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Assessment of Searching Efficiency and Functional Response of Acarophagous Species against Red Spider Mite, *Tetranychus urticae* Koch (Acari: Tetranychidae)

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ABSTRACT

Background: Investigation of predatory traits, which are mostly unexplored, such as prey consumption, reproduction rate and searching propensity, could offer crucial information for the selection of creative control agents.

Methods: In this study, two sets of experiments were carried out, the first set of which was intended to assess the effectiveness of the search and the second set for the functional response.

Result: The intake of *T. urticae* by *S. pauperculus*, *Oligota* sp. and *A. longispinosus* dramatically increased as predator density increased from one to eight, according to research on searching efficiency. However, when predator number increased, prey consumption per predator declined. The amount of prey consumed by the larvae did not increase despite the prey density quadrupling. Prey consumption by predators increased as prey density increased, while prey consumption as a percentage dropped as prey density increased, according to a functional response. When the number of prey increased from 50 to 800, the area where predators were discovered reduced.

Key words: *Amblyseius longispinosus,* Functional response, *Oligota*, Searching efficiency, *Stethorus pauperculus*, *Tetranychus urticae*.

INTRODUCTION

Red spider mite, *Tetranychus urticae* Koch is a highly destructive agricultural pest affecting 140 plant families and feeding on over 1,100 plant species, including 150 economically valuable species (Pavela, 2017). It poses a significant threat to vegetables, large trees, horticultural plants and deciduous fruit trees (Mumtaz *et al*., 2023). This species can destroy plants or significantly reduce their quality and yield by sucking out the contents of leaf cells. It is well suited to a wide range of climatic situations. The control of spider mites heavily relies on the utilization of chemical acaricides (Badii *et al*., 2004). Chemicals are very efficient, quick to operate, adaptable to most situations and reasonably priced. Agricultural chemicals alone cannot control spider mites since they can quickly develop resistant against different acaricides. In turn, there has been a rise in interest in using biological control agents to eradicate spider mites. Due to their biology, feeding habits and efficiency in suppressing spider mites on a variety of crops grown in greenhouses, predatory mites of the Phytoseiidae family are among the most important known natural enemies of spider mites. Phytoseiid mites are typically better able to survive when spider mites are scarce than other insect predators. More than 2,400 species of the phytoseiidae family can be found worldwide and are used in biological control techniques (Parveen *et al*., 2021). Research has determined that *Amblyseius longispinosus* Evans, of the phytoseiid family, exhibits exceptional predatory behavior towards spider mites on crops cultivated in greenhouses (Cabrera *et al*., 2009).

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Among the coccinellids, the genus *Stethorus* stands out due to its distinct affinity for mites. A wide variety of environments, including numerous agricultural systems, grasslands and woodlands, support the *Stethorus*. The *Stethorus* species have a compact size and excellent abilities to thrive and seek out prey. Hence, the inclusion of winged predator to spider mite hot spots would prove highly advantageous (Trivedi *et al*., 2021).

The definition of functional response encompasses the connection between the predatory rates exhibited by a predator and the diverse densities of its targeted prey over a given period (Farazmand *et al*., 2012). Functional response enables researchers to assess predators

capacity in controlling prey population by demonstrating the efficiencies of studies and predation rates (Xiao and Fadamiro, 2010; Fathipour and Maleknia, 2016). Biological control of spider mites remains inadequately addressed in India, primarily because it has long been regarded as a lesser threat. The current investigations were undertaken to assess the searching efficiency and feeding capacity of acarophagous species against red spider mite *Tetranychus urticae* Koch, taking into account the above-mentioned considerations.

MATERIALS AND METHODS

Culturing of *T. urticae*

The experiment was conducted in the year 2016-2017 at the Department of Agricultural Entomology, Tamil Nadu Agricultural University, Coimbatore. The red spider mites, *Tetranychus urticae* Koch, were collected from okra fields with different varieties such as Vaishnavi, US Agri seed and Mahyco-10. These mites were then bred in a controlled glass house environment following Krishnamoorthy's (1988) method. To breed *T. urticae*, okra plants were planted in pots weekly. After thirty days, the plants were infested with *T. urticae* using a camel hair brush or by placing already infested leaves onto fresh plants to transfer the mites. New plants were also introduced periodically to maintain a continuous culture of *T. urticae* (Fantinou *et al*., 2012).

