Shelter Belt Trees for Cacao Pollination

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Introduction

Cacao (*Theobroma cacao*) is an economically viable crop in Hawaii. In the artisanal chocolate market, Hawaiian cacao beans are among the most sought-after due to its rare flavor profiles (Heaton, 2021). This special flavor allows Hawaii-grown cacao to be priced 2 to 4 times greater than other cacao traded in the world, creating a profitable entrepreneur's opportunity (HDOA, 2009). As agriculture in Hawaii transitions from intensive plantation practice of pineapple and sugarcane into diversified agriculture, interest in cacao farming began in 1990s, starting from the 20 acres of cacao planted in Dole Plantation in 1996 (Lydgate Farms, 2023). Cacao is a unique agroforestry crop whose productivity is integrally linked to soil health, water retention properties, and canopy cover of the immediate farm. The traditional Cabruca production system (cultivating cacao trees under a native forest canopy) holistically links these aspects together (Leal, 2018). However, the Cabruca production system of cacao production is impractical in Hawaii, where cacao is planted into former plantation lands that has been heavily deforested. On the bright side, many cacao farmers in Hawaii are already aware of the importance of planting shelterbelt trees which are non-cash crop trees either planted intermittently or on the border of a cacao orchard as windbreaks or as shelters to enhance wildlife habitats. This project evaluates the benefits of different shelterbelt trees on cacao fruit set, pollination rates or pollinator health in Hawaii.

Cacao pollen is self-incompatible, meaning cacao needs cross pollination to set fruits. Only insects smaller than 2-3 mm can enter the small space inside the hoods and the staminode cage of the flowers to access pollen (Groeneveld et al., 2010, Fig 1). Groeneveld et al. (2010) further reported that cacao yield can be doubled through manual pollination. Several species of Forcipomyia midges (Diptera: Ceratopogonidae) are known to be pollinators of cacao (Young, 1982). O'Doherty and Zoll (2012) found an endemic midge, *Forcipomyia hardyi,* present in abundance in cacao orchards in Hawaii and plays a role in pollinating cacao flowers. High field densities of this pollinator might explain the high pollination rate and subsequently high cacao yields in Hawaii.

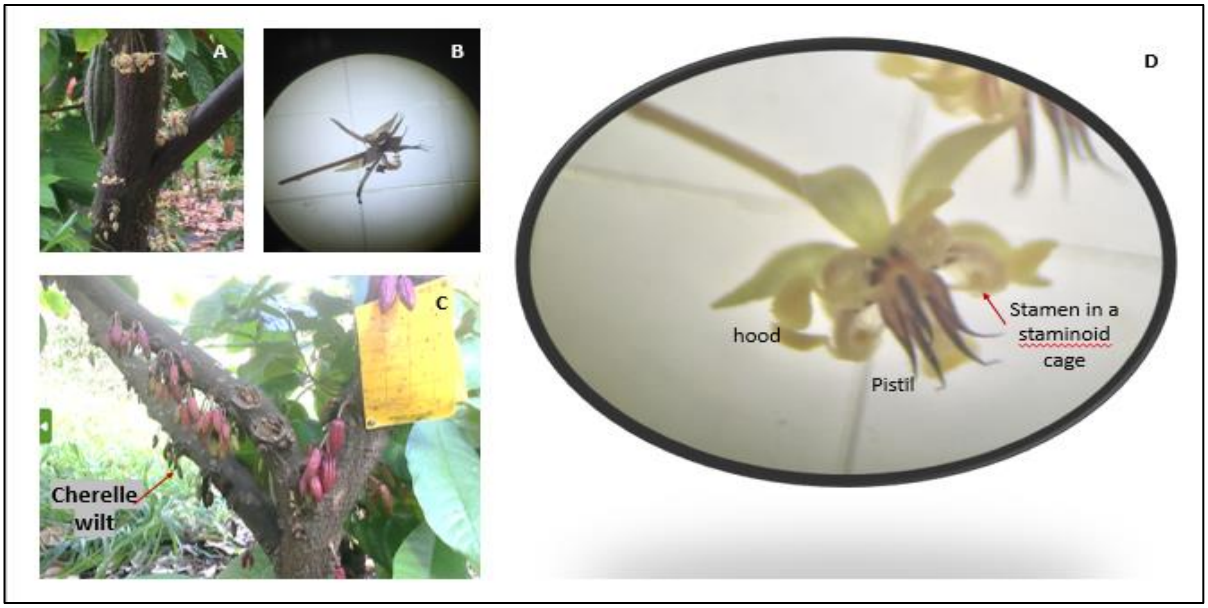

Fig. 1. A) Cacao flowers on the trunk of a cacao tree, B) each flower is small (1cm^2 grid); c) set young fruits on cacao tree. Some fruits are aborted and not fully ripen (Cherelle wilt); D) Close up view of a cacao flower with pistil and stamen in staminoid cages protected by a hood.

