Foraging Behavior of Two Coccinellid Species (Coleoptera: Coccinellidae) Fed on Aphids[1]

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ABSTRACT   Searching rate, mutual interference, and killing power were studied for two predator species, *Coccinella undecimpunctata* L. and *Hippodamia tredecimpunctata* L. (Coleoptera: Coccinellidae), provided with two prey species, *Aphis gossypii* (Glover) and *Aphis punicae* (Shinji) (Hemiptera: Aphididae), under laboratory conditions of $27 \pm 2°C$ and $70 \pm 5\%$ RH. The searching rate of larvae and adult female *C. undecimpunctata* was higher than that of *H. tredecimpunctata*. Both *C. undecimpunctata* and *H. tredecimpunctata* exhibited higher searching rates when fed on *A. gossypii* than when fed on *A. punicae*. Larvae and adults of *C. undecimpunctata* showed higher searching rates than *H. tredecimpunctata* on both prey species. Mutual interference values for larval stage of both *C. undecimpunctata* and *H. tredecimpunctata* were higher than those for adults. For *H. tredecimpunctata* feeding on *A. gossypii*, respective values were 0.148, 0.190, 0.118, 0.070, and 0.069 for 1st, 2nd, 3rd, 4th larval instars and adults, respectively; while these values were 0.161, 0.167, 0.218, 0.140, and 0.058 on *A. punicae*, respectively. In conclusion, our laboratory data suggest that *C. undecimpunctata* might be a more efficient predator of *A. gossypii* and *A. punicae* compared with *H. tredecimpunctata*.

Aphids are cosmopolitan plant pests that occur in tropical, subtropical, and warm temperate regions. These pests may become more abundant due to the intensive use of insecticides, which can alter the natural balance between pests and their natural enemies (Cook 1993). The evolution of insecticide resistance and growing concerns of the environmental hazards of frequent insecticide applications have prompted more emphasis on biological control agents of aphids (van Emden & Harrington 2007), especially the use of predators (Sarmento et al. 2007). For example, the predatory gall midge, *Aphidoletes aphidomyza* Rondani (Diptera: Cecidomyiidae), has been employed successfully for aphid control in cucumber culture (Bennison & Corless 1993).

Coccinellid beetles (Coleoptera: Coccinellidae) are an important group of predatory insects with considerable biocontrol potential against aphids and other pests (Srikanth & Lokkundi 1990, Hodek & Honek 1996, Michaud 2012). They

feed on a wide range of prey and can exhibit rapid numerical responses (Hodek & Honek 1996, Bayoumy 2011a). However, they do not always maintain prey populations in check (Michaud 2012). Nevertheless, evaluation of particular aphidophagous species in specific agronomic situations are needed to assess their biological control potential (Heimpel & Jervis 2005). According to our field observations (unpublished data), *Coccinella undecimpunctata* L. and *Hippodamia tredecimpunctata* L. (Coleoptera: Coccinellidae) are among the most dominant predators associated with aphids in Qassim Province, Saudi Arabia.

Several previous studies of coccinellid predators have dealt with functional and numerical responses (Ofuya & Akingbohungbe 1988, Veeravel & Baskaran 1997, Agarwala & Bardhanroy 1999, Xia et al. 2003, Farhadi et al. 2010, Bayoumy 2011a). According to Hassel & Varley (1969), Hassel (1971), and Delong & Vasseur (2011), mutual interference is known as the interference competition which occurs when access to resources is negatively affected by the presence of other individuals. Searching behavior is the active movement by which insects seek food (Bell 1990). On the other hand, Abd El-Kareim (1998) defined the killing power as a specific mortality caused by factors such as predation, parasitism, and natural mortality.

Abd El-Kareim (1998, 2002) and Bayoumy & Michaud (2012) studied searching rate, mutual interference, and killing power of the coccinellids *C. undecimpunctata*, *Chilocorus bipustulatus* (L.), *Exochomus flavipes* (Thunb), and *Nephus includens* (Kirsch). However, there is a lack of information about foraging behavior of *H. tredecimpunctata*. Therefore, the present study aims to evaluate the searching rate, mutual interference, and killing power of *H. tredecimpunctata* in comparison with *C. undecimpunctata* when they were fed on *Aphis gossypii* (Glover) and *Aphis punicae* (Shinji) (Hemiptera: Aphididae) in the laboratory.

