Dynamics of insect pollinators as influenced by Cocoa Production systems in Ghana

Article *in* Journal of Pollination Ecology · July 2011

DOI: 10.26786/1920-7603(2011)12

4 authors:

Kofi Frimpong-Anin
CSIR-Crops Research Institute

Barbara Gemmill-Herren
World Agroforestry Centre

Ian J. Gordon

Kwapong Peter. Kofi
University of Cape Coast

Journal of Pollination Ecology, 5(10), 2011, pp 74-80

DYNAMICS OF INSECT POLLINATORS AS INFLUENCED BY COCOA PRODUCTION SYSTEMS IN GHANA

Eric A. Frimpong[1]*, Barbara Gemmill-Herren[2], Ian Gordon[3] and Peter K. Kwapong[1]

[1]*Department of Entomology and Wildlife, School of Biological Sciences, University of Cape Coast, Cape Coast, Ghana*
[2]*AGPS – FAO, Viale Terme di Caracalla, Roma, Italy*
[3]*International Centre of Insect Physiology and Ecology (ICIPE), P.O. Box 30772-00100 Nairobi, Kenya*

Abstract—Cocoa is strictly entomophilous but studies on the influence of the ecosystem on insect pollinators in cocoa production systems are limited. The abundance of cocoa pollinators and pod-set of cocoa as influenced by a gradient of farm distances from natural forest and proportion of plantain/banana clusters in or adjacent to cocoa farms were therefore investigated. Cocoa pollinators trapped were predominantly ceratopogonid midges hence, analyses were based on their population. Variation in farm distance to forest did neither influence ceratopogonid midge abundance nor cocoa pod-set. However, we found a positive relationship between pollinator abundance and pod set and the proportion of plantain/banana intercropped with cocoa. The results suggest appropriate cocoa intercrop can enhance cocoa pollination, and the current farming system in Ghana can conveniently accommodate such interventions without significant changes in farm practices.

Keywords: *Pollination, cocoa pod-set, ceratopogonid midges, plantain/banana, forest.*

INTRODUCTION

The estimated value of food crops directly consumed by humans attributed to insect pollination services in 2005 was US$ 153 billion, representing about 9.5% of total world production of human food (FAO, 2008). Insect exclusion experiments have shown that cocoa is strictly entomophilous and obligatorily requires insect pollinators (Cilas 1988; Ibrahim 1988; Posnette 1950). Klein et al (2007) have categorized cocoa among the 13 leading crops whose production would be reduced by over 90% in the absence of animal pollinators. Moreover, pollination in cocoa has been evaluated to be a higher order limiting factor in cocoa yield than agronomic resources (Groeneveld et al. 2010). Reports of decline in pollinator populations in agro-ecosystems and consequential decrease in food crop production (Ahmad et al. 2006; FAO 2008) suggest the languid nature of studies on natural pollination of cocoa should be intensified.

In recognition of the fact that pollination is a vital crop production factor, integrated crop production strategies are incorporating pollinator-friendly and conservation modules to enhance production. Landscape approaches have hitherto been the most frequently emphasized interventions, particularly through the conservation of native habitats (Aidoo 2008; Gemmill-Herren & Ochieng 2008; Klein et al. 2003a; Kremen et al. 2007). Studies focusing on bee pollinated crops such as melon (Kremen et al. 2002), grapefruit (Chacoff & Aizen 2006), eggplant (Gemmill-Herren & Ochieng 2008) and coffee (Klein et al. 2003a,b) show pollination services are influenced by gradients of distances between agricultural landscapes and natural forests. It is not sure that this phenomenon holds at all in cocoa, which is pollinated by ceratopogonid flies (Posnette 1950; Young 1982a). However, South and Central American cocoa plantations have been postulated to be under-pollinated due to a shift from more diverse agroforest systems to simple cocoa monocultures (Young 1986). Young (1982a; 1986) subsequently postulated that critical associations exist between cocoa pollinators and natural forest, because cocoa in its native wild in the Amazon occurs as understory tropical tree distributed in aggregates along small streams.

As noted by Klein et al. (2008), studies on cocoa pollinators have centred on breeding substrates rather than the role of landscape matrices. Artificial introduction of slices of banana stems have been found to be a good breeding substrate for midges, which increases their population and pod-set in cocoa farms (Elizondo & Enriquez 1988; Young 1982b). Its practical application is however yet to be developed. Most newly established cocoa farms in Ghana are intercropped with plantain or banana as temporal shade cover, as staple food, and for income prior to and at initial fruiting stages (Acquaah, 1999). Evaluating the impact of plantain or banana stands on cocoa pollinators may help develop its mass application. This study therefore assessed two landscape features, the relative contribution of natural forest and proportion of cocoa and plantain/banana intercrop to cocoa pollination, which are familiar components of cocoa cropping practices in Ghana.

