The status of trochus (*Trochus niloticus*) in Tongatapu Lagoon, Kingdom of Tonga

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Abstract

Trochus niloticus was introduced into Tonga in 1992 and 1994 at Tabana Island in the Vavau Group, and at Fukave and Euaiki islands on Tongatapu. Surveys conducted at released sites from 1995 to 2000 indicate positive recruitment of trochus on the reefs of Tongatapu. A baseline resource survey is required in order to provide stock information for management purposes. Independent surveys conducted in August 2006 by the Secretariat of the Pacific Community recorded *Trochus niloticus* at 70% of stations (total n = 1,125 individuals recorded). Trochus distribution across the lagoon was uneven, with western areas having denser aggregations than eastern areas. Aggregations were found on lagoonal reefs, fringing reefs of Atata and Poloa islands, and Sopu Reef. The mean size of trochus at Tongatapu (n = 697) was 9.5 cm ± 0.1 SE. With a mode of 10 cm, trochus stocks at Tongatapu comprise relatively young individuals, which is indicative of a young trochus resource in Tonga. The basal width of shells is split from west to east where significantly larger and older individuals were found in the eastern sector of Tongatapu Lagoon (mean size: eastern = 11.0 cm ± 0.2), while the central and western sectors had smaller individuals (central = 8.7 cm ± 0.1, western = 9.6 cm ± 0.1). It was difficult to determine (due to a lack of data) whether trochus reseeding efforts at Tongatapu contributed to this distribution pattern. We concluded that the existing stock is due to the successful recruitment from introduced breeders. Water circulation in Tongatapu Lagoon was analysed, and it was determined that there was a dominant lagoon flushing from east and north driven by 1) tidal flow from the open ocean in the north, 2) easterly winds that dominate 70% of the year, and 3) currents created from waves breaking over the reef at the southeast corner of the lagoon rim. Also, a system of weak currents develops in the central lagoon in front of Nukualofa where the currents converge. At this convergence zone, current flow weakens and any floating trochus larvae are expected to sink to the bottom and settle on suitable reefs. This finding supports the "source and sink" phenomenon, where the central lagoon area (Atata Island to Nukualofa Harbor) receives larval recruitment originating from the source population (breeding stocks) at the lagoon's eastern sector. This result explains the dense aggregation of trochus found in the western sector of the lagoon at Atata Island.

Introduction

Trochus biology

Trochus niloticus tend to be distributed according to age across the reef profile. Juveniles are found in shallow areas among coral rubble, while adults are found in increasing densities towards the reef edge. The optimum depth for trochus is between 10 m and 15 m, although they can be found as deep as 27 m. Trochus feed by grazing on corals and rocks for microscopic algae and diatoms. They reach reproductive maturity in the wild at around 2 years of age (approximately 6 cm basal diameter), while in captivity trochus reach sexual maturity at 12 months. The lifespan of trochus is around 15–20 years, when their maximum basal diameter is around 14–15 cm. Like most other tropical gastropods *T. niloticus* is a dioecious (separate male and female individuals) broadcast spawner, and fertilisation takes place in the water column. Spawning is initiated by males, and females spawn in response to the presence of sperm in the water. Females generally spawn for 5–10 minutes, with individuals releasing more than 1 million oocytes (Nash 1985). Spawning often occurs in synchrony with lunar or tidal cycles, generally occurring at night and within one or two nights of either a full or new moon. Spawning occurs throughout the year in low latitudes and only during the warmer months

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in higher latitudes (Nash 1985). However, in the central region of the Great Barrier Reef, spawning occurs throughout the year. Hatching occurs after the larvae reach the trochophore stage (planktonic phase), approximately 12 hours after fertilisation. The larval phase lasts approximately three to five days and the veligers then settle onto the reef substrate and begin grazing on fine filamentous algae and microorganisms (Nash 1985). This short larval phase may limit long-distance dispersal, hence trochus populations are not likely to spread to reefs far away from the reproductive adults. Adult trochus are largely non-selective herbivores, grazing on the epibenthos of a wide variety of biotic and abiotic materials, including algae, foraminifera, mollusks and crustaceans. Small to medium sized individuals are cryptic, while larger specimens are often exposed and visible on the reef.

Trochus fishery in the Pacific

Trochus shell is an important commodity for many Pacific Island communities. It has been exploited traditionally as raw material for natural shell button and jewelleries. Its demand and easy access by fishers has led to overexploitation on many reefs. Adult trochus individuals have been introduced in areas that are naturally deficient. Historically, over 100 trochus broodstock transplantations have been carried out in the South Pacific since the 1920s. These transplantations were made between reefs, islands, atolls and among different countries (Gillett 2002). However, these activities have achieved varying levels of success. Trochus were introduced at Aitutaki Atoll (Cook Islands) from Fiji in 1957, and these individuals became a breeding population that provided a first harvest in 1981 of almost 200 t of shells (Sims 1988). Broodstock introduced into Tahiti in 1957 from Vanuatu (formerly New Hebrides) and New Caledonia developed a breeding population that provided a first commercial harvest of 350 t of shells 17 years later (Cheneson 1997). On the other hand, the introduction of trochus at Funafuti Atoll (in Tuvalu) from Fiji in 1985 was not successful (Wilson 1995).

Introduction of trochus into Tonga

Trochus niloticus was naturally absent in the Tongan islands, but was introduced from Fiji in 1992 and 1994 (Table 1). The first shipment of 250 individuals was released onto Tabana Island in the Vavau Group. The second shipment of 1,045 individuals was released on Fukave (645 individuals) and Euaiki (400 individuals) islands on Tongatapu (Manu et al. 1994; Gillett 2002). The reason for releasing trochus at Fukave and Euaiki islands was to promote the westward dispersal of the species to other reefs in the lagoon using the influence of the dominant southeasterly wind on wave currents at the southeastern end of Tongatapu Lagoon.

Monitoring surveys conducted at Fukave Reef by Tonga's Department of Fisheries staff from 1994–1996 continually recorded trochus, indicating the survival of broodstock. Surveys from 1999 and 2000 recorded an increased number of trochus at Fukave and an increasing number of trochus at other locations west of Fukave (Table 2) at sizes ranging from 50–125 mm. These findings confirmed that the newly introduced trochus had established a spawning population, and that recruitment had begun to spread to other reefs in the lagoon. Release sites at Euaiki and at Vavau were not assessed during this time, but local sources confirm that trochus have been observed at both of these sites (Ulunga Fa'anunu, Tonga Ministry of Fisheries, pers. comm. 2006).

