REVIEW
Biological Aspects and Predatory Abilities of Hemipterans Attacking Stored-Product Insects

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Abstract

The subject of this study was to examine biological aspects and predatory abilities of predatory bugs that prey on stored-product insects. Biological controls in stored products are being regarded with increasing interest since they are nontoxic and do not damage human health or the environment. Several species of predatory bugs have been studied as biological control agents. Specifically, *Xylocoris flavipes* (Reuter) is the most studied candidate biological control agent among predatory bugs. *X. flavipes* is advantageous because it has a high population increase capacity and wide distribution. *X. flavipes* has been reported to suppress populations of small insects, but it can not predate large insects and internal grain feeding insects. As *Amphibolus venator* (Klug), *Peregrinator biannulipes* (Montrouzier & Signoret) and *Joppeicus paradoxus* Puton can attack large insects, more research should be carried out on the suppression effects of these bugs. A combination of several biological control agents that can attack different types of insects will be needed to control whole pest complexes in various stored environments.

Introduction

Methyl bromide (MeBr) is one of the most useful chemical agents for pest control of stored products. Fumigation with MeBr, however, may not be desirable from the standpoint of human health. More importantly, MeBr probably has ozone layer depleting effects, and for this reason was banned in most cases after 2005 in developed countries and will be banned after 2015 in developing counties. Therefore, the development of alternative methods and the switch to integrated pest management (IPM) are urgently needed. Biological control is thus being regarded with increasing interest, since it is nontoxic and does not damage human health or the environment. The use of natural enemies has been studied by various researchers for stored-product pests[9].

In the past, several species of predatory bugs have shown good promise for suppressing populations of external feeding grain pests. Most of them belong to the family Anthocoridae. Among them, *Xylocoris flavipes* (Reuter) (Hemiptera: Anthocoridae) has been the most studied as a biological control agent[9]. This bug has already been commercialized in North America, and currently is the only predatory bug marketed for biocontrol of stored-product insects[20]. Recently, we collected several predatory bugs belonging to the families Reduviidae and Joppeicidae. In this review, we introduce the biological aspects and predatory abilities of these predatory bugs, and consider their applicability as biological control agents.

Biology of Predatory Bugs

1. Field investigation and species of predatory bugs

Stored-product insects and their natural enemies were investigated in Thailand[15] and tropical and subtropical regions of Japan (Okinawa-jima, Ishigaki-jima, Amami-oshima and Chichi-jima Islands)[23,32,33]. Table 1 shows the list of predatory bugs collected in these investigations. *X. flavipes* (Fig. 1A) was abundant in Thailand, but none were collected in Japan[23,32,33,36], although it is known to be a cosmopolitan species[15]. *X. flavipes* is small in body size, so it preys on the eggs and smaller larvae of beetles and moths[9]. *Amphibolus venator* (Klug)

Table 1. Predatory bugs of stored-product insects collected in Thailand and tropical and subtropical regions of Japan

Family	Species	Thailand[15]	Okinawa-jima[33]	Chichi-jima[32]
Anthocoridae	*Xylocoris flavipes* (Reuter)	◎		
	Xylocoris spp.	○		
	Cardiastethus pygmaeus Poppius	○		
	Amphiareus constrictus (Stål)	○		
	Physopleurella sp.	○		
	Dufouriellini gen. A. sp.	○		
	Dufouriellini gen. B. sp.	○		
Reduviidae	*Amphibolus venator* (Klug)	◎	○	
	Peregrinator biannulipes (Montrouzier & Signoret)	◎	○	
	Vesbius purpureus (Thunberg)	○		
Joppeicidae	*Joppeicus paradoxus* Puton	◎		
Lygaeidae	*Clerada apicicornis* (Erichson)			△
Miridae	*Fulvius anthocoroides* (Reuter)			△