Although shelterbelt trees sometimes are planted as windbreaks to protect cacao from wind damage in areas receiving sea breezes, they may also enhance pollinator health and improving fruit set. Specific objectives of this study were to 1) provide insights on if specific shelterbelt trees could enhance cacao pollination and increase the endemic cacao pollinators, 2) determine the season in which *Forcipomyia hardyi* is most active, and 3) determine other factors that potentially affect the pollination rates of cacao in Hawaii.

Materials and Methods

Nine field surveys were conducted over 3 growing seasons in 2022 (as shown in Table 1) across 5 farms to evaluate the effects of shelterbelt trees on cacao. This study was based on existing shelterbelt trees established on these farms with different ages of cacao trees.

Table 1. Shelterbelt trees present in cacao farms visited at three seasons in 2023 on Oahu.

Farm	Spring (April 22)	Summer (July 22)	Winter (Dec 22)
Dole Waialua Estate	Gliricidia, neem, banana, mahogany	Gliricidia, neem, banana, mahogany	Gliricidia, neem, banana, mahogany
GoFarm Waialua	-	Gliricidia + neem	-
GoFarm Waimanalo	-	Gliricidia, hale koa, mango	Gliricidia, hale koa, mango
Kahuku Farm	Ironwood	-	-
Three-Acre Farm	Panax	Panax	-

- Indicates no data collected.

During each visit, 4 cacao plants in close proximity (< 20 ft) to a shelterbelt tree (Table 1) were tagged with a 10×15cm^2 yellow sticky card (Fig. 1C). Total number of flowers (Fig. 1A), Cherelle fruits and successful fruit set (Fig. 1B) on each tree that was tagged were counted. Knowing that cacao peak harvest season is in March to early April, we avoid taking data during this time, to reduce fruit counts interfere by fruit removal for harvesting purpose. The purpose of recording the percentage of fruit set was to document the successful pollination rate that led to development of healthy fruits. Thus, the fruit set data was referring to fruits that were fertilized, without showing Cherelle wilt symptoms, and can vary in size from 1- to 4-cm diameter but were not ready for harvest. One week later, the yellow sticky cards were collected, wrapped in Saran wrap, and brought back to the laboratory to count the number of midges under a dissecting microscope. The % fruit set and % pollinated fruits per tree were calculated as:

% fruit set = no. healthy fruits/(no. flowers + no. healthy fruits + no Cherelle fruits)

% pollinated = (no. healthy fruits + no Cherelle fruits)/(no. flowers + no. healthy fruits + no Cherelle fruits)

Data were square-root transformed to normalize the data distribution prior to statistical analysis. Since not all farm sites planted all the shelterbelt tree tested, number of data for each shelterbelt tree varied. To increase the number of shelterbelt trees examined, new farm sites were added in the later season. Hence, the number of season observations also varied. None-the-less, all data collected were polled together and subjected to 2-way analysis of variance (ANOVA) (shelterbelt tree × season) nested by farm site using PROG GLM in SAS 9.4 (SAS Inc., Cory, NC). However, means from each main factor were presented, and separated by Waller-Duncan *k*-ratio (*k*=100) *t*-test wherever appropriate. When significant interaction among shelterbelt tree, season and farm site occurred, ANOVA was performed by farm (Dole and GoFarm Waimanalo that had more than one type of shelterbelt trees tested). To examine if abundance of midges contributed to % fruit set and % pollinated, these three parameters were further subjected to correlation analysis in SAS using PROC CORR.

Results and Discussion

Table 2. Analysis of variance of % fruit set, % pollinated and number of midges/card affected by shelterbelt trees, season and farm sites of cacao.

		P value		
	df	% fruit set	% pollinated	No. midges/card^z
Shelterbelt tree	8	0.003	<0.001	< 0.001
Season	2	< 0.001	0.236	< 0.001
Shelterbelt ×Season	5	0.076	0.205	0.001
Farm	1	0.013	0.862	0.015
Shelterbelt×Season ×Farm	1	<0.001	0.306	<0.001

df = degree of freedom.

