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ORIGINAL PAPER

Potential impacts of the invasive flatworm *Platydemus manokwari* on arboreal snails

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Abstract The introduction of the snail-eating flatworm *Platydemus manokwari* (Tricladida: Rhynchodemidae) has been considered a cause of the extinction of native land snails on several Pacific islands. Although *P. manokwari* is known to attack land snails on the ground, whether *P. manokwari* attacks snails on trees remains unclear. To clarify the effect of *P. manokwari* on arboreal snails, we examined survival rates of land snails experimentally placed on tree trunks (0.5–2.0 m above the ground) in a forest on Chichijima, Ogasawara (Bonin) Islands, in the northwestern Pacific Ocean. The survival of snails experimentally placed on tree trunks with artificially created snail scent trails rapidly decreased for 7 days, and the mortality was caused by *P. manokwari* predation. However, snails placed on tree trunks without snail scent trails were not attacked by *P. manokwari*. Therefore, *P. manokwari* climbed tree trunks, likely tracking the snail scent. We found that over 40% of the snails placed on tree trunks with snail scent trails were eaten by *P. manokwari* within 7 days. This experiment supports the hypothesis that *P. manokwari* predation is an important cause of the rapid decline or extinction of native arboreal snails on Pacific islands.

Keywords Conservation · Invasive alien species · Land molluscans · Land planarians · Oceanic islands · Pacific islands · Predation · Snail predators · Tree-dwelling species

Introduction

Terrestrial mollusks have the highest number of documented extinctions of any major taxonomic group (Lydeard et al. 2004). Pacific islands support unique land snail faunas with high endemism. However, most endemic species have become extinct or have dramatically declined since human colonization of the islands because of habitat destruction and the impacts of introduced species (reviewed in Lydeard et al. 2004). The predatory snail *Euglandina rosea* (Férussac) (Gastropoda: Spiraxidae) and the snail-eating flatworm *Platydemus manokwari* De Beauchamp (Tricladida: Rhynchodemidae) have been introduced to several areas of the Pacific as biological control agents against the giant African snail *Achatina fulica* (Férussac) (e.g., Muniappan 1990; Eldredge and Smith 1995; Civeyrel and Simberloff 1996; Cowie 2001). However, these species pose a serious threat to endemic land snails because both *E. rosea* and *P. manokwari* feed on live snails of any species, including *A. fulica* (Kaneda et al. 1990; Hopper and Smith 1992; Civeyrel and Simberloff 1996; Cowie 2001; Cowie and Robinson 2003).

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Island land snails live in various types of habitats such as terrestrial, semiarboreal, and arboreal surroundings (Chiba 1999). The diversity and endemism of arboreal snails such as tree snails of the genera *Achatinella* and *Partula* characterize the Pacific land snail fauna (Cowie 1992; Lydeard et al. 2004). It is well documented that the predatory snail *E. rosea* impacts tree snails of the genera *Achatinella* (Hadfield et al. 1993) and *Partula* (Clarke et al. 1984; Murray et al. 1988). Like *E. rosea*, *P. manokwari* is considered to impact arboreal snails, and the extinction and decline of tree snails of the genus *Partula* on Guam are considered to have been caused by *P. manokwari* predation (Hopper and Smith 1992). However, the arboreal behavior of *P. manokwari* has rarely been observed. Therefore, the impact of *P. manokwari* on arboreal snails remains unclear.

Here, we examined the survival rates of snails experimentally placed on tree trunks on an island of the Ogasawara (Bonin) Islands, which *P. manokwari* has already invaded, in order to address the following questions: (1) to what extent are arboreal snails attacked by *P. manokwari*? and (2) how does *P. manokwari* locate arboreal snails to attack?

Materials and methods

Study site and species

The Ogasawara Islands are oceanic islands located in the northwestern Pacific Ocean, about 1,000 km south of the mainland of Japan (Shimizu 2003). The climate is subtropical; the mean annual temperature was 23.2°C and the annual precipitation was 1,292 mm during 1987–1998 on Chichijima (Toyoda 2003).

