Optimising mirid control on cocoa farms through complementary monitoring systems

JOURNAL OF APPLIED ENTOMOLOGY

J. Appl. Entomol.

ORIGINAL CONTRIBUTION

Optimizing mirid control on cocoa farms through complementary monitoring systems

G. K. Awudzi[1], A. R. Cudjoe[1], P. Hadley[2], P. E. Hatcher[3] & A. J. Daymond[2]

1 Cocoa Research Institute of Ghana, New Tafo-Akim, Ghana
2 School of Agriculture Policy and Development, University of Reading, Reading, UK
3 School of Biological Sciences, University of Reading, Reading, UK

Keywords
Distantiella theobroma, mirid, pheromone, population dynamics, *Sahlbergella singularis*, timing

Correspondence
Godfred K. Awudzi (corresponding author), Cocoa Research Institute of Ghana, Box 8, New Tafo-Akim, Ghana.
E-mails: anthocyanin22@yahoo.com and godfred.awudzi@crig.org.gh

Received: December 8, 2015; accepted: April 17, 2016.

doi: 10.1111/jen.12332

Abstract

Mirids (*Sahlbergella singularis* and *Distantiella theobroma*) are the most important insect pests affecting cocoa production across West Africa. Understanding the population dynamics of mirids is key to their management; however, the current recommended hand-height assessment method is labour intensive. The objective of the study was to compare recently developed mirid sex pheromone trapping and visual hand-height assessment methods as monitoring tools on cocoa farms and to consider implications for a decision support system. Ten farms from the Eastern and Ashanti regions of Ghana were used for the study. Mirid numbers and damage were assessed fortnightly on twenty trees per farm, using both methods, from January 2012 to April 2013. The mirid population increased rapidly in June, reached a peak in September and began to decline in October. There was a significant linear relationship between numbers of mirids sampled to hand-height and mirid damage. High numbers of male mirids were recorded in pheromone traps between January and April 2012 after which there was a gradual decline. There was a significant inverse relationship between numbers of trapped adult mirids and mirids sampled to hand-height (predominantly nymphs). Higher temperatures and lower relative humidities in the first half of the year were associated with fewer mirids at hand-height, but larger numbers of adult males were caught in pheromone traps. The study showed that relying solely on one method is not sufficient to provide accurate information on mirid population dynamics and a combination of the two methods is necessary.

Introduction

Cocoa is an economically important crop in many parts of the humid tropics. In West Africa, where over 70% of cocoa is produced (ICCO 2010/11), crop damage by mirid species (mainly *Sahlbergella singularis* and *Distantiella theobroma*) represents one of the major constraints to production. In a recent survey, Ghanaian farmers typically reported cocoa losses to mirids in the region of 30–40%(Awudzi et al. 2016). Past research efforts on mirid control in Ghana and elsewhere in West Africa have concentrated on developing biological and chemical control strategies (Bruneau de Mire 1977; Owusu-Manu 1995; Padi 1997). More recently, emphasis has been placed on an integrated pest management approach that is environmentally safe and easily adopted by smallholder cocoa farmers (Padi and Owusu 1998). To reduce losses due to pests and diseases on cocoa in Ghana, the government in 2001 introduced a number of interventions including the cocoa diseases and pests control programme (CODAPEC) (Asante et al. 2002). This has involved the spraying of cocoa farms with recommended conventional insecticides and fungicides. Although the programme has achieved some success in increasing yields, application of pesticides on a routine rather than a need basis can result in excessive pesticide use, with negative environmental consequences. With global concerns on pesticide use and food safety, it is increasingly necessary for a need-based assessment to be carried out before pesticides are applied on cocoa farms. Mirid population monitoring could be used to provide such a system alongside climatic data to decide on the most appropriate time to apply a control strategy. Pest monitoring is an important tool as it helps to determine when pest numbers have built up to warrant control or to predict the correct timing for interventions (Taylor 1984; Diana and Sannino 1995; Van-Emden 1996).

Pheromone trapping has been tested as a means to assess mirid numbers in some countries in West Africa. This has shown promise as a monitoring tool and could be incorporated into pest control programmes for effective mirid management (Sarfo 2008; Mahob et al. 2011). However, the method currently used for determining mirid populations is the visual hand-height assessment method described by Collingwood (1971). In contrast to the pheromone trapping method where mirids caught in traps can be counted at any time of the day, the visual hand-height assessment method must be carried out between 6:30 a.m. and 9:00 a.m. since the pest is less active in the early mornings of the day. The visual hand-height assessment method is tedious and difficult to adopt by smallholder farmers. Both assessment methods were therefore compared to ascertain whether pheromone trapping could provide a true representation of mirid populations and give an indication of the level of damage in cocoa farms compared to the visual hand-height method. As pest numbers are influenced by climatic factors, the relationship between climate, pest numbers and their damage was also investigated.

The specific objectives of the study were therefore:

i To evaluate pheromone trapping as a means of monitoring mirid population dynamics in cocoa farms in comparison with the currently used hand-height method.
ii To examine the relationship between mirid numbers, damage caused and climatic factors.

