Preliminary re-survey of the land snail fauna of Rotuma: conservation and biosecurity implications

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In May 2012 Rotuma Island, the main island of the remote Rotuma Group (Fiji), was surveyed to document the composition of the non-native land snail fauna and to investigate if populations of previously recorded native land snail species persist. From sampling at nine locations, twenty-one land snail species from eleven gastropod families were found. Of these, eight species are non-native and two of these *Parmarion martensi* Simroth, 1893 and *Quantula striata* (Gray, 1834) (Ariophantidae) are new records for the Rotuma Group. Ten of the 13 species of native land snails found — including the endemic partulid *Partula leefi* E. A. Smith, 1897 and the rhytidid *Delos gardineri* (E. A. Smith, 1897) — were detected only as empty shells. The native *Ouagapia perryi* (E. A. Smith, 1897) and the endemic *Succinea rotumana* E. A. Smith, 1897 and *Sinployea rotumana* (E. A. Smith, 1897) remain undetected on Rotuma Island since their first collection in 1897. The non-native, invasive predatory flatworm, *Platydemus manokwari*, was also found and represents a major threat to the island's land snail fauna. This non-native species appears to be absent in many other parts of the Fiji Island archipelago and thus a re-evaluation of existing quarantine measures is required to address its potential spread to non-invaded areas. Comparisons with earlier surveys indicate a shift in the structure of the Rotuman land snail fauna over a 115-year period, with declining native components and increasing prevalence of non-native species. Further sampling, focusing on residual native habitat in less accessible areas such as coastal cliffs and offshore islets, is urgently needed to establish the conservation status of Rotuman native land snails and determine the threat posed by both, non-native snails and *P. manokwari.*

Key words: island, Fiji, Partulidae, endemic, non-native species, invasive species, *Platydemus manokwari*

INTRODUCTION

ISOLATED oceanic islands are of global significance because their biogeographic setting generates distinctive biotas and ecosystems (Gulick 1932) that are often highly vulnerable to anthropogenic disturbances (Deidum 2010). Land snail [1] diversity is particularly high in the insular tropical Pacific with estimates of over 4,000 species (Cowie 2000). Five entire families (Achatinellidae, Amastridae, Draparnaudiidae, Endodontidae, Partulidae) are endemic to Pacific Islands. Subfamilies and genera are commonly endemic to individual archipelagos or single islands, while species typically are confined to single islands. Fourteen additional families (Assimineidae, Bulimulidae, Charopidae, Euconulidae, Diplommatinidae, Helicarionidae, Helicinidae, Microcystidae, Neocyclotidae, Pupillidae, Rhytididae, Succineidae, Trochomorphidae and Truncatellidae) have undergone significant radiations in the Pacific.

Terrestrial and freshwater gastropods have the highest recorded modern extinctions of all animal groups (Lydeard *et al*. 2004). Extinction has been particularly pronounced in land snails endemic to oceanic islands (Solem 1976; Bouchet 1998; Abdou and Bouchet 2000, 2001; Bouchet and Abdou 2003; Boyko and Cordeiro 2001; Zimmermann *et al*. 2009; Brook 2010). The exact causes of decline are often poorly understood. While it is clear that a significant component of extinction in island faunas can be attributed to severe habitat loss (e.g., Hadfield 1986; Coppois 1995; Preece 1998; Lydeard *et al*. 2004; Chiba *et al*. 2009), there is concern that extinctions are ongoing in residual indigenous forests (Brook 2010; Brook *et al*. 2010). These residual forests are considered important biodiversity refugia in island systems otherwise heavily impacted by human activities (Olson and Dinerstein 1998, Allison and Eldredge 1999; Olson *et al*. 2009; Schmitt *et al*. 2009; Woinarski 2010). Some high-profile cases of land snail declines in forested areas, such as Polynesian Partulidae, have been attributed to non-target effects of purposely introduced biological control agents such as the predatory Rosy wolf snail *Euglandina rosea* (Férussac, 1821), introduced to control the Giant African snail *Achatina* (*Lissachatina*) *fulica* Bowdich, 1822 (Clarke *et al*. 1984; Hadfield 1986; Murray *et al*. 1988; Cowie 1992; Griffiths *et al*. 1993). In other cases, authors point to non-native rats, flatworms, mongoose and ants as significant causes of land snail decline (e.g., Solem 1976, 1983, 1990; Parkinson 1988; Hasegawa *et al*. 2009; Brook 2010). In invasion ecology, there is an emerging consensus that impacts, including extinctions, are contingent on the ecological context (e.g.,

[1]"Land snail" is used in this paper when referring to both 'snails' and 'slugs'. The word 'snail' refers to a gastropod mollusc possessing a fully developed shell that is capable of housing the retracted animal. The word 'slug' refers to the gastropod body form where the shell is reduced to the extent that it is no longer capable of housing the animal.

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Williamson 1996; Kiesecker *et al*. 2001; Shea and Chesson 2002; Pyšek *et al*. 2012), suggesting causes of decline in Pacific Island land snails is likely to vary within (Meyer and Cowie 2011) as well as across island groups.

The Fiji archipelago is comprised of over 1900 islands (only 95 of which are over 100 ha). Fiji lies near the centre of the south-west Pacific, on the boundary of the traditional cultural areas of Polynesia and Melanesia (Hunt 1987). Its land snail fauna is both phylogenetically diverse and largely endemic. Over 230 species are recorded, of which ~90% are native and ~78% are endemic to the archipelago (Barker and Bouchet unpublished data; Brodie and Barker 2011). Despite the record of extensive land snail extinctions on Pacific islands, there had been no published synthesis of the conservation status of Fijian land snail fauna. However, because of the high diversity and high extinction record, land snails were recently identified as a priority taxon in the Polynesia-Micronesia Biodiversity Hotspot (CEPF 2007). Accordingly, the majority of Fiji's native land snails (> 200 species) were assessed for the IUCN Red-List in late 2011 and published in 2012 (IUCN 2012; Pippard 2012). Of land snail species endemic to Fiji, 39% were identified as being of high conservation concern (IUCN Red List categories 'Critically Endangered'; 'Endangered'), and a further 14% identified as "Vulnerable", suggesting a decline in the Fijian fauna similar to that recorded elsewhere in the Pacific.