When combining all the data of % fruit set, % pollinated and number of midges/card, shelterbelt tree affected all the parameters ($P \leq 0.05$). In addition, % fruit set and number of midges/card were also affected by season and farm site, with significant interaction among Shelterbelt × Season × Farm ($P \leq 0.05$). Significant interaction also occurred between shelterbelt tree × Season ($P < 0.001$; Table 2). Means from each main factors were presented in Table 3. Since significant 3-way interaction occurred ($P \leq 0.05$) for % fruit set and number of midges/card, these parameters were further analyzed by farm site. Only farms that showed significant effects of season or shelterbelt tree were presented in Tables 4 and 5.

Table 3. Effect of shelterbelt trees on cacao fruit set (%), pollinated fruits (%) and number of midges monitored on yellow sticky cards by 3 seasons on five farms on Oahu in 2022.

	N	% Fruit set		% pollinated		No. midges/card[z]	
<u>season</u>							
Spring (Apr)	24	13.04	b	80.99	a	0	c
Summer (Jul-Aug)	24	12.04	b	70.06	a	3	b
Winter (Dec)	16	45.90	a	77.47	a	143	a
<u>Shelterbelt tree</u>							
Banana	4	10.65	ABCD	90.12	A	0	D
Gliricidia	16	26.99	ABC	79.38	A	48	B
Hale koa	8	35.39	A	94.93	A	152	A
Ironwood	4	6.75	CD	75.88	A	0	D
Mahagony	4	7.72	D	82.07	A	0	D
Mango	4	32.72	AB	70.59	AB	26	B
Neem	12	15.12	BCD	85.89	A	21	BC
Neem + Gliricidia[y]	4	7.50	D	50.00	C	3	BC
Panex	8	22.31	ABC	41.26	BC	1	CD
<u>Farm</u>							
Dole	32	15.99	bc'	83.81	a'	30	b'
GF[x] Waialua	4	7.50	d'	50.00	b'	3	b'
GF Waimanalo	16	36.82	a'	84.34	a'	87	a'
Kahuku Farm	4	6.75	cd'	75.88	a'	0	b'
3-Acre Farm	8	22.31	ab'	41.26	ab'	1	b'

[z] card = yellow sticky card (10 × 15 cm^2).

[y] Neem + gliricidia samples were placed in proximity to both types of shelterbelt trees not necessarily close to neem and gliricidia but in a field plot with both trees interplanted with cacao trees.

[x] GF = GoFarm Hawaii sites

Means (average of N samples) in a column followed by the same letter for each main factor are not different according to the Waller-Duncan *k*-ration (*k*=100) *t*-test.

Seasonal effect: Although, % of flowers pollinated did not differ among seasons (all seasons had higher than 70% flowers pollinated), the % of cacao fruit set per tree and number of midges counted per card on each tree observed were highest during the winter ($P \leq 0.05$; Table 3). Less than a third of the fruits were set in the summer or spring compared to that in the winter (Table 3). The percentage of fruit set in the winter was expected to develop fully for the peak cacao harvesting season in March and April in Hawaii. This average of 45.9% in the winter in Hawaii was considered very high compared to average of ≤ 10% in other parts of the world (Groeneveld et al., 2010). On the other hand, % flowers pollinated was not affected by season (Table 3). The high count of biting midges (143/card) was only detected in the winter, with an average of only 3 in the summer and none in the spring (Table 3).

When analyzed the data by farm site, no significant interaction ($P > 0.05$) between season and shelterbelt tree occurred in all the farms except for Waimanalo. At Waimanalo, % fruit set was increased by planting of gliricidia as shelterbelt trees in the summer but not in the winter (Table 4) as % fruit set in the winter were already high regardless of which shelterbelt trees were planted (Table 4).

Seasonal effect on number of midges/card at Waimanalo was also affected by shelterbelt tree planted (Table 4). During the summer, planting of gliricidia or hale koa both increased abundance of midges compared to planting mango, but during the winter, only hale koa shelterbelt trees further increased abundance of midges compared to mango and gliricidia (Table 4). These data supported the hypothesis that certain shelterbelt trees could enhance the seasonality of cacao fruit set as well as pollinator abundance.

Table 4. Effect of shelterbelt trees on cacao fruit set and number of midges on yellow sticky cards at Waimanalo in 2022.

	N	% Fruit set		No midges/card	
Summer (Jul-Aug)					
Gliricidia	2	64.43	a	5	a
Hale koa	4	6.21	b	7	a
Mango	2	11.90	b	2	b
Winter (Dec)					
Gliricidia	4	23.14	A	32	B
Hale koa	8	64.57	A	297	A
Mango	4	53.53	A	51	B

Means (N) in a column followed by the same letter for each season are not different according to Waller-Duncan *k*-ration (*k*=100) *t*-test.

