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Evaluation of cocoa mirid (*Distantiella theobroma* Dist. and *Sahlbergella singularis* Hagl.) control practices in Côte d'Ivoire

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Rapid pod damage evaluations were performed in four cocoa producing regions in Côte d'Ivoire to assess the severity and regional variability of the mirid pest problem. We further tested the impact of three insecticide products at two different dosages, applied at two different periods on cocoa pod production and mirid infestation on sixty cocoa farms. It was found that in Côte d'Ivoire, cocoa production and mirid infestation levels vary greatly between and within regions. All applied insecticide products were effective, but combinations of products, dosages and application timings were found which resulted in significantly higher amounts of harvestable cocoa pods.

Key words: *Distantiella theobroma*, neonicotinoids, pyrethroids, *Sahlbergella singularis*, *Theobroma cacao* L.

INTRODUCTION

Mirids (Hemiptera, Miridae) are considered to be the most important pest problem in West African cocoa (*Theobroma cacao* L.) cultivation (Anikwe, 2010; Anikwe and Otuonye, 2015; Awudzi et al., 2016a; Babin et al., 2010). Mirid problems in West Africa are caused by several species of which two, *Distantiella theobroma* Dist. and *Sahlbergella singularis* Hagl. are the most important (Awudzi et al., 2016a; Babin et al., 2010; Leston, 1970; Wheeler, 2001; Youdeowei, 1973). Across West Africa, *S. singularis* is reported to be more damaging than *D. Theobroma* (Anikwe, 2010; Anikwe and Otuonye, 2015; Babin et al., 2011; Gidoin et al., 2014; Bagny et al., 2018). Mirid damage on cocoa trees is caused by the feeding activities of both mirid nymphs and adults on cocoa pods and young shoots (Anikwe, 2010; Babin et al., 2010; Babin et al., 2011). Mirids suck sap from these plant parts and inject histolytic saliva causing dark markings (lesions) on the tissue, leading to destruction of

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foliage and young pods (Anikwe, 2010; Babin et al., 2010; Babin et al., 2011; Adu-Acheampong et al., 2017). Mirid attacks are usually lethal to cocoa pods that are less than three months old (Anikwe and Otuonye, 2015; Wheeler, 2001). Parasitic fungi may invade the lesions, leading to secondary infections such as cankers (Babin et al., 2010, 2011). Mirid damage, particularly in combination with secondary diseases cause physiological dieback and – when severe – can lead to a delay in first pod production or even death of young trees (Babin et al., 2011; Adu-Acheampong et al., 2017; Wood and Lass, 1985). Notwithstanding that apart from pest and disease pressure, cocoa pod production also depends on genetic and environmental factors, it is often claimed that cocoa yield losses as a result from mirid infestation can be as high as 30-40% (Anikwe, 2010; Anikwe and Otuonye, 2015; Awudzi et al., 2016a; Bagny et al., 2018; Anikwe et al., 2009b; Kouamé et al., 2014) although it is not clear how these estimates were made.

D. *theobroma* and *S. singularis* females bury eggs in the epidermal layer of cocoa pods, pod stalks, chupons and fan branches. Eggs hatch after 10-17 days and develop in 5 successive juvenile stages (nymphs), with a total duration of 18-30 days, into winged adults of 7-12 mm long (Wheeler, 2001; Wood, 1975). Although mirid population numbers in West Africa vary between countries or regions and between years, mirid population peaks are reported for the April until November period (Anikwe, 2010; Kouamé et al., 2014; Adu-Acheampong et al., 2014; Awudzi et al., 2016b), the period that in West Africa concurs with the most abundant cherelle and mature pod production of the main harvesting season and in which most of the annual precipitation occurs (Awudzi et al., 2016b). In Côte d'Ivoire, in the region of Haut-Sassandra, a second peak in mirid populations was observed in January, which coincides with a peak in cherelle production for the secondary harvesting season (with smaller volumes)(Kouamé et al., 2014).

In West African cocoa agroforestry systems, a negative correlation between shade density and mirid numbers was observed (Babin et al., 2010; Gidoin et al., 2014; Bisseleua et al., 2013). Also, more severe mirid damage can be concentrated in sunny patches, resulting from dead or degraded trees inside a cocoa plantation, the so-called mirid pockets (Anikwe and Otuonye, 2015; Wood and Lass, 1985).

