortality was achieved at 1ml/L of Wetter 1000™ plus 0.5% E.S. Increasing the concentration of surfactant did not appear to make much difference.

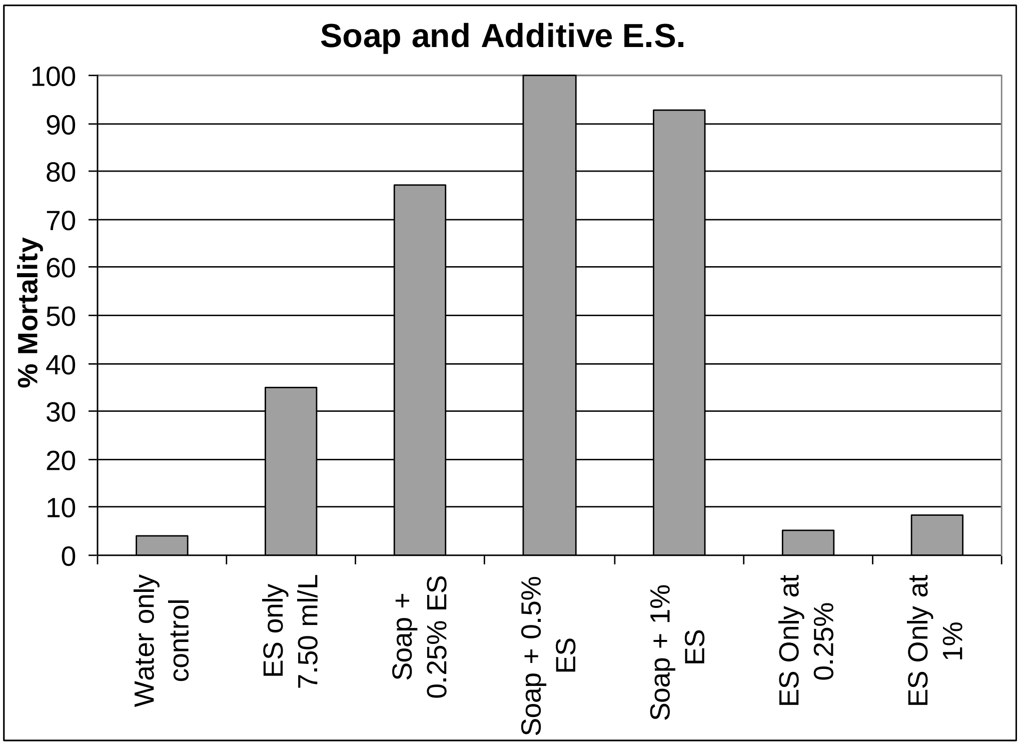


Figure 25. Insecticidal soap (Natrasoap™) bioassay using leafhopper nymphs on pecan leaves, showing mortality (%) at 20hrs post treatment. Soap was applied at 7.5ml/L, E.S. was applied at various rates.

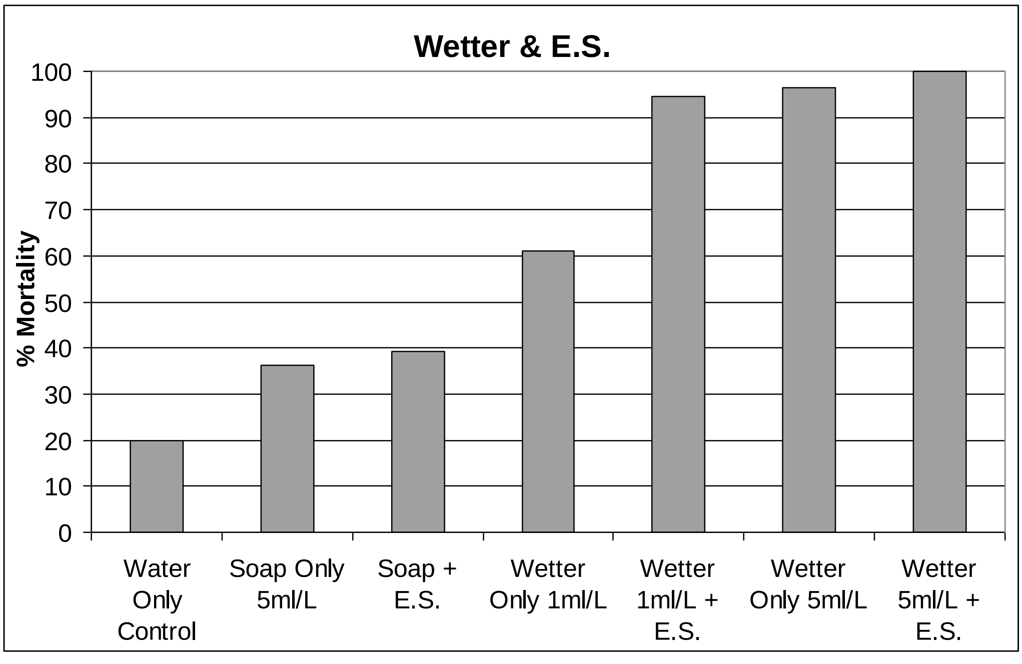


Figure 26. Bioassays of insecticidal soap (Natrasoap™) a surfactant (Wetter 1000™) and 0.5% E.S., using leafhopper nymphs on pecan leaves, showing mortality (%) at 20hrs post treatment. Soap was applied at 5ml/L, surfactant (Wetter) was applied at various rates.

A bioassay was undertaken at various rates of surfactant (Wetter 1000™), to determine if lower concentrations of surfactant will still synergise with E.S. (Figure 27). It was found that concentrations as low as 0.3 ml/L of surfactant and 0.5% (W/V) E.S. produced over 90% leafhopper mortality. Although it was not quantified, the surfactant (Wetter 1000™) at 1ml/L and 0.5% E.S. was also effective at controlling two-spotted mites on castor oil leaves (mites were a problem in the leafhopper culture).

Horticultural oil

This bioassay tested various vegetable based horticultural crop oils. The commercial formulations used were: Synertrol Horti Oil™ (Organic Crop Protectants), Eco Oil™ (Organic Crop Protectants) and Spraytech Oil™ (AgroBest Australia Pty Ltd). Canola cooking oil was also tested (Coles brand). The cooking oil was formulated at: at 66% oil and 33% Natrasoap™ and another formulation at 80% Canola oil and 20% Sunlight™ dishwashing liquid. Each formulated oil treatment (commercial formulations and cooking oil formulations) was applied at 5ml/L (0.5%). The treatment which produced the highest mortality was the canola and dishwashing liquid (Figure 28). This may be produced from the powerful surfactants in the dishwashing liquid. Of the commercial formulations Synertrol Horti Oil™ appeared to be the most effective. However, it was only marginally better than Eco Oil™.

Horticultural Oil Dose-Response

A dose-response bioassay was conducted to determine the optimum rate to apply Synertrol Horti Oil™ for the control of leafhopper nymphs on pecan foliage. A concentration of 10ml/L was required to kill 90% of leafhoppers and 20ml/L resulted 97% mortality (Figure 29).

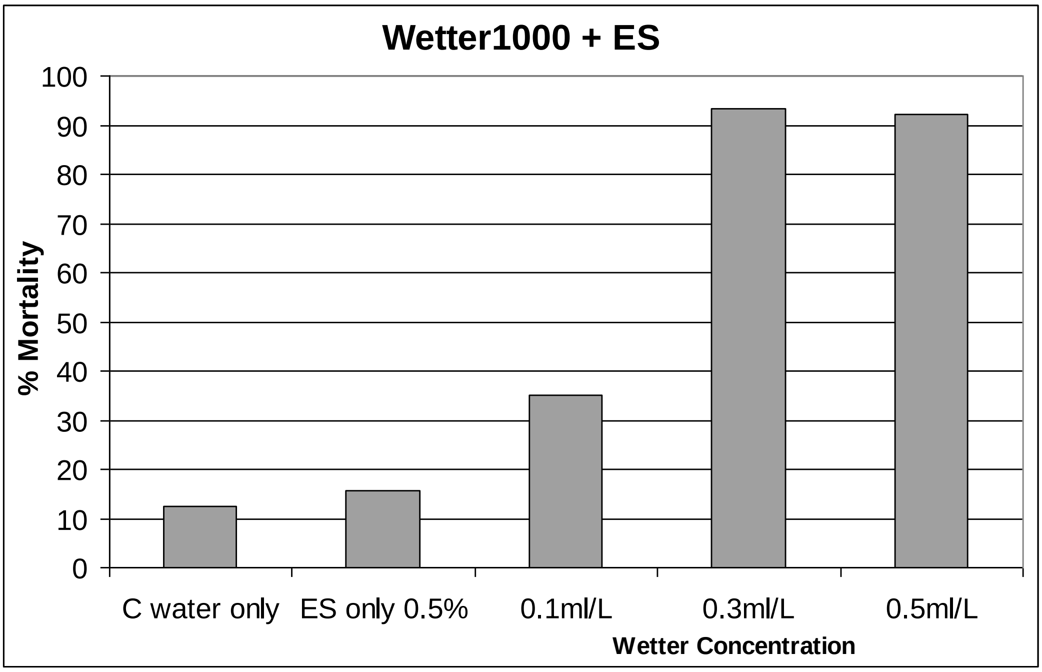


Figure 27. Bioassay of a surfactant (Wetter 1000™) and E.S., using leafhopper nymphs on pecan leaves, showing mortality (%) at 20hrs post treatment. Surfactant was applied at 0.1, 0.3 and 0.5ml/L, E.S. was applied at 0.5% for all treatments.

