Review

Paederus Outbreaks in Human Settings: A Review of Current Knowledge

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ABSTRACT Although rove beetles (*Paederus* spp.) play a beneficial role as biological control agents to manage crop pests in agro-ecosystems, their high prevalence in human settings has elevated them to pest status in urban areas. Rove beetles neither bite nor sting, but accidental crushing on human skin causes them to release the toxin paederin, which causes dermatitis linearis. This review integrates currently available knowledge about the issues pertaining to *Paederus* infestation. For instance, the results of life history studies conducted under different food and temperature regimes are summarized, as they indicate how large a population can be in a habitat to cause massive and widespread infestation and illustrate the physiological traits required to maintain the population at the maximum level even under adverse conditions. In contrast to what is generally reported, we speculate that climatic factors do not necessarily result in *Paederus* dispersal in temperate regions; instead, habitat disturbance and site unsuitability may be the main factors that lead to massive dispersal to human settings. Factors such as whether dispersers are adaptable to xeric conditions in human settings, the probability that dispersed *Paederus* mate with the opposite sex, and whether dispersers have adequate nutrient intake to reproduce are considered to evaluate their potential to reproduce in human settings. Finally, the effectiveness of current commercial insecticides, challenges faced in managing infestations, and sustainable management practices are discussed to provide information for long-term control programs.

KEY WORDS dermatitis linearis, urban expansion, life history, population dynamics, habitat disturbance

Members of the family Staphylinidae are among the coleopterans that constitute a major and ecologically important group of arthropod predators that inhabit arable land (Frank and Kanamitsu 1987, Dennis et al. 1990, Winder 1990, Andersen 1992, Chatzimanolis et al. 2004, Thorbek and Bilde 2004). These generalist predators effectively suppress both indigenous and exotic phytophagous pests in crop fields (Symondson et al. 2002, Thorbek and Bilde 2004). Of the 50,000 staphylinid species distributed worldwide (Grebennikov and Newton 2009), at least 650 species of the genus *Paederus* have been described (Willers 2003). In general, *Paederus* species inhabit moist environments such as marshes, edges of freshwater lakes, river banks, and crop fields (Frank and Kanamitsu 1987). Due to their polyphagous predatory behavior, these beetles are renowned for the ecosystem service they provide, namely biological control of crop pests in agro-ecosystems (Kurosa 1958, Frank and Kanamitsu 1987).

However, the benefits provided by *Paederus* are countered by the problems they can cause for humans. Because of urban expansion close to agricultural fields and other sites where the beetles reside, the prevalence of *Paederus* invasion into human settings is on the rise (Bong et al. 2013b). Adult *Paederus* are attracted to incandescent and fluorescent lights (Baba 1943, Scott 1950); thus, adult flights are just observed at night, when the insects congregate around fluorescent lights in human-dominated areas. In such situations, humans can inadvertently come into contact with the beetle (Frank and Kanamitsu 1987). Although they neither bite nor sting, accidental brushing against or crushing them causes them to release the toxic hemolymph called paederin, and this potent vesicant causes dermatitis linearis on human skin (Frank and Kanamitsu 1987). The lesions are sometimes called "kissing lesions" because they occur when the beetle is crushed between two skin surfaces (Kerdel-Vegas and Goihman-Yahr 1966).

Dermatitis linearis occurs within 24 to 48 h after contact with the vesicant; it is a self-healing dermatitis, taking more than one week to heal (George and Hart 1990, Vegas et al. 1996). Clinically, dermatitis linearis is a necrotic blister that is characterized by linear vesiculobullous lesions on erythematous bases and pruritus (Frank and Kanamitsu 1987, Nicholls et al. 1990,

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Zargari et al. 2003). Lesions usually are elongated due to smearing of the crushed beetle on the skin, and they occur mostly on exposed skin, especially the face and neck, and on the upper arm, forearm, and thigh (Frank and Kanamitsu 1987, Sendur et al. 1999). Ocular reaction can occur due to secondary transfer of the vesicant from the infected skin by fingers to eyes (Frank and Kanamitsu 1987, Zargari et al. 2003). Complications such as postinflammatory hyperpigmentation, secondary infections, and extensive exfoliating and ulcerating dermatitis can occur without proper care (Frank and Kanamitsu 1987, Todd et al. 1996, Zargari et al. 2003).