Shelterbelt effect: Across all seasons and farms, hale koa followed by gliricidia and mango supported the highest number of biting midges among the shelterbelt examined (Table 3). These 3 shelterbelt trees also supported the highest % fruit set, significantly better than ironwood and mahogany (the latter two were considered as not ideal shelterbelt for cacao pollination) ($P \leq 0.05$). Banana, neem and panax were considered intermediate shelterbelt for cacao pollination as they were either not supportive of cacao fruit set or midges. Contradictorily, GF Waialua farm that grew both gliricidia and neem together close to a small patch of cacao performed poorer than either of these trees planted a part. This farm could be an outlier due to lack of maintenance of the cacao plot with weeds overgrown.

Similar to the seasonal effect, % flowers pollinated were not different among most of the shelterbelt trees examined except for lower in neem+gliricidia and panax shelterbelt treatments than most other shelterbelt treatments (Table 3). The neem+gliricidia site had weeds overgrown, whereas the panax site was a young cacao orchard (3-year-old) with little accumulation of leaf litter which is thought to be favorable habitat or midges to lay eggs (Vandromme et al., 2023). Our correlation analysis also revealed significant correlation between number of midges/card and % fruit set (r = 0.59, P < 0.0001) but not with % pollinated. These data suggested that shelterbelt planting mostly affected the abundance of midges in the cacao fields, and the visit of midges to cacao flowers affected the success of cacao fruit set rather than % of flowers pollinated. This result is consistent with that reported by Young (1982) that the cacao fruit set was higher where the number of midges was increased. While monitoring insects on the yellow sticky cards, other insects commonly found included ants (Formicidae, Hymenoptera), mosquitoes (Culicidae, Diptera), cockroaches (Blattodea, Blattoda), and Erotylidae (coleoptera). These other insect visits might have contributed to pollination though they might not be efficient pollinators of cacao.

Effects of shelterbelt trees by farm: Since we did not have same shelterbelt trees tested in all the farms surveyed as these trees were previously installed by the farm managers, we analyzed performance of shelterbelt trees at GoFarm Waimanalo and Dole Waialua Estate individually. These were the only two farms we studied that had data from different shelterbelt trees.

At the GoFarm Waimanalo site, significant interaction between season and shelterbelt were detected for % fruit set and midges/cards ($P \leq 0.01$). When the effect of shelterbelt was analyzed by season (Table 4), gliricidia had higher % fruit set than hale koa and mango (P = 0.01), but mango had higher counts of midges than hale koa and gliricidia (P = 0.02) during the summer. However, in the winter, shelterbelt trees did not affect cacao fruit set, but hale koa resulted significantly higher (P= 0.02) counts of midges on cacao, approximately 6 times more midges than the second highest count observed in mango. At the hale koa site, a thick stand of hale koa forest was surrounding the cacao plot, providing a "Cabruca" effect on the cacao, probably led to the high count of midges. Unexpected lower performance of gliricidia in the winter at GF Waimanalo could be due to the unexpected tree trimming of gliricidia by the farm manager.

Some suggested that having cacao pod husks, cacao leaf litter, bromeliad plants or banana cut stumps around could accumulate water puddles and thus provide breeding sites for midges (CACPOL, 2023). However, Young (1982) did not see the benefits of these niches increasing the population of cacao midges when he artificially installed cocoa pod husks, cocoa leaves, bromeliad, or banana cut stumps into two cacao fields. Similarly, at the Dole Waialua Estate, banana or mahogany did not improve cacao fruit set and attracted no midges (Table 5). It could be because banana and mahogany were planted on the border (Fig. 2A, C) instead of intercropping with the cacao at Dole Waialua Estate, even though we only monitored cacao trees < 20 ft away from the shelterbelt trees. On the other hand, cacao planted close to gliricidia, and neem (Fig. 2B, D) had numerically higher % fruit set and significantly higher biting midges than those close to banana and mahogany (Table 5). These shelterbelt effects were not different among seasons (Table 5).

Fig. 2. A) Banana at the border, B) gliricidia planted intermittently within cacao, C) mahogany planted at the border, and D) neem trees established at the border of cacao fields at Dole.

Table 5. Effect of shelterbelt trees on cacao fruit set (%), pollinated fruits (%) and number of midges monitored on yellow sticky card over 3 seasons at Dole Waialua Estate in 2022.