Land snail assemblages vary greatly throughout the Fijian archipelago (Barker and Bouchet unpublished data), reflecting varied geology, topography, and classical island biogeographic processes governing dispersal and *in-situ* speciation. Furthermore, many of these islands have a long history of human occupation, with modification of vegetation and introduction of alien flora and fauna. A case in point is the Rotuma Group (12°S, 177°E) that comprises one main island (Rotuma Island) with eight small islands or "islets" (Uea, Hafliua, Hatana, 'Afgaha, Haf haveiaglolo, Solnoho, Haua ti'u and Solkope) that vary considerably in size. With a total land area of approximately 43km^2, the Rotuma Group is very isolated being over 600km north of Fiji's capital city Suva and approximately 550km west of its closest neighbour Futuna Island in the French overseas collectivity of Wallis and Futuna. Rotuma's terrestrial biodiversity has elements of Central Pacific or Samoan character, which thus distinguish it from being merely a Fijian outlier (DoE 2007). Consequently from a Fiji government perspective, the Rotuma Group requires special consideration in biodiversity conservation. From a land snail perspective, the foundational paper by Smith (1897) established the Rotuman fauna as distinctive, with a unique mix of Pacific tramp[2], native and endemic species.

Stanley Gardiner (in Smith 1897) reported "There is no indigenous forest left anywhere on the island". Given this level of disturbance, there has since been concern that the Rotuman land snail fauna had suffered the same high extinction rate documented for a number of other Pacific islands. There has indeed been substantial alternation of the vegetation of the main island, Rotuma, since human settlement, with clearance of coastal and inland forests alike for housing, plantations and shifting cultivation (Rigamoto and Tyagi 2005). However, satellite imagery (Google Earth, images May 2006 and January 2009) suggests that while substantial modification of the vegetation of Rotuma Island has occurred, potential residual snail habitats are present. This impression is supported by a description of terrestrial environments of Rotuma Island by Zug *et al*. (1988), with secondary forest in areas of heavy lava rubble not presently utilized for gardening. The human population on Rotuma Island has been relatively stable over the past century and indeed is possibly lower now than prior to arrival of Europeans in the Pacific. These trends suggest a new equilibrium may have been reached between human extractive uses of the land and natural vegetation regenerative processes. There is circumstantial evidence for the present condition of the vegetation, and thus snail habitats, having considerably improved since J. S. Gardiner's (in Smith 1897) lament. Nonetheless, the vegetation is now dominated by non-native species (Rensel 1993). Potential habitats for native land snail species also occur on the islets of Uea, Solkope and Hauatia — satellite imagery from 2009 shows the islets to be covered in intact forest, consistent with the infrequent human visitations and disturbances due to physical isolation, local customs and beliefs.

A number of non-native species have already established in the Rotuma Group and are of concern to land snail conservation, including Pacific rat (*Rattus exulans*), black rat (*Rattus rattus*), yellow crazy ant (*Anoplolepis gracilipes*) and big-headed ant (*Pheidole megacephala*) (Ward and Wetterer 2006; ISSG 2011). On Rotuma Island, domestic livestock such as fowl (*Gallus gallus domesticus*), pigs (*Sus scrofa*), cattle (*Bos primigenius*) and goats (*Capra aegagrus hircus*) (Fatiaki *et al*. 1991; Howard and Rensel 1991; Rensel 1993) are also likely threats to land snails though predation and disturbance of the vegetation and underlying litter habitat.

[2]Diamond (1974) coined the term "supertramp" for species of high dispersability that are only found on small or isolated islands. This term has been generalized to 'tramp species', defined as being r-strategists, largely dispersed by human commerce, and living in close association with humans (Wilson and Taylor 1967; Hölldobler and Wilson 1990).

The continuing spread of non-native, invasive land snails through the Pacific Islands has heightened awareness of associated risks for the Rotuma Group, both as potential agents of decline in the native land snail fauna, and as threats to the economic prosperity and health of the Rotuman community. Because of Rotuma's desire to trade fresh produce with Viti Levu (Fiji) and with neighbouring countries (e.g., Wallis and Futuna, and Tuvalu), there is a pressing need for better data on non-native, invasive land snails already in Rotuma so as to inform biosecurity policy development and island quarantine services.

The present paper is an initial assessment of the status of the Rotuman land snail fauna, based on both a review of previous records, and a survey undertaken in May 2012. The survey was a preliminary reconnaissance, laying the ground work for a detailed assessment of the conservation and biosecurity of the Rotuma fauna and thus contributing to Fiji's National Biodiversity Strategy Action Plan (DoE 2007) which states the need to establish specific research programmes in Rotuma.

MATERIALS AND METHODS

Geographic Setting

Geologically the Rotuma Group is of volcanic origin, and presently consists of one large island (Rotuma) and eight rocky islets (Fatiaki *et al.* 1991). Rotuma Island is hilly with a number of craters rising to elevations of 200–260 m. The resident human population of a little over 1900 people (2011 Health Count) is spread along the coastline of Rotuma Island. Much of the island is comprised of gardens and human-disturbed "bushland", with coconut trees in abundance. Undisturbed indigenous forest does not remain on Rotuma, but forests and shrub lands of largely indigenous character persist as remnants in less accessible areas, notably on coastal cliffs and on upland volcanic rubbles (Zimmerman 1943).

The islets include the highly distinctive Hafliua (Split Island) which is almost bisected by a massive fissure, and the largest islet of Uea which is approximately one kilometre wide and rises steeply to over 200 m in elevation. The islets are uninhabited and, as described above, are covered in indigenous forest.

Review of Previous Records and Collections from Rotuma

Records of land snails previously collected from the Rotuma group were obtained by query of the catalogue and distributional database compiled by Barker and Bouchet (unpublished data) from the published malacological literature and museum and private collections.

Resurvey of Rotuman Land Snails

In May 2012, G. Brodie and F. Stevens undertook sampling at nine locations within four