Materials and Methods

Predator cultures. Approximately 100 adults each of *C. undecimpunctata* and *H. tredecimpunctata* were collected using a sweep net in a greenhouse of sweet pepper (*Capsicum fruitascens* L.) located at the College of Agriculture and Veterinary Medicine, Qassim University, Saudi Arabia in 2013. Under laboratory conditions of $27 \pm 2°C$ and $70 \pm 5\%$ RH, the collected individuals of each species were kept in plastic chimney cages (30 cm in diam. and 25 cm height) and provided daily with cucumber leaves (*Cucumis sativus* L.) (Cucurbitaceae) that were highly infested with *A. gossypii* as a food source. Twenty pairs each of *C. undecimpunctata* and *H. tredecimpunctata* were sexed. Mated females were isolated in Petri dishes (12-cm diam.) containing the same prey. Dishes were examined daily and the numbers of eggs that had been deposited were recorded. Eggs were transferred to new Petri-dishes and their development was daily checked. Hatching larvae were provided with aphids as food throughout the experiments.

Foraging behavior. Searching rate and mutual interference values for *C. undecimpunctata* and *H. tredecimpunctata* were examined using the two prey species, *A. gossypii* and *A. punicae* under laboratory conditions of $27 \pm 2°C$ and $70 \pm 5\%$ RH. Newly molted predator larvae (1st, 2nd, 3rd, and 4th instars) and newly eclosed adult females were starved for 24 hours before experiments. To evaluate searching rate and mutual interference values, five densities (1, 2, 3, 4, or 5

individuals) of each predator stage (including adults) were tested in response to both prey species. Naturally infested leaves of cucumber with *A. gossypii* and pomegranate (*Punica granatum* L.) (Lythraceae) with *A. punicae* were used. Quantities of 50, 150, 250, and 500 aphid individuals (mixture of 2nd and 3rd nymphal instars) were introduced daily into 12-cm Petri dishes containing the starved 1st, 2nd, 3rd, and 4th instar predator larvae, respectively. Adults of each predator were provided with other 500 aphids. After two days, treatments were examined and the numbers of remaining live aphids were counted. Experiments were replicated five times for each predator density.

The formula of Varley et al. (1973) was used to estimate predator searching rate:

$$a_t = 1/P \: log_e \: N/N\text{-}N_a;$$

where, a is the searching rate, t is the time of exposure (2 days), P is the predator density, N is the prey density, and N_a is the number of prey consumed.

Because searching rate is not constant and there is mutual interference among predators, the model of Hassel &Varley (1969) was used:

$$a_t = QP^{-m};$$

where, a is the searching rate, t is the time of exposure (2 days), Q is the quest constant (searching rate of one predator individual), m is the mutual interference constant (slope of regression of log a_t divided by log P), and P is the predator density. Thus, the equation becomes linear as follows:

$$log \: a_t = log \: Q - m \: log \: P.$$

Killing power. The killing power (K-value) for larvae and adult predators was examined at three predators:prey ratios for the two prey species tested. In Petri-dishes (12 cm diam.), ratios of 1:50, 1:100, and 1:150 (predator:prey) were evaluated. Cucumber leaves naturally infested with *A. gossypii* and pomegranate infested with *A. punicae* were used. After two days, treatments were examined and the numbers of remaining live aphids were counted. Experiments were replicated five times for each predator:prey ratio.

The K-value was calculated according to Varley et al. (1973):

$$K\text{-}value = log_e \: N/N\text{-}N_a;$$

where, N is the prey density and N_a is the number of prey consumed.

Results

First instar predators. Searching rate values (a) of first instar *C. undecimpunctata* were higher than that of *H. tredecimpunctata*, while both
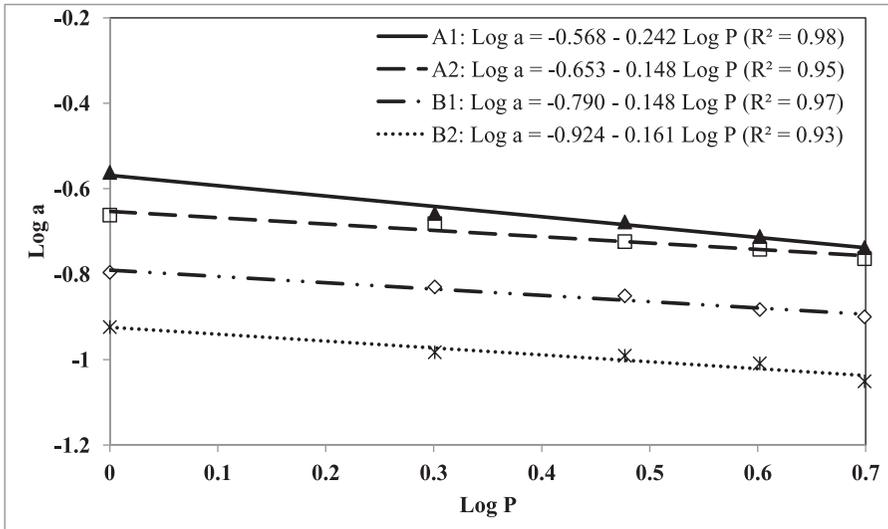
Legend inside figure:
A1: Log a = -0.568 - 0.242 Log P (R² = 0.98)
A2: Log a = -0.653 - 0.148 Log P (R² = 0.95)
B1: Log a = -0.790 - 0.148 Log P (R² = 0.97)
B2: Log a = -0.924 - 0.161 Log P (R² = 0.93)