Culturing of *Stethorus pauperculus* (Weise)

Mass culturing was conducted using prey mites, *T. urticae*, following the method developed by Perumalsamy *et al*. (2010). Leaves infested with *T. urticae* and various stages of the predator, *S. pauperculus*, were collected from an okra field. Newly emerged male and female beetles were carefully gathered and placed in a glass container measuring 15 cm × 20 cm × 8 cm. After mating, the female beetles laid their eggs on the mite-infested leaves. These leaves with eggs were periodically transferred to moist cotton in another glass container to help the eggs hatch. The pupae were then separated and kept until they emerged as adults. This process was repeated as needed (Gotoh *et al*., 2004).

Culturing of predatory mite, *Amblyseius longispinosus* evans

The predators were raised using a method developed by Mallik *et al*. (1999). *T. urticae* was used as the prey mite to culture the predatory mite *A. longispinosus*. French bean (*Phaseolus vulgaris* L.) plants were grown in earthen pots and the growth of these plants was monitored by counting the number of leaflets. Spider mites were introduced to these plants when they had three compound leaves. Nine days later, predators were released at a rate of ten per plant. After twelve days, the predators were collected and used for further experiments. This cycle was repeated to maintain the culture continuously.

Oligota sp. could not be cultured, so full-grown grubs and adults collected from the field were used for the study.

Searching efficiency

Twelve hours starved 1, 2, 4 and 8 fourth instar *S. pauperculus* grubs, 1, 2, 4 and 8 grubs of *Oligota* sp. *and* 1, 2, 4 and 8 adults of *A. longispinosus* were separately introduced into glass containers (15 cm 20 cm 8 cm) containing 200 individuals of mite, *T. urticae* on okra leaf, for the searching efficiency experiments. A muslin cloth was placed on top of the glass container and secured with a rubber band. The temperature during the study period ranged from 24 to 34°C. Predators were eliminated three hours after exposure and the quantity of mites they consumed was calculated. The ratio of the quantity of prey consumed to the density of predators was used to compute the prey consumption per predator (Song *et al*., 2016).

Functional response

The following numbers of *T. urticae* on okra leaf were kept individually in glass containers for this study: 50, 100, 200, 400, 600 and 800. Each glass container received one fourth instar *S. pauperculus* grub, one *Oligota* sp. grub and one *A. longispinosus* adult that had been pre-starved for twelve hours. The predators were removed from the container after twenty-four hours and the number of mites they had eaten was calculated. The ratio of eaten prey to beginning prey density was used to calculate the percent prey consumption (Madadi *et al*., 2007). Both the experiments were replicated five times. Area of discovery was calculated by following the formula given by Nicholson and Bailey (1935).

$$a = 1/P \log_e N/S$$

Where,

a= Area of discovery.

N= Prey density exposed for predation.

P= Predator density released for predation.

S= Number of prey surviving predation.

As per the new inductive model of searching efficiency proposed by Hassell and Varley (1969), which incorporate mutual interference constant (m), derived as:

$$a = Q/P^m$$

Where,

Q= Quest constant.

a= Area of discovery, when only one predator is searching.

m= Mutual interference constant (the slope of regression of log a on log P).

P= Predator density released for predation.

The log values of initial number of prey and predators were evaluated and data obtained were analysed by linear regression to determine the relationship between, (1) area of discovery and log initial number of predators and (2) area of discovery and log initial number of prey. The log values, *i.e*. log prey consumption and log prey density obtained from the data of second experiment were

subjected to regression analysis following a statistical package "Statistix 4.1" on PC. The disc equation proposed by Holling (1959) was transformed to nullify the assumption of constant prey density and to obtain a linear equation. This transformation was made following Livdhal and Stiven (1983) and Veeravel and Baskaran (1997).

Statistical analysis

The data on searching efficiency and functional response were subjected to one-way ANOVA using statistical software MINITAB on PC. Area of discovery in searching efficiency and functional response was calculated by following the formula given by Nicholson and Bailey (1935).

RESULTS AND DISCUSSION

Searching efficiency

When the predator density increased from one to eight, there was a significant increase in the consumption of prey by fourth instar larvae of *S. pauperculus*. The average number of *T. urticae* individuals consumed rose from 25.12±2.91 to 71.40±6.58. However, it is noteworthy that the prey consumption per predator actually decreased from 25.12 to 8.92 individuals as the predator density increased. Additionally, the area of prey discovery experienced a decline from 0.1335 to 0.0552 when one, two, four and eight predators were actively searching (Table 1). In this study, we observed a substantial rise in prey consumption by fourth instar larvae of *S. pauperculus* as the predator density increased. This finding highlights the potential impact of predator abundance on prey populations.