Ninety-five species of land snails have been recorded from the Ogasawara Islands, of which about 90% are endemic to the islands (Tomiyama and Kurozumi 1992; Chiba et al. 2007). However, over 70% of native land snail species on the largest of the Ogasawara Islands, Chichijima, have become extinct (Chiba et al. 2007). Furthermore, endemic land snails have been rapidly declining on Chichijima since the early 1990s (Ohbayashi et al. 2005, 2007). *Platydemus manokwari* (Fig. 1a) is thought to have been introduced to Chichijima accidentally and became established in the early 1990s (Ohbayashi et al. 2005). *Platydemus manokwari* predation is considered an important cause of the rapid decline of land snails on Chichijima (Ohbayashi et al. 2005, 2007; Sugiura et al. 2006). *Platydemus manokwari* feeds on dead animals (e.g., earthworms), as well as live snails, and has thus survived in areas where snails have been absent since its invasion (Ohbayashi et al. 2005).

Field experiment

To estimate potential impacts of *P. manokwari* on arboreal snails, we examined the survival of snails experimentally placed on tree trunks in a forest of the Kiyose Experimental Station of the Forestry and Forest Products Research Institute on Chichijima (Kiyose; 27°06′ N, 142°11′ E). The forest was composed of palms, pines, and broad-leaved tree species. *Platydemus manokwari* was observed to hide under stones during the day, and crawl along the forest floor at night. In this forest, the predation pressure by *P. manokwari* on ground-dwelling snails was extremely high, and therefore few snails survived (Sugiura et al. 2006). The experiment was conducted in early November 2007. The mean temperature, mean relative humidity, and mean daily precipitation during the experiment was 24.2°C, 78.3%, and 3.9 mm, respectively (Chichijima Meteorological Observation Station, 27°05′ N, 142°11′ E).

To compare the survival rates of land snails on the ground and on tree trunks, we placed nylon bags containing land snails on the ground, on tree trunks 0.5 m above the ground, and on tree trunks 1.0 m above the ground. We used juveniles and adults of the introduced species *Acusta despecta* (Sowerby) (shell diameter $<$20 mm) collected from coastal areas of Chichijima where many introduced snails survive because of the absence of *P. manokwari* (Sugiura et al. 2006). We placed land snails in 2-mm mesh nylon bags (approximately 30 $\times$ 25 cm) that allowed the entry of *P. manokwari* but not the escape of the snails. Fleshy mulberry leaves and pieces of rigid plastic were also placed in the bags as food and resting sites for snails, respectively. Five *A. despecta* individuals were placed in each bag. In an earlier study (Sugiura et al. 2006), we also used bags that excluded *P. manokwari* to clarify the effects of *P. manokwari* on land snails in bags that do allow the flatworm to enter. *Platydemus manokwari* did not

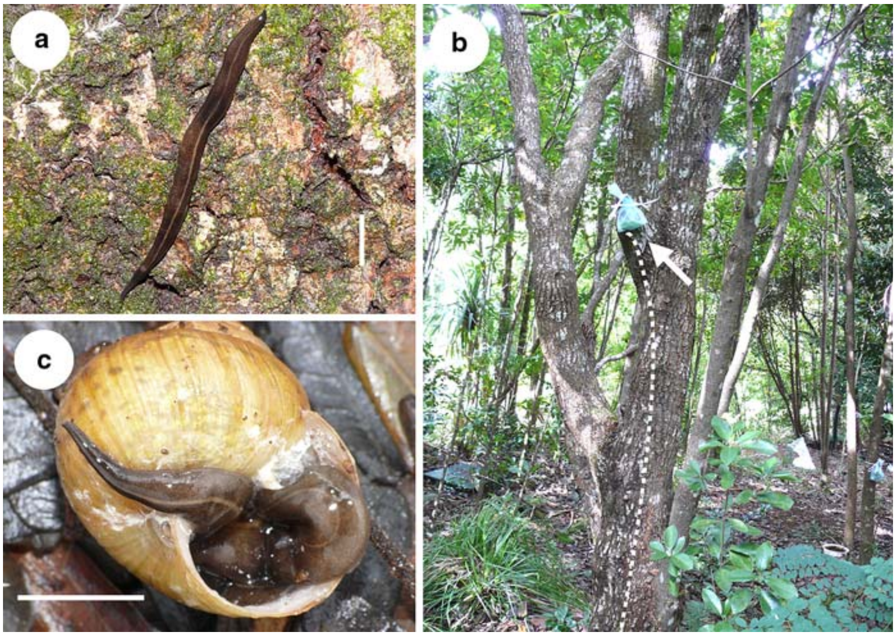

Fig. 1 (**a**) *Platydemus manokwari*. (**b**) A 2-mm mesh nylon bag (containing five snails) tied to a tree trunk 2 m above the ground. The arrow indicates the bag. The dashed line indicates the tree trunk to which a 10-mm wide snail scent trail was applied. (**c**) *Platydemus manokwari* feeding on a snail. Bars: 10 mm

