ICES Journal of Marine Science Advance Access published May 22, 2009

A comparison of two surveys of invertebrates at Pacific Ocean islands: the giant clam at Raivavae Island, Australes Archipelago, French Polynesia

Serge Andréfouët, Kim Friedman, Antoine Gilbert, and Georges Remoissenet

Andréfouët, S., Friedman, K., Gilbert, A., and Remoissenet, G. 2009. A comparison of two surveys of invertebrates at Pacific Ocean islands: the giant clam at Raivavae Island, Australes Archipelago, French Polynesia. – ICES Journal of Marine Science, 66: 000–000.

An assessment of invertebrate fisheries is currently taking place at several Pacific Ocean islands. The objectives are to obtain either detailed information on certain stocks at limited sites or to assess more broadly a variety of benthic resources across different islands. In French Polynesia, giant clam (*Tridacna maxima*) populations were surveyed by Service de la Pêche and Institut de Recherche pour le Développement (SPE/IRD). Sampling was optimized to determine stock abundance as a tool to enhance management of the clam fishery. Currently, the Secretariat of the Pacific Community (SPC) is investigating throughout the Pacific the status of invertebrate resources; a large-scale study not necessarily establishing a precise stock estimate for resources such as clams, but comparing resource status for several target species using coverage, density, and size measures. Raivavae Island (French Polynesia) was investigated by both programmes and offered an opportunity to verify whether the different sampling schedules provided consistent perspectives of the status of the *T. maxima* resource. The different strategies that SPE/IRD and SPC adopted resulted in no direct spatial overlap between the locations investigated: nevertheless, the ranges of densities and clam sizes recorded were generally consistent between surveys, and both programmes described similar spatial variation in clam presence at an island scale. SPE/IRD provided a detailed map of clam densities per habitat using a high-resolution satellite image, which yielded an estimated standing stock of 8.16 ± 0.91 million clams, representing a flesh biomass of 354 ± 41 t. SPC's study delivered coverage, density, and clam length, but no stock estimate. Unavailable from SPE/IRD, SPC also described the status of a variety of important invertebrate species targeted by fishers in the Pacific. Both programmes independently made similar fishery management recommendations. The relative merits and complementarities of the two approaches in the context of Pacific Ocean Island resource management are discussed.

Keywords: coral reefs, French Polynesia, giant clam, invertebrate fishery, PROCFish, Quickbird, remote-sensing.

Received 23 May 2008; accepted 23 December 2008.

S. Andréfouët: Institut de Recherche pour le Développement, BP A5, 98848 Nouméa, New Caledonia. K. Friedman: Formerly Secretariat of the Pacific Community, BP D5, 98848 Noumea, New Caledonia; now Department of Environment and Conservation, Marine Science Programme, 17 Dick Perry Avenue, Kensington, WA 6151, Australia. A. Gilbert: Tahiti Eco Clams, BP 140 211, Arue, French Polynesia. G. Remoissenet: Service de la Pêche, BP 20, Papeete Tahiti 98713, French Polynesia. Correspondence to S. Andréfouët: tel: +687 26 08 00; fax: +687 26 43 26; e-mail: serge.andrefouet@noumea.ird.nc.

Introduction

Coastal communities on Pacific Ocean island countries use a range of invertebrate resources in their coastal habitats for food security or export, or both. Management of those resources is according to two perspectives and priorities. At a local scale (village, island, archipelago, country), needs are generally expressed in terms of stock status to answer basic questions on resource availability and sustainability, and to facilitate the institution of conservation planning (MPA, closures, quotas, etc.). Ideally, the biological data required would include an accurate description of resource location and habitat extent, and sufficient information on stock and population structure to establish with confidence whether the targeted resource was healthy and with a sustainable outlook. This would be determined through maintaining sufficient fecund adults and recruitment to the fished population and the habitats in which they were found. At a wider scale, in this case considering all Pacific Island countries, indicators of reef-resource status are needed to promote the sustainable use of resources and to guide country development. At that scale, it is necessary to collect key data to help country fishery managers to determine quickly the strength and weaknesses in the health of resource stocks and the geographic and cultural habitats in which they live. In such a comparative approach, understanding how anthropomorphic pressures and environment have affected fishery stocks should promote more-informed management. A regional-scale perspective requires quick, consistent multi-resource sampling for which sampling effort must be scaled appropriately, whereas *ad hoc*, detailed, local-scale stock information is useful in providing much of the needed detail in terms of local variability.

