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Life table and predatory efficiency of *Stethorus gilvifrons* (Coleoptera: Coccinellidae), an important predator of the red spider mite, *Oligonychus coffeae* (Acari: Tetranychidae), infesting tea

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Abstract The ladybird beetle, *Stethorus gilvifrons*, is a major predator of the red spider mite, *Oligonychus coffeae*, infesting tea. Biology, life table and predatory efficiency of *S. gilvifrons* were studied under laboratory conditions. Its average developmental period from egg to adult emergence was 19.2 days. After a mean pre-oviposition period of 5.3 days, each female laid an average of 149.3 eggs. Adult females lived for 117.3 days and males for 41.5 days. The life table of the beetle was characterized by an intrinsic rate of increase (r) of 0.066 day^{-1}, net reproductive rate (R_0) of 72.2 eggs/female, gross reproduction rate (Σm_x) of 82.3 eggs/female, generation time (T) of 64.9 days, doubling time of 10.5 days and finite rate of increase (λ) of 1.07 day^{-1}. Population dynamics of *S. gilvifrons* and its prey, *O. coffeae*, was monitored by sampling 25 tea leaves from each experimental block grown under the prevailing field conditions. Populations of *S. gilvifrons* reached a peak during January to March and had low incidence during June to November. Peaks in the populations of *S. gilvifrons* coincided with the abundance of *O. coffeae* in tea fields. Weather factors such as low temperature, high humidity and heavy rainfall adversely affected the populations of *S. gilvifrons*. The predatory efficiency of *S. gilvifrons* increased during the growth of larval instars. An adult female consumed 205.0 eggs, 92.2 larvae, 81.8 nymphs and 52.4 adult mites per day.

Keywords *Stethorus gilvifrons* · Red spider mite · Life table · Population dynamics · Predation · Biological control · Tea plants

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Introduction

Ladybird beetles belonging to the genus *Stethorus* (Coleoptera: Coccinellidae) are obligate predators of tetranychid mites (Putman 1955). They frequent a wide range of crop plants where tetranychid mites are abundant (McMurtry et al. 1970). Several species have been reported to be effective biological control agents. They are known to be voracious predators with all the motile life stages feeding on all prey stages. They have high host-finding ability, high dispersal potential and long-living adults (Roy et al. 2005).

Spider mites (Acari: Tetranychidae) infesting commercially cultivated tea plants, *Camellia sinensis* L. (O. Kuntze) are typical colonizing species characterized by very high rate of population increase and high densities (Muraleedharan et al. 2005). Among them, the red spider mite (RSM), *Oligonychus coffeae* (Nietner), normally infests the upper surface of mature tea leaves and when the severity of infestation increases they move even to the lower surface of older leaves as well as tender tea shoots. Due to feeding, the maintenance foliage turns ruddy bronze, making RSM-infested fields distinct even from a distance. Severe infestation ultimately leads to defoliation (Selvasundaram and Muraleedharan 2003). The control of RSM is mainly achieved by the use of synthetic acaricides. Extensive use of these chemicals leads to pesticide residue problems in the made tea (Muraleedharan 1995).

These complex problems of environmental contamination and food safety require the development of alternative control methods. In this context, many studies had been conducted on the natural enemies of spider mites to evaluate their potential as biological control agents. Muraleedharan (1988) had reported the lady beetle, *Stethorus gilvifrons* Mulsant as an important predator of this tea mite in south India. Published information on *S. gilvifrons* is limited and more information is needed to explore the possibility of using this species as a potential control agent against RSM. Therefore, bioecological studies of *S. gilvifrons* were undertaken to document the population dynamics and its predatory efficiency against RSM infesting tea. Data relating to the biological and life table parameters will help to include *S. gilvifrons* as a potential predator in IPM strategies against RSM.