Trochus mariculture and seeding

Mariculture provides an option for using artificially produced juvenile trochus for stock enhancement. The Tonga trochus breeding programme, funded by the Japanese government, began in 1994. The aim of the breeding programme was to supplement the introduction programme. The first trochus seeds were released in 1998 in the Haapai and Vavau groups, at an average size of 50 mm (Ministry of Fisheries Tonga 2004). More releases were made between 1999 and 2003, one in the Haapai Group and the rest at Fukave and Euaiki islands. Table 3 provides a summary of juvenile trochus that have been reseeded in Tonga. All released juveniles were tagged and measured at the hatchery before being transported to their release sites in plastic boxes. Juveniles were released by carefully placing them in an upright position inside a reef crevice for protection from predators.

Monitoring surveys of released juveniles were planned for 1, 12, 24 and 36 months after their release in order to assess survival, mortality, growth and dispersal (Kikutani and Yamakawa 1999). However, despite requests to Tonga's Ministry of Fisheries and the Japan International Cooperation Agency (JICA) expert (Kenichi Kikutani) in charge of the Tonga mariculture programme, no data were made available. We conclude that it is likely that juvenile recovery data were never collected, otherwise the information would have been made available to us or would have been published.

Trochus distribution and dispersal

There is currently little understanding of recruitment patterns in *T. niloticus* and the impacts of environmental factors, particularly water circulation, on trochus population and distribution. However, studies have been made on other invertebrate species, such as the coral-eating crown-of-thorns sea star, *Acanthaster planci*. Studies on *A. planci* on the

Table 1. Summary of trochus introductions into Tonga.

Date	Origin	Number	Alive	Release site
8/1992	Lakeba, Fiji	250	250	Tabana Island, Vavau (250 untagged)
5/1994	Lakeba, Fiji	1092	1046	
11/5/1994				Fukave, Tongatapu (400 untagged)
11/5/1994				Euaiki, Tongatapu (400 untagged)
30/5/1994				Fukave, Tongatapu (100 tagged) 140 adult trochus were reserved for breeding purposes at Tonga's Ministry of Fisheries hatchery.

Source: Gillett 2002; Manu et al. 1994

Table 2. Recapture of released trochus broodstock and newly recruited trochus at Tongatapu Lagoon.

	1994	1995	1996	1997	1998	1999	2000	2001	2002
Fukave	147	57	78			208	125		
Euaiki	65								
Onevao						1			
Nuku						0			
Velitoa						2			
Malinoa						0			
Fafa						2			
Pangaimotu						4	5		
Makaha					1	4			
Manima							2		
Kolonga							1	41	15
Navutoka								8	
Ulanga Lalo					3			93	

Source: Niumeitolu et al. 1999; Fa'anunu et al. 2000; Kikutani et al. 2006

Table 3. Hatchery-produced trochus seeding in Tonga.

Year	Release site	No. released	Size (mm)	Comments
1998	Haapai	350	50 +	sites unknown
	Vavau	380	50 +	sites unknown
1999	Haapai	450	50 +	sites unknown
2000	Fukave, Tongatapu	350	50 +	
	Haapai	500	50 +	sites unknown
2001				
2002	Ulanga Lalo, Tongatapu	400	50 +	
	Atata, Tongatapu	400	50 +	
2003	Ulanga Lalo, Tongatapu	600	50 +	

Source: Ministry of Fisheries Tonga 2004

Great Barrier Reef show that ocean current movements and speed, and water residence time are responsible for larval recruitment, which leads to outbreaks of *A. planci* in certain areas (Moran et al. 1992). The final destination of a recruiting larva is known as the "sink" where settlement occurs. Larval dispersal depends also on the pelagic larval duration; when considering the relatively short larval phase for *T. niloticus* (i.e. three to five days), localised recruitment is expected. However, studying recruitment behavior and patterns where a resident population exists can be difficult due to the ambiguity of results. The Tongatapu trochus is a new population that can provide a good case study in understanding the role of hydrodynamic conditions on the distribution of *T. niloticus*.

Study site

Tongatapu is the largest and main island in Tonga. It is an upraised atoll with a land area of 259 km^2. The lower northern side of the island is only a few meters above sea level while the southern coast is 65 m above sea level. Tongatapu has a bifurcated shallow lagoon (Fangauta Lagoon) with an average depth of about 1.2 m and a total area of 2,788 ha. Corals are found at the mouth of Fangauta Lagoon but are absent from most of the lagoon's interior due to low salinity levels.

Tongatapu Lagoon, the study site for our survey work, includes all the waters outside of Fangauta Lagoon, and is bounded by the western barrier reef, eastern barrier reef and the waters just north of Mainoa Island (See Fig. 1). The barrier reef system opens up at the northern end of Tongatapu Lagoon, thus representing the sunken part of the atoll formation. A series of fringing reefs, barrier reefs and coral islands are spread across the lagoon, making up 90% of the island's coral reef. Tongatapu Lagoon is 321.5 km^2 with a total reef area of 63.1 km^2. The lagoon's western sector has 14.3 km^2 of reef area, the central sector has 17.3 km^2 and the eastern sector 12.1 km^2.

Temperatures on Tongatapu range between 11°C and 32°C, with a mean of 23°C. Southeast trade winds blow for nine months of the year and influence water circulation dynamics within the lagoon. There is a distinct wet season from November to April, but rainfall is generally moderate by Pacific Island standards (Lovell and Palaki 2003). Most fishing activity on Tongatapu takes place along the northern leeward coast on the reefs and shelf area.