Materials and Methods

Study site

The study was conducted in the Ashanti and Eastern regions of Ghana at Adobewura (2°0′49.3″W, 6°32′11.4″N); Ntobrosu (2°2′46.7″W, 6°31′50″N); Achiase (2°2′20.9″W, 6°28′37.3″N); and Tafo (2°22′10.4″W, 6°13′25.8″N). Six farms were used on which hybrid cocoa (biparental crosses) was grown and four farms on which the Amelonado variety was grown. Planting distance for hybrid farms was 3 × 3 m, while that for farms with Amelonado varied and was planted irregularly. Farm size averaged 0.4 hectares with approximately 445 cocoa trees per farm. The age of farms used ranged between 6 and 15 years. These farms were lightly shaded (averagely 5–9 trees per 0.4 hectares) with *Terminalia ivorensis*, *Terminalia superba*, *Funtumia elastica* and *Albizia coriaria* as the most encountered shade trees. The farms were organic certified and had not received conventional insecticide for at least 5 years. Sampling for mirid population was carried out by pheromone trapping and the conventional visual hand-height assessment methods. Mirid population size and field assessment of mirid damage on cocoa pods and chupons were carried out fortnightly for 16 months from January 2012 to April 2013.

Visual hand-height assessment method

The visual hand-height assessment of mirid population (Collingwood 1971) was carried out on twenty randomly selected trees per farm. This involved visually inspecting mirid inhabiting sites (pods, pod peduncles, chupons, flower cushions, crevices on pods as well as the pod–stem interface) on each tree for mirids at hand-height and recording their numbers. Assessments were carried out from the base of the tree up to maximum hand stretch of the assessor (about 2 m) along the stem between 6:30 a.m. and 9:00 a.m. since mirids are less active before sunrise. Trained insect assessors helped in data collection to ensure that data were collected within this limited time frame. Data collected by trained insect assessors were cross-checked in the field to ensure accuracy and reliability. Pods and chupons were also assessed visually for mirid damage. Pods and chupons with characteristic vivid circular or elliptical dark feeding lesions were counted as mirid damage.

Mirid sex pheromone trapping method

Mirid pheromones produced by the Natural Resources Institute (NRI), UK, and previously tested in Ghana (Sarfo 2008) were used for this study. The study relied on the optimum pheromone blend, lure longevity, optimum trap design and optimum trap height reported by Sarfo (2008) to investigate mirid trapping suitability as a monitoring tool. The traps were made from 4.5 l plastic containers. Two 15 × 8 cm oblong holes or windows were created on opposite sides at 5 cm from the base of each container. At 2 cm below the lower edge of the cut surfaces, small holes (<5 mm) were made to drain off excess water from traps when it rained, to ensure that trapped mirids do not overflow from the traps. Traps were hung upside down, filled with water to a level just below the overflow holes. Lures containing the pheromone impregnated in vials were suspended in the traps about 2 cm above the water surface and held in place by a copper wire attached to the central top of the trap. Ten traps were evenly distributed in each farm at a height of 2.7 m above ground level with an average intertrap distance of 30 m (Sarfo 2013). Lures in each trap were changed at monthly intervals. Traps were inspected every other week for trapped mirids (*Sahlbergella singularis* and *Distantiella theobroma*), and their numbers recorded from January 2012 to April 2013.

Meteorological data

Data on rainfall, temperature and relative humidity were taken fortnightly from the nearest meteorological stations (Kumasi: 000°10′02.6″W; 05°36′16.8″N; Tafo: 2°22′10.4″W, 6°13′25.8″N). Miniature data loggers (Gemini Tiny Tags, UK) in Stevenson screens were also placed in farms to record temperature and relative humidity to compare with data obtained from the meteorological stations. Data loggers were set to log weather data at 1 h intervals each day and downloaded every other week for comparison.

Data analysis

The number of mirids counted (both to hand-height and by pheromone trapping) was analysed using the linear mixed-model approach to repeated measurements where the correlation within the subjects was modelled as first-order autocorrelation (AR) (1). The fixed effects in the model were specified to account for location, variety, assessment method and the interaction between variety and assessment method. This was carried out using the mixed-model procedure in GenStat. The relationship between mirid numbers, their damage and climatic data was investigated by means of regression analysis in GenStat.

Results

Mirid population: the visual hand-height assessment method

Mirids numbers recorded by the hand-height method were generally low from January to May for both 2012 and 2013 (fig. 1). Rapid mirid population increase began in June, reaching a peak in September and began to decline after October. Temperature, relative humidity and rainfall patterns from January 2012 to April 2013 for the Ashanti and Eastern regions are presented in fig. 2. A significant inverse relationship was observed between mirids sampled at hand-height and mean temperatures for the Ashanti ($y = -0.0515x + 1.491$; $r^2 = 0.25$; $P = 0.03$) and Eastern regions ($y = -0.137x + 4.1934$; $r^2 = 0.30$; $P = 0.02$) such that more mirids were sampled at lower temperatures. In addition, there was a positive correlation between relative humidity and mirid numbers for both regions (Ashanti: $y = 0.0098x - 0.6984$; $r^2 = 0.23$; $P = 0.02$ and