MATERIALS AND METHODS

Study Areas and Farm Management

The study was carried out in 18 small scale (1.6 - 4.0 ha) farmer managed cocoa farms in three cocoa growing areas in

Received 4 January 2011, accepted 18 June 2011
*Corresponding author; Tel. +233 24 4379549 / +233 26 8371353
Email: nanakofy@yahoo.com

TABLE 1: Characteristics of the experimental cocoa farms

Site	Focal forest reserve	Farm code	Farm distance from forest (km)	Distance category	Latitude	Longitude	Elevation (m)	Variety	Plantain or banana cluster/ha
Kubease-Wuraponso	Bobiri	A1	0	Adjacent	N06°40.899'	W001°21.217'	245	Hybrid, Amazonia	8.0
		A2	0	Adjacent	N06°41.550'	W001°21.859'	237	Amazonia, Amelonado	2.0
		B1	0.81	0.8 - 1.0	N06°40.621'	W001°21.240'	241	Amazonia	9.0
		B2	0.85	0.8 - 1.0	N06°40.452'	W001°20.777'	243	Amazonia, Amelonado	3.4
		C1	1.80	1.5 - 2.0	N06°40.163'	W001°20.528'	248	Hybrid, Amazonia	3.2
		C2	1.60	1.5 - 2.0	N06°39.947'	W001 °20.321	231	Amazonia	0.8
Abrafo-Ebekawopa	Kakum	A3	0	Adjacent	N05°19.432'	W001°24.107'	161	Hybrid, Amazonia	2.8
		A4	0	Adjacent	N05°19.212'	W001°24.743'	174	Amazonia	1.2
		B3	1.00	0.8 - 1.0	N05 °19.873'	W001°22.753'	128	Hybrid, Amazonia	≥10
		B4	0.93	0.8 - 1.0	N05°19.744'	W001°22.634'	127	Hybrid, Amazonia	2.0
		C3	1.90	1.5 - 2.0	N05°19.410'	W001°24.211'	159	Amazonia	3.6
		C4	1.95	1.5 - 2.0	N05°19.516'	W001°24.107'	171	Amazonia, Hybrid	9.0
Edwenease	Pra-Suhyen	A5	0	Adjacent	N05°14.486	W001°29.619'	198	Hybrid, Amazonia	1.0
		A6	0	Adjacent	N05°14.575	W001°29.68'	124	Hybrid	2.0
		B5	0.97	0.8 - 1.0	N05°14.517	W001°29.140'	237	Hybrid, Amazonia	2.4
		B6	0.90	0.8 - 1.0	N05 ° 14.348	W001°29.376'	231	Amazonia, Amelonado	0.9
		C5	1.55	1.5 - 2.0	N05 °14.379	W001°28.744'	266	Amazonia	0.0
		C6	2.00	1.5 - 2.0	N05 °14.619	W001°28.714'	265	Hybrid, Amazonia	9.4

Ghana. The areas are within the semi-deciduous rainforest belt with dual rainfall in April-July and September-November. These areas had scattered cocoa farms at varying distances from natural forest reserves. The areas were Kubease (Ashanti Region), Abrafo-Ebekawopa (Central Region) and Edwenease (Western Region) each of which has Bobiri, Kakum and Pra-Suhyen as focal forest reserves respectively (Tab. 1). Farms were selected such that they fell within three specified distances of 0 km (adjacent), 0.8 - 1.0 km, 1.5 - 2.0 km) from the forest reserves. Farms were subsequently grouped under those three distances.

Varieties grown were Upper Amazon and hybrids. Farms were ten to twenty-five years old with varying plantain/banana intercrop distribution. Standing plantain/banana was included due to the observation by Young (1982a) that artificially provided banana stems favours breeding cocoa pollinating midges and for the fact that these crops are planted as temporary shade for cocoa in Ghana. Insecticides were sprayed monthly, from September to

December 2007, to conform to the recommended cocoa management practices in Ghana (Opoku et al. 2008). Weeds were manually cleared twice while parasitic mistletoe *Tapinanthus bangwensis* (Engl. and Krause) was pruned off the cocoa trees once within the study period.

Estimation of Pollinator Abundance

A pair of farms from each distance (adjacent, 0.8 - 1.0 km, 1.5 - 2.0 km) from a focal forest was selected from each site and every farm was divided into four quadrants (plots) of mean size (± SD) of 0.5 ± 0.1 ha. Three pollinator sampling methods described below were used concurrently at monthly intervals from April 2007 through April 2008 (Frimpong et al. 2009).