The latter is currently applied throughout the Pacific. For instance, assessment of the giant clam, *Tridacna maxima*, in

French Polynesia has been conducted since 2002 by the local fishery service (SPE, the Service de la Pêche of French Polynesia) and a research institute (IRD, Institut de Recherche pour le Développement). Stocks at seven of the islands and atolls have been mapped and studied in detail using a combination of (i) remote-sensing, high-resolution images that provide habitat maps, and (ii) *in situ* fieldwork to provide fine-scale data on clam populations. The information is used to manage commercial and artisanal clam harvests and to develop plans for a sustainable clam fishery. The results have been reported for Fangatau and Tatakoto Atolls in the Tuamotu Archipelago and for Tubuai Island in the Australes Archipelago (Andréfouët *et al.*, 2005a; Gilbert *et al.*, 2006). Initial results led quickly to management action (e.g. the establishment of no-take areas at Tatakoto Atoll; Gilbert *et al.*, 2005), and further actions are currently being considered for other sites. This illustrates the local-scale approach.

The regional-scale approach is illustrated by an international programme launched in 2002 by the Pacific's lead agency in coastal fisheries (Secretariat of the Pacific Community, SPC). Their Reef Fisheries Observatory (PROCFish/C programme) compares Pacific island finfish and invertebrate fisheries to build indicators of fishery status and to make proposals to management to assist the 17 participating countries and territories. Within the SPC study, a suite of fishery-independent survey methods is applied to provide information on key, commonly targeted species. These provide information on the status of target resources at scales relevant to species (or species groups) and the fishing grounds being studied, which can be compared across sites, countries, and the region. Clam surveys were completed as part of this overall status assessment at five sites in French Polynesia, including Tikehau and Fakarava Atolls in the Tuamotu Archipelago, two sites in the Society Archipelago, and at Raivavae Island in the Australes Archipelago. Unlike the SPE/IRD approach, SPC assessments at each site do not aim to determine the size of invertebrate populations. Instead, the assessments examine the key data indicators (e.g. coverage, density, and length measures) to compare resource status within the main fishing grounds, areas of naturally greater abundance, or suitable benthos. The implications of this approach are important because the haphazard measures taken are indicative of stock health in these locations and are not valid for extrapolation across all habitats at a study site to gain population estimates, which is exactly what SPE/IRD seek to achieve for their seven targeted atolls and islands.

With the multiplication of the SPC sites (or fishery grounds) across the Pacific (70+ to date), the data generated will soon provide new, much-needed reference for regional management. However, given the existence of many ongoing and detailed surveys on a local scale, such as those conducted in French Polynesia for giant clams, we decided to evaluate whether and how the two approaches were consistent and could be reconciled to maximize mutual benefit. Specifically, we were interested in checking:

(i) whether the multispecies data collected by SPC provide a picture of clam-resource status consistent with detailed mono-specific assessment (the reference base);

(ii) how sampling designs could benefit from each other to optimize the assessment process, e.g. in the level of sampling effort or in the use of remote imagery for survey planning.

By addressing these questions, we can assess how the relative interests of both programmes and their approaches can be used out of their own context, i.e. evaluate the benefits of detailed local-scale stock surveys for regional-scale management, along with the benefits of resource-status assessment for local-scale management.

Although the focus of this manuscript is on in-water surveys, both SPE/IRD and SPC complement fishery-independent surveys (direct, in-water resource assessments) with fishery-dependent questionnaire surveys that provide an estimate of landings and resource use. As Raivavae Island (Australes Archipelago, French Polynesia) was included in both the SPE/IRD and SPC programmes, this allowed us an opportunity to compare directly the implementation of survey processes and the outcomes derived from them. We report here on the results of the two programmes, concentrating particularly on the points of comparison outlined above.

Material and methods

Raivavae Island

Raivavae Island is in the South Pacific Ocean, at 23°S and 147°W (Figure 1). It belongs to the Australes Archipelago, the most southern archipelago of French Polynesia. Raivavae is located

