Relationships between flower-visiting insects and forest cover in cocoa-growing landscapes in Ghana

Supplementary Material

Richard G. Boakye,[1,2¤] Rofela Combey,[3] Blánaid White,[4,5] Dara A. Stanley[1,2]

[1] School of Agriculture and Food Science, University College Dublin, Dublin 4, Ireland

[2] Earth Institute, University College Dublin, Belfield, Dublin 4, Ireland

[3] Conservation Biology and Entomology, University of Cape Coast, Ghana

[4] School of Chemical Sciences, Dublin City University, Dublin 9, Ireland

[5] National Centre for Sensor Research, DCU Water Institute, Dublin City University, Ireland

¤Corresponding author: rgboakye@yahoo.co.uk

The supplementary material contains the following:

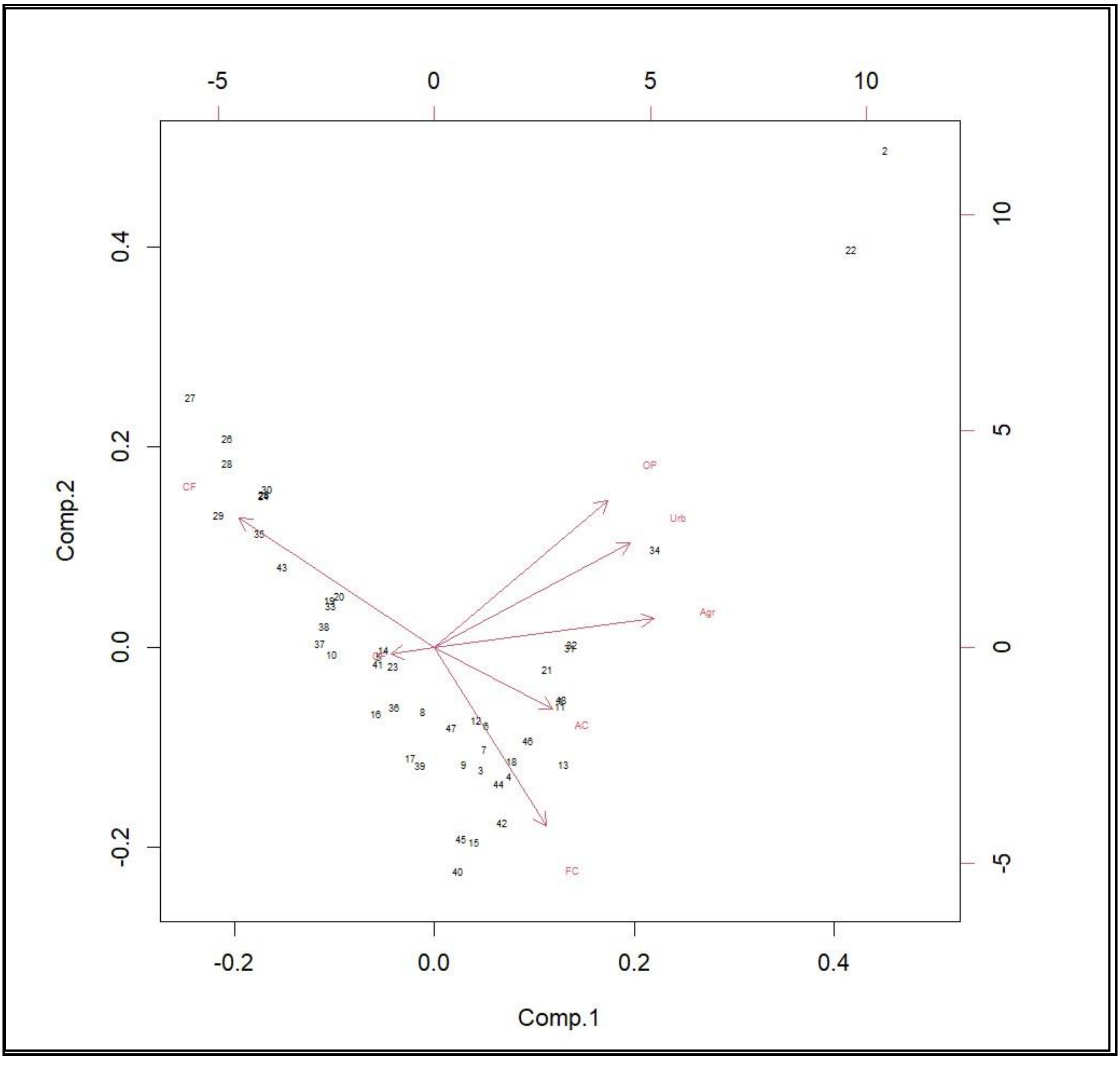

Fig S1 Output of principal component analysis conducted. Sites were selected along the gradient from the closed forest (CF) to fullsun cocoa (FC). Sites were selected as close as possible to this gradient to minimise variation in other landscape types. Sites were selected to ensure they were kept at least 4km apart and spatially distributed in the landscape

Table S 1

The total number of candidate sites which were subjected to principal component analysis leading to the final selection of the 18 sampled sites. The Percent cover of habitat types within 2km around both total sites was evaluated. The column labelled NV connotes the sum of open and closed forests. The colour-shaded areas are the selected and sampled sites based on the PCA performed.