In this review paper, we describe the life history and physiological traits of *Paederus*, the ecological aspects of their flight activity, and approaches used and challenges encountered in the management of *Paederus* infestation. We address issues such as how large the population of *Paederus* can be in a habitat to cause massive and widespread infestation; whether *Paederus* infestation is climate mediated or driven by habitat disturbance; whether *Paederus* can reproduce in human settings after infestation; the challenges facing management of infestations; and sustainable approaches to pest management.

Paederus Infestation

The first report of dermatitis linearis dates back to the late nineteenth century, when local staff stationed at the Anjet-Kidoel lighthouse in Java, Indonesia, suffered from skin irritation after coming in contact with an ant-like beetle that was later identified as *Paederus* (Vorderman 1901). Since then, sporadic cases have been reported elsewhere in both tropical and temperate countries (Fig. 1). Appendix 1 lists the outbreaks reported in the published papers and non-peer reviewed proceedings that are available to date. It should be noted that the incidence of outbreaks is underestimated, as many cases likely are unreported.

Although *Paederus* is distributed worldwide, massive outbreaks are frequently reported in tropical regions of Asia, including India, Pakistan, Sri Lanka, Iran, Iraq, and Southeast Asia. For example, in mainland Penang along the North Malaysian Peninsula, outbreaks have been reported every year since 2004 (Fig. 2). Bong et al. (2013b) trapped a total of 628,513 beetles in one year, and the highest mean weekly capture was ∼1,100 individuals per insect trap (Fig. 3). This report was based on three selected study sites out of 71 infestation-prone residential areas that are situated adjacent to rice fields (Fig. 4). So, the total number of beetles present in infested premises is expected to be greater than that reported by Bong et al. (2013b).

Based on the case reports worldwide, most incidences of infestation share two similarities. First, outbreaks commonly occur in residential areas that are adjacent to crop fields or wet areas such as riverbanks, drains, pools, and lakes where *Paederus* typically lives. Second, outbreaks often occur once a year. However, in the tropics, multiple outbreaks have been reported (Fig. 2).

Paederus Population Dynamics

To date, information about the population dynamics of *Paederus* is scarce. In one study, Bong et al. (2012) used TWOSEX life table analysis to estimate the potential population size that could be reached under ideal rearing conditions. This study was the first to document the population growth capacity of *Paederus.* Under laboratory conditions of 28°C and 63.5% relative humidity (RH), Bong et al. (2012) reported that adult *Paederus fuscipes* Curtis lived for ∼42–58 d, and the female laid substantial numbers of eggs in her lifetime (121–147 eggs per female). The total development time of the immatures ranged from 17 to 19 d. It was calculated that *Paederus* required only 43–49 d before a new generation of offspring was produced, which translates to at least seven to eight generations throughout a year in the hot and humid tropics.

Recent data suggest that at least two unique life history traits help maintain *Paederus* populations under adverse environmental conditions. The first involves a trade-off between short life span and increased reproductive efficiency. In laboratory studies using three strains of *P. fuscipes* from three different locales, Bong et al. (2012) found that the strain with a 20–25% shorter life span exhibited two main peaks of reproduction at ages of ∼40–50 d and 70–75 d. This phenomenon compensated for the short life span by increasing reproductive activity and also brought the population's net reproductive rate close to that of the strains with the normal life span. Similarly, Polak and Starmer (1998) reported that the frequency of mating of male *Drosophila nigrospiracula* Patterson and Wheeler parasitized by the ectoparasitic mite *Macrocheles subbadius* Berlese increased when the mortality risk rose.

The second life history trait that allows *Paederus* populations to survive under adverse conditions (e.g., in the event of food scarcity) is the ability to invest acquired energy into life maintenance instead of high-cost reproduction. This phenomenon has been documented in other arthropods such as the harvestman, *Pachylus paessleri* Roewer (Naya et al. 2007), grasshopper, *Ageneotettix deorum* (Scudder) (Joern and Behmer 1997), and wolf spider, *Pardosa amenlata* (Clerk) (Mayntz and Toft 2001). Bong et al. (2014) found that when *Paederus* specimens were fed three rich macronutrient sources (i.e., carbohydrate, protein, and lipid), the life span of adult *Paederus* that fed on the carbohydrate-rich food was at least 0.5- and 0.7-fold longer for males and females, respectively, compared with those that fed on protein-rich food. In the study, zero to a limited number of eggs were produced by females fed on the carbohydrate-rich food due to the impeded follicle development, although the total number of immature follicles was comparable with that of protein-fed females. This scenario may reflect the situation under field conditions, as carbohydrate-rich plant materials likely are the main food source for *Paederus* when prey abundance is low. The females may commence reproduction once protein-rich prey become available. However, additional field experiments are necessary to support this.