In the 1950s and 1960s, organochlorides (lindane, dieldrin, DDT) were widely used in cocoa pest control (Wood and Lass, 1985; Entwistle, 1972) until mirid resistance, mostly to lindane (Dunn, 1963; Gerard, 1964) was reported. Later (1960s – 1990s). Carbamates (e.g. propoxur, promecarb) and organophospates (e.g. chlorpiryfos, diazinon) were used until they were banned because of environmental and health hazards (Bateman, 2015). Today, mirid control in West Africa is almost exclusively done using pyrethroids (such as bifenthrin, deltamethrin, cypermethrin and lambda-cyhalothrin) and neonicotinoids (such as imidacloprid and thiamethoxam) (Bateman, 2015; Anikwe et al., 2009a; Asogwa and Dongo, 2009). Although the latter insecticides have a lower (acute) toxicity than the earlier-used organochlorides, organophosphates and carbamates ((Bateman, 2015), their widespread use continues to pose human health hazards and risks to terrestrial and aquatic wildlife (Diakite et al., 2018; Jepson et al., 2014; Williamson, 2011). There is particular concern on the neurotoxicity of neonicotinoids on bees. Widespread use of neonicotinoids is linked with bee colony collapses (Blacquiere et al., 2012; Gill et al., 2012; Sanchez-Bayo and Goka, 2014). Thus, health and environmental concerns linked to pesticide applications in West African cocoa production, together with the labour and product costs of pesticide application urge for their rational application. However, West African cocoa producers apply an array of insecticides at frequencies that vary between 0 to 11 times per year (Mahob et al., 2011; Antwi-Agyakwa et al., 2015). Since the 1950s, West African governmental agencies have recommended (Awudzi et al., 2016b; Adu-Acheampong et al., 2014; Antwi-Agyakwa et al., 2015; Ahoutou et al., 2015) a calendar-based insecticide application scheme, using motorised knapsack mistblowers, targeting mirid populations when they are most abundant (August – November).

In Côte d'Ivoire, the largest cocoa-producing country in the world, the *Conseil Cacao-Café* (CCC), the government body regulating the commercialisation of cocoa and coffee recommends two applications per year (July – September and December – January) (Ahoutou et al., 2015), presumable on the alleged two mirid population peaks occurring in the country (Kouamé et al., 2014). Analysis of recommendations on labels of 16 different pesticide products (from 7 different brands) sampled from commercial shops in Abidjan (unpublished) confirmed the binary application periods recommended by the CCC.

It is nevertheless unclear if the recommended applications effectively control mirid infestation in Ivorian cocoa production. In order to shed more light on this issue, we evaluated the cocoa mirid infestation in Côte d'Ivoire using a rapid assessment method (March - April 2017) and performed experiments (January – March 2018) in which we evaluated the impact of different common insecticide products applied during different application periods within the recommended range and at a normal (that is, recommended) and reduced dosage (33% of recommended dosage), on cocoa production and mirid infestation in Ivorian cocoa farms. We hypothesize that insecticides containing only a systemic (neonicotinoid) insecticide, will have a different impact on mirid infestation than when products are applied that combine systemic with contact insecticides (pyrethroids). Moreover, assuming that mirid populations show indeed a peak in a certain period, applying insecticides at

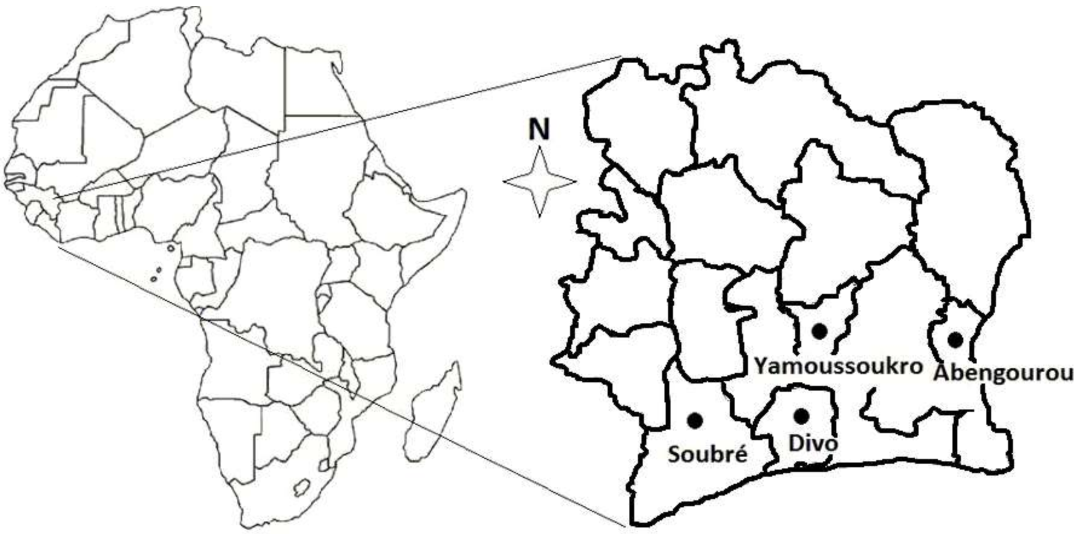

Figure 1. Location of Côte d'Ivoire in Africa (left) and the 4 cities within the country (right) around which the rapid mirid infestation assessment was performed.

different occasions within that period could have a different impact on mirid infestation symptoms after insecticide treatments. Pesticide companies' recommended application dosages might be above optimum rates for a certain cocoa region, because they usually guaranteed good results in company trials at several locations. We therefore hypothesize that a lower insecticide dosage can have the same impact on mirid infestation in cocoa production as the dosage recommended on commercial product labels.