Fig. 1. Relationship between predator density (log P) and searching rate (log a) of 1st instar *C. undecimpunctata* (A) and *H. tredecimpunctata* (B) in response to *A. gossypii* (1) and *A. punicae* (2).

predators exhibited relatively higher searching rates when fed on *A. gossypii* compared with *A. punicae* (Figure 1). Searching rates of *C. undecimpunctata* on *A. gossypii* and *A. punicae* were 0.270 and 0.222 respectively; while, these values were 0.162 and 0.119 for *H. tredecimpunctata*. Mutual interference values for *C. undecimpunctata* and *H. tredecimpunctata* were 0.148 and 0.161, respectively, for *A. punicae* and 0.242 and 0.148, respectively, for *A. gossypii*. Intraspecific competition (interference values) between individuals of *C. undecimpunctata* was higher on a diet of *A. gossypii* than on *A. punicae*, while for *H. tredecimpunctata*, these values were higher on *A. punicae* than *A. gossypii* (Figure 1). The highest K-values were obtained at the 1:50 predator:prey ratio. K-values for both predators were higher on *A. gossypii* than on *A. punicae*. Furthermore, K-values for *C. undecimpunctata* were higher than those for *H. tredecimpunctata* (Figure 2).

Second instar predators. Searching rate values of *C. undecimpunctata* on *A. gossypii* and *A. punicae* were 0.225 and 0.215; while these values were 0.192 and 0.166 for *H. tredecimpunctata* (Figure 3). Mutual interference values for *C. undecimpunctata* on *A. gossypii* and *A. punicae* were 0.091 and 0.092, and reached 0.190 and 0.167 for *H. tredecimpunctata* fed on *A. gossypii* and *A. punicae* (Figure 3). K-values for *C. undecimpunctata* at the 1:50 predator:prey ratio reached 0.63 and 0.44 for *A. gossypii* and *A. punicae*, respectively, and decreased with an increase of prey numbers (Figure 4). At the highest ratio (1:150), K-values were 0.16 and 0.13 for *C. undecimpunctata* on *A. gossypii* and *A. punicae*, respectively. K-values for *H. tredecimpunctata* also decreased with increasing prey numbers (Figure 4). At the predator:prey ratio of 1:50, K-values were 0.48 and 0.43, and at 1:150 they were 0.16 and 0.13 for *A. gossypii* and *A. punicae*, respectively.
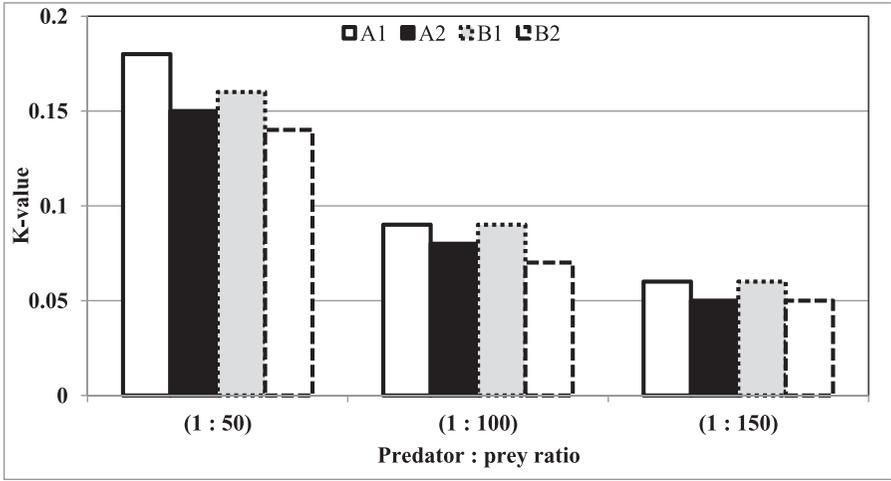
Fig. 2. K-values of 1ˢᵗ instar *C. undecimpunctata* (A) and *H. tredecimpunctata* (B) at different predator: prey ratios in response to *A. gossypii* (1) and *A. punicae* (2).