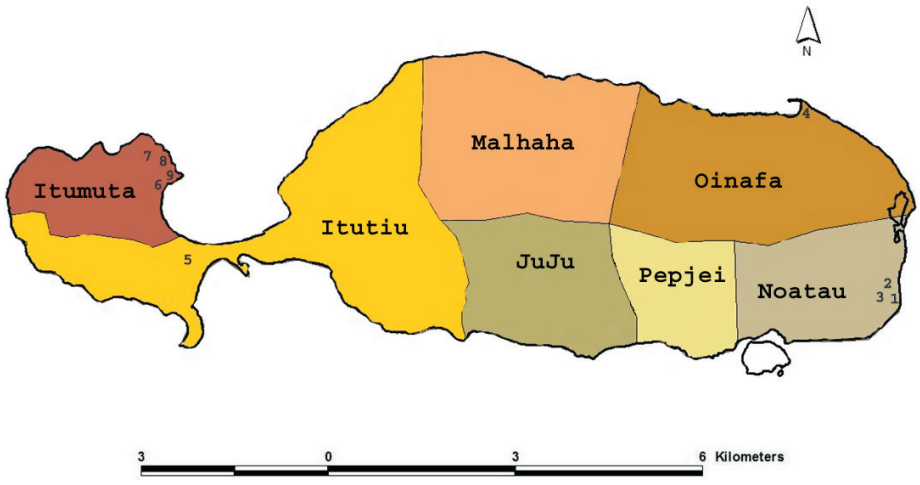

Fig. 1. Map showing the seven districts of Rotuma Island and the nine locations sampled during the 2012 survey. Sampling locations: Noa'tau District — 1. Palag as ta (near Methodist Church), coastal village surrounds, some ground vegetation, predominately coconut trees and associated debris; 2. Palag as ta (sal uaf ta), inland, adjacent to roadside, mixed tree canopy with coconut husk ground cover and lava rock walls; 3. Palag as ta (taro patch and surrounds), inland household taro patch away from houses, mixed tree canopy, muddy ground with lava rocks. Oinafa District — 4. Oinafa Bay near wharf, coastal, exposed roadside. Itu'ti'u District — 5. Upu east side of Mount Kugai, inland, disturbed "forest", shady tree canopy, understorey shrubby, ground cover of leaf litter and rocky ledges. Itu'muta District — 6. Savaea, O'oagruru, village surrounds, grass and cassava patch with lava rocks; 7. Mount Solroroa (Faniua side), inland forest with little disturbance, steep with large boulders and rocky ledges, shady, tall tree canopy, thick leaf litter; 8. Faniua near cemetery, coastal, rocky and sandy, with some surrounding shrubs; 9. Maftoa near cemetery, coastal, rocky with few surrounding shrubs.

of the seven districts of Rotuma Island (Figure 1) to obtain information on the current species composition of the land snail fauna. The survey primarily focused on documenting the non-native fauna and thus the majority of sampling effort was in relatively disturbed sites in close proximity to settlements and associated gardens and agricultural areas. Nonetheless, sampling at several locations also extended into residual 'forested' sites to both document the level of persistence in the native land snail fauna and to document the extent of spread of non-native land snails.

Sampling was qualitative, but with a similar overall time of approximately 2 hours at each location. Searching was conducted during "cooler" daylight hours when the normally nocturnal snails were located in their day-time refuges. Since the objective was to locate as many species as possible in the limited time available, sampling effort and method varied slightly depending on the physical complexity of the habitat in the location being searched. Thus samples were primarily obtained by targeted visual searching by hand beneath stones, logs, rotting organic debris and beneath the leaves of vegetation below eye-level. However, in the locations where a relatively dense tree canopy and/or understory vegetation occurred two 10 metre line transects were used to provide focus to visual searches of the tree trunks and understory vegetation below eye level. Two directed 1 m × 1m leaf litter areas were also searched at sites were leaf litter occurred and two directed small rock crevice soil surface samples were taken by trowel on rocky slopes.

Species identifications were based on our prior extensive experience with the Fijian land snail fauna and comparison with authoratively-identified material (including type specimens) in various collections. All collected vouchers were assigned to species. It should be acknowledged, however, that for many Fijian land snail families there is a need for systematic revision in a regional context and, as such the nomenclature applied here reflects current taxonomic concepts. Ellobiidae were included for completeness, albeit many members of this family in the Pacific are not strictly terrestrial but littoral to supralittoral. Voucher specimens are deposited in the reference collections of the University of the South Pacific.

Analyses of Community Composition

The adequacy of sampling in 1896–1897, 1938 and 2012 was assessed by computing in EstimateS (Colwell 2005) the individual-based expected species accumulation curves, and for the 2012 survey sample-based accumulation curves, each with 95% confidence intervals, using the analytical formulas of Colwell *et al*. (2004). Additionally, total species richness, including species not present in the sample, was computed using Chao1 (Chao 1987), ACE (Abundance-base Coverage Estimator) (Chao and Lee 1992), and First-order jackknife (incidence-based) Estimator (Burnham and Overton 1978, 1979; Heltshe and Forrester 1983). We have not attempted to do accumulation curves for individual locations within surveys because (i) it is recognized that a reasonable estimate of the composition of the community at the island scale is achievable without necessarily obtaining complete coverage at the location level, (ii) location details for the 1897 survey are not available, (iii) the three surveys had different objectives and the significant differences in sampling methods (which we are unable to quantify) precludes rigorous survey comparisons, and (iv) there are likely to have been significant changes in the spatial structure and quality of land snail habitats over the 115 years between the first and last surveys and, as such, proper analysis would demand quantitative assessment of sample representativeness of habitat variation.

Sample similarities were computed in EstimateS as the Chao estimated number of shared species (Chen *et al*. 1995) and Chao Abundance-based Sorensen index (Chao *et al*. 2005). These estimates are based on the probability that two randomly chosen individuals, one from each of two samples, both belong to species shared by both samples (but not necessarily to the same shared species). The estimators for these indexes take into account the contribution to the true value of this probability made by species actually present at both sites, but not detected in one or both samples. This approach has been shown to reduce substantially the negative bias that undermines the usefulness of traditional similarity indexes, especially with incomplete sampling of rich communities (Chao *et al*. 2005).

Discrimination of land snail communities sampled in 1938 and 2012 surveys was examined by semi-strong-hybrid (SSH) multi-dimensional scaling ordination (Belbin 1991), with the Bray and Curtis (1957) metric as the measure of community distance. The generated association matrix was used in an analysis of similarity (ANOSIM) to determine if surveys as *a priori* groups differed significantly in land snail composition. The ordination and ANOSIM were implemented in the PATN software package (Belbin, 1995).

The above analyses were based on the sum of empty shells and live-collected specimens (but exclude several subfossil Ellobiidae). Empty shells were included in the counts as they persist in the environment over several months to

perhaps a year or two, and thus integrate short-term temporal variability in species occurrence (Barker 2005; Schilthuizen 2011). This is a useful attribute when surveying remote oceanic islands where opportunity for repeated visits is severely limited. It is acknowledged that under special environmental circumstances, such as dry or non-acidic caves and rock crevices, empty-shell death assemblages can accumulate and may lead to inflated estimates of contemporaneous faunal composition (Schilthuizen 2011). However, our analyses focused on faunal changes between surveys separated by many decades and thus estimates of faunal turnover may be biased only if a significant number of these empty shells present in 2012 represented cohorts also present during the 1896–1897 and/or 1938 surveys. The conditions during the period of the 2012 survey were favourable for activity of slugs and these animals were well represented in our samples.