Materials and methods

Study area and sampling

The study area was located in the Anamallais (Coimbatore District, TamilNadu state) at an altitude of 1,065 m above the mean sea level. The experimental block consisted of 500 tea bushes (mixed tea clones) planted at a spacing of 1.2 × 1.2 m and last pruned in 2005 at a height of 60 cm above the ground. The experimental block was divided into five plots (A–E) each consisting of 100 tea bushes to take into consideration the influence of microclimate where the tea plants are grown under shade trees. The field was kept free from pesticide application since pruning. Leaves (25) were collected at random from each plot at fortnightly interval for a period of 2 years from January 2006 to December 2007. Leaves were individually placed in plastic bags with holes for proper air circulation and brought to the laboratory where the number of different life stages of *S. gilvifrons* and the red spider mites was counted under stereomicroscope (Olympus No. 1220) using 10× magnification. Weather data were obtained from the metrological observatory of UPASI Tea Research Institute, Valparai.

Stock culture of *Stethorus gilvifrons* and red spider mites

Stethorus gilvifrons and its prey, *O. coffeae* were collected from tea fields of UPASI Experimental Farm. A stock colony of *S. gilvifrons* had been maintained in the insectary at 25 ± 1°C, 75 ± 5% RH and 16L:8D photoperiod in a large screened box (40 × 25 × 10 cm) containing tea leaves infested with RSM. After field collection, spider mites were immediately transferred onto 1-year-old potted tea plants grown under greenhouse conditions and used as stock culture. From the stock, RSM adults were transferred onto fresh tea leaf (6 × 6 cm) placed on moistened cotton pads (ca. 1.5 cm thick) in plastic trays (42 × 30 × 6.5 cm). Rearing trays were kept under controlled conditions of 25 ± 1°C, 75 ± 5% RH and 16L:8D photoperiod. Withered and drying leaves were regularly replaced.

Life history and life table studies

Adults of *S. gilvifrons* were collected with a clean pipette aspirator from the RSM colony and introduced into a Plexiglas box (8 cm diameter, 7 cm depth) containing mite-infested tea leaf placed on moist cotton. Adults were allowed to lay eggs for 24 h and egg laden tea leaf was placed in a Petri dish (9.5 cm diameter) containing cotton wool soaked with water and the number of eggs laid by each beetle was counted. All the eggs were observed at 8 h intervals for their development till hatching. Newly hatched larvae were individually transferred onto mite-infested tea leaf (6 × 6 cm) for development and moulting until pupation. Pupae were placed in small clear plastic Petri dishes (9 cm in diameter, 1.5 cm in depth). As soon as adults emerged, they were sexed and a pair of male and female was introduced into each Plexiglas box with mite-infested tea leaf and the duration of copulation was observed. In order to document fecundity and longevity of adults they were transferred to another tea leaf infested with RSM at every 24 h till the female beetle died. Number of eggs laid on each leaf was counted daily under a stereomicroscope. All experiments were conducted with 10 replicates in an insectary at 25 ± 1°C, 75 ± 5% RH and a photoperiod of 16L:8D. For morphometric study, semi-permanent slides were prepared and measurements were taken using ocular and stage micrometer in a research microscope (ZEISS-Jeneval GF-PA).

Predatory efficiency of *Stethorus gilvifrons*

Stethorus gilvifrons and its prey, *O. coffeae* were collected as described above. All life stages of *O. coffeae* (300 in total) were transferred individually onto tea leaf (4 × 4 cm) placed in Plexiglas boxes (8 cm diameter, 7 cm depth) and then a single *S. gilvifrons* larva/adult was released. The box was covered with fine muslin net to provide sufficient ventilation and placed in an incubator at 25 ± 1°C, 75 ± 5% RH and 16L:8D photoperiod. Daily consumption of *S. gilvifrons* was examined under stereomicroscope at every 24 h. *Stethorus gilvifrons* was transferred to another Plexiglas box with pre-determined number of RSM and this procedure was repeated until their pupation. Each experiment was replicated five times.

