Taxonomic inventories and assessments of terrestrial snails on the islands of Tinian and Aguiguan in the Commonwealth of the Northern Mariana islands

by

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ABSTRACT

The purpose of this study was to conduct coordinated taxonomic inventories and assessments of terrestrial snails on the islands of Tinian (28 November to 2 December 2008) and Aguiguan (30 October to 3 November 2006) in the Commonwealth of the Northern Mariana Islands as part of a natural resource pursuant to Cooperative Service Agreement (MIPR No. M6738507POFM189) between the U.S. Fish and Wildlife Service and U.S. Marine Corps. No living *Partula gibba* were observed at any of the 12 sampling stations on Tinian. On Aguiguan, no living *Partula gibba* or *Partula langfordi* were observed at any of the seven sampling stations or any of the forested areas investigated. *Partula langfordi*, endemic to Aguiguan, may be extinct now. The present study indicates that the ground-dwelling snails of Tinian and Aguiguan have also declined in a pattern similar to that of the tree snails.

CONTENTS

Taxonomic Inventories and Assessments of Terrestrial Snails on the Islands of Tinian and Aguiguan in the Commonwealth of the Northern Mariana Islands

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Introduction

Terrestrial gastropods are possibly the most extinction-prone organisms on oceanic islands (Hadfield et al., 1993; Paulay, 1994). Because most of the land snails on islands are small and relatively drab in appearance, they have not received the attention given to the larger and more formidable vertebrates. Such is the case for the terrestrial snails of the Mariana Islands.

Early reports on terrestrial gastropods of the Mariana Islands were largely taxonomically oriented (Férussac, 1821; Pfeiffer, 1846, 1857; Quadras and Möllendorff, 1894a, 1894b). These were followed by investigations of the evolution and status of tree snails in the Family Partulidae (Crampton, 1920; Kondo, 1970; Hopper and Smith, 1992; Smith and Hopper, 1994). Declines and extinctions of terrestrial gastropods of the Mariana Islands were reported by Hopper and Smith (1992), Smith and Hopper (1994), Bauman (1996), and Smith (2008b).

While dominated by relatively few families, the land snails on islands of the tropical Pacific exhibit spectacular evolutionary radiations (Cowie, 1996). Despite this diversity, native land snail faunas of the Pacific islands are composed almost entirely of narrow-range endemics. Tragically, these unique native snail faunas are now disappearing rapidly (Lydeard et al., 2004). In the Northern Mariana Islands, the tree snail *Partula gibba* has disappeared from historical locations in Saipan studied by Crampton (1925) in 1920 and by Kondo in 1949 (Smith and Hopper, 1994). No living *Partula gibba* were found in former habitations in Tinian and Rota, as well (Smith and Hopper, 1994; Smith, 1995). Of the 39 native species of land snails recorded in Rota, 68% are extinct or declining (Bauman, 1996). These and other data suggest that overall perhaps 50% of the land snail fauna has disappeared throughout the Pacific islands as a whole, mostly in recent times (Lydeard et al., 2004). Documented causes of these extinctions include loss of habitat to agricultural and urban development, alteration of habitat by invasive ungulates, and invasive predators (Hopper and Smith, 1992).

The purpose of this study was to conduct coordinated taxonomic inventories and assessments of terrestrial snails on the islands of Tinian and Aguiguan in the Commonwealth of the Northern Mariana Islands as part of a natural resource pursuant to Cooperative Service Agreement (MIPR No. M6738507POFM189) between the U.S. Fish and Wildlife Service and U.S. Marine Corps.

MATERIALS AND METHODS

Tinian, the third-largest island in the Mariana Islands, is located between latitude 14°55' N and 15°06' N and longitude 145°35' E and 145°40' E, some 8 km south southwest of Saipan and 128 km north of Guam (Figure 1). The island is about 20 km long on its north-south axis and 10 km wide on its east-west axis, with a land area of about 102 km^2. Basement Eocene volcanic rocks are overlain by Miocene and Plio-Pleistocene coral and algal limestone and Holocene raised beach and reef deposits. Doan et al. (1960) mapped and described five physiographic divisions of the island: 1) a high, southern ridge, where the island's highest elevation (187 m) is located; 2) a low, median valley that bisects the island in a northeast-southwest direction; 3) a large central plateau; 4) a small, north-central highland with a maximum elevation of 166 m; and 5) a northern lowland (Figure 2).

Aguiguan is a small, steep-sided island of approximately 7.2 km^2 located 8 km southwest of Tinian at 14°51' N and145°33' E. The island is composed entirely of limestone and rises to an elevation of 157 m. Most of the coastline consists of sheer limestone cliffs rising abruptly from the sea in a series of eight separate terraces (Tayama and Ota, 1940). The terraces have been variously grouped into three (Butler, 1992) or four (Tayama and Ota, 1940) major terraces. The uppermost terrace forms a nearly flat, central plateau. There are no beaches or embayments (Figure 3).

Terrestrial gastropod populations were surveyed by two methods. For arboreal species, a modification of the method used by Hopper and Smith (1992) was used. Thirty-minute visual surveys were conducted by observers in forested areas of the islands. Locations of sampling sites were determined by GPS (Garmin® GPS 72™). Presence or absence of snails was determined by examining leaves of broad-leaved tree species, including *Hernandia sonora*, *Guamia mariannae*, *Cynometra ramiflora*, *Neisosperma oppositifolia*, *Ochrosia mariannensis*, *Mammea odorata*, and *Aglaia mariannensis*, which serve as host species for partulids in other Mariana Islands. Special emphasis was given to re-visiting sites in Aguiguan where *Partula langfordi*, an Aguiguan endemic, and *Partula gibba* were reported historically (Craig and Chandran, 1992; Smith, 1995; Kondo, unpublished data). These species were listed as Candidate Species for protection under the U.S. Endangered Species Act. No published records of partulid tree snail distribution in Tinian are known; Kondo (1970) reported *Partula gibba* from Tinian, but he did not provide locality data.

When live arboreal snails were located within the visual census period, 25-m^2 plots were established under the densest understory, as determined by a spherical densiometer. During a 30-min search, all snails located to 2 m height within the plots were identified to species or collected and preserved in 75.5% ethanol for identification in the laboratory. Shell lengths of specimens were measured to the nearest 0.1 mm with sliding vernier calipers (Digimatic® 500-136, Mitutoyo Corp.) or with a Peak® 10x Scale Loupe. Host tree species were recorded for each snail observed.

Leaf litter was examined for 10 min in search of fresh partulid ground shells at each sampling site. Observations of dead ground shells were recorded. If no live snails or fresh

Figure 1. Map of the Mariana Islands. Inset shows the position of the Mariana Islands in relation to Asia and the western Pacific. Arrows indicate the location of Tinian and Aguiguan, south southwest of Saipan.

Figure 2. Map of Tinian showing locations of study sites. Visual survey sites are shaded in purple, and quadrat-sampled sites are indicated by orange circles. Modified from U.S. Geological Survey (1999).