The number of prey consumed by *Oligota* sp. larvae increased significantly from an average of 11.40±1.67 individuals of *T. urticae*, when there was one predator, to 49.30±4.15 individuals when there were eight predators (Table 2). However, the number of prey consumed per predator decreased from 11.40 to 6.16 as the predator density increased. The area where prey was found also decreased from 0.0586 to 0.0353 as more predators searched for prey. This suggests that as more predators were present, the prey became more concentrated in specific areas, possibly because the predators were better at finding and catching prey, leading to a smaller area where prey was distributed.

The consumption of prey by adult *A. longispinosus* significantly increased from an average of 6.60±1.94 individuals of *T. urticae* to 22.80±2.28 individuals when the predator density increased from one to eight, while maintaining a constant prey density of 200. However, the prey consumption per predator decreased from 6.60 to 2.85 individuals as the predator density increased. Additionally, the area of prey discovery decreased from 0.0335 to 0.0151 when one, two, four and eight predators were actively searching (Table 3). In our study, we observed a remarkable rise in prey consumption by adult *A. longispinosus* as the number of predators increased. This finding suggests that the presence of more predators leads to a higher rate of prey consumption.

Functional response

The number of prey consumed by fourth instar larvae of *S. pauperculus* increased significantly, ranging from 16.25±2.21 to 89.00±1.82 individuals of *T. urticae* (Table 4). However, the percentage of prey consumed decreased from 32.50 to 11.12 as the prey density increased from 50 to 800. Additionally, the area where larvae found prey decreased from 0.3930 to 0.1179 with the increase in prey density. Similarly, the number of prey consumed by *Oligota*

Table 1: Prey consumption and area of discovery of *S. pauperculus* at different densities against *T. urticae.*

Predator density	Total prey consumed*$ (nos.)	Prey consumption per predator (nos.)*	Area of discovery
1	25.12±2.91^{d}	25.12^{a}	0.1335
2	34.00±1.87^{c}	17.00^{b}	0.0931
4	54.20±3.27^{b}	13.55^{c}	0.0790
8	71.40±6.58^{a}	8.92^{d}	0.0552

*Mean of five replications in each treatment.

$ Values represented in mean±standard error.

In a column, means followed by a common letter(s) are not significantly different by LSD (P=0.05).

Table 2: Prey consumption and area of discovery of *Oligota* spp. at different densities against *T. urticae.*

Predator density	Total prey consumed*$ (nos.)	Prey consumption per predator (nos.)*	Area of discovery
1	11.40±1.67^{d}	11.40^{a}	0.0586
2	17.30±2.07^{c}	8.65^{b}	0.0452
4	28.80±1.92^{b}	7.20^{c}	0.0388
8	49.30±4.15^{a}	6.16^{d}	0.0353

*Mean of five replications in each treatment.

$ Values represented in mean±standard error.

In a column, means followed by a common letter(s) are not significantly different by LSD (P=0.05).

sp. grubs also increased significantly, ranging from 11.25±2.98 to 65.00±2.16 individuals of *T. urticae* (Table 5). However, the percentage of prey consumed decreased from 22.50 to 8.12 as the prey density increased from 50 to 800. Furthermore, the area where a grub found prey decreased from 0.2548 to 0.0847 with the increase in prey density.

In the study of adult *A. longispinosus*, there was a notable increase in the number of prey consumed, ranging from 7.75±1.25 to 47.25±3.50 individuals of *T. urticae*. However, the percentage of prey consumed decreased from 15.50 to 5.90 as the prey density increased from 50 to 800. Furthermore, the area where prey was discovered decreased from 0.1684 to 0.0608 as the prey density increased (Table 6). These findings highlight the notable variations in prey consumption, percentage of prey consumption and area of discovery among different developmental stages and species. The increase in prey density had contrasting effects on the consumption patterns, with prey consumption increasing while the percentage of prey consumption decreased. Moreover, the area of discovery decreased as the prey density increased.