Objectives of this study

The objective of this survey was to provide baseline information on trochus, and to recommend man-

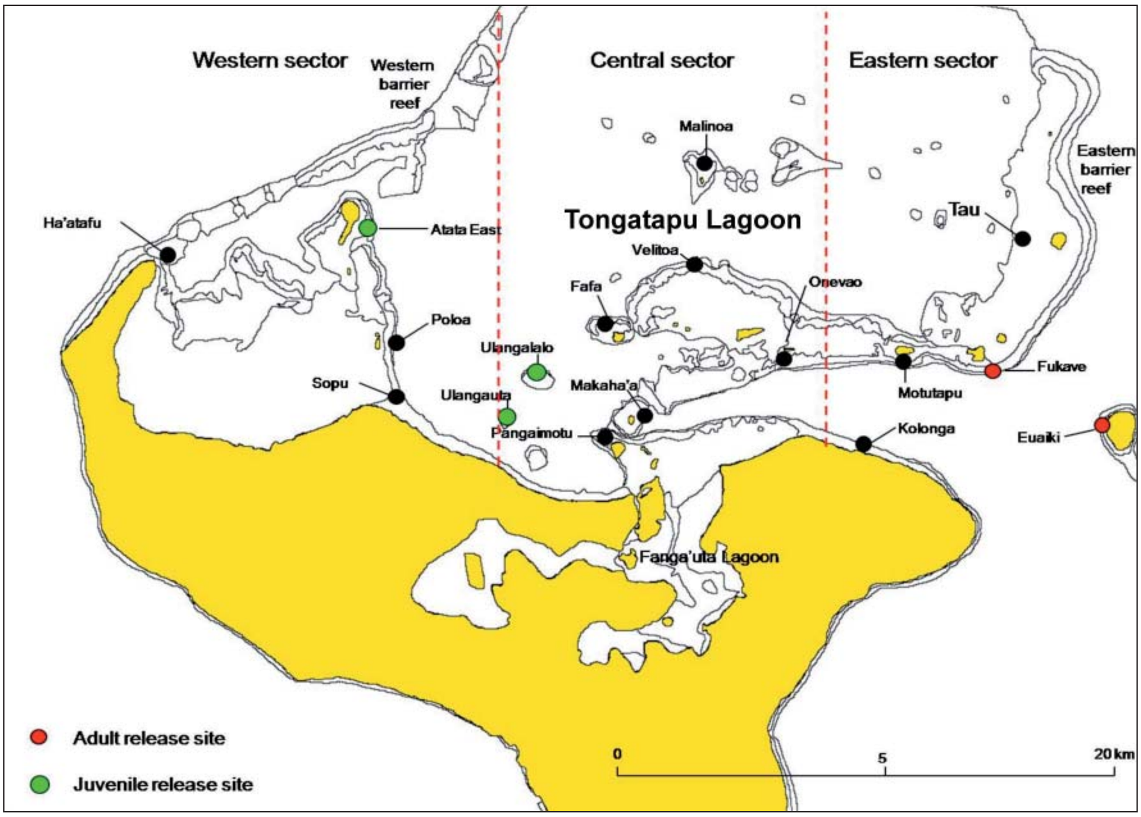

Figure 1. Tongatapu Lagoon and trochus study sites.

agement measures to manage this resource sustainably. In addition, the present work on the Tongatapu trochus provides a good case study for understanding the population dynamics and the role of environmental factors, particularly the impact of water circulation, on recruitment patterns. Specifically the survey aimed to provide:

- baseline information about the resource;
- information on the impacts of adult release and the juvenile seeding programmes;
- information on distribution patterns of *T. niloticus*;
- information on abundance and size distribution of trochus in the lagoon; and
- information on water circulation dynamics in the lagoon and its influence on trochus distribution and abundance.

Methodology

Resource surveys

The baseline trochus resource survey was conducted from 29 August to 8 September 2006, 12 years after broodstock were introduced, and 3–8 years after the beginning of the juvenile reseeding programme. The survey was designed to provide a comparative assessment across the lagoon by dividing the study area into three arbitrary sectors: western, central and eastern (Fig. 1). Euaiki was not included in this survey due to time limitations. The actual positions (longitude and latitude) of sampling stations were recorded using a Garmin GPS 72 (Garmin Corporation, 2002).

The regional invertebrate resource survey techniques used in this survey included: 1) reef benthos transects (RBts), 2) reef front searches (RFs), 3) mother-of-pearl transect (MOPt), and (4) mother-of-pearl searches (MOPs) (survey type naming developed by PROCFish/C). The profile in Figure 2 shows the different survey techniques and the locations where they are typically used. These protocols were carried out by two surveyors working side by side or on either side of the transect in order to record epi-benthic invertebrate resources, with a particular emphasis on commercial invertebrate species.

Reef benthos transects

Reef benthos transects were conducted in areas representative of suitable trochus habitats. Six 40-m transects (1-m wide) were surveyed at each station by snorkeling. Transects were positioned randomly across environmental gradients where possible (usually across reefs and not along reef edges). A waypoint was logged for each station (to an accuracy of ~ 10 m), and habitat recordings were made for each transect.

Reef front timed swim search

Timed swims, referred to here as reef front searches, were done by snorkelling along the reef front, usually when swell conditions were favorable. Every

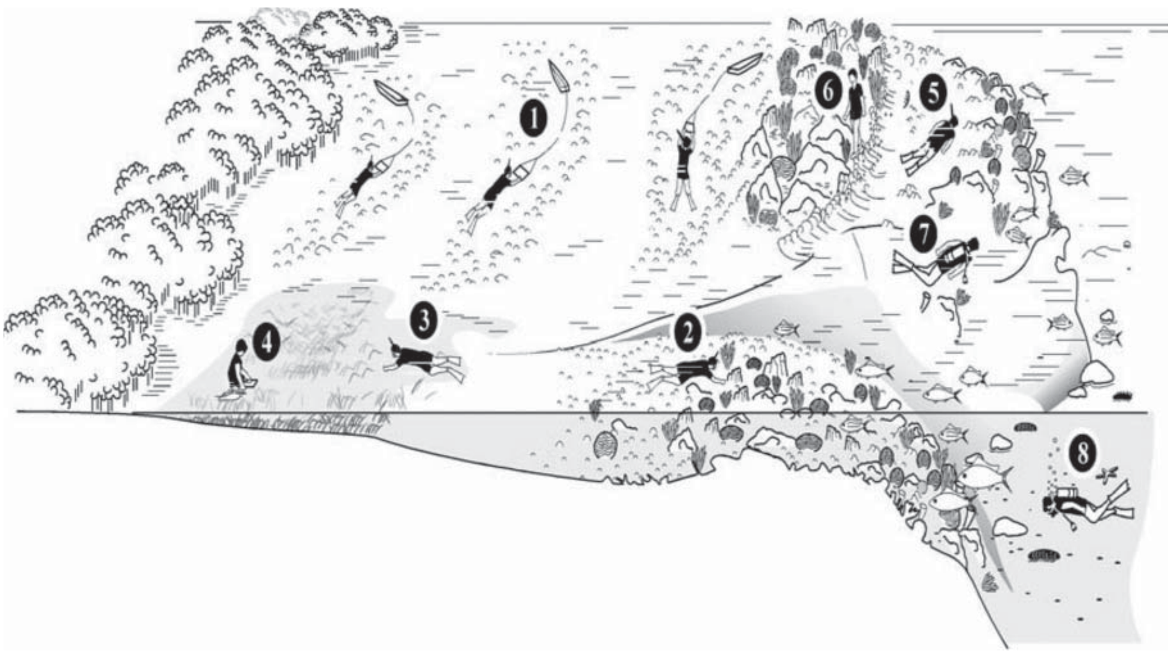

Figure 2. Reef profile showing typical locations of invertebrate surveys conducted by PROCFish/C, in the Pacific Islands region. Trochus surveys are numbers: 2 – reef benthos transects, 5 – reef front searches, 6 – reef front search walk, and 7 – mother-of-pearl searches and mother-of-pearl transect.