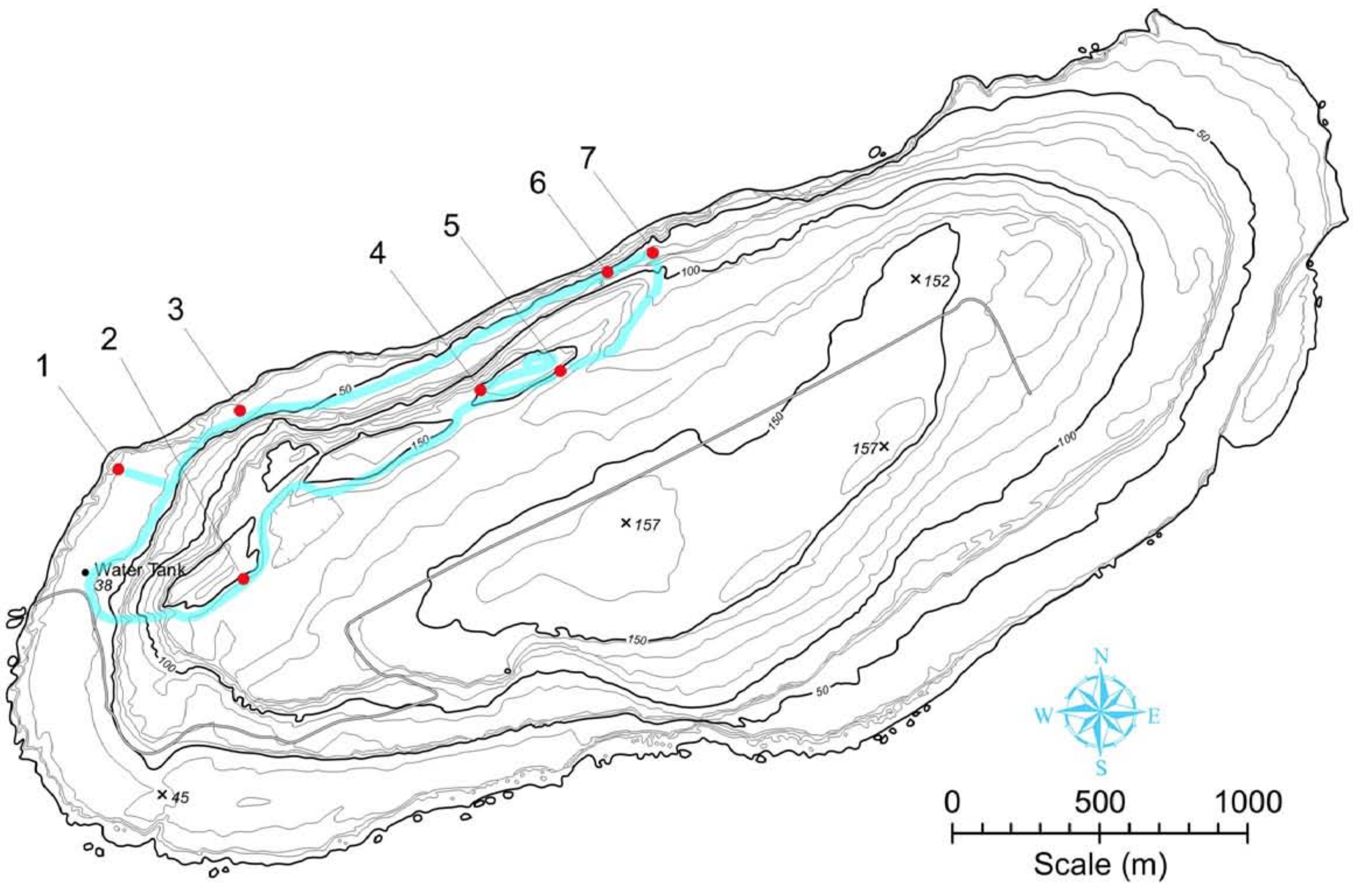

Figure 3. Topographic map of Aguiguan showing locations of sampling sites (•) and general area surveyed by observers walking transects (). Craig and Chandran (1992) previously reported tree snails at Sites 1, 3, and 7, and Smith (1995) previously reported tree snails at Sites 6, and 7. Modified from U.S. Geological Survey (1999).

ground shells were found during the timed search, the site was recorded as not supporting arboreal snails. Additional areas were surveyed by observers walking through forested tracts accessible by foot and examining likely tree snail habitat.

For ground-dwelling gastropods in Aguiguan, a 5 m x 5 m plot was delineated with a metered transect tape. Within each 25-m^2 plot, average percent canopy cover was determined from five readings with a spherical densiometer, one in the center of the plot, and one at a distance of 1 m from each corner. Four replicate 1-m^2 quadrats were sampled within each 25-m^2 plot. All leaf litter, decaying wood, stones, and vegetation from ground level to 2 m height were examined for the presence of snails in each quadrat. All snails were collected and preserved in 75.5% alcohol (Mana Bay® 151 Rum) for identification and analysis in the laboratory. Each specimen was identified to species, and the axial length of the shells was measured to the nearest 0.1 mm with a Peak® 10x Scale Loupe or sliding digital calipers (Digimatic® 500-136, Mitutoyo Corp.). These data were analyzed with SigmaStat® 3.5 software (Systat® Software, Inc., 2006) and plotted with SigmaPlot® 11.0 software (Systat® Software, Inc. 2008).

Because the effort to collect ground-dwelling species in 1-m^2 quadrats in Aguiguan limited the number of sites that could be examined, smaller quadrats and standardized effort were employed for investigations in Tinian. Four replicate 50 cm × 50 cm (i.e., 0.25 m^2) quadrats were sampled within 25-m^2 plots at three study sites in Tinian (Figure 4). Leaf litter, decaying wood, stones, and vegetation were examined for the presence of gastropods for 30 min in each quadrat. All snails were collected and preserved in 75.5% alcohol (Mana Bay® 151 Rum) for identification and analysis in the laboratory. Specimens were identified to species, and the axial length of the shells were measured to the nearest 0.1 mm with a Peak® 10x Scale Loupe or sliding digital calipers (Digimatic® 500-136, Mitutoyo Corp.). These data were analyzed and plotted as for the Aguiguan samples.

RESULTS

Tinian

Twelve study sites in Tinian, ranging from halophytic grasslands to primary forest, are characterized in Table 1. The only extant species of arboreal snail observed was *Lamellidea* sp. at the Mahalang station. No living *Partula gibba* were observed at any of the 12 sampling stations. Sun-bleached shells of *Partula gibba* (Figure 5) were found at the surface or in leaf litter only at the Laderan Mahalang site. These shells lacked the color and luster of shells of live snails or recent mortalities, indicating that the observed shells are very old. Large numbers of dead Achatina fulica littered the ground at the Hagoi site (Figure 6) and the Mahalang site (Figure 7). A species assemblage of dead ground shells observed at sampling stations during this survey is given in Table 2.

Seven species in four families of ground-dwelling snails were found living in 4 m^2 of forest floor sampled in Aguiguan (Table 3). *Georissa laevigata* was the predominant species of ground-dwelling snail, occurring in all quadrats at the three sampling station supporting living

Figure 4. An investigator collecting ground-dwelling gastropods from leaf litter in a quadrat at the Mahalang sampling station. The plot size is 25 m^2, and the quadrat size is 0.5 m^2. Each quadrat was sampled for 30 min.

snails and exhibiting the highest mean densities (>25 snails/0.25 m^2 quadrat) at those sampling stations. Although present in low densities (<2 snails/0.25 m^2 quadrat), *Georissa elegans* was also found at all three sampling stations. The remaining species each occurred at only one sampling station, and mean densities generally were low (<2 snails/0.25 m^2 quadrat). Only Paropeas achatinaceum, a tramp species, attained moderate densities (>10 snails/m^2 quadrat) at the Mahalang sampling station. Three species occurred as single individuals. No living snails were found in quadrats at the Sabaneton Chiget sampling station.

Size-frequency distributions for the *Georissa laevigata* at the Hagoi, Mt. Lasu, and Mahalang stations are presented in Figures 8, 9, and 10, respectively. Demographics for *Lamellidea* sp. at Hagoi and *Paropeas achatinaceum* at Mahalang are presented in Figures 11 and 12, respectively. A One-Way Analysis of Variance (ANOVA) for *Georissa laevigata* data at Hagoi revealed that the differences in the mean values among the treatment groups are greater than would be expected by chance; there is a statistically significant difference ($P < 0.001$).

Figure 5. Sun-bleached *Partula gibba* ground shell from the Mahalang sampling station.

Figure 6. Numerous bleached, dead shells of *Achatina fulica* at the Hagoi sampling station.

Figure 7. A "midden" of dead *Achatina fulica* shells at the base of a limestone scarp near the Mahalang sampling station.

ANOVAs were not possible for *Georissa laevigata* data at Mt. Lasu and Mahalang, because the data do not satisfy the assumption that they are normally distributed. The Normality Test (Shapiro-Wilk) failed ($P<0.050$) for this species at both sites. A Kruskal-Wallis One Way Analysis of Variance on Ranks revealed that the differences in the median values among the quadrats at Mt. Lasu are greater than would be expected by chance, meaning that there is a statistically significant difference ($P = 0.002$) between the quadrats within the plot. A Kruskal-Wallis One Way Analysis of Variance on Ranks of data from Mahalang indicated no statistically significant difference ($P = 0.478$) between the quadrats within the plot. Therefore, no direct comparison of data between the two plots would be statistically valid. ANOVA for demographic data for *Paropeas achatinaceum* at Mahalang indicated a statistically significant difference ($P = <0.001$) in the mean values among the quadrats.

Table 1. Habitat characterization and locations of landsnail study sites in Tinian.