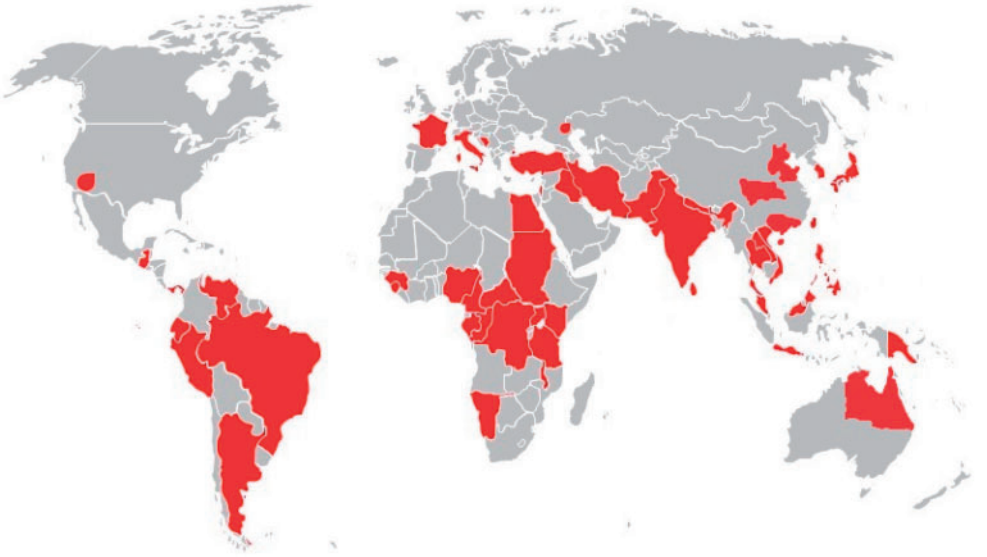

Fig. 1. Global map of *Paederus* outbreak cases (marked in red).

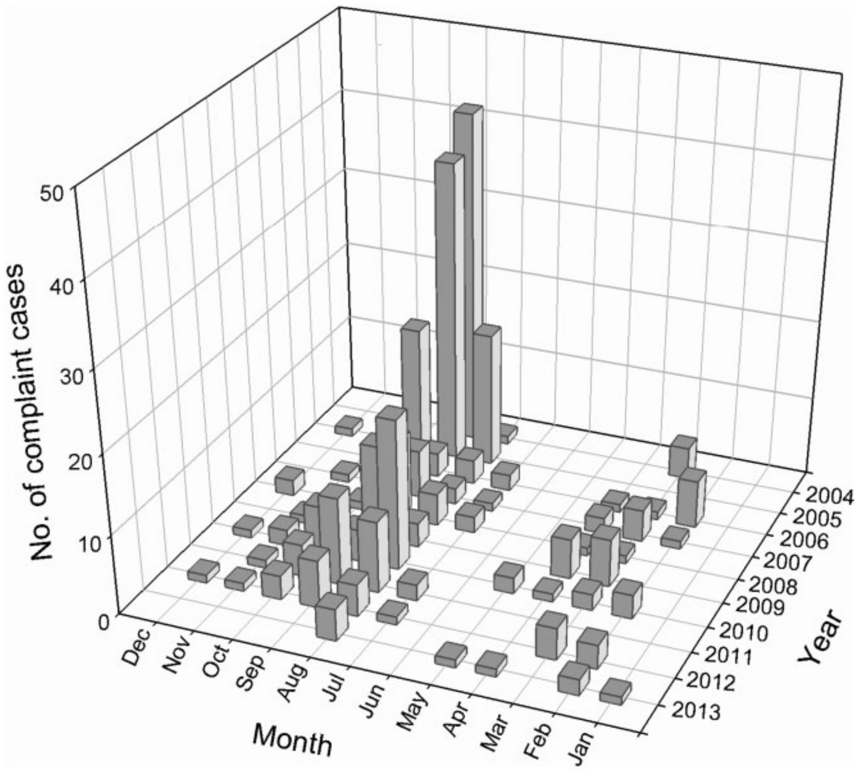

Fig. 2. Numbers of complaints about adult *P. fuscipes* infestation from 2004 to 2013 in mainland Penang (data provided by Seberang Perai Municipal Council, Penang, Malaysia).