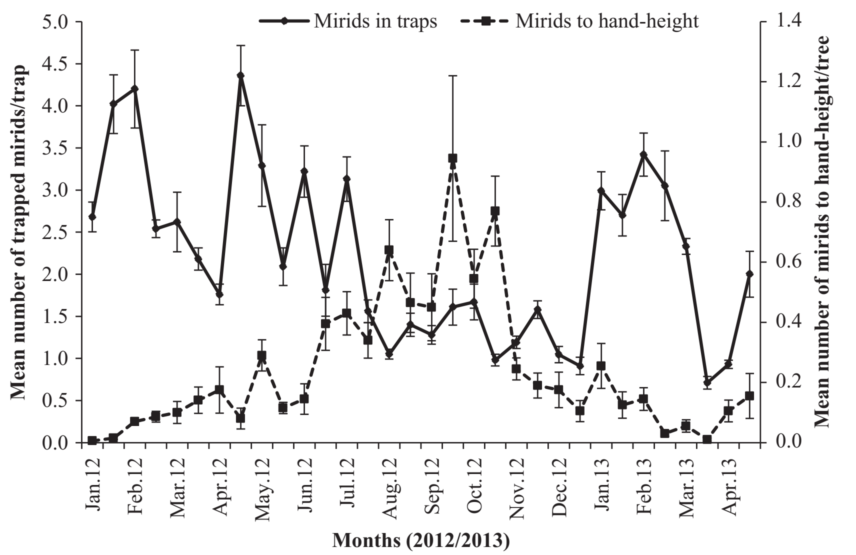

Fig. 1 Mirid numbers recorded by the visual hand-height and pheromone trapping assessment methods from January 2012 to April 2013 (at each 2-weekly interval, data points represent the mean values from 10 farms; 20 observations per farm for the visual hand-height method and 10 observations for pheromone trapping). Vertical bars represent standard error of means.

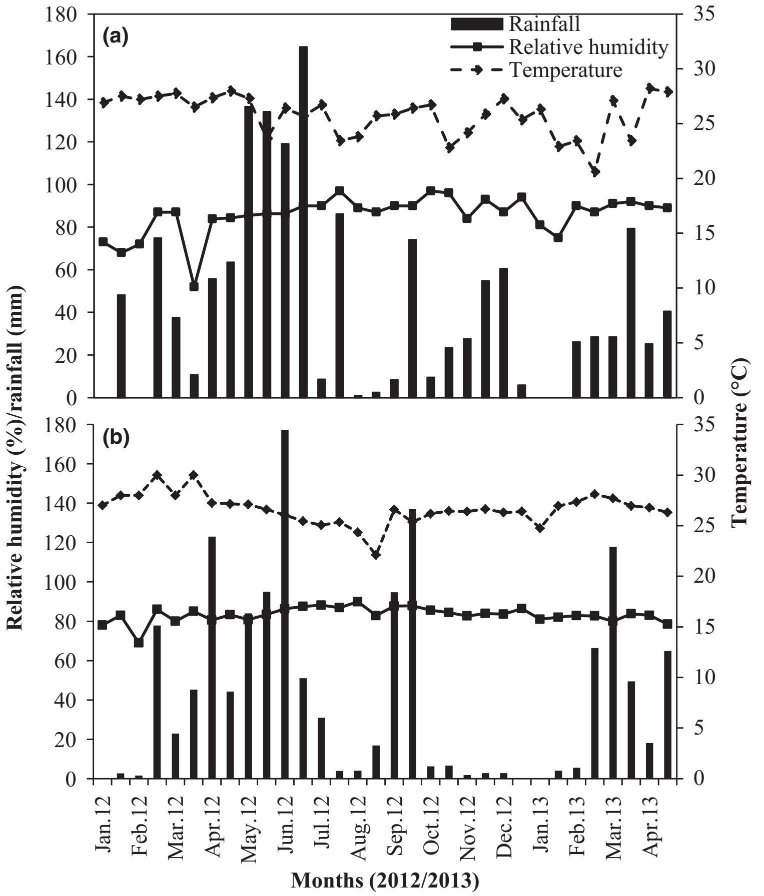

Fig. 2 Rainfall totals (15 day intervals), mean daily relative humidity and mean daily temperatures from January 2012 to April 2013 for the Ashanti (a) and Eastern (b) regions.

Eastern: $y = 0.1024x - 8.0151$; $r^2 = 0.33$; $P < 0.001$). Significantly, more mirid nymphs (mean = 0.31) than adults (mean = 0.10) were counted to hand-height (Lsd = 0.04, $P < 0.001$). Higher temperatures and low relative humidity prevail between January and May compared to the rest of the year, whilst rainfall patterns varied greatly across the year with the highest rainfall figures recorded in June (see fig. 2). However, no relationship was found between rainfall and mirid population assessed to hand-height. There was a significant positive linear relationship between the number of mirids assessed to hand-height and mirid damaged pods and chupons (fig. 3).

