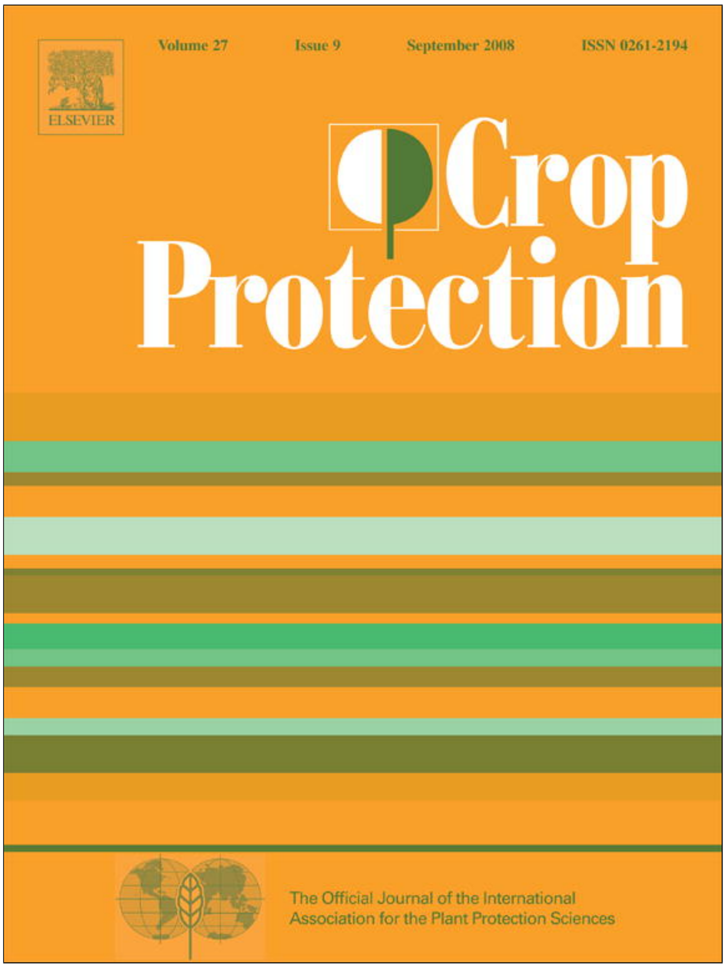
Volume 27
Issue 9
September 2008
ISSN 0261-2194
ELSEVIER
Crop Protection
The Official Journal of the International Association for the Plant Protection Sciences

Crop Protection 27 (2008) 1262–1268

Contents lists available at ScienceDirect

Crop Protection

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

Sampling and management of *Bemisia tabaci* (Genn.) biotype B in Australian cotton ☆

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ARTICLE INFO

Article history:
Received 6 September 2007
Received in revised form
3 April 2008
Accepted 7 April 2008

Keywords:
Bemisia tabaci
Cotton
Management zones
Binomial sampling plan

ABSTRACT

Data on seasonal population abundance of *Bemisia tabaci* biotype B (silverleaf whitefly (SLW)) in Australian cotton fields collected over four consecutive growing seasons (2002/2003–2005/2006) were used to develop and validate a multiple-threshold-based management and sampling plan. Non-linear growth trajectories estimated from the field sampling data were used as benchmarks to classify adult SLW field populations into six density-based management zones with associated control recommendations in the context of peak flowering and open boll crop growth stages. Control options based on application of insect growth regulators (IGRs) are recommended for high-density populations (>2 adults/leaf) whereas conventional (non-IGR) products are recommended for the control of low to moderate population densities. A computerised re-sampling program was used to develop and test a binomial sampling plan. Binomial models with thresholds of $T=1$, 2 and 3 adults/leaf were tested using the field abundance data. A binomial plan based on a tally threshold of $T=2$ adults/leaf and a minimum sample of 20 leaves at nodes 3, 4 or 5 below the terminal is recommended as the most parsimonious and practical sampling protocol for Australian cotton fields. A decision support guide with management zone boundaries expressed as binomial counts and control options appropriate for various SLW density situations is presented. Appropriate use of chemical insecticides and tactics for successful field control of whiteflies are discussed.

1. Introduction

In 2001, the whitefly, *Bemisia tabaci* (Gennadius), emerged as a significant threat to Australian field crops following a major outbreak of the pest in the cotton-growing area surrounding the township of Emerald (23°23′S, 148°10′E) in central Queensland (CQ) (Moore et al., 2004). Extensive whitefly surveys by CSIRO entomologists throughout the CQ region in 2001 and 2002, and diagnostic testing for biotype determination using RAPD PCR techniques (De Barro and Driver, 1997) revealed only the B biotype in all population samples (P. De Barro, unpublished data).

The threat posed by the B biotype, also referred to as the silverleaf whitefly (SLW), to cotton is two-fold. Firstly, the sugary secretion (honeydew) deposited on open cotton bolls by adults and nymphs feeding on the abaxial surface of leaves makes the lint sticky and unmarketable. Yield losses can also occur due to whitefly feeding, especially when population densities are high (De Barro, 1995; Naranjo et al., 1998). Secondly, rapidly evolving resistance to chemical control agents (Dennehy et al., 2005; Horowitz et al., 2005) makes management of SLW infestations challenging.