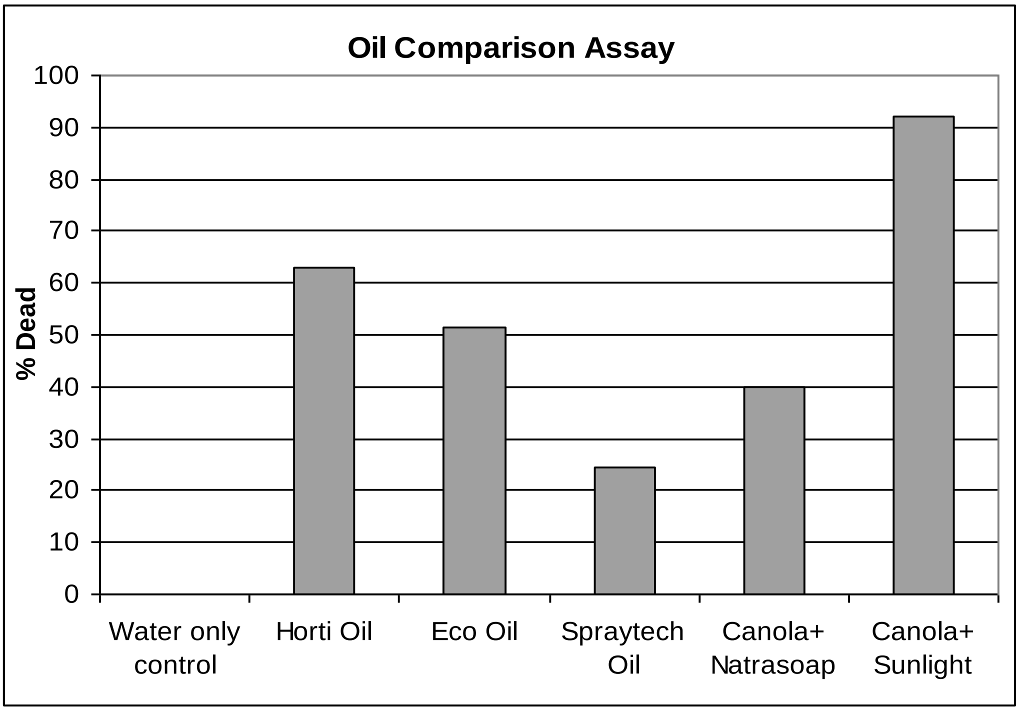


Figure 28. Oil comparison bioassay using leafhopper nymphs on pecan leaves, showing mortality (%) at 20hrs post treatment. Each formulated oil treatment was applied at 5ml/L (0.5%). Canola +Natrasoap™ was formulated at 66% Canola + 33% Natrasoap™. Canola + Sunlight was formulated at 80% Canola + 20% Sunlight™ dishwashing liquid.

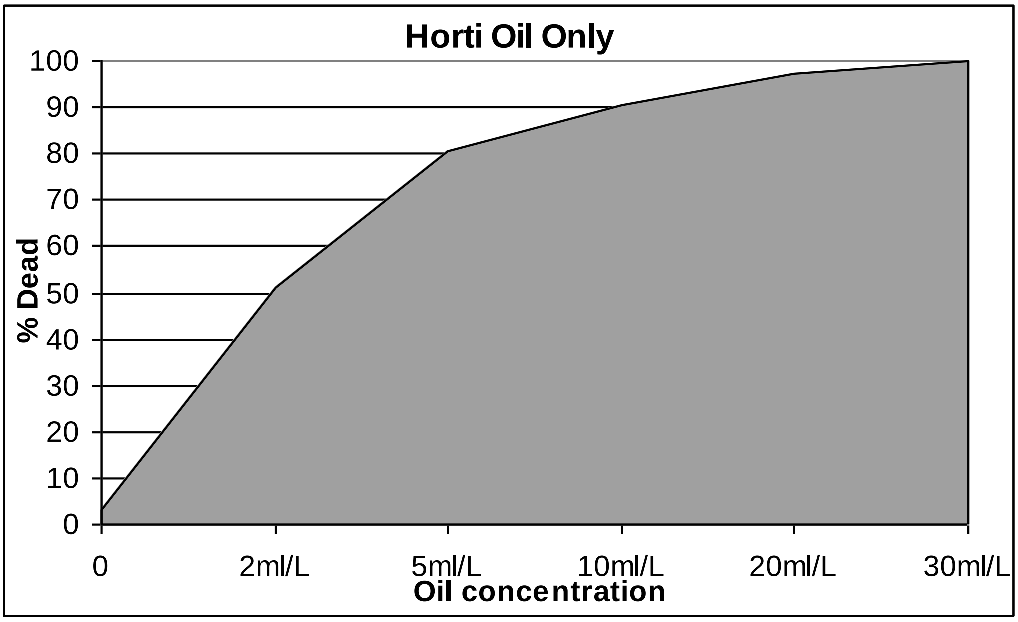


Figure 29. Horticultural oil (Synertrol Horti Oil™) bioassay using leafhopper nymphs on pecan leaves, showing mortality (%) at 20hrs post treatment.

Field Trials

Neem trial

In this trail the neem product did not reduce leafhoppers. The highest rate of neem had the highest rate of leafhoppers and the negative control had the least number of leafhoppers (ANOVA, $P<0.05$, $F=3.42$, $DF=2,21$) (Figure 30). However, the number of leafhoppers in the low rate neem treatment was not significantly different than that of the negative control.

Surfactant and oil trial

In this trail only the high rate of surfactant reduced leafhopper feeding damage more than the negative control (ANOVA, $P<0.001$, $F=6.78$, $DF=4,145$) (Figure 31). All other treatments were no different than the control. However, overall leafhopper abundance was low that year and the leafhoppers did not appear until late in the season when most foliage had "hardened off" and was no longer susceptible.

Orchard Understory Management Mowing Trials

Leafhopper incidence and damage

The data from the yellow sticky traps showed that the early season leafhoppers were least abundant in the alternative row mowing treatment and most abundant in the full mow treatment (Figure 32). As leafhopper incidence continued to grow throughout the season, this pattern continued, into January (Figure 33). The abundance of leafhoppers in the short mow treatment was at an intermediate level. The incidence of leafhoppers that was measured with yellow sticky traps was reflected in the foliage damage, with the most number of feeding damage marks found in the full mow treatment (Figure 34).

Beneficial Predators

From the sweep-net samples of the orchard understory the short mow treatment was generally the most detrimental to the generalist predators (Figures 35 to 40). There was little difference between the numbers of predators in the alternative row treatment and the full mow treatment (Figures 35 to 40). High numbers of predators were found in the weeds of the herbicide strip (under the trees) and in the neighbouring lucerne field. Other predatory insect species that were present in the sweeps included: two-spotted ladybirds, three-banded ladybirds (particularily in the neighbouring lucerne), hoverflies, roberflies, lacewings and earwigs (data not shown). There were also many unidentified hymenopteran micro-parasitoids seen in the yellow sticky traps.

Green Vegetable Bug

Of the mowing treatments the most number of GVB nymphs were found in the full mow treatment in November (Figure 41), but they were similar in numbers to the alternative row treatment in January (Figure 42). The short mow treatment contained the least number of GVB nymphs. The weeds of the herbicide strip (under the trees) and the neighbouring lucerne field were a source of GVB nymphs (Figures 41 and 42), but more importantly they were harbouring adult GVB. In November there were 5 adults (total from 20 transects) found in the herbicide strip. In January 18 adults were found in the lucerne (from 5 transects). Very few GVB adults were found in any of the mowing treatments. One adult GVB was found in the full mow treatment (from 20 transects) in January and no other adults were found in the mowed treatments.