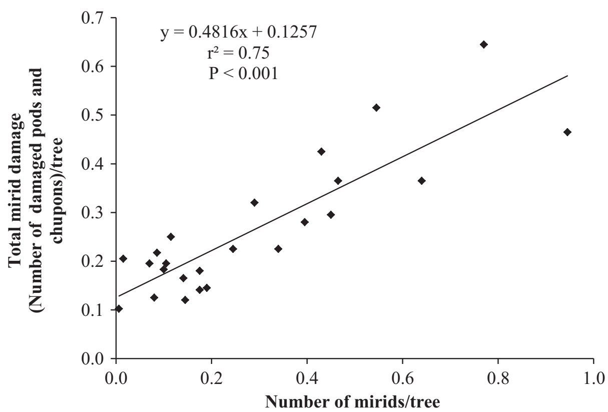

Fig. 3 Relationship between the number of mirids assessed at hand-height and their damage on pods and chupons (total mirid damage) (mean values measured at **2**-weekly intervals over a period of 15 months).

The pheromone trapping method of assessing mirid populations

The population dynamics of mirids recorded from pheromone traps differed from that observed using the visual hand-height assessment method (fig. 1). This method indicated that mirids were present on cocoa all year round as observed with the visual hand-height method but with different peak periods. With pheromone trapping, three major peaks in mirid numbers were observed in January, February and April followed by a gradual decline through the rest of the year. The population profile in the first quarter of

2013 was similar to that observed during the same period in 2012. There was a significant positive linear relationship between the number of mirids caught in traps and mean temperatures for the Ashanti (fig. 4a) and Eastern (fig. 4b) regions even though the regression coefficient for the Eastern region only explained a small proportion of the variation making the relationship a weak one ($r^2 = 0.22$, P = 0.02). There was no significant relationship between numbers of mirids caught in traps with rainfall, relative humidity and mirid damage on cocoa trees.

Comparison of mirid numbers sampled with pheromone trapping and the visual hand-height assessment methods

When comparing the two assessment methods, the first half of the year showed a significant difference in monthly mean mirid numbers caught in traps (3.0) compared to mirids counted at hand-height (0.1) (P < 0.001; Lsd = 0.55). Population dynamics were

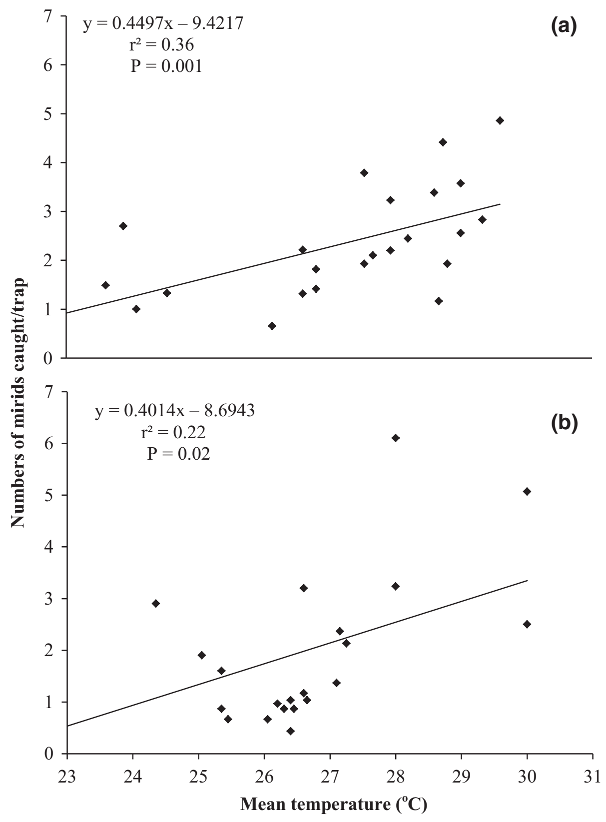

Fig. 4 Relationship between the mean numbers of mirids caught per trap and the mean daily temperatures (at **2**-week intervals over a period of 15 months) for the Ashanti (a) and Eastern (b) regions.

the same for the second half of the year although more mirids were caught in traps (mean = 2.6) than mirids assessed to hand-height (mean = 0.25) (P < 0.001; Lsd = 0.42). Data analysed for the whole year therefore showed significantly more mirids in traps (monthly mean = 2.3) than to hand-height (monthly mean = 0.3) (P < 0.001; Lsd = 0.47). The trend in the total number of mirids recorded from January to April 2012 was similar to the pattern observed in the same period of 2013 for the two sampling methods. A significant inverse relationship was established between the two assessment methods even though the coefficient of determination explained a relatively small proportion of the variation ($r^2 = 0.25$, P = 0.01).

Differences between regions and varieties in mirid numbers and mirid damage

The mixed-model approach used to analyse the repeated measurements showed a substantial autocorrelation (0.64 ± 0.22) among the measurements. The fixed effects of interest in this study are sampling method, variety and location. There was no effect of location on the number of mirids caught in traps (mean value for the Eastern Region = 2.26 and for the Ashanti Region = 2.25; P = 0.97, Lsd = 0.46). The mean number of mirids caught in traps in the Eastern and Ashanti regions was similar through most of the year except in the period between August and December (fig. 5a) where the number of mirids increased in the Ashanti region and decreased in the Eastern region. The number of mirids assessed to hand-height was different for the locations as significantly more mirids were counted to hand-height in the Eastern (mean = 0.53) than the Ashanti (mean = 0.13) region (P < 0.001; Lsd = 0.12). The number of mirid damaged pods and chupons was also significantly greater in the Eastern region (0.42) than in the Ashanti region (0.14) (P < 0.001; Lsd = 0.1). The pattern of the number of mirids assessed to hand-height in the two locations across the study period is presented in fig. 5b. Generally, differences observed in mirid populations between the different locations occurred in the second half of the year.

