Asia Pacific Journal of Sustainable Agriculture Food and Energy (APJSAFE)

Biological Studies on the Natural Enemies in Suppression of Coconut Stick Insect, *Graeffea crouanii* (Le Guillou) in Fiji

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Abstract — Coconut stick insect, *Graeffea crouanii* (Le Guillou) is one of the important pests of coconut palms in Fiji. It causes extensive leaf damage resulting in production losses. The field surveys revealed the presence of several naturally-occurring natural enemies (predators and parasitoids) on *G. crouanii* in the major coconut growing regions in the Fiji Islands *viz.*, Viti Levu, Vanua Levu and Taveuni. Two species of egg parasitoids, *Paranastatus verticalis* Eady and *Paranastatus nigriscutellatus* Eady were recorded as the most prevalent natural enemies, of which *P. verticalis* was the dominant species. This paper presents information from field and laboratory studies on the pest and dominant natural enemy and role of *P. verticalis* on the population suppression of *G. crouanii* in Fiji. The release of *P. verticalis* and field sanitation were the two best management practices identified that contributed to the improvement of plant health toward the management of *G. crouanii*.

***Keywords* — *Cocos nucifera* L., Coconut stick insect pest, *Graeffea crouanii*, natural enemies, *Paranastatus verticalis*, Fiji**.

INTRODUCTION

Coconut palm, *Cocos nucifera* L., is widely regarded as "The Tree of Life" due to the use of all its parts in supporting livelihood supporting in the South Pacific. The coconut palms provide environment services, support food security and livelihood of most people in the South Pacific region. Besides, the food, nutrition, and income securities, *C. nucifera* is also considered as more important component for the tourism industry in the South Pacific Islands Countries and Territories (Luigi, 2005). In Fiji, the coconut palm is one of the most economically important crops occupying the coastal areas supporting livelihood in terms of providing food, fuel and shelter, and adding value to the tourism industry by way of beautifying the beaches. Coconuts and copra (the dried meat of the coconut) are important agricultural products that are widely used and exported from Fiji.

The coconut plantations are affected by various categories of plant pests in different growing regions, and a few of them are fatal to the palms. Child (1974) has reported 751 species of insects as pests of coconuts around the world. In Fiji, the coconut stick insect, *Graeffea crouanii* (Le Guillou) is one of the principal insect pests causing severe losses to the coconut industry (Deesh *et al*. 2020). They cause severe defoliation resulting in crop losses, and even death of trees. Knowledge on the natural enemies is of paramount importance towards

the development of ecologically sustainable integrated pest management approach against this chronic pest in coconut plantations.

This paper provides information from the field and laboratory studies on the diversity of the naturally-occurring natural enemies, their spatial and temporal population dynamics, biology and role of the dominant egg parasitoid, *Paranastatus verticalis* Eady, on the population suppression of *G. crouanii* in Fiji. It also provides guidance on the practical integration of IPM options against *G. crouanii* for smallholders.

MATERIALS AND METHODS

Field Survey of Natural Enemies

Field surveys for natural enemies of the coconut stick insect, *Graeffea crouanii* (Le Guillou) were carried out in the major coconut growing areas of three main islands of Fiji group *viz*., Viti Levu, Vanua Levu and Taveuni (**Figure 1**). The survey was confined to the wet zones of the major coconut plantations since preliminary studies between 2009 -2012 on pest status showed that the pest was localized mostly in wet areas compared to dry zone, where the incidence was lower (Deesh *et al*., 2013). The geo-positional coordinates of the surveyed area lay between 17.4057(S), 178.2454(E) & 18.1641(S), 177.4559(E) for Viti Levu; 16.8595(S), 178.8621(E) & 16.6284(S), 179.8677(E) for Vanua Levu; and 16.8115(S), 179.8650(E) & 16.9925(S), 180.4717(E) for Taveuni (Deesh, 2018).

Laboratory Evaluation of Natural Enemies

Observations on natural enemies made during the field surveys were further tested in the laboratory conditions to ascertain the stages of *G. crouanii* that were vulnerable to natural enemies. The freshly laid eggs, nymphs and adults of *G. crouanii* were exposed to these different natural enemies identified and collected during field samplings in Vanua Levu (Dawara), Viti Levu (Namaumada), and Taveuni (Salialevu), Fiji (**Figure 2**). This was undertaken to determine the most dominant and effective indigenous natural enemies of the *G. crouanii*. The collected specimens of *G. crouanii* and mass reared egg parasitoids were preserved in 70% ethanol for geometric analysis and species identification. The species determination was conducted by the Unitec Institute of Technology, New Zealand.

Egg Parasitoids and their Population Dynamics

To study the parasitism level in field, five coconut palms were randomly selected at each of the hotspots for the sampling of *G. crouanii* eggs. In this sampling technique, the litter was collected from palm crown (area between the axial of the coconut leaves) and base area (around the palm base) to understand the spatial and temporal population dynamics of egg parasitoids in the fields. The eggs of *G. crouanii* were separated from the debris and kept in labeled Petri dishes. These eggs were observed at the laboratory and kept at room temperature ranging