Community /Location	GPS coordinates	Site name	Agriculture	Agroforestry Cocoa	Closed forest	Open forest	Fullsun cocoa	Oil palm	Urban	NF*
	N 06˚38.037' W 003˚07.221'	S1	0.15	0.14	0.00	0.15	0.51	0.00	0.05	0.15
Debiso	N 06˚39.398' W 003˚05.440'	S10	0.20	0.21	0.00	0.12	0.23	0.00	0.24	0.12
Adjoafua	N 06˚35.871' W 002˚09.711'	S11	0.05	0.11	0.00	0.16	0.61	0.00	0.07	0.16
Adjoafua	N 06˚34.323' W 003˚00.551'	S12	0.06	0.11	0	0.09	0.67	0.00	0.08	0.09
Akuoko	N 06˚31.849' W 003˚01.838'	S13	0.06	0.11	0.30	0.19	0.33	0.00	0.01	0.49
Obeykrom	N 06˚30.881' W 003˚01.361'	S14	0.12	0.25	0.06	0.21	0.35	0.00	0.01	0.27
Asanteman	N 06˚28.686' W 003˚00.941'	S15	0.09	0.37	0.00	0.25	0.29	0.00	0.01	0.25
Asafo Adjei	N 06˚27.136' W 003˚01.174'	S16	0.05	0.34	0.10	0.28	0.22	0.00	0.01	0.38
Safo Nkwanta	N 06˚26.785' W 003˚00.362'	S17	0.05	0.44	0.00	0.25	0.25	0.00	0.01	0.25
Camp 5	N 06˚21.993' W 002˚59.032'	S18	0.02	0.08	0.31	0.25	0.32	0.00	0.01	0.56

Asempaneye	N 06˚30.905' W 002˚54.544'	S19	0.10	0.18	0.00	0.09	0.51	0.00	0.11	0.10
Gyesewobre	N 06˚41.833' W 003˚04.105'	S2	0.09	0.28	0.03	0.27	0.30	0.00	0.03	0.30
Asuontaa	N 06˚32.556' W 002˚58.772'	S20	0.14	0.13	0.00	0.04	0.63	0.00	0.06	0.04
Kunkumso	N 06˚37.322' W 003˚03.671'	S21	0.02	0.27	0.32	0.13	0.24	0.00	0.02	0.45
Abosi	N 06˚32.461' W 003˚09.519'	S22	0.05	0.16	0.00	0.09	0.68	0.00	0.02	0.09
Koffie Abisim	N 06˚27.759' W 003˚10.905'	S23	0.03	0.06	0.25	0.14	0.50	0.00	0.02	0.39
Nafana	N 06˚25.317' W 003˚07.157'	S24	0.06	0.07	0.10	0.24	0.52	0.00	0.00	0.34
Kwamebikrom	N 06˚37.395' W 003˚07.510'	S25	0.10	0.14	0.00	0.15	0.56	0.00	0.05	0.15
Chimps Camp	N 06˚36.271' W 003˚05.862'	S26	0.02	0.11	0.48	0.09	0.28	0.00	0.02	0.58
Nana Kwasi	N 06˚36.948' W 003˚04.656'	S27	0.07	0.16	0.45	0.08	0.23	0.00	0.01	0.53
Debiso road	N 06˚38.642' W 003˚04.329'	S28	0.09	0.33	0.00	0.20	0.36	0.00	0.03	0.20
Debiso	N 06˚40.014' W 003˚05.348'	S29	0.22	0.18	0.00	0.09	0.26	0.00	0.25	0.09
Tanokrom	N 06˚43.070' W 003˚04.892'	S3	0.06	0.18	0.18	0.30	0.27	0.00	0.02	0.48
Bia Conservation Area	N 06˚36.571' W 003˚04.438'	S30	0.01	0.08	0.72	0.06	0.12	0.00	0.01	0.79
Bia Conservation Area	N 06˚36.326' W 003˚04.888'	S31	0.02	0.06	0.72	0.07	0.12	0.00	0.01	0.79

