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RESEARCH ARTICLE

Effect of temperature on the development and consumption of *Phaenochilus kashaya* (Coleoptera: Coccinellidae), a predator of the cycad aulacaspis scale, *Aulacaspis yasumatsui*

Veronica Manrique[a]*, Daniel A. Mancero-Castillo[a], Ronald D. Cave[a] and Ru Nguyen[b]

[a]*Indian River Research & Education Center, University of Florida, Fort Pierce, FL, USA;* [b]*Florida Department of Agriculture and Consumer Services, Division of Plant Industry, Gainesville, FL, USA*

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The cycad aulacaspis scale (CAS), *Aulacaspis yasumatsui* Takagi (Hemiptera: Diaspididae), is a serious pest of ornamental cycads in the southeastern United States. In Florida, CAS was first reported in Miami in 1996 and is now present in 43 Florida counties. Chemical control of CAS can be effective, but it is expensive, and insecticides must be frequently and regularly applied. Recent surveys of natural enemies in Thailand identified a new potential biological control agent of CAS. The objective of this study was to examine the temperature requirements and consumption rates of *Phaenochilus kashaya* Giorgi and Vandenberg (Coleoptera: Coccinellidae). Survival, developmental time and number of scales consumed by *P. kashaya* were measured at four constant temperatures (20, 25, 30 and 35°C). In addition, adult longevity and consumption were recorded at three constant temperatures (20, 25 and 30°C). *Phaenochilus kashaya* completed development to adulthood at temperatures ranging from 20 to 30°C. The highest survival rate (48%) was obtained at 25°C, and the accumulated degree-days for this species was 714. *Phaenochilus kashaya* is a voracious predator of CAS, consuming 380 scales during the larval stage and an estimated 4700 scales during the adult stage. Adult longevity varied from 59 days at 30°C to 220 days at 20°C for females, and 31 days at 30°C to 148 days at 20°C for males. The intrinsic rate of increase (r_m) was 0.34 at 20°C, which is high compared with other coccinellid species. According to this study, *P. kashaya* has the potential to be an effective biological control agent of the CAS in Florida.

Keywords: biological control; temperature-dependent development; consumption rates; adult longevity

1. Introduction

The cycad aulacaspis scale (CAS), *Aulacaspis yasumatsui* Takagi (Hemiptera: Diaspididae), a native of Asia, is a serious pest of popular ornamental cycads in Florida, Texas, Alabama, Louisiana, Georgia, Hawaii, Guam and the West Indies (Howard, Hamon, McLaughlin, Weissling, and Yang 1999; Weissling, Howard, and Hamon 1999; Marler 2004; Moore, Iriarta, and Quintugua 2005). In Florida, CAS was first found infesting several species of *Cycas* and *Stangeria* in the collection of

*Corresponding author. Email: vero72@ufl.edu

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the Montgomery Botanical Center in Miami, and is now reported in 43 Florida counties (Howard et al. 1999). This pest infests leaves, stems and roots of their host plants, and dense infestations result in yellowing of leaves and eventual death of the plant (Howard et al. 1999; Heu, Chun, and Nagamine 2003). Cycads, or 'sago palms', are economically important plants since they are widely used as ornamentals by homeowners and landscaping companies in Florida. *Cycas revoluta* (Thunberg) is one of the most popular ornamental cycads due to its low maintenance requirements, resistance to dry conditions and few pests before the arrival of the CAS (Hodges, Howard, and Buss 2003). However, high CAS infestations are causing major problems for cycad growers, and nurseries have been particularly affected because cycads can no longer be exported to other states.

Chemical pest management of CAS is difficult because expensive pesticide applications must be frequent and regular. Emshousen, Mannion, and Glenn (2004) tested pyriproxyfen as a single foliar spray and obtained excellent control of female scales and eggs on lightly infested plants, and adequate control on densely infested plants. Mannion (2006) found that excellent control of female scales was achieved with foliar applications of fish oil alone, foliar application of fish oil in combination with a drench application of imidacloprid, foliar application of pyriproxyfen and foliar and drench applications of dimethoate. Horticultural oils must be applied at 2–3 week intervals, but frequent oil treatments can result in phytotoxicity and an unsightly build-up of oil and dead scales (Hodges et al. 2003). Dinotefuran may be applied as a soil drench, or applied twice a year to foliage to give excellent control (Caldwell 2005; Webb 2009). Unfortunately, dimethoate, horticultural oil, and imidacloprid, a neonicotinoid similar to dinotefuran, are highly toxic to natural enemies (Smith and Cave 2006).