(1) Focal tree observation and sampling with motorized aspirator: Stratified tree sampling was used; 4 cocoa trees (1 per plot) with 10 – 20 open flowers were selected from each farm. It must be noted that flowers are scarcely available from August to November hence lesser number (average of 11.3 flowers) were sampled. A mean of 19.5 flowers were, however, sampled during normal flowering. Thus, trees were selected monthly based on availability of open-flowers on the lower section of the trunk. Open-flowers within 0.3 m above the soil to 1.3 m section of the trunk were observed for 10 minutes and all visiting insects were collected using a motorized suction pump. Samplings were conducted between 07:00 h and 11:00 h, and collected insects (except Lepidopterans) were preserved in 70% alcohol.

(2) UV-bright Painted Pan Traps (UVPPT): Another set of cocoa trees, 1 per plot, were randomly selected from each farm and marked. A set of UVPPT, comprising yellow, blue and white were filled to three-quarters full with soapy water and hung in the canopy of each experimental tree. Traps were removed after 48 hours and trapped insects were sieved off with muslin cloth, collected using fine camel hair brush and preserved.

(3) McPhail trap: A third set of 4 cocoa trees (1 per plot) were again randomly selected from each farm. Steam distilled cocoa floral oil was inoculated into cotton wool suspended in McPhail traps (Young et al. 1988). The trough of the traps were filled with soapy water and hung in the canopies of the third set of trees. Traps remained in the canopy for 48 hours and trapped insects were collected and preserved.

The three complementary methods were used in order to increase sampling efficiency because midge populations are generally low, especially during the dry season. Moreover, efficiency and ease of application of each method varies with respect to the vertical plane of the cocoa tree. Whilst the motorized aspirator easily and efficiently samples sections below the canopy, UVPPT and McPhail traps are more efficient at the canopy level (Frimpong et al. 2009).

Counts of ceratopogonid midges were made after they were sorted out in the laboratory using dipteran taxonomic identification key (Scudder & Cannings 2006). Some samples were then barcoded by Barcoding of Life Datasystems (BOLD), for further identification but specimens could only be identified to families (Appendix I; Anon 2008).

Estimation of Cocoa Pod-set

A fourth set of 4 cocoa trees per farm were randomly selected and 0.3 m - 1.3 m section of the trunk above the soil marked (Sarfo et al. 2003). All open flowers, cherelles (young pods) and pods were excised from the marked section on the first study month (April). Flower buds, open-flowers, cherelles (both viable and wilted) were counted at 30 day intervals (Appendix II). This interval was based on the 28 days that a flower bud takes to fully develop and open (Swanson et al. 2005) and the approximately 2 days survival span of open-flowers (McKelvie, 1962). To ensure that all new cherelles and ripe pods which might have been incidentally removed by farmers prior to a sampling date were counted, stalks of newly formed cherelles were carefully marked with permanent marker, and matured unripe pods were remarked during each sampling. Wilted cherelles and ripe pods were excised from the trees on each sampling occasion. This was to ensure that cherelles which wilted within the month were also counted. Monthly percent pod-set P_s of the cocoa trees was calculated as:

$$P_s = \frac{[(C_u + C_w + P_u + P_r) - (C_m + P_u)]100}{F_b + F_o}$$

Where C_u , unmarked cherelles for the month; C_w , wilted cherelles; P_u , unripe pods; P_r , ripe pods; C_m , previous months' cherelles; P_u , unripe pods; F_b . 95% of flower buds [according to McKelvie (1962), estimated 95% of flower buds become open flowers]; F_o , open flowers of the previous month.

Data Analysis

The numbers of midges and percent pod-set of cocoa were normalized through square root and arcsine transformations respectively, after testing for normality and homogeneity by plotting mean against variance (Gomez & Gomez 1984). A Multiple regression was run to determine the relationship between farm distance to forest, availability of plantain/banana clusters, and abundance of pollinators and cocoa pod-set, using Minitab release 13.2. All data were back-transformed to original scales before interpreting.

Data for farm distance to forest were re-categorised to adjacent, 0.8 - 1.0 km and 2.0 - 2.5 km and availability of plantain/banana to abundant (> 8 clusters) and scanty/ absent (< 4 clusters). This allowed the dynamics of monthly pollinator populations and cocoa pod-sets under these landscape parameters to be analyzed.