Third instars. The searching rate of *C. undecimpunctata* was higher than that of *H. tredecimpunctata*, while both predators exhibited higher searching rates when fed on *A. gossypii* (Figure 5). Searching rates for *C. undecimpunctata* on *A. gossypii* and *A. punicae* were 0.234 and 0.219, respectively; while, for *H. tredecimpunctata*, theses values were 0.164 and 0.136, respectively. The mutual
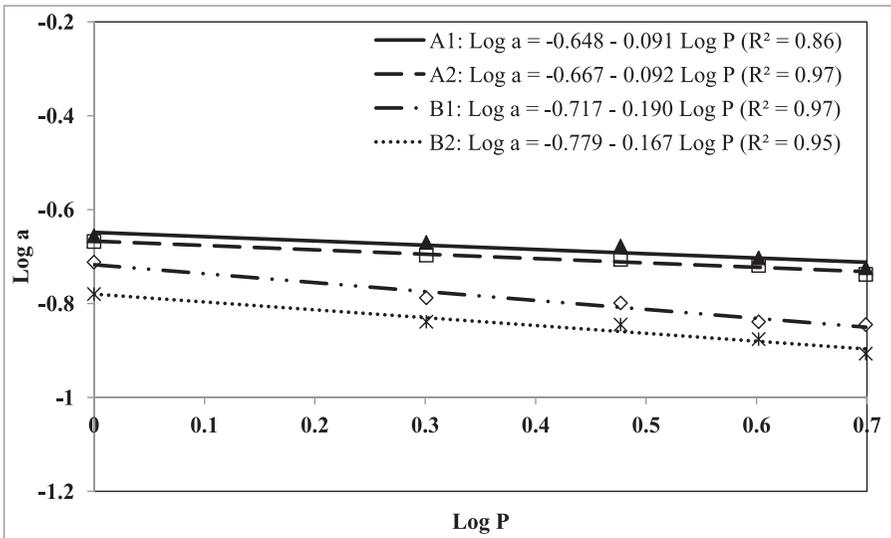

Fig. 3. Relation between predator density (log P) and searching rate (log a) of 2ⁿᵈ instar *C. undecimpunctata* (A) and *H. tredecimpunctata* (B) in response to *A. gossypii* (1) and *A. punicae* (2).
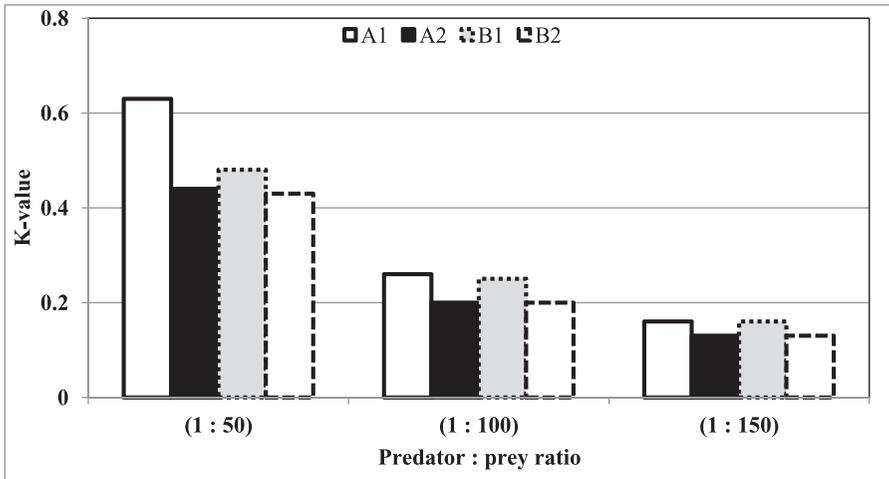
Fig. 4. K-values of 2nd instar *C. undecimpunctata* (A) and *H. tredecimpunctata* (B) at different predator:prey ratios in response to *A. gossypii* (1) and *A. punicae* (2).