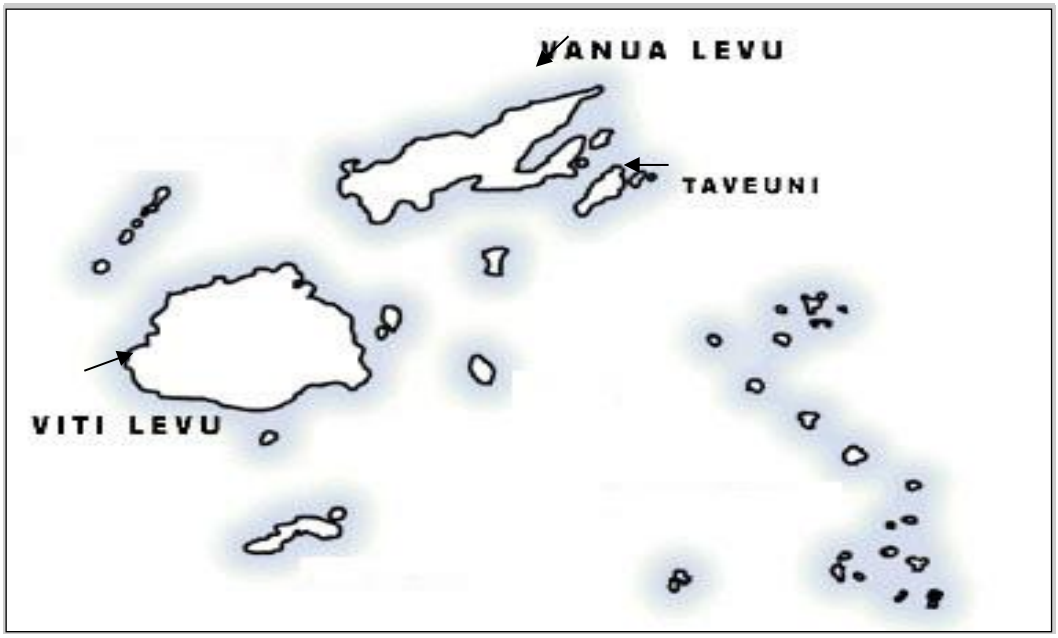

Figure 1. Location of the field surveys sites for the coconut stick insect, *G. crouanii* and its natural enemies in Fiji (Viti Levu, Vanua Levu and Taveuni). (Source: Polynesian Cultural Centre, www.polynesia.com).

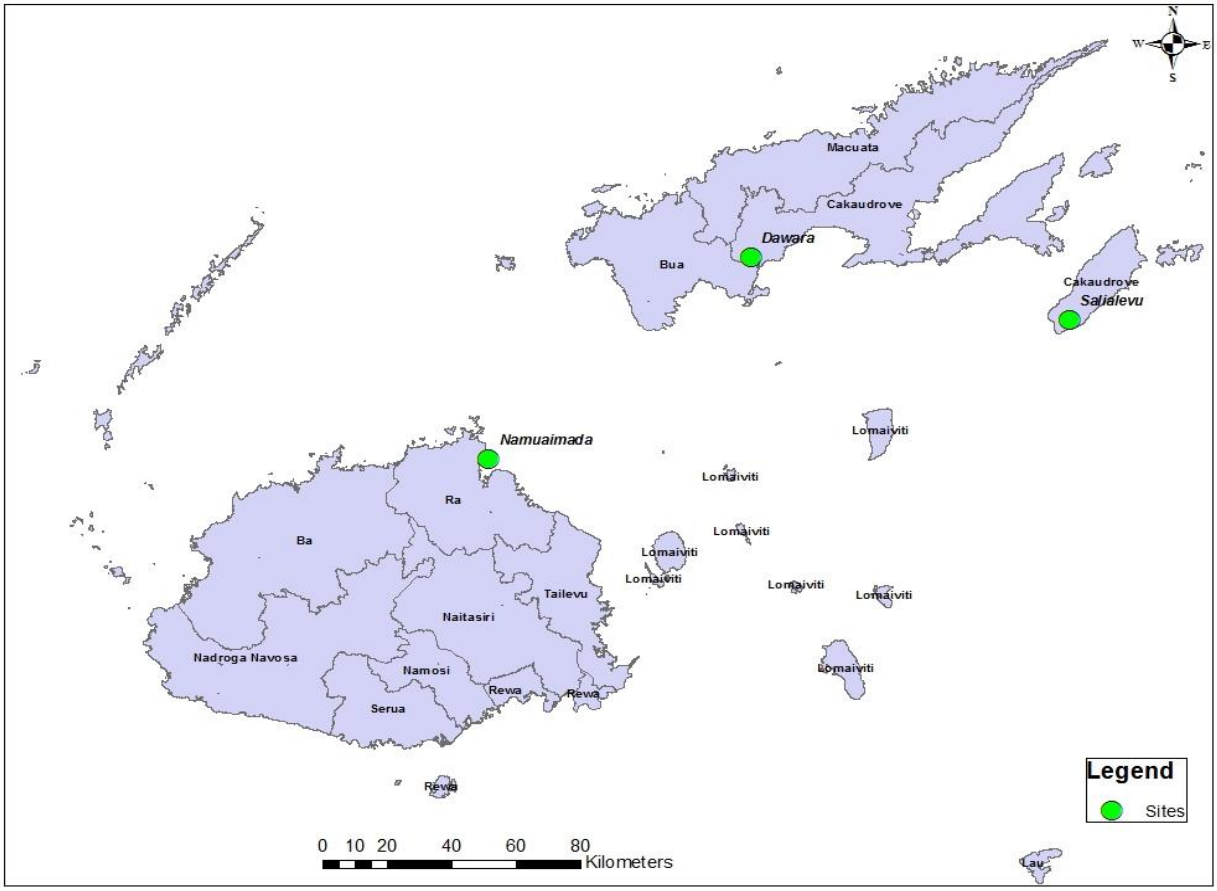

Figure 2. Location of the sampling sites (hotspots) for the coconut stick insect, *G. crouanii* natural enemies in Vanua Levu (Dawara), Viti Levu (Namaumada) and Taveuni (Salialevu), Fiji.

The parasitoids that emerged were used for identification and detailed life-table studies. The significant difference in the average percentage parasitism found in *G. crouanii* eggs retrieved from palm crown and around base area were analyzed

using the Independent Two-sample *t*-test in SPSS (Allen and Kellie, 2010).

