Black Rat (*Rattus rattus*) Predation on Nonindigenous Snails in Hawai'i: Complex Management Implications[1]

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Abstract: Understanding interactions among nonindigenous species that pose a threat to native species is crucial to effectively preserve native biodiversity. Captive feeding trials demonstrated that the black rat, *Rattus rattus*, will readily consume two of the most destructive nonindigenous snails, the giant African snail, *Achatina fulica* (100% predation), and the predatory snail *Euglandina rosea* (80% predation). Rats consumed snails from the entire size range offered (11.5 to 59.0 mm shell length), suggesting that there is no size refuge above which snails can escape rat predation. Damaged *E. rosea* shells from the captive feeding trials were compared with shells collected in the Wai'anae Mountains, O'ahu. This revealed evidence that *R. rattus* is responsible for at least 7%–20% of *E. rosea* mortality. However, this is likely a substantial underestimate because 67% of *E. rosea* shells in the captive feeding trials were damaged in such a way that they would not have been collected in the field. Therefore, we hypothesize that reduction or eradication of *R. rattus* populations may cause an ecological release of some nonindigenous snail species where these groups coexist. As such, effective restoration for native snails and plants may not be realized after *R. rattus* removal in forest ecosystems as a consequence of the complex interactions that currently exist among rats, nonindigenous snails, and the remaining food web.

RAPID POPULATION DECLINES and species extinctions have been reported following the widespread introduction of nonindigenous species in Hawai'i (Burney et al. 2001, Athens et al. 2002). Human intervention is then often required for short-term recovery or maintenance of native biodiversity (Burney and Burney 2007). Unfortunately, insufficient understanding of both the magnitude of the threat that nonindigenous species pose to native biodiversity and the potentially complex interactions among the introduced species can lead to unexpected outcomes (Novacek and Cleland 2001, Doak et al. 2008). Given the large number of nonindigenous species that have altered Hawaiian ecosystems, understanding the interactions among nonindigenous species is crucial to effectively preserve the remaining native biodiversity.

Introductions of rats (*Rattus exulans* Peale, *R. norvegicus* Berkenhout, *R. rattus* L.) and terrestrial snails have been implicated in the decline of native Hawaiian flora and fauna (Hadfield 1986, Burney et al. 2001, Athens et al. 2002, Joe and Daehler 2008). All three rat species were introduced to the Hawaiian Islands by people and are among the most noxious invasive species on islands worldwide (Lowe et al. 2000, Russell and Clout 2004,

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Towns et al. 2006). The first rat species introduced to most islands in Polynesia, *Rattus exulans*, may have contributed to rapid forest decline and loss of animal species in Hawai'i (Burney et al. 2001, Athens et al. 2002). *Rattus rattus* and *R. norvegicus* became established in Hawai'i in the late 1700s after European arrival, and both *R. rattus* and *R. norvegicus* typically outcompete *R. exulans* (Lindsey et al. 1999, Russell and Clout 2004). *Rattus norvegicus* is more common in urban areas, and *R. rattus* is the most abundant rat species in conservation areas in the Hawaiian Islands (Lindsey et al. 1999; A.B.S., unpubl. data). Nonnative terrestrial snails were also brought to Hawai'i by humans and have established and spread in both urban and conservation areas (Cowie 1997). The giant African snail, *Achatina fulica* Bowdich, is one of the largest land snails in the world, reaching up to 19 cm in length (Peterson 1957). *Achatina fulica* has been recognized as one of the world's most damaging pests (Lowe et al. 2000). This designation is primarily a result of this species' large size, polyphagous diet, and ability to reach high population densities in areas where it has become established (Kekauoha 1966, Raut and Barker 2002, Meyer et al. 2008). *Euglandina rosea* (Férussac) was purposely introduced to Hawai'i in 1955 to control populations of *A. fulica* (Davis and Butler 1964, Civeyrel and Simberloff 1996, Cowie 2001). However, *E. rosea* has not reduced *A. fulica* populations (Civeyrel and Simberloff 1996, Cowie 2001) but has been associated with the decline and extinction of many of the endemic terrestrial snail species in Hawai'i and elsewhere in the Pacific where it has also been introduced (Clarke et al. 1984, Hadfield 1986, Murray et al. 1988, Cowie 2001, Coote and Loève 2003).

