PREDATION OF THE LADYBEETLE *CHILOCORUS KUWANAE* ON THE SCALE *UNASPIS YANONENSIS*

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Abstract The prey consumption of ovipositing female adults of the ladybeetle *Chilocorus kuwanae* on the scale *Unaspis yanonensis* was found to be significantly greater than that of the male adults. At 25℃ one female adult ladybeetle, on average, would consume 42.7 female scale adult per day while one male adult only destroyed 22.3 female scale adults. However, after a deprivation of the prey for 48 h, this difference was eliminated. A *C. kuwanae* female adult had to prey on at least 15 *U. yanonensis* female adults in order to lay eggs. The funcional responses of the beetle adults to densities of different stages of the scale followed Holling's type Ⅱ. The functional responses to female scale adults indicated that the maximum prey consumption went up with the increase in temperature from 16℃ to 35℃, and dropped sharply at 37℃. However, temperature did not alter the type of the functional response. Based on the predation of *C. kuwanae* adults on *U. yanonensis* female adults, the minimum critical, optimal and maximum critical temperatures for their attack were estimated to be 10.6℃, 31.5℃ and 38.2℃ respectively. The increase in predation space or in predator density could result in a reduction in the attack rate, but with the increase of predator density, the effect of predation space became much smaller. *C. kuwanae* adults preferred male pupae to other stages of the scale, and their preference for various stages of the prey was in the order of male pupae, 2nd-instar male nymphs, 2nd-instar female nymphs, adult females and 1st-instar nymphs.

Key words *Chilocorus kuwanae*, *Unaspis yanonensis*, predation, functional response, selective efficiency, interference

1 INTRODUCTION

Chilocorus kuwanae (Silvestri), a predaceous coccinellid of armored scales, is widely distributed in many countries such as China, Japan, Korea and Italy (Pang and Mao 1979). In the practice of classical biological control, many good results have been achieved with this predator in controlling some armored scales that seriously affect agricultural production (Huang 1985). When *C. kuwanae* was successfully introduced into the United States, it became an important factor in suppressing the local armored scales with remarkable control effects (Huang 1985, Drea and Carlson 1987, Hendrickson *et al.* 1991, Nalepa *et al.* 1993). There are many reports dealing with the ladybeetle's biology (Xia *et al.* 1985, Yang *et al.* 1996), mass rearing (Xia *et al.* 1987)and field control trials (Zhang 1983, Xia *et al.* 1985, Yang *et al.* 1992).

One of its favorite preys is the arrowhead scale *Unaspis yanonensis* (Kuwana), a key insect pest of citrus in Guizhou Province and many other places in China. Citrus trees can be greatly debilitated by the infestation of the scale, or even withered. Though slightly infested, a citrus orchard can be easily ruined by the pest within a short period of time if no appropriate control measures are taken. Furthermore, this scale is resistant to insecticides which would eliminate its natural enmies. However, good results could be achieved with *C. kuwanae* and other predaceous ladybeetles (Yang *et al.* 1992). As an outstanding natural enemy of arrowhead scale, *C. kuwanae* deserves to be studied in detail in its predation behavior. Unfortunately, the predation attribute of *C. kuwanae* is poorly documented. This paper reports a detailed study on the predation of *C. kuwanae* adults upon *U. yanonensis*.

2 MATERIALS AND METHODS

All experiments, except for the functional responses which were carried out at several temperatures, were conducted at 25±0.5℃ and about 75% relative humidity with photoperiod regime of 14L:10D. *C. kuwanae* adults used in the experiments of functional responses, selective efficiency and interferences, were under deprivation of food for 48h before the tests. In the experiments, each of the *U. yanonensis* densities tested was replicated for 30 times.

2.1 Predation difference between *C. kuwanae* male and female adults

The authors randomly collected *C. kuwanae* adults from the citrus orchards near our campus, and identified their sexes. Then they were divied into two groups, male and female, 30 adults each. One adult *C. kuwanae* and a middle-sized citrus leaf with 100 *U. yanonensis* adult females were put into a small widemouthed glass jar (250ml) covered with a piece of gauze. The experiments were conducted in two ways. One was to be performed immediately after the ladybeetles were sexed and the other after depriving the prey for 48h. The numbers of *U. yanonensis* female adults consumed and eggs laid by *C. kuwanae* females during 24h were recorded.