RESULTS

Abundance of Cocoa Pollinators

Midges belonging to Ceratopogonidae and Cecidomyiidae families were the predominant cocoa flower visitors recorded for all the trapping methods, with the former being overly abundant (see details in Frimpong et al. 2009). The number of *Liotrigona parvula* Darchen (Hymenoptera: Apidae: Meliponini), the only recorded bee with the potential to pollinate cocoa (Frimpong et al. 2009) occurred in very low numbers – 38 individuals over the whole sampling period. Detailed analysis and discussion of the results presented here therefore focused on the ceratopogonids, conventionally acknowledged prime pollinators of cocoa (Kaufmann 1975; Posnette 1950; Young 1982a). The validity of this is justified by the significantly positive correlation between the number of ceratopogonids midges and cocoa pod-set (Fig. 1a).

The abundance of ceratopogonid midges did not correspond to variation in distance of farm from natural forest (Fig. 1b). Availability of plantain/banana, however, had a marked influence on the abundance of ceratopogonids. We obtained a positive association between ceratopogonid midges abundance and the number of plantain/banana clusters intercropped with cocoa (or within 50 m radius from farm; Fig. 1c). Thus, farms which had higher proportions of plantain/banana intercropped with cocoa or close by, had more abundant ceratopogonid midges compared to farms with no or scanty remnants of plantain/banana.

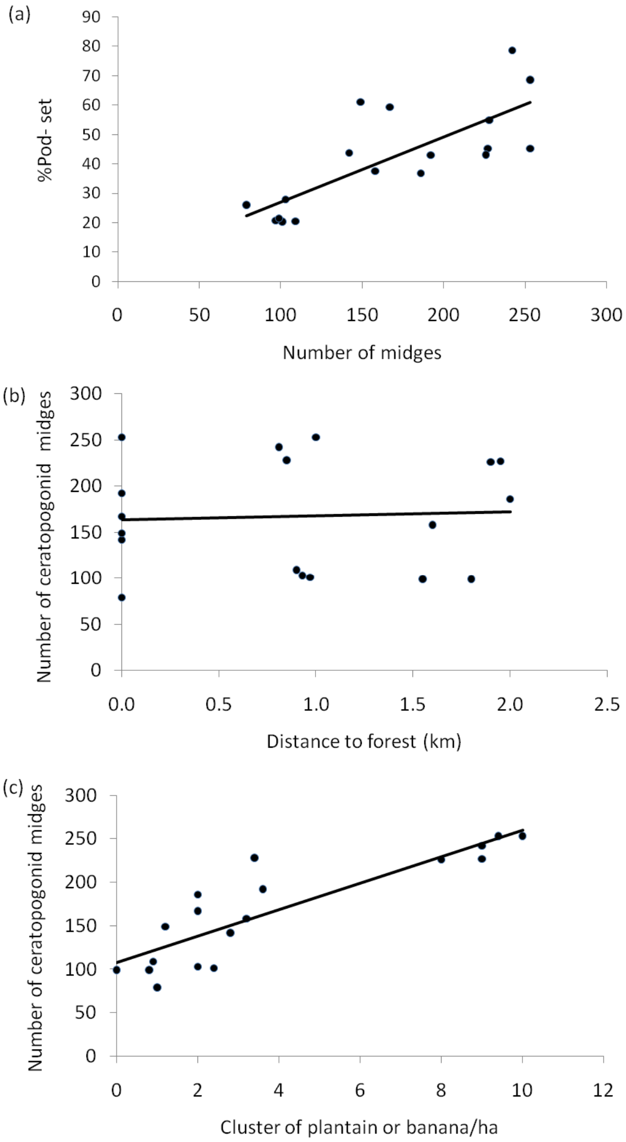

FIG. 1. Relationship between number of cocoa pollinating ceratopogond midges: (a) Pod-set of cocoa; $y = 4.839 + 0.221 x$, r2 = 0.59, n =18, f = 22.77, $p < 0.001$. (b) Distance of cocoa farm from forest; $y = 154.88 + 0.04 x2$, r2 = 0.02, n = 18, f = 0.02, p = 0.884. (c) Cluster of plantain/banana in or near cocoa farm; $y = 107.5 + 15.24$, r2 = 0.75, n = 18, f = 45.11, $p < 0.001$.