five minutes, observers recorded large invertebrates such as trochus (*Trochus niloticus*), green snail (*Turbo marmoratus*), giant clams and sea cucumbers such as surf redfish (*Actinopyga mauritiana*), all of which aggregate in this reef zone. Each surveyor completed a set of three swims that made up a total of six swims (or replicates), which completed a station. The start and end positions of the station were recorded and used to calculate the total distance swum using MAPInfo. The distance of swims varied between stations depending on conditions such as wind and currents and on the swimmers themselves.

Shallow dive transect and shallow dive timed searches

These assessments were made using scuba in depths typically 4–10 m, never exceeding 15 m. A 40-m transect (2-m wide) was run perpendicular to the reef edge where suitable habitat exists for gastropods. A hip-mounted chainman® measurement kit with a thread release was used to measure transects. This allowed swimmers to work with their hands free, and saved time and energy on tape retrieval in the often dynamic conditions where *T. niloticus* are found. In sites suspected to have low densities, preliminary searches were conducted to rapidly check the reef for the presence of trochus. Once trochus were located, transects were run. The start and end positions of each station were noted.

Lagoon water circulation

The data used for this study came from various projects of the South Pacific Applied Geoscience Commission (SOPAC) and from the Government of Tonga. Bathymetric data were obtained from two SOPAC/European Union bathymetric surveys, which collected multibeam data on the periphery of Tongatapu, singlebeam data from Fangauta Lagoon, and data extracted from LANSAT imagery. Lagoon bathymetry was determined from marine charts of Tongatapu, and deep ocean data were extracted from the coastal and marine geology Infobank (http://walrus.wr.usgs.gov/infobank). Tidal data were obtained from a permanent gauge at Nukualofa wharf, and wind data came from Tonga's Meteorological Services. Wave climate data were extracted from Barstow and Haug (1994). These data were used to develop a model circulation system for Tongatapu Lagoon.

Results and discussion

Survey coverage

The structure of Tongatapu's reef system is complex. Although there is a barrier reef and lagoon, the barrier reef does not encircle the lagoon entirely, and inshore and midshore (middle) reefs are a mix of land-influenced and ocean-influenced structures, due to water flow characteristics and the presence of lagoonal islands and sub-lagoons. Reefs in the northern lagoon and the outer reef constitute an extensive suitable habitat for *T. niloticus*, and this area could potentially support significant trochus populations. The whole lagoon is 321.5 km^2 with a total reef area of 63.1 km^2. The western sector of the lagoon has 14.3 km^2 of reef area, the central sector has 17.3 km^2 and the eastern sector 12.1 km^2.

Potentially suitable trochus habitats at the barrier and outer reefs are estimated to be 6.8 km^2 for the western sector, 1.5 km^2 for the central sector and 11.1 km^2 for the eastern sector. Table 4 provides a summary of stations and the number of survey types completed. Figure 3 shows the actual positions of survey stations at Tongatapu.

Table 4. Replicate measures of the independent assessment types in the three sectors.

Sectors	RBt	RFs	MOPs	MOPt
Western	42	48	24	45
Central	66	48	12	42
Eastern	51	63	0	24

Presence, abundance and density of trochus

The presence and density of trochus were independently determined using a range of survey techniques designed for specific reef and benthic habitats (Table 5). Distribution patterns (e.g. rareness, commonness, patchiness) and the abundance (i.e. density ha^{-1}) of trochus in target areas were assessed in order to describe the status of the resource in those areas of naturally higher abundance and/or most suitable habitats. *T. niloticus* were present at many locations (total n = 1,125 individuals), but unevenly distributed across lagoonal reefs. The density results of the deep water assessment by mother-of-pearl transects (Fig. 4) show a clear distribution pattern from east to west compared with the density distribution for shallow water reef benthos transect assessments (Fig. 5).

Larger densities were present at central and western inner fringing reefs, while lower densities were observed at eastern reefs. Comparative analysis of densities showed that the westerly sector held denser aggregations than the eastern sector (Fig. 6). This result was not ubiquitous, as the barrier reef in the western sector did not have significant quantities of trochus (Figs. 4 and 5), despite having suitable habitat (no trochus were found during RBts).

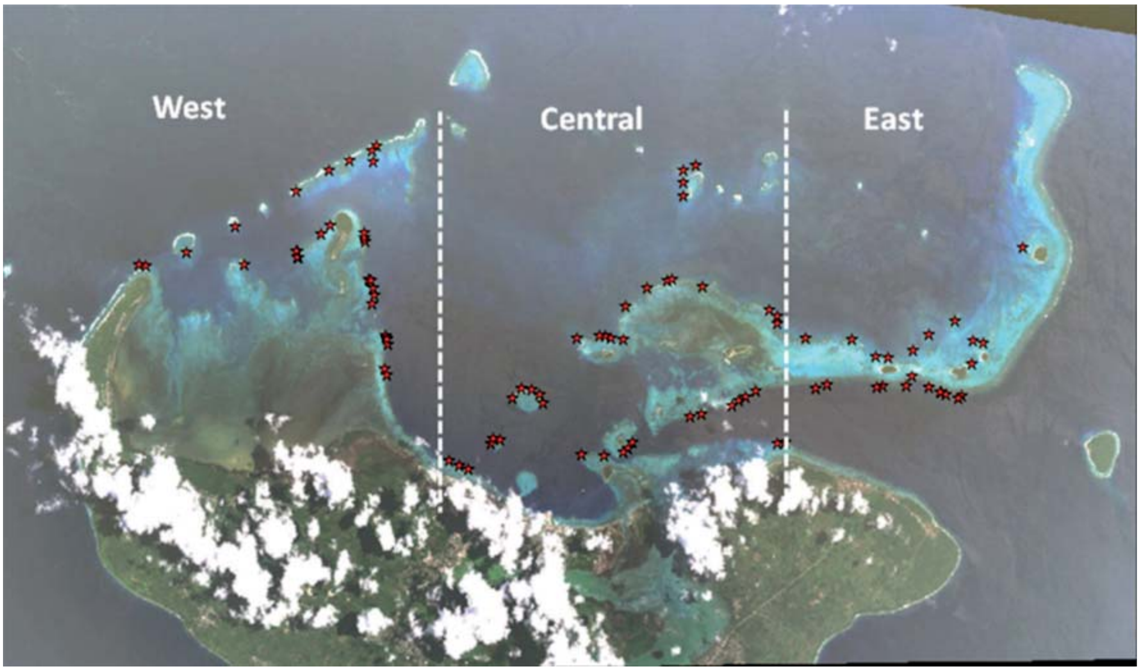

Figure 3. Resource survey coverage at Tongatapu Lagoon (red stars are start and end positions of stations).