2.2 Functional response

In the same size of glass jars (250ml), the functional responese of *C. kuwanae* adultst of *U. yanonensis* female adults were investigated at 16℃, 21℃, 25℃, 30℃, 35℃ and 37±0.5℃. Their responses to *U. yanonensis* lst-instar nymphs, 2nd-instar male and female nymphs and male pupae were determined at 25±0.5℃. The density levels of the first instar nymphs were 40, 80, 160, 320, 480 and 800 scales per jar, the second instar male and female nymphs 10, 20, 40, 80, 160 and 320 per jar, the male pupae 100, 200, 400, 600 and 800 per jar, and the adult females 10, 20, 40, 80 and 160 per jar.

2.3 Interference

The interference of *C. kuwanae* adults was determined in small (250 ml), middle (1 300 ml) and large (2 955 ml) widemouthed glass jars. Each of the jars contained two middle-sized citrus leaves with a small branch, on which there were a total of 150 female adults of *U. yanonensis*. The predator densities tested were 1, 2, 4, 6 and 8 beetles per jar.

2.4 Selective efficiency

Two stages of the scale were compared in each treatment in a small widemouthed glass jar with the method of fixing the density of one stage and altering the other stage's number, or letting the numbers of the two stages be added to a constant. One *C. kuwanae* adult was put in each of the jars.

3 RESULTS

3.1 Predation difference between *C. kuwanae* male and female adults

The results indicated that the prey consumption of *C. kuwanae* female adults upon *U. yanonensis* female adults was significantly greater than that of its male adults if the ladybeetles were not starved (Table 1). At 25℃, female adult on an average, consumed 42.7 *U. yanonensis* female adults per day, while male adult only destroyed 22.3 female scale adults. However, this difference become unimportant after 48 h of starvation. In this latter case, the *C. kuwanae* females ceased laying eggs. According to this result, in some studies on the predation of *C. kuwanae* adults on *U. yanonensis* female adults the ladybeetles do not need to be sexed after deprivation of prey for 48 h.

3.2 Relationship between egg production and prey consumption of *C. kuwanae* females

The fecundity of *C. kuwanae* females was closely related to their prey consumption. The more *U. yanonensis* they consumed, the more eggs the ladybeetles laid. There was a significantly linear relationship between the prey consumption (x) and the egg production (y).

$$y=-4.5501+0.2957x \qquad (r=0.6654^{**}) \cdots\cdots\cdots\cdots (1)$$

This equation suggsted that a *C. kuwanae* female had to prey on more that 15 *U. yanonensis* female adults per day to carry out oviposition.

Table 1 Predation difference between male adults of *C. kuwanae* on *U. yanonensis* female adults.

Sex	Predator number	Daily prey consumption (scales)	Daily egg production (eggs)	F check	t check
			without starvation		
Female	30	42.7±15.8	8.1±7.0	$F=13.83^{**}$	$t=3.72^{**}$
Male	30	22.3±13.0	—	($F_{0.01(1,58)}=7.09$,	$t_{0.01(df=58)}=2.66$)
			with 48 h of starvation		
Female	30	16.3±8.0	0.07	$F=0.72$	$t=0.85$
Male	30	15.3±4.3	—	($F_{0.1(1,58)}=2.79$,	$t_{0.1(df=58)}=1.677$

3.3 Functional response of *C. kuwanae* to *U. yanonensis*

The functional response measures the change in number of prey attacked by a predator in response to the variation in prey density. It is useful for determining the control ability of a predator against its prey and comparing the relative effectiveness of predators in controlling a common prey. Holling's disk equation (Holling 1959) was used to fit all the data obtained.

$$Na=aNT/(1+aThN) \quad \cdots\cdots\cdots\cdots (2)$$

where N=initial number of prey, Na=number of prey attacked, a=attack coefficient, Th=handling time, T=duration of the experiment (in these cases $T=1$ day). The results showed that the equation fits to all the tested predator-prey combinations well (Table 2). According to the estimated parameters of the equation (2), the relevant functional response curves are shown in Fig. 1. It is obvious that Na rose at negatively accelerated rates as prey number increased. Therefore, functional responses of *C. kuwanae* adults to the densities of *U. yanonensis* followed Holling's type II.

In this article, $Na\infty$, the reciprocal of Th is the maximum daily prey consumption when the prey density tends to the infinity. From Table 2, it is evident that when temperature increased from 16℃ to 35℃, $Na\infty$ went up and the handling time (Th) decreased, and this means that the predator would have more time for searching the prey. However, at 37℃, $Na\infty$ decreased sharply. In addition, we can also see that the temperature did not alter the type of the functional response from 16℃ to 37℃.