MATERIALS AND METHODS

Rapid mirid infestation assessment

A rapid mirid assessment was performed between 20 March and 1 April 2017 in the Ivorian cocoa producing regions of Indénié-Djuablin, Lôh-Djiboua, Nawa and Belier, more specifically in the areas around the cities of Abengourou, Divo, Soubré and Yamoussoukro (Figure 1). These areas cover the Ivorian cocoa-producing area which ranges from the Southeast to the Southwest of the country. In each area, 6 cocoa farms from two different cocoa cooperatives (three per cooperative) were randomly selected for the assessment (Table 3). In order to assess the impact on mirid infestation of earlier insecticide treatments, farmers were asked if and which insecticide products they had used during the latest pesticide application period (December 2016 – February 2017).

Next, on each farm 30 cocoa trees that had at least one mature cocoa pod were randomly selected at the center of the plot and ensuring at least 3 unselected cocoa trees occupied the space between selected trees. Each tree was scored for the presence or absence (on at least 1 pod) of mirid infestation symptoms (black lesions). Next, 5 out of the 30 trees per farm were randomly selected for more detailed observations of mirid infestation. Total number of cherelles (defined as pods with a length < 10 cm), mature pods, cherelles with mirid infestation symptoms and infested mature pods were registered. Differences in the number of cherelles and mature pods and of the percentage of mirid-infested cherelles and of mirid-infested mature pods between farms that had used insecticide during the latest application period (December 2016 – January 2017) and those that had not, were was assessed by T-tests, using SPSS 26.0. Prior to ANOVA, percentage data were transformed by Arcsin[sqrt(×/100)].

Influence of dosage, timing and Côte d'Ivoire-used insecticide products on mirid infestation levels

Experimental design

Experiments were performed with a selection of cocoa smallholders of the SOCAS cocoa cooperative that has its administration office is in the community Blé (Divo Department, Côte d'Ivoire) (5° 53' 48.91" N, 5° 9' 29.46" W). The cooperative unites 532 farmers from 8 administrative subsections around Blé. Seventy farmers (10 from Ahouanou-II, 9 from Beheri, 9 from Bodo, 15 from Divo Nord, 4 from Kouassikankro and 23 from Obie subsections) were selected by the cooperative president based on i) their willingness to cooperate; ii) the earlier demonstrated ability of the farmer to adequately weed their plots and prune their cocoa trees; and iii) farm distance (that is, reachable on foot in less than 30 min beyond the point where a car could go no further). Experiments consisted of a fully randomized 3x2x2 factorial design with 5 replicates (60 farms) and with 10 untreated control farms (3 from Beheri and 7 from Obie subsections) in addition to the 60 treated farms. Factors considered were 'product', 'dosage' and 'timing'. Five farmer plots were thus entirely treated with the unique combination of one out of three tested insecticide products, at one out of two different dosages and at one out of two different application timings. Control plots (relying on farmer statements) had not been treated with insecticides since December 2016.

Tested products

A selection of commercially available insecticides was used, each containing a different systemic neonicotinoid insecticide, together with or without a pyrethroid contact insecticide (Table 1). Each product was administered to 20 different cocoa farms.

Table 1. Products used in the insecticide treatment efficiency test, with active ingredients and their concentrations in the bottles.

Product brand	Supplier	Neonicotinoid	Pyrethroid
Callifan Super BD	Callivoire	Acetamiprid (20 g/L)	Bifenthrin (20 g/L)
Caotop 30 SC	DMG	Imidacloprid (30 g/L)	None
Azudine 50 SD	RMG	Thiamethoxam (30 g/L)	Deltamethrin (20 g/L)

Table 2 . Standard and reduced dosage (L/ha) for each product tested.

Product	Standard dosage	Reduced dosage
Acetamiprid (20 g/L) + Bifenthrin (20 g/L)	0.50	0.15
Imidacloprid (30 g/L)	1.00	0.30
Thiamethoxam (30 g/L) + Deltamethrin (20 g/L)	0.50	0.15

Applied dosages

Anikwe et al. (2009) exposed *S. singularis* nymphs and adults to filter papers impregnated with various concentrations of the neonicotenoid thiamethoxam, during several exposure periods and found that a reduced dosage (50 or 0.01% instead of 0.02%) reduced mirid mortality from 100% after 90 min (dosage of 0.02%) to 13.3% after 90 min and to 33.3% after 120 min. Tan et al. (2012) defined lethal doses (LD_{50}) of the neonicotinoid imidacloprid to the mirid *Apolygus lucorum* at 6.70 ng of active ingredient (a.i.) per adult, whereas a 'low lethal dose' (LD_{25}) was found to be 1.96 ng a.i. per adult (= 29% of LD_{50}). Based on the latter studies, we compared the effect of spraying with the standard dosage (that is, the dosage recommended on the product bottle) with a lower dosage of (30%) of the standard dosage (Table 2). Application was done using Cifarelli Nuvola^{TM} 5HP mist blowers (77 cc single-cylinder two-stroke gasoline engine with a power of 3.6 kW, liquid tank capacity of 17 L) at a flow rate of 1.25 L per min. Application was done by diluting a quarter of the recommended standard or the reduced dosage per ha in 10 L of water and by applying 4 × 10 L of solution per ha to the cocoa field. The standard and reduced dosages were each applied by 30 farmers.