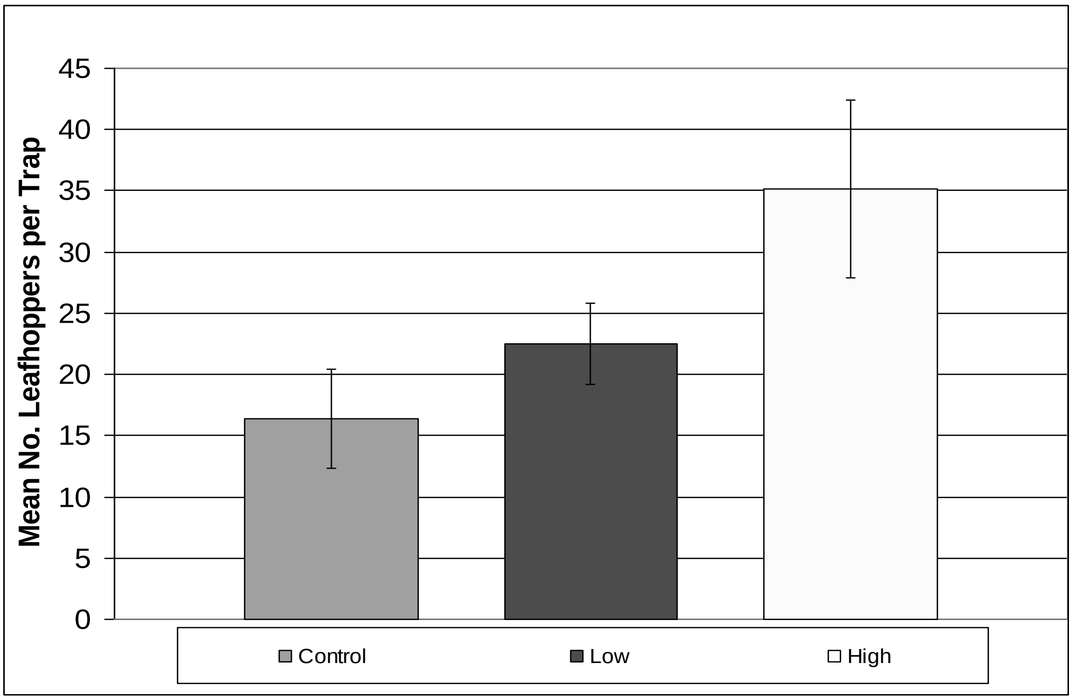


Figure 30. Leafhopper Neem trial, mean number of leafhoppers per yellow sticky trap. There were significantly more leafhoppers in the high rate of neem compared to the control. The low rate of neem was not significantly different than the control or the high rate.

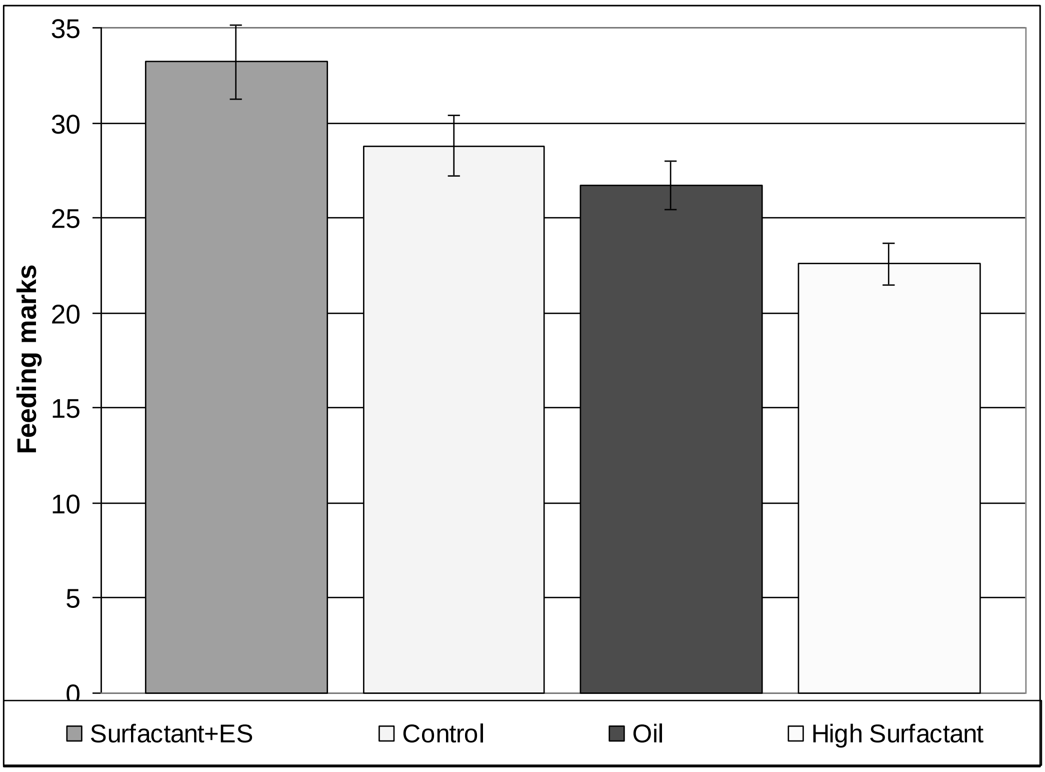


Figure 31. Leafhopper surfactant and oil trial results, showing pecan leaf damage from leafhoppers. Activity and damage measured in average feeding marks per cm of midrib. The high rate of surfactant had the least number of damage marks which was significantly lower than the control. There was no significant difference between the control and other treatments.

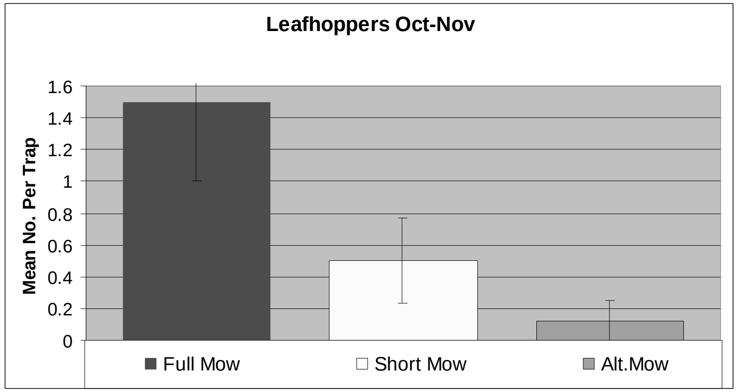


Figure 32. Leafhopper mowing trial results at November. Results show the mean number of leafhoppers caught per yellow sticky trap. The full mow treatment had the most number of leafhoppers. Bar = standard error.

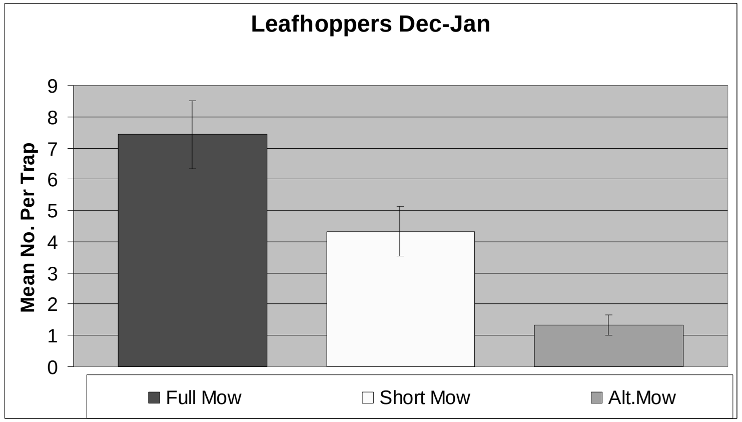


Figure 33. Leafhopper mowing trial results at January. Results show the mean number of leafhoppers caught per yellow sticky trap. The full mow treatment had the most number of leafhoppers. Bar = standard error.

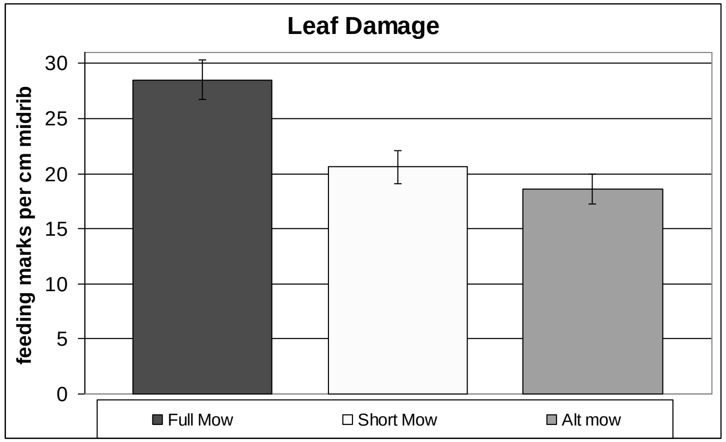


Figure 34. Leafhopper mowing trial results, showing pecan leaf damage from leafhoppers. Activity and damage measured in average feeding marks per cm of midrib. The full mow treatment had the maximum number of damage marks which was significantly higher than the short mow and the alternate row treatment. There was no significant difference between the short mow and the alternate row treatment. Bar = standard error.