Classical biological control of CAS began in 1998 when a parasitic wasp, *Coccobius fulvus* (Compere and Annecke) (Hymenoptera: Aphelinidae), and a predatory beetle, *Cybocephalus nipponicus* Endrody-Younga (Coleoptera: Cybocephalidae), were imported from Thailand and released against the pest in Florida (Hodges et al. 2003). Although these natural enemies became established and spread throughout South Florida, they do not provide adequate control (Cave 2006). During surveys of natural enemies in Thailand in 2007, a new species in the genus *Phaenochilus* (Coleoptera: Coccinellidae) was found feeding on CAS in a dipterocarp forest (R.D. Cave and R. Nguyen, unpublished data). Giorgi and Vandenberg (2012) recently described the species and named it *Phaenochilus kashaya* Giorgi and Vandenberg. The objective of this study was to determine the temperature-dependent development and consumption rates of *P. kashaya* when feeding on CAS in the laboratory. Results from this study will provide valuable information of the temperature requirements for this species and its efficacy as a biological control agent of the CAS in Florida and elsewhere.

2. Materials and methods

2.1. Insects and plants

This study was conducted during 2009 in the quarantine facility of the Biological Control Research and Containment Laboratory of the University of Florida, Indian River Research and Education Center, Fort Pierce, FL. Cycad plants were obtained from Carow Nursery, Fort Pierce, FL, kept inside a greenhouse, watered weekly and fertilised every 3 months with a slow release fertiliser 24–7–8 N-P-K (Harrell's Inc., The Cycad Jungle, Lakeland, FL, USA). Initial stock of *P. kashaya* adults was collected on *Cycas siamensis* Miquel in a dipterocarp forest near Sub Tao (N 14° 29.45′ E 101° 58.60′, ca. 320 m elevation), Thailand, and hand-carried to quarantine in Gainesville, FL, in October 2007 for colony establishment. Individuals from this colony were later shipped to the quarantine facility in Ft. Pierce. New material was collected on *C. siamensis* at the Sakaerat Environmental Research Station (N 14° 32.36′ E 101° 55.76′, ca. 450 m elevation), Thailand, in June 2009 and incorporated in the quarantine colonies. Voucher specimens have been deposited in the Florida State Collection of Arthropods, Gainesville, FL, and in the research collection of the Biological Control Research and Containment Laboratory.

Colonies of CAS and *P. kashaya* were maintained inside an environmentally controlled chamber set at 28 ± 2°C, 14:10 L:D photoperiod, and 70–80% relative humidity (RH). Adult beetles were placed inside $60 \times 60 \times 60$ cm ventilated cages (BugDorm 2120, MegaView Science, Taiwan) containing *C. revoluta* with a dense infestation of CAS and cotton wicks saturated with a 1:1 water:honey solution. The cotton wicks and CAS-infested plants were replaced as needed, and newly emerged *P. kashaya* adults were moved to new cages for colony maintenance.

2.2. Development and consumption of **P. kashaya** *at four constant temperatures*

Survival, developmental time and number of scales consumed by the larvae of *P. kashaya* were measured at four constant temperatures (20, 25, 30 and 35°C) using environmental growth chambers set at 70–80% RH and 14:10 L:D of photoperiod. Mating pairs from the colony were placed individually inside a plastic container ($15 \times 15 \times 19$ cm) with CAS-infested cycad leaflets and cotton wicks with 1:1 water: honey solution. Cycad leaflets were checked daily under a microscope to collect eggs. A total of 160 beetle eggs were moved to small Petri dishes (5.5 cm diameter) with ventilated lids, and the Petri dishes were placed at each of the aforementioned temperatures (40 eggs per temperature). All Petri dishes were checked daily, and egg stage duration and total number of hatched eggs were recorded. Neonate larvae were placed individually inside small Petri dishes containing moist filter paper and cycad leaflets with 10–40 CAS (equal numbers of female and male scales). All Petri dishes were checked daily, molting and numbers of scales consumed were observed with a microscope and recorded. A scale was considered consumed if a hole was found in the armour and the scale was missing.