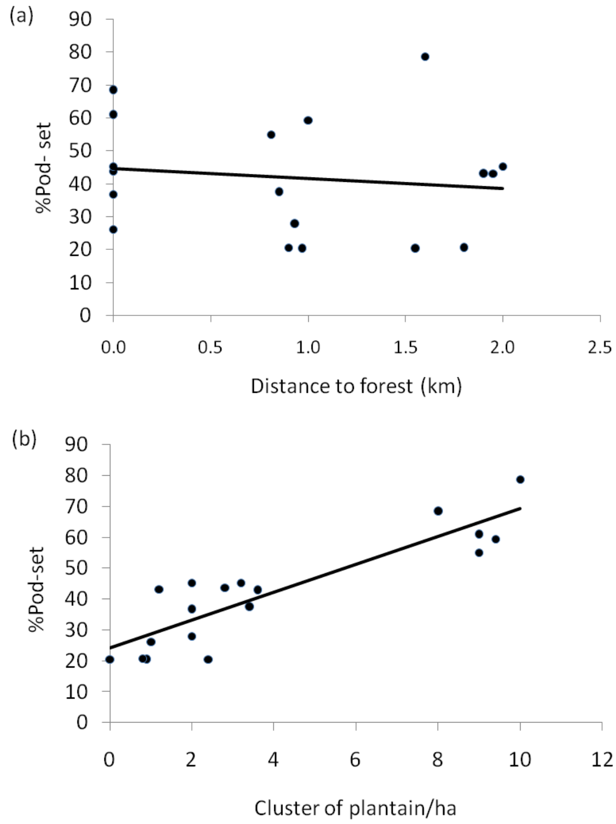

FIG. 2. Relationship between cocoa pod-set: (a) Distance of farm from forest: $y = 44.52 - 0.03 x2$, r2 = 0.02, n = 18, f = 0.38, p = 0.544. (b) Cluster of plantain/banana in or near cocoa farm: $y = 24.06 + 4.525 x$, r2 = 0.78, n = 18, f = 58.00, $p < 0.001$.

Cocoa Pod-set

The pod-sets were also independent of the proximity of the cocoa farms to natural forest (Fig. 2a). Nevertheless, we found a positive relationship between availability of plantain/banana clusters and pod-set (Fig. 2b).

Dynamics of ceratopogonid midge populations and pod-set

There were marked monthly variations in ceratopogonid populations and these corresponded with cocoa pod-sets. The dynamics of these two variables were similar under both varying farm distances from forest and availability of plantain/banana (Figs. 3a-b and 4a-b). We recorded high numbers of ceratopogonid midges and cocoa pod-set from June to November before dropping sharply to a minimum in February and March, under the two farm characteristics investigated. Abundance of ceratopogonid midges and pod-sets were comparable under the three distances relative to the focal forests (Figs. 3a and 4a). Farms with high proportions of plantain/banana intercropped with cocoa, however, exhibited significantly bigger ceratopogonid populations and higher cocoa pod-set throughout the season (Figs. 3b and 4b).

DISCUSSION

Clusters of wild cocoa found in the Amazon forest are postulated to provide the right proportion of cocoa

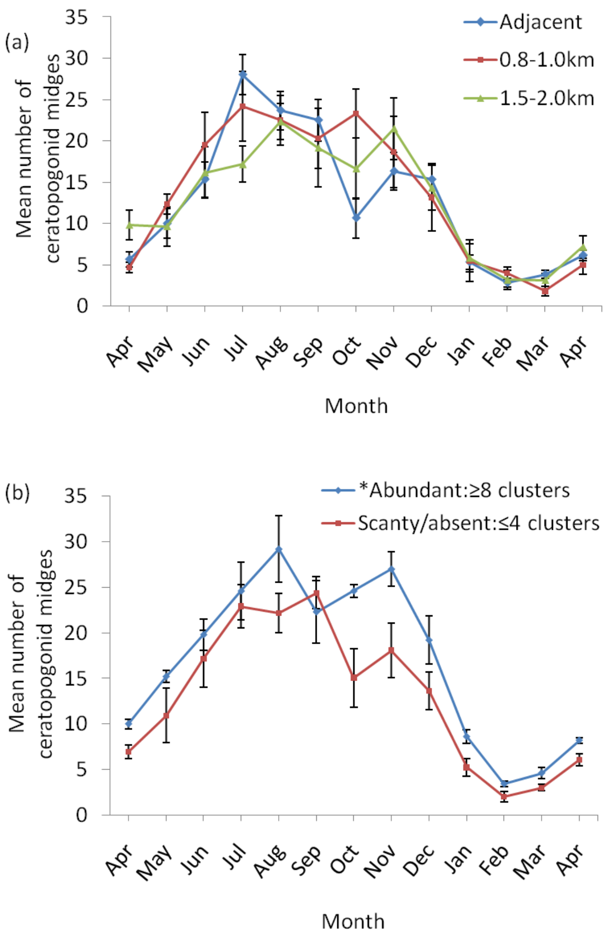

FIG. 3. Monthly population dynamics of ceratopogonid midges under: (a) Varying farm distance from natural forest. (b) Availability of plantain/banana [*see figs. 1c & 2, basis for re-categorizing to abundance and scanty/absent].