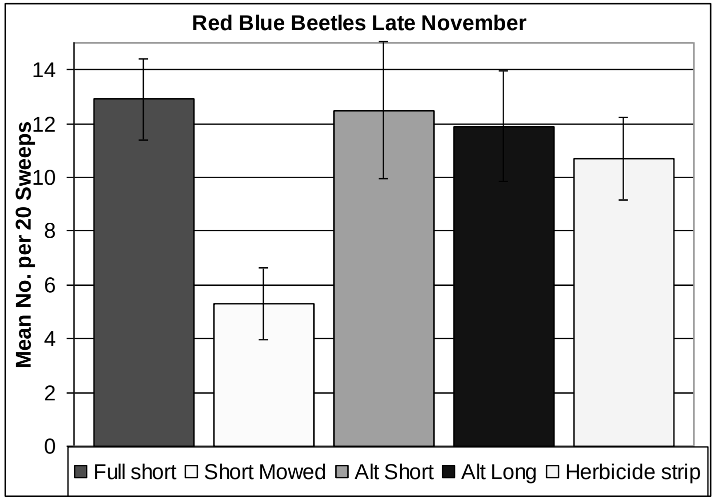


Figure 35. Mowing trial results in late November, showing activity of predatory red-blue beetles, in average number of beetles per 20 sweeps of a sweep-net in the understory. Bar = standard error.

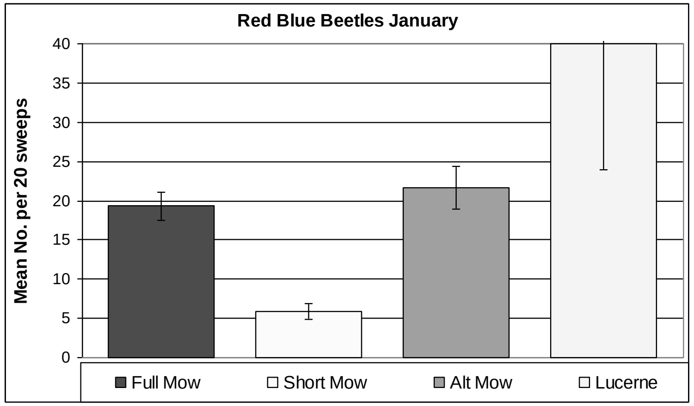


Figure 36. Mowing trial results in January, showing activity of predatory red-blue beetles, in average number of beetles per 20 sweeps of a sweep-net in the understory. Bar = standard error.

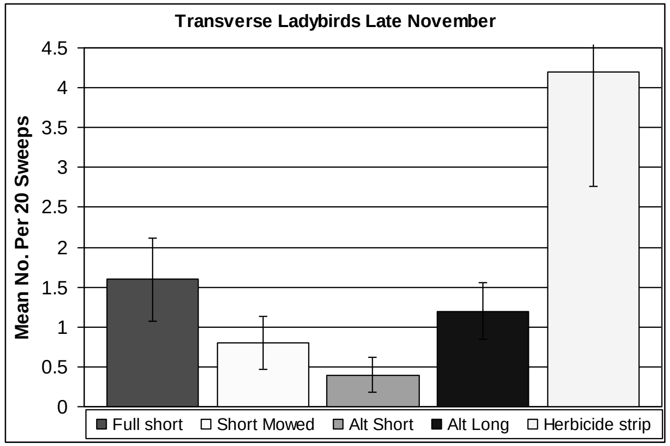


Figure 37. Mowing trial results in late November, showing activity of predatory transverse ladybird beetles, in average number of beetles per 20 sweeps of a sweep-net in the understory. Bar = standard error.

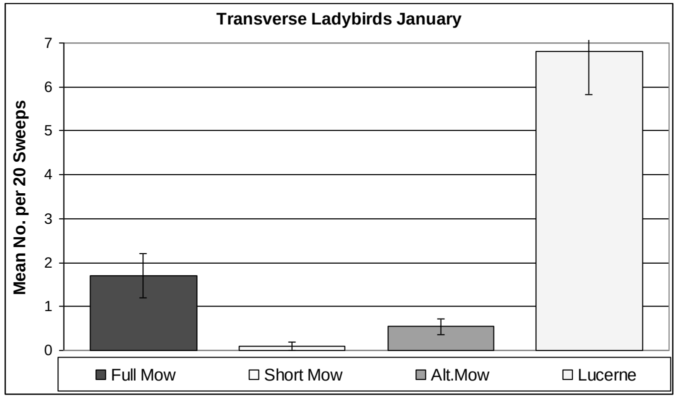


Figure 38. Mowing trial results in January, showing activity of predatory transverse ladybird beetles, in average number of beetles per 20 sweeps of a sweep-net in the understory. Bar = standard error.

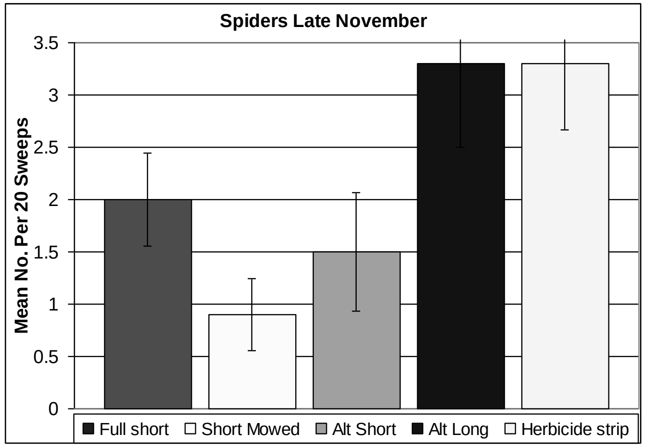


Figure 39. Mowing trial results in late November, showing activity of spiders, in average number of spiders per 20 sweeps of a sweep-net in the understory. Bar = standard error.

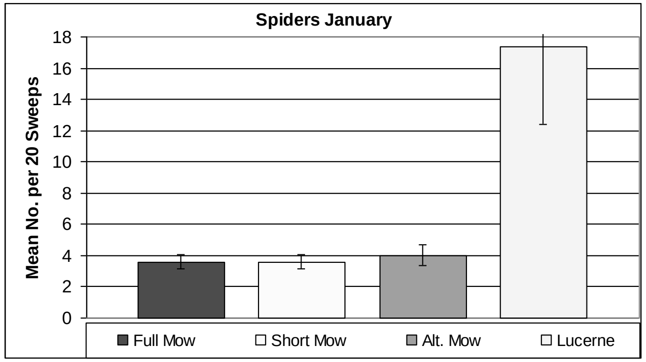


Figure 40. Mowing trial results in January, showing activity of spiders, in average number of spiders per 20 sweeps of a sweep-net in the understory. Bar = standard error.

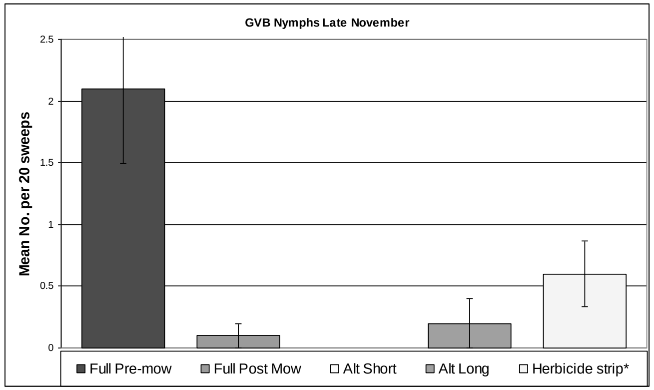


Figure 41. Mowing trial results in late November, showing activity of Green Vegetable Bug nymphs, in average number of nymphs per 20 sweeps of a sweep-net in the understory. Bar = standard error.