Statistical analysis

The multiple regression analysis among the populations of *S. gilvifrons* and certain biotic (RSM population) and abiotic factors (sunshine, relative humidity, rainfall and

temperature) was carried out using 'SigmaStat 3.5' software, to develop a model to predict the population dynamics of *S. gilvifrons*. Predation of *S. gilvifrons* on RSM was determined by analysis of variance (ANOVA) and means were separated by Duncan's multiple range test (DMRT). The data on the duration of developmental stages of *S. gilvifrons* were used to calculate life table parameters which included age-specific survival rate (l_x), age-specific fecundity (m_x), intrinsic rate of increase (r), finite rate of increase (λ), net reproductive rate (R_0), mean generation time ($T = \ln R_0)/r$) and gross reproductive rate (GRR $= \Sigma m_x$) (Brich 1948; Southwood 1978). Doubling time (DT $= (\ln 2)/r$) was calculated as described by Mackauer (1983).

Results

Population dynamics of *Stethorus gilvifrons* and its prey

Incidence of *S. gilvifrons* coincided with cyclic oscillations of RSM population during the study period (Fig. 1). Populations of *S. gilvifrons* showed an increasing trend from December onwards and reached a peak between January and March. Red spider mite population was extremely low until mid-September, increased to a maximum from mid-November to March and again declined after a few weeks. The multiple regression equation fitted with certain biotic and abiotic factors to predict the population of *S. gilvifrons* was (Table 1): $Y = -42.51 + 0.05\ \text{RSM} - 0.65\ T_{\min} + 3.05\ T_{\max} - 1.04\ \text{RH}_{\min} + 0.95\ \text{RH}_{\max} - 0.0056$ rainfall $- 5.68$ sunshine ($R^2 = 0.851$, $F_{7,21} = 17.143$, $P < 0.001$). Low temperature, low RH, heavy rainfall and low sunshine hours had a negative influence on the predator population, whereas high temperature and high humidity had significant positive effects.

Life history and life table parameters

Newly laid eggs of *S. gilvifrons* are shiny, yellow and elliptical (0.36 ± 0.003 mm long, 0.18 ± 0.004 mm wide). They were deposited individually on midribs and veins, firmly glued to the leaves. Mean duration of hatching was 5.9 days. Fertilized eggs appeared

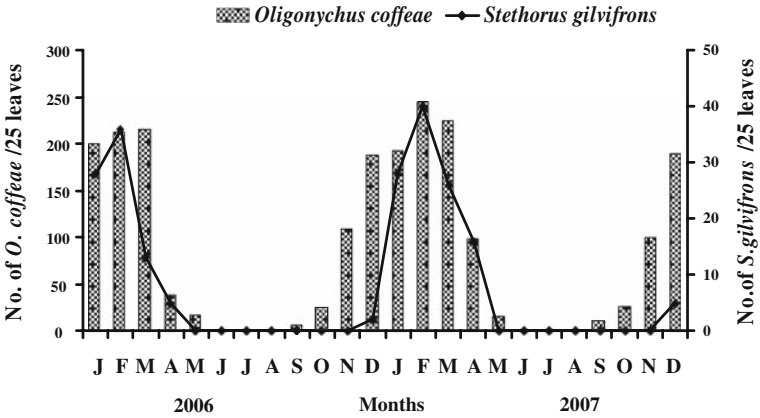

Fig. 1 Population dynamics of *Stethorus gilvifrons* and red spider mite infesting tea during 2006–2007

Table 1 Multiple regression analysis among weather factors and *Stethorus gilvifrons*

Variable	Partial regression coefficient ± SE	*t*-value	*P*	R^2
Red spider mite	0.0501 ± 0.0318	1.576	0.130	0.851
Temperature minimum (°C)	−0.652 ± 1.121	−0.581	0.567	
Temperature maximum (°C)	3.049 ± 1.631	1.869	0.076	
Relative humidity minimum (%)	−1.042 ± 0.282	−3.692	0.001	
Relative humidity maximum (%)	0.949 ± 0.410	2.316	0.031	
Rainfall (cm)	−0.00556 ± 0.00777	−0.716	0.482	
Sunshine (h)	−5.675 ± 2.171	−2.614	0.016	

granular in the first 2 days, and two red eyespots developed 1 day before hatching. The eggs became transparent on the day of hatching and the developing embryo could clearly be seen through the chorion of the egg. Unfertilized eggs were slightly smaller and didn't show any colour changes as they gradually shriveled and died.