Location	GPS Coordinates	General Habitat Type	Dominant Vegetation	Ancillary Species
Old quarry SW of Masalog	0355416 1659190	Grassland	*Lantana camara* *Chromolaena odorata*	*Casuarina equisetifolia* *Leucaena leucocephala* *Bidens pilosa* *Mimosa diplotricha* Vine w/red flowers
Sabanetan Chiget	0355484 1667059	Halophytic grass community	*Fimbristylis cymosa* *Zoysia matrella* var. *pacifica* *Paspalum vaginatum*	*Ipomoea pes-caprae* *Scaevola taccada*
Mt. Lasso—A	0352739 1663387	Secondary forest	*Hibiscus tiliaceus*	*Premna obtusifolia* *Leucaena leucocephala* *Polypodium* sp. *Passiflora suberosa*
Mt. Lasso—B	0352687 1663350	Limestone forest	*Cynometra ramiflora* *Aglaia mariannensis*	*Nephrolepis* sp. *Polypodium* sp.
Hagoi	0352366 1666277	Wetland community (hummock)	*Ficus tinctoria* *Guamia mariannae*	*Guamia mariannae* *Melanolepis multiglandulosa* *Leucaena leucocephala* *Mikania scandens* *Phragmites karka*
North Field	0352373 1666447	Secondary forest	*Melanolepis multiglandulosa* *Delonix regia*	*Leucaena leucocephala* *Polypodium* sp.
Kahet	0348221 1660907	Secondary forest	*Leucaena leucocephala*	*Casuarina equisetifolia* *Lantana camara* *Chromolaena odorata* *Mikania scandens*

Table 1. Continued.

Location	GPS Coordinates	General Habitat Type	Dominant Vegetation	Ancillary Species
				Mimosa diplotricha *Pennisetum* sp. *Desmodium umbellatum* *Bidens pilosa* *Coccinea* sp. *Spathodea campanulata*
South Kahet	0349801 1659656	Scrub forest in pasturelands	*Leucaena leucocephala*	*Acacia confusa* *Casuarina equisetifolia* *Carica papaya* *Senna alata* *Mimosa diplotricha* *Chromolaena odorata* *Bidens pilosa* *Psidium guajava* *Mikania scandens* *Melanolepis multiglandulosa* *Bambusa vulgaris* *Pandanus tectorius* *Premna obtusifolia*
Bateha—A	0351600 1660562	Limestone forest	*Cynometra ramiflora* *Albizia lebbeck*	*Eugenia* sp. *Melanolepis multiglandulosa* *Polypodium* sp. *Capsicum frutescens* *Carica papaya*
Bateha—B	0351600 1660562	Limestone forest	*Albizia lebbeck* *Guamia mariannae*	*Aglaia mariannensis* *Cynometra ramiflora* *Capsicum frutescens* *Polypodium* sp.

Table 1. Continued.

Location	GPS Coordinates	General Habitat Type	Dominant Vegetation	Ancillary Species
Bateha—C	0351567 1660567	Secondary forest	*Ficus tinctoria* *Leucaena leucocephala*	*Carica papaya* *Melanolepis multiglandulosa* *Casuarina equisetifolia* *Guamia mariannae* *Aglaia mariannensis* *Mikania scandens* *Lantana camara* *Pennisetum* sp. *Coccinea* *Morinda citrifolia* *Eugenia* cf. *palumbis* *Polypodium* sp.
Laderan Mahalang	0352037 1665470	Limestone forest on steep sloop	*Pisonia grandis* *Aglaia mariannensis*	*Cynometra ramiflora* *Guamia mariannae* *Eugenia* cf. *palumbis* *Polypodium* sp.

Table 2. Species assemblage of dead ground shells observed at sampling sites in Aguiguan.

Sampling Site	Dead Ground Shells Observed
Masalog quarry	*Achatina fulica* Bowdich, 1822
Sabanetan Chiget	Subulinidae spp.
Mt. Lasso	*Achatina fulica* Bowdich, 1822 *Palaina taeniolata* Quadras & Möllendorff, 1894 *Omphalotropis* cf. *elongatula* Quadras & Möllendorff, 1894 *Lamprocystis misella* (Férussac, 1821) *Elasmias quadrasi* (Möllendorff, 1894) *Lamellidea* spp. *Paropeas achatinaceum* (Pfeiffer, 1840) *Georissa elegans* Quadras & Möllendorff, 1894 *Georissa laevigata* Quadras & Möllendorff, 1894
Hagoi	*Achatina fulica* Bowdich, 1822 *Georissa laevigata* Quadras & Möllendorff, 1894 *Subulina octona* (Bruguière, 1792)
North Field	*Achatina fulica* Bowdich, 1822
Kahet	*Achatina fulica* Bowdich, 1822
South Kahet	na
Bateha	na
Laderan Mahalang	*Achatina fulica* Bowdich, 1822 *Paropeas achatinaceum* (Pfeiffer, 1840) *Georissa laevigata* Quadras & Möllendorff, 1894 *Lamprocystis* sp. *Elasmias quadrasi* (Möllendorff, 1894) *Subulina octona* (Bruguière, 1792) *Partula gibba* Férussac, 1821 *Omphalotropis* spp. *Lamprocystis* cf. *fastigata* (Gude, 1917) *Lamellidea* spp.

Table 3. Mean densities of extant ground-dwelling snails at three sites in Tinian. Densities are presented as mean ± S.D. in four 0.25-m^2 quadrat samples at each site, except for Lamellidea sp., with is the count from one 25-m^2 quadrat. Total numbers of snails are given in parentheses.

	Hagoi	Mt. Lasu	Mahalang
Georissa biangulata	---	---	0.25 ± 0.50 (1)
Georissa elegans	1.50 ± 0.58 (6)	1.5 ± 0.14 (2)	1.50 ± 1.29 (6)
Georissa laevigata	25.75 ± 22.32 (103)	25.25 ± 10.24 (101)	31.50 ± 33.67 (126)
Palaina taeniolata	---	1.50 ± 3.00 (6)	---
Paropeas achatinaceum	---	---	14.00 ± 2.94 (56)
Subulina octona	---	0.25 ± 0.50 (1)	---
Elasmias quadrasi	---	0.25 ± 0.50 (1)	---
Lamellidea sp.	8.00 (8)	---	---

Mean shell sizes for *Georissa laevigata* occurring at Hagoi, Mt. Lasu, and Mahalang are presented in Figures 13, 14, and 15, respectively. Mean shell sizes for *Paropeas achatinaceum* at the Mahalang study site are provided in Figure 16.

Aguiguan

No living *Partula gibba* or *Partula langfordi* were observed at any of the seven sampling stations or any of the forested areas investigated in Aguiguan during this survey. Sun-bleached shells of *Partula gibba* were at the surface or in leaf litter at five of the seven sites sampled, including those previously studied by Craig and Chandran (1992) and Smith (1995). Dead shells of *Partula langfordi* were found at only two of the seven sites. Shells of both species lacked the color and luster of shells of live snails or recent mortalities, leading to a conclusion that the observed shells are very old. A summary of species of dead ground shells observed during this survey is given in Table 4.

Only four species in two families of ground-dwelling snails were found living in 8 m^2 of forest floor sampled in Aguiguan. Three of these species dominated at Site 5, and two species at Site 6 (Table 5). *Palaina taeniolata* reached the highest mean density at 80.9 snails/m^2 at Station 5, while *Georissa laevigata* was more evenly distributed between the two sites. *Palaina hyalina* reached moderate densities at Site 5, but only a single individual was found at Site 6. A total of only two *Georissa biangulata* were encountered, both at Station 6.

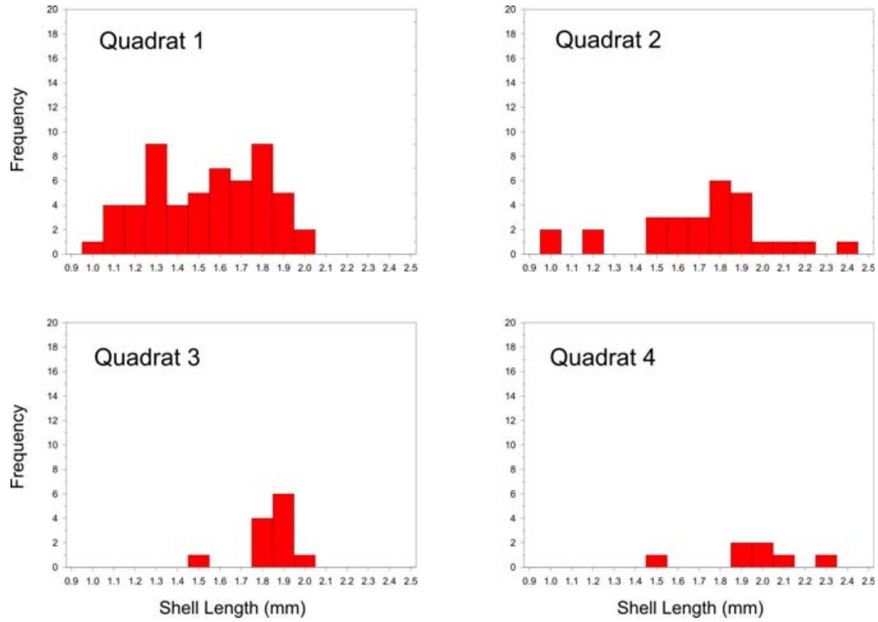

Figure 8. Size-frequency distributions of *Georissa laevigata* in four 0.25-m^2 quadrats at the Hagoi sampling station.