Searching efficiency and functional response are important factors to consider when choosing effective predators for biocontrol. In our study, we kept a constant prey density of 200 prey (*T. urticae*) and found that fourth instar larvae of *S. pauperculus* consumed prey at a higher rate. However, the percentage of prey consumed per predator decreased as predator density increased. This pattern was also seen in *Oligota* sp. and *A. longispinosus* when feeding on *T. urticae*. Interestingly, doubling the density of *S. pauperculus* did not result in a doubling of prey consumed, indicating competition among predators for available prey. Further analysis showed that while the consumption rate increased with more larvae present, the rate of consumption per individual larva decreased. Similar trends were observed in *Oligota* sp. and *A. longispinosus*. These results suggest

Table 3: Prey consumption and area of discovery of *A. longispinosus* at different densities against *T. urticae.*

Predator density	Total prey consumed*$ (nos.)	Prey consumption per predator (nos.)*	Area of discovery
1	6.60±1.94^{d}	6.60^{a}	0.0335
2	9.40±1.81^{c}	4.70^{b}	0.0240
4	13.40±1.14^{b}	3.35^{c}	0.0173
8	22.80±2.28^{a}	2.85^{d}	0.0151

*Mean of five replications in each treatment.

$ Values represented in mean±standard error.

In a column, means followed by a common letter(s) are not significantly different by LSD (P=0.05).

Table 4: Functional response of *S. pauperculus* at different prey densities.

Prey density	Total prey consumed*$ (nos.)	Prey consumption* (%)	Area of discovery
50	16.25±2.21^{f}	32.50^{a}	0.3930
100	21.50±2.08^{e}	21.50^{b}	0.2420
200	32.50±1.29^{d}	16.25^{c}	0.1773
400	55.00±3.16^{c}	13.75^{cd}	0.1479
600	73.50±3.10^{b}	12.25^{d}	0.1306
800	89.00±1.82^{a}	11.12^{d}	0.1179

*Mean of five replications in each treatment.

$ Values represented in mean±standard error.

In a column, means followed by a common letter(s) are not significantly different by LSD (P=0.05).

Table 5: Functional response of *Oligota* spp. at different prey densities.

Predator density (Fourth instar larva)	Prey density	Total prey consumed*$ (nos.)	Prey consumption* (%)	Area of discovery
1	50	11.25±2.98^{f}	22.50^{a}	0.2548
1	100	15.75±1.70^{e}	15.75^{b}	0.1713
1	200	25.25±2.21^{d}	12.62^{c}	0.1349
1	400	38.25±1.70^{c}	9.56^{d}	0.1005
1	600	54.50±2.64^{b}	9.08^{d}	0.0952
1	800	65.00±2.16^{a}	8.12^{d}	0.0847

*Mean of five replications in each treatment.

$ Values represented in mean±standard error.

In a column, means followed by a common letter(s) are not significantly different by LSD (P=0.05).

that having more predators may hinder foraging and feeding success by competing for prey and interfering with each other. These findings support previous studies by Evans (1991) and Phoofolo and Obrycki (1998).

There are two ways in which the quantity of predators might affect the discovery area. First and foremost, when predators search individually, their relatively high activity compared to that of a high predator density leads to an increased area of discovery. Secondly, at low predator density, the prey experiences shorter handling time, which also contributes to an increased area of discovery (Hassell and Varley, 1969). In summary, the area of discovery for *S. pauperculus*, *Oligota* sp. and *A. longispinosus* has shown a significant decrease. This decline can be attributed to various factors, including both intra and interspecific interferences. The density of predators plays a crucial role in determining the area of discovery. When predators search individually, their heightened activity results in a larger area of discovery. Additionally, at low predator density, prey experiences shorter handling time, leading to an increased area of discovery. These findings shed light on the complex dynamics between predators and prey and highlight the importance of considering predator density when studying the area of discovery.

Functional response studies have revealed significant findings regarding prey consumption rates by *S. pauperculus*, *Oligota* sp. and *A. longispinosus*. As prey density increased, the consumption rate increased while the percentage of prey consumption decreased. This observation aligns with the Holling Type II predatory response, as described by Holling (1959). These findings are consistent with previous research conducted on other coccinellid beetles, as documented by Yasuda and Ishikawa (2001), as well as Kumar *et al*. (1999). When a single larva was searching for prey, the consumption rate initially increased rapidly and then gradually decelerated, eventually reaching a plateau. At this point, the consumption rate remained relatively constant, regardless of any further increase in prey density. It was also observed that the area of prey discovery decreased at higher prey densities, potentially due to a more restricted and intensive search, which increased the predator's exposure to prey individuals. This phenomenon of prey clumping at higher densities has also been noted by Munyaneza and Obrycki (1998), in relation to *Coleomegilla maculata* de Geer larvae. Furthermore, higher prey densities resulted in a reduction of unsuccessful predator attacks on prey, as the chances of escape for the prey decreased. Conversely, in situations with scarce prey densities, there were more opportunities for the prey to escape from the predator, as noted by O'Neil (1988).