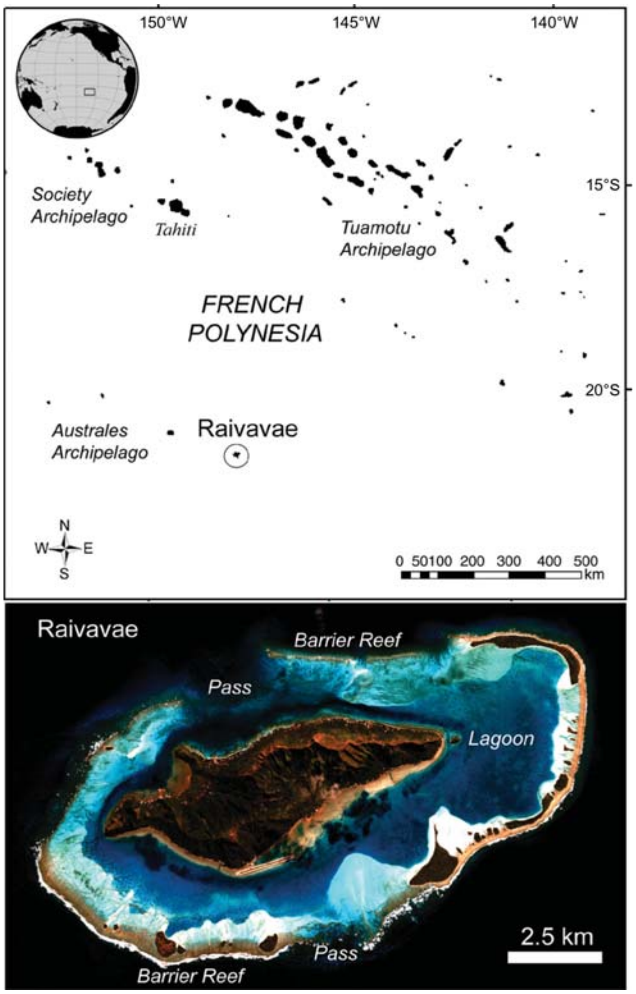

Figure 1. Location of Raivavae Island and Quickbird satellite imagery showing the island structure, with its large barrier reef, shallow sandy terraces, and lagoon.

730 km south of Tahiti, the capital of French Polynesia. In 2002, 995 people lived in three villages on Raivavae: Anatonu (260 inhabitants), Rairua-Mahanatoa (490), and Vaiuru (245). It is a remote, rural island seldom visited by tourists, although the creation of an airport in 2001 contributed significantly to its development. The giant clam is the main source of income from the reef because ciguatoxin is present in most reef finfish. The island was surveyed in October 2005 and March 2004 by SPE/IRD and SPC, respectively.

The island and its reef system (Figure 1) cover 135 km^2, and the perimeter along the barrier-reef crest is 47.6 km. Emerged land at Raivavae includes the main high island (15 km^2), plus several low altitude cays (2.9 km^2) on the eastern barrier-reef system. The barrier reef is cut into two shallow and wide passes (2.5 km^2), one in the south and the other in the north. The outer reef flats are wide and extensive (7.9 km^2), especially in the south. Large sedimentary terraces make up most of the back reef and lagoon (41.4 km^2), which includes several deep basins (4.8 km^2) and thousands of patch reefs of different sizes. A narrow, degraded fringing reef covers 4.6 km^2. Finally, the outer oceanic fore-reef is unusually wide (a total of 56.2 km^2) for an oceanic island, extending several kilometres offshore at relatively shallow depth (<20 m). All surface areas reported here are derived from Andréfouët *et al.* (2005b).

Principles of the SPC and SPE/IRD sampling protocols for fishery-independent resource survey

Tables 1 and 2 summarize the different protocols and survey outputs of the two surveys. Information common to the two is used to compare survey results and to discuss consistency.

In-water surveys for both programmes needed to be wide-ranging within sites to overcome the fact that the distribution patterns of the target species could be strongly influenced by habitat, and also well-replicated, because invertebrates often aggregate within a single habitat type. However, the two programmes used different techniques to capture the spatial variations. For SPE/IRD, the sampling was designed according to satellite imagery, and the final stock estimates were derived from habitat maps that reflected the spatial distribution of the resource across each of the habitats sampled. For SPC, spatial variation was captured by a multiscale sampling design that sought to view the invertebrate resources initially through a broad-scale survey, before conducting targeted surveys. The approach was adopted because of the limited time allocated for surveying, and the realization that there was a need to develop a simple process for gauging the status of many invertebrate resources, as opposed to estimating the standing stock of just one.

The SPC reef fisheries observation protocol

A suite of methods was used to conduct fishery-independent surveys, and these sought to establish datasets relevant to the wider multispecies scope of the SPC programme. Methods are fully detailed in SPC reports (e.g. for Vanuatu, see Friedman *et al.*, 2008). Broad-scale manta surveys were conducted first to survey large sedentary invertebrates and habitat. The tow-board technique was applied (English *et al.*, 1997) by a snorkeller towed slowly at ~ 2.5 km h^{-1}, for 12 stations per site, split into three sets of four stations; fringing reefs (inner stations), within the lagoon system (middle stations), and in areas most influenced by oceanic conditions (outer stations). Six replicate measures (300 m × 2 m belt transects) per station were conducted. The

Table 1. Protocols for each survey and the availability of resource indicators.