interference value for *C. undecimpunctata* fed *A. punicae* (0.097) was lower than it was on *A. gossypii* (0.128). In contrast, the mutual interference value for *H. tredecimpunctata* on *A. gossypii* (0.118) was lower than it was on *A. punicae* (0.218) (Figure 5). K-values for *C. undecimpunctata* were relatively higher than
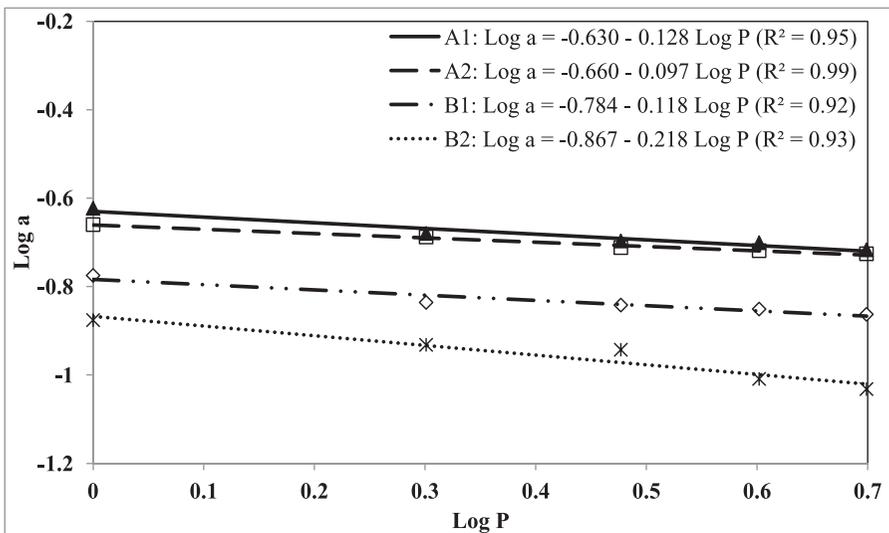

Fig. 5. Relationship between predator density (log P) and searching rate (log a) of 3rd instar *C. undecimpunctata* (A) and *H. tredecimpunctata* (B) in response to *A. gossypii* (1) and *A. punicae* (2).
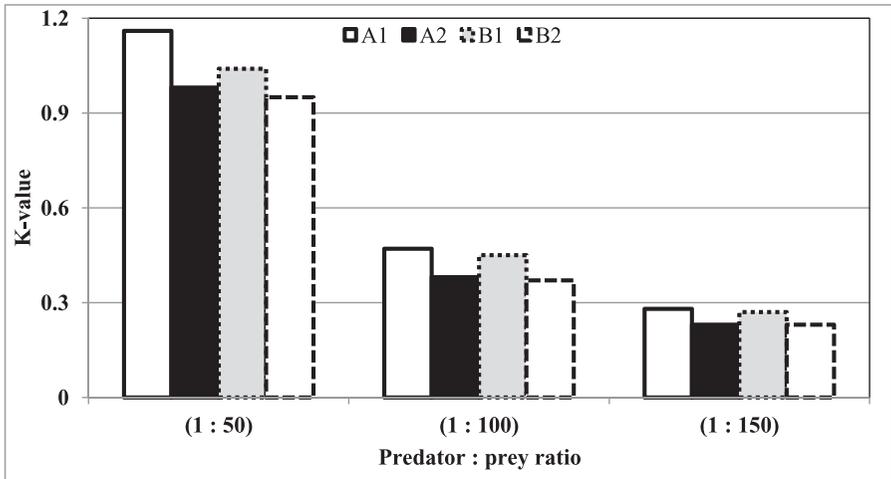
Fig. 6. K-values caused by 3rd instar *C. undecimpunctata* (A) and *H. tredecimpunctata* (B) at different predator: prey ratios in response to *A. gossypii* (1) and *A. punicae* (2).

those for *H. tredecimpunctata* on both *A. gossypii* and *A. punicae* (Figure 6). At the 1:50 predator:prey ratio, K-values for *C. undecimpunctata* on *A. gossypii* and *A. punicae* were 1.16 and 0.98, respectively; while for *H. tredecimpunctata*, these values were 1.04 and 0.95 on *A. gossypii* and *A. punicae*, respectively. All K-values decreased with an increase in prey numbers.