In 2002, the CQ cotton industry responded to the SLW threat by implementing a field sampling and management plan developed and used successfully in Arizona (USA) cotton crops (summarised in Ellsworth and Martinez-Carrillo, 2001) to equip cotton growers with an emergency, stop-gap pest management framework. Briefly, the Arizona SLW management plan involves use of highly effective insecticides (insect growth regulators, IGRs) in conjunction with adult and nymph density action thresholds, and an efficient binomial sampling scheme anchored within a broadly based integrated pest management framework (Naranjo et al., 1996, 1998; Ellsworth and Martinez-Carrillo, 2001; Naranjo, 2001; Palumbo et al., 2001).

Since the introduction of the Arizona SLW protocols in 2002, control of SLW in CQ commercial cotton has been underpinned by the use of the IGR pyriproxifen (Admiral®), in conjunction with the dual Arizona action thresholds of 3–5 adults/leaf and 0.5–1 nymphs per 3.88 cm^2 circular leaf area based on a sample size of 30 leaves (Naranjo et al., 1996; Ellsworth and Martinez-Carrillo, 2001). Field reports from crop consultants have consistently

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doi:10.1016/j.cropro.2008.04.002

indicated that whilst the IGRs have proven to be highly effective in controlling SLW populations, varying degrees of lint contamination still occurs in commercial cotton fields.

The recurrence of SLW and lint contamination each growing season indicated the need for an indigenous pest management framework tailored to local crop production practices, plant phenology and pest population characteristics in order to provide effective long-term control of the problem in Australian cotton. In this paper, we present a new decision support framework and control recommendations for SLW in Australian cotton based on population abundance data collected under the auspices of a research project initiated in 2002 to investigate the invasion ecology and population dynamics of the invader. The field density data, collected over four consecutive cotton seasons (September–March; 2002/2003–2005/2006) in commercial cotton fields, were used to characterise seasonal population growth trajectories, which in turn, were used as the basis for the development of intervention and control guidelines. A new binomial sampling scheme is presented and discussed in relation to effective SLW management.

2. Materials and methods

2.1. Sampling

Population density of SLW adults and nymphs was estimated at seasonally fixed geo-referenced sampling sites in commercial cotton fields scattered throughout the Emerald irrigation area. Sampling was conducted at fortnightly intervals in crops planted between 15 September and 30 October over three consecutive cotton seasons (2002/2003–2004/2005) at 90, 34 and 24 sampling sites, respectively. Each sampling site was located within a 5–20 ha field of cotton. Large fields (>20 ha) were arbitrarily subdivided into two or more units that were sampled separately.

GPS coordinates marked the centre of each site. No samples were collected within 20 m from the edge of the field. Population density was estimated by sampling one leaf from each of 30 plants at each sampling site. The leaves were sampled in a zigzag or U-shaped pattern, allowing approximately 5 m between individual plants. The abundance of adults was estimated by whole leaf sampling, whereas the abundance of large nymphs was estimated within a 3.88 cm^2 area defined by a circular disc placed in sector 2 formed by the left and middle major veins on the abaxial surface of each leaf (Fig. 1; Naranjo and Flint, 1994, 1995).

In 2002/2003, following the implementation of Arizona SLW protocols (Naranjo et al., 1997) in CQ commercial cotton, sampling was restricted to the 5th node leaf (node 1 = 1st fully unfurled terminal leaf). Adult density was estimated by gently turning over a single leaf and counting the total number of insects on the abaxial side. The same leaf was subsequently used to estimate the density of large nymphs (instars III and IV) using the disc method. In subsequent seasons, the estimation of SLW density was based on a more flexible sampling protocol to account for variation in plant phenology and SLW distribution within and between fields and plants; adult density was assessed on a randomly selected 3rd, 4th or 5th node leaf, whereas the density of large nymphs was assessed on a 5th, 6th or 7th node leaf using a 3.88 cm^2 disc.

The validity of the leaf-sampling protocol, including the justification for choice of sampling nodes for adult and juvenile SLW, accuracy of the leaf disc method for estimating juvenile abundance and temporal changes in within-plant distribution associated with plant maturity, was tested in a separate series of field assessments that will be reported elsewhere.