Timing

Applications were done in the recommended periods of July and August 2017 (presumed mirid peak) and January and February 2018 (alleged second mirid population peak in Côte d'Ivoire). For 30 farmers, treatments were performed early in these recommended period: i.e. from 1 until 20 July 2017 and from 3 until 10 January 2018 for the first and second applications, respectively (henceforth called 'early' treatment) whereas for another 30 farmers, treatments were done later in the recommended periods, that is, from 19 August until 1 September 2017 and from 20 February until 9 March 2018 for the first and second applications, respectively (henceforth called 'late treatment).

Treatments

Treatments were performed by spraying teams consisting of two persons who had been trained by the cocoa cooperative for safe and adequate pesticide application. Products were applied in the morning (before 10 am) by the two sprayers simultaneously until the whole farm plot (Min. 0.3 ha, Max. 14 ha; average area = 3.25 ± 0.39 (SE) ha) had been treated. Treatments were postponed until the next day in case of rain. Application was done while walking through each cocoa row, as recommended by Bateman (2015). Mist, which had a median droplet size of 90 µm, was aimed at the canopy and pods on the main branches and stems.

Evaluation

Two evaluations were performed: from 16 until 20 October 2017 (that is, after the first application) and from 3 until 25 April 2018 (that is, after the second application). Number of cherelles and mature pods, as well as mirid infestation levels on cherelles and mature pods were evaluated on 15 trees per farm following the same procedure as for the rapid mirid infestation assessment (§ 2.1). Main and interaction effects of products, dosages and timings were revealed by analysis of variance (ANOVA) in SPSS 26.0. Control farms were those that have not received any insecticide treatment at all, which implies that they act as a control for all three factors 'product', 'dosage' and 'timing'. In the analysis, we will consider the cherelle and mature pod numbers, and their mirid infestation levels recorded at the second evaluation (that is, after both treatments) as well as the changes in these parameter values between the first and the second evaluation periods. For the latter, we used per farm parameter averages as different trees were evaluated in the first and the second evaluation. Parameter differences between the first and the second evaluation were assessed using a paired samples T-test. Factor interaction effects were computed without considering the control plots, because there is no control for each individual factor. Prior to ANOVA, percentage data were transformed by Arcsin[sqrt(×/100)]. Means are always reported ± their standard error (SE).

RESULTS

Rapid mirid infestation assessment

Fourteen out of 24 sampled cocoa farms from 4 cocoa-growing regions had applied insecticides in the period December 2016 – February 2017. Insecticides applied were either i) only imidacloprid; ii) acetamiprid in combination with either bifenthrin, cypermethrin or

Table 3. Insecticides applied in the December 2016 – February 2017 period, by cocoa farmers from 8 cocoa cooperatives from 4 cocoa-growing regions in Côte d'Ivoire, selected for rapid mirid infestation evaluation.

Area	Cocoa Cooperative	Farm	Insecticide used	Active ingredient
Abengourou	CA CAADI	1	None	
		2	None	
		3	Phytocao	Acetamiprid (20 g/L) + Bifenthrin (20 g/L)
	CAGRAMIA	1	Phytocao	See above
		2	Phytocao	See above
		3	None	
Divo	SOCAS	1	None	
		2	Thiosulfan	imidacloprid (60 g/L)
		3	Phytocao	See above
	SCAC	1	None	
		2	Onex Super 40 EC	Acetamiprid (20 g/L) + cypermethrin (20 g/L)
		3	Phytocao	See above
Soubré	ECAO	1	None	
		2	None	
		3	None	
	CPAY	1	Grosudine Super 50	Imidacloprid (30 g/L) + Bifenthrin (20 g/L)
		2	Grosudine Super 50	See above
		3	Onex Super 40 EC	See above
Yamoussoukro	BINKADI	1	Toro	Acetamiprid (20 g/L) + Deltamethrin (20 g/L)
		2	None	
		3	None	
	COOPABIN	1	Phytocao	See above
		2	Phytocao	See above
		3	Phytocao	See above

deltamethrin; or iii) imidacloprid in combination with bifenthrin (Table 3).

Our rapid mirid survey of 4 cocoa producing areas shows that on all farms, the rate of mirid infested trees (that is, showing at least 1 infested pod or cherelle) was 40.6% in Soubré, 61.1% in Yamoussoukro, 61,7% in Abengourou, and 75.6% in Divo. The more detailed evaluation of 5 trees per farm revealed that trees contained on average 4.07 ± 0.53 cherelles and 15.03 ± 0.94 mature pods and 17.97 ± 2.46% and 24.73 ± 2.45% mirid infested cherelles and mature pods, respectively. There were no significant differences in the four parameters between trees on farms that had received insecticide treatments one year before the evaluation and trees on farms that had not.

Influence of dosage, timing and insecticide products on mirid infestation levels

In the second evaluation period (that is, after two pesticide applications), mean per-tree cherelle number was 2.55 (± 0.16), whereas mean per-tree number of mature pods was 10.8 (± 0.26). Main effects of products, dosage and timing of application were significant ($p < 0.01$) for all considered parameters (Table 4). Significant ($p < 0.05$) interaction effects were found between factors 'product' and 'dosage' for the number of mature pods and between 'product' and 'dosage', 'product' and 'timing' and 'dosage' and 'timing' for mean number of cherelles (Table 4).