Survey	Duration (d)	Investigators	Target group	Structure	Total clam population (total, commercial, per habitat)	Habitat extent	Clam coverage, density, size	Density, shell length, per habitat	Potential for monitoring (sampling sites, by GPS)
SPC	7	2	Multispecies	Broad-scale survey and local knowledge	No	No	Yes	No	Yes
SPE/IRD	7–10	3–4	Single species	Remote-sensing and habitat	Yes	Yes	Yes	Yes	Yes

Table 2. Survey stations and replicates completed at Raivavae.

Stations/replicates	SPC broad- scale manta assessments	SPC reef-benthos transects	SPC reef-front searches	SPC MOP Trochus searches	SPC sea-cucumber night searches	IRD reef-benthos transects
Stations	12	12	4	4	2	72
Replicate measures	72 transects (300 m × 2 m)	72 transects (40 m × 1 m)	24 search periods (30 min each)	24 search periods (30 min each)	12 search periods (30 min each)	331 replicates

slower speed, reduced swathe, and greater length of tows used within SPC protocols were adopted to maximize efficiency when spotting and identifying cryptic invertebrates, while covering areas that were large enough to make measures representative. Broad-scale manta stations take ∼1 h to complete.

Targeted, smaller-scale surveys focused on particular areas of reef to assess the range, abundance, size (generally length), and condition of invertebrate species and their habitat with greater accuracy. They comprised reef-benthos transect stations (RBt), reef-front search stations (RFs and RFs_w), and mother-of-pearl stations (MOPt or MOPs). These survey stations, each completed within an area covering $\sim 3000-5000\ \mathrm{m}^2$, were selected within areas generally accessed by fishers, were areas deemed representative of suitable shallow reef habitat, or featured in both categories. Other specific surveys focused on target species or species groups not well represented in broad-scale or standard shallow-reef surveys. In general, these other assessments were not relevant to clams, but are listed here for completeness. They included soft-benthos transect stations in or near seagrass beds to assess particular species groups of sea cucumbers (SBt), soft-benthos infaunal quadrats (SBq) to determine densities of infaunal shell beds, and deep-water day (Ds, to 25–35 m) and night searches (Ns, shallow-water inshore reef) for lagoon floor and nocturnal species groups.

Habitat-characterization information was collected for all surveys, using a rapid, semi-quantitative, reef-scape approach. An evaluation was made of architecture and major influences (oceanic influence, topography, complexity, depth), benthos (sand, rubble, boulders, pavement, live hard coral, dead coral), and cover (soft coral, crustose coralline algae, coralline algae, fleshy algae, grass, epiphytes, silt). Habitat was documented for each station by replicate.

The SPE/IRD sampling protocol

In contrast to the SPC multispecies sampling, the protocol applied by the SPE/IRD team was designed to assess giant-clam resources only. Detailed descriptions of the sampling protocols applied for three different atolls and islands are provided in Andréfouët *et al.* (2005a) and Gilbert *et al.* (2006). One team focused on habitat description, another surveyed the clam population along belt transects 1 m wide. Transect length was varied in response to differing *T. maxima* densities, transects being longer when clam densities were lower, but transects were generally 10, 20, or 40 m long. All transects were swum with a snorkel, with a maximum recorded depth of 3 m. Transect orientation was random and not necessarily linear, following clam habitat (e.g. along-patch-reef slope). Transect depth and length were selected according to the type of habitat and the presence of currents. At least three transects were swum per station (average 4.6). Along each transect, all live clams were counted and measured (shell length).

Another major difference with the SPC approach lies in the use of high-spatial-resolution (2.4 m) Quickbird satellite imagery to design the sampling. Selection of the sampling stations was primarily driven by the diversity of colour and texture visible on satellite images to ensure coverage of all reef-habitat configurations. Further, as in Gilbert *et al.* (2006) for Tubuai Island, the stations were selected to account for the different geomorphological units (crests, reef flats, slopes, ridges, lagoon floor patches, fringing reef, barrier reef, back-reef coral patches), exposure to wind and swell, the presence of hard and soft bottom, and the distances to the coast and to the villages.

Habitat characterization was achieved *in situ* using a reef-scape approach: a rapid, semi-quantitative evaluation of benthos (sand, rubble, rocky floor, pavement, live coral, dead coral, algae) and architecture (topography, complexity, coral growth form) was performed (Gilbert *et al.*, 2006). This methodology is very similar to the SPC method of habitat recording and description of habitats, except that here, only point sites (∼10 × 10 m) were described, and there were no records collected along transects because sampling for each station was within a single habitat, by design.