3.4 Relationship between attack rate and temperature

In order to analyse further relationship between the predation and temperature, the authors used the data obtained from the experiment of functional response in which 160

U. yanonensis adult females, a surplus prey density, were offered as initial prey density (Table 3). With the Marquard's method of damped least squares, the model developed by Ding *et al.* (1983) was used to fit the data, and depict the attack rate (E') in the whole temperature (T) range.

$$E' = (K/1+e^{-r(T-T_f)})(1-e^{-(T-T_L/\delta_1)^2})(1-e^{-(T-T_H/\delta_2)^2}) \cdots\cdots\cdots\cdots\cdots\cdots \quad (3)$$

Table 2 Parameters of functional response (Holling's type I) of adult *C. kuwanae* to increase in density of *U. yanonensis*.

Stage	a	Th	$Na\infty$	r^2
		To immature stages of at 25℃		
1st-instar nymph	0.9832	7.8096×10^{-4}	1280.47	0.9996
2nd-instar male nymph	1.0098	1.1675×10^{-3}	856.54	0.9998
2nd-instar female nymph	1.0107	1.3150×10^{-3}	760.44	0.9999
Male pupa	1.6435	3.7348×10^{-3}	267.75	0.9787
		To female adults at seven temperatures (℃)		
16	1.2086	0.0335	29.8412	0.9981
21	1.2885	0.0303	32.9804	0.9899
25	1.2190	0.0244	41.0125	0.9999
28	1.1933	0.0227	44.0956	0.9987
30	1.1842	0.0192	51.9521	0.9966
35	1.1210	0.0126	79.5960	0.9775
37	0.9986	0.0364	27.4381	0.9741

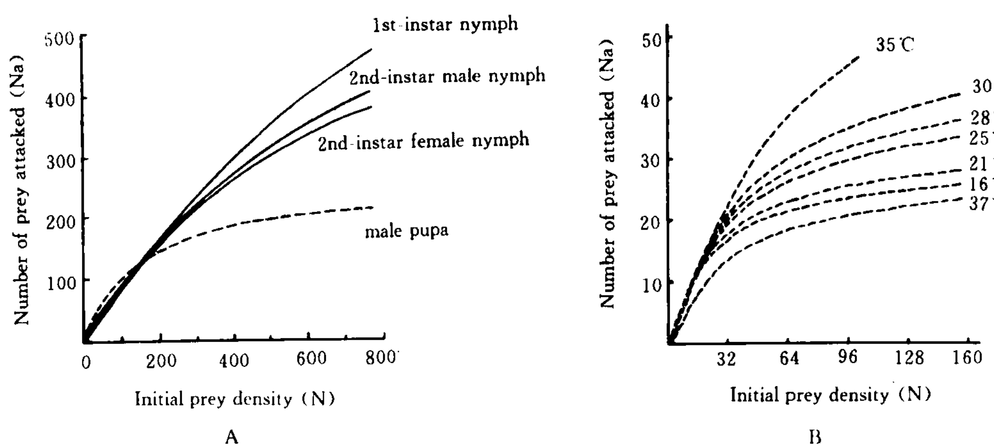

Fig. 1 Functional responses (Holling's type I) of *C. kuwanae* adults to increasing density of *U. yanonensis* immature stages at 25℃ (A), and to adult females at seven temperatures (B).

where K=potential saturation of attack rate, r=intrinsic attack rate, T_f=optimal temperature for attack, T_L=minimum critical temperature for attack, T_H=maximum critical temperature for attack, δ_1=possible temperature extent about T_L, δ_2=possible temperature extent about T_H in which the rapid declines definitely occur. In the model simulation we let $\delta_1=\delta_2=\delta$. The simulation result is as follows: $K=0.5118$, $r=0.0635$, $T_L=10.5799$℃, $T_f=31.5312$℃, $T_H=38.2040$℃, $\delta=1.6715$℃, and the root-mean-square error$=1.4835\times10^{-4}$.

Table 3 Attack rates of adult *C. kuwanae* on *U. yanonensis* female adults at seven temperatures.

Temperature (℃)	16	21	25	28	30	35	37
Attack rate	0.1418	0.1719	0.2014	0.2246	0.2398	0.2828	0.1250

According to the curve of the fitted model (Fig. 2), it is evident that from T_L to T_H the curve can be divided into three segments: a short and rapid exponential increase stage, a long and nearly linear increase stage which covers the temperature range of 16℃-35℃, and a very steep exponential decline stage.