Rats and introduced snails have some diet overlap and therefore may have some similar environmental effects. For instance, both rats and many snail species introduced to Hawai'i eat various plant parts and reduce plant survival (Mead 1961, Cole et al. 2000, Joe and Daehler 2008, Pérez et al. 2008). Also, both rats and introduced predatory snails, most notably *E. rosea*, prey on native Hawaiian land snail species (Hadfield 1986, Hadfield et al. 1993, Cowie 2001). However, understanding the environmental impact of rats and snails is complicated by the fact that rats may feed on nonindigenous snails such as *E. rosea* (Hadfield et al. 1993). Therefore, rats may reduce the impacts of nonindigenous snails through predation (see Courchamp et al. [1999] for a discussion on mesopredator release).

It is unknown to what extent rats consume introduced snail species. Vulnerability to rat predation may be influenced by snail size. *Rattus rattus* is known to prey upon native snails, which are much smaller than *A. fulica* and *E. rosea* (Hadfield et al. 1993). However, to the best of our knowledge *R. rattus* predation on larger introduced snail species has not been addressed. This study addressed the following questions: (1) Will *R. rattus* feed on *A. fulica* and *E. rosea*? (2) Is there a size refuge above which snails are not vulnerable to *R. rattus*? (3) Can damage to *E. rosea* shells observed in feeding trials be matched to *E. rosea* shells (snails not alive) collected in the wild to allow estimation of rat predation on *E. rosea* in the wild? Because *R. rattus*, *A. fulica*, and *E. rosea* have become established and threaten native biodiversity on many other Pacific islands, understanding the interactions among these nonindigenous species can have wide-ranging utility for natural resource managers throughout much of the Pacific.

MATERIALS AND METHODS

Captive Feeding Trials

Ten adult *R. rattus* (six females and four males) were captured from wild populations in the Wai'anae Mountains, O'ahu, and taken to the University of Hawai'i Lyon Arboretum Rodent Housing Facility. Each rat was held in an individual 38 by 22 by 18 cm metal-mesh (8 mm) cage. Rats were allowed to acclimate for at least 1 week before beginning feeding trials, during which time the rats were fed a diet of mixed seeds (e.g., corn, sunflower, wheat, barley, oats, sorghum) and wedges of fruit (tangerine). Rats were checked daily to ensure that there was ample

food and fresh water, and to clean urine/fecal trays.

Snail prey of various sizes, *A. fulica* (11.5–59.0 mm shell length) and *E. rosea* (32.3–45.7 mm shell length), were collected on O'ahu from conservation areas (Wai'anae Mountains) and urban areas (Honolulu), respectively, less than 1 week before the feeding trials.

Feeding trials were performed on 7 and 10 April 2008. Each trial lasted 24 hr and consisted of 10 experimental cages (each containing one rat and one prey snail) and 10 control cages (prey snail without rat). During each trial, five rats were offered *A. fulica* and five were offered *E. rosea*. Each rat was exposed to each prey species only once during the two feeding trials. Snails placed in cages without rats accounted for any incidence of mortality due to the laboratory conditions. The two trials were separated by a 48 hr period, during which the rats were fed their regular diet. After each trial, snail mortality was recorded, and shell fragments were recovered and photographed for later comparison with shells collected in the wild. Fisher's exact test (Sokal and Rohlf 1995) was used to assess differences in mortality between the experimental and control treatments for each prey species.