Fourth instars. Both predators exhibited relatively higher searching rates on *A. gossypii* (0.326 and 0.220) than they did on *A. punicae* (0.318 and 0.204). Mutual interference values for *C. undecimpunctata* and *H. tredecimpunctata* on *A. gossypii* were 0.142 and 0.070, while on *A. punicae*, these values were 0.144 and 0.140, respectively. Therefore, by increasing predator density, the searching rate per fourth instar was decreased more on *A. punicae* than on *A. gossypii* (Figure 7). At the 1:50 predator:prey ratio, the K-values of *C. undecimpunctata* on *A. gossypii* and *A. punicae* were 3.62 and 2.72, respectively; while these values were 3.40 and 2.01 for *H. tredecimpunctata* on *A. gossypii* and *A. punicae*, respectively (Figure 8). K-values for *C. undecimpunctata* and *H. tredecimpunctata* on *A. gossypii* at the 1:100 predator:prey ratio were 1.26 and 1.23, respectively; while for *A. punicae*, these values were 1.08 and 1.06 for *C. undecimpunctata* and *H. tredecimpunctata*, respectively. At the predator:prey ratio of 1:150, K-values of *C. undecimpunctata* on *A. gossypii* and *A. punicae* were 0.65 and 0.59, respectively; while these values were 0.64 and 0.58 for *H. tredecimpunctata* on *A. gossypii* and *A. punicae*, respectively.

Adults. Adult predators showed higher searching rates on *A. gossypii* than on *A. punicae* (Figure 9). Searching rates for *C. undecimpunctata* on *A. gossypii* and *A. punicae* were 0.283 and 0.221, respectively; while, these values were 0.216 and 0.174 for *H. tredecimpunctata*. Mutual interference values for *C. undecimpunctata* on *A. gossypii* and *A. punicae* were the same (0.025) while the value for *H. tredecimpunctata* on *A. punicae* (0.058) was lower than it was on *A. gossypii*
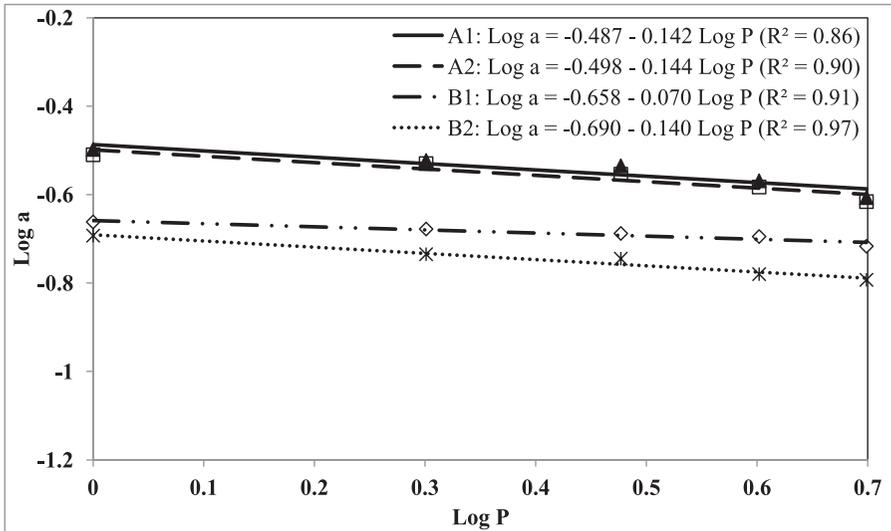
Fig. 7. Relationship between predator density (log P) and searching rate (log a) of 4th instar *C. undecimpunctata* (A) and *H. tredecimpunctata* (B) in response to *A. gossypii* (1) and *A. punicae* (2).

(0.069). In this case, by increasing predator density, searching rate per adult was decreased more on *A. gossypii* than it was on *A. punicae* (Figure 9). K-values for *C. undecimpunctata* and *H. tredecimpunctata* on *A. gossypii*, at 1:50 predator: prey ratio, were 4.22 and 4.32, respectively; while these values were 3.55 and 3.22
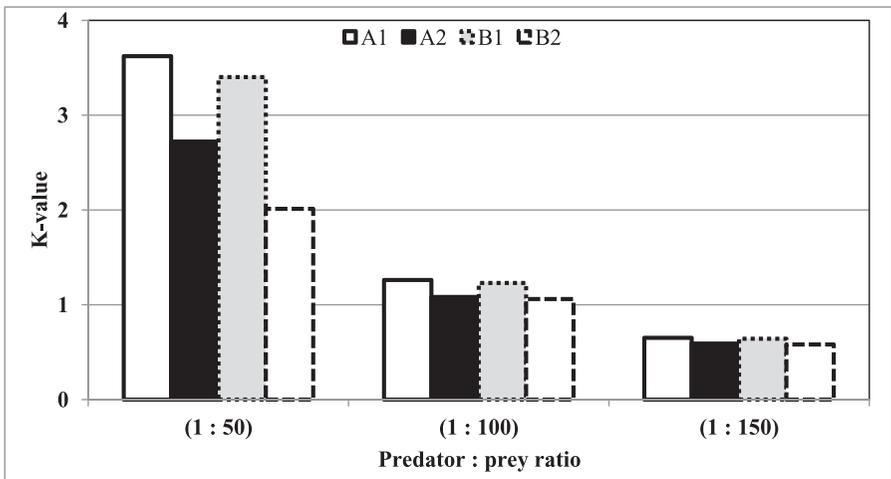