Biology of the Egg Parasitoids on G. crouanii

Elucidating the biology of *G. crouanii* is crucial for evaluating the efficacy of the natural enemies under laboratory conditions. Various conditions of culturing *G. crouanii* was undertaken and the observations made on the biology of *G. crouanii* reared in the laboratory conditions are in conformation with O'Connor *et al.* (1954). Detailed biological studies were carried out in the laboratory on the egg parasitoids, *Paranastatus* spp. using the host eggs of *G. crouanii*. The emergence periodicity, oviposition and longevity of *Paranastatus* spp. were observed over a period of
one year using the eggs of *G. crouanii* reared in the cages, and eggs collected from the fields.

After 48 hours of exposure of fresh eggs of *G. crouanii* to *Paranastatus* spp., the eggs were isolated from each other. The eggs were kept in individually labelled Petri dishes to determine the incubation time for parasitoids, number of adult parasitoids emerged per egg and their sex ratio. This was conducted to investigate if there were any patterns of periodicity in adult emergence as well as patterns in the sex ratio of the egg parasitoids emerging from parasitised eggs. The measurement (length and width) of *G. crouanii* individual egg was recorded using the graduated eye piece stage microscope, while the weight was measured using an analytical balance, respectively. The male and female adult parasitoids that emerged were identified through visual observation of its size, presence or absence of ovipositor, and using the taxonomic keys (Eady, 1956).

Field Evaluation of the Egg Parasitoids

Field experiment was conducted during 2012-2013 to evaluate the efficacy of biological control agents against *G. crouanii* on coconut at the Agricultural Research Station in Koronivia, Nausori. The parasitism was recorded at three different parts of the coconut plant (underneath the leaves, the leaf axial area and at the base of palms) at ten different sites, for assessment of natural enemies which are either air-borne (found on the palm) or soil-borne (found around palm base). The fresh eggs of *G. crouanii* from the cages were exposed in fields to monitor the prevalence of the biological control wasps (parasitoids) in the natural environment with three methods: (i) sticking the eggs on leaf, (ii) eggs placed at the base of palms, and (iii) eggs hanged at the crown area of palms.

Field releases of egg parasitoids, *Paranastatus* spp. were made in *G. crouanii* infested coconut plantations in Salialevu, Taveuni Island to evaluate their impacts on *G. crouanii*. Releases of *Paranastatus* spp. were made in two kinds of coconut plantations, namely coconut plantations without field sanitation/intercropping, and coconut plantation with field sanitation/intercropping.

RESULTS AND DISCUSSIONS

Field Survey of Natural Enemies

During the field surveys, several kinds of natural enemies were observed with different functional feeding guilds. General predators like Indian myna (*Acridotheres tristis*), chicken (*Gallus gallus domesticus*), spiders, lizards, cattle and ants were encountered feeding on eggs, nymphs, and adults of *G. crouanii* in coconut plantations. Their abundance varied across sites and sampling dates. The populations of lizards and ants were highest followed by *A. tristis* and spiders, while the cattle and *G. domesticus* were very low **(Table 1).** Similar observations on predation by *G. domesticus* were reported from Tokelau Island (Dharmaraju, 1978), where they were found picking up the eggs of *G. crouanii* under coconut and pandanus canopies. However, in Western Samoa, Fiji and some other countries *G. domesticus* consumed the nymphs and adults of *G. crouanii* that fell on ground when palms fronds were burnt beneath the palm on a still day (Lever 1946; Lever 1947). *G. domesticus* managed to find all eggs on bare soil, whereas the eggs escaped predation in grassy areas. However, in our field surveys, the *G. domesticus* and cattle populations ranged from not present to few where the severe infestation of *G. crouanii* was also recorded (Deesh and Swamy, 2012). They observed that the eggs of *G. crouanii* were damaged by the cattle stamping eggs and nymphs in areas where cattle were allowed to graze. Hence, recommended establishing free range poultry and controlled grazing of cattle in coconut plantations as one of the ecofriendly strategies to contain the *G. crouanii* infestations.

Eggs of *G. crouanii* consumed by several predatory ant species, *Pheidole megacephala* and *Tapinoma melanocephalum* in Fiji and Tonga (O' Connor, 1949; Bedford, 1976; Bedford, 1978;

Crooker, 1979 and Singh, 1979), *Solenopsis geminata* (Crooker, 1979) (Mariau, 2001), and *Pheidole caldwelli* (Singh, 1972) have been reported. In Fiji, Singh (1977, 1979 & 1981) obtained up to 76% of predation, and highlighted major role of predators in controlling the stick insect. In Australia, eggs and young nymphs of the Phasmid *Dydimuria* were found in the nests of *Iridomyrmex* spp. (Readshaw, 1965). Dharmaraju (1978) observed the blue-tailed skink lizard (also referred to as western skink), commonly found on palm groves and the vicinity of building, predating on the eggs of *G. crouanii*.

Though we have good information on the diversity of predators on *G. crouanii* developmental stages in Fiji and across the infested Pacific Islands Countries, we currently lack data on their impacts on *G. crouanii* population regulation, and also on approaches to enhance their populations and predatory actions. In future more research is needed on the influence of habitat manipulation and natural enemy and pest interactions.

Two species of parasitoids belonging to the Order Hymenoptera under Family Eupelmidae and Genus *Paranastatus* were recorded from the eggs of *G. crouanii* that were collected from palm crown and palm basal areas in three selected hotspots in Vanua Levu, Viti Levu and Taveuni Islands. The two egg parasitoids species were *Paranastatus verticalis* Eady and *Paranastatus nigriscutellatus* Eady (Lal, 2009), of which *P. verticalis* was the most dominant species. These parasitoids were described earlier by Eady (1956). In Fiji, Singh (1977, 1979 & 1981) has reported 0% to 11% parasitization by *P. verticalis*, while the parasitization by *P. nigriscutellatus* was close to nil.

Table 1. Predator diversity and abundance on or near coconut palms, at three hot-spots of coconut stick insect, *G. crouanii*, in Vanua Levu (Dawara), Viti Levu (Namaumada) and Taveuni (Salialevu), during November 2012- September 2013, Fiji.