In another study, Bong et al. (2013c) simulated the population dynamics of *Paederus* in the temperate zone by rearing them at different temperatures (from 15 to 35°C). Their results suggested that both eggs and newly emerged larvae require at least 80 degree-days above a threshold of ∼10°C for development to occur. Although 100% egg hatchability was recorded at 15°C, the low temperature did not favor development of the late instar larvae and pupa stages. The survival rate of the aforementioned stages was low, as only 2.1% of the

Fig. 3. Sticky traps deployed below a fluorescent lamp along an open-air corridor in a residential setting (left). Thousands of *Paederus* can be captured by each sticky trap (right).

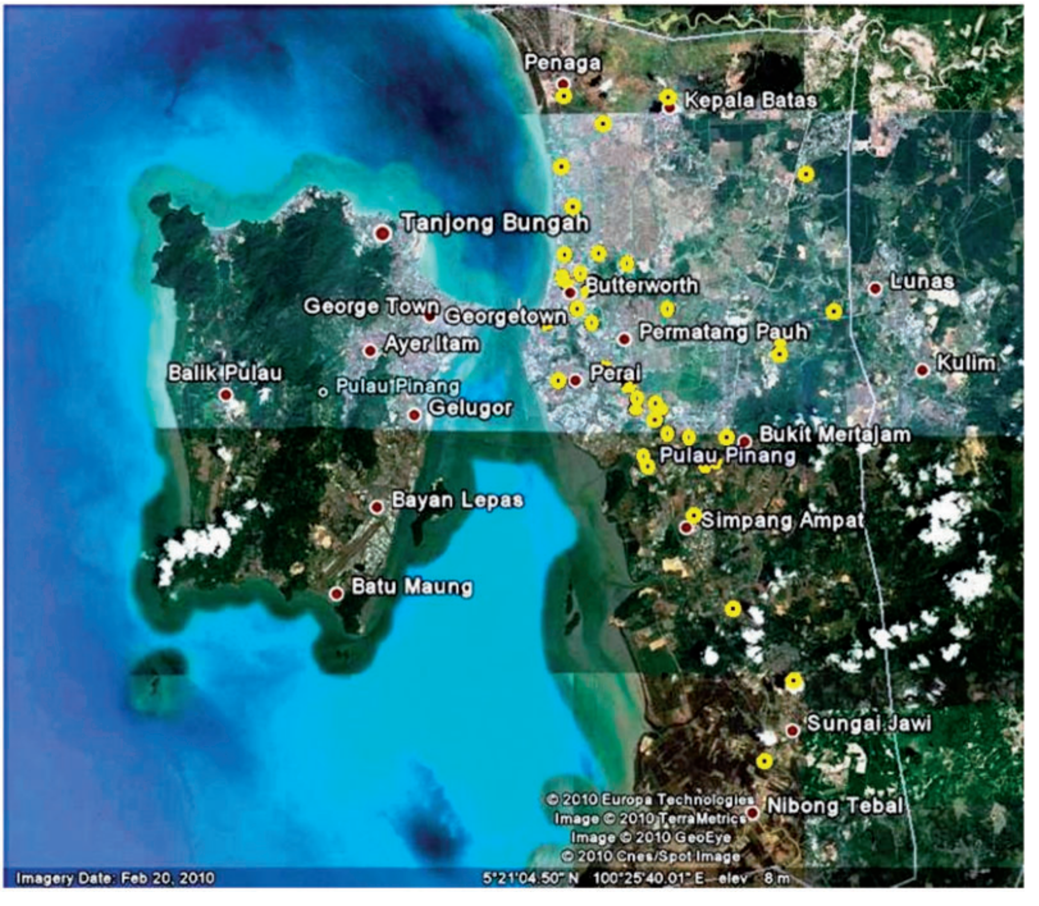

Fig. 4. Areas in mainland Penang, Malaysia, marked with yellow pin-points are adjacent to rice fields and are infested by *Paederus* (Information provided by Seberang Perai Municipal Council, Penang, Malaysia).