Four instars were recognized. Larvae moulted 3× with instars closely resembling each other; the presence of a shed exoskeleton and head capsule size was used to differentiate between instars. All instars had numerous dark brown setae over the tergites and pleurites with dark brown pigmentation at the bases of the dorsal setae. Before each moult, a sticky substance was secreted at the end of the abdomen, gluing the larva to the leaf surface. Mean instar period lasted from 1.5 (1st) to 2.9 days (2nd), and total larval period (1st–4th instar) was 8.7 days (Table 2).

After the last moult, the 4th instar firmly attached itself to the substratum by means of a sticky fluid. The quiescent prepupa stage at the end of the 4th instar lasted several hours, during which it changed color from red to black. The pupal stage of *S. gilvifrons* lasted an average of 4.8 days. Newly emerged adults are light reddish and gradually changed to black. Mean length and width of males and females were 1.20 × 0.86 and 1.30 × 0.90 mm, respectively (Table 3). Multiple matings were observed and copulation lasted for 15–30 min. Overall egg-to-adult period was 19.2 days (Table 4). Out of the 40 *S. gilvifrons* eggs, only 28 adults emerged of which 15 were females (53.6%) and 13 were males (46.4%) indicating a 1: 0.86 female:male sex ratio.

Life table studies

Adults of *S. gilvifrons* lived an average of 117 days and females lived longer than males (Table 5). Adults mated 24 h after emergence and mated females began laying eggs after an average preoviposition period of 5.3 days. Females oviposited for 97.9 days and average

Table 2 Development, survival rate and distribution of *Stethorus gilvifrons* feeding on red spider mite

Stages	Mean developmental period ± SE ($n = 10$)	Survival (%)	Stable stage distribution (%)
Egg	5.92 ± 0.21	97.50	35.95
First instar	1.48 ± 0.12	94.87	8.95
Second instar	2.86 ± 0.15	94.59	11.30
Third instar	1.65 ± 0.19	91.43	6.08
Fourth instar	2.55 ± 0.13	93.75	7.01
Pupa	4.77 ± 0.30	93.33	8.63

Table 3 Morphometric (mm) characteristics of *Stethorus gilvifrons* ($n = 10$)

Stage		Mean ± SE (range)
Egg	Width	0.358 ± 0.003 (0.35–0.37)
	Length	0.184 ± 0.004 (0.17–0.19)
First instar	Length	0.812 ± 0.004 (0.80–0.82)
Second instar	Length	1.298 ± 0.004 (1.29–1.31)
Third instar	Length	2.082 ± 0.004 (2.07–2.09)
Fourth instar	Length	2.878 ± 0.009 (2.85–2.90)
Pupa	Width	1.730 ± 0.009 (1.71–1.76)
	Length	0.912 ± 0.004 (0.90–0.92)
Male	Width	1.200 ± 0.005 (1.18–1.21)
	Length	0.862 ± 0.004 (0.85–0.87)
Female	Width	1.300 ± 0.007 (1.28–1.31)
	Length	0.900 ± 0.005 (0.88–0.91)

Table 4 Biological parameters of *Stethorus gilvifrons* on red spider mite ($n = 10$)

Parameters	Mean ± SE
Egg to adult emergence (days)	19.23 ± 1.10
Pre-oviposition period (days)	5.30 ± 0.42
Oviposition period (days)	97.87 ± 7.90
Mean fecundity/female	149.25 ± 11.03
Mean eggs/female/day	4.44 ± 0.50
Mean adult longevity (days)	79.38 ± 6.36
Mean male longevity (days)	41.50 ± 3.23
Mean female longevity (days)	117.25 ± 9.48
Sex ratio (Female:Male)	1:0.86

Table 5 Life table studies on *Stethorus gilvifrons* feeding on *Oligonychus coffeae*