Figure 4. Density (ind ha^{-1} ± SE) distribution of *Trochus niloticus* at Tongatapu Lagoon in mother-of-pearl assessments (4–10 m).

Figure 5. Density (ind ha^{-1} ± SE) distribution of *Trochus niloticus* at Tongatapu in reef benthos transect assessments (0.5–3 m).

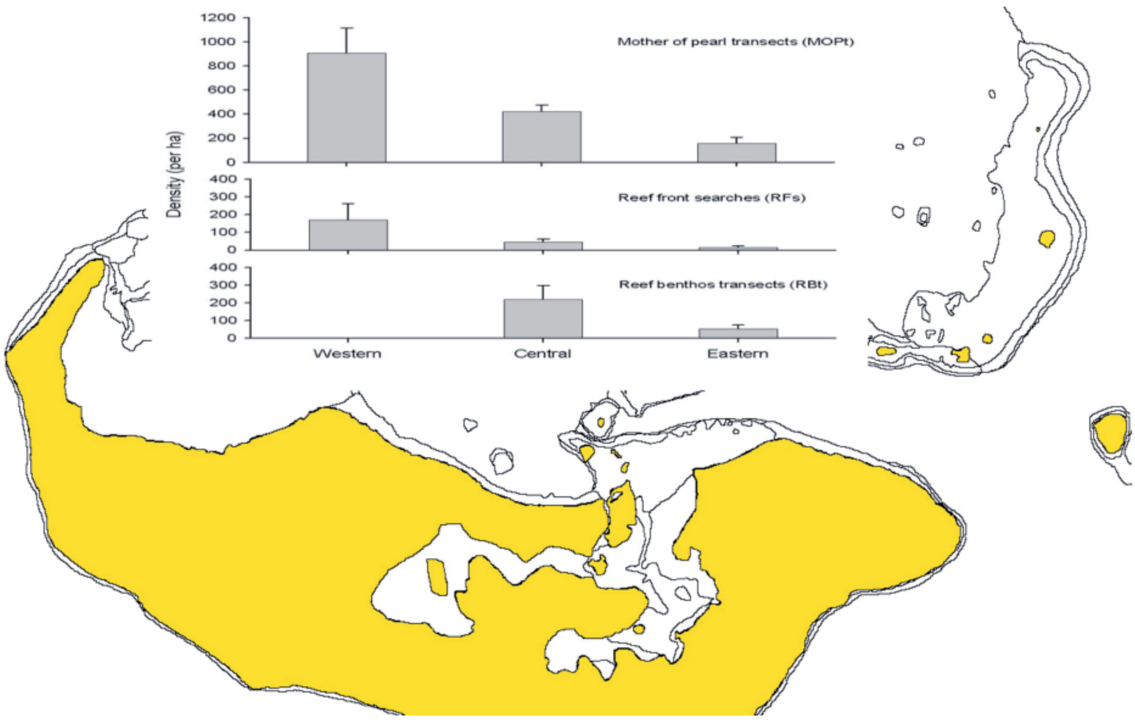

Figure 6. Mean density (ind ha^{-1} ± SE) of *Trochus niloticus* in the three sectors by survey types.

Dense aggregations were found on fringing reefs in the lagoon east of Atata and Poloa islands, in relatively shallow depths.

Atata and Poloa reefs experience a mix of oceanic and terrigenous influences from northern oceanic inflow, easterly winds that influence ocean currents, and coastal runoff from the Sopu area. Trochus inhabit the edges and slopes at 1–10 m depth. Reef complexity is moderately high, ensuring live coral cover (mainly *Acropora*) at 30%. The habitat on the lagoon side becomes less substantial in areas below 10 m, with increased siltation. Habitat at the lagoon's fringing reef (near Nukualofa harbor) is limited to the face of a drop-off to 7–8 m depth. Both adults and juveniles were recorded along the reef face in this study. A rubble zone on the fringing reef platform provides good juvenile habitat (i.e. algae-covered rubble and boulders) but exposure at low tide is a problem as dead juvenile trochus shells (>40 mm, occupied by hermit crabs) were recorded in the area.

The reef on the seaward side of the east barrier reef is quite substantial, sloping gently into deeper water. The barrier reef platform is affected by wave action, but "embayments" behind undulations provide some protection in this high-energy environment.

Mean density comparisons (ind ha^{-1} ± SE) with other mother-of-pearl species (i.e. *Tectus pyramis* and *Pinctada margaritifera*) (Table 5) show that *T. niloticus* was present in much higher densities in all surveys than the other two species. The mean density of trochus was higher than the sustainable harvest limit (500 shells ha^{-1}), although it should be noted that this high density was recorded in only one station at Atata.

Shell size distribution

Shell size (basal diameter) distribution is an indicator of stock condition (e.g. the occurrence of spawning in recent years and successful recruitment with the presence of juveniles entering the adult population). Shell size data can also show spatial differences in population dynamics, which are important in understanding the "source" and "sink" areas acting as "supplier" and "receiver" of new individuals. The sampled population in Tongatapu (Fig. 7 all sites) is representative, covering a wide range of sizes from small juveniles (3 cm basal diameter) up to large adults (14 cm basal diameter). The mean basal diameter of trochus shells at Tongatapu Lagoon (n = 697) was 9.5 cm ± 0.1 cm SE, with a dominant mode around 10 cm, which highlights that the stock in Tongatapu Lagoon includes many individuals that are relatively young (10 cm shells characterise individuals just over four years old). Trochus are male or female, and reach first sexual maturity at 7–8 cm (data from another relatively southerly site, New Caledonia) but only become significant producers of viable gametes when they are larger. In fact, the largest female trochus are by far

Table 5. Mean density comparison for trochus and two other mother-of-pearl species by assessment types.