Mean rates of infested cherelles and mature pods were always significantly higher in control plots than in plots treated with insecticides. The reduced insecticide dosage resulted in a significantly ($p < 0.0005$) higher rate of infested mature pods (29.12 ± 1.43) as compared with the normal dose (18.22 ± 1.19 mature pods). However, the latter values were both significantly ($p < 0.0005$) lower than the rate of infested mature pods in the control plots (64.38 ± 2.36) (Figure 2).

Considering only the treatments with imidacloprid, it was found that the reduced pesticide dosage resulted in a significantly lower number of mature pods (10.40 ± 0.69) ($p = 0.001$) and cherelles (1.90 ± 0.23) ($p = 0.003$), as compared to the normal dosage (14.27 ± 0.99 for mature pods and 4.19 ± 0.73 for cherelles, respectively). However, in cocoa trees treated with thiamethoxam + deltamethrin, a reduced dosage resulted in significantly($p = 0.001$) higher number of cherelles (4.44 ± 0.63) as

Table 4. Factorial ANOVA of tested products, dosages and application timing on average number of cherelles and mature cocoa pods as well as on the rate of mirid-infested cherelles and mature pods, recorded per tree in the second evaluation period; * Significant (p < 0.05) factorial main or interaction effects; control plot tree data was included in the factorial ANOVA for the main factors, but not in the analysis of interaction effects.

Variable	df	Total number of				Mirid-infested			
		Cherelles		Mature Pods		Cherelles		Mature Pods	
		F	p	F	p	F	p	F	p
Product	3	6.19	0.000*	6.78	0.000*	78.4	0.000*	22.09	0.000*
Dosage	2	5.98	0.003*	4.99	0.007*	132.77	0.000*	32.39	0.000*
Timing	2	6.19	0.002*	4.95	0.007*	118.58	0.000*	32.16	0.000*
Product x Dosage	2	8.17	0.000*	13.75	0.000*	2.74	0.065	1	0.368
Product x Timing	2	2.92	0.054	7.08	0.001*	1.02	0.361	0.35	0.707
Dosage x Timing	1	0.2	0.654	45.2	0.000*	0.09	0.769	2.97	0.086
Product x Dosage x Timing	2	0.39	0.681	0.71	0.493	7.12	0.001*	2.94	0.054

compared to the normal dosage (2.08 ± 0.31), whereas the number of cherelles did not differ significantly between reduced and normal dosages for the other two products.

Furthermore, when imidacloprid was applied, late treatments resulted in a significantly (p < 0.01) higher number of cherelles (4.32 ± 0.81) as compared to early treatments with only 2.03 ± 0.25 cherelles. Different treatment timings of the other two products did not cause significant differences in cherelle numbers. Analysis of the interaction effect between 'timing' and 'dosage' reveals that when insecticides are applied early in the recommended period the mean number of cherelles was significantly (p < 0.0005) lower for the normal (1.42 ± 0.19) than for the reduced dosage (3.75 ± 0.42), whereas the opposite was found when insecticides are applied late in the recommended period, where 4.07 ± 0.55 cherelles were observed for the normal dose, which was significantly (p < 0.0005) higher than was the case with the reduced dose (1.77 ± 0.21).

As compared to the first evaluation (October 2017), during the second evaluation (April, 2018) the cocoa farms on average had produced significantly less cherelles (2.87 ± 0.52 as compared to 12.65 ± 0.73), and had a significantly higher rate of infested cherelles (36.39 ± 2.45% as compared to 21.51 ± 1.46%) and a significantly higher rate of infested mature pods (to 21.51 ± 1.46% as compared to 10.86 ± 1.15%). When reduced pesticide dosages were applied, the increase in the mean rate of infested mature pods was significantly (p < 0.05) higher (+16.30 ± 3.34 %) than when the normal dosages were applied (+3.51 ± 2.79%) (Figure 2).

DISCUSSION

Rapid mirid infestation assessment in 4 different cocoa producing regions in Côte d'Ivoire revealed that mirid infestation is highly variable, both between and within regions. In all regions, at least half of the cocoa farmers had used insecticides three months prior to our assessment. The latter period is also the recommended application period, that is, concurring with one of the reported mirid population peaks in Côte d'Ivoire (Kouamé et al., 2014). Products used are approved for use in cocoa cultivation in Côte d'Ivoire (Ahoutou et al., 2015). Also in Ghana (Awudzi et al., 2016a; Anikwe et al., 2009a; Adu-Acheampong et al., 2014; Antwi-Agyakwa et al., 2015), Cameroon (Mahob et al., 2011) and Nigeria (Asogwa and Dongo, 2009), after Côte d'Ivoire, respectively second, fourth and fifth largest cocoa-producing countries in the world, similar neonicotenoids (imidacloprid, acetamiprid) and pyrethroids (bifenthrin, deltamethrin and cypermethrin) are common in cocoa cultivation. The rapid mirid assessment did not reveal significant differences in tree infestation rates between plots that were treated with insecticides in the latest application period and those that were not. However, in the experiment on the impact of different products, dosages and application timings, all four parameters under consideration were significantly different on the treated farms from those on the control farms. These different findings can be due to the fact that in the latter experiment control farms not only were not treated with insecticides in the application period of December 2016 – February 2017, but continued not to be treated until the second evaluation of April 2018. In the former experiment (rapid mirid assessment), untreated plots might have been treated with insecticides in the year before December 2016. The effects of those treatments might still have had an effect on cherelles and pod production as well as on observed infestation rates.