2.3. Adult longevity and reproductive parameters of **P. kashaya**

Adult longevity was recorded for *P. kashaya* at three constant temperatures (20, 25 and 30°C). Because only one individual was reared to adult at 20°C, fourth instars from the colony (22 larvae) were placed inside small Petri dishes and kept at 20°C until adult emergence. Adults were placed individually inside small Petri dishes with ventilated lids containing cycad leaflets with 40–50 CAS (equal numbers of female and male scales) and cotton wicks with 1:1 water: honey solution. The cycad leaflets were replaced daily. Consumption was recorded for adults for only 5 days after emergence from the pupa. Pre-oviposition period and lifetime fecundity were recorded for four pairs of adults at 20°C; males dying before females were not replaced. In addition, the net reproductive rate ($R_o = \Sigma l_x m_x$) and intrinsic rate of increase ($r_m = \ln R_o / T$) were calculated at 20°C. Experiments were terminated when all adults died.

2.4. Data analyses

Time of development and daily and total number of scales consumed by *P. kashaya* were analysed using a two-way analysis of variance (ANOVA) with temperature (25, 30°C) and stage, or instar, as factors. If significant interactions were detected, single ANOVAs were used separately to compare data among temperatures or stages. Because only one larva reached the third instar at 20°C, this temperature was not included in the statistical analysis. The developmental rate relationship [$R(\mathrm{T}) = a + b\mathrm{T}$] for each immature stage and all immature stages combined was modelled using the least squares linear regression (PROC GLM, SAS Institute 1999), where T is temperature, a is the intercept and b is the slope estimate. Degree-day requirements for each immature stage and all immature stages combined were calculated using the inverse slope ($1/b$) of the fitted linear regression line (Campbell, Frazer, Gilbert, Gutierrez, and Mackauer 1974). Adult longevity was analysed using a two-way ANOVA with temperature (20, 25 and 30°C) and gender (female, male) as factors. Means were separated using the Student–Neuman–Keuls test (SAS Institute 1999). A significance level of $\alpha = 0.05$ was used for all statistical analyses.

3. Results

3.1. Development and consumption of P. kashaya at four constant temperatures

High percentages of *P. kashaya* eggs hatched at 20, 25 and 30°C (ca. 78% overall), but no eggs hatched at 35°C. Survival from neonate larva to adult varied among temperatures, with the highest survival rate at 25°C (Table 1).

Time of development was shorter with increasing temperatures for each immature stage (Table 2), with a significant interaction between stage and temperature (25, 30°C) ($F = 42.34$, df = 6, 232, $P < 0.0001$). Single ANOVAs detected faster development for all stages at 30°C compared to 25°C, except for second instar (Table 2). The degree-day requirements for *P. kashaya* varied from 110 for eggs to 435

Table 1. Percent survival of immature stages of *Phaenochilus kashaya* at three constant temperatures.

	Temperatures					
Stage	20°C	*n*	25°C	*n*	30°C	*n*
Egg	77.5	40	87.5	40	70.0	40
First instar	16.1	31	68.6	35	46.4	28
Second instar	60.0	5	91.6	24	84.6	13
Third instar	33.3	3	95.4	22	100	11
Fourth instar	100	1	90.4	21	81.8	11
Pupa	100	1	100	19	88.9	9
Egg-adult	2.5		45.0		20.0	

Table 2. Time of development in days (mean ± SE) of the immature stages of *Phaenochilus kashaya* at three constant temperatures.

Stage	Temperatures					
	20°C	*n*	25°C	*n*	30°C	*n*
Egg	13.7 ± 0.2	31	9.3 ± 0.1a	35	6.4 ± 0.1b	28
First instar	11.0 ± 1.2	5	5.8 ± 0.1a	24	5.0 ± 0.4b	13
Second instar	10.5 ± 1.5	3	3.9 ± 0.3a	22	4.9 ± 0.5a	11
Third instar	8 ± 0	1	9.7 ± 0.6a	21	5.4 ± 0.4b	11
Fourth instar	17 ± 0	1	12.2 ± 0.5a	19	7.0 ± 0.6b	9
Pupa	11 ± 0	1	7.0 ± 0.3a	19	5.5 ± 0.4b	8
Egg-adult	67 ± 0	1	48.0 ± 0.6a	18	34.7 ± 1.4b	8

Note: Different letters indicate significant differences between 25 and 30°C ($P < 0.05$).

for all instars combined and was 714 from egg to adult (Table 3). The sex ratio was 0.6:1 (females:males) at both 25 and 30°C.