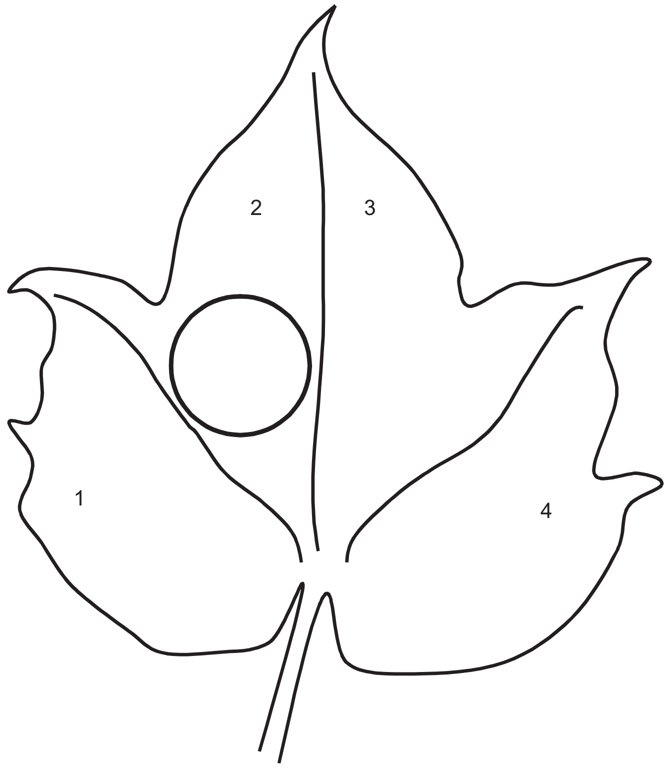

Fig. 1. Abaxial surface of a cotton leaf compartmentalised into sectors by major veins and the positioning of a 3.88 cm^2 disc for sampling silverleaf whitefly (SLW) nymphs.

2.2. Population growth trajectories

Non-linear regression curves were used to quantify changes in the mean and maximum estimated field population density of adult SLW between sampling dates in each growing season. Population density data for nymphs were analysed separately. A physiological time scale based on accumulated heat units (Day-Degree, DD hereafter) above the cotton development threshold of 12 °C (Constable and Shaw, 1988) was used to characterise and compare population growth trajectories among seasons. The daily accumulation of heat units was calculated using the formula

$$DD = [(T_{max} + T_{min}) - 24]/2,$$

where T_{max} and T_{min} are maximum and minimum daily temperatures for Emerald recorded by the Australian Bureau of Meteorology.

In the calculation of DD, all commercial fields sampled for estimation of SLW abundance were assumed to have been sown on 23 September with emergence on 1 October each year. A single planting date was deemed to be a reasonable simplification because the bulk of commercial cotton in the Emerald irrigation area was in the cotyledon/seedling stage by the first week of October during the sampling period (2002/2003–2004/2005).

An exponential model was used to describe population growth trajectories:

$$\text{Log density}_{(X)} = A + B(R^X), \quad (1)$$

where A, B and R are parameters, and X is DDs.

The raw leaf count data were $\log_{10}(X+1)$ transformed prior to analysis. Sampling site means were used as the basic units of density for generating population growth trajectories. GENSTAT Release 8 (Payne et al., 2005) was used for all statistical analyses of the data. Curve fitting was done using the NONLIN procedure in GENSTAT.

The non-linear curves describing changes in population density were used to classify SLW field populations into management categories with associated control recommendations in relation to crop growth stage and the potential for damage.

2.3. Sampling plan

A fixed sample size binomial sampling plan was developed and tested using a public-domain computer program, *Resampling for Validation of Sample Plans* (RVSP), developed by Naranjo and Hutchison (1997). The RVSP program has been widely tested and used to develop sampling plans for several insect pests in crops worldwide (Hodgson et al., 2004).

The combined 2002/2003 and 2003/2004 adult abundance data (counts on individual leaves) were used to develop the sampling plan. Data from adjacent fields within farms were aggregated to yield 67 individual data sets with sample sizes of 60–390 leaves. Aggregation of the raw abundance data based on samples of 30 leaves was necessary to generate data sets that were large enough to facilitate re-sampling procedures (see below).

The key elements of a binomial sampling plan—the binomial model and effective sample size—were identified in two stages. In the first stage, we investigated the relationship between mean population density (m) and the proportion of leaves infested with at least T individuals (P_T) using an empirical equation:

$$\ln(m) = \alpha + \beta \ln(-\ln[1 - P_T]) \quad (2)$$

where α and β are parameters estimated by linear regression (Kono and Sugino, 1958; Gerrard and Chiang, 1970). Binomial models that use P_T as a predictor of m using Eq. (2) were developed for tally thresholds (T) of 1, 2 and 3 adults per leaf.

In the second stage we compared the performance of the three models at specific values of m (action thresholds) based on their operating characteristic (OC) functions and actual errors in classification for fixed sample sizes of 20, 30 and 40 leaves. The OC function, generated by the RVSP program, is a useful graphical indicator of the model's accuracy in population classification in relation to an action threshold. A four-parameter logistic model was fitted to the OC data to facilitate interpretation (Naranjo et al., 1997):

$$\mathrm{OC}_{(X)} = D + (A - D)/(1 + [m/C]^B) \quad (3)$$

where D, A, C and B are constants and m is field population density of adults.

The OC value for each data set indicates the proportion of re-sampled means that are classified as being above or below the action threshold by the binomial model being analysed. Thus, the OC may be interpreted as the probability of taking no action in relation to the action threshold. For fixed sample size plans, the shape of the OC curve may be influenced by the binomial model used and sample size (Naranjo et al., 1996, 1997). The shape of the OC function reflects the accuracy of the model. The steeper the OC function in the vicinity of the action threshold, the greater the accuracy of the underlying binomial model. If the underlying model is sound the OC should be near 0.5 at the action threshold.