Snail Mortality in the Field

To estimate *E. rosea* mortality caused by *R. rattus* in the wild, shells of dead *E. rosea* from two sites (550–625 m elevation) on O'ahu (Kahanahāiki Management Unit, northern Wai'anae Mountains, 21° 32′ N, 158° 11′ W; Kalua'a Preserve, southern Wai'anae Mountains, 21° 28′ N, 158° 5′ W) were compared with *E. rosea* shells damaged in the captive feeding trials. Matching the damaged shells in the field with those specifically damaged by *R. rattus* in the captive feeding trials gave us confidence that the majority of the field-damaged shells were by *R. rattus* rather than other *Rattus* species. In addition, *R. rattus* is much more abundant than the other rat species in these conservation areas, as revealed by bimonthly relative abundance measures from these two sites using mark-and-recapture sampling during 2007–2008 (ratio of *R. rattus*: *R. exulans* is 12: 1 for Kahanahāiki and 135: 1 for Kalua'a; *R. norvegicus* was never captured at either site [A.B.S., unpubl. data]). The *E. rosea* shells were collected opportunistically between July 2005 and May 2008. All shells from the wild were categorized according to shell size and whether they were undamaged, damaged dorsally (i.e., opposite side of shell to aperture), or damaged at the aperture (see Figure 1). Shell fragments were not collected or recorded in the field because the shell fragments could not be confidently identified, and land managers often crush *E. rosea* if found. Fisher's exact test was used to assess if the frequency of damaged shells (aperture and dorsal damage combined) was significantly different between Kahanahāiki and Kalua'a.

FIGURE 1. Damage to *Euglandina rosea* shells by *R. rattus* in captive feeding trials: *A*, aperture damage; *B*, dorsal damage; *C*, shell apex remaining.
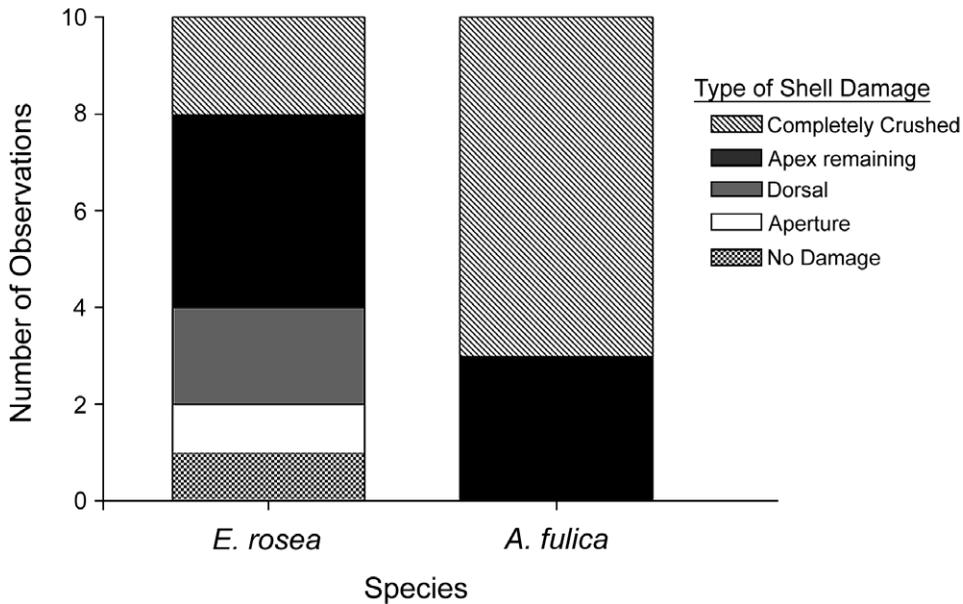
FIGURE 2. Frequency of shell damage categories in *Euglandina rosea* and *Achatina fulica* resulting from *R. rattus* predation in captive feeding trials.

RESULTS

Captive Feeding Trials

Rattus rattus consumed both snail species. All 10 *A. fulica* and eight of the 10 *E. rosea* were killed. There was no snail mortality in any control (rat-free) cages. The difference between experimental and control treatments for both snails was significant: *A. fulica* ($Z = 4.472$, $P < .001$) and *E. rosea* ($Z = 3.652$, $P = .007$).