RESULTS

Land Snail Community Composition

With the advent of our survey in 2012, assessment of the land snail fauna of the Rotuma Group is available for three points in time over a period of 115 years: namely (i) collections by J.S. Gardiner and R.B. Leefe in 1896–1897 as described by Smith (1897), presently housed predominantly in the Natural History Museum, London; (ii) a large number of specimens collected by Harold St. John and colleagues in 1938, on behalf of the Bernice P. Bishop Museum (St. John 1938) where the material presently resides; and (iv) a modest number of specimens collected by Brodie and Stevens during the 2012 survey which, as mention above, are lodged with the University of the South Pacific. Additionally, members of the C. Templeton Crocker Expedition [= Zaca Expedition] of 1933 made a collection land

Table 1. Composition of the land snail fauna of Rotuma Island, Rotuma Group as indicated by sampling on four occasions, with estimators of total richness. Data in body of table are numbers of individuals (live-collected individuals in parentheses). [a.] *Melampus fasciatus* (Deshayes, 1830) is here treated as distinct from *Melampus flava* (Gmelin, 1791), but further research may indicate their synonymy (e.g., Cernohorsky 1972: 213). [b.] Numerous specimens sighted but only selected examples collected. [c.] Tentative identification based on juvenile shell material.

Family	Species	1896–1897 Smith	1933 Crocker Expedition	1938 St. John, BPBM*	2012 Brodie and Stevens USP**	Total
Achatinellidae	*Elasmias apertum* (Pease, 1865)	2		4 (3)	25 (25)	31
Ariophantidae	*Parmarion martensi* Simroth, 1893				15 (15)[b]	15
Ariophantidae	*Quantula striata* (Gray, 1834)				16 (6)	16
Assimineidae	*Fijianella* sp.			4 (0)	5 (0)	9
Assimineidae	*Omphalotropis* sp.			18 (8)	1 (0)	19
Assimineidae	*Omphalotropis zebriolata* Mousson, 1865	11		232 (113)	29 (0)	272
Bradybaenidae	*Bradybaena similaris* (Rang, 1831)			52 (45)	16 (0)	68
Charopidae	*Sinployea rotumana* (E.A. Smith, 1897)	7				7
Ellobiidae	*Melampus fasciatus* (Deshayes, 1830)[a]	2		2 (0)		4
Ellobiidae	*Melampus flava* (Gmelin, 1791)	2		2 (0)	36 (36)	40
Ellobiidae	*Pythia scarabaeus* (Linnaeus, 1758)	2		2 (0)	16 (0)	20
Helicinidae	*Pleuropoma* sp.			41 (6)	3 (3)	44
Helicinidae	*Pleuropoma fulgora* (Gould, 1847)	2		1189 (461)	19 (0)	1520
Helicinidae	*Sturanga modesta* (L. Pfeiffer, 1854)	2		279 (198)	2 (0)	4
Partulidae	*Partula leefei* E.A. Smith, 1897	13		525 (510)	5 (0)	543
Rhytididae	*Delos gardineri* (E.A. Smith, 1897)	2			2 (0)[c]	4
Rhytididae	*Ouagapia perryi* (E.A. Smith, 1897)	1				1
Subulididae	*Allopeas gracile* (Hutton, 1834)	2		32 (18)	15 (0)	49
Subulididae	*Paropeas achatinaceum* L. Pfeifer, 1846			4 (1)	17 (17)	21
Subulididae	*Subulina octona* (Bruguiere, 1792)			292 (282)	83 (83)	375
Succineidae	*Succinea rotumana* E.A. Smith, 1897	6				6
Truncatellidae	*Truncatella guerinii* Villa and Villa, 1841				40 (0)	40
Truncatellidae	*Truncatella* sp.				2 (0)	2
Veronicellidae	*Sarasinula plebeia* (Fischer, 1868)		1 (1)	1 (1)	4 (4)	6
Veronicellidae	*Semperula wallacei* (Issel, 1874)		1 (1)	1 (1)	16 (16)[b]	18
	Total individuals (observed)	54	2	2680	276	3012
	Total species richness (observed)	13	2	17	21	26
	Native species richness (observed)	12	0	11	13	17
	Non-native species richness (observed)	1	2	6	8	9
	Total richness estimator Chao 1	13.1 (13.0–14.9)		17.75 (17.1–25.4)	21 (21.0–21.1)	26.5 (26.0–34.3)
	Total richness estimator Jack-knife	19.6 (19.6–19.6)		30.4 (23.1–37.8)	28.5 (25.0–32.0)	26.0 (26.0–26.0)
	Total richness estimator ACE	20.3 (10.8–30.0)		25.6 (23.3–28.5)	26.6 (25.8–27.4)	26.0 (26.0–26.0)

* Bernice P. Bishop Museum
** University of the South Pacific

Table 2. Species recorded from Rotuma Group, with information on habitat, locations at which found during the survey in May 2012, and conservation status.