◎: Abundant, ○: Occasionally, △: Few.
No predatory bug of stored-product insects was collected on Ishigaki-jima and Amami-oshima Islands in our investigation[23,33].
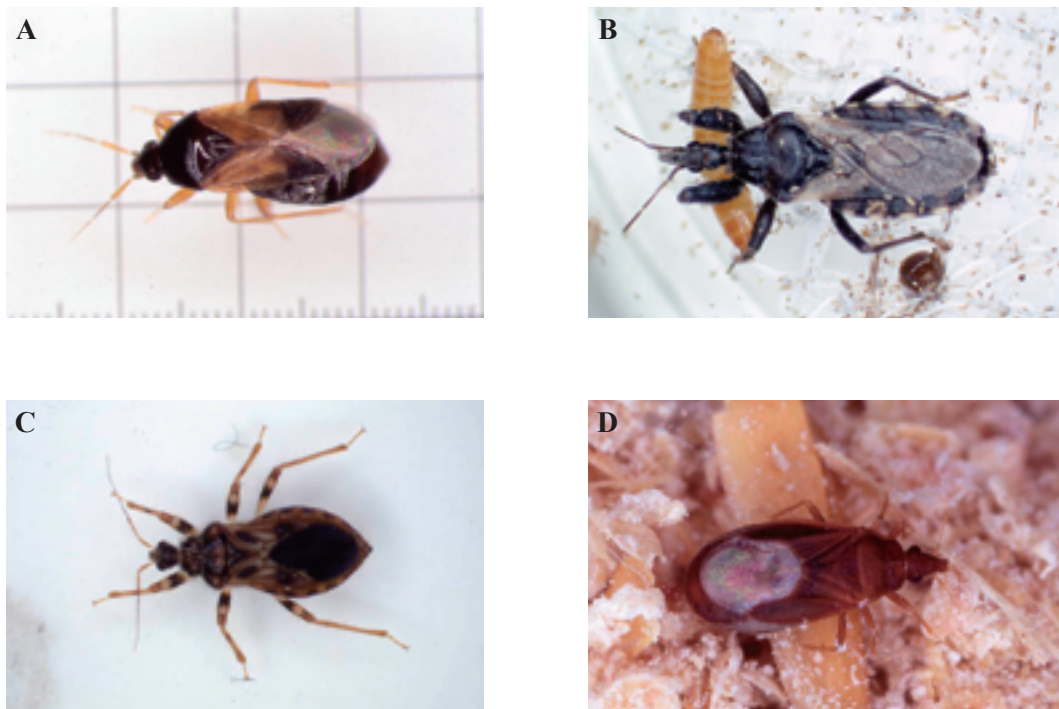

Fig. 1. Predatory bugs of stored product insects
(A): *Xylocoris flavipes* adult, about 2.1 mm long, (B): *Amphibolus venator* adult attacking *Tribolium* sp. larva, about 10 mm long, (C): *Peregrinator biannulipes* adult, about 7 mm long, (D): *Joppeicus paradoxus* adult in its habitat, about 3 mm long.

(Hemiptera: Reduviidae) (Fig. 1B) is a large bug, and was very common in rice stores in Thailand[15]. In Japan, it was found in rice milling facilities on Okinawa-jima Island[33]. *A. venator* has also been reported in North Africa, the Middle East and Malaysia[15]. This bug preys on various stored-product insects[14,28], and in the rice milling facilities on Okinawa-jima Island, it is a major predatory insect[33]. *Peregrinator biannulipes* (Montrouzier &

Signoret) (Hemiptera: Reduviidae) (Fig. 1C) was commonly found in rice stores all over Thailand[15] and in a rice milling facility on Okinawa-jima Island[33]. This bug has been found in pantropical regions[15], and is known as a predator of various stored-product pests[6,13,35]. In Thailand and Palau, some individuals were collected from under the bark of trees[34]. *Joppeicus paradoxus* Puton (Hemiptera: Joppeicidae) (Fig. 1D) is the only member of the family Joppeicidae. It was collected from a bean store in northern Thailand[15]. *J. paradoxus* has been recorded in Egypt, Sudan, Ethiopia, and Israel, and its habitats have been reported to be sheltered situations, for example, under the bark of trees, among human and bat feces, in bat colonies, and on dusty and sandy ground[31]. It has also been found in warehouses and mills in Egypt[1]. Under laboratory conditions, *J. paradoxus* has been observed to feed on several insect species[10,31].

As mentioned above, these four predatory bugs (*X. flavipes*, *A. venator*, *P. biannulipes*, and *J. paradoxus*) have already been reported as predators of stored-product insects, and are widely distributed in tropical and subtropical regions. Conversely, the other predatory bugs that were collected in our investigation (Table 1) were not so common. Therefore *X. flavipes*, *A. venator*, *P. biannulipes*, and *J. paradoxus* appear promising for biological control agents.