Significantly, more mirids were caught in traps on farms growing Amelonado (mirids per trap = 2.57) compared to farms growing hybrid cocoa (mirids per trap = 1.94)(P = 0.001, Lsd = 0.38). Significantly, more mirids were counted to hand-height on farms growing hybrid cocoa (mean = 0.40) than farms growing Amelonado (mean = 0.28) (P = 0.03, Lsd = 0.10). Mirid damage assessed visually to hand-

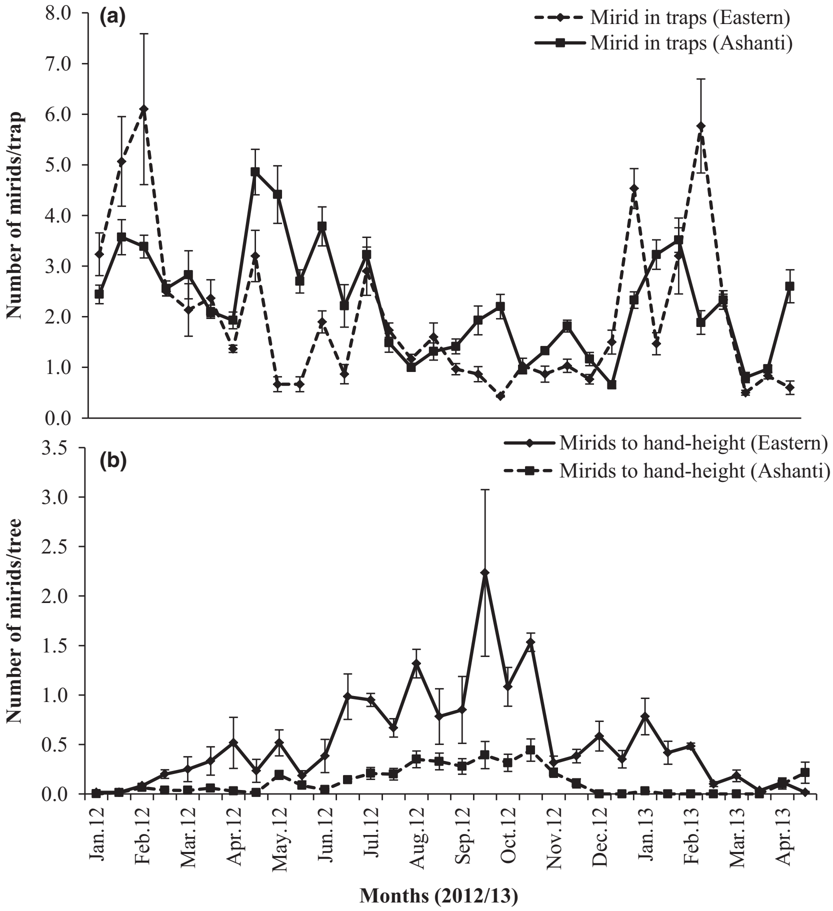

Fig. 5 Comparison of the mean number of mirids caught in pheromone traps (a) and that counted to hand-height (b) in the Ashanti and Eastern regions from January 2012 to April 2013 (at each 2-weekly interval, data points represent the mean values from six farms in the Ashanti Region and four farms in the Eastern Regions; 20 observations per farm for the visual hand-height method and 10 observations for pheromone trapping). Vertical bars represent standard error of means. Note differences in scales.

height on pods and chupons was significantly higher in farms growing Amelonado compared to those growing hybrid cocoa (1.53 and 0.26, respectively; $P < 0.001$, Lsd = 0.4). The trends in the number of mirids counted to hand-height and in traps on hybrid, and Amelonado cocoa is presented in fig. 6.

Discussion

Understanding the population dynamics of insect pests is crucial for monitoring, forecasting pest populations and designing IPM programmes (Dormon et al. 2007). Pest population monitoring is also a means for determining when pests enter a crop and when their numbers have built up sufficiently to warrant separate control measures or to predict correct timing for such measures (Van-Emden 1996).

The broad pattern of mirid numbers across the season recorded by the visual hand-height assessment method was broadly similar to other reports on mirid population dynamics on cocoa in West Africa (Anikwe et al. 2009; Babin et al. 2010). However, the results from the hand-height method did not correlate with the observation of high mirid numbers in the first half of the year as seen using pheromone trapping. Visual hand-height assessment largely provides information on nymph populations, whilst winged adult males were caught in traps. In the first half of the year, adult male mirids caught in traps reached their peaks while mirids assessed to hand-height (both adults and nymphs but mostly nymphs) reached their peak in the second half of the year. The difference between the two sampling methods reflects generational changes of the pest. Pheromone traps mainly catch adults when they are abundant. After mating, eggs are laid and as a result nymph numbers rise while the numbers of adults then decline. On the other hand, when nymph numbers decline, a concomitant increase in the number of adult males caught in pheromone traps is observed.