Bia Conservation Area	N 06˚35.569' W 003˚05.678'	S32	0.01	0.02	0.84	0.07	0.05	0.00	0.01	0.91
Bia Conservation Area	N 06˚34.784' W 003˚05.561'	S33	0.00	0.00	0.96	0.04	0.00	0.00	0.00	1.00
Bia Conservation Area	N 06˚32.121' W 003˚02.703'	S34	0.01	0.02	0.76	0.15	0.06	0.00	0.00	0.91
Bia North Forest Reserve	N 06˚39.339' W 003˚00.087'	S35	0.00	0.01	0.45	0.53	0.01	0.00	0.00	0.98
Bia North Forest Reserve	N 06˚43.412' W 003˚03.847'	S36	0.02	0.06	0.62	0.22	0.06	0.00	0.01	0.84
New Debiso road	N 06˚38.931' W 003˚04.424'	S37	0.12	0.29	0.00	0.19	0.36	0.00	0.03	0.19
New Debiso road	N 06˚38.905' W 003˚04.445'	S38	0.12	0.29	0.00	0.19	0.36	0.00	0.04	0.19
Corporal Nkwanta	N 06˚36.042' W 003˚06.297'	S39	0.02	0.11	0.47	0.11	0.28	0.00	0.02	0.57
Essam	N 06˚39.625' W 003˚06.982'	S4	0.17	0.18	0.00	0.13	0.37	0.00	0.15	0.13
Bia Conservation Area	N 06˚31.388' W 003˚06.980'	S40	0.01	0.06	0.61	0.18	0.14	0.00	0.00	0.79
Abosi	N 06˚31.956' W 003˚08.589'	S41	0.03	0.13	0.27	0.09	0.45	0.00	0.02	0.36
Teacherkrom	N 06˚29.401' W 003˚09.495'	S42	0.02	0.06	0.40	0.17	0.35	0.00	0.00	0.57
Nafana	N 06˚25.950' W 003˚09.397'	S43	0.04	0.03	0.39	0.21	0.32	0.00	0	0.6
Akaatiso junction	N 06˚25.351' W 003˚09.209'	S44	0.07	0.06	0.15	0.14	0.59	0.00	0.00	0.29
Bonsu Nkwanta	N 06˚22.654' W 003˚09.721'	S45	0.04	0.09	0.00	0.08	0.78	0.00	0.01	0.08

Yambediagro	N 06˚20.674' W 003˚01.069'	S46	0.05	0.10	0.27	0.21	0.36	0.00	0.02	0.47
Pokukrom	N 06˚18.803' W 002˚59.044'	S47	0.09	0.05	0	0.11	0.74	0.00	0.02	0.11
Bia Conservation Area	N 06˚22.104' W 002˚59.400'	S48	0.01	0.07	0.48	0.26	0.17	0.00	0.01	0.74
New Berekum	N 06˚37.741' W 003˚02.392'	S8	0.05	0.35	0.00	0.13	0.46	0.00	0.01	0.13
New Wenchi	N 06˚34.604' W 003˚08.415'	S6	0.03	0.19	0.02	0.08	0.65	0.00	0.02	0.10
Adjoafua	N 06˚35.503' W 003˚00.136'	S7	0.05	0.13	0.00	0.08	0.62	0.00	0.11	0.08
New Berekum	N 06˚37.765' W 003˚03.389'	S5	0.05	0.34	0.11	0.18	0.31	0.00	0.02	0.28
KBK	N 06˚38.037' W 003˚07.221'	S9	0.15	0.14	0.00	0.15	0.51	0.00	0.05	0.15

NF* = Natural Forest (calculated as the sum of open and closed forest)