The binomial models with satisfactory OC functions were further evaluated for accuracy in population classification based on actual Type I (α) and Type II (β) errors. The RVSP output includes re-sampled estimates of m and P_T for each data set. Individual data sets were re-sampled 500 times with replacement. We used the RVSP output for the 2002–2004 data set to classify the outcome of each iteration for each data set as accurate or inaccurate in relation to the action threshold and its binomial (proportion infested) counterpart (see Naranjo et al., 1997 for further details and methodology). The α error rate is the probability of taking control action when none is needed whereas the β error rate is the probability of failing to take action when needed. The latter is considered more important in making pest management decisions because of the associated higher risk of economic damage (Naranjo et al., 1997).

The binomial model with the lowest error rates in population classification was tested using independent field data not used in any facet of model development. In the 2005/2006 season, independent data were collected from eight commercial cotton fields planted at various times between 15 September and 25 December 2005, specifically for validation of the binomial sampling plan for adult SLW. Each crop was sampled 2–3 times at arbitrary intervals and a total of 30 data sets, each containing 90–200 leaves at the 5th node, were collected over the season.

3. Results

3.1. Population growth trajectories and intervention triggers

Seasonal population density profiles for adult SLW were all consistent with exponential growth described by Eq. (1) up to approximately 2000 DD (Fig. 2A). A plateau or decline in density is evident at the end of the season, primarily as a result of intervention with chemical insecticides. The abundance of large nymphs generally increased as the crop matured (2000 DD).

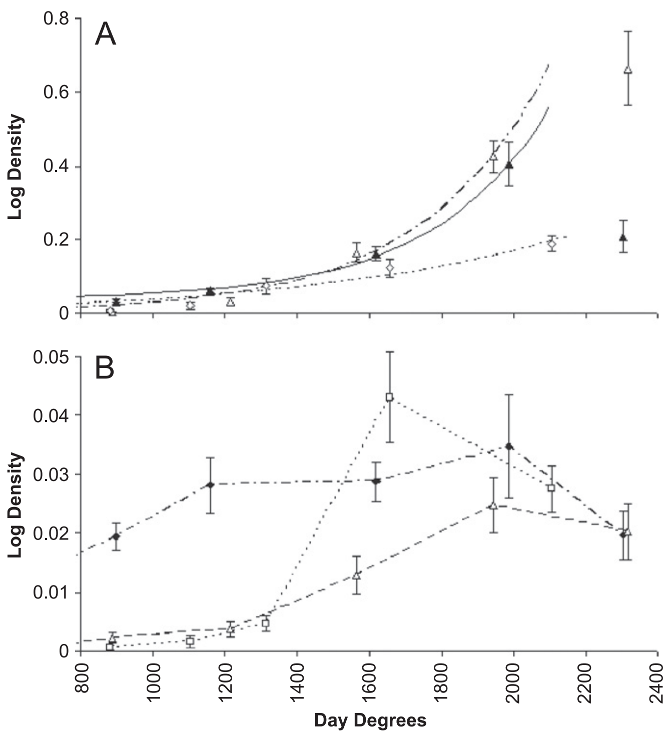

Fig. 2. (A) Mean population growth trajectories of adult SLW from cotton fields in three consecutive growing seasons (2002/2003–2004/2005) in the Emerald Irrigation Area. Vertical lines show SEM. Non-linear regression curves were fitted to data from individual seasons using Eq. (1): Log Density$_{(X)} = A+B(R^X)$. Parameter estimates (±SE) for Eq. (1): (a) 2002/2003 (▲); $R = 1.00312$ (4×10^{-4}), $B = 0.00077$ (6.1×10^{-4}), $A = 0.0352$ (8.1×10^{-3}), $r^2 = 98.6$; (b) 2003/04 (△); $R = 1.00289$ (2.4×10^{-4}), $B = 0.00156$ (7.1×10^{-4}), $A = -0.00156$ (7.1×10^{-4}), $r^2 = 97.8$; (c) 2004/2005 (○); $R = 1.00135$ (4×10^{-4}), $B = 0.01196$ (1×10^{-2}), $A = -0.01196$ (1×10^{-2}), $r^2 = 90.4$. (B). Mean seasonal density profiles of SLW large nymphs for 2002/2003 (◆), 2003/2004 (△) and 2004/2005 (□) in cotton fields in the Emerald Irrigation Area. Vertical lines represent SEM.

Seasonal population profiles of large nymphs were highly variable between seasons (Fig. 2B). The discord amongst nymph population profiles can be explained in part by sampling error inherent in the leaf disc method used to estimate abundance. Independent field assessments indicated that estimates of changes in large nymph density obtained using the leaf disc were poorly correlated with the corresponding whole leaf counts (R. Sequeira, unpublished data). Thus, the nymph abundance data based on leaf disc counts were not sufficiently robust to warrant further analysis and interpretation. The development of a management decision support framework for SLW (see below) was based exclusively on the adult abundance data.

Due to the limited range in field population densities of adults observed within individual seasons and the similarity of the 2002/2003 and 2003/2004 profiles (Fig. 2A), the combined data from these seasons were used to estimate generalised population growth trajectories. The 2004/2005 data were excluded because SLW densities were too low to be considered economically injurious. A scatter graph of adult density (sampling site mean) in the combined data set (Fig. 3) shows an exponential increase in dispersion with increasing DDs. Non-linear regression curves describing predicted maximum and mean population density for the 2002–2004 data partition the *time* (DD) × *density* response area into three discrete regions of low (1), medium (2) and high (3) SLW population density and future growth potential in the context of key crop physiological stages.