kill land snails placed in <0.5-mm mesh fabric bags that excluded *P. manokwari* at this study site; therefore, this treatment was not repeated in the present study. We randomly selected 14 trees (diameter at breast height (DBH) 67–191 mm) and tied single bags (containing five snails each) to each tree using plastic ropes (Fig. 1b). We placed one bag per tree trunk. Because *P. manokwari* uses chemical senses to locate prey under laboratory conditions (Kaneda et al. 1990), *P. manokwari* may follow the scent of snails on trees to track and find arboreal snails in the field. Therefore, we used live individuals of *A. despecta* to apply their scent along a 10-mm-wide trail to tree trunks from the ground to each bag (Fig. 1b). We used seven bags per height treatment: 0 m (on the ground), 0.5 m (on tree trunks), and 1.0 m (on tree trunks). Tree DBH did not differ among height treatments (Welch's t-test, $t_9 = -1.06$, $P = 0.32$). Bags were placed >1 m apart. We checked the survival of land snails and counted the number of *P. manokwari* invading each bag 1, 2, 3, and 7 days after placement.

Another experiment was conducted to test whether *P. manokwari* climb trees while tracking the snail scent applied to tree trunks. We randomly selected 28 trees (DBH 64–354 mm) and tied a single bag (containing five snails) to each tree using plastic ropes (Fig. 1b). Twenty-one and seven bags were tied to tree trunks 1.0 and 2.0 m above the ground, respectively. We compared the number of bags invaded by *P. manokwari* among the different treatments. The first treatment consisted of a snail scent trail applied to tree trunks from the ground to the bags (Fig. 1b; height 1.0 m, $N = 7$; height 2.0 m, $N = 7$). We used live individuals of *A. despecta* to apply their scent along a 10-mm-wide trail to tree trunks from the ground to each bag (Fig. 1b). The alternative treatment included water applied to tree trunks from the ground to the bags (height 1.0 m, $N = 7$). As the control, nothing was applied to tree trunks (height 1.0 m, $N = 7$). Tree DBH did not differ among treatments (one-way ANOVA, $F_{3,24} = 0.08$, $P = 0.97$). We checked the survival of snails and counted the number of *P. manokwari* invading each bag 1, 5, and 7 days after the placement. When *P. manokwari* escaped from the bags after predation, we measured the invasion of *P. manokwari* into each bag by checking land snails killed by *P. manokwari* in the bags.

Data analysis

To examine the effects of snail bag position (i.e., on the ground and on trunks at 0.5 and 1.0 m height) on the number of live snails per bag, we used generalized linear models (GLMs) with Poisson error distribution and log link (i.e., Poisson regression).

We also examined the effects of snail bag position on the number of *P. manokwari* invading each snail bag using Poisson regression. We examined these effects at 1, 2, 3, and 7 days separately. To clarify what *P. manokwari* used to climb tree trunks, we also examined the effects of tree trunk treatments (control, water, snail scent trails at 1.0 m, and snail scent at 2.0 m) on invasion or non-invasion (1/0) of *P. manokwari* into each bag using GLMs with binomial error distribution and logit link (i.e., logistic regression). When residual deviance was larger than residual degrees of freedom (i.e., overdispersion), we used quasi-Poisson or quasi-binomial error distribution instead of Poisson or binomial error distribution, respectively (Crawley 2007). Then we tested these effects using *F*-tests or chi-square tests (Crawley 2007). We used R Ver. 2.4.1 for these statistical analyses (R Development Core Team 2006).

Results

Survival of the snails experimentally placed on tree trunks as well as on the ground rapidly decreased over only 3 days (Table 1). *Platydemus manokwari* was frequently observed feeding on snails in bags for 2 days after bag placement (Fig. 1c; Table 2). Although the number of *P. manokwari* per bag differed significantly with bag position, its significance disappeared after considering overdispersion (Table 2). Soft parts of most dead snails were completely consumed by *P. manokwari*, and only empty shells remained. All mortalities of land snails were caused by *P. manokwari* predation. We found that 91.4% (32/35), 40.0% (14/35), and 45.7% (16/35) of the snails placed on the ground, on tree trunks at 0.5 m height, and on tree trunks at 1.0 m height, respectively, were eaten by *P. manokwari* within 7 days. Therefore, survival of land snails differed significantly with snail bag position (Table 1).