SPE/IRD habitat mapping with high-resolution satellite images

After the fieldwork, a final set of habitat types was retained to provide the best discrimination of clam densities, with the further strong constraint that all habitats had to be mapped accurately using Quickbird imagery (Gilbert *et al.*, 2006; Figure 2). In each case, the satellite image was processed using simple habitat-mapping techniques, as recommended in Andréfouët (2008), which differ from more traditional classification methods (Capolsini *et al.*, 2003). First, the Quickbird image was masked to remove land, deep lagoon, and oceanic areas. Then, the rest of the area was classified using (i) visual-interpretation segmentation and supervised classification for the habitat classes defined by their geomorphology and exposure, (ii) supervised classification for the southwestern barrier-reef flat, and (iii) contextual editing to remove any errors that could be spotted using simple rules of spatial organization between habitats. As we considered only the shallow areas of the reef system (0–3 m), no depth-correction algorithm was necessary (Andréfouët *et al.*, 2005a; Gilbert *et al.*, 2006). The final map was composed using the different habitats with clams at differing densities, sedimentary areas without clams, and geomorphological structures without clams but of interest on a reef-habitat map (e.g. fringing reef flat).

The final habitat map provided the spatial distribution of clam densities. Surface areas of each habitat and clam densities per habitat allow estimation of total stock with a 95% confidence interval (*CI*; Andréfouët *et al.*, 2005a). Moreover, biomass (shell and flesh) and flesh biomass were estimated per habitat and for the entire island as in Gilbert *et al.* (2006), using biomass vs. length relationships established for two atolls.

Results

SPC survey

The sampling stations and surveys at Raivavae (Figure 3) yielded data on a number of species or species groupings (groups of species within a genus). Among these were four bivalves, eight gastropods, six sea cucumbers, three urchins, one sea star, and one cnidarian. Although the reefs at neighbouring Tubuai Island hold both elongated clam (*T. maxima*) and fluted clam (*Tridacna squamosa*; Gilbert *et al.*, 2007), only *T. maxima* was recorded at Raivavae. Records from broad-scale sampling using the manta tow-board technique revealed that *T. maxima* was widely distributed at Raivavae because it was found at all 12 manta stations, and on 66 of the 72 transects. The shallow reef habitat suitable for giant clams was extensive within the lagoon and on the back reef.

Despite the presence of some non-suitable habitat, the overall average station density recorded for *T. maxima* was 0.16 ± 0.05 s.e. clams m^{-2} (Figure 4, top panel), with the range of average densities varying markedly across stations (from 0.001 to