We identified peak flowering and open bolls as the key crop physiological stages in relation to SLW management. Changes in the rate of acceleration calculated from differencing transformations ($N_{t+1}-N_t$) of log density indicate that peak flowering of cotton at around 1300 DD (10–14 days after first flower) coincides with an inflection point in SLW population growth trajectories. A sharp increase in the acceleration of growth rate (not shown) is evident at around peak flowering when population density exceeds 1 adult/leaf. At the upper end, the presence of significant SLW populations in fields with open bolls (>1650 DD) makes lint contamination and the resultant threat to the industry inevitable.

We used the partitioned *time* × *density* response area as a multiple-threshold framework to classify SLW populations into management zones with associated control options (Fig. 4). The mean (lower) threshold curve separates regions 1 and 2, whereas the maximum (upper) threshold curve separates regions 2 and 3.

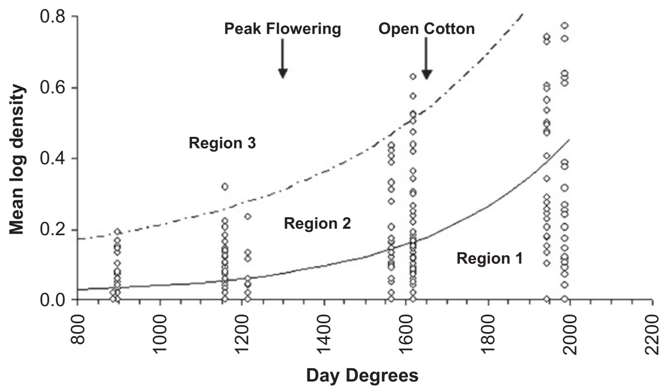

Fig. 3. Non-linear regression curves fitted to combined adult SLW data for 2002/2003 and 2003/2004 using Eq. (1): Log density$_{(X)}=A+B(R^X)$. Symbols represent mean density at each field sampling location. Upper (dashed) and lower (solid) curves indicate predicted maximum and mean density at each sampling date, respectively. Parameter estimates (±SE) for Eq. (1): (a) Mean density curve; $R=1.00283$ (4×10^{-4}), $B=0.00155$ (1.2×10^{-3}), $A=0.0139$ (1×10^{-2}), $r^2=96.3$; (b) Maximum density curve; $R=1.002$ (6×10^{-4}), $B=0.0166$ (2×10^{-2}), $A=0.0869$ (6.5×10^{-2}), $r^2=87.5$. The curves define three regions of low, medium and high population density.

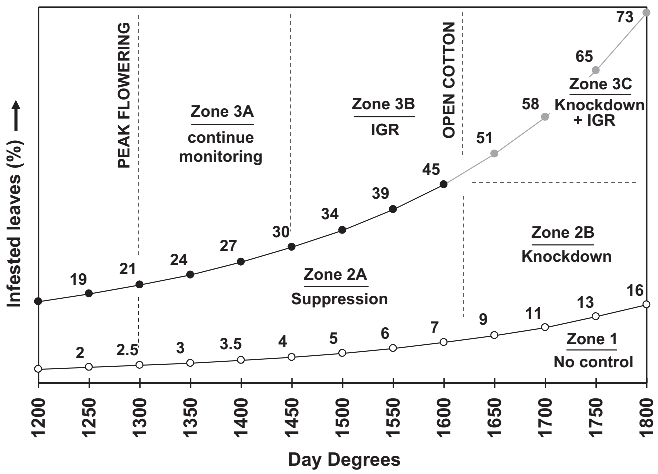

Fig. 4. Changes in the predicted maximum (upper curve) (●) and mean (lower curve) (○) population density of adult SLW in Emerald cotton crops planted on 23 September in relation to crop age (accumulated Day Degrees (DD)) estimated from the 2002/2003–2003/2004 combined abundance data. Vertical dashed lines indicate key physiological crop stages and delineate various pest management decision zones. Proportions of infested leaves were calculated using the $T=2$ binomial model; values are provided along the curves at 50 DD intervals (see text for detail).