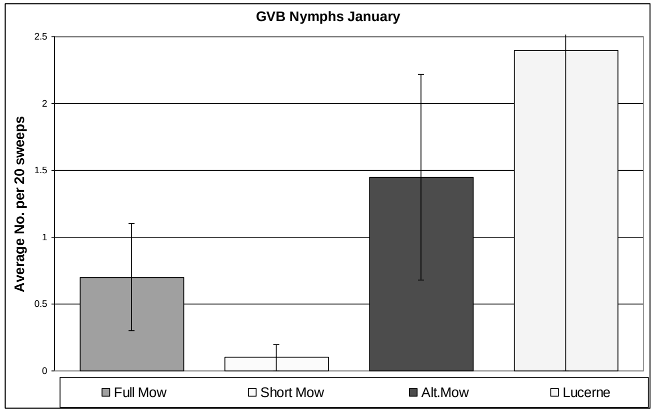


Figure 42. Mowing trial results in January, showing activity of Green Vegetable Bug nymphs, in average number of nymphs per 20 sweeps of a sweep-net in the understory. Bar = standard error.

Discussion

The research from this project indicates that the pecan borer and lucerne leafhopper are unlikely to have any significant impact on pecan production and are therefore not key pests to the pecan industry.

Previous researchers had described the borer as a significant pest which can lead to structural weakness, limb death and debilitation of the tree (Coombs 2003). Coombs (2003) hypothesised that an increase in borer incidence was attributed to damage caused by mechanically pruning large (>10cm dia) limbs. However, the findings from the current research indicate that borer infestations are not the direct cause of pruning damage, but are the result of dead or dying timber which was caused by lower limb shading. Lower limb death is caused directly by shading and is not caused by borers or mechanical pruning. Tree collapse was rare and was not caused by borers, but is caused by cutting open trees (with chainsaws to remove borers) and allowing the timber to die and become dry and brittle. Therefore, manual removal of borers from the trunk is likely to cause more damage to the trees than the presence of borers. As the borer is no longer considered a pest manual removal and further control methods are no longer required.

Outcomes

1. *Cost effective borer control resulting in lower production costs.* As borers are no longer considered a key pest, borer control is not necessary. This has resulted in a significant reduction in production costs and an increased profit margin. A spinoff of this research is that improved canopy management should improve pecan yields and quality.
2. *Reduce the reliance on, or eliminate manual removal of established borers, without using chemical insecticides.* This has been achieved as manual borer removal has now been eliminated. The Australian pecan industry has predominantly remained chemical insecticide free, thus retaining a sustainable "clean" industry with significant domestic and export value.
3. *Estimate of leafhopper damage and effects on yields and alternate bearing.* We have an understanding of leafhopper damage and how it is caused. The effects on yields and alternate bearing are not clear, but with improved orchard management practices (see IPM options below) it is unlikely to affect yields or require further inputs.
4. *Have IPM options for controlling leafhoppers.* By simply changing mowing practices (to mowing alternate rows) leafhoppers can be reduced whilst beneficial organisms are preserved. Soaps, surfactants and oils could reduce leafhopper incidence, but are unlikely to be required.

Other objectives

1. *Development and implementation of biopesticides.* Although the *Metarhizium* based biopesticide was shown to reduce established borers it is no longer required, as borers are no longer considered a key pest and borer control is not necessary.
2. *Improved cultural control practices through improved tree health (canopy management).* Pruning practices that have led to poor tree health (resulting in limb die-back, borer infestation and declining nut yields) have been identified and improved pruning practices have been suggested. By producing a healthy more productive tree, not only will limb death and borer incidence decrease, but yield and nut quality will increase, resulting in increased profits.

3. *The role of predatory earwigs in controlling borers.* Predatory earwigs are likely to play a significant role in naturally regulating borers. However, augmentation (by mass rear and release) is not necessary because they are already well established and borer control is no longer considered necessary. Earwigs could be beneficial for controlling other pests in other horticultural industries.

Cost Benefit implications

Manual borer removal costs have been eliminated. The cost of physical removal of borers is very expensive and previously costed over $1M (AU) per annum to Stahmann Farms alone. A by-product of the tree health and canopy management research is that improved canopy management should also improve pecan nut yields and quality. Yields could be improved by an additional 50% in some places (e.g. in existing E-W rows).

The Pecan Borer

Biopesticides: neonate control

The fungal bio-pesticide failed to control the neonate borers in these trials. There was no evidence to show that the *Metarhizium* treatments worked at reducing neonate borer numbers. The logs that were sprayed with *Metarhizium* did not reduce borer numbers any more than in the oil only applications or the negative controls.
A large proportion (62-90%) of the controls died of "natural" causes, i.e. causes other than being sprayed with *Metarhizium*. However, the *Metarhizium* sprayed treatments were also well within this range. The standard error rates were reasonably high, but were within reason given the high natural mortality rates. Large numbers of earwigs were observed that may have predated on the borers causing the high mortality.
Even the highest *Metarhizium* rates (applied once or twice) did not increase borer mortality. At this concentration the *Metarhizium* will easily kill 90% of large larvae in the lab, as was demonstrated with the positive controls. Neonate larvae should be more susceptible to the fungus. Therefore, we would expect it to kill at least 90% of the neonates that come into contact with the product. In appears most likely that the product did not adequately contact the neonate larvae.
Another problem could have been a result of the larvae boring into the timber becoming inaccessible before the sprays were applied. This could be seen as somewhat of an issue if sprayed commercially. So in some ways it could be a very real simulation. However, a pre-spray (applying before egg hatch) may overcome this issue. Getting the timing right and trying to simulate or measure this would be extremely difficult.

Biopesticides: established larvae

The *Metarhizium* did have an effect on the established larvae as there was a higher mortality in the *Metarhizium* treated sites. However, it produced less than 10% mortality, which is not a practical level of control. The established larvae were applied with a very high rate of *Metarhizium*, which should kill most borer larvae on contact. It was also applied in a very large volume of water which completely saturated the borer sites. This volume and rate was applied so as to get maximum chance of contact with the borers. Increasing the rates and volumes would be unlikely to increase the efficacy. Repeated or multiple applications could further reduce the borer incidence. However, this would not be financial viable and as discussed below is no longer necessary.

Mechanical hedging limb death and borer attack

Limb death and borer attack is not caused by the use of mechanical pruning equipment. In the observations and studies conducted here it was found that limbs that were mechanically pruned, but received full sunlight rarely suffered from limb death or borer attack. Limb death and borer attack only occurred when limbs were cut and were then shaded. Thus, the use of mechanical hedging equipment can be ruled out as the cause of limb death and borer attack. The factor in limb death and borer attack is shade, not mechanical hedging. However, limb death and borer attack is linked to past pruning practices and the borer's biology, as described below.

Borer biology and pest status

The observations in this study show that the borers are feeding directly on the dead and dying timber and are rarely observed to travel far into live heartwood. Where the borers were observed in live timber they were always near a wound with dead timber, usually with the majority of the gallery in the dead wood section. The fact that they are always found in or around dead and dying timber and are never observed in the live healthy sealed timber, demonstrates that they are probably a pioneer species, being the first to invade dying timber. Hanks (1999) described such species as "stressed host" species, that often attack freshly felled trees or branches, that are technically not as yet dead (i.e. the timber is still technically alive but will soon die). This dying timber produces ethanol (and other chemicals) that have been shown to attract the pecan borer *A. spinicolis* (Newton 2006). The absence of borers in sealed live heartwood (e.g. above or below trunk wounds), suggests that they are intolerant of the high moisture content and high turgor pressure, as observed in other cerambycids (Hanks 1999, Hanks *et al.* 2006) and are not a genuine pest of live healthy timber. Each longicorn beetle species appears to have a defined moisture requirement and timber condition (Hanks 1999, Hanks *et al.* 2006). The pecan borer *A. spinicolis* appears to have a requirement for some moisture which is why they are found near live timber, but most live sealed timber appears too moist.

The pecan borer may be considered a minor nuisance, but is not a key pest. The borer was occasionally observed to travel a small distance into live timber and this may cause some minor damage to the tree. However, it is unlikely to lead to limb collapse in healthy live limbs, nor is it likely to lead to total tree collapse. The majority of limbs that were observed to be dead or dying were absent of borers and were caused by past pruning practices that led to shade out (as is described below). The presence of the borers could be seen as a symptom of decay.

In some cases the pecan borer could even be considered somewhat beneficial. By attacking the dead limbs the borers are effectively speeding up the decay process and assisting to remove the limbs, thus speeding up the healing process.

The history of pruning and consequences for borer infestation

In the period 1999 to 2001 canopy management changed at Trawalla from a discrete 6.7m (22ft) block (where hedging 3.35 m from trunk centre, alternated from North-South one year to East-West the next) to a continuous narrow hedge row system. To convert to the hedge row system the trees were cut back hard to 1.2 or 1.8m from trunk centre, which removed a significant portion of many lower limbs and often left a short thick stump remaining. The hard prune conversion was done using the rotating machine mounted circular saws, normally used for annual tip pruning.