Daily consumption of CAS by larvae of *P. kashaya* was greater at 25 than at 30°C, and fourth instars consumed more scales than younger instars (temperature: $F = 12.2$, df = 1, 121, $P = 0.0007$; instar: $F = 53.5$, df = 3, 121, $P < 0.0001$; temperature × instar: $F = 2.6$, df = 3, 121, $P = 0.052$; Table 4). Significant interaction of temperature and instar was obtained for total consumption (temperature × instar: $F = 38.3$, df = 4, 147, $P < 0.0001$), and single ANOVAs indicated more total consumption at 25 compared to 30°C (Table 4). The total number of scales consumed by the larval stage was 420 at 20°C, 380 at 25°C and 145 at 30°C (Table 4).

3.2. *Adult longevity and reproductive parameters of* P. kashaya

Adults of *P. kashaya* lived longer at 20 and 25°C compared to 30°C, and females lived slightly, but not significantly, longer than males (temperature: $F = 9.81$, df = 2, 31, $P = 0.0005$; gender: $F = 3.19$, df = 1, 31, $P = 0.08$; temperature × gender: $F = 0.38$, df = 2, 31, $P = 0.68$; Table 5). Daily consumption of CAS by adult *P. kashaya* did not differ among temperatures ($F = 1.2$, df = 2, 16, $P = 0.32$). On average, 29.3 ± 2.8 scales were consumed daily by adults during a 5-day period. At 20°C, mean pre-oviposition period was 39.7 ± 0.7 days, females laid on average 1.4 ± 0.4 eggs daily, and mean lifetime fecundity was 338.5 ± 96.6 eggs. Net reproductive rate (R_o) was 6.09, and the intrinsic rate of increase (r_m) was 0.34 at 20°C.

Table 3. Linear regression parameters describing relationship between temperature and developmental rate of *Phaenochilus kashaya*.

Stage	Intercept	Slope	R^2	*n*	Degree-days
Egg	−0.0988	0.0084	0.9884	94	119
Larva	−0.0255	0.0023	0.9948	29	435
Pupa	−0.0891	0.0091	0.9952	28	110
Egg to adult	−0.0131	0.0014	0.9929	27	714

Table 4. Daily and total consumption of cycad aulacaspis scale (mean ± SE) by larvae of *Phaenochilus kashaya* at three constant temperatures.

	Temperatures		
Stage	20°C	25°C	30°C
Daily			
First instar	2.9 ± 0.2	3.9 ± 0.2aC	2.2 ± 0.5bC
Second instar	3.4 ± 0.6	7.6 ± 0.3aB	5.4 ± 1.2bB
Third instar	10.0 ± 0.0	8.0 ± 0.6aB	7.3 ± 2.0bB
Fourth instar	15.0 ± 0.0	20.8 ± 1.2aA	13.2 ± 4.4bA
Total			
First instar	33.2 ± 5.6	22.8 ± 1.0aD	10.0 ± 1.9bC
Second instar	35.0 ± 1.0	29.0 ± 2.3aD	19.5 ± 3.3bC
Third instar	80.0 ± 0	78.6 ± 9.1aC	36.3 ± 8.1bC
Fourth instar	267.0 ± 0	246.4 ± 12.4aB	76.8 ± 19.3bB
Larval stage	420.0 ± 0	379.8 ± 15.2aA	144.7 ± 28.8bA

Note: Different letters indicate significant differences between 25 and 30°C (lower case) or among instars (upper case) ($P < 0.05$).