In the experiment on the impact of different products, dosages and application timings, we used 4 proxy parameters (number of cherelles and mature pods, and rate of mirid-infested cherelles and mature pods per tree) for assessing the impact on mirid infestation. Since cocoa mirids are particularly harmful (and usually lethal) to

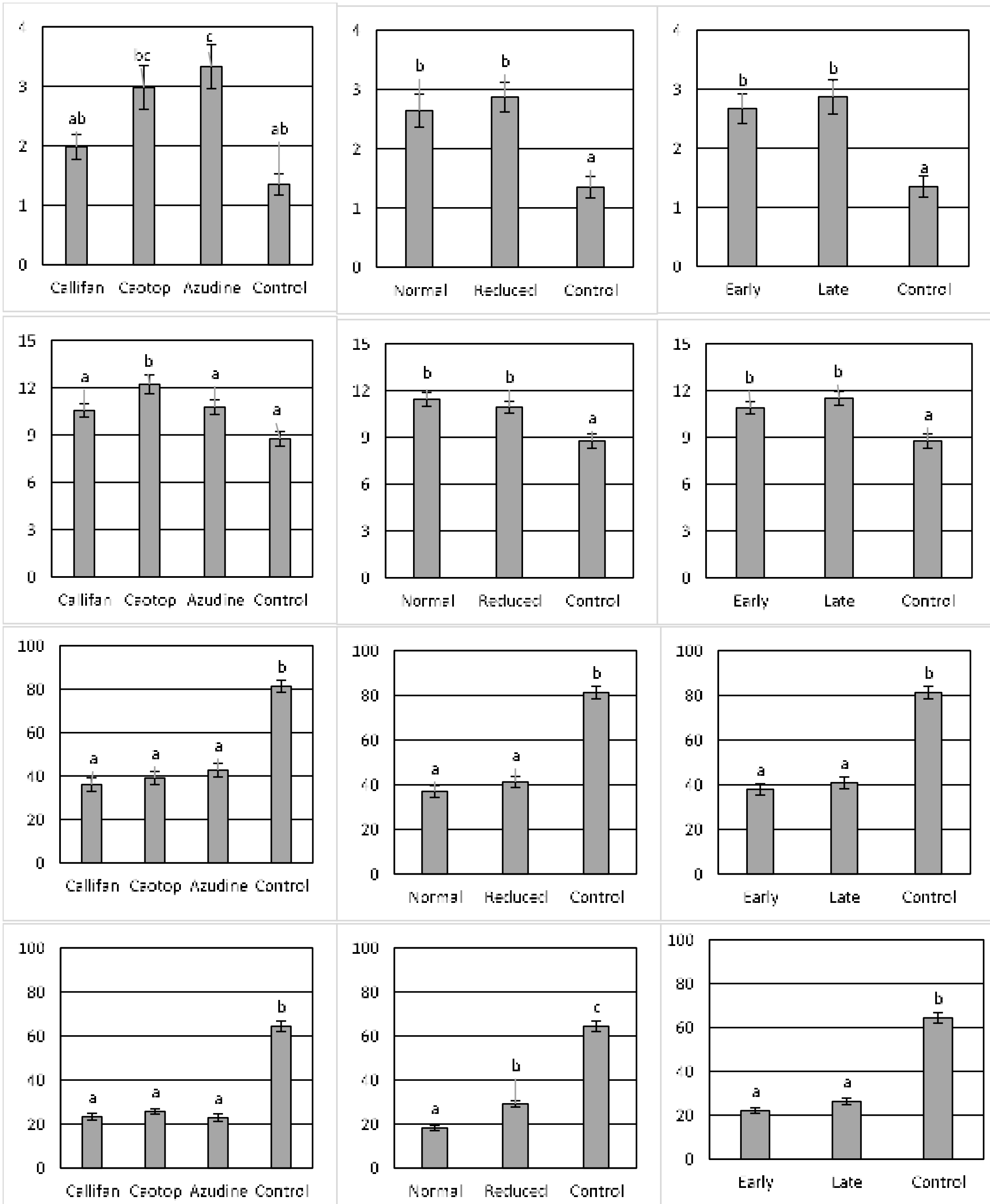

Figure 2. Average per tree number of cherelles (top row) and mature pods (second row) and rates (%) of mirid-infested cherelles (third row) and mature pods (fourth row) observed in the second evaluation after treatment with different products (first column), at different dosages (second column) and application timings (third column) as well as for untreated control plots. Different lowercase letters indicate significant ($p < 0.05$) differences in parameter values within each factor. Error bars show standard errors of the mean.

mirids are particularly harmful (and usually lethal) to cocoa cherelles (Anikwe and Otuonye, 2015; Wheeler, 2001), trees where lower cherelle numbers were recorded, were probably more affected by mirids than other trees. It is, however, also possible that differences in cherelle numbers are caused by differences in cocoa genotypes, soil nutrition or pollinator abundance between the studied cocoa farms, which will cause differences in physiological cherelle wilt, a natural fruit thinning mechanism in cocoa (Valle et al., 1990; Claus et al., 2017).