The continuous hedge row was then pruned annually in the same direction each year in winter. The Western Schley rows were topped annually at 11m high, but the

neighbouring Wichita rows were not topped and were allowed to grow to over 18m in places.
After the change in pruning it was observed that the borer incidence increased. It was noted at the time that the mechanical hedging (using the rotating machine mounted circular saws) caused damage to the larger limbs resulting in shattering and splits in the timber. Coombs (2003) and an independently contracted tree-doctor (an unpublished private report) attributed the increase in borer incidence to this mechanical pruning damage. Coombs (2003) hypothesised that the splits and cracks caused by mechanical pruning equipment provided an entry point for the borers, from where they could subsequently gain access into the limb and trunk. However, the researches at the time did not look at wound healing and how the limbs could repair and seal-off damaged limbs if they were exposed to full sunlight (such as higher in the trees and some row ends), nor did they examine where within the tree or what quality of timber was being attacked.
In the current research program it was observed that where lower limbs were mechanically pruned, but were exposed to full sunlight, they would repair and seal off the exposed timber. These limbs had very little dead or dying timber and were rarely attacked by borers. Conversely, where pruning had taken place within the shaded part of the orchard, the limbs did not repair or seal off and subsequently the limbs died off (regardless of borers being present). As the sun exposed limbs were also mechanically hedged, the factor causing limb death was shading and not mechanical hedging. These shaded dead and dying limbs where then more prone to borer attack.
Prior to hedging, the large lower limbs were angled upwards into the upper canopy, where they reached full sunlight (as was observed in historic photographic evidence, not shown). Some lower limbs that were not growing into the inter-row space (i.e. limbs that were kept within the hedge), were not cut off and can still be seen angled upwards into the upper canopy, where they reach full sunlight. The act of cutting off a large lower limb at 1 or 2 m from trunk centre has effectively cut off the direct sunlight to that limb (regardless of cutting method). These lower limbs (often short stumps) then become shaded by the upper limbs. The upper limbs have grown more rapidly as they received more sunlight and because pecans are strongly apically dominant (meaning that most new shoot growth tends to be in the upper parts of the tree) (Wood and Payne 1983). The upper limbs then repaired rapidly whilst the lower limbs gradually died off and become susceptible to borers.
The problem has been exacerbated in the Western Schley rows because they have been annually topped, whilst the Wichita trees have been allowed to grow unrestricted in height. Topping the Western Schley has produced very long water-shoots of up to 2m (I. Newton unpublished data) at the top of the tree which shades the lower canopy (within row shading). The neighbouring un-topped Wichita rows have also shaded out the lower limbs of Western Schley trees (between row shading) but have had little effect on the upper part of the Western Schley, which is largely unshaded by the neighbouring Wichita trees. This has allowed the Western Schley upper canopy water-shoots to continue to dominate at the expense of the lower canopy. The overall effect is that the Western Schley has been left with a vigorous vegetative growth upper canopy and a dead lower canopy. The dead lower canopy has had many of its dead and dying limbs removed. Tree maintenance workers removed these limbs to avoid future borer attacks (as they had observed that they were often attacked by the borer). Tree maintenance workers also removed borers from the trunks. However, cutting open tree trunks has allowing the timber to die and become dry and brittle. These trunk wounds have a considerable amount of dead exposed timber, which is

often re-invaded by the borers. Therefore, manual removal of borers from the trunk is likely to cause more damage to the trees than the original presence of borers.

The Wichita trees are not as affected as Western Schley trees in terms of lower limb dieback and subsequent borer attack (Newton 2006). This is because they have not been annually topped and are not shaded out by their neighbouring row. However, some lower limb dieback and borer attack was observed in places where the trees have grown more vigorously and taller (over 18m high, e.g. F3 Figure 5, Results section). These differences in vigour and tree height are probably attributed to differences in soil types across the Trawalla orchard (Deanne Stahmann, Matthew Durack, Pers. Com). The modelling studies and personal observations have demonstrated that most of the productive canopy is limited to the top 10m of the tree (less in EW rows). So growing the trees taller has effectively just pushed the production further up the tree at the expense of the lower canopy and neighbouring tree rows (the Western Schleys). This has resulted in limb dieback and borer attack in the lower parts of the taller Wichita trees (e.g. F3).

Canopy modelling studies

The problem with East-West rows

The modelling studies show East-West rows suffer from severe within row shading, with most of the available light restricted to the top 4-5m of the tree. Total light interception is also low (30 -50%) for E-W rows in summer, meaning much of the available light is wasted as it does not reach the pecan canopy.

East-West rows are not affected by between row shading during most of the summer growing season. This is because in summer the sun tracks directly overhead from east to west, directly over the top of the E-W row. The sun also tracks directly over the E-W inter-row for most of the day, with more than 50% of the light going directly to the orchard floor. Furthermore, this causes severe within canopy (or within row) shading on the lower parts of the tree, because the sunlight is intercepted directly on top of the canopy and does not contact the side faces. Later in the season, as the sun tracks more of a northerly arc, the solar angle allows some light in the north facing lower canopy, but it does not reach the southern lower face. By the end of the season total light interception could be too high (over 90%), resulting in too much inter-row shading of the lower canopy. At this time of year the taller Wichita rows (which were over 18m high in places) will completely shade out the lowest 8-10m of the shorter Western Schley trees. This end of season shading may contribute to the shuck decline (i.e. shucks die and nuts not do not fill) that is often observed at the Trawalla orchard in Western Schley trees.

The advantage of tapered North-South rows

Most of the orchard shading is caused by within canopy (or within row) shading and the modelling suggests tapered N-S rows suffer far less within row shading than other models. Tapered N-S rows (compared to rectangular EW rows) receive nearly double the total orchard light interception, three times the light at the periphery of the lower canopy and about six times the light inside the lower canopy. This efficiency is gained because N-S rows receive light at multiple angles throughout the day, regardless of season, i.e. in the morning the east face receives light (at multiple angles through out the morning) and in the afternoon the west face receives light (again at multiple angles). So the entire hedge is irradiated on all faces throughout the entire season.

Production is height limited
North-South rows are affected season-long by inter-row shading (shade cast between rows). The modelling and observations suggest they suffer shade-out at about 8-10m down from the tallest neighbour row, meaning the tallest Wichita trees (18m+) will shade out the lowest 8-10m of the shorter Western Schley trees. The shorter Western Schley trees will have very little impact on the taller Wichita trees. In tapered N-S rows, production is limited to the top 10-12m of the tree (with the current 10 x10m tree spacing). Therefore, for maximum production and the least amount of lower limb shade-out, trees should be limited to 12 m in height (provided they are cut tapered and not rectangular). However, as it is not practical to have the canopy down to ground level (because machines need access under the canopy), tree height should be limited to no more than 14m (46ft).

Increased nut yields
The modelling studies showed that tapered N-S rows will intercept more light and suffer less lower canopy shading than the existing rectangular E-W rows. Similar results have been modelled and observed in macadamia canopy hedges, for a similar latitude (Olesen *et al.* 2007). Olesen *et al.* (2007) found that the actual measured light was similar to that which was modelled and nut yields also reflected the modelling results. There is generally a linear relationship between light interception and dry matter production (i.e. total amount of foliage, stems, wood, fruit, nut etc..) (Monteith 1977). Increasing light interception has also been shown to be related to increased fruit yield (Palmer 1989a). Therefore, we would expect that N-S hedgerows of pecan (as modelled in this study) should have greater nut yields than E-W hedgerows. At Trawalla, N-S hedgerows have historically always produced higher yields of nuts than the E-W rows. Wood and Stahmann (2004) found N-S rows at Trawalla produce 58% (Wichita) and 74% (Western Schley) more yields than E-W rows. This is consistent with long term yield records at Trawalla, which show that N-S rows consistently produce 20-60% more yields than E-W rows (I. Newton, unpublished data).

Modelling and dieback
The modelling studies show results that are consistent with the pattern of limb death and subsequent borer attack that has been observed at Trawalla. The modelling studies show that Western Schley trees suffer the most amount of shade in their lower limbs and that most of the sunlight they receive is in the top 4-5m of canopy. The observations at the Trawalla orchard show that the modelling data accurately represents the true canopy shading. There is often no lower canopy remaining in the Western Schley tree rows and the only remaining productive foliage is often restricted to the top 4-5m of the tree (see Figure 6 in results section).
With the taller Wichita trees (that were18m+), it was observed that E-W rows were suffering more lower limb dieback than N-S rows (as predicted by the models). This can be observed by visiting Trawalla and examining F1 (a N-S row block) and F2 (a neighbouring E-W block). However, in these taller N-S row blocks (e.g. F1) the Western Schley trees appear to be suffering from lower limb dieback. This is also predicted in the modelling, as N-S rows are affected by between row shading at about 8-10m down from the tallest neighbour row. Therefore, the modelling and observations show that N-S rows do have an advantage, but only if tree height is restricted.