The visual hand-height assessment method indicated that mirid populations (predominately nymphs) began to increase rapidly in April with an initial peak

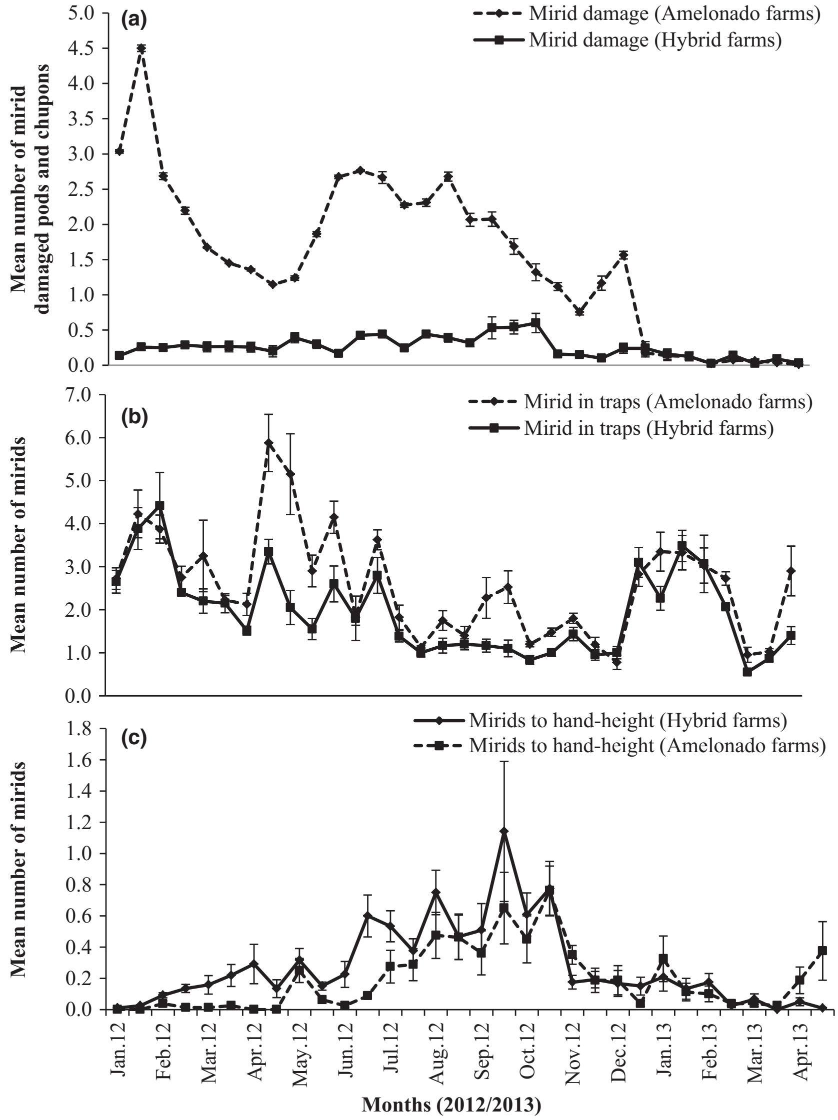

Fig. 6 Difference in mirid damage trends (a), mirid population trends using the pheromone trapping (b) and the visual hand-height assessment method (c) for farms growing Amelonado and farms growing hybrids from January 2012 to April 2013 (For a, at each **2**-weekly interval, data points represent mean values from 10 farms and 20 trees per farm. For (b) and (c), at each 2-weekly interval, data points represent the mean values from four farms growing Amelonado and six farms growing hybrids; 20 observations per farm for the visual hand-height method and 10 observations for pheromone trapping). Vertical bars on line graph represent standard error of means. Note difference in scale between b and c.

in May, followed by a rapid build-up in June. This is a couple of months earlier than reported in the major producing countries in West Africa (Padi and Owusu 1998; Anikwe et al. 2010). Between June and July 2012, there was a significant increase in the number of adult mirids in traps, due to the progression of nymphs seen in April/May. Therefore, given that nymph numbers are starting to build up in April, this would be the most effective time to disrupt the population cycle. Application of insecticides at the point when pest numbers are beginning to rise may be a more effective strategy to suppress the mirid population before it reaches damaging levels. Timely application of insecticides could alter or delay the onset of subsequent peaks in the growing season observed in our data. Whether or not subsequent applications of insecticides are needed in August/September would depend on how effective the early applications were. The results support a reappraisal of the optimum timing of insecticide application in Ghana (Adu-Acheampong et al. 2014).