Survey Sites Island (Site)	Abundance of Predators						
	Month & Year	Indian Myna *Acridotheres* tristis L.	Chicken *Gallus gallus domesticus* (L.)	Spiders	Lizards	Cattle	Ants
Vanua Levu (Dawara)	Nov. 2012	+	–	++	++	–	++
	Jan. 2013	+	+	++	+	+	++
	Mar. 2013	+	–	+	+	–	++
	May 2013	++	+	++	+	–	+
	July 2013	+	+	+	++	–	++
	Sept. 2013	++	–	++	++	+	+
Viti Levu (Namaumada)	Nov. 2012	++	+	+	++	+	++
	Jan. 2013	+	–	+	++	–	++
	Mar. 2013	+	–	++	++	–	++
	May 2013	+	+	+	++	+	+
	July 2013	+	+	+	+	–	++
	Sept. 2013	++	–	+	+	–	+
Taveuni (Salialevu)	Nov. 2012	++	+	++	++	+	++
	Jan. 2013	++	+	+	++	+	+
	Mar. 2013	++	–	+	+	+	++
	May 2013	+	–	+	++	+	++
	July 2013	+	+	++	++	+	++
	Sept. 2013	++	–	+	+	+	++

Foot Notes:	– Not present	+ Few numbers	++ Moderate numbers	+++ Large numbers
Scale for Birds & Chicken:	– Not present	+ Few (0-10)	++ Moderate (11-20)	+++ Large (21-30)
Scale for Spiders & Lizards:	– Not present	+ Few (0-20)	++ Moderate (21-30)	+++ Large (31-40)
Scale for Cattle:	– Not present	+ Few (0-15)	++ Moderate (16-25)	+++ Large (26-50)
Scale for Ants:	– Not present	+ Few (0-50)	++ Moderate (51-100)	+++ Large (101-150)

Laboratory Evaluation of Natural Enemies

The natural enemies (predators and parasitoids) encountered during the field surveys, had varied preferences to *G. crouanii* growth stages exposed. For the egg parasitoids, their only preference was eggs of *G. crouanii*, while for the predators all the stages were attacked, but preference differed among the predator species (**Table 2**).

Table 2. Laboratory evaluation to determine parasitism/ predation by natural enemies on different stages of *G. crouanii*.

Natural Enemies		**Stages of *G. crouanii***			
		Egg	**Nymph**	**Adult Male**	**Adult Female**
Parasitoids	*Paranastatus verticalis* Eady *Paranastatus nigriscutellatus* Eady	√	x	x	x
Predators	Indian myna (*Acridotheres tristis*)	x	√	√	√
	Poultry/Chicken (*Gallus gallus domesticus*)	√	x	√	√
	Spiders	x	√	x	x
	Lizards	√	√	x	x
	Cattle	√	x	x	x
	Ants	x	√	√	√

Foot Notes: √ - with parasitism/predation; x- without parasitism/predation.

Egg Parasitoids and their Population Dynamics

The number of *G. crouanii* eggs retrieved from the crown area were less, as compared to the base of the canopy (**Table 3**). Interestingly, the percent egg parasitism was slightly lower for eggs retrieved from the palm base area, compared to those retrieved from the crown area. Our results are in line with the findings of the earlier researchers (O'Connor *et al.* 1954; Stechmann, 1985).

Among the two *Paranastatus* species, the percent parasitism recorded from the eggs retrieved from both the crown and/or base of palm in all the sampling sites, showed that *P. verticalis* always had higher percent of eggs parasitized, as compared to *P. nigriscutellatus* **(Table 3)**. The percent eggs parasitized from the crown area by *P. verticalis* were 19.2, 18.8 and 10.9, and the average number of eggs parasitized from the base of the palm were 16.7, 18.0, and 14.1, in Vanua Levu (Dawara), Viti Levu (Namaumada) and Taveuni (Salialevu), respectively **(Table 3 & Figure 3)**. The egg parasitism ranges reported by earlier researchers for the two species of *Paranastatus* are either similar and /or slightly higher to those recorded by us. O'Conner *et al.* (1954) in Taveuni and Vanua Levu, recorded parasitism ranging from less than 10% to as high as 52%. He further noticed that the emergence of the parasitoids may be delayed or prevented depending on conditions that are affecting the emergence of eggs. In Taveuni in 1963, less than 10% parasitism was obtained by Paine (1968). In Tonga, Crooker (1979) reported that *P. nigriscutellatus* was responsible for killing 30% to 40% of the *G. crouanii* eggs.

Biology of the G. crouanii and Egg Parasitoids

In the present study, the incubation period of *G. crouanii* egg was recorded to be 64 to 153 days for nymph emergence **(Table 4)**, at room temperature ranging from 24°C to 28°C with a relative humidity varying from 65 to 70%. Fully grown female nymph had six nymphal stages and measured from 80 to 90 mm long and from 3 to 4 mm broad. Total development period of female nymph ranged from 105 to 112 days with a mean of 108.5 days. Male *G. crouanii* had five nymphal stages and its development was completed in 95 to 102 days with a mean of 98.5 days. Males had a pair of wings, and a pair of antennae at the anterior end of the body measured from 75-80 mm in length and 2-3 mm in width. The findings of this study on the number of nymphal instars for male and female of *G. crouanii* are in conformation with the studies of O'Connor *et al.* (1954) and Taleaua (1980).

Table 3. Egg parasitoids emergence from eggs of the coconut stick insect, *G. crouanii* collected from the crown area and palm base area in Vanua Levu (Dawara), Viti Levu (Namaumada) and Taveuni (Salialevu), during November 2012- September 2013, Fiji.