	Density (ind ha^{-1})	± SE	% of stations	% of transects or search periods
Trochus niloticus				
RBt	109	37.7	12/26 = 46	30/159 = 19
RFs	72.8	29.9	14/20 = 70	83/159 = 52
MOPs	16.2	11.8	2/5 = 40	6/36 = 17
MOPt	536.9	110.2	16/16 = 100	97/111 = 87
Tectus pyramis				
RBt	52.9	12.1	15/26 = 58	26/159 = 16
RFs	9.4	2.6	10/20 = 50	38/159 = 24
MOPs	15.2	11.7	2/5 = 40	6/36 = 17
MOPt	0	0	0/16 = 0	0/111 = 0
Pinctada margaritifera				
RBt	3.2	3.2	1/26 = 4	2/159 = 1
RFs	0.4	0.2	2/20 = 10	3/159 = 2
MOPs	4.5	4.5	1/5 = 20	3/36 = 17
MOPt	1.3	1.3	1/16 = 6	1/111 = 1

RBt = reef benthos transect, MOPt = mother-of-pearl transect, RFs = reef front search

the most fecund. A 10-cm female trochus produces approximately 2 million oocytes, whereas a 13-cm trochus produces up to 6 million (Heslinga 1981; Bour 1990; McGowan 1958).

Shell size analysis revealed a regional split from west to east (Fig. 8). Significantly larger and older trochus are found in Tongatapu's eastern sector (mean size: eastern = 11.0 ± 0.2 cm, SE) and smaller and younger individuals in the central and western sectors (central = 8.7 ± 0.1 cm, western = 9.6 ± 0.1 cm). This result could be due to fishing preferences, or alternatively, be an indicator that the central and western sectors are acting as "sinks" for recruitment originating from the eastern sector. Because Tongatapu Lagoon's population is unfished (under monitoring), fishing preference as a mechanism for driving such results, is effectively ruled out.

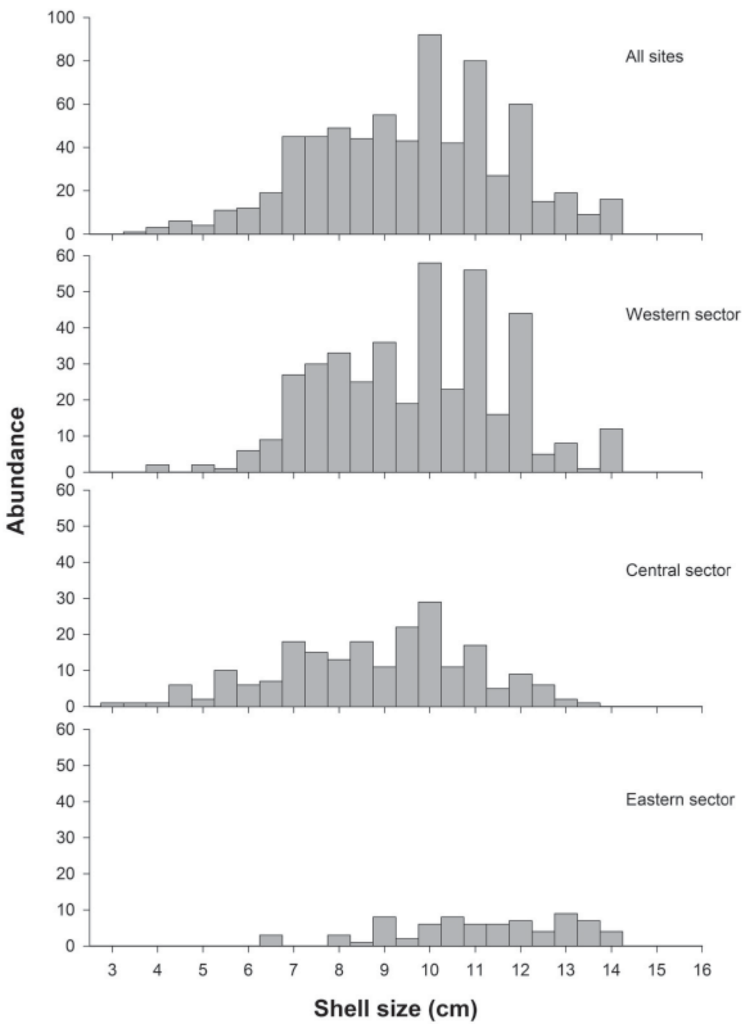

Figure 7.
Trochus population structure in Tongatapu Lagoon for all sites combined and for the three sectors. Note: Abundance on y-axis is the number of trochus found during the surveys.

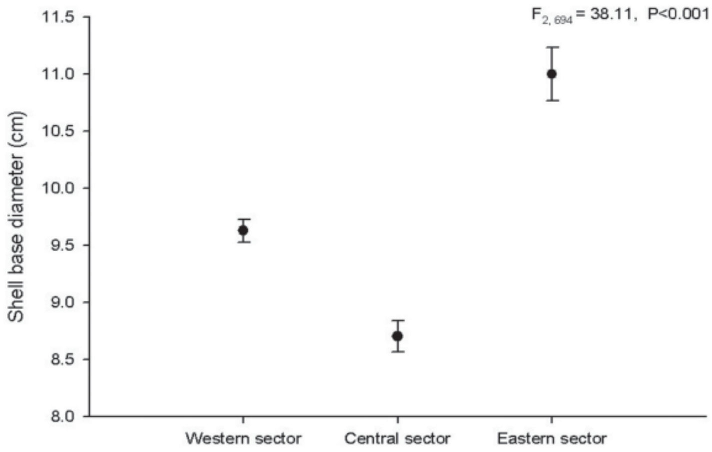

Figure 8. Trochus shell mean basal diameter (cm) for the three sectors. All sectors have trochus of significantly different mean sizes (P> 0.001, unequal n HSD).