Indirectly, seasonal variation in climate can modify the population dynamics of mirids by altering the physiology of host cocoa trees making them more or less unpalatable to insect pests. However, it has been difficult to identify the direct effect of environmental factors on the population dynamics of cocoa mirids because of the interaction between environmental factors and host plant factors (such as the availability of feeding and breeding sites) as well as favourable climatic factors necessary for the growth and development of the pest and its natural enemy complex (Gurr and Kvedaras 2010). However, it was clear from this study that there exists a positive relationship between mirid number counted to hand-height and relative humidity which is inversely related to temperature. Lower temperatures and higher humidity therefore favour mirid survival. High temperatures result in lower population size due to high desiccation risk for mirids because of their soft bodies (Babin et al. 2010). Anikwe et al. (2010) also noted that mirid populations decline in periods of low humidity. Higher temperature and lower humidity in the West African dry season would also reduce the survival rate of mirids by reducing the amount of water in feeding sites and the availability of suitable feeding and breeding sites. In a study of water stress in cocoa under greenhouse conditions, plants watered less frequently had lower water and nitrogen contents in their leaves relative to those watered frequently (Acheampong 2010), suggesting that availability of moisture alters the physical and nutritional properties of host plants which may eventually affect feeding. In contrast to mirids counted to hand-height (mainly nymphs), this study showed a significant positive linear relationship between trapped adult mirid numbers and mean temperatures. A possible hypothesis for this apparent contradiction is that at higher temperatures, winged adults may fly to cooler parts of the canopy. Attraction to pheromones in traps then becomes stronger as mirids get closer and so they are more likely to be trapped.

Differences in mirid numbers and levels of damage observed in the Eastern and Ashanti regions may be due to slight differences in weather conditions. Although farming practices (e.g. insecticide application and pruning) were not observed in surrounding farms, it is possible that these may also have had an impact on mirid numbers. The present study suggests the need for multilocational studies to ascertain regional differences in mirid numbers, damage trends and for location-specific control strategies to be put in place. More mirids were caught in traps, and greater tissue damage was observed on Amelonado compared to hybrid cocoa farms and is in agreement with reports suggesting that hybrid cocoa varieties are more resistant to mirid attack than the Amelonado varieties (Sounigo et al. 2003; Anikwe et al. 2009).

When considering practical applications of the two methods, this study confirmed that the visual hand-height assessment method is effective in predicting the level of mirid damage in cocoa farms. This method mostly provides information on mirid nymphs (over 85% of mirids counted at hand-height were wingless nymphs). In contrast, pheromone trapping provides information on winged male adults, but does not account for female adults and nymphs and so will not give a true representation of the mirid population in farms. However, it has the practical advantage that data can be collected at any time of the day, unlike the hand-height method which must be carried out between 6:30 a.m. and 9:00 a.m. (Collingwood 1971; N'Guessan et al. 3000). Ideally, a combination of both the hand-height method and the pheromone trap method should be employed in the field by extension agents to monitor different stages of the mirid life cycle. In practice, the distances between farmers' farms and their homes could sometimes make hand-height assessment difficult and tedious particularly when farmers have more than one plot of land. In the absence of capacity to carry out hand-height assessments, the pheromone trap could provide an early warning of future nymph numbers.

For efficient monitoring and scouting as a component of integrated pest management strategy, the use of economic threshold levels to inform pest management decisions becomes important. Work is therefore needed to estimate the economic threshold level for mirids in the presence of natural enemies and prevailing environmental conditions when using the pheromone trap and hand-height methods (Owusu-Manu 1995).

In Ghana and most West African countries, mirid control is carried out using a calendar-date system. Blanket applications of insecticides are made from August to December but omitting November. This is based on work performed on mirid population dynamics decades ago (Raw 1959; Owusu-Manu 1974) and not on current or expected population trends. In the case of Ghana, 111.3 million US Dollars was spent on the cocoa pest and diseases control programme during the 2009/10 cocoa season (World Bank 2009/2010). Instituting a monitoring component to complement control activities would be very useful and cost effective. Communication systems could be developed to disseminate information on the expected mirid population and inform farmers and cocoa pest and diseases sprayers on when to spray recommended insecticides. Insecticide application could therefore be carried out on a need-based system based on information from a national monitoring programme. To achieve this, a well-coordinated national pest management framework with a monitoring component is needed.

Acknowledgement

The authors would like to express their gratitude to Mondelez Inc. and BBSRC, Dorothy Hodgkin

Postgraduate Award for sponsoring this study and CRIG management for logistical support. We thank Prof. David Hall of the Natural Resources Institute, University of Greenwich, for providing mirid sex pheromones and his advice. We are also grateful to staff of the Entomology division of CRIG for their help in collecting data for the study, notably Dickson Ampadu, Abraham Sowah, Ebenezer Obeng Mintah, Godson Fiakegbe and Enoch Chawudzi. The article is published with the kind permission of the Executive Director of CRIG.

References

Acheampong K, 2010. A physiological study on the field establishment of cacao clones through the improvement of agro-ecological conditions. University of Reading, Reading, School of Biological Science. 297.

Adu-Acheampong R, Jiggins J, van Huis A, Cudjoe AR, Johnson V, Sakyi-Dawson O, Ofori-Frimpong K, Osei-Fosu P, Tei-Quartey E, Jonfia-Essien W, Owusu-Manu M, Nana Karikari Addo MS, Afari-Mintah C, Amuzu M, Nyarko Eku-X N, Quarshie ETN, 2014. The cocoa mirid (Hemiptera: Miridae) problem: evidence to support new recommendations on the timing of insecticide application on cocoa in Ghana. Int J Trop Insect Sci, 34, 58–71.