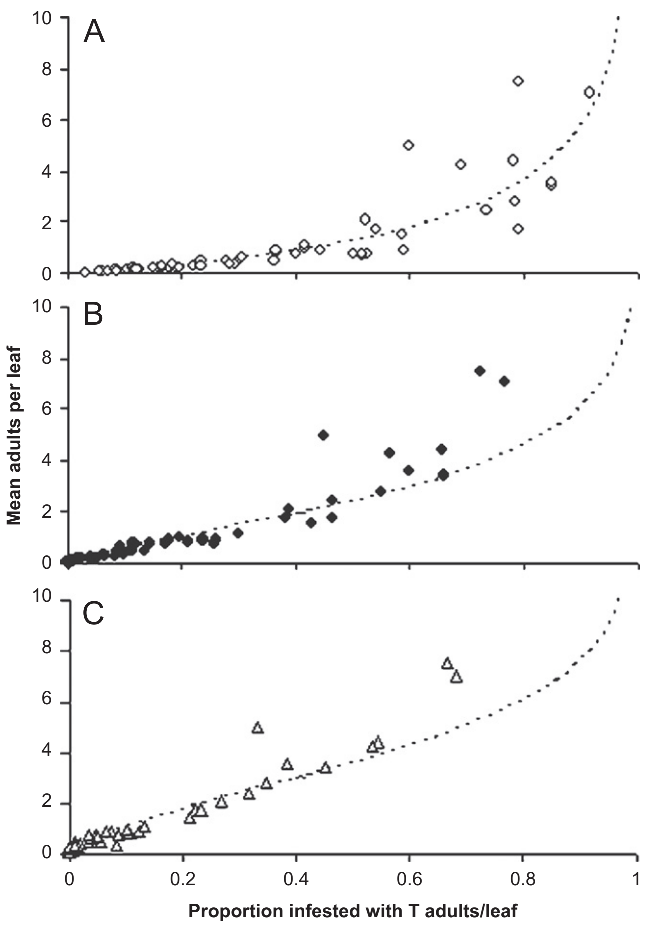

Fig. 5. The relationship between mean observed field density of adults and the proportion of sample units infested with ⩾T adult SLW per leaf for the combined data from the 2002/2003 and 2003/2004 seasons in Emerald cotton fields. The smooth curves were fitted using the exponential form of Eq. (2): $m=\ln(\alpha)(-\ln[1-P_T]^{\beta})$. Parameter estimates (±SE): (A) $T=1$, $\alpha=0.6898$ (6.8×10^{-2}), $\beta=1.2721$ (4.5×10^{-2}), $r^2=0.9435$; (B) $T=2$, $\alpha=1.1564$ (8.4×10^{-2}), $\beta=0.7720$ (2.9×10^{-2}), $r^2=0.9387$; (C) $T=3$, $\alpha=1.5074$ (9.4×10^{-2}), $\beta=0.6220$ (2.8×10^{-2}), $r^2=0.9252$.

Field populations are assigned to regions and zones based upon a consistent density deviation above or below the time-specific threshold density over several sampling intervals.

Intervention with insecticides is not warranted in fields falling into region 1 (zone 1) because the risk of lint contamination is negligible. Fields falling into region 2 may be further grouped into two zones. Application of conventional (non-IGR) insecticides may be useful for population suppression in early crop stages (zone 2A) or in the open boll stage for rapid knockdown (zone 2B). IGRs, alone or in tandem with conventional insecticides, are the recommended control options for fields in region 3, which is further partitioned into three zones. Application of an IGR prior to about 1450 DD (zone 3A) is not recommended due to the possibility of SLW population resurgence and the need for additional intervention in later stages of the crop. The ideal positioning of IGR applications is between 1450 and 1650 DD (zone 3B) prior to the onset of boll opening. In fields with open bolls (> 1650 DD) and > 2 adults/leaf (zone 3C) the use of an IGR by itself is unlikely to prevent lint contamination due to the inherent time delay in the onset of population decline following application; rapid knockdown of the population using a conventional insecticide followed by IGR application for residual control may be required to limit the extent of lint contamination.

3.2. Sampling plan

The development of binomial models was based on 54 useful data sets derived from the combined 2002–2004 abundance data, with mean densities in the range of 0.01–8 adults per leaf. The relationship between proportion infested (P_T) and mean density (m) for tally thresholds (T) of 1, 2 and 3 adults per leaf was adequately represented by Eq. (2), with r^2 values >0.92 (Fig. 5). The best fit was in the mean density range of about 0.01–4 adults/per leaf. Above this range, the relationship was compromised by the paucity of observed sample means.

In a preliminary analysis intended to differentiate the three binomial models, their OC function characteristics were compared at an action threshold of 2.25 adults/leaf (upper limit of zone 3B), which equates to proportion infested values of $P_{T(1)}=0.65$, $P_{T(2)}=0.47$ and $P_{T(3)}=0.28$ (Fig. 5). The $T=1$ model was characterised by comparatively poor OC function that was relatively flat, with a high degree of scatter (Fig. 6). By comparison, OC functions for the $T=2$ and 3 models were similar in shape, with steeper drops in the vicinity of the action threshold and less scatter.

Actual types I and II classification error rates for the 2002–2004 data used in parameterisation and the 2005–2006 independent validation data sets were used to further discriminate between the $T=2$ and 3 models in term of accuracy. Errors were assessed at two action thresholds corresponding to the boundaries of management zone 3B (Fig. 5) and three sample sizes. Mean types I and II error rates were well below 10% across all model × action threshold combinations (Table 1). There was no evidence of a sample size effect on error rates. Mean type I error rates were consistently higher than their corresponding type II counterparts, indicative of conservative behaviour by both models. As indicated by the OCs, the $T=2$ and 3 models were