Category	Life table parameters
Intrinsic rate of increase (r) (day^{-1})	0.066
Net reproductive rate (R_0) (eggs/female)	72.22
Gross reproduction rate (GRR = Σm_x) (eggs/female)	82.26
Mean generation time (T) (days)	64.85
Finite rate of increase (λ) (day^{-1})	1.07
Weekly multiplication	1.59
Doubling time (ln 2/r) (days)	10.50
Survival rate at stable age-stage distribution (%)	100

life time egg production was 149. Average daily oviposition was 4.4 eggs/day. Age-specific survival rate (l_x) and age-specific fertility (m_x) are presented in Fig. 2. Intrinsic rate of natural population increase (r) was 0.066 day^{-1}, while net reproductive rate (R_o) was estimated as 72.2 eggs/female. Gross reproduction rate (Σm_x) was 82.3 eggs/female,

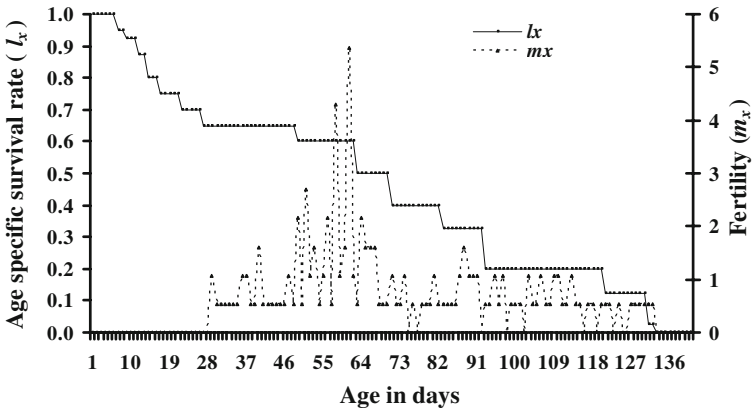

Fig. 2 Age-specific survival rate (l_x) and age-specific fertility (m_x) of *Stethorus gilvifrons* feeding on *Oligonychus coffeae*

generation time (T) 64.9 days, doubling time (DT) 10.5 days and finite rate of increase (λ) 1.1 day^{-1}.

Predatory efficiency of *Stethorus gilvifrons*

Number of mites consumed by *S. gilvifrons* larvae increased from the 1st to the 4th instar. Adult female beetles consumed significantly more RSM eggs ($F_{4,24} = 252.09$, $P < 0.001$), larvae ($F_{4,24} = 161.38$, $P < 0.001$), nymphs ($F_{4,24} = 99.23$, $P < 0.001$) and adults ($F_{4,24} = 101.86$, $P < 0.001$) than the males and larval instars (Table 6).

Discussion

Peaks in population density of *S. gilvifrons* coincided with those of *O. coffeae*. Kishimoto (2002) reported the seasonal occurrence of spider mites and their predators in three Japanese pear orchards where predacious beetles such as *Stethorus japonicus* Kamiya (Coccinellidae) and *Oligota* spp. (Staphylinidae) and predatory thrips, *Scolothirps*

Table 6 Predatory efficiency of *Stethorus gilvifrons* on immature and adult red spider mite

Predator stages	Mean no. of red spider mites consumed ± SE ($n = 5$)			
	Eggs	Larvae	Nymphs	Adults
First instar	26.4 ± 5.7 a	26.0 ± 1.1 a	10.6 ± 2.2 a	6.0 ± 0.4 a
Second instar	34.2 ± 4.5 ab	39.4 ± 1.9 b	20.2 ± 1.2 b	10.0 ± 1.1 a
Third instar	43.2 ± 1.5 b	55.6 ± 2.4 c	39.6 ± 5.4 c	18.8 ± 2.6 b
Fourth instar	68.8 ± 3.7 c	85.4 ± 2.2 d	52.2 ± 3.3 d	20.0 ± 1.1 b
Adult male	172.6 ± 3.3 d	86.4 ± 3.3 d	76.8 ± 1.6 e	42.0 ± 1.8 c
Adult female	205.0 ± 7.9 e	92.2 ± 3.1 e	81.8 ± 1.6 e	52.4 ± 2.7 d

Means followed by the same letter do not differ significantly according to Duncan's multiple range test ($P > 0.05$)

takahashii Priesner (Thripidae) were abundant and their population trend was closely associated with that of the prey. Roy et al. (2005) reported that seasonal activity of the predators *Stethorus punctillum* Weise (Coccinellidae) and *Neoseiulus fallacis* (Garman) (Acari: Phytoseiidae) also coincided with that of their prey, *Tetranychus mcdanieli* McGregor in raspberry. *Stethorus gilvifrons* completely disappeared from tea fields in June when RSM density became very low.