3.5 Effects of predator density and predation space on predation

The experiments showed that the increase in predator density or predation space caused attack rates to drop (Table 4). The authors used Hasell (1969) model, which describes the relationship between predation rate (E') and the number of predator (P), to fit the data in Table 4.

$$E'=QP^{-m} \quad (4)$$

Where Q is the searching coefficient and m is the interference coefficient. The results were listed in Table 5. Obviously, the smaller the predation spaces were, the greater the searching coefficients and interference coefficients would be. In Fig. 3 are the curves of the equation (4) reflecting the characteristics of interferences of the predators in different predation spaces. When the densities of *C. kuwanae* adults were small, their attack rates dropped rather quickly with the increase of predator numbers and, in addition, there were considerable differences among the attack rates in different predation spaces when the predator number was the same. Nevertheless, when the densities of the predator were large, the effect of predation space became much smaller.

3.6 Selective efficiency of *C. kuwanae* to different stages of *U. yanonensis*

C. kuwanae can prey in all the tested life stages of *U. yanonensis* of both sexes, but when different stages coexisted the predator exhibited a prey preference for certain stage (s). This preference is important for analyzing the ability of *C. kuwanae* to control *U.*

yanonensis in the field. The authors applied Manly and Cook's (1972) selective coefficient (α) to compare and determine the prey preference of *C. kuwanae* adults to *U. yanonensis*. (Ding and Chen 1986).

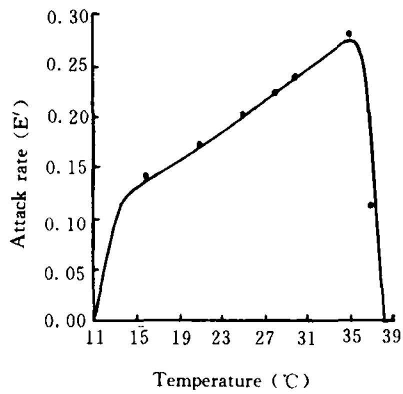

Fig. 2 Effects of temperature on the attack rate of *C. kuwanae* adults on *U. yanonensis* adult females.

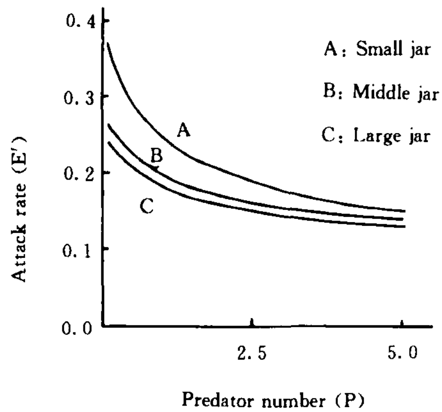

Fig. 3 Interference of *C. kuwanae* adults at 3 predation spaces at 25℃.

Table 4 Attack rates of adult *C. kuwanae* on *U. yanonensis* female adults in different predator densities and different predation spaces at 25℃.

Predator density (*P*)	Attack rate		
	Small jar (250 ml)	Middle jar (1 300 ml)	Large jar (2 955 ml)
1	0. 2550	0. 2083	0. 1967
2	0. 2400	0. 1767	0. 1625
4	0. 1908	0. 1733	0. 1617
6	0. 1431	0. 1333	0. 1211
8	0. 1123	0. 1098	0. 1085

Table 5 Searching coefficients (Q) and interference coefficients (m) of adult *C. kuwanae* in 3 predation spaces at 25℃.

Parameter	Small jar (250 ml)	Middle jar (1 300 ml)	Large jar (2 955 ml)
Q	0. 2848	0. 2176	0. 2017
m	0. 3878	0. 2769	0. 2678

$$\alpha = \ln \frac{B}{b} / \ln \frac{R}{r} \cdots\cdots (5)$$

where, B, R are initial numbers of the prey 1 and 2 respectively, and b, r are numbers of the prey 1 and 2 not attacked respectively. If $\alpha > 1$, the prey 1 is preferred, and if $\alpha < 1$, the prey 2 is preferred.

Table 6 Manly and Cook's selective coefficient (α) of *C. kuwanae* adults preying on different stages of *U. yanonensis* at 25℃.