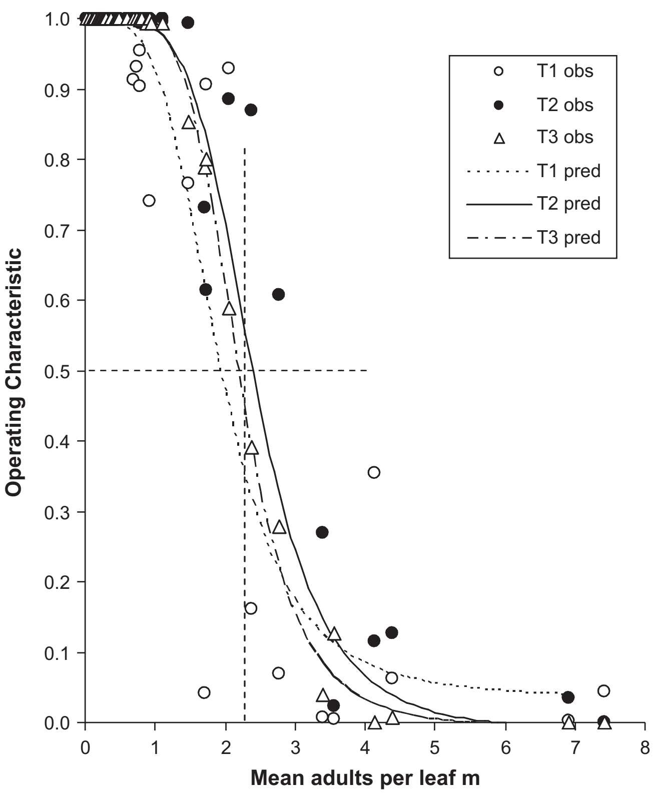

Fig. 6. Operating characteristic (probability of taking no action) curves for fixed-sample size binomial models using a tally threshold of $T=1$, 2 or 3 adults/leaf, corresponding binomial action thresholds (P_T) of 0.65, 0.47 and 0.28 and a sample size of $N=30$ leaves for the combined 2002–2004 SLW adult abundance data. Values of the operating characteristic (OC) were generated by the RVSP re-sampling software (see text for details). The smooth curves represent fitted values of Eq. (3); the horizontal and vertical dashed lines indicate an OC value of 0.5 and the action threshold of 2.25 adults/leaf, respectively.

Table 1
Actual type I (α) and type II (β) error in classification for adult SLW abundance data from Australian cotton fields using binomial models with tally threshold $\geqslant T$ adults/leaf and sample sizes (n) of 20, 30 and 40 leaves

Data/model	n	Type I error (%)		Type II error (%)	
		Mean	Max	Mean	Max
2002–2004 (combined): 54 data sets					
Model: $T=2$ $m=1.44$	20	3.2	29.0	1.2	11.8
	30	3.2	31.6	0.7	10.6
	40	3.0	37.2	0.5	9.2
Model: $T=3$ $m=1.44$	20	6.5	36.6	0.4	5.6
	30	3.7	30.2	0.4	5.0
	40	4.6	35.8	0.2	4.4
Model: $T=2$ $m=2.25$	20	2.2	35.6	1.9	24.2
	30	1.7	31.6	1.9	26.2
	40	2.1	46.4	1.2	24.4
Model: $T=3$ $m=2.25$	20	2.2	19.4	0.9	13.2
	30	1.7	17.2	0.9	12.0
	40	1.2	14.2	0.9	11.6
2005–2006: 30 independent data sets					
Model: $T=2$ $m=1.44$	20	4.1	24.2	0.6	6.6
	30	5.2	40.8	0.4	7.6
	40	5.0	42.4	0.3	5.0
Model: $T=3$ $m=1.44$	20	8.5	65.8	0.1	1.4
	30	6.6	64.6	0.3	5.2
	40	7.9	71.6	0.1	2.6
Model: $T=2$ $m=2.25$	20	4.0	33.6	1.0	9.6
	30	3.2	34.4	0.9	10.2
	40	3.6	37.0	0.6	7.8
Model: $T=3$ $m=2.25$	20	4.4	29.0	0.5	8.4
	30	3.8	30.4	0.6	9.4
	40	3.1	28.2	0.6	7.2

The models were evaluated at action thresholds (m) of 1.44 and 2.25 adults/leaf. Classification errors were computed manually from the output of the RVSP computer program based on 500 re-sampling iterations for each data set.

very similar in terms of types I and II error rates across action thresholds. However, the relationship between proportion infested and mean density was slightly better for the $T = 2$ model and it would provide better resolution at lower SLW densities.

4. Discussion

We propose a SLW management strategy that provides the requisite scope and flexibility to address the complexity of pest management in Australian cotton production systems. Individualism in crop management practices is one of several factors that make SLW management challenging. Virtually, 100% of Australia's annual cotton crop is managed by professional agricultural consultants. Adjacent cotton farms can often be managed by different consultants employing individualistic pest control strategies. This often results in situation where fields with similar SLW densities can be managed differently and fields with significantly different population densities may be treated with the same product.

The cost of insecticide application has had a significant impact on the evolution of SLW management in Australian cotton. Whilst threshold-based intervention with IGRs has provided effective control of SLW populations in commercial cotton fields (Horcott Pty. Ltd., unpublished data), in reality the treatment of sub-threshold populations has become common practice. The use of IGRs for SLW control has declined substantially in recent years. At around \$100/ha, IGR application contributes significantly to the cost of production. The decline in IGR use has been matched by an increase in the use of less-expensive conventional (non-IGR) insecticides. However, experiences of using non-IGR insecticides for SLW control have been variable. A good example of this is diafenthiuron, which appears to provide consistently good field control at low-moderate densities but is variable in efficacy at higher densities.