The effect of reducing the insecticide dosage to one third of the recommended level on total cherelle and mature pod production depends on the insecticide product used, as well as on the timing of application. Only when imidacloprid was used, the reduced dosage did significantly reduce the number of observed cherelles as well as mature pods. A hypothesis for the different effects of a decreased dosage is that when systemic insecticides such as thiamethoxam or acetamiprid are combined with contact insecticides such as deltamethrin or bifenthrin, not only mirids are killed, but also significant numbers of mirid predators are knocked down. As a result, reducing the dosage would decrease the impact of the contact insecticides on mirid predators leading to a higher amount of cherelles observed after treatments. Weaver ants *Oecophylla longinoda* and *Oecophylla smaragdina* have been suggested as key-predators to mirids in cocoa cropping systems in Cameroon (Babin et al., 2010; 2011, 2012,) and Australia (Forbes and Northfield, 2017), respectively. Those predatory ants will less likely be killed by insecticide products that do not contain pyrethroids and will consequently be able to maintain their populations to levels that are able to significantly reduce mirid numbers.

The effect of the reduced pesticide dosage further depends on the timing of application in the recommended periods. When applied early, the reduced dosage had a significantly positive impact on the number of observed cherelles, whereas a late application resulted in significantly less observed cherelles as compared to the normal dosage. Furthermore, only for imidacloprid we found a significant difference between the early and the late application period in the average number of cherelles and the average number of mature pods per tree. The later imidacloprid application resulted in significantly more cherelles ($p < 0.01$) than the earlier imidacloprid application. In the Haut-Sassandra region of Côte d'Ivoire, between 2009 and 2013, Kouamé et al. (2014) evidenced a first mirid population peak in January, after which mirid populations rapidly declined. It would thus be logical that a later application period that is, when mirid population numbers have declined due to natural reasons, irrespective of pesticide applications - would result in lower cherelle and mature pod numbers per tree, as application timing in that case would not coincide with mirid population peaks. The fact that only for imidacloprid the application period influences cherelle numbers, suggests that the absence of a pyrethroid – as opposed to the two insecticide combinations tested – probably has a higher impact on predator conservation than on mirid control in the application period.

The latter results could suggest that the normal imidacloprid dosage, applied in the latest two weeks of the recommended period, is the most optimum chemical mirid control method in our study region. Indeed, considering average values of the 15 evaluated trees on the 5 farms per unique factor combination, we found the highest mean number of cherelles (6.39 ± 1.33) after the application of a normal dosage of imidacloprid, late in the recommended application period (Annex 1). However, there are several reasons why such a recommendation cannot be generalized: i) although also a significantly higher number of mature pods (which is the objective of pest control efforts) is produced after normal imidacloprid application as compared with the reduced imidacloprid application, there were no interaction effects observed between factors 'product' and 'timing' or between 'dosage' and 'timing' for the number of mature pods; ii) experiments took place in an area of ± 120 km² around Blé, which might have a specific ecology, influencing mirid populations; iii) recommendation of a single insecticide would rapidly lead to mirid resistance (Bateman, 2015). With only 2 different neonicotinoid and 3 different pyrethroid applications observed during our rapid mirid infestation assessment (Table 3), mirid resistance is a potential risk in mirid control in Côte d'Ivoire (Bateman, 2015). Even though our results suggest imidacloprid as the most appropriate insecticide, the risk of resistance urges for rotation in the use of insecticides with different modes of action. A rotation scheme could be developed in which insecticides with active ingredients with different modes of action are used in different Ivorian cocoa areas, and in which after a number of years, insecticide applications are rotated between different areas, following e.g. a similar rotation scheme for acaricides to control *Tetranychus* spp. spider mites in cotton (*Gossypium hirsutum* L.) production in Zimbabwe (Tibugari et al., 2012).

We used a motorized mistblower to perform insecticide treatments, because this is the only pesticide application equipment that is able to project insecticides to the cocoa canopy, which in some cases in West-Africa (as a result of inadequate pruning) can be as high as 14 m (Bateman, 2015). Adequate pruning, keeping tree height below 4 m, is therefore an important part of mirid control in cocoa cultivation (Wood and Lass, 1985). The disadvantage of motorized mistblowers is that not all active ingredients reach their biological target due to spray drift (Graham-Bryce, 1977). Inadequate spraying (e.g. in rainy or windy conditions, or aiming at stems and soil, rather than at the cocoa canopy) will increase pesticide drift and will consequently require higher dosages to deposit the same amounts of active ingredients to cocoa leaves and pods as would be the case with appropriate spraying.