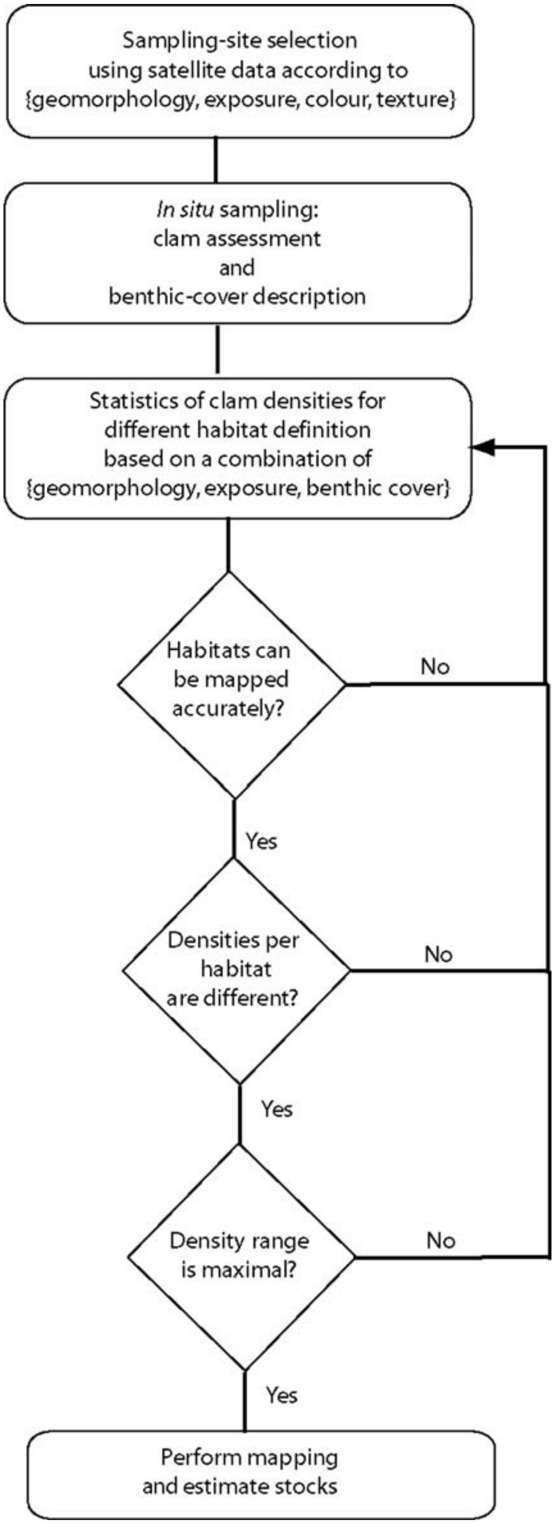

Figure 2. Flowchart summarizing the different steps required by the remote-sensing-based approach. The final typology of habitats needs to be mapped accurately, providing habitats as different as possible in terms of clam density, and those habitats should cover the range of densities observed in the field.

0.67 clams m^{-2}). The lowest mean densities were recorded at the reef fringing the main island (average density $<$0.03 clams m^{-2}) and at the northern sections of the lagoon (average density 0.06 clams m^{-2}), clams being most common in the southwest, on mid-lagoon patch reef and the back reef leading to the barrier (average density 0.23–0.67 clams m^{-2}).

Based on the findings of the broad-scale survey, reef-benthos transect surveys (RBt) targeted a range of shallow-water reef habitats suitable for giant clams (Figure 4, middle panel). The density of *T. maxima* ranged from 0.05 to 2.79 clams m^{-2} for the 12 stations assessed (overall mean density 1.60 ± 0.31 s.e. clams m^{-2}). The highest density was in the southwest on the shallow reef that stretched towards the lagoon behind the barrier reef. There, the mean density for five shallow-reef stations was 2.40 ± 0.09 s.e. clams m^{-2}, and the greatest density recorded was 3.60 clams m^{-2} over a single transect of 40 m^2.

Densities of clams on reef-front search walks ranged between 0.02 and 0.26 clams m^{-2} in the surge zone just behind the reef crest of the barrier (average station density 0.10 ± 0.01 s.e. clams m^{-2}). Outside the lagoon, searches along the reef fronts and slope (reef front and mother-of-pearl searches) returned average densities of 0.03 ± 0.01 s.e. clams m^{-2} on snorkel (RFs) and 0.01 ± 0.00 s.e. clams m^{-2} on scuba transects (MOPs).

Shell-length records from reef-benthos transect stations was 14.9 ± 0.1 cm ($n = 1675$; Figure 5). At RBt stations, clams $>$12 cm in size (the legally harvestable size) made up 70.6% of the population, and clams $>$18 cm just 8.1% of the population.

SPE/IRD survey

The location of the SPE/IRD sampling sites is shown in Figure 3. As at Tubuai Island (Gilbert *et al.*, 2006), an optimal gradient of habitat vs. clam density was achieved when data were pooled from different stations based principally on their exposure (i.e. sector of orientation of barrier-reef units) and the geomorphology (barrier-reef flats, crests, lagoon patch reefs, back-reef ridges, passes). Lagoon structures were considered without exposure given their level of protection. However, we did not consider the southwest barrier-reef flat as a single habitat class given the gradient of clam densities observed there. Therefore, cover in pavement, boulder, rock, and topography were considered to achieve a more optimal habitat typology from a clam-density standpoint. Combining geomorphology, exposure, and seabed type (for just the southwest barrier-reef flats) yielded 13 habitat classes of interest for Raivavae, with mean clam-density extrema between 0.06 and 7.40 clams m^{-2} (Figure 6).

We mapped the 13-class habitat typology and associated densities (Figure 7) using high-resolution Quickbird imagery. Errors in mapping could occur at the boundaries between the different seabed types along the southwest barrier-reef flats. However, the changes in floor type were parallel with the crest because they reflected a gradient of hydrodynamic energy. These strong patterns were fairly obvious in Quickbird imagery, and mapping errors seem to be limited to a narrow ecotone band of a few tens of metres. A large part of the lagoon and barrier reef (51.4 km^2) was mapped as "no clam area". This was a sedimentary area of mostly deeper zones. Overall, just 7.4 km^2 of lagoon patch reefs and barrier reef included habitats with clam densities other than zero. Given the areas of each habitat and the clam densities per habitat (Figures 6 and 7), the stock (±95% *CI*s) was estimated at 8.16 ± 0.91 million clams. The distribution of the stock according to the 13 different habitats is shown in Table 3. Some half the stock (~4 million) was located along the southwest barrier-reef flats. The eastern barrier-reef flats, which are intersected by islets