The spectrum of insect problems endemic to Australian cotton production systems is yet another factor that impinges on management of SLW. In the current GM cotton era, sap-sucking bugs, particularly mirids (*Creontiades* spp.), are major and frequent pests requiring 1–2 insecticide sprays on most crops each season. Aphids, mites, jassids and thrips also need to be controlled on many crops each year. These pests are commonly controlled with insecticides such as fipronil, dimethoate and various pyrethroids, which also impact on beneficial insect populations. Consequently, the 'bio-residual' factor (Ellsworth and Martinez-Carrillo, 2001; Naranjo, 2001) that makes IGRs so effective in other cotton systems by providing ongoing control of SLW through natural enemies after the residual effect of the chemical has evaporated is often in-effective in Australia. Thus, the need to control other pests constrains the timing of IGR use in Australian cotton fields.

Fields treated early (before ~1450 DD) with insecticide (including IGRs) to control SLW have a higher probability of re-colonisation from other sources or resurgence of the population in the 9–10 weeks from peak flowering to defoliation. Pest resurgence is a key consideration in management decisions due also partly to a restriction on insecticides for whitefly control to one application of a single product per season from each chemical group (including IGRs) voluntarily adopted by the Australian cotton industry as part of a national Insecticide Resistance Management Strategy (Forrester et al., 1993; Fitt, 1994).

Collectively, the six management zones and associated control options we propose here address the majority of whitefly population density scenarios and crop consultant behaviours in Australian cotton fields. The proposed proactive management options involving the use of conventional insecticides (zone 2A) or IGRs (zone 3B) aim to minimise the risk of lint contamination whereas reactive population control in the open boll stage (zones 2B, 3C) primarily minimise the level of lint contamination.

Population control with IGRs remains the principal platform of our strategy. IGRs have provided sustainable and IPM-friendly control of whiteflies in Australia, the USA and other cotton-producing countries in the world (Ellsworth and Martinez-Carrillo, 2001; Naranjo, 2001; Palumbo et al., 2001). The IGRs Pyriproxifen and buprofezin are highly effective against SLW, give excellent control across a broad range of densities and are very selective, allowing unimpeded survival of predators and parasites (Palumbo et al., 2001; Naranjo et al., 2004). With an accumulation rate of around 18–20 DD/day under typical CQ summer conditions, zone 3B provides an optimum IGR application window of at least 10 days between 1450 and 1650 DDs.

The boundaries between regions and zones (Fig. 4) are discretionary areas with regard to population management options. For example, SLW field populations with estimated densities and/or growth rates just below the zone-3B boundary would be correctly placed in zone 2A and targeted with conventional insecticides for suppression but more reliably controlled by application of an IGR. Local information pertaining to the crop, weather and the pest and beneficial populations will be important in determining the appropriate course of action in discretionary areas.

Robust sampling procedures and accurate population estimation or classification are fundamental to effective pest management. Binomial sampling can often be more accurate than complete enumeration for classifying populations as above or below a given threshold because presence/absence sampling based on a tally threshold is fairly resistant to the effects of a few outlier observations (Jones, 1994; Naranjo et al., 1996; Hodgson et al., 2004). The re-sampling analysis of the 2005–2006 field data provides a robust test of the binomial models under field conditions. Type II error rates (Table 1), which are more important than their Type I counterparts for minimising the risk of crop damage indicate on average >90% accuracy in population classification for both binomial models. Based on our results we recommend a tally threshold of $T = 2$ adults/leaf and a minimum sample size of 20 leaves at terminal nodes 3, 4 or 5 as the most parsimonious and practical sampling plan for Australian cotton fields.

Threshold population densities of adult SLW that define the boundaries between regions and management zones relative to crop growth stage, expressed as binomial counts (% infested), are presented as a SLW control decision support guide for growers and crop managers (Fig. 4). The success of the strategy hinges on rigorous sampling of adult and nymph populations after the onset of flowering. Whilst sampling for adults provides more accurate estimates of SLW abundance in the crop than nymph sampling, the latter is vital for gauging future population growth potential and is critical for validating the population dynamics assumptions that underpin the pest management strategy proposed here.

Our management strategy and sampling plan are expected to be valid in crops that experience pest population growth as a result of endogenous processes and gradual immigration over a period of several weeks or months as opposed to mass immigration events. The pattern of SLW population dynamics in CQ cotton planted in the prime commercial window (15 September–31 October) appears to be consistent with a gradual build up of SLW through a combination of steady, low-level immigration from over-wintering weed hosts and endogenous population growth. The presence of adults and concomitant absence of large nymphs within crops at or beyond cut-out is strongly indicative of mass immigration in which case the management strategy discussed here may not be fully applicable.

Acknowledgements

We thank Steve Castle (USDA-ARS, Maricopa, AZ), Dale Spurgeon (USDA-ARS, Shafter, CA) and an anonymous referee for helpful comments on earlier drafts of this manuscript. We thank Alison Shields, Andrew Moore and Jennifer Blacklock for their hard work in collecting the data and dedication to the project. This work was jointly funded by the Australian cotton and grains research and development corporations (CRDC and GRDC).

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