Types of shell damage caused by *R. rattus* in the captive feeding trials included aperture damage (Figure 1*A*), dorsal damage (Figure 1*B*), anterior damage with the apex remaining intact (Figure 1*C*), and completely crushed shells. The two most common types of shell damage observed (combining data for both snail species) was the anterior portion damaged with the apex remaining intact (nine snails), and the shells being completely crushed into small pieces (seven snails) (Figure 2). Dorsal damage to the shell was observed in only two *E. rosea* that were killed (Figure 2). Aperture damage was observed in one *E. rosea* that survived the 24 hr rat expo-

sure (Figure 1); it is not known if this damage impacts the survival or fitness of the snail. Among all snails offered, both the largest (59.0 mm shell length) and the five smallest (11.5, 19.6, 21.3, 24.0, and 24.1 mm) were completely crushed. The types of shell damage that we observed for the two snail species tended to differ: *A. fulica* shells were either completely crushed or partially crushed with the apex preserved, whereas *E. rosea* shells were either damaged dorsally or at the aperture, completely crushed, or partially crushed with the apex preserved (Figure 2).

Snail Mortality in the Field

In total, 166 *E. rosea* shells were collected from the two forest sites on Oʻahu: Kaluaʻa (96 shells) and Kahanahāiki (70 shells) (Figure 3). All shells were 25–55 mm in shell length. The absence of small shells (<25 mm) is probably not a result of collection bias because smaller shells of other snail species were noticed. Incidence of rat damage to shells was significantly higher ($Z = 2.025$, $P = .022$) in Kahanahāiki (24.5%) than in
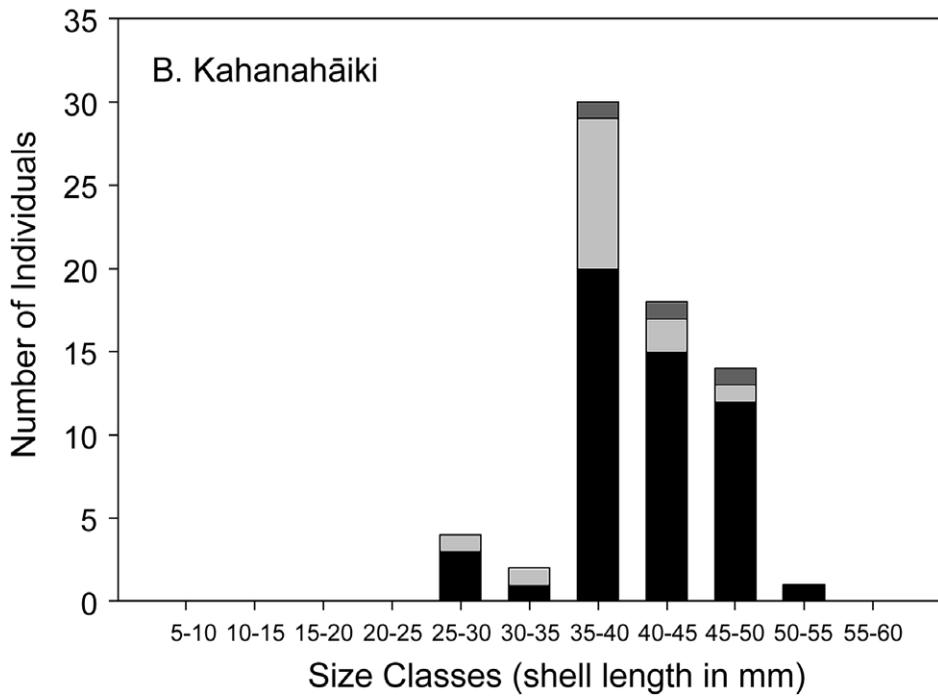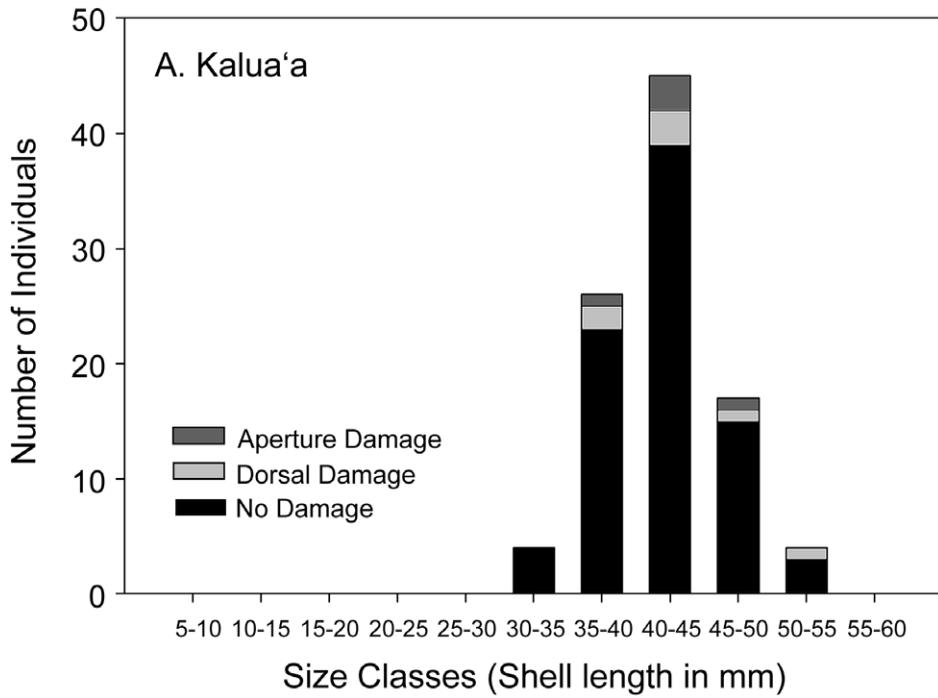
FIGURE 3. *Euglandina rosea* shell (dead snail) assemblage in two mesic forest sites on Oʻahu: *A*, Kaluaʻa Preserve, southern Waiʻanae Mountains; *B*, Kahanahāiki Management Unit, northern Waiʻanae Mountains. Dorsal and aperture shell damage is attributed to rats, based on matching shells with those used in captive feeding trials with *R. rattus*.