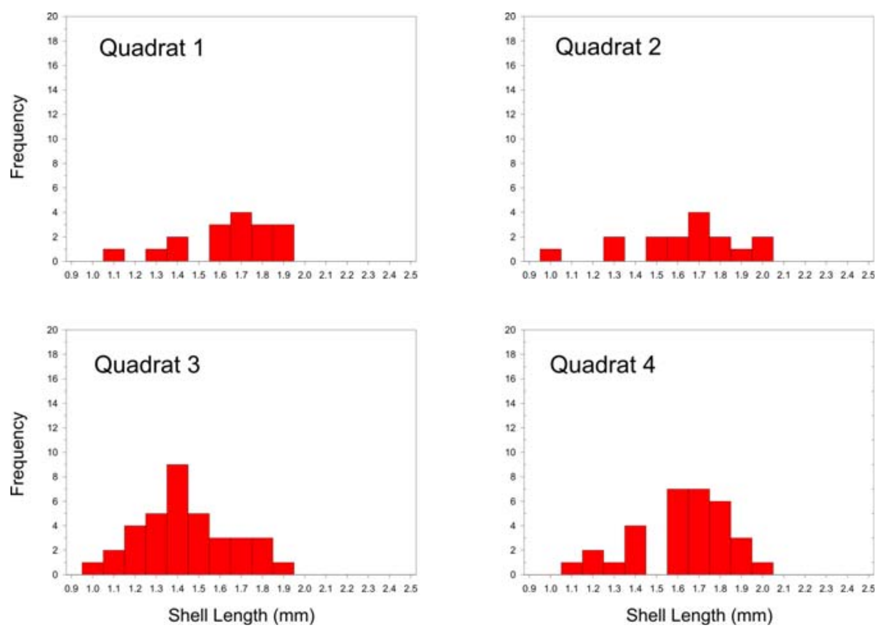

Figure 9. Size-frequency distributions of *Georissa laevigata* in four 0.25-m^2 quadrats at the Mt. Lasu Hagoi sampling station.

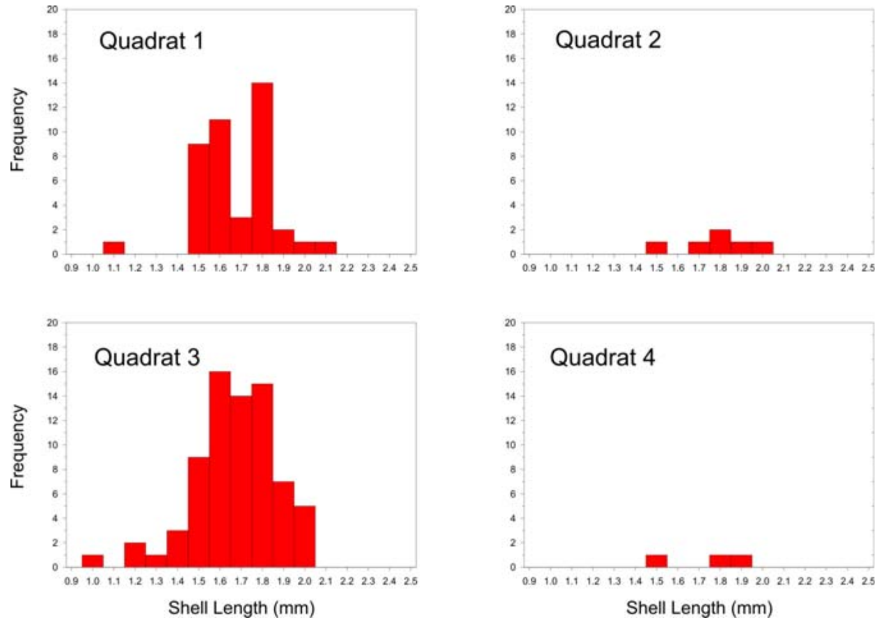

Figure 10. Size-frequency distributions of *Georissa laevigata* in four 0.25-m^2 quadrats at the Mahalang sampling station.

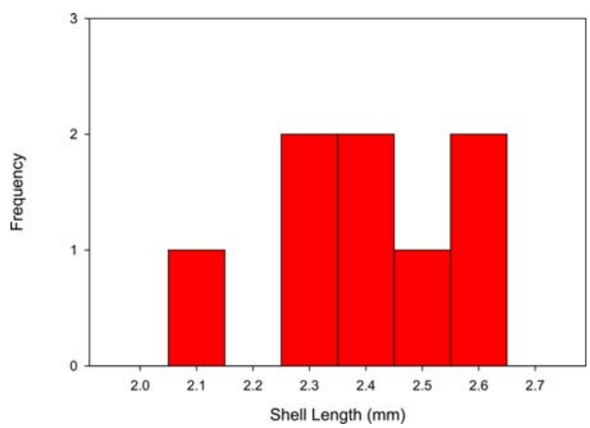

Figure 11. Size-frequency distributions of *Lamellidea* sp. in the 25-m^2 plot at the Hagoi sampling station.

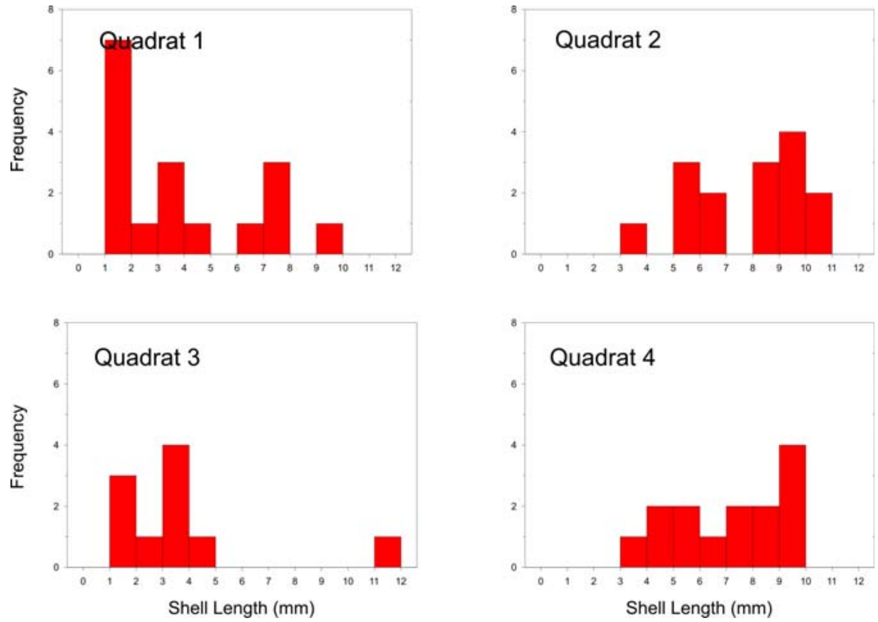

Figure 12. Size-frequency distributions of *Paropeas achatinaceum* in four 0.25-m^2 quadrats at the Mahalang sampling station.

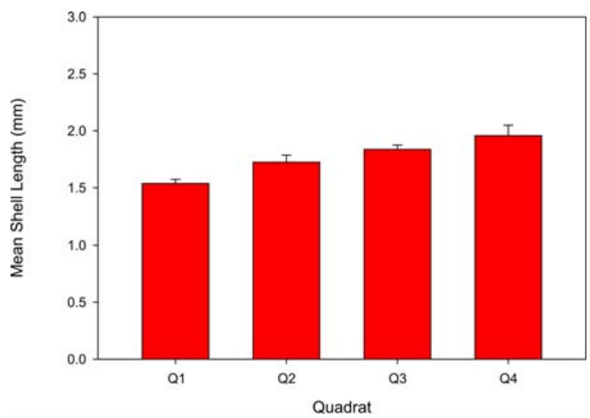

Figure 13. Mean shell sizes of *Georissa laevigata* in four 0.25-m^2 quadrats at the Hagoi sampling station. Error bars are 1 SE.