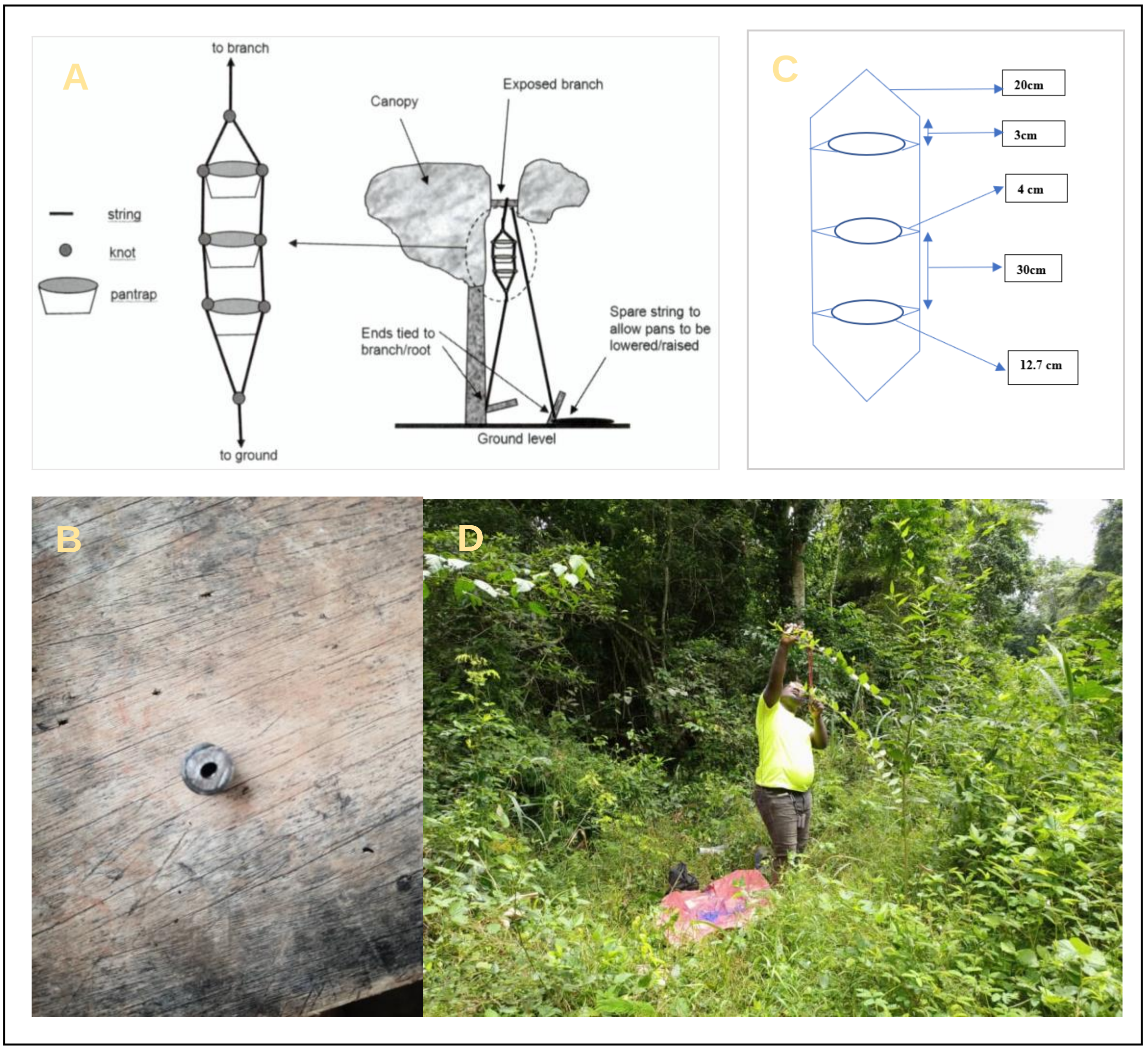

Fig S 2 A) The diagrammatic representation of how the aerial pan traps were guided into the tree canopies. We made a slight modification to the design of Nuttman et al. (2011)]. In our study, we used a metal frame/seat to construct the bowl seats as opposed to the recommended string for the seat (Nuttman et al., 2011). This provided a more stable seat for the bee bowls when raising them into the tree canopies; B) Metal projectile. A hole is drilled through the metal. The nylon fishing line is tied to it by passing it through the drilled hole. The projectile helps carry the nylon rope over the emergent tree branch; C) Dimensions for metal frame for aerial pan trap. The bowls used to make the pan traps were of 6" diameter at the tip, 5" deep and 4" at the base and D) Metal projectile being fired using a catapult into the tree canopies.