2. Development times and life history parameters

To determine the optimal rearing temperature for mass rearing and assess the suitability of the environmental conditions in the regions of the world where they are being evaluated as biological agents, information about the development times and life history parameters is needed.

Fig. 2 shows the development times of bugs known as predators of stored-product insects[2–4,6,21,22,27]. The development times of anthocorid bugs are generally shorter than those of reduviid bugs and *J. paradoxus*. In *Dufouriellus ater* (Dufour), *Lyctocoris campestris* (F.) (Hemiptera: Anthocoridae), *A. venator* and *P. biannulipes*, the development times decrease with increasing temperature, with the shortest development times observed at the highest temperature tested. In *X. flavipes*, the development time was the shortest at 30 and 35ºC, but immature mortality at 35ºC was greatly higher than those at 25–30ºC[2]. It appeared that 30ºC was suitable for the immature development of *X. flavipes*. The development time of *Xylocoris sordidus* (Reuter) (Hemiptera: Anthocoridae) decreased with increasing temperature in the 20–35ºC range, but immature development was inhibited at 15 and 40ºC, with neither egg hatch nor nymph molt observed at these temperatures[3]. The development

time of *J. paradoxus* decreased with increasing temperature in the range of 25 to 30ºC. Immature mortality of *J. paradoxus* at 34ºC was greatly higher than at 25–32ºC, indicating temperatures between 30 and 32ºC are suitable for the immature development of this insect[21].

The finite rate of natural increase (*λ*) of predatory bugs is shown in Fig. 3[2–4,17,21,25]. The *λ*-values of *X. flavipes*, *X. sordidus* and *L. campestris* were generally higher than for the other species. The *λ*-values of *D. ater* were lower than for the other anthocorid bugs, although the development times of *D. ater* were similar to those of the other anthocorid bugs due to the lower daily egg production of this bug as compared with the other anthocorid bugs[4]. The *λ*-values of *A. venator* and *J. paradoxus* were lower than for the other bugs due to their longer development times and lower fecundities[17,21,22]. In *X. sordidus*, *D. ater* and *A. venator*, the *λ*-values increased with increasing temperature for temperatures at and below 35ºC. This indicates that temperatures ≥ 35ºC are suitable for increasing the population of these bugs. In *X. sordidus*, however, no adults emerged at 40ºC[3], indicating extremely high temperatures will have harmful effects on increasing the population of this bug. The *λ*-value of *X. flavipes* increased with increasing temperature in the range of 20–30ºC, and then decreased due to a higher immature mortality and lower fecundity at 35ºC[2]. A similar trend was observed in *J. paradoxus*, for which the *λ*-value increased with increasing temperature to a peak at 30ºC and then decreased. It
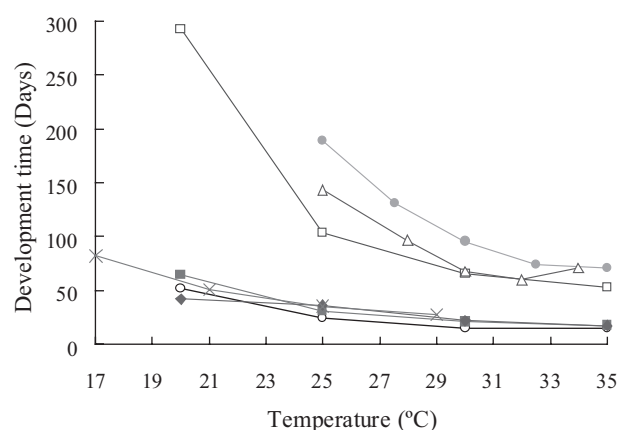

