The Ghana Cocoa Board (COCOBOD) approved insecticides, imidacloprid, thiamethoxam and bifenthrin, for the control of cocoa mirids (Hemiptera: Miridae): Implications for insecticide-resistance development in *Distantiella theobroma* (Dist.) and *Sahlbergella singularis* Hagl.

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ABSTRACT

The Ghana Cocoa Board (COCOBOD) in 2001 initiated a national Cocoa Diseases and Pest Control (CODAPEC) programme (popularly known as mass-spraying programme) against the cocoa mirids (Hemiptera: Miridae), which are predominantly *Distantiella theobroma* (Dist.) and S*ahlbergella singularis* Hagl. The insecticides approved by COCOBOD for controlling the cocoa mirids under CODAPEC and for individual farmer applications are Confidor® (imidacloprid 200 g/l), Actara® (thiamethoxam 240 g/l) and Akate Master® (bifenthrin 27 g/l). Imidacloprid and thiamethoxam are both neonicotinoid insecticides with cross-resistance between them, while cross-resistance has been established between the neonicotinoids and bifenthrin, a pyrethroid insecticide. Using imidacloprid, thiamethoxam and bifenthrin singly or rotationally selects for genes that confer resistance to the approved insecticides. The detection of ɣ-BHC-resistant *D. theobroma* in Ghana after widespread use of the insecticide against mirids from the mid 1950s through early 1960s indicated the genetic ability of mirids to develop resistance to insecticides. The mass-spraying of imidacloprid, thiamethoxam or bifenthrin to control mirids is, therefore, increasing selection pressure on field populations of mirids, and escalating the risk of the mirids developing resistance to all three insecticides. Preventing resistance development in the cocoa mirids to the COCOBOD approved insecticides is crucial to avert resistance associated yield losses, reduce the risk of insecticide residues in cocoa beans and safeguards Ghana's foreign exchange earnings from cocoa. Measures for protecting imidacloprid, thiamethoxam and bifenthrin from mirid resistance development are recommended.

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Introduction

The cocoa mirids, *Distantiella theobroma* (Dist.) and S*ahlbergella singularis* Hagl. (Hemiptera: Miridae), were noted as serious pests of cocoa in Ghana since the early 1990s (Dudgeon, 1910a; Dudgeon, 1910b). The insects cause damage to cocoa trees by feeding on the cocoa pods and shoots. Further damage to the cocoa tree results from the invasion of the mirid feeding lesions by fungus species of the genus *Fusarium* and *Lasiodiplodia*, which leads to dieback disease (Adu-Acheampong & Archer, 2011; Adu-Acheampong, Archer & Leather, 2012). Owusu-Manu (1984) estimated damage by the cocoa mirids at about 25 per cent of cultivated cocoa, which leads to about 30 per cent loss in cocoa yield. In order to protect cocoa trees from mirid damage, measures to control the pests were implemented immediately the insects were noted as serious pests of cocoa using kerosene emulsion (Dudgeon, 1910a; Dudgeon, 1910b). Large scale field trials of ɣ-BHC in 1954 effectively controlled *D. theobroma* and S. *singularis*, and the resultant cocoa yields were so outstanding that the insecticide was used country-wide for mirid control (Dunn, 1963).

Ghana recorded cocoa output of 557,000 tonnes for the 1964/65 cocoa season, making the country the leading producer of cocoa in the world (Adjinah & Opoku, 2010). However, cocoa output dropped to a low level of 159,000 tonnes for the 1983/84 season (Adjinah & Opoku, 2010). Cocoa production in Ghana continued to decline through the 1990s (Adu-Acheampong *et al*., 2014). In 2001, as part of the efforts to arrest the decline in cocoa production, the Ghana Cocoa Board (COCOBOD) initiated a national Cocoa Diseases and Pest Control (CODAPEC) programme (popularly known as mass-spraying programme) to assist all cocoa farmers in the country to combat cocoa mirids and the black pod disease (Adjinah & Opoku, 2010). As a result of the CODAPEC programme, black pod disease incidence and mirid infestation dropped significantly (Adjinah & Opoku, 2010). The CODAPEC programme raised cocoa output from 380,000 tonnes at its inception in 2001 (Adjinah & Opoku, 2010) to more than 1,000,000 tonnes in the 2010/2011 season (Adu-Acheampong *et al*., 2014).