The pre-oviposition and oviposition periods and the duration of developmental stages of *S. gilvifrons* were similar to those of other species, such as *Stethorus siphonulus* Kapur on *Tetranychus urticae* Koch in Papaw (Raros and Haramoto 1974), *Stethorus picipes* Casey on *Oligonychus punicae* Hirst (Tanigoshi and McMurtry 1977), *Stethorus vagans* (Blackburn) on *T. urticae* (Ullah 2000), and *S. japonicus* on *T. urticae* (Mori et al. 2005). Total fecundity at 25 ± 1°C in *S. gilvifrons* (149 eggs) was less than that measured at or around the same temperature for *S. japonicus* (501 eggs; Mori et al. 2005), *Stethorus madecassus* Chazeau (184; Chazeau 1974), *S. picipes* (221; Tanigoshi and McMurtry 1977) and *S. punctillum* (279; Roy et al. 2003), suggesting that *S. gilvifrons* has lower total fecundity at this temperature in comparison with above mentioned species. The sex ratio obtained for *S. gilvifrons* was within the range of values reported for *S. japonicus*, *Stethorus punctum* (LeConte), *S. siphonulus*, *S. vagans* and *Stethorus vinsoni* Kapur (Putman 1955; Raros and Haramoto 1974; Tanigoshi and McMurtry 1977; Ullah 2000; Mori et al. 2005). Longevity of *S. gilvifrons* was also similar to that of other *Stethorus* species (Mathur 1969; Puttaswamy and Channabasavanna 1977; Richardson 1977).

The intrinsic rate of natural increase (r) is a key demographic parameter useful for predicting the population growth potential of an animal under given environmental conditions (Ricklefs and Miller 2000). The r value of *S. gilvifrons* (0.066) was less than that measured for *Stethorus loxtoni* Britton & Lee (0.152; Richardson 1977), *S. madecassus* (0.155; Chazeau 1974), *S. picipes* $F_{4,24} = 252.09$, $P < 0.001$ (0.121; Tanigoshi and McMurtry 1977), *Stethorus loi* Sasaji. (0.160; Shih et al.1991), *S. japonicus* (0.156; Mori et al. 2005) and *S. gilvifrons* (0.133; Taghizadec et al. 2008). Theoretically, a predator that has a population growth rate equal to or greater than its prey should efficiently regulate the population of its prey (Sabelis 1992). In biological control practice, r value is increasingly used as a means for selecting promising biocontrol candidates on the basis of their reproductive potential and to predict the outcome of pest-natural enemy interactions (Jervis and Copland 1996). The r value of *S. gilvifrons* was lower than that of its prey, *O. coffeae* on tea at 25 ± 2°C (Muraleedharan et al. 2005). Nevertheless, the voracious *S. gilvifrons* consistently suppressed populations of *O. coffeae*. A similar situation was observed by McMurtry et al. (1974) on *S. picipes* ($r_m = 0.12$ day^{-1} at 25°C) preying on *O. punicae* on avocados. It is possible that under favorable conditions, *S. gilvifrons* can eliminate prey more rapidly than they can reproduce.

Adults and larvae of *S. gilvifrons* fed on all stages of RSM, and adult females consumed more RSM than larvae. Similar results were reported by Ahmed and Ahmed (1989), Afshari (1999) and Fiaboe et al. (2007). The high rate of RSM consumption by *S. gilvifrons* adults suggested that this effective winged predator has certain advantages as a potential control agent due to its high longevity and ability to rapidly locate RSM 'hot spots'. Therefore, conservation and augmentation of this predator in the tea ecosystem may prove to be an essential component in the IPM strategy against red spider mite.

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