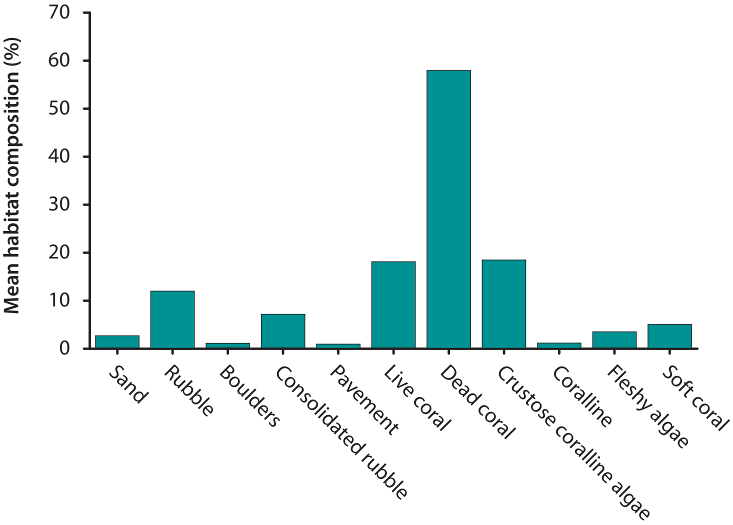

Figure 9. Mean habitat composition at Tongatapu Lagoon.

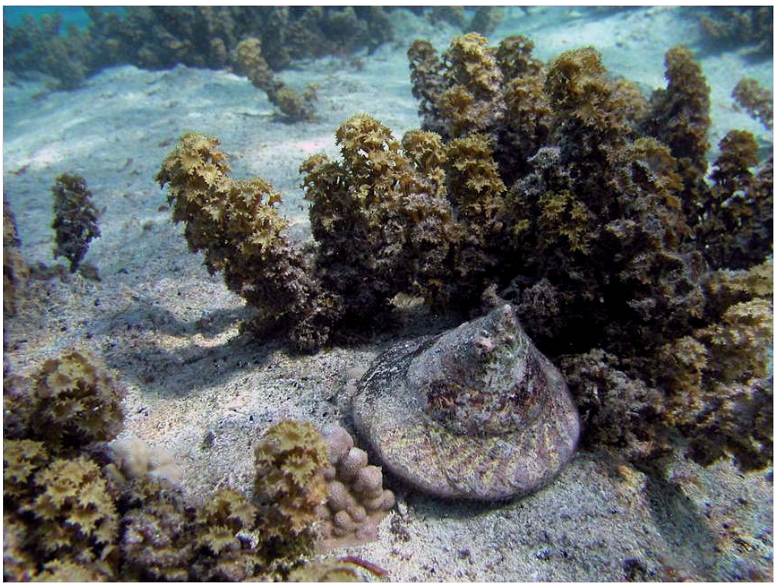

Figure 10. The alga *Turbinaria ornata* is common on the reefs of Tongatapu Lagoon. Note also the presence of an adult *Trochus niloticus*.

Broodstock transplantation versus juvenile seeding

None of the trochus surveyed in 2006 can be identified as originating from the hatchery-produced juveniles that were released at Tongatapu. Despite recapture surveys that were were planned for 1, 12, 24 and 36 months after release (Kikutani and Yamakawa 1999), no data were available, suggesting that data may not have been collected. It is thus impossible to determine if the existing trochus population at Tongatapu Lagoon is being contributed to also by hatchery-produced juveniles. Juvenile seeding in Tonga stopped in 2000 when it became obvious that the transplanted broodstock had become established (Kenichi Kikutani, JICA expert, pers. comm. January 2008). It is thus believed that the established spawning population is the main contributor to the newly recruited trochus at Tongatapu (Niumeitolu et. al. 1999; Fa'anunu et al. 2001). Seeding success with hatchery-produced juvenile trochus is once again questionable due to a lack of data on the recovery of released juveniles.

Reef habitat condition

Reef habitat data were collected in order to understand the status of resources in relation to habitat condition. Mean habitat condition was analyzed as a percentage of habitat composition, and is presented in Figure 9. Dead coral was the dominant substratum, representing approximately 60% of the composition. Dead coral covered by encrusting crustose coralline algae (CCA) was moderately high (20%). Therefore, dead coral with or without algae accounts for approximately 80% of the substratum, indicating that a large part of the reef at Tongatapu Lagoon is dead. Growth of CCA on dead coral rocks is the main component of "live rock", which is one of Tonga's main export products for the aquarium trade. Most live rock is harvested from Tongatapu Lagoon, mainly around the central reefs such as Ulanga Uta and Ulanga Lalo and up to Fafa and Onevai.

In some areas, such as back reefs of the western barrier reef in front of Haatafu and along the back reef areas of the main central lagoon reef from Fafa to Onevai and Motutapu, *Acropora* tabulate rubble dominates the bottom. Rubble bottoms are unsuitable for trochus, because they lack microhabitats and food resources (few trochus were found in these habitats). Similarly, in consolidated rubble areas — such as those present at Fafa, Ulanga Lalo and Ulanga Uta — despite the presence of good CCA growth, inadequate topography and low habitat complexity limit the ability of these areas to support a greater increase in trochus populations.

Live coral coverage was relatively low at most stations, comprising 20% of the substratum. Notable live coral coverage was present along lagoonal fringing reefs at Atata. Significant coverage of fleshy algae, mainly *Turbinaria ornata*, was recorded at Ulanga Lalo and Ulanga Uta and along the shallow reef slope at Motutapu, Onevao, and Makahaa (Fig. 10). Dense macro-algal mats such as those present in these areas can effectively reduce grazing surfaces for gastropods such as trochus, and have been found to inhibit larval settlement of benthic organisms (Heslinga 1981). Despite good topography and complexity in some of these sites, very few trochus were recorded in areas covered with *Turbinaria* mats in this survey. Soft coral is present in some areas of the central and eastern reef slopes.

The population of the crown-of-thorns sea star *Acanthaster planci* is relatively low (n = 16) and does not seem to be a major problem within Tongatapu Lagoon. However, one small aggregation recorded at the inner reef west of Atata has killed significant live coral growth and could, in the future, spread to other areas. Past aggregations of *A. planci* have been recorded at Haatafu and Pangaimotu by Zann and Muldoon (1993). Live coral coverage at these sites is relatively low, suggesting that predation by crown-of-thorns sea stars may have had an impact in the past.