Survey Sites Island (Site)		Crown Area					Base Area				
			P. verticalis		*P. nigriscutellatus*			*P. verticalis*		*P. nigriscutellatus*	
	Sampling Time (Month & Year)	Total No. of Eggs Retrieved	No. of Eggs Parasitised	% Parasitism	No. of Eggs Parasitised	% Parasitism	Total No. of Eggs Retrieved	No. of Eggs Parasitised	% Parasitism	No. of Eggs Parasitised	% Parasitism
Vanua Levu (Dawara)	Nov. 2012	8	1	12.5	0	0	13	1	7.7	2	15.4
	Jan. 2013	6	2	33.3	0	0	15	4	26.7	1	6.7
	Mar. 2013	10	1	10	1	10	14	4	28.6	1	7.1
	May 2013	11	2	18.1	1	9	17	1	5.9	1	5.9
	July 2013	8	1	12.5	0	0	22	4	18.1	1	4.5
	Sept. 2013	7	3	28.5	0	0	15	2	13.3	2	13.3
	Average			**19.2**		**3.2**			**16.7**		**8.8**
Viti Levu (Namaumada)	Nov. 2012	6	2	33.3	1	16.7	9	2	22.2	0	0
	Jan. 2013	8	1	12.5	1	12.5	14	3	21.4	1	7.1
	Mar. 2013	8	1	12.5	0	0	13	2	15.4	2	15.4
	May 2013	7	1	14.3	0	0	11	1	9.1	0	0
	July 2013	4	0	0	1	25	23	4	17.4	2	8.7
	Sept. 2013	5	2	40	0	0	9	2	22.2	0	0
	Average			**18.8**		**9.0**			**18.0**		**5.2**
Taveuni (Salialevu)	Nov. 2012	9	1	11.1	1	11.1	17	3	17.6	1	5.9
	Jan. 2013	10	2	20	1	10	16	2	12.5	2	12.5
	Mar. 2013	14	2	2	1	7.1	20	3	15	1	5.5
	May 2013	9	2	2	0	0	19	3	15.8	1	5.3
	July 2013	10	2	20	1	10	17	2	11.8	1	5.9
	Sept. 2013	10	1	10	1	10	17	2	11.8	1	5.9
	Average			**10.9**		**8.0**			**14.1**		**6.8**

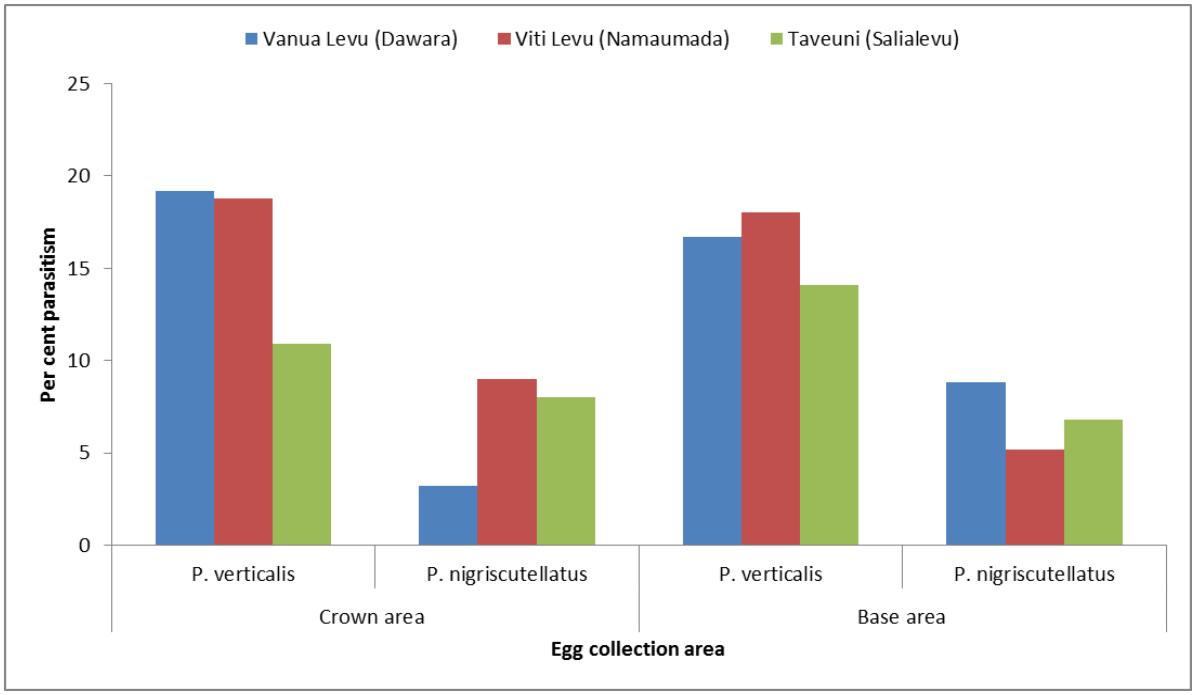

Figure 3. Percent egg parasitism by egg parasitoids, *Paranastatus verticalis* and *Paranastatus nigriscutellatus* from the coconut stick insect, *G. crouanii* eggs collected from crown and base area of palms in Vanua Levu (Dawara), Viti Levu (Namaumada) and Taveuni (Salialevu), Fiji.

Table 4. Biology of *G. crouanii* observed under laboratory conditions, Koronivia, Nausori, Fiji.