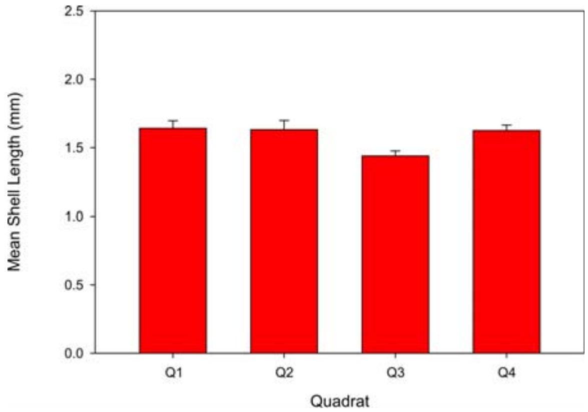

Figure 14. Mean shell sizes of *Georissa laevigata* in four 0.25-m^2 quadrats at the Mt. Lasu sampling station. Error bars are 1 SE.

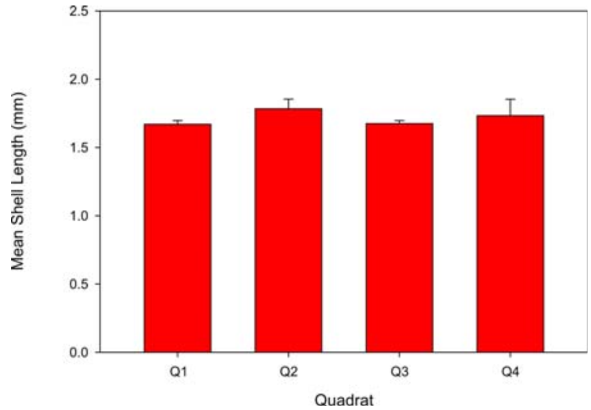

Figure 15. Mean shell sizes of *Georissa laevigata* in four 0.25-m^2 quadrats at the Mahalang sampling station. Error bars are 1 SE.

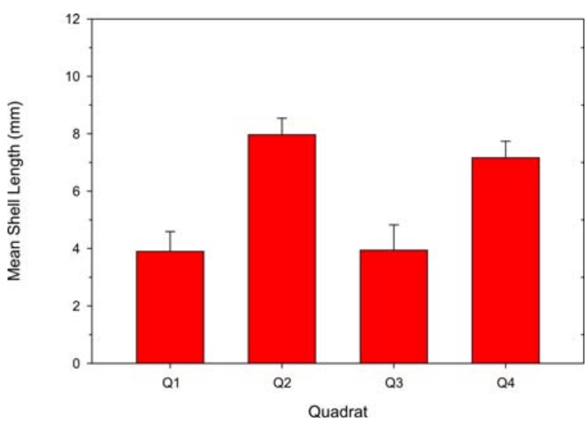

Figure 16. Mean shell sizes of *Paropeas achatinaceum* in four 0.25-m^2 quadrats at the Mahalang sampling station. Error bars are 1 SE.

Table 4. Summary of species of dead ground shells observed at seven sampling sites in Aguiguan.

Sampling Site	Dead Ground Shells Observed
1	none
2	none
3	*Partula gibba* Férussac, 1821
4	*Partula gibba* Férussac, 1821 *Partula langfordi* Kondo, 1970 *Gonaxis kibweziensis* (Smith, 1894) *Pythia scarabaeus* (Linnaeus, 1758) *Lamprocystis* sp.
5	*Partula gibba* Férussac, 1821 *Omphalotropis* spp. *Allopeas* sp. *Paropeas achatinaceum* (Pfeiffer, 1840) *Elasmias quadrasi* (Möllendorff, 1894)
6	*Partula gibba* Férussac, 1821 *Partula langfordi* Kondo, 1970 *Gonaxis kibweziensis* (Smith, 1894) *Pythia scarabaeus* (Linnaeus, 1758) cf. *Pacificella variabilis* Odhner 1922 *Omphalotropis* cf. *elongatula* *Omphalotropis* spp. *Subulina octona* (Bruguière, 1792)
7	*Partula gibba* Férussac, 1821

Table 5. Mean densities of extant ground-dwelling snails at two sites in Aguiguan. Densities are presented as mean ± S.D. in four 1-m^2 quadrat samples at each site. Total numbers of snails are given in parentheses.

	Site 5	Site 6
Georissa biangulata	---	0.5 ± 1.0 (2)
Georissa laevigata	33.3 ± 26.3 (133)	46.5 ± 26.8 (166)
Palaina hyalina	35.0 ± 61.3 (141)	0.3 ± 0.5 (1)
Palaina taeniolata	80.8 ± 73.4 (323)	15.3 ± 6.2 (61)

Size-frequency distributions for the ground-dwelling species at Site 5 are presented in Figures 17, 18, and 19. Demographics for Site 6 are presented in Figures 20 and 21. A One-Way Analysis of Variance (ANOVA) for these data was not possible, because the data do not satisfy the assumption that they are normally distributed. The Normality Test (Shapiro-Wilk) failed ($P<0.050$) for all species except for *Georissa laevigata* at Site 5. A Kruskal-Wallis One Way Analysis of Variance on Ranks revealed that the differences in the median values among the treatment groups are greater than would be expected by chance, meaning that there is a statistically significant difference between the quadrats within each plot. Therefore, no direct comparison of data between the two plots would be statistically valid. Mean shell sizes for species occurring at Sites 5 and 6 are presented in Figures 22, 23, 24, 25, and 26.

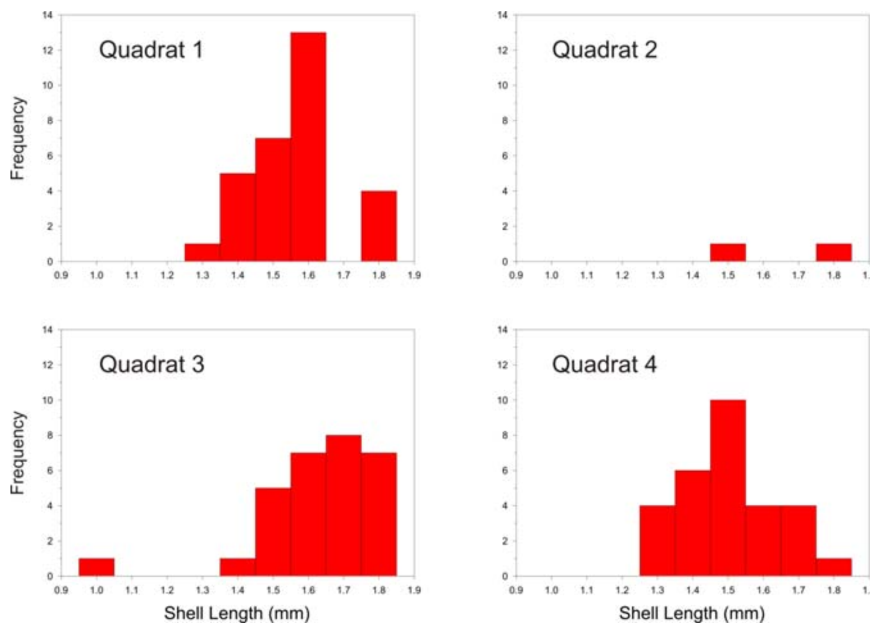

Figure 17. Size-frequency distribution of *Georissa laevigata* in four 1-m^2 quadrats at Site 5. All specimens are reported for Quadrats 2 and 3. Distributions for Quadrats 1 and 4 represent 30-specimen subsamples.

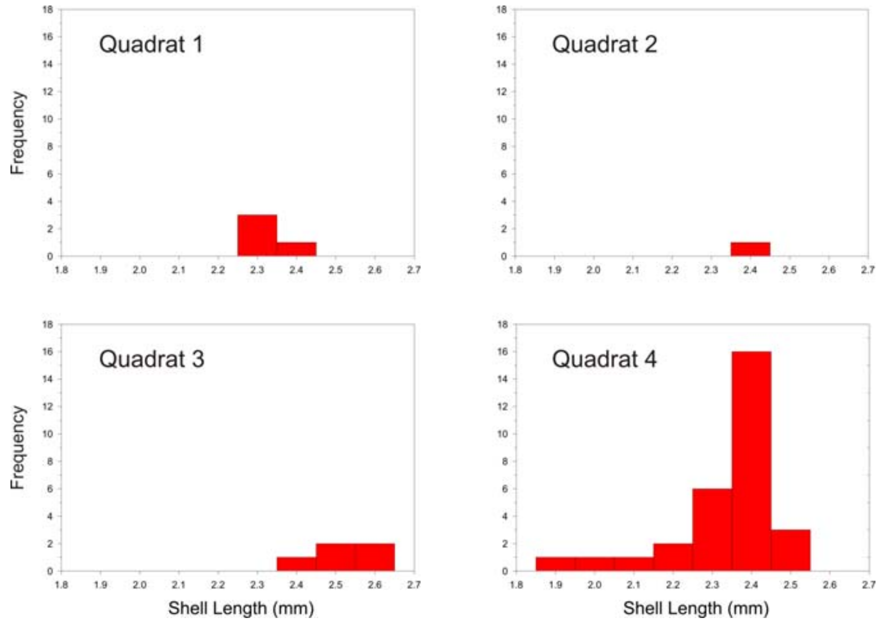

Figure 18. Size-frequency distribution of *Palaina hyalina* in four 1-m^2 quadrats at Site 5. All specimens are reported for Quadrats 1, 2, and 3. Distribution for Quadrat 4 represents a 30-specimen subsample.