immatures developed into adults. In total, eggs to adult development took 2.5 mo, which was three- to four-fold longer than those reared at 23°C and 28°C. Slow development at low temperature is in agreement with previous reports that this insect has only a single annual breeding season in the warmer months, with only one to three generations produced in a year (Isaacs 1934, Kamal 1951, Kurosa 1958, Focarile 1964, Kurosa 1977). In all likelihood, eggs and early instar larvae of *Paederus* can overwinter in cracks and crevices, which create a microenvironment warmer than the minimum temperature threshold required by the insects.

Development of these stages could be delayed until the weather turns warm enough to favor late instar larval and pupal development and adult survivorship and reproduction. At the time, the intrinsic rate of increase could be as high as 0.0583 and 0.0788 at 23°C and 28°C, respectively. However, this population parameter must be treated with caution, as predation was not considered in the study reference. Nevertheless, these results allow us to infer that a drastic increase in population growth could lead to a spectacular population size under warm and humid conditions, and this could be responsible for the massive and widespread infestations observed in both tropical and temperate countries (Frank and Kanamitsu 1987).

Paederus Dispersal

Climatic factors have long been known to play a pronounced role in insect dispersal (Williams 1961, Taylor 1963, Johnson 1969, Abrol 1991, Peng et al. 1992, Isard et al. 1999, Elliot et al. 2000, Edde et al. 2006, Neoh and Lee 2009). In the temperate zone, the beginning of warmer months is thought to trigger physiological activities of insects (Corbet 1999, Kaspari et al. 2001). Copulation begins when the weather turns warm, and under ideal environmental conditions and high food availability, rapid reproduction causes an increase in the insect population density. This in turn leads to massive flights during warmer months when the population reaches its peak. Frank and Kanamitsu (1987) reviewed previous studies and concluded that the dispersal of adult *Paederus* is associated with temperature, and occurs during warmer months. This pattern is particularly true for temperate countries such as Japan, where *Paederus* flights occur from April to October and peak during the summer (Nishihara 1939, Soeda 1950), and Italy, where high population production during the summer results in massive flights in autumn (Baccaredda 1935, Castelli 1935). High humidity also aids dispersal during warmer months.

Rainfall and moist conditions favor flights of most small insects, as high humidity prevents desiccation during flight (Baccaredda 1935, Pickel 1940, Kaspari 1993). In adult *Paederus*, the soft sclerotized thorax is exposed during flight and can pose a risk of desiccation. Thus, observed adult flights typically are restricted to periods of rainfall during the warmer months (Kurosa 1977, Frank and Kanamitsu 1987). This premise is supported by observations of high incidences of dermatitis linearis caused by flying *Paederus* during the rainy season in Africa (Roberts 1942, Service 1963), Europe (Castelli 1934, Baccaredda 1935), Asia (Pujatti 1947, de Leon 1952, Armstrong and Winfield 1969), and Australia (McKeown 1951, Joyce 1952). However, heavy rainfall may be detrimental to flight and foraging activity of *Paederus* (Isaacs 1934, Papasarathorn et al. 1961).

In a recent study, Bong et al. (2013b) conducted weekly sampling throughout a year in Penang, Malaysia, which is a tropical region that experiences uniform tropical weather. The study was designed to correlate numbers of trapped insects with meteorological data collected on a weekly basis from the nearest meteorological stations. This enhanced the reliability of assessing the relationship between week-to-week patterns. The results showed that *Paederus* dispersal to human-dominated areas was not climate dependent, as the weather conditions in the tropics are warm and humid throughout the year. Slight climatic variation in the tropics was not enough to impact flight activity. Conversely, dispersal was initiated when the habitat of the beetles was severely disturbed.