Water circulation at Tongatapu Lagoon

A water circulation model for Tongatapu Lagoon, which was developed by SOPAC (Fig. 11), was used to assess water movement patterns in the lagoon. Easterly winds dominant the area, with annual

A. Circulation pattern during the spring tide flood, Tongatapu Lagoon

B. Circulation pattern during the spring tide ebb, Tongatapu Lagoon

C. Circulation pattern during the neap tide flood, Tongatapu Lagoon

D. Circulation pattern during the neap tide ebb, Tongatapu Lagoon

Figure 11. Tongatapu Lagoon water circulation systems (light = shallow water; dark = deep water).

mean direction of 130°, more than 70% of the year, at a mean speed of 4 m s^{-1}. Seasonal wave height is 2.2 m from November to March, increasing to 2.4 m between May and September. The eastern barrier reef is exposed to southeast waves hitting the reef at a height of 1.0–1.5 m. The model indicated fairly well the involvement of tides and currents induced by wind and waves in the lagoon's circulation pattern. During spring tide floods, tidal current largely controls the circulation, while the influence of wave-induced and wind-induced currents is slight. At the peak of the flood, the lagoon is filled from all sides. Inflows weaken as they meet in the central lagoon region (Fig. 11). Waves break over the reef at the southeast corner of the lagoon and create a westward current toward the central lagoon. During ebb tides, tidal current pushes water out of the lagoon. Again, this westward flow is assisted by flushing over the reef at the southeast and east corners of the atoll rim, as the wave-induced current is the strongest at this location. Inside the lagoon, the current is directed towards the west, and highlights the wind's effect on this circulation system. During neap tides, tidal current decreases and westerly winds dominate.

The rate of discharge (as calculated by the model) highlighted the dominant movement westward across the lagoon. Indeed, more than 95% of the flush on the western reef is towards the ocean, and almost 90% of the flush on the eastern reef is towards the lagoon. A relatively high water residence time occurs in the basin adjacent to Nukualofa where current speeds weaken (0.07–0.03 m s^{-1}). The mean water speed in the lagoon is around 0.06 m s^{-1}. A low water speed region occurs in the middle reef, islets reefs and the lagoon fringing reef (Atata to Sopu). Past studies using small-scale modeling (Black et al. 1995) have shown that local retention of larvae around reefs or within reef groups is critically dependent on current strength (because faster current speeds decrease larval settlement). In slow currents, larvae could be retained in greater numbers, at both an individual reef as well as on a regional scale. Trochus spawn throughout the year in low latitudes, but only during warmer months in higher latitudes (Nash 1985). According to this model, trochus aggregations in the central region where there are weak currents represent the "sink" for recruitment coming from the "source" in the eastern region.

Conclusion

The *Trochus niloticus* resource in Tonga is new and represents another recent successful introduction for the species. Trochus is less well distributed in the lagoon, and some reefs are still lacking trochus. Assistance through translocation is needed on Tongatapu and other islands to increase distribution and further develop the resource base. Any form of fishing should be discouraged or made illegal, and harvest control regulations should be developed and enforced in order to ensure maximum protection.

As a newly established population in an area naturally lacking the species, this area served as a good case study for understanding trochus recruitment patterns. The results of the water circulation model indicated that water dynamics are the main influence on trochus distribution patterns in Tongatapu Lagoon. Releasing adult trochus spawners at Fukave Island reef was, therefore, a good decision, which showed that even without the best scientific information on water dynamics, good decisions on release sites could be made from observatory information and local knowledge of winds and currents. This paper demonstrates that future trochus releasing activities should take into account water and wind dynamics.

The impact of the juvenile releasing programme cannot be fully measured because there are no data available on the recovery of the released trochus. Despite plans for data collection, a lack of data suggests that none were ever collected. This is understandable as the project focused on mariculture and reseeding rather than solely on reseeding. We thus conclude that the seeding programme in Tonga has, once again, failed to produce any concrete results to support the usefulness of this option as a tool for helping trochus to establish a breeding population. This adds to similar results of reseeding studies in the Asia-Pacific region (Purcell et al 2003; Hoang et al 2007; Lee 2000).

Management and recommendations

- The trochus resource in Tonga is a young population with the potential to spread to more reefs in the lagoon and reefs of the main island. Time should be given for the resource to mature and become suitable for a fishery. Only 12 years have passed since introduction; a minimum of 20 years is recommended before a fishery potential can be re-assessed.
- So far, no re-introduction has been carried out locally. The first harvest(s) should be used for re-introduction purposes only in order to expand the resource to other reefs and islands in Tonga. A stronger resource base can better support the fishery.
- Authorities should consider moving spawners from some of the aggregations in the western sector (Atata reef) to areas that have not received recruitment or where recruitment has been slow. Some of these areas are the outer and inner lagoonal reefs of the eastern barrier reef (from Fukave to Tau) because the dominant westerly flow would make it impossible

for larvae from the Fukave stock to disperse northward. Other reefs to consider for transplantation are Malinoa, the western barrier reef and the inner reefs at Haatafu, and the south-eastern end of Kolonga to increase the capacity of recruitment in those areas.

- Any form of fishing or sale of trochus at this stage would not help the spread of the species and would instead hamper development of the stock. Efforts should be made to educate the community and encourage its members to assist in protecting trochus, while any form of harvesting and selling should be discouraged at this point.
- Public awareness and education are urgently required to inform fishers about preserving trochus. This could be achieved through posters, newspaper articles, radio and television ads, and billboard notices placed at the main beaches.
- Trochus shells should not be offered for sale as souvenirs — even dead shells — as this would indicate to fishers that the resource has been officially opened for harvest.
- The development of management regulations to ban the collection of trochus for meat or for sale is necessary in order to give maximum protection to the resource. This regulation and its enforcement are a matter of priority. Legislation on minimum or maximum harvest sizes should be developed as a priority before the fishery opens.
- Trochus at Euaiki, Eua, Haapai and Vavau need to be assessed in order to establish baseline data. Tonga's Department of Fisheries staff have been trained on the standardised invertebrate assessment protocols used by SPC (PROCFish) in this survey. It is important that the same assessment techniques be used in all other areas so that results can be compared. It would be useful to notify SPC in advance about plans to undertake such surveys so that advice can be provided (if necessary) to assist local staff in planning.
- Lack of available data on the reseeding activities conducted in Tonga from 1998 to 2003 made it impossible to draw any conclusions about the juvenile reseeding programme. More organised data collection and record keeping on reseeding activities would be helpful in assessing the impact of such programmes in the future. Reseeding with hatchery-produced trochus has not yet delivered any results to suggest that this method is useful for establishing a trochus breeding stock.
- Trochus was present around the edges at Ulanga Lalo (one of the main reseeding sites), while none were recorded in the middle reef flat zone. Ulanga Lalo is one of the prime live rock collection sites by aquarium trade exporters. It would be beneficial to look into what the impact of removing the rocks has on juvenile trochus settlement. Perhaps this activity has some effect on trochus recruitment on the reef flat.

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