Time of Emergence	Av. Days for Nymphs Emergence	Av. Length of Egg (mm)	Av. Width of Egg (mm)	Av. Weight of Egg (g)	No. of Nymphs /Egg
May 2013	153	4.06	1.94	0.46	1
June 2013	99	4.12	1.95	0.46	1
July 2013	151	4.09	1.96	0.46	1
Aug. 2013	91	4.09	1.95	0.46	1
Sept. 2013	98	4.08	1.95	0.46	1
Oct. 2013	97	4.08	1.95	0.46	1
Nov. 2013	64	4.09	1.96	0.45	1
Dec. 2013	89	4.08	1.95	0.45	1
Jan. 2014	86	4.08	1.96	0.45	1
Feb. 2014	96	4.08	1.95	0.45	1
Mar. 2014	91	4.09	1.95	0.45	1
Apr. 2014	90	4.07	1.95	0.46	1
Range	64 -153	4.06 - 4.12	1.94 -1.96	0.45 – 0.46	1
Mean ± S. D.	100 ± 25.78	4.08 ± 0.01	1.95 ± 0.01	0.46 ± 0.01	-

S. D.: Standard Deviation.

Fully grown female nymphs are light brown/greenish in color and measured from 80 to 90 mm long and from 3 to 4 mm broad. Total development period of female nymph ranged from 105 to 112 days with a mean of 108.5 days. Male *G. crouanii* mostly brown in color and development was completed in 95 to 102 days with

a mean of 98.5 days. Similar findings on biology of *G. crouanii* was made by Clausen (1978) and O'Connor *et al.* (1954). Paine (1968) who reported that the period from hatching to emergence of the

adult female is 15 to 16 weeks, and in males 13.5 to 14.5 weeks. The adult female have two pairs of small movable wings, but cannot fly. About 3 weeks after becoming an adult, the female adult started laying eggs, up to 130 beings produced in their lifetime, which may last up to 18 weeks. Males are able to fly, and may survive up to 25 weeks. Mating was also observed whereby the male climbed on the back of female and stayed in that position until actual mating commenced. When ready for mating, the adult male moved slightly down from usual position to properly pass its abdomen down and around one side of the female's abdomen to insert the aedeagus. Even though the male was carried around by the female from place to place in this position, the attached male was observed feeding independently. The number of eggs laid by a female *G. crouanii* varied slightly with the host on which it was reared.

Development of two species of *Paranastatu*s in the laboratory by rearing on the freshly laid eggs of *G. crouanii* revealed that the eggs hatch in 18 to 135 days **(Table 5)**. Similar observations were made by O'Connor *et al.* (1954) who found the incubation period ranging from 50 to 68 days. Their study also suggested possibility that under certain conditions, emergence of the parasitoids may be delayed or prevented. The data of the present study has higher range since data was gathered over a period of one year as compared to similar study by O'Connor *et al*. (1954) whose data was for period of two months.

From the laboratory study on the rearing of *Paranastatus* of the total of 6,782 adult egg parasitoids 1,060 were male and 5,722 were female parasitoids. There were more adult females than the males of *Paranastatus*, with the sex ratio of 1 male to 5.2 females **(Table 5)**. Present findings are in conformation with the studies of O'Connor *et al*. (1954), who reported greater preponderance of the females *Paranastatus* spp. from the *G. crouanii* eggs collected in axils of fronds of coconut palms and on the ground on islands of Taveuni and Vanua Levu. In the current study, the development of pest *G. crouanii* egg and two species of egg parasitoids, *Paranastatus* spp. reared on its host (eggs of *G. crouanii*) revealed that the time taken for egg parasitoids development was shorter than that of the host. *Paranastatus* spp. with its high proportion of females and a developmental period much shorter than that of its host, might be expected to exert efficient control of the stick insect as reported by O'Connor *et al*. (1954).

Paranastatus spp. laid eggs for 1- 3 days, but it decreased over the days (**Figure 4**). The rate of oviposition significantly varied with the age of the parasitoids. The highest oviposition was found in the one-day old parasitoids (av. 13.4 eggs per female per day) and it was 33.33% of the total egg exposed in this study **(Table 6)**. This is in conformity with study of Perera and Hemachandra (2014) who reported that one-day-old parasitoid laid more eggs per female with 56.05% of total fecundity. The number of eggs parasitised on second and third days was 8.48 and 5.00, respectively which represented 26.67% and 13.33% of the total fecundity.

The male adults of *Paranastatus* spp. life span were significantly shorter than the female adults (**Figure 5**). Male average longevity was 4.24 days, while female survived on an average of 5 days. The longevity is an important character of adult parasitoids, that has effect on oviposition and eventually the overall production of mass culture (Lee and Heimpel, 2005). This biological information is vital to mass rear *Paranastatus* spp. for field releases in the IPM program of *G. crouanii.*

*Field Evaluation of the Egg Parasitoids, Paranastatu*s spp.

G. crouanii eggs exposed around different positions of the coconut palm tree to the natural enemies showed that for eggs pasted underneath the coconut leaves, and those pasted on small pieces of coconut leaves hung around the crown area had 80.89% and 90.62% egg retrieval, respectively, compared to the eggs placed in Petri dish around the palm base **(Table 7)**. The percentage of *G. crouanii* nymphs hatched and percentage of egg parasitism by parasitoids were similar for eggs pasted underneath the leaves or pasted on pieces of leaves hung around the palm crown. The exposed eggs of the *G. crouanii* had equal opportunity for parasitism by the natural enemies presents around the eggs in both situations. In Tonga, while assessing the role of natural enemies in the field, Rapp (1995) also reported that the *P. verticalis* emerged from less than 1% of all the eggs recovered.

Field releases of egg parasitoids, *Paranastatus* spp. in two kinds of coconut plantations, namely coconut plantations without field sanitation/intercropping, and coconut plantation with field sanitation/intercropping resulted in slight reduction of *G. crouanii* infestations in field without field sanitation/intercropping, as compared to field with sanitation/intercropping (**Figure 6**).

Table 5. Biology of *Paranastatus* spp. on coconut stick insect, *G. crouanii* eggs, under laboratory conditions, Koronivia, Nausori, Fiji.