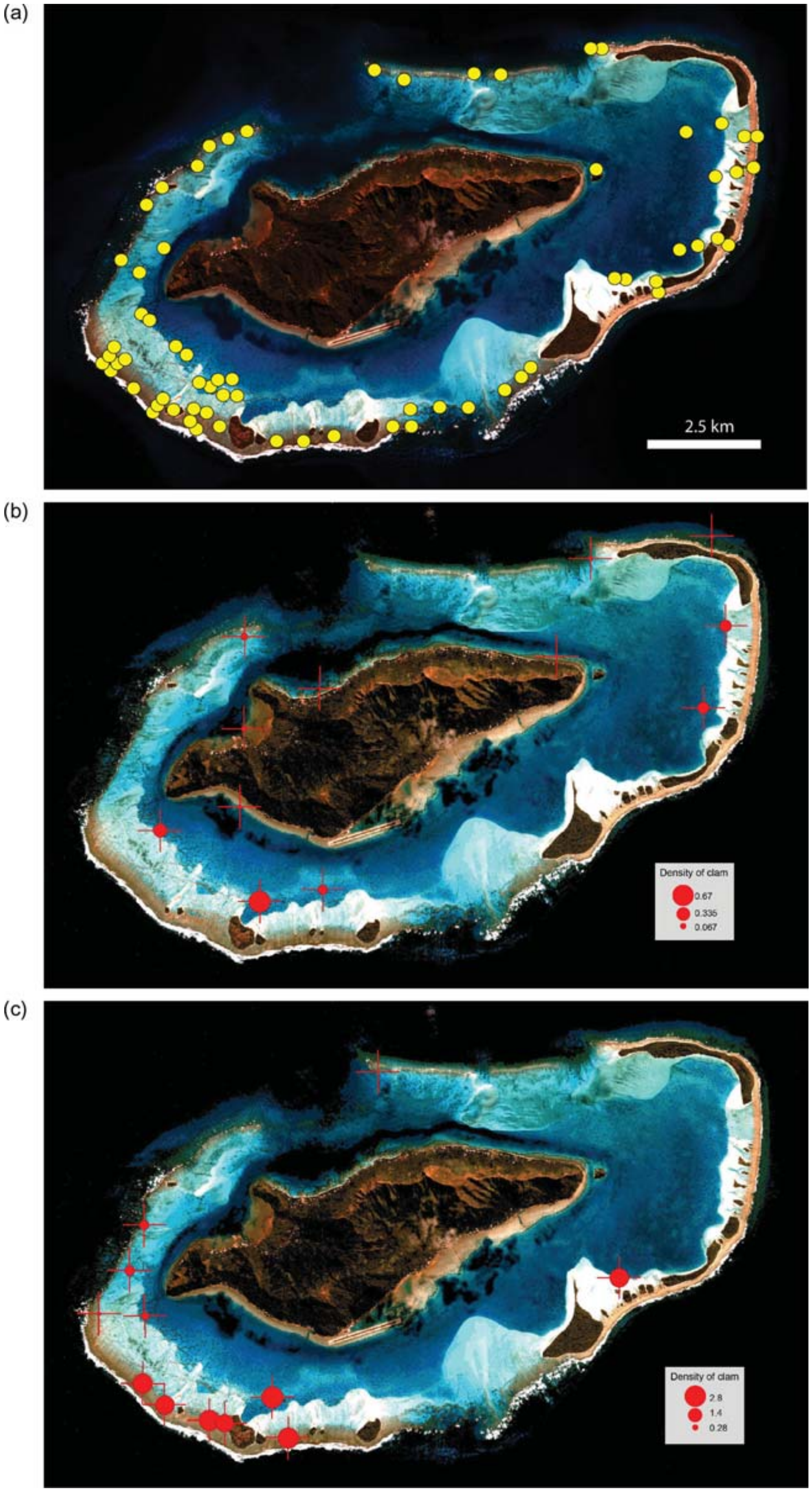

Figure 3. (a) Locator map of SPE/IRD sampling sites (yellow dots, each dot representing several transects). Densities are mapped in Figure 7. (b) SPC manta-clam densities from broad-scale surveys. (c) SPC reef-benthos, transect-station clam densities.

and clam-rich spillways, included two million clams, or 25% of the stock. There were virtually no clams (~1% of the stock) on the northern and western barrier-reef flats. Finally, lagoon patch reefs held ~1.3 million clams. The total estimate does not include shallow-water reef outside the lagoon which is likely to hold clams, so is likely to be a minimum estimate of overall stock size of clams at Raivavae.