Bags placed on tree trunks with snail scent trails were invaded by *P. manokwari*, whereas bags placed on tree trunks without snail scent were rarely invaded (Table 3; GLM, bimodal distribution, $\chi^2{}_3 = 8.64$, $P = 0.03$; quasi-bimodal error distribution, $F_{3,24} = 3.29$, $P = 0.04$). Some snails (one or two per bag) were killed in the bags invaded by *P. manokwari*. Therefore, *P. manokwari* probably located bagged snails by tracking the snail scent on tree trunks.

Table 1 Effects of different bag positions on survival of snails in bags

	Numbers[a] of live snails per bag			Test[b]		
	On the ground	Tree trunk (0.5 m)	Tree trunk (1.0 m)	d.f.	χ^2	*P*
Set (Day 0)	5 (5–5)	5 (5–5)	5 (5–5)			
Day 1	3 (1–5)	4 (2–4)	3 (3–4)	2	0.21	0.90
Day 2	1 (0–3)	3 (2–4)	3 (2–4)	2	6.40	0.04
Day 3	1 (0–2)	3 (2–4)	3 (2–4)	2	8.97	0.01
Day 7	0 (0–1)	3 (2–4)	3 (2–4)	2	17.37	0.0002

[a] Median (min–max)

[b] GLM using Poisson error distribution

Table 2 Effects of different bag positions on *Platydemus manokwari* invasions into bags

Bag positions	Numbers[a] of *P. manokwari* per bag			Chi-squared test[b]			*F*-test[c]		
	On the ground	Tree trunk (0.5 m)	Tree trunk (1.0 m)	d.f.	χ^2	*P*	d.f.	*F*	*P*
Day 1	2 (1–16)	1 (1–3)	2 (1–3)	2	8.85	0.01	2,18	1.61	0.23
Day 2	3 (0–10)	1 (0–5)	1 (0–5)	2	10.01	0.01	2,18	2.17	0.14
Day 3	0 (0–6)	0 (0–0)	0 (0–1)	2	9.64	0.01	2,18	2.07	0.16
Day 7	0 (0–0)	0 (0–0)	0 (0–0)	2	0.00	1.00			

[a] Median (min–max)

[b] Poisson error distribution

[c] Quasi-Poisson error distribution

Table 3 Effects of different treatments on invasions by *Platydemus manokwari* into bags

Tree trunk treatment	Tree trunk height (m)	No. bags	No. bags invaded by *P. manokwari* (%)*
None (control)	1.0	7	0 (0.0)
Water	1.0	7	1 (14.3)
Snail scent	1.0	7	4 (57.1)
Snail scent	2.0	7	3 (42.9)

* Significant difference among treatments; GLM, bimodal distribution, $\chi^2_3 = 8.64$, $P = 0.03$; quasi-bimodal error distribution, $F_{3,24} = 3.29$, $P = 0.04$. The values did not differ with number of days (1, 5, or 7) after placement

Discussion

Platydemus manokwari is an important mortality factor for arboreal snails (Table 1). Furthermore, our findings suggest that snail scent is an important cue to *P. manokwari* for locating arboreal snails in the field (Table 3). Locating prey using chemical cues has been found previously under laboratory conditions (Kaneda et al. 1990). This study is (1) the first demonstration of the rapid decrease in arboreal snail survival caused by *P. manokwari* predation and (2) the first field evidence of *P. manokwari* locating prey using chemical cues.

Some arboreal snail species do not descend from trees to the ground (e.g., Hadfield and Mountain 1980). Thus, how would the ground-dwelling *P. manokwari* locate such arboreal snails? Heavy rains may result in the scent of tree snails being carried down tree trunks to the ground, thereby enabling *P. manokwari* to locate tree snails using the snail scent trails on tree trunks. Our experiment also indicated that an individual *P. manokwari* could climb a tree trunk subjected only to the water treatment (Table 3), suggesting that conditions of heavy rain, which make tree trunks wet, enable *P. manokwari* to be able to search for prey on tree trunks. Furthermore, some species of arboreal snails that descend from and move among trees (Cowie 1992; Chiba 1999) may leave trails (i.e., chemical cues) for *P. manokwari* to follow up tree trunks.

Mortality in this experiment may have been overestimated because the snails were kept in closed bags in which their movement was limited. However, even if arboreal snails can escape from *P. manokwari* attacks by falling to the ground, they may experience higher *P. manokwari* predation pressure on the ground. Therefore, our results support the hypothesis that the introduction of *P. manokwari* is an important cause of the rapid decline or extinction of native arboreal snails as well as ground-dwelling snails on Pacific islands.

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