In general, insects are disturbance sensitive. Habitat disturbances generally pose a serious threat to insects and trigger dispersal that results in infestation of human settings. Holway (1998) illustrated this concept clearly in his study of the Argentine ant. Bong et al. (2013b) found that the dispersal of *P. fuscipes* to human-dominated areas occurred throughout the year, with peak flight activity from February to April, and from July to September in the study sites. The timing of the dispersal patterns was in agreement with the timing of complaints of *Paederus* infestation in residential areas (Fig. 2). The peaks were primarily triggered by rice field activity, particularly harvesting and plowing (Bong et al. 2013b). These activities, to a certain extent, disrupted the habitat of *P. fuscipes*, thereby making the rice fields unfavorable refuges. The situation became worse when rice stubble was burned in order to fertilize the land. In addition, the prey–predator system in the rice fields was impacted; the prey population decreased as the vegetation that served as food and reproduction sites was removed during extensive crop management. Thus, habitat destruction coupled with the lack of available food resulted in adult dispersal. Based on the report of Bong et al. (2013b), we question whether climatic factors play a pronounced role in triggering *Paederus* dispersal in temperate countries or whether habitat disturbance is the primary driver.

Paederus Survival and Reproduction in Residential Settings

To date, it is not known whether dispersed beetles reproduce in the premises they infest. For successful reproduction, dispersers must be able to adapt to xeric conditions in human settings to mate, and have adequate nutrient intake. Bong et al. (2013c) reported that adult *Paederus* tolerated a xeric environment and were able to survive for a certain period of time under severe water constraints.

Mating is seen as one of the underlying stimuli for oviposition as evidenced from the observation of high egg loads in unmated female *Paederus* (Bong et al. 2014); the eggs eventually degenerate (oosorption) if oviposition does not take place. In the staphylinid species *Aleochara curtula* Goeze and *Aleochara bilineata* Gyll, frequent mating provides nutrient transfer to females via nutritious spermatophores for successful oviposition (Gack and Peschke 1994, Langlet et al. 1998). This implies that any bias in sex ratio may decrease the overall reproductive success due to increased intensity of mating competition in the male-biased scenario or a reduction in the number of fertilized females in the female-biased scenario. In *P.*

fuscipes, Bong et al. (2012) confirmed that parental investment on offspring sex ratios were not significantly skewed. Assuming that this ratio similarly applies to the dispersers in human settings, we could expect a high rate of courtship might have occurred.

Arthropod predators generally require a protein-rich diet for reproduction to succeed and to sustain their population in nature (Denno and Fagan 2003, Matsumura et al. 2004, Bong et al. 2014), and *Paederus* is no exception (Bong et al. 2014). *Paederus* encounters abundant prey under natural conditions, and it is thought to forage for protein-rich prey or overconsumed low-quality prey to meet the nutritional requirements for optimal reproduction. A diet too high in lipids or too low in protein does not favor reproduction (Bong et al. 2014). Given the nutritional requirements for successful reproduction, it is unlikely that *Paederus* can breed in residential settings after dispersal, even though mating may occur. Several lines of evidence support this premise. First, Bong et al. (2014) found no mature follicles in females collected from infested settings, likely due to the severe food constraints. Second, even if the eggs and the immature stages of *Paederus* had been successfully produced, those stages are restricted to moist environments (Bong et al. 2013c).

Challenges Facing Management Programs

Limited control efforts are used to target *Paederus* in rice fields because this agriculturally beneficial arthropod predator needs to be conserved in this setting, but insecticide applications using thermal fogging or direct chemical spraying are used for beetle control in infested human settings. However, this approach provides only partial or temporal elimination. Generally, the infestation resurges within days following spraying; thus, repetitive treatments are required. Bong et al. (2013a) showed that some commercial insecticides, especially pyrethroids, were effective against the beetle due to their fast knockdown and long residual toxicity, but the high recovery rates still existed.

We suggest that management practices other than insecticide application are needed in both crop field and human settings for sustainable management of this beetle. Crop management strategies that cause only minimal disturbance to the habitat of *Paederus* should be used. The microbial rice stubble degradation method should be used instead of burning, as it elicits mass dispersal of the beetle to human settings. Moreover, crops should be harvested patch by patch so that the beetle can migrate to adjacent less disturbed arable fields instead of dispersing to human settings. In addition, placement of insect traps, such as light traps or sticky traps, below fluorescent lamps along open air corridors is a cheap means to manage *Paederus* (Fig. 3). Although this method does not trap every individual, it reduces the incidence of dermatitis linearis caused by the beetle.