The COCOBOD approved insecticides for cocoa mirid control in Ghana for the CODAPEC programme and individual farmer applications are: Confidor® (Imidacloprid 200g/l, neonicotinoid insecticide), Actara® (Thiamethoxam 240g/l, neonicotinoid insecticide) and Akate Master® (Bifenthrin 27g/l, pyrethroid insecticide) (COCOBOD, 2007). COCOBOD (2008) recommends spraying against the mirids to start in August every year with any of the approved insecticides. Spraying has to be done once in August, September, October and December. In addition, any spot outbreaks have to be treated, anytime they occur on a farm (COCOBOD, 2008).

Although the application of the COCOBOD approved insecticides has contributed to boosting cocoa output in Ghana, insecticide-resistance research suggests that it is not prudent to use imidacloprid, thiamethoxam and bifenthrin together in an insect pest control programme. Using these insecticides together increases the risk of resistance development in target pests. If resistance develops in *D. theobroma* and *S. singularis* to imidacloprid, thiamethoxam and bifenthrin, it would result in cocoa yield losses and severely undermine efforts to further increase cocoa output in Ghana to earn more foreign exchange for the country.
The paper highlights the basis for the increased resistance risk to the COCOBOD approved insecticides and suggests measures for preventing resistance development in *D. theobroma* and *S. singularis* to imidacloprid, thiamethoxam and bifenthrin.

Materials and methods

Resistance and cross-resistance to imidacloprid, thiamethoxam and bifenthrin

Imidacloprid and thiamethoxam are neonicotinoid insecticides. These insecticides have a novel mode of action, as agonist of the nicotinic acetylcholine receptor (nAChR) (Yamamoto *et al*., 1995). They mimic the agonist action of acetylcholine at nAChRs, causing hyper-excitation (Insecticide Resistance Action Committee [IRAC], 2012). The neonicotinoids have established themselves worldwide as key components in insect control programmes because of their novel mode of action, unique chemical and biological properties, such as excellent uptake and translocation in plants, and favourable safety profile (Maienfisch *et al*., 2001). Although no studies on the development of resistance to the neonicotinoids in cocoa mirids have been conducted, there are important lessons from studies on other insect pests. Selection for resistance in the diamondback moth, *Plutella xylostella* (L.), the second most resistant pest worldwide (Vasquez, 1995; Nauen, 2012), to four insecticides of different chemistries, acetamiprid (neonicotinoid), cartap (nereistoxin analogue), phenthoate (organophosphorous) and esfenvalerate (pyrethroid) showed that resistance to the neonicotinoid insecticides is slow to manifest compared to resistance to other insecticide chemistries (Ninsin, 2004a). How-ever, other studies have shown that insect pests eventually develop resistance to the neonicoti-noid insecticides following repeated exposure.

Laboratory studies have shown the development of resistance to the neonicotinoids in insect pests such as silverleaf whitefly, *Bemisia argentifolii* Bellows and Perring (Prabhaker *et al*., 1997), **brown planthopper, *Nilaparvata lugens* (Stål)** (Liu *et al*., 2003) and *P. xylostella* (Ninsin, 2004b). Resistance to the neonicotinoids has also been observed in field populations of insect pests such as the cotton whitefly, *Bemisia tabaci* (Gennadius) (Elbert & Nauen, 2000; Horowitz, Kontsedalov & Ishaaya, 2004), Colorado potato beetle, *Leptinotarsa decemlineata* (Say) (Zhao, Bishop & \Grafius, 2000; Mota-Sanchez *et al*., 2006) and ***N. lugens*** (Wang *et al*., 2008; Garrood *et al*., 2016).

The mechanisms that have been implicated to confer resistance to the neonicotinoids in insect pests are nAChR mutations, conferring target-site resistance (Liu *et al*., 2005; Bass *et al*., 2011) and the metabolic enzyme systems, cytochrome P-450 monooxygenases (having a major role), esterases and glutathione-S-transferases, conferring metabolic resistance (Zhao *et al*., 2000; Nauen, Stumpf & Elbert, 2002; Rauch & Nauen, 2003; Liu *et al*., 2003; Ninsin & Tanaka, 2005; Bass *et al*., 2011; Yang *et al*., 2013). A detailed review on resistance to the neonicotinoids in insect pests and the underlying mechanisms has been authored by Bass *et al*. (2015).