Anikwe JC, Omoloye AA, Aikpokpodion PO, Okelana FA, Eskes AB, 2009. Evaluation of resistance in selected cocoa genotypes to the brown cocoa mirid, *Sahlbergella singularis* Haglund in Nigeria. Crop Prot, 28, 350–355.

Anikwe JC, Okelana FA, Omoloye AA, 2010. The population dynamics of the brown cocoa mirid, *Sahlbergella singularis* Haglund in Ibadan, Nigeria. Afr J Food Agric Nutr Dev, 10, 2772–2783.

Asante EG, Baah F, Adu-Acheampong R, 2002. Preliminary report on monitoring of the mass spraying of cocoa in the Eastern central and Ashanti regions. Cocoa Research Institute of Ghana, Tafo, Ghana.

Awudzi GK, Asamoah M, Owusu-Ansah F, Hadley P, Hatcher PE, Daymond AJ, 2016. Knowledge and perception of Ghanaian cocoa farmers on mirid control and their willingness to use forecasting systems. Int J Trop Insect Sci, 36, 22–31.

Babin R, Ten Hoopen GM, Cilas C, Enjalric F, Gendre P, Lumaret J-P, 2010. Impact of shade on the spatial distribution of *Sahlbergella singularis* in traditional cocoa agroforests. Agric For Entomol, 12, 69–79.

Bruneau de Mire P, 1977. La dynamique des populations demirides et ses implications. In: Les mirides du cacaoyer. Ed. by Lavarbre EM, GP Maisonneuve et Larose, Paris, 171–186.

Collingwood CA, 1971. A comparison of assessment methods in cocoa mirid count trials In: 3rd International Cocoa Research Conference, Accra, Ghana, 161–168.

Diana G, Sannino L, 1995. Adversities of tobacco culture. Insect. Inf Fitopatol, 45, 24–31.

Dormon ENA, van Huis A, Leeuwis C, 2007. Effectiveness and profitability of integrated pest management for improving yield on smallholder cocoa farms in Ghana. Int J Trop Insect Sci, 27, 27–39.

Gurr GM, Kvedaras OL, 2010. Synergizing biological control: scope for sterile insect technique, induced plant defences and cultural techniques to enhance natural enemy impact. Biol Control, 52, 198–207.

ICCO, 2010/11. Annual report [WWW document]. URL http://www.icco.org/about-us/international-cocoa-agreements/cat_view/1-annual-report.html.

Mahob RJ, Babin R, ten Hoopen GM, Dibog L, Yede Hall DR, Bilong Bilong CF, 2011. Field evaluation of synthetic sex pheromone traps for the cocoa mirid *Sahlbergella singularis* (Hemiptera: Miridae). Pest Manag Sci, 76 (6), 672–676.

N'Guessan KF, N'Goran JAK, Eskes AB, 2008. Resistance of cacao (*Theobroma cacao* l.) to *Sahlbergella singularis* (Hemiptera: Miridae): Investigation of antixenosis, antibiosis and tolerance. Int J Trop Insect Sci 28, 201–210.

Owusu-Manu E, 1974. The effects of insecticides used in the control of cocoa mirids on non-target organisms. In: Proceedings of the 4th West African Cocoa Entomologist Conference, Legon, Accra, Ghana, 3–10.

Owusu-Manu E, 1995. The need for chemical control of cocoa mirids in Ghana. In: Cocoa Pests and Diseases Seminar, Accra, Ghana, 71–79.

Padi B, 1997. Prospects for the control of cocoa capsids - alternatives to chemical control. In: Proceedings of the 1st International Cocoa Pests and Diseases Seminar, Accra, Ghana, 28–36.

Padi B, Owusu GK, 1998. Towards an integrated pest management for sustainable cocoa production in Ghana. In: Workshop, Panama, Smithsonian Institution, Washington, D.C., 3/30–34/32.

Raw F, 1959. Studies on the chemical control of cacao mirids, *Distantiella theobroma* (dist.) and *Sahlbergella singularis* Hagl. Bull Entomol Res, 50, 13–23.

Sarfo JE, 2008. Experience with the mirid pheromone in w Africa [WWW document]. URL http://www.drop-data.net/thamesvalleycocoa/Joe%20Sarfo.pdf

Sarfo JE, 2013. Behavioural responses of cocoa mirids, *Sahlbergella singularis* hagl and *Distantiella theobroma* Dist. (Heteroptera: Miridae), to sex pheromones., University of Greenwich.

Sounigo O, Coulibaly N, Brun L, N'Goran J, Cilas C, Eskes AB, 2003. Evaluation of resistance of *Theobroma cacao* l. To mirids in côte d'ivoire: results of comparative progeny trials. Crop Prot, 22, 615–621.

Taylor LR, 1984. Assessing and interpreting the spatial distribution of insect population. Annu Rev Entomol, 29, 321–358.
Van-Emden H, 1996. Pest control. Springer, Netherlands, 150.
World Bank, 2009/2010. Supply chain risk assessment. Cocoa in Ghana [WWW document]. URL http://www.agriskmanagementforum.org/sites/agriskmanagementforum.org/files/Documents/Ghana%20Cocoa%20SCRA%20Report%202011%20ARMT.pdf.