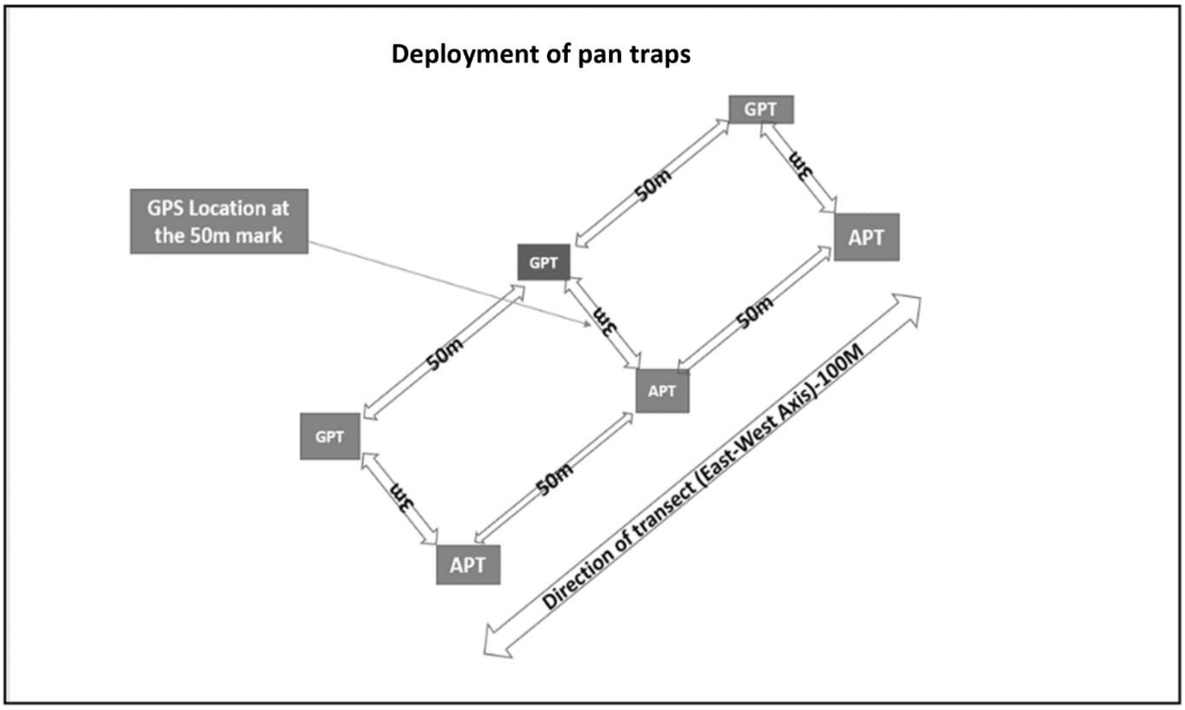

Fig S 3 The outlay of transects at study sites. A 100 m transect was placed at each selected study site along an East-West axis with the GPS coordinate of the site placed exactly at the 50m mark on the transect. 3 GPTs (Ground pan traps) and 3 APTs (Aerial pan traps) placed at were placed on the transect.

Fig S 4 Field and lab works: A) Collected specimens being sieved on the field; B) Alcohol being poured on the bottled specimen to preserve it during transport; C) Collected specimen in a bowl; D) Collected bees being separated and dry mounted for identification and F) Sorting of specimen at the Department of Conservation Biology at the University of Cape Coast into the different insect orders.

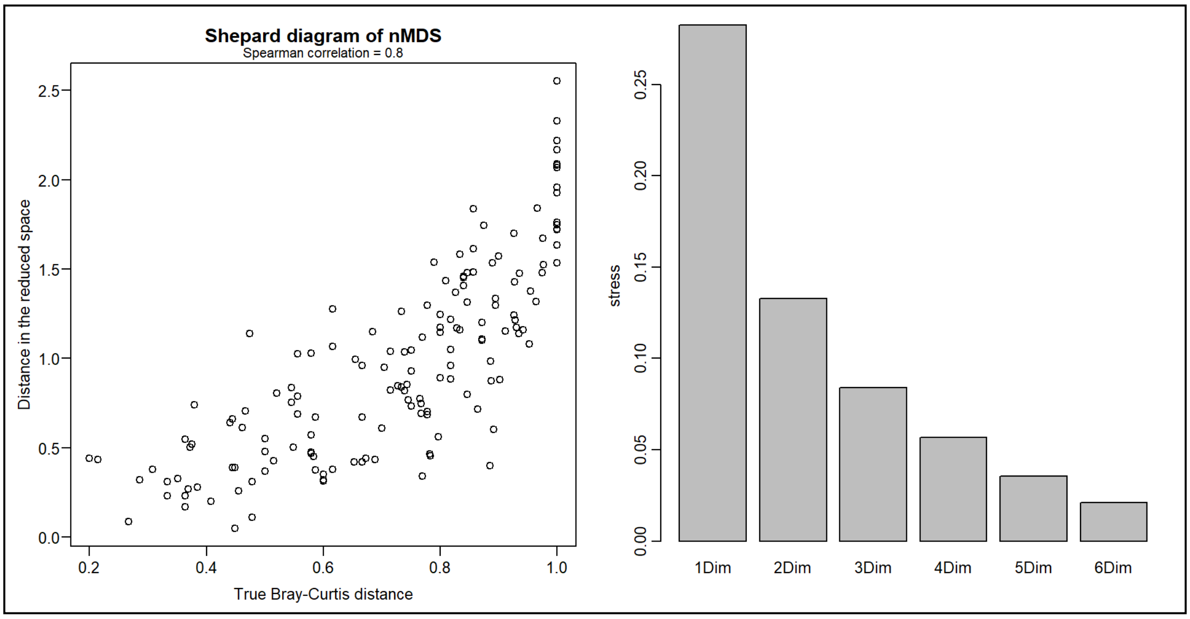

Fig S 5 Shepard Diagram evaluating the NMDS goodness-of-fit *of* the relationship between species composition and environmental variable. Left) Sheperd diagram showing the distances in the 2-dimension of the ordination of the original distance. Right) The Possible dimension of representation is based on the Bray-Curtis distance. The bars represent the total stress based on the stress of the solution of the dimension selected. A 2-dimension was applied in this study which achieved a good presentation of the community composition.