Bifenthrin is a pyrethroid insecticide that modulates the sodium channel by keeping the channel open, causing hyperexcitation and, in some cases, nerve block (IRAC, 2012). There are also no studies on cocoa mirid resistance to bifenthrin. Resistance to bifenthrin has, however, been observed in other arthropod pests such as the tarnished plant bug, *Lygus lineoralis* (Palisot de Beauvois) (Snodgrass, 1996), the two-spotted spider mite, *Tetranychus urticae* Koch (Herron, Rophail & Wilaon, 2001), *B. argentifolii* (Riley & Tan, 2003) and the southern chinch bug, *Blissus insularis* Barber (Cherry & Nagata, 2005). The involvement of esterases in the resistance of arthropod pests to bifenthrin has been demonstrated by Van Leeuwen & Tirry (2007).

In addition to an insecticide becoming ineffective as a result of insect pests developing resistance from exposure to the insecticide, cross-resistance, which is when an insect pest that is resistant to a given insecticide is able to resist another insecticide that has not been used against it, also renders insecticides ineffective. Cross-resistance exists between insecticides of same chemistry. Since all insecticides in a chemical group have a common mode of action, the mechanisms that confer resistance against one insecticide also confer resistance against other insecticides in the group. Thus, cross-resistance exists between imidacloprid and thiamethoxam, as demonstrated by Rauch & Nauen (2003) and Alyokhin *et al*. (2007). Cross-resistance can also exist between insecticides of different chemistries and is usually due to the action of metabolic enzyme systems. Such cross-resistance between insecticides from different chemical groups has been established between the neonicotinoids and bifenthrin (Prabhaker *et al.*, 1997; Basit *et al*., 2011; Basit *et al*., 2013).

The evidence of resistance and cross-resistance to imidacloprid, thiamethoxam and bifenthrin suggests that applying the insecticides singly or rotationally would select for resistance-conferring genes that could confer resistance to all three insecticides in an insect population, and render all the insecticides ineffective at the same time.

Results and discussions

Risks and consequences of mirid resistance to imidacloprid, thiamethoxam and bifenthrin

The detection of resistance in *D. theobroma* to ɣ-BHC at Pankese in the Eastern Region of Ghana, following the widespread use of the compound for mirid control (Dunn, 1963), indicates that the cocoa mirids have the genetic ability to develop resistance to insecticides. The resistance and cross-resistance to imidacloprid, thiamethoxam and bifenthrin also suggest that widespread application of Confidor®, Actara® and Akate Master® to control *D. theobroma* and *S. singularis* is subjecting the mirids on the cocoa farms to a high insecticide selection pressure and selecting for resistant individuals in field populations of the pests. If the resistant mirids become sufficiently available in the field, they would spread and become the predominant individuals on cocoa farms. When this happens, Confidor®, Actara® and Akate Master® would become ineffective against the resistant mirids, leading to mirid control failures and cocoa yield losses. An attempt to overcome the resistant mirids by increasing insecticide concentrations and, or frequency of applications would make the mirids more resistant and also create additional problems such as insecticide residues in cocoa beans.

Moreover, if *D. theobroma* and S. *singularis* develop resistance to imidacloprid, thiamethoxam and bifenthrin, it may not be possible to successfully reuse these insecticides for mirid control. This is because once selected, insecticide-resistance conferring genes possess virtually limitless persistence in pest populations (Metcalf, 1980). Although the gene frequency of a specific resistant allele may decrease upon the removal of insecticide pressure, there persists a changed background of residual inheritance in the insect's genome that causes the strain to regain its resistance as soon as the insecticide is reapplied for pest control (Brown, 1977). Finding replacement insecticides for imidacloprid, thiamethoxam and bifenthrin if resistance develops would also be extremely difficult since global research and development for the discovery and development of new insecticide chemistries is long, complicated and very expensive.