	N	% Fruit set		% Pollinated		No midges/card	
Season							
Spring (Apr)	16	10.97	b	87.66	a	0	b
Summer (Jul-Aug	8	1.68	c	87.43	a	1	b
Winter (Dec)	8	40.36	a	72.49	a	117	a
Shelterbelt							
Banana	4	10.65	A	90.12	A	0	B
Gliricidia	12	21.40	A	80.20	A	58	A
Mahogany	4	7.72	A	82.07	A	0	B
Neem	12	15.12	A	85.89	A	21	A

Other factors could also affect the abundance of midges besides the direct effect of shelterbelt trees. For example, low counts of midges at Three-Acre Farm with panax as shelterbelt could be due to young cacao trees that did not accumulate sufficient leaf litter to support a breeding site for the biting midges (Fig. 3A). On the other hand, Dole Waialua Estate with cacao planted 10-20 years ago, accumulated a thick thatch of cacao leaf litter (Fig. 3B) would have a better breeding ground for the biting midges. Although Kahuku Farm established their cacao 10 years ago, windy conditions during the spring resulted in minimal leaf litter on the ground (Fig. 3C). In addition, the shelterbelt of ironwood at Kahuku Farm was only planted on one side of the orchard and did not provide sufficient shade cover to support the midges, with 0 midges detected during the spring of 2023.

Fig. 3. A) Lack of cacao leaf litters in a young cacao orchard compared to B) a thick thatch of cacao leaf letters in an old established cacao orchard; C) lack of shading provided by ironwood as shelterbelt and D) windy conditions at Kahuku Farm that led to minimal cacao leaf litters on the ground.

Summary

Although this study had a short fall of not having all the shelterbelt trees examined at each study site and at each season, the results of this study provided some insights on cacao pollination in Hawaii: 1) Biting midges were most abundant and active in the winter; 2) Tall or thick stands of hale koa and gliricidia were most attractive to draw biting midges to cacao plants; 3) Mango can also be effective shelterbelt tree to attract biting midges in the winter but not in the summer; 4) Mango, hale koa, gliricidia, panax and banana were all equivalent in enhancing cacao fruit set compared to ironwood and mahogany when combining the data across the seasons; 5) distance of the shelterbelt trees planted in proximity to cacao, cacao leaf litter thatch, and shade cover provided by the shelterbelt trees could all affect the performance of specific shelterbelt trees in terms of enhancing cacao fruit set and pollinator abundance; 6) abundance of midges was positively correlated to % cacao fruit set. Future work should examine the same shelterbelt trees across all seasons and locations.

References

CACPOL. 2023. Cacao pollination. https://cacaopollination.com/publications/ (last accessed Dec 23, 2023).

Groeneveld, J., T. Tscharntke, G. Moser, and Y. Clough. 2010. Experimental evidence for stronger cacao yield limitation by pollination than by plant resources. Perspectives in Plant Ecology, Evolution and Systematics 1: 183-191. https://doi.org/10.1016/j.ppees.2010.02.005.

Heaton, T. 2021. There's a lot more to Hawaii's cacao industry than making chocolate. Honolulu Civil Beat December 10, 2021 (https://www.civilbeat.org/2021/12/the-key-to-hawaiis-cacao-industry-is-not-just-chocolate/).

HDOA. 2009. A report to expedite the production and delivery of Hawaii cacao to the marketplace. A Report to the Twenty-Fifth Legislature regular session of 2010 State of Hawaii.

Leal, G. 2018. Revitalizing Southern Bahia with Cabruca, cocoa, and chocolate. (https://www.worldcocoafoundation.org/blog/revitalizing-southern-bahia-with-cabruca-cocoa-and-chocolate/).

Lydgate Farms, 2023. The history and origin of Hawaiian chocolate. (https://lydgatefarms.com/the-history-and-origin-of-hawaiian-chocolate/).

Vandromme, M., van de Sande, E., Pinceel, T., Vanhove, W., Trekels, H., and Vanschoenwinkel, B. 2023. Resolving the identity and breeding habitats of cryptic dipteran cacao flower visitors in a neotropical cacao agroforestry system. Basic and Applied Ecology, 68. SCI: 3.8).

Young, A.M. 1982. Effects of shade cover and availability of midge breeding sites on pollinating midge populations and fruit set in two cacao farms. Journal of Applied Ecology 19: 47-63.

Acknowledgement

This project is supported by HDOA SCBG FY2020 Project 4, NRCS CIG (NR233A750011 G011), CTAHR Hatch, Multistate (NE2140) and Plan of Work (HAW9048-H, 9034-R and POW 16-964). We would also like to thank Lauren Braley and Justin Mew for technical assistance. Mahalo to Dole, GoFarm Hawaii, Kahuku Farm, and Three-Acre Farm for allowing us to study at their farms.

NRCS

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