pollinating midges compared to large plantations with numerous flowers which have to be pollinated by relatively few midges. The insects thus get satiated by sheer abundance of resources in large cocoa monocultures (Young 1982a). This suggests that cocoa farms at close proximity to natural forests potentially have supplementary midge populations from the forest to enhance pollination, hence increased pod-set. Results obtained in this study however imply that natural forest adjacent to cocoa farms did not significantly increase the population of ceratopogonid midges and therefore cocoa pod-set. All the experimental farms, however, had secondary or regenerating forest patches close by (common to most cocoa farms in Ghana) which possibly offered resources and conditions similar to the focal primary forests. Moreover, 16 out of the 18 farms were established along small streams similar to cocoa stands in the native wild forests hence conditions would possibly be closely related, particularly in the wet season. Streams, however, dry out during the dry season and conditions might deviate during this period from those of the native wild, where streams are mostly perennial (Young 1982a). Although conditions suitable for efficient pollination of cocoa under agro system conditions are widely discussed (Brew 1988; Cilas 1988; Falque et al. 1995; Groeneveld et al. 2010; Ibrahim 1988; Kaufmann 1975; Young 1982a,b; 1983; 1986) empirical data on the optimal pollination of wild cocoa in its native habitats are scarcely available. Cocoa is often designated as under-pollinated due to the small fraction of flowers pollinated (Paulin et al. 1985; Cilas 1988) although the proportion of pollinated flowers of the wild tree has not yet been established. It would be desirable to study pod-set rate of wild cocoa in the Amazon forest, as this will enlighten whether natural pollination deficits of the crop exist.

The results show availability of plantain/banana significantly influenced ceratopogonid midge population and pod-set. Remains of rotting plantain/banana stumps and stems after harvesting provide ideal breeding sites for midges (Elizondo & Enriquez 1988; Young 1982b) which explains high pollinator abundance with corresponding pod-set in farms where such substrates were available in substantial quantities. Most mature cocoa farms, however, does not benefit from cocoa/plantain or banana intercrop because plantain and banana planted as temporary shade crop at the early establishment of cocoa become stunted or die when the cocoa canopy closes. Development of a more persistent cocoa/plantain or cocoa/banana intercrop system will help augment population of pollinating ceratopogonids and therefore increase pod-set of cocoa. Nevertheless, some farmers fill wide gaps within mature cocoa farms with plantain as food crop and thus inadvertently increase

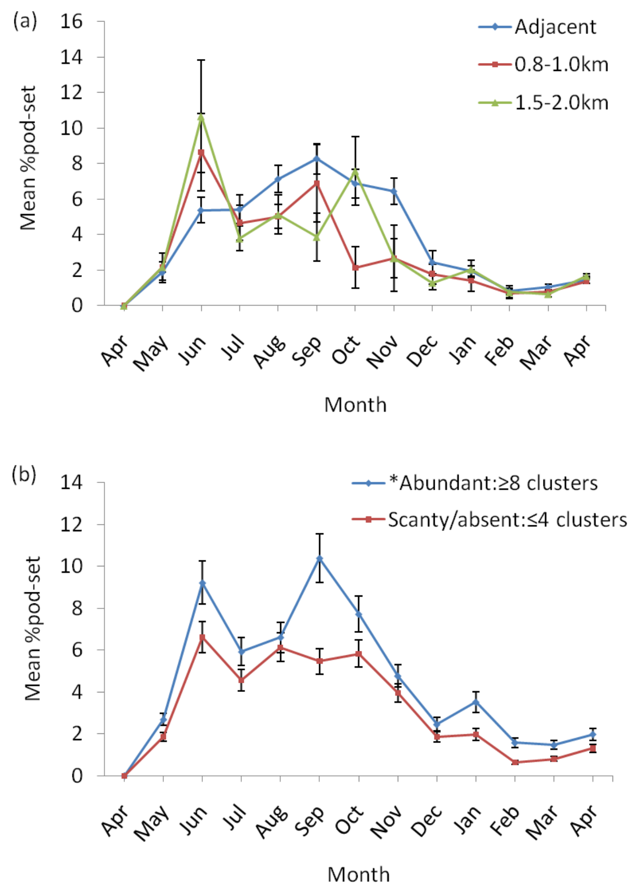

FIG. 4. Monthly dynamics of cocoa pod-set under: (a) Varying farm distance from natural forest. (b) Availability of plantain/banana [*see figs. 1c & 2].

pollination of their crop. Additionally, the plantain/banana could be planted at boundaries of already established cocoa farms.