Time of Emergence	Emergence of Parasitoids (Av. Days)	Av. Length of Egg (mm)	Av. Width of Egg (mm)	Av. Weight of Egg (g)	Total No. of Parasitoids Emerged	No. of Adult Parasitoids Emerged by Sex		Sex Ratio (Male: Female)	
						Male Parasitoids	Female Parasitoids	Male Parasitoid	Female Parasitoid
May 2013	135	4.06	1.94	0.46	12	2	10	1	5
June 2013	52	4.12	1.95	0.46	12	2	11	1	5.5
July 2013	128	4.09	1.96	0.46	12	2	10	1	5
Aug. 2013	61	4.09	1.95	0.46	12	2	10	1	5
Sept. 2013	65	4.08	1.95	0.46	12	2	10	1	5
Oct. 2013	72	4.08	1.95	0.46	12	2	10	1	5
Nov. 2013	18	4.09	1.96	0.45	14	2	12	1	6
Dec. 2013	86	4.08	1.95	0.45	11	2	9	1	4.5
Jan. 2014	55	4.08	1.96	0.45	12	2	10	1	5
Feb. 2014	49	4.08	1.95	0.45	13	2	11	1	5.5
Mar. 2014	48	4.09	1.95	0.45	14	2	12	1	6
Apr. 2014	50	4.07	1.95	0.46	12	2	10	1	5
Range	18 -135	4.06 - 4.12	1.94 -1.96	0.45 - 0.46	11-13	2	9-12	1	4.5-6
Mean ± S.D.	68 ± 33.70	4.08 ± 0.01	1.95 ± 0.01	0.46 ± 0.01	12.33 ± 0.89	-	10.42 ± 0.90	-	5.21 ± 0.45

Av. data from one-year laboratory study.
S.D.: Standard Deviation.

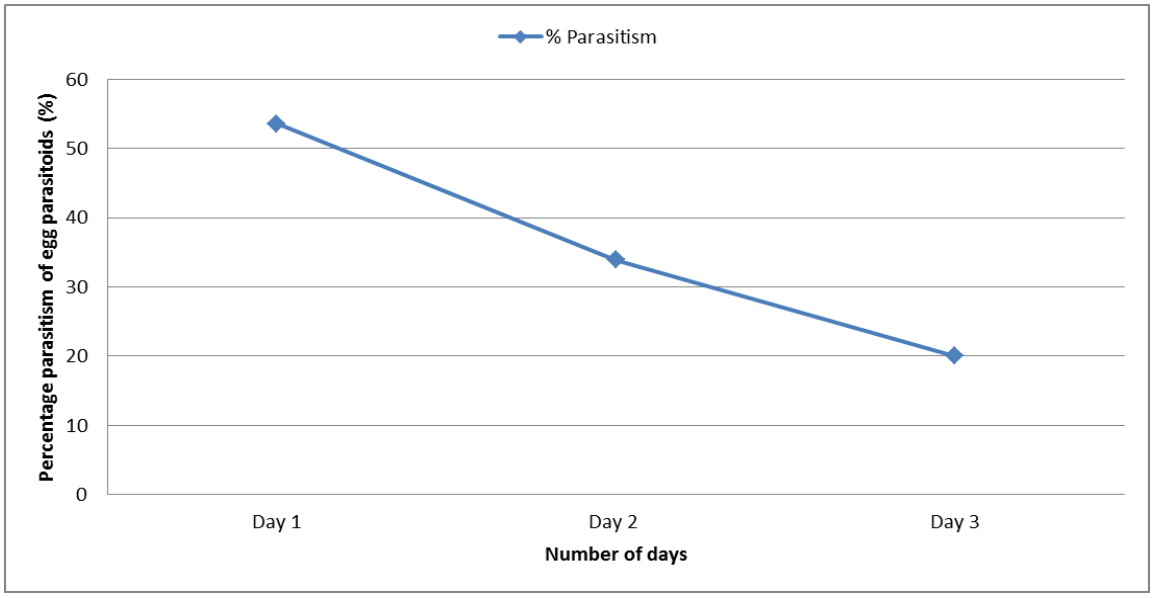

Figure 4. Relationship between the egg parasitism by two species of *Paranastatus* across the number of days under laboratory conditions, Koronivia, Nausori, Fiji, 2014.

Table 6. Longevity period of *Paranastatus* spp. and percent parasitism under laboratory conditions, Koronivia, Nausori, Fiji, 2014.

No. of the Parasitoids	**Oviposition Period [Days]**	**Details of Emergence**					
		Egg 1 (Mean ± S. D.)		Egg 2 (Mean ± S. D.)		Egg 3 (Mean ± S. D.)	
		Male Parasitoid	Female Parasitoid	Male Parasitoid	Female Parasitoid	Male Parasitoid	Female Parasitoid
Individual Mean	2.2	1.6	11.8	1.08	7.36	0.64	4.36
Total Mean ± S. D.		13.4 ± 2.98		8.48 ± 4.82		5 ± 6.5	
Parasitism (%)		33.33		26.67		13.33	

S.D.: Standard Deviation.

G. crouanii eggs are sensitive to high temperatures. In plantation with low ground cover, eggs probably become desiccated by the sun, while the high under growth of plantations with poor weed management provided shade cover for the eggs developing on the ground. This assumption is supported by literature: Crooker (1979) and Lever (1969) mention high pest densities in plantations with dense ground cover in Tonga. Singh (1981) reported that plantations with low ground cover were free from infestation in Fiji. In Fiji, Singh (1977, 1979, 1981) found a 12% to 44% increase in desiccated eggs in plantation with low ground cover when compared to areas under poor weed management. Thus, integration of cultural methods such as sanitation/intercropping, together with the use of naturally-occurring egg parasitoids, *Paranastatus* spp. is suggested for ecological sustainable management of *G. crouanii* infestations in Fiji.