Changing rectangular East-West rows to optimum tapered North-South rows
The modelling studies, long term yield data and observations made in these studies indicate that tapered N-S rows are more productive (in yields), more efficient at catching light and allow light further into the canopy than rectangular E-W rows. But this advantage is only maintained if the tallest tree height is restricted to no more than 14m (46ft). So by converting the current rectangular E-W hedgerows to the optimum tapered N-S hedgerows we should get:

- Greater total light interception and much less within row shading.
- Greater light and space efficiency.
- Less lower limb dieback & borer attack.
- Greater nut yields and profits.
- Possibly less alternate bearing from tree rejuvenation and the creation of new "nutwood".

In converting the orchard design to tapered N-S hedgerows, it is important not to make the same mistakes that were made in creating the original hedgerow system (i.e. not cutting back lower limbs too close too the trunk and "cutting off" their light supply). The lowest limbs do not shade any of the tree's canopy (nor do they shade the neighbouring tree row). Therefore, in cutting in a N-S direction, across the E-W rows, the lower limbs need to be preserved as wide as is possible and practical. The canopy then needs to be tapered to the top, where the height should not exceed 14m (in the case of a10x10m tree spacing).

Maintaining yields in the conversion process
It is also important not to cut off to much productive "nutwood" at once, as this could cause a sudden drop in yields, which may not be financially viable. Therefore, caution should be taken so as not to convert an entire orchard at once. This could be done by converting the orchard in sections, or starting with a trial block. Observations, trials and historic yield data at Trawalla (I. Newton unpublished data) have shown that Wichitas will start to recover yields two years after a pruning event, whereas Western Schley trees take three years to recover. Therefore, it is important to always have some productive "nutwood" on the tree that is 2-3 years old.
One way to achieve this is to allow the lower limbs of the existing E-W rows to "grow out", by only pruning the tops (and possibly the top sides). After allowing the lower limbs to "grow out" over a period of 2-4 years, then cutting in a N-S direction across the E-W rows. In this way some 3-4 year old "nutwood" will be preserved. This method should maintain yields and provide a more productive lower canopy.
Once tapered N-S rows are established the height and shape will need to be carefully monitored and maintained, as vegetative growth could soon dominate.

Leafhoppers

From the research undertaken in this project, we have developed a basic understanding of the lucerne leafhopper biology. We also have an understanding of the damage to pecan foliage and how it is caused. The effects of leafhoppers on yields and alternate bearing are not clear, but with simple improvements to orchard management practices it is unlikely to affect yields or require further inputs. By simply changing mowing practices (to mowing every alternate row, rather than mowing all rows simultaneously) leafhoppers can be reduced whilst beneficial organisms are preserved. The application of insecticidal soaps, surfactants and oils could further reduce leafhopper incidence, but is unlikely to be required.

Leafhopper host preference
The lucerne leafhopper feeds on and will reproduce in the tender new foliage flush of pecans, but does not attack the mature hardened foliage. It is a polyphagous insect and will attack many different plant species (Waite 1973). At Trawalla, it was found on plants in the orchard understory and in very high numbers on the castor oil plants at the edge of the orchard. There is a considerable amount of lucerne and cotton grown on the neighbouring farms and these hosts are also likely to harbour the lucerne leafhoppers (Waite 1973). Because of the leafhoppers mobility, its polyphagous nature and the amount of suitable hosts in the greater area, it may not be possible to control at the farm level. As with other mobile polyphagous pests; the leafhoppers seasonal abundance is likely to be controlled by external factors, such as the weather, weeds and crops grown in the region (Zalucki *et al.* 2009). Leafhoppers can be locally suppressed with low rates of endosulphan (Freebairn and Smith 2002), which was once widely used in cotton. The use endosulphan (and other braod sprectrum chemicals) in cotton has been significantly reduced with the introduction of transgenic cotton and changes to IPM practices (Zalucki *et al.* 2009). This change in cotton management may have increased leafhopper abundance in recent years.

Opportunistic on pecan flushes and other hosts
Pecans do not appear to be a preferred host for the lucerne leafhoppers, as it is only found in new flush and this was usually confined to the late season flush (December-January). In pecans, the leafhopper appears to be restricted both temporally (to mid summer) and by leaf age (only attacking the pecan flush). Whereas in other hosts (such as lucerne and castor oil), it can be found during most of the year. It appears that the leafhoppers attack pecan foliage opportunistically. Their numbers are likely to build up during the early season on other hosts such as lucerne, cotton, castor oil and plants in the orchard understory. During the early part of the season, the spring flush, the leafhopper numbers appear to be too low to cause significant damage to the pecan foliage. However, during the later part of the season when leafhopper numbers have built up (December to January) they will cause damage to the pecan foliage. However, by this stage in the season most of the pecan foliage has usually hardened off and is no longer susceptible to leafhopper attack. At this stage of the season most of the new foliage flush is restricted to the upper parts of Western Schley trees and this only occurs after the trees were winter top-pruned. When the Western Schley trees were winter top-pruned they produce a vegetative water-shoot which flushed late into the season, but does not produce nuts. When the Western Schley trees were not winter pruned leafhopper attack was minimal. The Wichita variety has not been top-pruned (until recently at Trawalla) and this may be the reason as to why this variety has had minimal leafhopper damage. It has also been observed that when the Wichita variety is pruned it does not produce as much vegetative growth as the Western Schley.

Mowing alternative rows reduces leafhopper damage
If pecans are not a preferred host, then the orchard understory plants could be more attractive than the pecan foliage. The results from the mowing trials would suggest that leafhoppers found in the orchard understory are disturbed if all rows are mowed simultaneously. Whereas, when every second (alternate) row was mowed, less leafhoppers were found in the pecan canopy and less foliage was subsequently damaged. If the orchard understory plants are more attractive than the pecan foliage, then the leafhoppers may simply migrate to the un-mowed rows, rather than attack the

pecan foliage. On the other hand if all rows are mowed simultaneously, then the pecan foliage is probably the closest (or only) available host for the flying adult leafhoppers. A similar event has been recorded for this species of leafhopper in Queensland citrus. Freebairn and Smith (2002) found large numbers of the lucerne leafhopper in the inter-rows or in close proximity to citrus trees. When this inter-row vegetation was mowed the adults moved onto the citrus trees. Freebairn and Smith (2002) also suggested that mowing the inter-row may be detrimental to the beneficial insects, and may contribute to citrus leafhopper (*Empoasca smithi*) outbreaks. They suggested allowing the undergrowth to grow during the spring to permit beneficials to accumulate. However, in pecans the orchard undergrowth and inter-rows must be mowed (or controlled) to stop the build up of green vegetable bug (Coombs 2000) and leafhoppers. The results from the mowing trials showed that by mowing one row and leaving every alternative row long, leafhoppers and GVB could be controlled whilst beneficials were also preserved. Weiser *et al.* (2003), found that a similar strategy could help to control leafhoppers (*Empoasca fabae*) in lucerne. They found an uncut strip acted as a trap-crop for leafhoppers and a refuge for predatory insects and other natural enemies.

Leaf hoppers may have little impact on yields

It is unlikely that the leafhoppers are causing any significant economic loss to the orchard at Trawalla. In Cotton trials conducted by CSIRO, it was found that if 80% of the surface of young leaves were stippled by leafhoppers, the photosynthetic rate of those leaves was only reduced by 20% (Wilson *et al.* 2007). This was very severe damage and the field still produced high yields. It was stressed that leaf damage should be examined rather than actual leafhopper numbers. If similar results were to occur in pecans, then any expensive control product (both product and labour cost) may not justify yield losses. The cost of control could be far greater than yield losses. For example, if 10% of the foliage is affected and the photosynthesis is reduced by as much as 20% (a worse case scenario in cotton), then we could assume a 2% loss in total photosynthesis to the tree. However, the trees appear to be affected for only part of the season and leaf curling may actually allow more light to reach the lower unaffected canopy leaves. Some trees, particularly Wichita, do not appear to be as affected. In this scenario, it would appear unlikely that total photosynthesis would be reduced by more than 1% and we could assume that yields would be reduced in a similar magnitude. With this level of yield loss, most control options may not be economically viable.