Unlike the farm-forest proximity experiment where no clear differences in pollinator population and pod-set were recorded, the differences between farms with abundant and scanty plantain/banana were significantly higher in both the rainy (June through November) and dry periods (December-March). This corroborates other findings that rotten banana stems sustain adequate moisture for the midges to breed in during the dry season (Young 1982b). Standing plantain and banana in cocoa farms could thus be manipulated to augment midge population in the dry season. This is particularly important because cocoa tends to produce flowers profusely around this period and at the on-set of rains, at which time midge population is minimal (Frimpong et al. 2009; McKelvie, 1962).

CONCLUSION

Results from the landscape features studied suggest farm practices such as small scale farming and intercropping cocoa with plantain/banana favours pollination services in the cocoa agro-ecosystem. We identified a relationship between standing plantain/banana and cocoa pollination, and therefore a proper spatial cocoa-plantain/banana intercrop outlay will help boost pollination of the crop. Nearness of farm to natural forest did not offer any pollination advantage and that secondary forest patches surrounding cocoa farms possibly offer pollinator resources similar to that of natural forest. We suggest that assessment of natural pollination of wild cocoa in its native forest habitat and also pollination under large cocoa plantations with varying vegetation interface should be conducted.

ACKNOWLEDGEMENTS

The authors are grateful to the Dutch Programme for Cooperation with International Institutions (Netherlands SII) for funding this research through ICIPE, and Entomology and Wildlife Department, University of Cape Coast for hosting the research. We also thank Dr. Laurence Parker (York University, Toronto) and Dr. Daniel Masiga (ICIPE, Nairobi) for the barcoding, and farmers whose farms were used. This research has been part of FAO Project on "conservation and management of pollinators for sustainable agriculture, through an ecosystem approach", supported by the Government of Norway, United Nations Environment Programme UNEP and Global Environment Facility (GEF).

APPENDICES

Additional supporting information may be found in the online version of this article:

Appendix I-Taxon data
Appendix II. Monthly cocoa flower production

REFERENCES

Acquaah B (1999) Cocoa development in West Africa: Early development with special reference on Ghana. Ghana Universities Press, Accra. 187 pp.

Ahmad F, Banne S, Castro M, Chavarria G, Clarke J, Collette L, Eardley C, Fonseca V, Freitas BM, French C, Gemmill-Herren B, Griswold T, Gross C, Kwapong P, Lundall-Magnuson E, Medellin R, Partap U, Potts SG, Roth D, Ruggiero M, Urban R, Willemse G (2006) Pollinators and Pollination: A resource book for policy and practice. Eardley C, Roth D Clarke J. Buchmann S, Gemmill-Herren B. (eds.), African Pollinator Initiative, Pretoria.

Aidoo SK (2008) Pollination and cashew (*Anarcadium occidentale* L) production in Ghana. PhD Thesis, University of Cape Coast. 162p.

Anon (2008) http://www.boldsystems.org/views/taxbrowser.php?taxid=567. (Last accessed: June, 2011).

Brew AH (1988) Cocoa pod husk as breeding substrate for forcipomyia midges and related species which pollinate cocoa in Ghana. Cocoa Growers Bulleting 40: 40-42.

Chacoff NP, Aizen MA (2006) Edge effects on flower-visiting insects in grapefruit plantations bordering premontane subtropical rainforest. Journal of Applied Ecology 43: 18-27.

Cilas C (1988) Study of natural cacao pollination in Togo and its implication for production. Proceedings of the 10th International Cocoa Research Conference 1987, Santo Domingo, pp283-286.

Elizondo JE, Enriquez GA (1988) Evaluation of 12 different types of musaceae as breeding sites for the cacao pollinating insects (Forcipomyia spp.) in shade and full sun at La Lola, Costa Rica. Proceedings of the 10th International Cocoa Research Conference 1987, Santo Domingo, pp297-302.

Falque M, Vincent A, Vaissiere BE, Eskes AB (1995) Effect of pollination intensity on fruit and seed set in cacao (*Theobroma cacao* L.). Sexual Plant Reproduction 8 (6): 354 – 360.

FAO (2008) Rapid Assessment of Pollinators' Status. Food and Agriculture Organization, Rome, Italy.

Frimpong EA, Gordon I, Kwapong PK, Gemmill-Herren B (2009) Dynamics of cocoa pollination: tools and applications for surveying and monitoring cocoa pollinators. International Journal of Tropical Insect Science 29: 62-69.

Gemmill-Herren B, Ochieng AO (2008) Role of native bees and natural habitats in eggplant (*Solanum melongena*) pollination in Kenya. Agriculture Ecosystem and Environment. 127: 31-36.