The series of experiments described herein highlight relatively unexplored aspects of *Paederus* biology, such as population dynamics, reproductive capacity under different diet and environment regimes, and current management strategies and challenges to effective pest control. These studies also add novel information to Frank and Kanamitsu's review paper (1987) on *Paederus* in general. However, many questions remain unanswered. For instance, the population capacity discussed in this review was based on ideal environmental and rearing conditions. It is not known if the observed population dynamics also apply to actual field conditions, where cannibalism is thought to be prevalent. In addition, studies of the cold hardiness of this species are needed to identify the strategies used by *Paederus* to withstand cold stress, as it is not known whether this species can freeze and then resume normal biological and physiological activities when the temperature rises or whether they can survive below the supercooling point. Detailed studies across different geographic regions also are required to ascertain the main driver that triggers *Paederus* dispersal in different locales. Finally, studies designed to assess the effectiveness of insecticides under actual field conditions (i.e., residential areas) should be conducted. All of these studies would provide useful information for long-term programs to control *Paederus* infestations in human settings.

Appendix 1: List of *Paederus* outbreaks throughout the world

	Source
Asia	
China	Jin (1990), Li (1990), Yao (1990), Huang et al. (2009), Ma et al. (2009)
Egypt	Morsy et al. (1996), Assaf et al. (2010), Awad et al. (2013)
India	Somerset (1961), Verma and Agarwal (2006), Gnanaraj et al. (2007), Padhi et al. (2007), Ali et al. (2013), Coondoo and Nandy (2013), Toppo et al. (2013)
Indonesia	Vonderman (1901)
Iran	Zargari et al. (2003), Nikbakhtzadeh and Tirgari (2008)
Iraq	Al-Dhalimi (2008), Davidson et al. (2009)
Japan	Yamamoto and Ito (1942), Armstrong and Winfield (1968)
Malaysia	Mokhtar et al. (1993), Rahmah and Norjaiza (2008), Heo et al. (2013)
Nepal	Panta and Poudyal (2013)
Pakistan	Dursteler and Nyquist (2004)
South Korea	Kim et al. (1989), Kim et al. (1995), Kim et al. (2007)
Sri Lanka	Kamaladasa et al. (1997)
Taiwan	Wang et al. (1969)
Thailand	Ekburanawat and Jakreng (2011)
Africa	
Central African Republic	Penchenier et al. (1994)
Democratic Republic of the Congo	Bequaert (1921), Penchenier et al. (1994)
Gabon	Penchenier et al. (1994)
Guinea	Couppié et al. (1992)
Kenya	William (1993), Hugh-Jones (1998), van Schayk et al. (2005)
Namibia	Deneys and Zumpt (1963)
Nigeria	Service (1963), George and Falope (1989), George and Hart (1990), Okiwelu et al. (1996)

(*Continued*)

Appendix 1: Continued

	Source
Republic of the Congo	Penchenier et al. (1994), Vasudevan and Joshi (2010), Roukhsi et al. (2013)
Sierra Leone	Qadir et al. (2006)
Sudan	Iserson and Walton (2012)
Tanzania	Mhalu and Mandara (1981), Fox (1993), Poole (1998)
Uganda	McCrae and Visser (1963)
Europe	
Bosnia	Croft et al. (1996)
France	Drouet et al. (2013)
Italy	Gelmetti and Grimalt (1993), Veraldi et al. (2013)
Russia	Sakharov (1915)
Turkey	Sendur et al. (1999), Uslular et al. (2002), Turan (2014)
Americas	
Amazon river	Mammino (2011)
Argentina	Baliña (1936)
Arizona	Claborn et al. (1999)
Brazil	Diógenes (1994)
Ecuador	Earle (1945)
Panama	Méndez and Iglesias (1982)
Peru	Alva-Dávalos et al. (2002)
Venezuela	Kerdel-Vegas and Goihman-Yahr (1966), Rivas et al. (2001), Cressey et al. (2013)
Oceania	
Australia	Todd et al. (1996), Banney et al. (2000)
Papua New Guinea	Szent-Ivany and Cleland (1966)

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