The most affected areas (i.e. the top water-shoots of the Western Schley variety) of the pecan trees to leafhopper attack may have little impact on nut yields. In these vegetative parts, the leaf-area to nut ratio is probably far in excess of what is required for optimum nut production. Marquard (1987) found that two leaves were sufficient to fill one kernel (in the cultivars Sioux and Western). In the Mohawk variety, a leaf to fruit ratio of 4, produced nuts superior in quality to those supported by 2 leaves. Most of this leafhopper affected vegetative production, appears to go into producing new vertical scaffold limbs, that do not produce nuts in the current or following season (they usually do not produce nuts until their 3rd season and were usually pruned off prior to this point, I. Newton, unpublished data). These vegetative shoots are unlikely to contribute much carbohydrate to the nuts that are further down the tree, but may be shading them. Pecan nuts appear to get most of their carbohydrate source locally and generally get smaller as they are more shaded within a trees canopy (Picchioni et al.

2000). So it could be possible that the leafhoppers will actually improve nut yields by stunting the vegetative leaf growth and allowing more light into the lower canopy.
It still remains unclear as to how much the leafhopper damage contributes to return blooms and alternate bearing. There is some debate as to the exact cause of return blooms and alternate bearing. One theory is the "growth regulator-carbohydrate theory" in which flowering is controlled by growth regulators produced by fruit and leaves, and by the size of the carbohydrate pool at budbreak (Wood *et al*. 2003, 2004). However, more recently it was found that stored carbohydrates may not always play a part in return blooms and alternate bearing. Rohla *et al.* (2007a,b,c) and Smith *et al.* (2007) found that stored non-structural carbohydrates were not related to return bloom or alternate bearing in well managed trees.

Neem, surfactants, insecticidal soaps and oils
Surfactants, insecticidal soaps and oils, could all reduce leafhoppers, but the amount of damage caused by the leafhoppers would unlikely justify the costs of application. Furthermore, changing mowing practices (to alternative row mowing) reduced leafhoppers and conserved the natural enemies better than any of the sprayed control options.
Neem did not reduce leafhoppers; in fact it appeared to have a negative effect, with the greatest leafhopper numbers in the highest neem rate treatment. Neem can have a detrimental effect of the natural enemies of leafhoppers (Silva and Martinez 2004, Raguraman and Singh 1999). In our trial, it may be possible that neem was having more of an effect on the natural enemies than it was on the leafhoppers.
The laboratory bioassays showed that insecticidal soaps, surfactants and oils could effectively kill leafhoppers. However, in the field trials, only the high rate of surfactant reduced leafhopper damage. The paraffinic oil did not reduce leafhopper damage, nor did the low rate of surfactant combined with E.S.. The reason for this failure in the field and success in the laboratory bioassays may be due to the application speed and volumes applied in the field. In the laboratory these products were applied in high volumes, so as to completely saturate the entire leaf surface. However, the field applications may have been applied in a smaller volume per leaf and perhaps were applied too fast. Slowing the tractor speed would increase the volume applied per leaf. However, this may not be financially (or practically) viable as this would increase water volumes, increase product volumes and increase labour and machine costs. The high rate of surfactant may have been more successful because the water droplets may have spread more, improving coverage. Other reasons the trials failed to get significant results may have been due to a low abundance of leafhoppers and rain may have washed the products off the foliage. However, the rain did not seem to affect the high surfactant rate treatment, which was applied last (whilst the rain had started).
The surfactant was one of the most economic products tested at approximately $36/ha (not including labour or machine costs), compared to $83/ha for paraffinic mineral oil and $112/ha for insecticidal soap. However, if the low rate of surfactant combined with E.S. was effective it would only cost about $13/ha. In the laboratory bioassays, the surfactant (Wetter 1000™) applied at the current registered rates (for addition to fungicides, foliar fertilizers and insecticides) of 0.4 to 1ml/L with E.S. added at 0.5% w/v killed most leafhopper nymphs. The addition of E.S. as a synergist could allow reduced rates of insecticidal soaps or surfactants to kill leafhoppers. This low cost synergist could reduce phyto-toxicity and application costs for controlling other pest insects and mites in other industries (including organic industries).Most chemical and

other sprayed control options would not be economically viable. What's more, leafhoppers are also food sources for predators, such as ladybeetles, lacewings and spiders. Removing the leafhoppers could decrease predatory insects, which could affect the natural control of other pests such as the pecan stem girdler (*Maroga melanostigm*a) and the green vegetable bug. The preferred control option is simply to change mowing practices (to mowing every alternate row, rather than mowing all rows simultaneously). In this way, leafhoppers can be reduced whilst beneficial organisms are preserved.

Technology Transfer

Newton I.R. (2006). Cultural and Biological Control of the Pecan Wood Borer *Agrianome spinicolis* (Coleoptera: Cerambycidae), Conference paper at: The Australian and New Zealand Entomological Societies Conference. 24-27th September 2006. University of Adelaide, South Australia.

Ian Newton met with pecan growers and gave a brief research update at the Pecan Growers Association AGM and field–day at Lismore on November 3-4, 2006.

Ian Newton met with pecan growers and gave a research update at the Pecan Growers Association field–day at Stahmann Farms Trawalla (Pallamallawa, NSW) on July 9, 2007.

Newton I.R. (2007). Managing Pests in Pecans. A report published in the Australian Nut Industry Council (ANIC) annual research report 06/07.

Newton I.R. (2008). Biological Control of Pecans: Past, Present and Future. Conference poster at: The Australian and New Zealand Biological Control Conference. 10-14th February 2008. Sydney, Australia.

Newton I.R. (2008). Broadening Integrated Pest Management in Pecans. A report published in the Australian Nut Industry Council (ANIC) annual research report 07/08:

Newton I.R. (2008). Chemical Free IPM and Biological Control in Pecans. A field day and workshop presentation, 30th May 2008, at Stahmann Farms Trawalla orchard, Pallamallawa NSW. Repeated at the Australian Pecan Growers Association annual AGM, in Eltham (near Lismore) NSW, 16th August 2008.

Newton I.R. (2008). Canopy Management and Pruning of Pecans. A field day and workshop presentation, 30th May 2008, at Stahmann Farms Trawalla orchard, Pallamallawa NSW. Repeated at the Australian Pecan Growers Association annual AGM, in Eltham (near Lismore) NSW, 16th August 2008.

Newton I.R. (2008). Cultural and Conservation Biological Control of Leafhoppers (*Austroasca alfalfa*) in Pecans. Conference paper at: The Australian Entomology Societies 39th AGM and Scientific Conference, 28th Sept –1st Oct 2008, Orange NSW.

Recommendations

Manual removal of borers (by chainsaw) from the trunk is likely to cause more damage to the trees than the presence of borers. As the borer is no longer considered a pest, manual removal and further control methods (including biopesticides and predatory earwigs) are no longer recommended.

When pruning or hedging, cutting off lower limbs close to the trunk in a rectangular shaped hedge should be avoided. Growing hedges too tall for their row space and pruning hedges in an east-west direction should also be avoided.
Improved canopy management and pruning practices include: pruning hedges into a tapered shape (preserving the lower limbs as wide as possible), pruning in a North-South direction and limiting tree height (to no more than 14m in a 10x10m row spacing).

More pruning research is required. In particular: trialling North-South tapered hedges verses conventional practices and also the timing and frequency of pruning. Once tapered N-S rows are established the height and shape will need to be carefully monitored and maintained, as vegetative growth could soon dominate.
A dynamic hedge system so as to avoid cutting in the same place each season (to avoid producing large water-shoots) should be investigated. Cutting one side of the hedge and then cutting the other side two years later could be trialled, in particular for Western Schley (as it usually only produces nuts from the 3rd season). Pruning coming into the off-season (for Western Schley – it may produce more nuts on the following off season). Continued research into viably converting existing designs to North-South tapered hedges. These trials need to be monitored for nut production, limb dieback and borer incidence.

To avoid the build-up of leafhoppers and green vegetable bug, the orchard understory needs to be mowed regularly in spring and early summer. However, mowing every second row (or alternate row) provides better leafhopper control than mowing all rows simultaneously. Each row should be mowed at least once every 6 weeks to avoid GVB build-up, but should be done more regularly to allow for weather or other unforseen circumstances that may delay mowing. Mowing can be somewhat relaxed after January when the nuts and foliage have hardened and are no longer susceptible to insect attack.

The use of E.S. as a synergist could allow reduced rates of insecticidal soaps to control other small soft bodied insects and mites in other industries (including organics). Furthermore, the addition of E.S. to the current registered rates of surfactants (e.g. Wetters at 0.4 to 1ml/L for fungicides, foliar fertilizers and insecticides) could potentially be used as an insecticide or could increase the efficacy of insecticides. This needs to be tested in bioassays and field trials on the other pests.

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Appendices

Appendix 1.

Map of Trawalla orchard, showing layout of irrigation blocks. Each irrigation block is represented by a code name (top) (e.g. A1), with the block area in hectares (middle figure) and acres (bottom figure). Trawalla is located 35km east of Moree in NSW.