Species	Habitat	Locations in 2012 Survey	Conservation Status
Elasmias apertum (Pease, 1865)	Arboreal, on foliage	5	Native, tropical Pacific tramp; first Rotuma record Smith (1897).
Parmarion martensi (Simroth, 1893)	Leaf litter and on vegetation	2, 3, 5, 6 and 7	Non-native, indigenous to SE Asia; widely distributed through human agency into islands of the Pacific, including Viti Levu, Fiji (Adams 1867; Brodie and Copeland 2009); here recorded from Rotuma for the first time; considered high risk and invasive (Brodie and Barker 2011, 2012a).
Quantula striata (Gray, 1834)	Under rocks and logs, primarily in gardens	2, 3 and 6	Non-native, indigenous to Malaysia; including Fiji (Gude 1913; Brodie and Barker 2012d); here recorded for Rotuma for the first time; considered low risk (Brodie and Barker 2011, 2012d).
Fijianella sp.	Leaf litter, damp soil	7	Probable Rotuman endemic, taxonomic study pending; presently known only from empty shells.
Omphalotrophis zebriolata (Mousson, 1865)	Leaf litter	8	Native, restricted to Fiji, Wallis and Futuna and Tuvalu; proposed IUCN Red List category — Vulnerable.
Omphalotrophis sp.	Leaf litter	3	Probable Rotuman endemic, taxonomic study pending.
Bradybaena similaris (Rang, 1831)	Rock walls and village gardens	2, 6, 7	Non-native; originates from Asia; widely distributed through human commerce, including Fiji (Gude 1913); considered medium to high risk for Fiji by Brodie and Barker (2011; 2012b); first unpublished record from Rotuma 1938.
Sinployea rotumana (E. A. Smith, 1897)	Leaf litter		Rotuman endemic; IUCN Red List category — Endangered.
Melampus fasciatus (Deshayes, 1830)	Coastal, supralittoral		Native, widespread in the Indo-Pacific.
Melampus flava (Gmelin, 1791)	Coastal, littoral to predominately supratidal	1 and 4	Native, widespread in the Pacific, north-eastern Australia.
Pythia scarabaeus (Linnaeus, 1758)	Coastal supralittoral and lowland forests	8	Native, widespread in Indo-Pacific.
Pleuropoma fulgora (Gould, 1847)	Arboreal	3, 7	Native, known from Fiji, Futuna, Samoa and Tonga.
Pleuropoma sp.	Arboreal	5	Probable Rotuman native, taxonomic study pending.
Sturanga modesta (L. Pfeiffer, 1854)	Arboreal	7	Native, known also from Vanuatu.
Partula leefei (E. A. Smith, 1897)	Arboreal	7	Rotuman endemic; proposed IUCN Red List category — Not Assessed, Data Deficient.
Gastrocopta pediculus (Shuttleworth, 1852)	Leaf litter		Non-native, probably originates from western Pacific-Australian area; widely distributed by human agency; including Fiji (Mousson 1870); considered low risk by Brodie and Barker (2011); first unpublished record from Rotuma 1938.
Delos gardineri (E. A. Smith, 1897)	Leaf litter	3	Rotuman endemic; IUCN Red List category — Critically Endangered, Possibly Extinct.
*Ouagapia perry*i (E. A. Smith, 1897)	Leaf litter		Native, known also from Vanuatu; IUCN Red List category — Endangered.
Allopeas gracile (Hutton, 1834)	Leaf litter and other debris on ground	9	Non-native, probably originates from the Neotropics; widely dispersed by human commerce, including Fiji (Mousson, 1870); first record for Rotuma by Smith (1897).
Paropeas achatinaceum (L. Pfeifer, 1846)	Leaf litter and other debris on ground	5	Non-native, originates from the Orient; widely distributed through human commerce, including Fiji (Cernohorsky 1977; Solem 1978); first unpublished record from Rotuma 1938.
Subulina octona (Bruguière, 1789)	Leaf litter and other debris on ground	2, 5, 6, 7 and 9	Non-native, from the tropical Americas; widely distributed through human commerce, including Fiji (Cernohorsky 1977; Solem 1978); considered low risk by Brodie and Barker (2011, 2012e); first unpublished record from Rotuma 1938.
Succinea rotumana (E. A. Smith, 1897)	Leaf litter		Rotuman endemic; IUCN Red List category — Critically Endangered, Possibly Extinct.
Truncatella guerinii (Villa and Villa, 1841)	Supralittoral to lowland forest	9	Native, widely distributed in islands of Indian and Pacific Oceans including Fiji (Gould, 1847), and mainland Australia, India and Africa.

Table 2 continued

Species	Habitat	Locations in 2012 Survey	Conservation Status
Truncatella sp.	Supralittoral to lowland forest	9	Probable native, taxonomic study pending.
Sarasinula plebeia (Fischer, 1868)	Leaf litter and other debris on ground	2, 6	Non-native, originates from Central America; widely distributed in the Americas, eastern Australia and the Pacific including Fiji (Collinge 1900); first unpublished record from Rotuma 1933; considered medium to high risk by Brodie and Barker (2011, 2012c).
Semperula wallacei (Issel, 1874)	Leaf litter and other debris on ground	3, 5, 6, 7	Non-native, from the Orient; widely dispersed in western Pacific through human commerce, including Fiji (Gomes and Thomé 2001); first unpublished record from Rotuma 1933; risk or invasiveness on Rotuma not well understood.

snails, of which we have located a small number of veronicellid slugs presently housed in the Bernice P. Bishop Museum, Honolulu. Data on the species collected from these four surveys are presented in Table 1. A combined list of all species recorded from Rotuma, with information on their habitat preferences and conservation status, is provided in Table 2.

The 13 land snail species included in the account by Smith (1897) were evidently collected only from Rotuma Island and are represented in museum collections primarily as empty shells: that some were live-collected is evident by dried animal tissues in some type specimens. This material comprised the Rotuman endemic species *Delos gardineri* (E. A. Smith, 1897) (Rhytididae); *Succinea rotumana* E. A. Smith, 1897 (Succineidae); *Partula leefei* E. A. Smith, 1897 (Partulidae); and *Sinployea rotumana* (E. A. Smith, 1897) (Charopidae). Also included were the presumptive native species *Omphalotropis zebriolata* Mousson, 1865 (Assimineidae) [described as a new species *Omphalotropis rotumana* E. A. Smith, 1897] known from Fiji, Samoa, Tonga and Futuna; *Ouagapia perryi* (E. A. Smith, 1897) (Rhytididae) known also from Vanuatu; *Pleuropoma fulgora* (Gould, 1847) (Helicineidae) known from Fiji, Samoa, Tonga and Futuna; and *Sturanyella modesta* (L. Pfeiffer, 1854) (Helicinidae) known from Vanuatu; the widespread Pacific element *Elasmias apertum* (Pease, 1865) (Achatinellidae); and the non-native *Allopeas gracile* (Hutton, 1834) (Subulinidae) [as *Opeas juncea* (Gould, 1846)].

The Templeton Crocker Expedition to the western Pacific in 1933 briefly visited Rotuma. Collections from Rotuma available from that expedition comprise only the non-native slugs *Sarasinula plebeia* (Fischer, 1868) and *Semperula wallacei* (Issel, 1874) (Veronicellidae) (Tables 1 and 2).

The material collected in 1938 by the Bernice P. Bishop Museum from a number of locations on Rotuma Island, comprised 17 species (Table 1). Species recorded by Smith (1897) but not recovered on Rotuma Island in 1938 included *Sinployea rotumana*, *Sturanga modesta*, *D. gardineri* and *O. perryi*. Conversely, native species represented in the collection additional to those reported by Smith (1897) include three species presently unidentified or undescribed, namely *Fijianella* sp. (Assimineidae), *Omphalotropis* sp. (Assimineidae), and *Pleuropoma* sp. (Helicinidae). The 1938 survey also found on Rotuma Island for the first time the following non-native species *Bradybaena similaris* (Rang, 1831) (Bradybaenidae), *Paropeas achatinaceum* L. Pfeifer, 1846 and *Subulina octona* (Bruguiere, 1792) (Subulinidae) (Table 2).