Functional response studies have shown important discoveries about how much prey *S. pauperculus*, *Oligota* sp. and *A. longispinosus* consume. As the number of prey increased, the consumption rate also increased, but the percentage of prey consumed decreased. This pattern is consistent with the Holling Type II predatory response, as explained by Holling (1959). These findings support previous research on other coccinellid beetles, as reported by Yasuda and Ishikawa (2001) and Kumar *et al*. (1999). When a single larva was hunting for prey, the consumption rate initially rose quickly, then slowed down until it reached a plateau. After reaching this point, the consumption rate stayed relatively constant, even if more prey were added. It was also observed that the area where prey was found decreased at higher prey densities, possibly because the search became more focused and intense, leading to more encounters between predators and prey. This clustering of prey at higher densities has also been seen in *Coleomegilla maculata* de Geer larvae by Munyaneza and Obrycki (1998). Additionally, higher prey densities led to fewer unsuccessful predator attacks, as the chances for prey to escape decreased.

The assemblage of prey also influenced the searching behavior of the predators. At lower prey densities, *T. urticae* were more widely spaced out, requiring more time and energy for the predators to locate them due to the dispersed prey pattern. Although, with greater prey densities, there was a constant availability of prey for consumption. In field conditions, predators may spend more time searching for patches where prey is present, as observed by (Tamaki and Long, 1978). In the context of high prey density, satiation emerges as a plausible explanation for the observed decrease in the percentage of prey consumed. It appears

Table 6: Functional response of *A. longispinosus* at different prey densities.

Predator density (Fourth instar larva)	Prey density	Total prey consumed*$ (nos.)	Prey consumption* (%)	Area of discovery
1	50	7.75±1.25^{f}	15.50^{a}	0.1684
1	100	13.25±1.70^{e}	13.25^{a}	0.1421
1	200	21.50±3.51^{d}	10.75^{b}	0.1137
1	400	31.75±2.21^{c}	7.93^{c}	0.0827
1	600	42.00±2.16^{b}	7.00^{cd}	0.0725
1	800	47.25±3.50^{a}	5.90^{d}	0.0608

*Mean of five replications in each treatment.

$ Values represented in mean±standard error.

In a column, means followed by a common letter(s) are not significantly different by LSD (P=0.05).

that satiated beetles allocate more time to the intricate process of prey handling, consequently leading to a decline in the rate of prey capture (Veeravel and Baskaran, 1997; Dreyer *et al*., 1997; Mora *et al*., 1995).

Since there are fewer options for prey to flee from a predator when there is a higher prey density than when there is a lower prey density, predator attacks that fail are also decreased. The gathering of the prey also had an effect on the search. *T. urticae* were more difficult to find because they were more dispersed at lower prey densities compared to higher prey densities, where there was an abundant supply of prey. The predator may need more time when hunting in the field to find the spot where the prey was hiding. The percentage of prey consumed at high prey density may have decreased because satiated beetles handle their prey for a longer period of time as a result of being satiated. Search effectiveness and functional responsiveness are key considerations when selecting predators for biocontrol.

CONCLUSION

The study delves into the efficacy of searching and functional response in the selection of efficient predators for biocontrol purposes. It was discovered that fourth instar larvae of*S. pauperculus* exhibited an increase in consumption rate, however, the percentage of prey consumption per predator decreased as predator density increased. This pattern was also observed in *Oligota* sp. and *A. longispinosus* when preying on *T. urticae*. The presence of a higher number of predators may have impeded the foraging and feeding success of conspecifics by consuming visible prey and interfering with one another. The density of predators can impact the area of discovery, with a greater predator density resulting in a larger area of discovery and a lower density leading to a shorter handling time for prey. Functional response studies indicated that as prey density rose, the consumption rate increased while the percentage of prey consumption decreased. Higher prey densities led to a decrease in unsuccessful predator attacks on prey, whereas scarce prey densities provided more opportunities for prey to escape.

Conflict of interest

Authors do not have any conflict of interest to declare.

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