Fig. 2. Development times of predatory bugs
  —○—: *Xylocoris flavipes* reared on *Plodia interpunctella* larvae[2], —■—: *Xylocoris sordidus* reared on *Cadra cautella* larvae[3], —◆—: *Dufouriellus ater* reared on *Plodia interpunctella* larvae[4], —✕—: *Lyctocoris campestris* reared on *Plodia interpunctella* larvae[27], —●—: *Amphibolus venator* reared on *Tribolium confusum* larvae[22], —□—: *Peregrinator biannulipes* reared on *Stegobium paniceum* larvae[6], —△—: *Joppeicus paradoxus* reared on *Tribolium confusum* eggs[21].
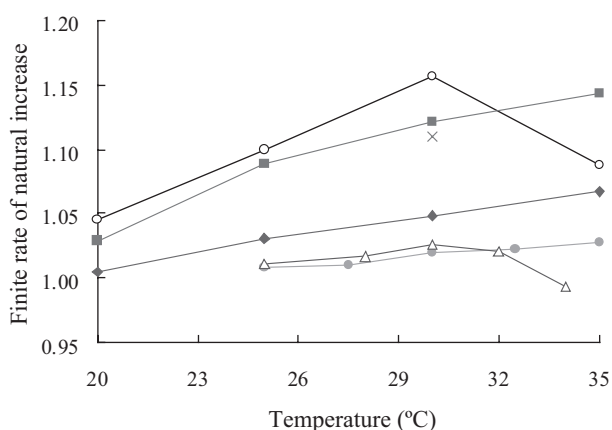
Fig 3. Finite rates of natural increase (λ) of predatory bugs
—○—: *Xylocoris flavipes* reared on *Plodia interpunctella* larvae[2], —■—: *Xylocoris sordidus* reared on *Cadra cautella* larvae[3], —◆—: *Dufouriellus ater* reared on *Plodia interpunctella* larvae[4], ×: *Lyctocoris campestris* reared on *Plodia interpunctella* larvae[25], —●—: *Amphibolus venator* reared on *Tribolium confusum* larvae[17], —△—: *Joppeicus paradoxus* reared on *Tribolium confusum* eggs[21].

appears that approximately 30ºC is the optimal temperature for population increases of *X. flavipes* and *J. paradoxus*. Awadallah et al.[6] reported the development and reproduction of *P. biannulipes* as a function of temperature. Considering its development time and fecundity, the λ-value of this bug would likely be lower than those of *X. flavipes*, *X. sordidus* and *L. campestris*, with its highest λ-value at 30ºC.

Temperatures ≥ 30ºC seem to be suitable for the development and population increase of all of the bugs in this study except *L. campestris*, for which there is a lack of information on reproduction as a function of temperature. Among the bugs studied here, *X. flavipes*, *X. sordidus* and *L. campestris* are suitable for mass rearing due to their high population increase capacities. However, it has been reported that *L. campestris* and *P. biannulipes* vary in their development times and fecundities according to the prey species[6,25]. More research on the optimal diet should be carried out to establish an easy method for rearing these bugs.

Predatory Abilities and Suppression Effects

1. Predatory range and abilities

There are some differences in the predatory ranges of bugs among bug species. Most of anthocorid bugs prey on the eggs and small larvae of stored-product moths and beetles. Brower et al.[9] listed 17 species of Coleoptera and

6 species of Lepidoptera as prey of *X. flavipes*. As *L. campestris* is considerably larger than *X. flavipes* and other anthocorids, this bug preys on larger size prey than other anthocorid bugs. Parajulee & Phillips[25] listed 20 species of Coleoptera, 6 species of Lepidoptera and 2 species of Hymenoptera as prey of this bug. *A. venator* is larger than anthocorid bugs and also preys on larger prey. For example, it preys on adults of *Tribolium* spp. (Coleoptera: Tenebrionidae)[24], which *X. flavipes* and *L. campestris* do not easily prey on. A comparison of the functional response to *Tribolium* spp. clearly shows the difference in the predatory abilities among *X. flavipes*, *L. campestris* and *A. venator*. It has been reported that a *X. flavipes* adult killed only 1 to 3 late-instar larvae of *Tribolium castaneum* (Herbst) in 24 h[11]. However, the maximum attack rate in 24 h of a *L. campestris* adult on the late-instar larvae of *T. castaneum* was estimated to be 5.0–11.7[26], and that of an *A. venator* adult on the late-instar larvae of *Tribolium confusum* Jacquelin du Val was estimated to be 6.5–14.9[24]. Furthermore, the maximum attack rate of an *A. venator* adult on *T. confusum* adults was estimated to be 3.6–27.8, revealing that *A. venator* is a good predator with regards to *T. confusum* adults[24]. It has been reported that *J. paradoxus* has a wide predatory range and kills the late-instar larvae and adults of *T. confusum*[10,18,31]. This bug may be a good predator of larger prey.