Stage combination	Stage proportion (N1:N2)	α
1st-instar nymphs (N1) and male pupae (N2)	100:20	0.8002
	100:40	0.6342
	100:80	0.3198
	100:160	0.2115
	100:320	0.3308
2nd-instar female nymphs (N1) and male pupae (N2)	100:20	0.6046
	100:40	0.4044
	100:80	0.5511
	100:160	0.1143
	100:320	0.3475
2nd-instar male nymphs (N1) and male pupae (N2)	100:10	0.6344
	100:20	0.5086
	100:40	0.4537
	100:80	0.4608
	100:100	0.2616
Male pupae (N1) and adult females (N2)	90:10	1.0681
	75:25	4.0591
	50:50	2.0741
	25:75	2.2337
	10:90	3.1737
	50:10	1.6946
	50:20	2.3403
	50:40	1.8440
Male pupae (N1) and adult females (N2)	50:80	2.8884
	50:160	4.9201
2nd-instar female nymphs (N1) and sdult females (N2)	90:10	1.2012
	70:30	1.5502
	50:50	2.4223
	30:70	3.9536
	10:90	5.6915
1st-instar nymphs (N1) and 2nd-instar female nymphs (N2)	100:10	0.5493
	100:20	0.9584
	100:40	0.7942
	100:80	0.7865
	100:160	0.6578
1st-instar nymphs (N1) and adult females (N2)	100:10	0.5076
	100:20	0.3305
	100:40	0.5481
	100:60	0.3586
	100:70	0.3955
2nd-instar male nymphs (N1) and 2nd-instar female nymphs (N2)	100:10	1.6213
	100:20	1.4110
	100:40	1.1583
	100:80	1.1906
	100:100	1.0960

Based on the results (Table 6), we can find that the prey selective order of *C. kuwanae* adults to different stages of *U. yanonensis*, is as follows: male pupae>2nd-instar male nymphs>2nd-instar female nymphs>adult females>1st-instar nymphs.

4 DISCUSSION

C. kuwanae adults preferred *U. yanonensis* male pupae to other stages of the scale and the preference might be related to the physical structure of this stage. The pupa has a relative big and soft body, only covered by a layer of fragile waxy scale. The waxy scale can be easily removed by *C. kuwanae* and , therefore causes a male pupa to be preyed on with less efforts. The relative big body, filled with body fluids, can provide rich nutrition for the predator. So, in the field, the authors often found that the reproductive peak of *C. kuwanae* coincided with the peak of *U. yanonensis* male pupae and, that the larvae and pupae of predator were all very fat and in well-developing conditions.

The second instar male nymphs, along with the male pupae of the scale comprised the first two favorite prey stages for *C. kuwanae* adults. Apparently, it seems to reduce the direct predation on *U. yanonensis* females, which are most damaging to plants. In fact, the life span of the male scale is far shorter than that of the female scale. In the most time of a year the male scale is unavailable to the predator. The authors think that the prey preference of *C. kuwanae* adults on the male scale helps them to make full use of the limited food resource. After the peak of the male scale, the developed *C. kuwanae* population will focus on destroying the female scales, especially the adult females. As a result, more *C. kuwanae* will be propagated, and more *U. yanonensis* will be eaten. Therefore, the authors suppose that this kind of prey preference can be regarded as an adroit predation strategy, and also as a good example of predation adaptability.

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红点唇瓢虫对矢尖蚧的捕食作用

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红点唇瓢虫(*Chilocorus kuwanae*)的产卵雌虫对矢尖蚧(*Unaspis yanonensis*)的捕食量显著大于雄性成虫。在25℃下，雌成虫日平均捕食矢尖蚧雌成蚧42.7头，而雄成虫的日捕食量仅为22.3头。但48 h饥饿处理可消除此差异。要使雌成虫产卵，每天必须至少捕食15头矢尖蚧的雌成蚧。红点唇瓢虫成虫对矢尖蚧各虫态的功能反应均为 Holling Ⅱ 型。根据对雌成蚧的功能反应，在16－35℃范围内最大捕食量随温度的升高而升高，在37℃下则急剧下降。温度并不改变功能反应的类型。由红点唇瓢虫成虫对雌成蚧的捕食作用，估算得最低临界攻击温度、最佳攻击温度和最高临界攻击温度分别为10.58℃、31.53℃和38.20℃。捕食空间增大或捕食者数量的增加都会使攻击率下降；但是捕食者密度变大时，捕食空间的影响将大大变小。红点唇瓢虫成虫对矢尖蚧的雄蛹表现出最大的猎物选择性。它们对矢尖蚧各虫态的捕食选择性依次为：雄蛹、2龄雄蚧、2龄雌蚧和1龄若虫。