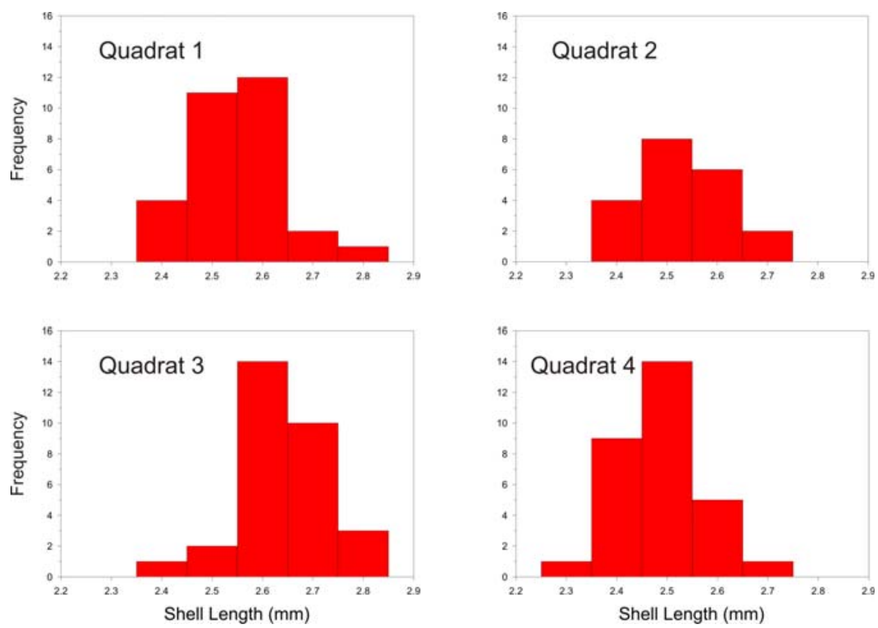

Figure 19. Size-frequency distribution of *Palaina taeniolata* in four 1-m^2 quadrats at Site 5. All specimens are reported for Quadrat 2. Distributions for Quadrats 1, 3, and 4 represent 30-specimen subsamples.

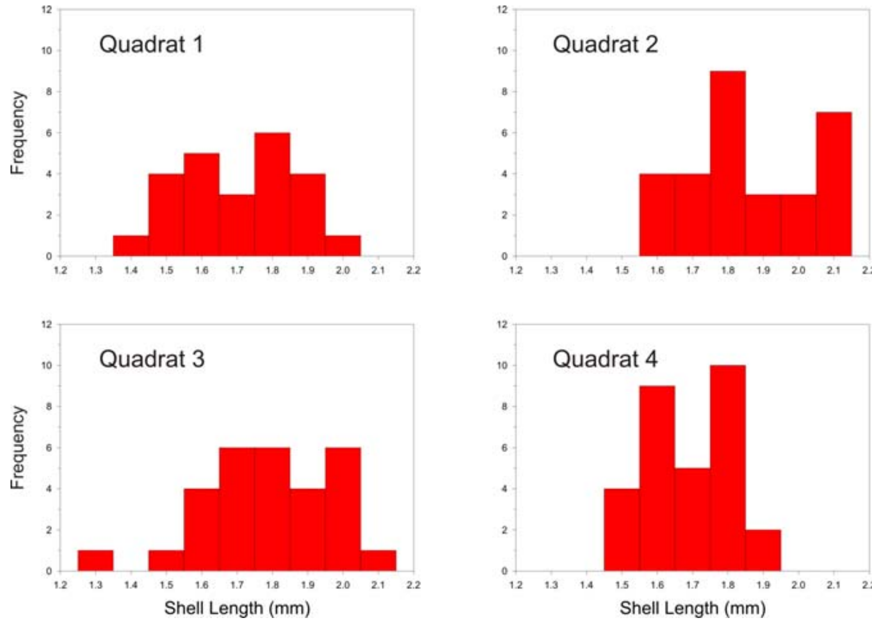

Figure 20. Size-frequency distribution of *Georissa laevigata* in four 1-m^2 quadrats at Site 6. All specimens are reported for Quadrat 1. Distributions for Quadrats 2, 3, and 4 represent 30-specimen subsamples.

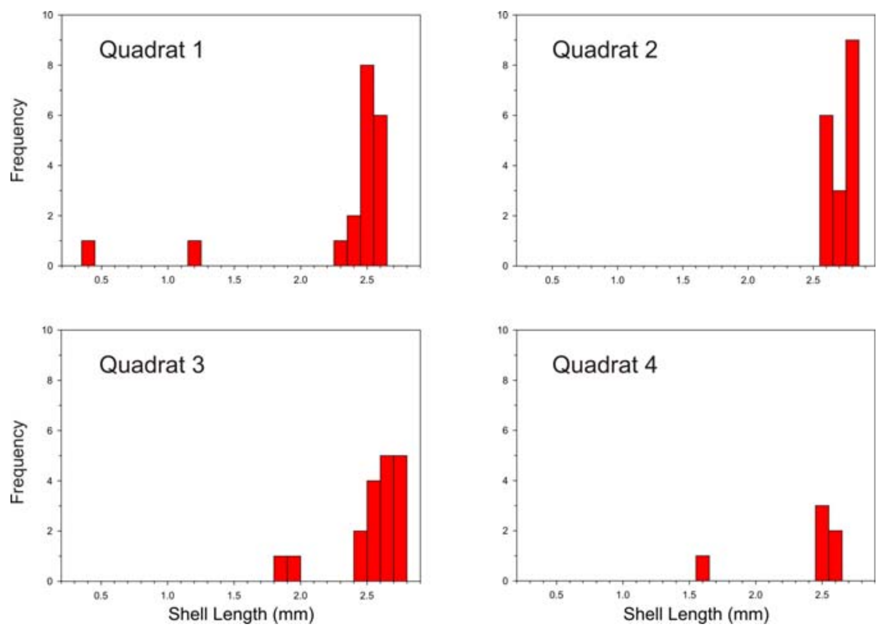

Figure 21. Size-frequency distribution of *Palaina taeniolata* in four 1-m^2 quadrats at Site 6.

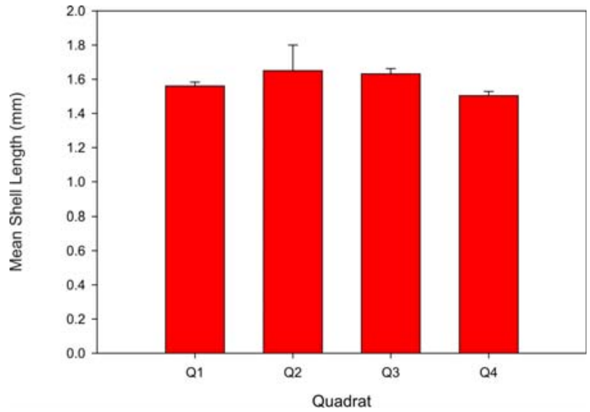

Figure 22. Mean shell sizes of *Georissa laevigata* in four 1-m^2 quadrats at Site 5. Error bars are 1 SE.

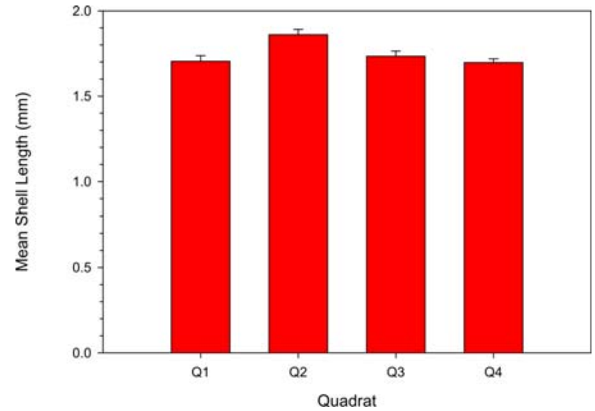

Figure 23. Mean shell sizes of *Georissa laevigata* in four 1-m^2 quadrats at Site 6. Error bars are 1 SE.