Lepidoptera

Variations were observed in the abundance of Lepidoptera between traps, with 138 individuals in APT and 128 in GPT. Out of the total abundance collected, 250 individuals were observed during the dry season, but only 16 individuals were recorded during the rainy season. The abundance of the Lepidoptera was not predicted by the forest (χ^2=3.42, df=1, p=0.06); the trap type (χ^2=0.38, df=1, p=0.54) or their interaction term. It must however be noted that pan trap is not a standard method for sampling Lepidoptera which are better sampled using malaise traps, light traps, pheromone traps, and netting among others (Freitas et al., 2021, Brehm and Axmacher, 2006). It was not surprising that the abundance of Lepidoptera was the lowest represented in our study using pan traps. The underrepresentation of Lepidoptera in our study aligns with observations by Vrdoljak and Samways (2012) and Csanády et al. (2021).

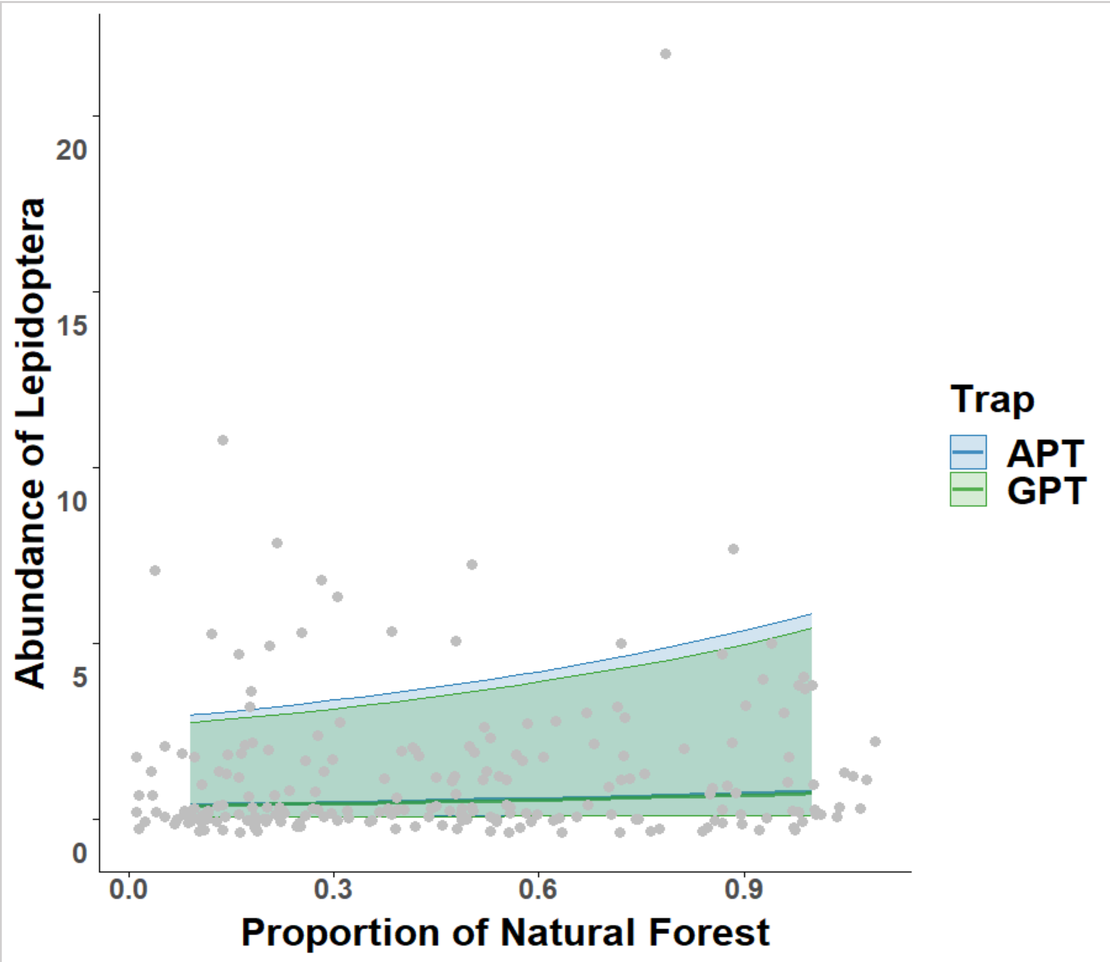

Fig S 6 The relationship between the abundance of Lepidoptera and the proportion of natural forests.