Measures for preventing mirid resistance development

It is imperative to prevent the development and spread of resistance in *D. theobroma* and S. *singularis* to imidacloprid, thiamethoxam and bifenthrin to avoid associated yield losses and preserve the efficacy of the COCOBOD approved insecticides. Measures for preventing resistance development in the mirids should be able to constantly maintain insecticide susceptible individuals in field populations of *D. theobroma* and *S. singularis* so that the mirids could always be effectively controlled with the three approved insecticides.

Mirid-resistance to the COCOBOD approved insecticides would develop through the selection of resistance-conferring genes in pest populations over successive generations which would be influenced by the selection pressure of the approved insecticides. Thus, the measures that would be successful in preventing the development of mirid-resistance to the approved insecticides should be able to decrease the use of the approved insecticides and reduce selection pressure. The following measures are, therefore, recommended:

Establish practical economic threshold for D. theobroma *and* S. singularis. According to Collingwood, Marchart & Manteaw (1973), 100 mirids per hectare is the recommended economic threshold. However, Adu-Acheampong *et al*. (2014) found that farmers were not using the recommended threshold. The farmers rather depended on a variety of local rules that guided their decision to apply insecticides for mirid control, a situation that could have severe negative consequences for pest management and farmers' income (Adu-Acheampong *et al*., 2014). Establishing a practical economic threshold would, therefore, ensure that the approved insecticides are applied against mirids when necessary.

Incorporate alternative effective mirid control methods. The incorporation of alternative effective mirid control methods into the CODAPEC programme would decrease the application of the approved insecticide. Thus, alternative control methods such as mycoinsecticides (Bateman, 2006) and sex pheromones for mass-trapping of mirids (Mahob *et al*., 2011; Sarfo, 2013) need to be optimized for field deployment.

Implement insecticide-resistance monitoring programmes on cocoa farms. The detection of resistance in an early stage of development is essential to the success of resistance management (Ninsin *et al*., 2000) as it allows for the early implementation or tweaking of resistance management strategies to prevent or retard full-blown resistance in a pest population (Ninsin, 2016). It is, therefore, important to monitor to detect changes in the susceptibility of *D. theobroma* and *S. singularis* to imidacloprid, thiamethoxam and bifenthrin.

Identify other efficacious insecticides of different chemistries to be used in a rotation with imidacloprid, thiamethoxam and bifenthrin. The rotational use of insecticides with no cross-resistance between them is an effective countermeasure against arthropod pest resistance to insecticides (Saito *et al.*, 1995). However, if the cross-resistance status of insecticides in an arthropod pest population has not been evaluated, the rotational use of insecticides with different modes of action has the potential to manage resistance development (Ninsin, 2014). Since cross-resistance studies in cocoa mirids that are resistant to imidaclo-prid, thiamethoxam and bifenthrin have not been conducted, other insecticides from different chemical groups that are effective against the mirids need to be identified and rotationally used with the approved insecticides.

*Characterize D***.** theobroma and *S.* singularis resistance to imidacloprid**,** *thiamethoxam and bifenthrin.* To characterize resistance, it is important to establish colonies of *D. theobroma* and *S. singularis* that are resistant and susceptible to the approved insecticides. Thereafter, key resistance studies such as stability of resistance, cross-resistance assessment and clarifying mirid resistance mechanisms can be conducted. Knowledge gathered from the characterization of *D. theobroma* and *S. singularis* resistance to the approved insecticides would then be used in formulating comprehensive resistance management strategies to preserve the efficacy of imidacloprid, thiamethoxam and bifenthrin.

Conclusion

Although the widespread application of imidacloprid, thiamethoxam and bifenthrin against the cocoa mirids has contributed to boosting cocoa output in Ghana, it has been shown in this paper that there is the likelihood of resistance developing in *D. theobroma* and *S. singularis*. Measures for preventing resistance from developing in *D. theobroma* and *S. singularis* have been recommended. However, in order to fully benefit from the recommended measures, it is important to provide funding for research to translate the measures into practical resistance management strategies to maintain the efficacy of the approved insecticides against mirids, avert resistance associated yield losses and safeguard Ghana's foreign exchange earnings from cocoa.

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