2. Suppression effects

The suppression effects on stored-product insects have been investigated for several bug species[9]. *X. flavipes* is among the most studied bugs, with many studies regarding its suppression effects[9]. For example, Brower & Mullen[7] reported that releases of large numbers of *X. flavipes* suppressed *Cadra cautella* (Walker) and *Plodia interpunctella* (Hübner) (Lepidoptera: Pyralidae) populations in experimental peanut storages. However, the populations of stored grain pests infesting grain residues in empty corn bins were affected differently by the release of *X. flavipes*[8]. In this test, the populations of small external feeding insects were greatly suppressed by the predator, but internal grain feeding insects such as *Sitophilus* spp. (Coleoptera: Curculionidae) and *Rhyzopertha dominica* (F.) (Coleoptera: Bostrichidae), and moths such as *C. cautella* and *P. interpunctella* were much less affected as compared with small external feeders such as *Oryzaephilus surinamensis* (L.) (Coleoptera: Silvanidae). This was attributed to the fact that internal feeding insects are protected in grain kernels, and *X. flavipes* has difficulty in attacking the large larvae and adults of pyralids. A combination of other biological control agents that can kill large or internal feeding pests is needed for this scenario.

There have been a few reports on the suppression effects of the bugs that attack larger pests. Awadallah et al.[5] examined the suppression effects of *P. biannulipes* on populations of *Ephestia kuehniella* (Zeller), *Corcyra cephalonica* (Stainton) (Lepidoptera: Pyralidae) and *T. confusum*, and reported their reduction rates to be 62.6%, 59.8% and 95.5%, respectively. The suppression effects of *A. venator* were also reported[28]. In a predator-treated warehouse, the populations of *C. cautella* and *Alphitobius diaperinus* (Panzer) (Coleoptera: Tenebrionidae) decreased 95.4% and 88.9% compared to the initial populations, respectively, while in the non-treated warehouse, these increased 197.8% and 161.5%, respectively. Recently, Ishijima et al.[18] conducted laboratory experiments to test the suppression effects of *X. flavipes* and another predatory bug *J. paradoxus*, whose adults can attack larger prey. The reduction rates of *T. confusum* populations with the release of *X. flavipes* and *J. paradoxus* were 97% and 67%, respectively. In the *J. paradoxus*-treated groups, *T. confusum* adults were completely eliminated by *J. paradoxus* adults. However, when *X. flavipes* and *J. paradoxus* were released simultaneously, the reduction rate was only 35%. This was attributed to *J. paradoxus* preying on *X. flavipes* as well as *T. confusum*. It is then necessary to find combinations of predators in which intraguild predation does not occur.

Intraguild predation has also been reported between *X. flavipes* and *Bracon hebetor* Say (Hymenoptera: Braconidae), which is a parasitoid of pyralid moth larvae[29]. The reduction rates of *P. interpunctella* with the release of *B. hebetor* and *X. flavipes* were 74% and 22%, respectively. When *B. hebetor* and *X. flavipes* were released simultaneously, the reduction rate was 52.6%. The number of *B. hebetor* was also reduced when *X. flavipes* was present, indicating that *X. flavipes* had fed on *B. hebetor* as well.

Combinations of predators of external feeding insects and parasitoids of internal feeding insects have yet to be tested. Pteromalid parasitoids such as *Anisopteromalus calandrae* (Howard), *Lariophagus distinguendus* (Förster) and *Theocolax elegans* (Westwood) (Hymenoptera: Pteromalidae) are expected to suppress populations of *Sitophilus* spp. and *R. dominica*[12,16,30,37]. More research is needed to suppress the entire pest complex in storage environments.

Future Prospects

X. flavipes is currently the most promising candidate as a biological control agent because of its high population increase capacity and wide distribution. However, this bug can not attack large pests, so more research is needed on the usage of other predatory bugs that can attack larger pests, like *A. venator*. Combinations of predators of external feeding insects and natural enemies of internal feeding insects should also be examined.

The rearing methods of the predatory bugs *X. flavipes*, *A. venator*, *P. biannulipes*, and *J. paradoxus* have been summarized by Ishijima et al[19], and variations in the development times and fecundities according to the prey species have been reported[6,25]. It is important to find suitable prey for each predator to develop economically viable methods for mass rearing.

Biological control using predatory bugs is a component of integrated pest management strategies. To control whole pest complexes in various storage environments, this type of control will be used with other biological control agents such as parasitoids, pathogens and other types of predators. Further research on combinations with other control strategies such as sanitation, fumigation, irradiation, and packaging should also be carried out.

Acknowledgments

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