Additionally, the 1938 survey recovered a single empty shell each of *Sinployea rotumana* and *Gastrocopta pediculus* (Shuttleworth, 1852) (Pupillidae) from Hauatia Islet; one specimen each of the non-native subulinids *A. gracile* and *S. octona* (empty and live-collected, respectively) from Solkope Islet; and eight live *S. octona* and one live *Succinea rotumana* from Uea Islet.

The 2012 survey included nine locations on Rotuma Island (Figure 1). It yielded twenty-one land snail species from eleven gastropod families (Table 1). Of these, eight species are non-native: *Parmarion martensi* Simroth, 1893, *Quantula striata* (Gray, 1834), *B. similaris*, *A. gracile*, *P. achatinaceum*, *S. octona*, *Sarasinula plebeia* and *Semperula wallacei*. Among these, *P. martensi* and *Q. striata* (both in family Ariophantidae) are new records for the Rotuma Group (Table 2), albeit both are previously known from Fiji (Barker and Bouchet unpublished data; Brodie and Barker 2012a, d). Of the non-native species *P. martensi* and *S. octona* were the most numerous and widespread.

The thirteen native species found in 2012 comprised *Melampus flava* (Gmelin, 1791) and *Pythia scarabaeus* (Linnaeus, 1758) (Ellobiidae); *Truncatella guerinii* Villa and Villa, 1841 and *Truncatella* sp. (Truncatellidae); and *E. apertum*, *Fijianella* sp., *Omphalotropis* sp., *O. zebriolata*, *Pleuropoma* sp., *P. fulgora*, *S. modesta*, *P. leefei*, and *D. gardineri* (Table 1). The truncatellid species has not previously been recorded from the

Rotuma Group (Table 2). As with the 1938 survey, no specimens of *O. perryi* and the Rotuman endemics *Succinea rotumana* and *Sinpolyea rotumana* were found, suggesting possible extinction from Rotuma Island.

Of interest is the possible change in the island land snail fauna between surveys. Comparison of the surveys is potentially constrained however by different sampling methods and differing levels of sampling effort. Individual-based rarefaction analyses for the 1886–1897, 1938 and 2012 surveys, presented in Figure 2, indicate a clear asymptote in species richness with numbers of collected specimens in each of the surveys, suggesting sampling effort in the respective surveys may have been adequate. That survey comparisons may be possible is however, also predicated on the assumption that the multiple sites or locations sampled in each of the surveys similarly covered the range of land snail habitats within Rotuma Island. Smith (1897) clearly indicates that snails were gathered throughout the island, but quantitative data are lacking. St. John and Bernice P. Bishop Museum colleagues sampled at 27 locations in 1938 and Brodie and Stevens at nine locations in 2012. The 1896–1897, 1938 and 2012 surveys yield different estimates of total species richness (Figure 2, Table 1), suggesting differences in faunal composition and/or sampling in different snail habitat space in the respective surveys. The sample-based rarefaction analysis of the data from 1938 indicates a near asymptotic relationship of species richness with number of sampled locations, indicating sampling at 27 locations provided a reasonably comprehensive coverage. In contrast, the sample-based rarefaction analysis of the data from 2012 survey (Figure 3) yielded at best weakly asymptotic relationship, indicating sampling at nine locations was not sufficient to fully characterize the land snail fauna at the island scale. Nonetheless, sampling in 2012 yielded a higher number of species than predicted for nine locations from the sample-based rarefaction analysis of the 1938 data.

Ordination analyses showed the 1938 and 2012 surveys were only partially overlapping in community space, which in large part may be due to different foci in the respective surveys (Figure 4). Specimen labels associated with material in the Bernice P. Bishop Museum indicate the 1938 survey was primarily focused on shrub land and forested areas (sampled locations ranging from open to dense tree cover), while the 2012 survey encompassed both modified habitat and much less disturbed 'forested' habitat. ANOSIM indicated significant difference in the faunal composition of 1938 and 2012 surveys ($P < 0.001$), primarily driven by the occurrence of non-native *P. martensi* and *Q. striata* in the 2012 samples.

Qualitatively, comparison of the surveys strongly indicates a shift in the composition of the land snail fauna of the Rotuma Island over time. Of the 13 land snail species included in the account by Smith (1897), the two Rotuman endemic species *Sinployea rotumana*, and *Succinea rotumana*, and the native *O. perryi*, were not subsequently detected in the 1938 and 2012 surveys. The 1938 survey indicated a different faunal structure from that indicated by Smith (1897), with detection of additional elements (*Fijianella* sp., *Omphalotropis* sp., *Pleuropoma* sp.) and changing dominance (e.g., *P. fulgora*) in the native fauna, and detection of several non-native species (namely *B. similaris*, *P. achatinaceum, S. octona*, *Sarasinula plebeia* and *Semperula wallacei*). These apparent changes between 1896–1897 and 1938 may have been due in part to different methods and different survey locations. The 2012 survey indicates a similar faunal structure to that indicated in 1938, but with detection of further elements in the native component (namely *T. guerinii* and *Truncatella* sp.), detection of additional non-native species (namely *P. martensi* and *Q. striata*), and changes in the relative dominance of at least some members of the native fauna (e.g., relative decline in *O. zebriolata, P. leefei*; relative increase in ellobiids such as *P. scarabaeus and M. flava*). These qualitative comparisons of the three surveys are supported by estimators of shared species and compositional similarity among the 1896–1897, 1938 and 2012 surveys (Table 3). The Chao Abundance-based Sorensen similarity index, for example, indicates higher faunal similarity between the 1896–1897 and 1938 surveys than between the 1896–1897 and 2012 surveys, consistent with change in faunal composition over time.

Table 3. Similarity in species composition of the Rotuma Island land snail fauna indicated by three surveys, corrected for sampling effort and undetected species.