4. Discussion

Several environmental factors (e.g., relative humidity and temperature) influence the development and survival of insects, which in turn affect their population dynamics and distribution (Howe 1967; Wagner, Wu, Sharpe, Schoolfield, and Coulson 1984; Sutherst 2000; Canhilal, Uygun, and Carner 2001; Davis, Radcliffe, and Ragsdale 2006). This is extremely important when selecting biological control agents, since the temperature requirements of the agent will influence its establishment in new areas following initiation of field releases (Ponsonby and Copland 1996; Uygun and Atlihan 2000; Goolsby et al. 2005; Pilkington and Hoddle 2006). According to our study, *P. kashaya* can complete development from egg to adult when feeding on the cycad aulacaspis scale at temperatures ranging from 20 to 30°C in the laboratory. A similar temperature range was recorded for the development of CAS (Cave, Sciacchetano, and Diaz 2009), which indicates that both species do well in the same climatic areas. Florida is characterised by having a subtropical climate, which is adequate for the establishment of this species. These results were expected since *P. kashaya* was originally collected in southeastern Thailand, which is characterised by a tropical climate with mean temperatures ranging from 15 to 38°C (http://www.tmd.go.th/en/thailand.php).

The highest survival rate to adulthood for *P. kashaya* was obtained at 25°C (48%), whereas lower survival was obtained at 20°C (2.5%) and 30°C (20%).

Table 5. Adult longevity in days (mean ± SE) of *Phaenochilus kashaya* at three constant temperatures.

	20°C	*n*	25°C	*n*	30°C	*n*
Female	219.7 ± 29.4a	7	157.5 ± 25.7a	8	59.3 ± 3.7b	3
Male	147.8 ± 41.4a	6	130.1 ± 26.6a	8	31.4 ± 8.0b	5

Note: Different letters indicate significant differences among temperatures ($P < 0.05$).

Therefore, we recommend maintaining this species at 25°C during mass rearing in quarantine. The time of development from egg to adult is about 48 days at 25°C, which is somewhat longer than the development time of the much smaller *C. nipponicus* (40 days) (Smith and Cave 2006) and the slightly smaller lady beetle *Rhyzobius lophanthae* Blaisdell (Coleoptera: Coccinellidae). *Cybocephalus nipponicus* is commercially available in the US and is widespread in Florida, but has not been successful in controlling CAS (Smith and Cave 2006). *Rhyzobius lophanthae* is a common predator of CAS in Hawaii (Hara et al. 2005) and Guam (Moore, Marler, Miller, and Muniappan 2005), but in Florida it has only been found in Tampa and Tallahassee (Cave 2006). Therefore, more effective biological control agents are needed in order to reduce scale populations and provide adequate control. Our study showed that *P. kashaya* is a voracious predator of CAS, able to consume 380 scales during its larval stage, which is high compared to *R. lophanthae* (58 scales; Thorson 2009). Moreover, an adult *P. kashaya* may kill approximately 4700 scales if we consider its potential longevity and daily consumption at 25°C. The intrinsic rate of increase (r_m) for *P. kashaya* feeding on CAS is 0.34 at 20°C, which is higher than that of *R. lophanthae* ($r_m = 0.019$ at 18°C) (Thorson 2009). In comparison to other species of Coccinellidae ($r_m = 0.05$–0.19 at 25°C) (Hodek, van Emden, and Honek 2012), this unusually high r_m obtained for *P. kashaya* should be considered cautiously since few replicates (four females) were used to calculate the reproductive parameters of this species. In addition, further studies should determine the demographic parameters of *P. kashaya* at higher temperatures (25–30°C) which better match the environmental conditions in Florida during the warmer months of the year when CAS outbreaks usually occur.

There are many examples in the literature of successful biological control programmes using predatory lady beetles against insect scales and mealybugs (Caltagirone and Doutt 1989; DeBach and Rosen 1991; Obrycki and Kring 1998; Hodek and Honek 2009). The most famous example is the vedalia beetle (*Rodalia cardinalis* Mulsant) against the cottony cushion scale (*Icerya purchasi* Maskell) in citrus in California in the late 1880s (Caltagirone and Doutt 1989). In some cases, however, non-target effects of coccinellid predators have been reported. For example, *Harmonia axyridis* (Pallas) was introduced as a biological control agent in the United States, but this beetle also feeds on non-target species, including native coccinellids, and has been reported as a pest in fruit production and households by invading homes during the winter (Koch 2003; Kenis, Roy, Zindel, and Majerus 2008). Preliminary studies on the host range of *P. kashaya* indicates that this beetle is a specialist on armoured scales and does not consume other insects (R. Cave, unpublished data). However, further studies on the biology and host range of this new candidate should be conducted before any field releases are undertaken.

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