Conclusions

Our assessment of production, and mirid infestation of cherelles and mature cocoa pods in 4 regions in Côte d'Ivoire, revealed that mirid infestation is highly variable, both within as well as between regions. Although our insecticide treatments had a positive impact on the cocoa parameters considered as compared to untreated control trees, we found no significant differences between the main effects of the two different application timings (on any of the parameters) and between the normal and reduced dosage (all parameters except for the rate of mirid-infested mature pods). However, the observed interaction effects reveal that there are combinations of products, dosages and application timings that after two applications in one year result in a significantly higher amount of mature, harvestable cocoa pods.

Before these findings can be translated into general mirid control recommendations, more research is needed on the effect of neonicotinoids and pyrethroids on mirid ecology and population dynamics. Natural vegetation (Leston, 1970) as well as the presence of predators such as weaver ants (Bagny et al., 2018; Babin et al., 2012) can influence mirid prevalence and therefore interact with insecticide application. Further research should ideally be performed in a wider area than the one used in the present study and should be performed over multiple years. In order to avoid the development of mirid resistance in multiple-year trials, different insecticide products need to be applied in subsequent applications. In such trials, it is important to assess how insecticides with different modes of action have an impact, not only on mirids, but also on their potential predators. Given the observed significant interactions of dosage and timing of insecticide applications on the number of mature pods produced on cocoa trees, it would further be interesting to test the effect on mirid infestation of reduced dosages of insecticides applied at more than two occasions per year.

The large variability of mirid infestation and damage between and within regions further suggests that insecticide applications, rather than following a fixed biannual calendar scheme should better be based on observed presence of mirids. Experiments in Ghana have shown that mirid monitoring can be easily done using pheromone-based monitoring traps (Awudzi et al., 2016a; Mahob et al., 2011; Sarfo et al., 2018). Mirid monitoring systems might in future be used by West African cocoa smallholders as a decision tool for insecticide applications, following e.g. Cruz et al. (2012) who used pheromone traps as a decision tool for insecticide applications against the fall army worm (*Spodoptera frugiperda*) in Brazil. Today, insecticide applications by West African cocoa farmers are influenced by socio-economic, farm-specific and institutional factors but also by pest incidence perceptions (Danso-Abbeam and Baiyegunhi, 2018). As a result, successful adoption of integrated mirid control, using insecticide applications in periods and at dosages guided by mirid population numbers will require farmer training and applied research support to determine best control practices. When successful, such integrated mirid control can contribute to decreased overall pesticide use in the West African cocoa sector, increase cocoa farm profitability and improve farmer health and environmental sustainability.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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Annex 1. Mean number of cherelles and mature pods per tree and mean rate of mirid-infested cherelles and mature pods for each combination of factors ‘product’, ‘dosage’, ‘timing’ recorded in the second evaluation after treatment with different products, at different dosages and application timings as well as for untreated control plots.; N = number of trees evaluated per factor combination.

Product	**Dosage**	**Timing**	**Number of**				**Rate of mirid-infested**			
			Cherelles		**Mature Pods**		**Cherelles**		**Mature Pods**	
			N	**Mean ± SE**	**N**	**Mean ± SE**	**N**	**Mean ± SE**	**N**	**Mean ± SE**
Acetamiprid + Bifenthrin	Normal	Early	60	0.78 ± 0.15	60	9.02 ± 0.70	25	0.2067 ± 0.0707	60	0.1957 ± 0.0275
		Late	60	2.53 ± 0.45	60	10.83 ± 0.91	43	0.3532 ± 0.0584	59	0.2159 ± 0.0328
	Decreased	Early	60	3.22 ± 0.68	60	11.13 ± 1.00	40	0.3849 ± 0.0609	60	0.2075 ± 0.0277
		Late	75	1.49 ± 0.23	75	11.11 ± 0.77	47	0.4281 ± 0.0614	74	0.2976 ± 0.0301
Imidacloprid	Normal	Early	59	1.92 ± 0.42	59	13.31 ± 1.39	34	0.4585 ± 0.0732	59	0.1422 ± 0.0257
		Late	61	6.39 ± 1.33	61	15.21 ± 1.41	48	0.3266 ± 0.0455	61	0.2454 ± 0.0329
	Decreased	Early	90	2.1 ± 0.31	90	9.8 ± 0.78	53	0.3365 ± 0.0524	87	0.3412 ± 0.0354
		Late	45	1.51 ± 0.29	45	11.6 ± 1.35	26	0.5308 ± 0.0866	43	0.2627 ± 0.0366
Thiamethoxam + Deltamethrin	Normal	Early	75	1.55 ± 0.34	75	10.68 ± 0.88	37	0.4251 ± 0.0731	75	0.1571 ± 0.0240
		Late	45	2.98 ± 0.56	45	9.07 ± 0.92	32	0.4254 ± 0.0732	43	0.1259 ± 0.0294
	Decreased	Early	75	6.16 ± 1.01	75	11.8 ± 0.96	60	0.4110 ± 0.0453	75	0.2371 ± 0.0312
		Late	60	2.30 ± 4.71	60	10.63 ± 0.85	31	0.4614 ± 0.0764	60	0.3823 ± 0.0416
Control	Control	Control	135	1.35 ± 2.06	135	8.76 ± 0.46	69	0.8127 ± 0.0278	134	0.6438 ± 0.0233