	Chao estimated shared species		Chao Abundance-based Sorensen similarity index	
	1896–1897	1938	1886–1897	1938
	Smith	St. John, BPBM*	Smith	St. John, BPBM
1896-97 Smith	□		□	
1938 St. John, BPBM	9	□	0.86	□
2012 Brodie *et al*., USP	9	17	0.57	0.90

* Bernice P. Bishop Museum

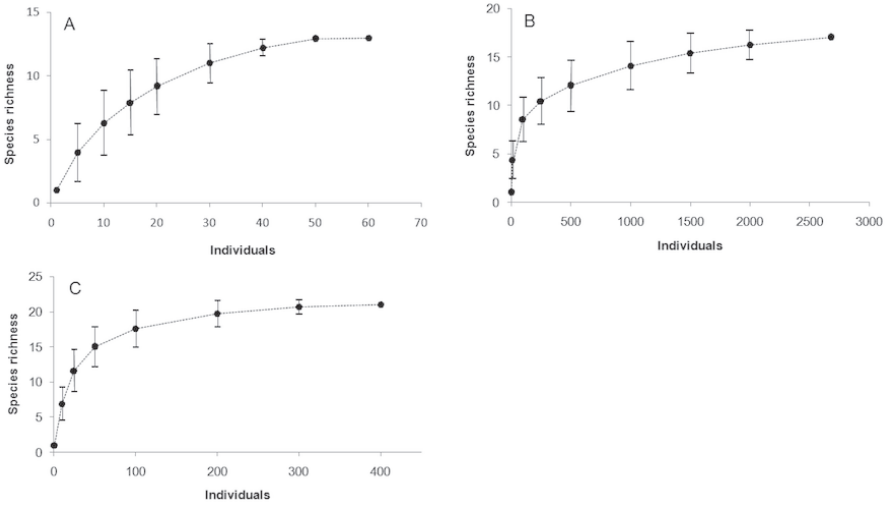

Fig. 2. Species accumulation curves from individual-based rarefaction analyses of data from three surveys on Rotuma Island: A. During 1896–1897 by J. S. Gardiner and R. B. Leefe as described by Smith (1897); B. During 1938 by H. St. John for Bernice P. Bishop Museum; and C. During 2012 by G. Brodie and F. Stevens. Error bars are 95% confidence intervals around the average accumulation curve.

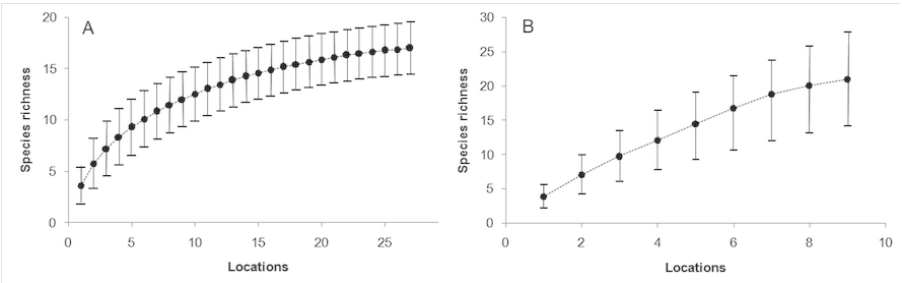

Fig. 3. Species accumulation curves from sample-based rarefaction analyses of data from two surveys on Rotuma Island: A. During 1938 by H. St. John for Bernice P. Bishop Museum; and B. During 2012 by G. Brodie and F. Stevens. Error bars are 95% confidence intervals around the average accumulation curve.

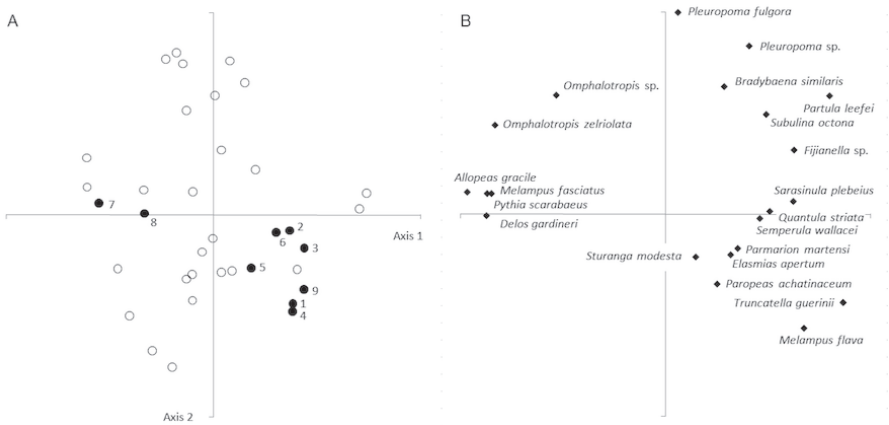

Fig. 4. Ordination of community compositional data from surveys on Rotuma Island. A. Site biplot (axes 1 and 2), showing locations sampled during 1938 by H. St. John for Bernice P. Bishop Museum (○), and during 2012 by G. Brodie and F. Stevens (●). Sampling locations from the 2012 survey numbered 1 to 9. B, Centroids for sampled land snail species in the same ordination space as depicted in A.

Presence of the Predatory Flatworm *Platydemus manokwari*

During the course of sampling in 2012 the well-known non-native and invasive flatworm *Platydemus manokwari* de Beauchamp, 1962 (Rhynchodemidae) was found. This is a new record for Rotuma and Fiji. The flatworm was observed at three locations (Upu, Savaea and Mount Solroroa) within the districts of Itu'ti'u and Itu'muta respectively on the far western end of Rotuma Island. Several *P. manokwari* was seen under lava rubble in a village garden (Savaea) but were found more abundantly in well-shaded leaf litter samples taken at higher elevations in Upu and on Mount Solroroa). It was also observed that in Upu and on Mount Solroroa *P. manokwari* was in relative abundance living sympatrically with a similar numbers of the non-native snail *Parmarion martensi*. Local people also commonly encounter this flatworm in the district of Juju, as far back as they could remember.

DISCUSSION

The surveys of the Rotuman land snail fauna addressed in the present work vary greatly in sampling methodology and effort. Only the 2012 survey was undertaken specifically for land snails, albeit a focus on the non-native fauna. Comparison among these surveys to detect changes in the composition of the fauna over time thus has to be treated with caution. Nonetheless, we utilized richness and compositional overlap estimators to correct for biases due to under sampling and undetected species. These tend to confirm composition changes in the land snail fauna of Rotuma Island over the 115 year period from 1896–1897 to 2012. Smith (1897) reported 13 species, one of which was an introduction. By 1938 the fauna on the island was seen to comprise just 11 native species, but the number of non-native species had risen to 6. The 2012 survey indicated a faunal composition similar to that indicated in 1938, but with detection of two additional native species and an additional two non-native species.