Gomez KA, Gomez AA (1984) Statistical procedures for agricultural research. 2nd edition. John Wiley and Sons Inc. New York.

Groeneveld JH, Tscharntke T, Moser G, Clough Y (2010) Experimental evidence for stronger cacao yield limitation by pollination than by plant resources. Perspectives in Plant Ecology, Evolution and Systematics 12:183-191.

Ibrahim GA (1988) Effects of insect pollinators on fruit set of cocoa flowers. Proceedings of the International Cocoa Research Conference 1987, Santo Domingo: 303-306.

Kaufmann T (1975) Studies on the ecology and biology of a cocoa pollinator, *Forcipomyia squamipennis* I. and M. (Diptera, Ceratopogonidae), in Ghana. Bulleting of Entomological Research 65: 263-268

Klein AM, Stefan-Dewenter I, Tscharntke T, (2003a) Bee pollination and fruit set of *Coffea arabica* and *C. canephora* (Rubiaceae). American Journal of Botany 90: 153-157.

Klein AM, Stefan-Dewenter I, Tscharntke T (2003b) Pollination of *Coffea canephora* in relation to local and regional agroforestry management. Journal of Applied Ecology 40: 837 – 845.

Klein AM, Vaissie`re BE, James H. Cane JH, Steffan-Dewenter I, Cunningham SA, Kremen C, Tscharntke T (2007) Importance of pollinators in changing landscapes for world crops. Proceedings of the Royal Society B: Biological Sciences 274: 303-313.

Klein AM, Cunningham SA, Bos M, Steffan-Dewenter I (2008). Advances in pollination ecology from tropical plantation crops. Ecological Society of America 89: 935-943.

Kremen C, Williams NM, Thorp RW (2002) Crop pollination from native bees at risk from agricultural intensification. Proceedings of the National Academy of Science 99: 16812-16816.

Kremen C, Williams NM, Aizen MA, Gemmill-Harren B, LeBuhn G, Minckley R, Packer L, Potts SG, Roulston T, Steffan-Dewenter I, Vazquez DP, Winfree R, Adams L, Crone EE, Greenlead SS, Keitt TH, Klein AM, Regetz J, Ricketts TH (2007) Pollination and other ecosystem services produced by mobile organisms: a conceptual framework for the effects of land-use change. Ecology Letters 10: 299-314.

McKelvie AD (1962) Cocoa physiology. In: Willis JB (ed) Agriculture and land use in Ghana. Oxford University Press, London, pp256-260.

Opoku IY, Frimpong-Ofori K, Sarfo JE (2008) The role of the national cocoa diseases and pests control (CODAPEC) and the hi-tech programmes in sustainable cocoa economy. In: Owusu GK (ed) Plenary presentations, 25th Biennial Conference of Ghana Science Association 2007, Tafo/Bunso, pp66-76.

Paulin D, Decazy B, Coulibaly N (1985) Seasonal variations in pollination and pod production in a cacao smallholding in Ivory Coast. Proceedings of the 9th International Cocoa Research Conference, 1984, Lome, pp549-556.

Posnette AF (1950) The pollination of cacao in the Gold Coast. Journal of Horticultural Science 25: 155 – 163.

Sarfo JE, Padi B, Oppong FM, Opoku IY, Akrofi AY (2003) Effects of two herbicides and four fungicides on insect pollination of cocoa. Proceedings of the 14th International Cocoa Research Conference 2, 1983, Accra, pp1387-1392.

Scudder GGE, Cannings RA, (2006) Diptera families of British Columbia. http://ditera.info/download (Last accessed on March 2007).

Young AM (1982a) Population biology of tropical insects. Plenum Press, New York.

Young AM (1982b). Effects of shade cover and availability of midge breeding sites on pollinating midge populations and fruit set in two cocoa farms. Journal of Applied Ecology 19: 47-63.

Young AM (1983) Seasonal differences in abundance and distribution of cocoa pollinating midges in relation to flowering and fruit set of between shaded and sunny habitat of the La Lola cocoa farms in Costa Rica. Journal of Applied Ecology 20: 801-831.

Young AM (1986) Habitat differences in cocoa tree flowering, fruit-set and pollinator availability in Costa Rica. Journal of Tropical Ecology 2: 163-186.

Young AM, Erickson BJ, Erickson EH (1988) Steam distilled floral oils of *Theobroma* sp. (Sterculiaceae) as attractants to flying insects during dry and wet seasons in a Costa Rican cocoa plantation. Proceedings of the 10th International Cocoa Research Conference 1987, Santo Domingo, pp289-296.