CONCLUSIONS

During the field surveys, several naturally-occurring biological control agents on coconut stick insect, *Graeffea crouanii* (Le Guillou) were found. Predators noticed were Indian myna (*Acridotheres tristis*), chicken (*Gallus gallus domesticus*), spiders, lizards, cattle and ants. Among the predators, the lizards and ants were highest in numbers. The only parasitoids encountered attacking eggs of *G. crouanii* were identified as *Paranastatus verticalis* Eady and *Paranastatus nigriscutellatus* Eady, and

Table 7. Field exposure and retrieval of laboratory reared *G. crouanii* eggs from the different positions of the coconut palm.

Egg Exposure	% Eggs Retrieved (Mean ± S.D.)	% Eggs not Retrieved (Mean ± S.D.)	% No. Emergence from Egg (Mean ± S.D.)	% No. Nymph Hatched (Mean ± S.D.)	% Parasitism by Parasitoids (Mean ± S.D.)
Eggs glued underneath leaves	80.89 ± 13.39	19.11 ± 13.39	12.82 ± 7.56	53.26 ± 14.42	14.81 ± 8.97
Eggs placed at palm base	61.70 ± 17.79	38.30 ± 17.79	11.16 ± 5.01	38.11 ± 12.32	12.43 ± 9.00
Eggs hung around palm crown	90.62 ± 7.62	9.38 ± 7.62	19.37 ± 9.65	55.74 ± 9.76	15.51 ± 7.00

S.D.: Standard Deviation.

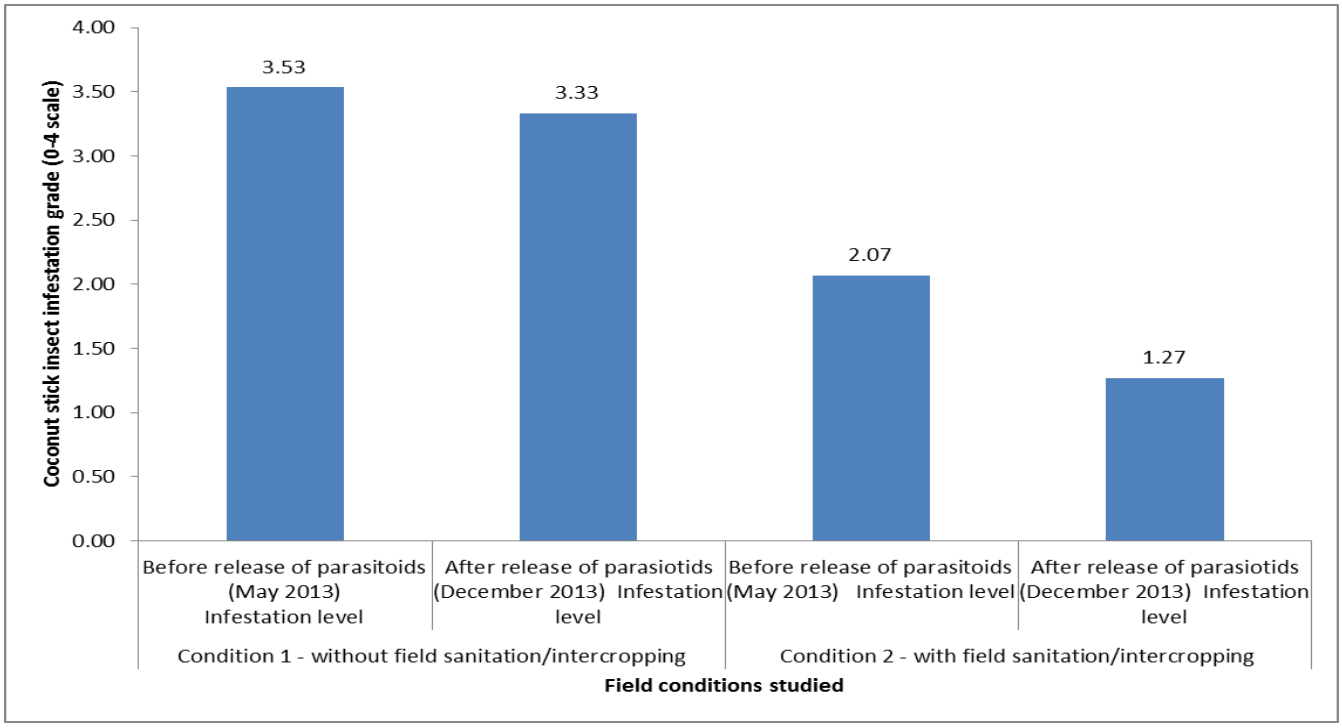

Figure 6. Impact of release of two species of egg parasitoids, *Paranastatus* spp. on the *G. crouanii* infestations in two kinds of coconut plantations, Salialevu, Taveuni Island, Fiji.

they were the most dominant one and present in all coconut plantations surveyed. *P. verticalis* always had the higher percent of *G. crouanii* eggs parasitized, as compared to *P. nigriscutellatus* in all coconut plantations surveyed *G. crouanii*. Information on the life cycle of *G. crouanii* under laboratory conditions facilitated in the development of the mass rearing techniques of egg parasitoids, *P. verticalis* and *P. nigriscutellatus*. This was crucial for evaluating the efficacy of the natural enemies under laboratory and field conditions. The series of biological studies on the *Paranastatus* spp. revealed vital information on their sex ratio, duration to adult stage, relation between fecundity and age of the adult female, life span of adult males and females, optimum host-parasite ratio, and other life history parameters were necessary to standardize mass rearing techniques for *Paranastatus* spp., and which can be used in future to manage *G. crouanii* infestations. More ecological engineering research is needed in future across various agroecological zones in Fiji, where the integration of cultural and

biological methods are fine-tuned for the development of the integrated pest management package against *G. crouanii* in Fiji Islands.

ACKNOWLEDGEMENT

The senior author (A.D. Deesh) thank the University of the South Pacific (USP), Suva Fiji for the research grant, to the Unitec Institute of Technology, New Zealand for species identification of the egg parasitoids, and to the Ministry of Agriculture, Fiji for providing resources and expertise.

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