Table S 2 Dataset of the abundances of the different insect orders collected during field sampling.

This is the dataset generated during the study. It consists of the abundances of the different insect orders collected during field sampling. Also included are the abundances of the different bee species collected. Insect abundances are linked to study sites, trap or bowl colour used, the season and sampling rounds as well as the habitat types and geographic coordinates.

The datasets are available in the *Dataset_Boakye_et_al_2024* and can be accessed at the link below:

https://figshare.com/articles/dataset/Abundance_and_diversity_of_flower-visiting_insects_in_cocoa_and_forest_landscapes_in_Ghana/25476187

Table S 3 Abbreviations and full names of the total number of bee species identified in this study

Common Name	Family	Genus	Species	Abbreviations	Abundance per season		Abundance per trap		Total
					Dry	Rainy	APT	GPT	
Honeybees	Apidae	*Apis*	*Apis mellifera adansonii*	Apis	57	23	42	38	80
Stingless bees	Apidae	*Meliponula*	*Meliponula (Axestotrigona) ferruginea* (Lepeletier, 1836)	MeliF	34	3	20	17	17
			Meliponula bocandei (Spinola, 1853)	MeliB	2	0	1	1	2
	Apidae	*Hypotrigona*	*Hypotrigona gribodoi (Magretti, 1884)*	Hypo	2	0	1	1	2
	Apidae	*Dactylurina*	*Dactylurina staudingeri (*Gribodo, 1893)	Dacty	3	6	6	3	9
Solitary bees	Apidae	*Compsomelissa*	*Compsomelissa nigrinervis (*Cameron, 1905)	Comps	7	86	18	75	93
	Apidae	*Braunsapis*	*Braunsapis facialis* (Gerstaecker, 1858),	Brau	54	0	18	36	54
	Apidae	*Ceratina*	*Ceratina calcarata* Vachal (1903)	Cere	0	1	0	1	1
	Apidae	*Xylocopa*	*Xylocopa nigrita* (Fabricius, 1775),	Nigrita	12	7	10	9	19
	Apidae		*Xylocopa varipes* Smith (1854)	Varipes	1	1	1	1	2
	Apidae		*Xylocopa hottentotta Smith (*1854*)*	XyloH	1	0	0	1	1
	Apidae		*Xylocopa imitator* Smith (1854)	XyloIm	1	0	0	1	1
	Apidae		*Xylocopa flavonifa (*De Gees, 1778*)*	Dbees	0	1	1	0	1
	Apidae	*Amegilla*	*Amegilla albocaudata* (Dours, 1869*)*	Albo	9	0	5	4	9
	Apidae		*Amegilla nila* Eardley (1994)	Nilla	2	2	2	2	4
	Apidae		*Amegilla acraensis (*Fabricius, 1793*)*	Acrea	3	0	0	3	3
	Megachilidae	*Lithurgus*	*Lithurgus pullatus* (Vachal, 1903)	Lith	3	0	3	0	3
	Halictidae	*Halictus*	*Halictus jucundus* Smith 1853	Hali	3	0	1	2	3
	Halictidae	*Lipotriches*	*Lipotriches cirrita (*Vachal, 1903)	Cribo	0	2	1	1	2
	Halictidae		*Lipotriches orientalis* (Friese, 1909)	Lipsp	2	0	2	0	2
	Halictidae	*Pseudapis*	*Pseudapis squamata* (Morawitz, 1895)	Pseu	1	0	1	0	1
	Halictidae	*Lasioglossum*	*Lasioglossum duponti* (Vachal, 1903)	Lasio	0	1	1	0	1
	Halictidae	*Nomia*	*Nomia bouyssoui* Vachal (1903)	Nom	2	0	1	1	2