Fig. 8. K-values of 4th instar *C. undecimpunctata* (A) and *H. tredecimpunctata* (B) at different predator: prey ratios in response to *A. gossypii* (1) and *A. punicae* (2).
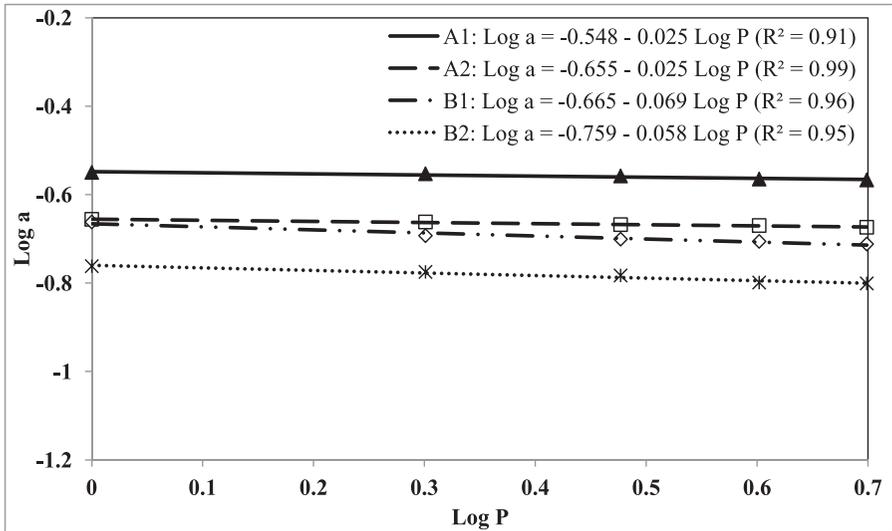
Fig. 9. Relationship between predator density (log P) and searching rate (log a) of *C. undecimpunctata* (A) and *H. tredecimpunctata* (B) adults in response to *A. gossypii* (1) and *A. punicae* (2).

on *A. punicae* (Figure 10). K-values decreased with the increase in prey numbers. The K-values for *C. undecimpunctata* and *H. tredecimpunctata* on *A. gossypii* at the ratio of 1:150 were 0.70 and 0.69, respectively; while these values were 0.63 and 0.62 on *A. punicae*.
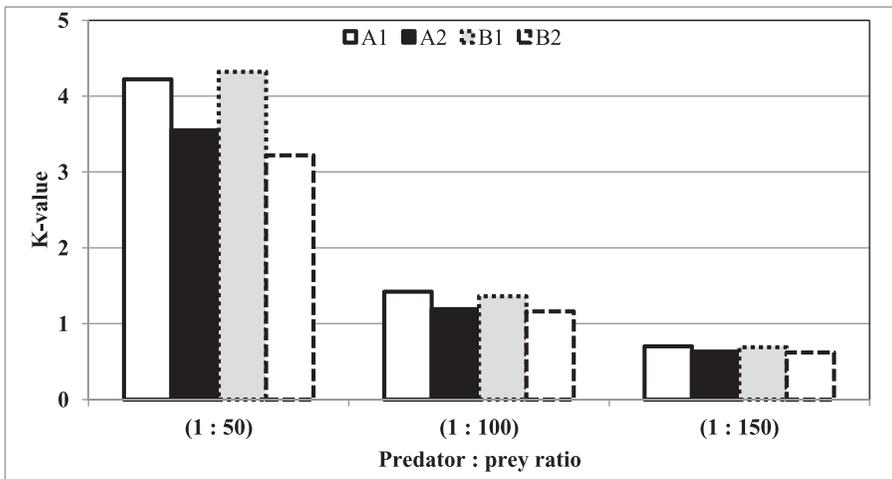

Fig. 10. K-values of adult *C. undecimpunctata* (A) and *H. tredecimpunctata* (B) at different predator: prey ratios in response to *A. gossypii* (1) and *A. punicae* (2).