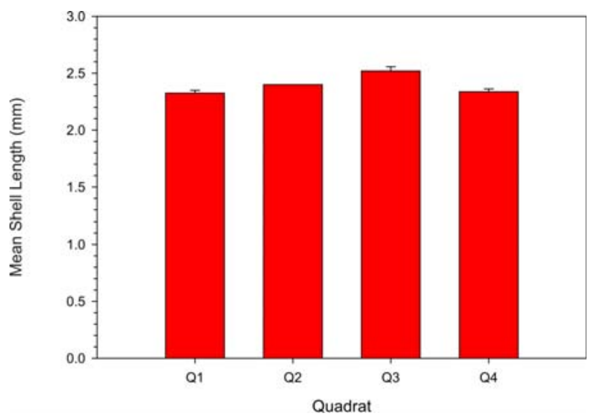

Figure 24. Mean shell sizes of *Palaina hyalina* in four 1-m^2 quadrats at Site 6. Error bars are 1 SE.

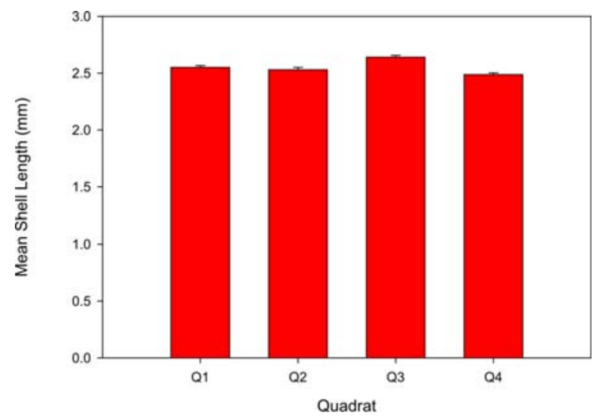

Figure 25. Mean shell sizes of *Palaina taeniolata* in four 1-m^2 quadrats at Sites 5. Error bars are 1 SE.

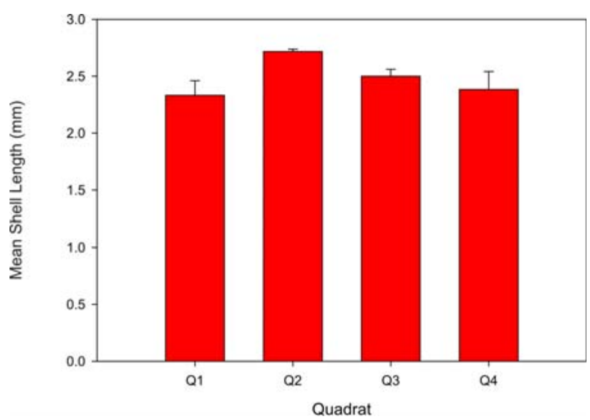

Figure 26. Mean shell sizes of *Palaina taeniolata* in four 1-m^2 quadrats at Sites 6. Error bars are 1 SE.

DISCUSSION

The natural environment in Tinian and Aguiguan has been subjected to substantial degradation of during human history. First in Saipan, and then in Tinian and Aguiguan, large-scale sugarcane plantations were developed by Japanese entrepreneurs during the Japanese Mandate period between the two world wars. Tinian was especially well-suited for sugarcane production, because its terrain was mostly level or gently sloping, and there were few inhabitants. Large-scale clearing of forests in Tinian began in 1929 (Peattie, 1988). By the early 1930s, about 80% of the island was under cultivation (Bowers, 1950), and as much as 10% of the land area was devoted to refineries, mills, railroads, and villages. The only areas left undisturbed for native fauna were too steep for agriculture, generally along the base and talus slopes of cliffs.

Significant disruption of the environment in Aguiguan began with the construction of facilities for sugarcane farming in March 1936. The forest on the central plateau and much of the area on the south end of the intermediate terraces was cleared in 1937 in preparation of fields for planting of the first sugarcane crop, which was harvested in 1938 (Butler, 1992). By the peak of agricultural production, some 50% of the island was cleared for cultivation, forever altering habitat for land snails and other terrestrial invertebrates.

Loss of habitat to agriculture in Tinian and Aguiguan was followed by a series of introductions of invasive snails. Despite the widely recognized invasive character of the species, the giant African snail *Achatina fulica* was introduced to Tinian between 1936 and 1938 (Mead, 1961), and they were apparently taken to Aguiguan around 1939 (Eldredge, 1988), although no published record exists. Although the snails were an important food item for residents of Aguiguan during the last months of World War II (Butler, 1992), their introduction set in motion events that would lead to widespread decline of native land snails in the islands.

Following World War II, Aguiguan was the focus of considerable research on land snails in the Mariana Islands. The motivation for this effort is related to the efforts of the Pacific Science Board (U.S. National Research Council) to control *Achatina fulica*, which had become a serious agricultural pest in islands throughout Micronesia where it was introduced. Townes (1946) reported that *Achatina fulica* was abundant in Saipan, Tinian, Rota, Koror, Pohnpei, southern Babeldaob, Peleliu, and part of Chuuk (Dublon), and there were small colonies in Guam.

In 1950, Aguiguan was selected by the Insect Control Committee of Micronesia as a suitable release site for field testing of the effectiveness of predatory snails in controlling *Achatina fulica* populations. In May 1950, some 400 *Gonaxis kibweziensis* were released at a site along the southwest coast of Aguiguan (Owen, 1950). One year later, Kondo (1952) observed that *Gonaxis kibweziensis* was feeding on *Achatina fulica*, and the number of *Gonaxis kibweziensis* was estimated at 21,750 and the number of *Achatina fulica* at 1,122,500. However, Kondo (1952) concluded that *Gonaxis kibweziensis* had little effect on *Achatina fulica*.

Two years later, Peterson (1954) made the first observation of *Gonaxis kibweziensis* feeding on native species of snails, as well as the target species *Achatina fulica* and its own young. By mid-1954, the population of *Gonaxis kibweziensis* was estimated to be 80,800, while the *Achatina fulica* population was estimated to be 37,600 (Davis, 1954). Davis (1954) calculated approximately 60% effectiveness for *Gonaxis kibweziensis*, and more than 500 *Gonaxis kibweziensis* were shipped to Hawaii for biological control of *Achatina fulica*. Additional specimens from Aguiguan were sent elsewhere in Micronesia (Peterson, 1957; Eldredge, 1988). Although no efforts to assess the threat of the introduced predator to indigenous land snails were reported, Kondo (1970) discovered a new species, *Partula langfordi*, living sympatrically with *Partula gibba* in Aguiguan during his field investigations in 1952.

Some 30 years after the experiment began in Aguiguan to determine the effectiveness of predatory control on the invasive African snail, a team of scientists from the University of Guam found no living *Achatina fulica* or *Gonaxis kibweziensis* during a two-day survey in 1984 on the western end of the lower terrace of the island (Eldredge, 1985). Similarly, Butler (1992) reported no live *Achatina fulica* were observed during an archaeological investigation covering some 57% of the island. However, partulid tree snails persisted in Aguiguan, as evidenced by collections by T. Pratt on February 2, 1985. Pratt collected 14 live tree snails (5 adult *Partula langfordi* and 7 adult *Partula gibba*, plus 2 unidentified juveniles) from “various trees and shrubs on the west end of the island,” and he deposited them in the synoptic invertebrate collections at the University of Guam Marine Laboratory (Lot No. UGI 6019).

Partulids were again recorded at Aguiguan by two independent survey groups in 1992. In May, 1992, a team of scientists and students from the Northern Marianas College observed tree snails at three locations (sites numbered 1, 3, and 7 of the present study, Figure 3) along the western slope of the island (Craig and Chandran, 1992). Snails identified as *Partula gibba* were encountered on trees in native and secondary forest. No snail counts or population estimates were given.

A second survey in November, 1992, by a team of scientists from the CNMI Division of Fish and Wildlife and the University of Guam, resulted in observations of three living tree snails, two *Partula gibba* and one *Partula langfordi* (Smith, 1995). Observations of both species were made on the 50-m terrace of the northwest coast. *Partula gibba*, one adult and one juvenile, were found on leaves of *Mammea odorata* along the terrace edge at Site 7 of the present study (Figure 2). *Partula langfordi* occurred on *Guamia mariannae*, on a leaf some 3 m above the ground at Site 6 of the present study (Figure 3). Although a case could be made for the introduction of goats in Aguiguan around 1818 as the initial step in the decline of the native snails, partulids had persisted with the goats for more than 170 years.