Our analyses are based on the sum of empty shells and live-collected specimens. Empty shells were included in the counts as they persist in the environment over several months, and thus integrate short-term temporal variability in species occurrence (Barker 2005; Schilthuizen 2011). The presence of empty shells is likely indicative of living populations, or most pessimistically of recently extinct populations. A case in point is the endemic partulid *Partula leefei*. This arboreal species was evidently common among the material examined by Smith (1897) and was plentiful in trees at several locations in the districts of Itu'ti'u and Itu'mutu on Rotuma Island in 1938 (information from Bernice P. Bishop Museum collections). In 2012 only a few empty shell specimens were found at a single site. These shell specimens retained some periostracum, indicating animal death within the preceding year or two and are thus indicative of a possible extant population. The records from the 2012 survey, the first from Rotuma in seventy-five years, will contribute substantially to a revized IUCN Red-List assessment of *P. leefei*. The species has not been recorded from the islets in the Rotuma Group and may be a single island endemic. Further work in the Rotuma Group is urgently needed to confirm persistence of *P. leefei* and to develop management plans for ongoing monitoring and protection.

Two juvenile shells recovered from Rotuma Island in 2012 have tentatively been identified as *Delos gardineri*, indicating possible persistence of the species. *Sinployea rotumana*, *Ouagapia perryi* and *Succinea rotumana* have not been detected on Rotuma Island since these species were described by Smith (1897). It is probable they are locally extinct, however the results of the 1938 survey suggest that these species may persist on the well vegetated islets in the Rotuma Group and surveys are needed to confirm this.

The increasing richness and prevalence of non-native land snails in the Rotuma Group is indicative of both increasing contact with the outside world through commerce and anthropogenic modification of the environment. Of the non-native species, *Parmarion martensi* and *Sarasinula plebeia* are considered to have medium to high risk "pest" status resulting from their links to human health and crop losses (Brodie and Barker 2011). *Sarasinula plebeia* has evidently long been established in the Rotuma Group, as it has in Fiji generally. The highest risk species for Fiji *Parmarion martensi*, was found in Rotuma Island at all inland locations surveyed in 2012. This result answers the quarantine related questions highlighted by Brodie and Barker (2011: 33) about the presence or absence of this non-native species in the Rotuma Group. There is therefore no need for specific quarantine restrictions to address the potential spread of this species, which is common in Viti Levu, to Rotuma because it is already present. However, there is a need to increase awareness among community members of the health risks associated with these snails as intermediate hosts and vectors for the rat lung worm *Angiostrongylus cantonensis* (Chen, 1935) (Nematoda: Metastrongylidae), the causative agent of human angiostrongyliasis and the most common cause of human eosinophilic meningoencephalitis (Hollingsworth *et al*. 2007; Lv *et al*. 2009; Brodie and Barker 2011). The

possible presence of *A. cantonensis* in *P. martensi*, *S. plebeia* or other species of land snail in the Rotuma Group requires investigation.

The importance of other non-native land snails for the survival of existing native snail fauna is presently not well understood.

Fortuitously two of the world's worst invasive land snail species, the Giant African snail and the Rosy wolf snail are currently absent from Fiji. Continuing strict quarantine regulations are required to keep them out as their introduction would have major negative implications for human health, crop production, tourism and biodiversity loss (see Brodie and Barker 2012f, g), all factors that would be detrimental to such a relatively small developing country.

The discovery of the notorious snail predator *Platydemus manokwari* at both lowland and elevated sites has serious implications for the Rotuman land snail fauna. Native to Papua New Guinea, *P. manokwari* has become increasingly widespread in the Pacific and Pacific-rim Islands and is implicated in decline of native land snail faunas (e.g., Sugiura *et al*. 2006; Sugiura and Yamaura 2009). Additionally, *P. manokwari* is a patent host of rat lung worm (Asato *et al*. 2004).

P. manokwari is an active and voracious predator of snails both native and non-native (Winsor *et al*. 2004) and is therefore not suitable for use as a biological control agent against non-native crop pests. The presence of *P. manokwari* on Rotuma is one likely reason that only empty shells of the non-native snail *B. similaris* were found in the 2012 survey as the flatworm is documented to feed readily on this species as well as on partulids (Winsor *et al*. 2004). The high proportion of native species recorded as dead-shells only (77%) may also result from the influence of *P. manokwari* predation, or other forms of native habitat degradation — however, additional research is required to investigate such relationships.

P. manokwari is well documented as one of the world's top 100 invasive species (Lowe *et al*. 2004). We have very recently observed *P. manokwari* at a single location in Suva, south-eastern Viti Levu, however to date it appears absent from several other Fijian provinces. Biosecurity initiatives are thus urgently needed to prevent the spread of this species throughout Fiji.

The Rotuma Island land snail assemblage is notable in its absence of elements characteristic of the native land snail fauna in other regions of Fiji — Hydrocenidae, Pupinidae, Diplommatinidae, Neocyclotidae, Bulimulidae, Euconulidae, Helicarionidae, Microcystidae, Trochomorphidae and Endodontidae. Several of these taxonomic groups include small species that may have escaped detection on Rotuma to date, but for the most part their absence can be taken as a true indication of the faunal difference from Fijian provinces to the south. The special nature of the land snail fauna of Rotuma — with its unique mix of tramp species, native elements shared variously with Futuna, Samoa, Tonga, Vanuatu and other Fijian provinces, and its endemic species — coupled with the unique cultural heritage, strongly supports its specific recognition in Fiji's National Biodiversity Strategy Action Plan (DoE 2007). However, the apparent decline in the native land snail fauna and the increasing burden of non-native species is of considerable concern. The present research, particularly the 2012 survey, lays the foundation for establishment of continuing specific longer-term research programmes on Rotuma and acknowledges the fundamental need for these programmes to closely involve the local community.

CONCLUSIONS

Our data suggest loss of native snail species, and increasing dominance of non-native species, within land snail assemblage of Rotuma. This result conforms to the trend of native snail decline and homogenization found for other Pacific Islands (Cowie 2001; Cowie *et al*. 2008). The impact of non-native species is considered to be ecologically more significant on inherently fragile small-island ecosystems (like Rotuma) than they are on larger continental systems (Reser *et al*. 2007; Veitch *et al*. 2011). Such continued changes in the environment are likely to impact on human livelihoods (Myers 1996) making future investment in quarantine services of considerable value.

A more comprehensive survey of native land snail fauna, which includes sampling in the less accessible areas of Rotuma Island, and the islets, is needed. However, the results of this paper will make a significant contribution to future conservation assessments of Rotuma's endemic snail fauna, including revision of the IUCN Red List. Our new discovery of the invasive predatory flatworm *P. manokwari* on Rotuma Island adds urgency to conservation actions as its presence is likely to greatly increase the extinction risk of an already impoverished land snail fauna.

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