Kaluaʻa (12.5%). Dorsal shell damage tended to be much higher in Kahanahāiki (20.0%) compared to the dorsal shell damage in Kaluaʻa (7.3%) (Figure 3). Damage to the aperture was noticed on 4.5% and 5.2% of the shells collected from Kahanahāiki and Kaluaʻa, respectively. Although aperture damage may suggest interaction among rats and snails, it may not imply mortality based on the one observation made in the captive feeding trials. Alternatively, damage to the dorsal portion of the shell can be used to indicate mortality likely caused by *R. rattus*.

Crushed shells, which were rarely seen, and remnants of shells such as shell apexes that might have been preyed upon by *R. rattus* were not collected in the field because we presumed that most of those shells were intentionally crushed by land managers and conservationists who frequently visit the sites. However, in retrospect, on examining shell damage in the feeding trials, this was probably a false assumption and many of these shells may have been preyed upon by *R. rattus*. Therefore, our estimate of *R. rattus* predation on *E. rosea* is probably an underestimate.

DISCUSSION

Our captive feeding trials demonstrate that *R. rattus* can consume nonindigenous snails of various sizes (100% of *A. fulica* and 80% of *E. rosea* offered). The largest *A. fulica* (6 cm in shell length) and *E. rosea* (4.5 cm in shell length) offered were eaten, although we do not know whether very large *A. fulica*, which can reach 19.0 cm in shell length (Peterson 1957), would be preyed upon. Such large *A. fulica* are rarely observed in Hawaiʻi (W.M.M., pers. obs.). Comparison of rat damage to *E. rosea* in the captive feeding trials with shells of *E. rosea* from the wild showed that rats likely caused a minimum of 7%–20% of *E. rosea* mortality.