Results of the surveys in Aguiguan in 1992 suggested that tree snail populations had declined markedly in range and abundance. Kondo (1970) reported on six colonies of partulids inhabiting “open forest, on native plants predominantly *Aglaia*” in the vicinity of Site 1 of the present study, i.e., “1000 yards northeast of the Boat Landing... altitude 200 feet.” Nine additional colonies were sampled on the north and west coasts of the island.

Evidence of the former abundance of tree snails in Aguiguan was reported by Smith (1995), who noted numerous dead shells of both partulid species littering the ground, as well as shells of assimineids, succineids, helicarionids, subulinids, and *Gonaxis kibweziensis*. In sampling leaf litter and surface rocks in Aguiguan, Smith (1995) discovered yet another snail predator in 1992, the triclad turbellarian *Platydemus manokwari*. As many as eight large flatworms were found beneath individual surface rocks measuring 23 × 15 cm (Smith, unpublished 1992 data). Because many of the ground shells of *Partula gibba* and *Partula langfordi* were still relatively lustrous in appearance, it was concluded that the mortalities occurred within the previous year. This flatworm was apparently introduced to Aguiguan from Tinian in potted plants as part of a reforestation project in1991 (C. Rice, personal communication, November 1992). *Platydemus manokwari* was previously reported to be established in Tinian by 1984 (Eldredge, 1988; Eldredge and Smith, 1994).

As a consequence of the decline of the tree snails and the introduction of *Platydemus manokwari* in Aguiguan, *Partula gibba* and *Partula langfordi* were proposed for listing as Candidate Species for protection under the U.S. Endangered Species Act (16 U.S.C. 1531 *et seq*.) in 1994 (Federal Register, 1994). In 1996, these and two additional species of partulid tree snails from the Mariana Islands were listed as Candidate Species. Tragically, the listing did not result in immediate efforts to conserve the snails, and *Partula langfordi*, endemic to Aguiguan, may be extinct now. *Partula gibba* survives in Guam, Rota, Saipan, Sarigan, and Pagan; the status of this species in Anatahan and Alamagan is presently unknown.

The present study indicates that the ground-dwelling snails of Tinian and Aguiguan have declined in a pattern similar to that of the tree snails. Synoptic collections in the Bernice P. Bishop Museum contain some 19 indigenous species of land snails (Smith, 2008b and Table 6) plus the introduced *Gonaxis kibweziensis*. Interestingly, *Achatina fulica* specimens were not among the species lots from Aguiguan. Four species of live ground-dwelling snails and one live arboreal species were encountered in 8 m^2 sampled in this study, (see Tables 4 and 5). Because these five species may be lumped under three of the genera in Table 6, the total land snail fauna is now 22 species, when *Gonaxis kibweziensis* is included. Therefore, some 84% (16 of 19 species) of the ground-dwelling snail fauna of Aguiguan is in precipitous decline or is extinct. When combined with the tree snails, the figure rises to 86% (19 of 22 species).

No specimens from Tinian were located in the Bishop Museum collections. The present study found at least 14 species of land snails in Tinian, of which 11 are thought to be indigenous and three to be introduced. Five species of living native landsnails were found, suggesting that the extinction rate in Tinian is at least 55%; for all snails, the rate is at least 64%. Because this estimate is based upon dead shells, the figure could be much higher. No reliable estimation of how long dead shells persist in Tinian and Aguiguan is possible, because there are few reports on the rate of dissolution of the empty shells of small gastropod shells in leaf litter, and none from Pacific islands. Factors that contribute to dissolution of dead shells include rainfall, pH of soil and leaf litter, exposure to sunlight, and bioerosion (Cadée, 1998, 1999; Barrientos, 2000; Pearce, 2008).

Table 6. Land snail species from Aguiguan in the collections of Bishop Museum, Honolulu. From Smith (2008b).

Taxon	Specimen Lot No.
Family Hydrocenidae	
Georissa sp.	213809
Family Diplommatinidae	
Palaina sp.	231809
Family Assimineidae	
Assiminea sp.	214761
Omphalotropis submaritima Quadras & Möllendorff, 1894	213806
Family Truncatellidae	
Truncatella sp.	213813
Family Ellobiidae	
Melampus sp.	206330
Pythia scarabaeus (Linnaeus, 1758)	213642
Family Achatinellidae	
Elasmias sp.	213311
Lamellidea sp.	213314
Family Vertiginidae	
Gastrocopta sp.	213783
Nesopupa sp.	213309
Family Partulidae	
Partula gibba Férussac, 1821	213078
Partula langfordi Kondo1970	213063
Family Subulinidae	
Opeas sp.	214779
Subulina octona (Bruguière, 1792)	213070
Family Spiraxidae	
Gonaxis kibweziensis (Smith, 1894)	217479
Family Succineidae	
Succinea sp.	213634
Family Helicarionidae	
Lamprocystis hornbosteli Baker, 1938	214752
Lamprocystis misella (Férussac, 1821)	214723
Liardetia sculpta (Möllendorff, 1883)	214704

CONCLUSIONS AND RECOMMENDATIONS

Less conspicuous because of their smaller size and cryptic habits, the ground-dwelling species of snails have been generally overlooked in previous surveys throughout much of the Pacific. The quantitative data on the ground-dwelling snail populations of Tinian and Aguiguan in the present study are among the first reported. In the absence of similar data from other islands, it is not possible to reach any conclusions about the relative status of populations of these snails in Tinian and Aguiguan. For future surveys, points for comparison to be considered when data from those islands become available include: a) the low numbers of juvenile snails encountered in Tinian and Aguiguan, b) the high variance of shell length among quadrats within sites for all species, and c) the relative abundances of sympatric species.

Molluscan conservation strategies (e.g., Killeen et al., 1998) are needed throughout the Pacific islands, nowhere more so than in Aguiguan. Despite the bleak situation for land snails in Aguiguan at present, continued monitoring of the island is critically important, particularly in poorly inventoried areas. Biologists must provide an accurate picture of the true levels of species richness and extinction so that managers can determine appropriate locations for conservation efforts. Biologists need to identify land snail hotspots to improve or modify management practices to accommodate the needs of molluscs and, if necessary, to guide the establishment of new areas specifically related to molluscs (Lydeard et al., 2004).

With these factors in mind, the following recommendations are offered.

1. **Protocols should be developed to assure that no new invasive species from Okinawa are introduced to Guam and other Mariana Islands as a result of the relocation of the Marine forces.**

It is imperative that the relocation the Marine base from Okinawa to Guam does not introduce new invasive species to Guam and Micronesia. The native species of the islands are extremely vulnerable to invasive species, as demonstrated by the invasive brown tree snake *Boiga irregularis*, which was introduced into Guam with war materiel from the Solomon Islands during World War II and extirpated the native avifauna in four decades (Savidge, 1987). The very existence of the Okinawan snail *Satsuma mercatoria* in Guam is more than adequate evidence that such island-to-island introductions are possible.

2. **Conservation management policies should be developed for the remaining colonies of endangered tree snails in the Mariana Islands.**

Although population declines and extinctions of native taxa are characteristic of the human-populated islands, remaining tree snail colonies in the Mariana Islands should be surveyed on a regular basis to monitor populations of these unique species. Management and conservation efforts should include protection and enhancement of the forest habitat that supports these species. This is especially important for species or colonies that persist at single locations. Pugua Point, Guam is inhabited by the only colony of *Samoana fragilis* known to exist. Haputo is the only site where *Partula gibba* remains in Guam (see Smith et al., 2008), and the American Memorial Park in Garapan is the last known location of a *Partula gibba* colony in Saipan.

3. **Protocols should be developed to manage populations of feral ungulates.**

Where present, large populations of feral pigs and deer in forests in the islands cause extensive environmental damage. The forested areas of these lands are shrinking, and the structure of the remaining forests has been compromised by overgrazing. In Sarigan in the northern Mariana Islands, the eradication of feral goats was followed by recovery of tree snail populations along with the recovery of the forest in as little as six years (Smith, 2008a).

4. **Consideration should be given to construction of ungulate exclusion areas to restore tree snail populations to their former range and former abundance.**

In the absence of ungulate removal, habitat that are fenced to exclude ungulates have been shown to be very effective for restoration of native forests, and, therefore, snail habitat. As noted above, the eradication of feral goats in Sarigan resulted in the growth of dense *Partula gibba* populations, as well as other species of native snails.

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