Discussion

For all life stages, *C. undecimpunctata* exhibited higher searching efficiency than *H. tredecimpunctata* on both prey species that were tested. According to Rogers & Hassell (1974), searching rate for a natural enemy may be inversely correlated with increases in its density, which is thought to stem from intra specific interference. As the density of conspecifics increases, each individual predator spends less time searching for prey and more time interacting with other conspecifics (i.e., mutual interference) (Hassell 1971). Thus, increasing predator density causes a reduction in foraging efficiency. This negative effect was greater for *H. tredecimpunctata* larvae and adults than it was for *C. undecimpunctata*. In addition, these negative influences were greater on larvae than they were on adults for both predator species. While laboratory studies cannot be directly extrapolated to field conditions, the data suggest that aggregation of both predator species in a specific prey patch will increase negative conspecific interactions. The same effect has been documented for other coccinellid predators in relation to their prey (Abd El-Fattah et al. 1987, Abd El-Kareim 1998, Bayoumy & Michaud 2012). Abdel-Fattah et al. (1987) reported that intraspecific competition among *C. undecimpunctata* individuals reduced their searching rate.

Arditi et al. (2004) suggested that predator searching parameters other than interference are important. Natural enemy populations will be enhanced by higher searching efficiency, higher conversion efficiency, lower handling time, and lower mortality. According to Hassel & Varley (1969), there was an adverse influence of predator density on searching efficiency in the same experimental arena. This effect was due to the direct behavioral interference between searching individuals (e.g., being more aggressive to obtain more food). However, aggregation of predator in the same patches with high prey density could lead to a similar effect (Free et al. 1977).

The present investigation revealed that the searching rate and interference value of *C. undecimpunctata* and *H. tredecimpunctata* were affected by the prey species. Specifically, searching rates of both predators were higher on *A. gossypii* than on *A. punicae*, which implies that *A. gossypii* may be the favorable food source. The foraging behavior and predatory efficiency of coccinellids may be affected by many factors including their developmental stage (Koch et al. 2003, Osman & Bayoumy 2011), body size (Kajita & Evans 2010), the prey species (Abd El-Kareim 2002, Sarmento et al. 2007), prey density (Matter et al. 2011), temperature (Skirvin et al. 1997), foraging cues (Hodek & Honek 1996, Pasteels 2007), plant architecture (Grevstad & Klepetka 1992), cannibalism and intraguild predation (Burgio et al. 2002), food deprivation (Santos-Cividanes et al. 2011), and entomopathogenic fungi (Poprawski et al. 1998).

The present results indicated that killing power (k-values) for *C. undecimpunctata* were higher than *H. tredecimpunctata*. The higher killing power for *C. undecimpunctata* is derived from its higher searching rates. According to Abd El-Kareim (1998), Bayoumy (2011a), and Bayoumy & Michaud (2012), searching rate increased as the predator density increased. While the number of consumed prey by both predators increased with prey density, the highest power of killing occurred at the lower prey density. This type II functional response (inverse-density dependent mortality) is the most common type reported for coccinellid

predators (Ofuya & Akingbohungbe 1988, Uygun & Atlihan 2000, Isikber 2005, Bayoumy 2011b). For a type II response, there should be a decline in the proportion of prey consumed as the density increases, so that the linear term should be negative. Natural enemies with a type II response are regulative biocontrol agents (Fernandez-Arhex & Corley 2003).

The adult stage of both predators had the highest prey consumption rate in our studies. Lohar et al. (2012) similarly found that *Hippodamia convergens* adults were the most voracious stage, which was attributed to their higher requirement of proteins for oviposition. In contrast, another study reported that fourth-instar *C. undecimpunctata* had a higher consumption rate compared with adults (Cabral et al. 2006, Moura et al. 2006). This difference may be due to the different prey species or experimental conditions used in the latter studies.

In conclusion, due to its higher searching rate, higher killing power, and lower mutual interference, *C. undecimpunctata* may play a more effective role in controlling *A. gossypii* and *A. punicae* than *H. tredecimpunctata*. Field studies are needed to confirm how behavior of different life stages of these predators may be used in biological pest control strategies. For example, the adult stage may be more likely to disperse from release sites compared with immature stages.

Acknowledgments

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