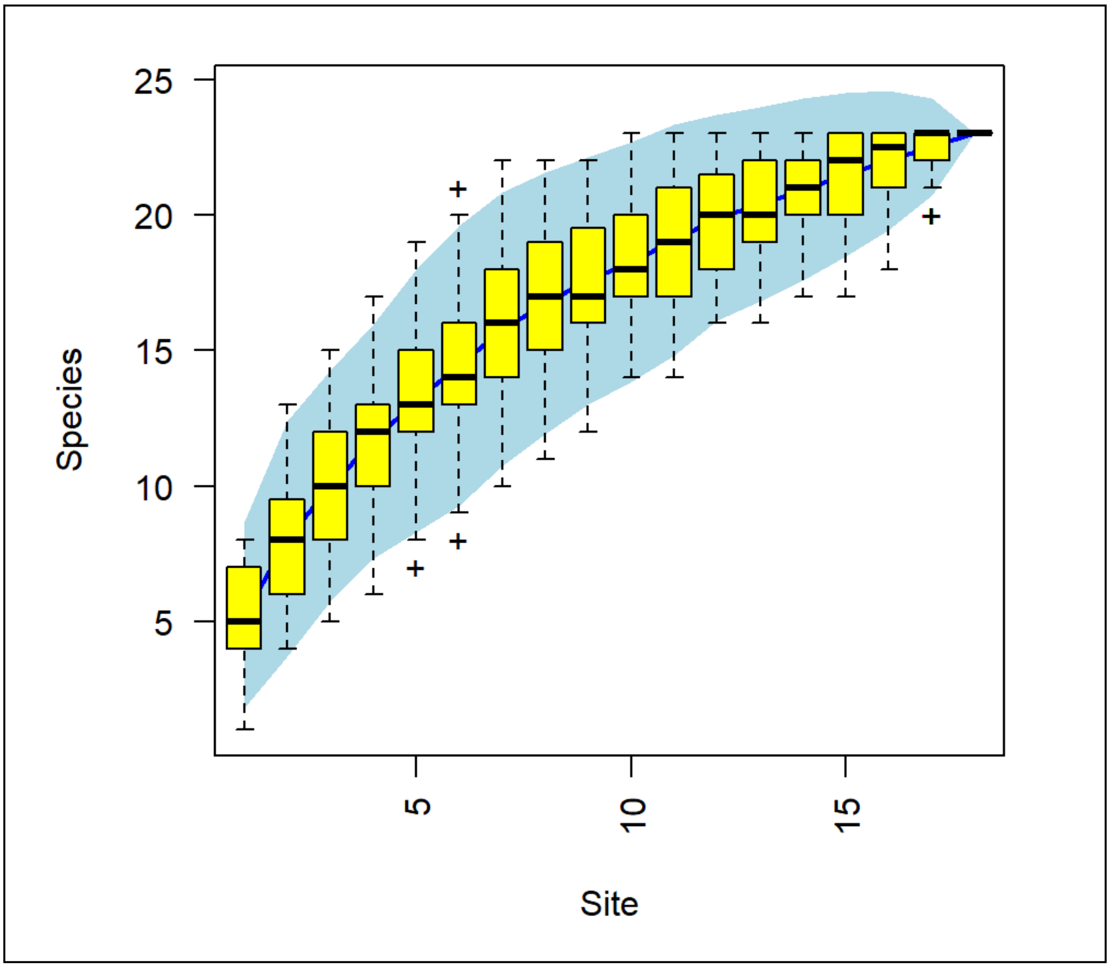

Fig S 7 A randomized species accumulation curve, showing the cumulative number of species observed across the entire study area. The curve reflects the increasing count of unique species as sampling efforts intensify. The boxplots represent the distribution and variability in species richness at each sampling site. The yellow boxes and blue borders showcase the interquartile range, while the horizontal lines within the boxes signify the median species count.

Fig S 8 Samples of bee species identified. A) *Ceratina calcarata* B) *Xylocopa flavonifa (De Bees),* the first time to have been identified in tropical evergreen forest in the southern part of Ghana; C) *Dactylurina staudingeri; D) Lipotriches cirrita of the* Halictidae family; E) *Meliponula ferruginea* of the Apidae family and F) *Xylocopa nigrita* of the Apidae family

Reference

BREHM, G. & AXMACHER, J. C. 2006. A comparison of manual and automatic moth sampling methods (Lepidoptera: Arctiidae, Geometridae) in a rain forest in Costa Rica. *Environmental Entomology,* 35**,** 757-764.

CSANÁDY, A., OBOŇA, J., ZAPLETALOVÁ, L., PANIGAJ, Ľ., DOJČAKOVÁ, D. & ZÁLETA, B. 2021. Hymenopteran colour preference using multiple colours of pan traps in Slovakia. *Acta Musei Silesiae. Scientiae Naturales,* 70**,** 33-46.

FREITAS, A. V., SANTOS, J. P., ROSA, A. H., ISERHARD, C. A., RICHTER, A., SIEWERT, R. R., GUERATTO, P. E., CARREIRA, J. Y. & LOURENÇO, G. M. 2021. Sampling methods for butterflies (Lepidoptera). *Measuring arthropod biodiversity: a handbook of sampling methods***,** 101-123.

NUTTMAN, C. V., OTIENO, M., KWAPONG, P. K., COMBEY, R., WILLMER, P. & POTTS, S. G. 2011. The utility of aerial pan-trapping for assessing insect pollinators across vertical strata. *Journal of the Kansas Entomological Society,* 84**,** 260-270.

VRDOLJAK, S. M. & SAMWAYS, M. J. 2012. Optimising coloured pan traps to survey flower visiting insects. *Journal of Insect Conservation,* 16**,** 345-354.