Rats crushed entire shells in 45% of the captive feeding trials (Figure 2). Unfortunately, it is unlikely that a high proportion of crushed shells could reliably be collected in the field. However, not accounting for completely crushed shells may result in an underestimate of the impact of *R. rattus* on snail populations and may therefore lead to inappropriate conclusions regarding predation levels. For example, no small *E. rosea* shells (<25 mm in shell length) were collected at the two field sites (Figure 3). This pattern might suggest very low juvenile mortality, but it seems more likely that juvenile mortality was not detected because shell fragments were not analyzed. Although rats crushed shells across the size range offered, smaller snails might be crushed more often, because this was the fate of the five smallest snails in the feeding trials. In addition, the shape of the shell may also influence the likelihood that the shell is crushed, because the more conically shaped shells of *E. rosea* were often damaged without completely crushing whereas the more rounded shells of *A. fulica* were most often crushed. In areas where native snails occur, presence of *E. rosea* shells and native snail shells with characteristic rat damage (Figure 4) are used to assess the predation risk from both predators and to initiate a rapid management response (V. Costello, pers. comm.). Rats crushing either *E. rosea* or native shells may limit the ability to adequately quantify the threat from either predator.

FIGURE 4. A shell of the endemic Oʻahu tree snail *Achatinella mustelina* after *R. rattus* predation in a snail conservation area in the Waiʻanae Mountains.

Predation levels on *E. rosea* of 7% and 20% at Kalua'a and Kahanahāiki, respectively, correlate with *R. rattus* relative abundance, which was approximately 2.5 times greater at Kahanahāiki than at Kalua'a based on bimonthly mark-and-recapture technique during 2007–2008 (A.B.S., unpubl. data). However, *E. rosea* mortality caused by *R. rattus* at those two sites is probably greater than that because only damage to the dorsal portion of the shell was used to indicate mortality. This potential underestimate is likely substantial, because 67% of *E. rosea* shells in the captive feeding trials were damaged in such a way that they would not have been collected in the field (Figure 2). As such, we suggest that *R. rattus* may substantially contribute to *E. rosea* mortality where they coexist. However, determining if *R. rattus* predation regulates *E. rosea* population densities requires a more in-depth understanding of *E. rosea* population dynamics.

Conservation of Hawai'i's native forest ecosystems requires reducing or controlling the impacts of introduced plants and animals, including rodents and nonindigenous snails. Rats are increasingly being controlled in conservation areas on O'ahu. Recent federal approval of aerial broadcast of rodenticide into conservation areas in Hawai'i will probably lead to increased rat control efforts. However, the complex interactions among *R. rattus* and nonindigenous snail species, particularly *E. rosea*, suggest that managers should proceed cautiously with management and control efforts that involve these species. Removal of *R. rattus* in the Wai'anae Mountains may result in *E. rosea* population increases. This may have negative effects on native snail populations, which may be irreversible because of the difficulty of controlling *E. rosea* while not harming other, native snail species. It is unknown if *E. rosea* predation on other mollusk species would equal or exceed that of *R. rattus*. In 85%–100% of rat stomachs examined on Maui, invertebrate material (including slugs, snails, and earthworms) was found (Sugihara 1997).

Rat predation on herbivorous nonindigenous snail species may also influence the preservation of Hawai'i's native forest ecosystems. *Achatina fulica* is known to consume over 500 plant species (Mead 1961) and can reach densities of 7.75 snails per square meter in the low-elevation areas of Hawai'i (Kekauoha 1966). Slugs (snails without shells) were specifically mentioned as threats or potential threats to 59 rare plant species (22% of all endangered and threatened plants) in Hawai'i (Joe and Daehler 2008). Further experiments should examine rat prey preferences among various snail prey and the influence of rat predation on snail populations, especially those species that are widespread and are recognized as a threat to native ecosystems.

Until we understand how nonindigenous snail populations will respond to rat removal, it is difficult to predict the probability of success for native snail and plant recovery after *R. rattus* eradication. Prudent management will require precautionary and adaptive management approaches (Doak et al. 2008). Removal of species to help facilitate increases in other species can fail as a result of complex and unpredicted interactions (Doak et al. 2008 and references therein). However, our goal is not to impede rat control efforts in Hawai'i. Instead, we hope that concurrent invertebrate and plant monitoring programs are established before and after such rat control efforts. Also, we suggest, as did Cole et al. (2000), that rodent exclusion studies are needed to evaluate the magnitude of impact of rats on various plant and animal populations and to provide a more in-depth understanding of both native and nonindigenous species in Hawaiian ecosystems.

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