In all, 6351 clams were measured during the survey (Figure 5, top). The sample had an average length close to 12 cm (11.7 ± 4.9 cm), and if extrapolated to the entire population, suggests

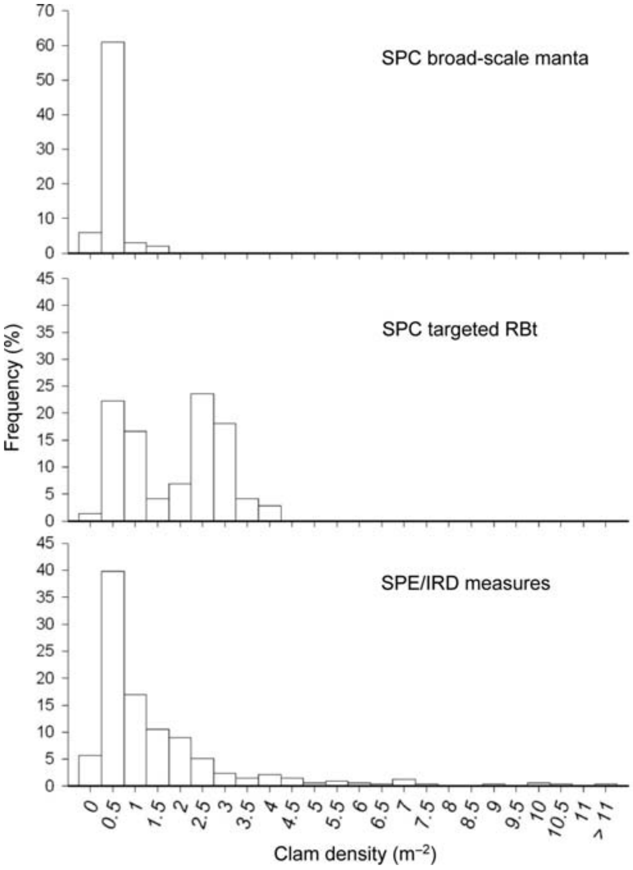

Figure 4. Frequency plot of the density of *T. maxima* at Raivavae. (Top) SPC survey results per 300 m transect, based on the broad-scale manta assessments throughout the reef system. (Middle) SPC survey results per 40 m transect, based on reef-benthos transects (RBt), on barrier and patch reefs. (Bottom) SPE/IRD variable transect-size measures, at all sites with shallow-water transects.

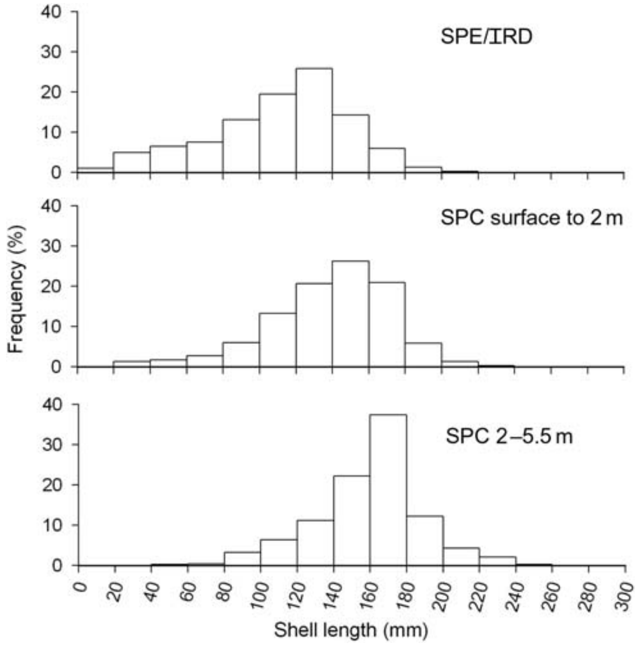

Figure 5. Histograms of the shell length of giant clams according to method and depth. (Top) Clam length frequency from SPE/IRD surveys ($n = 6351$). (Middle and bottom) Clam length frequency from all SPC techniques ($n = 1711$), but separated into depths of <2 m ($n = 1275$) and 2–5 m ($n = 436$).

that 4.87 ± 0.54 million clams (60%) were >12 cm, and hence legally harvestable under current legislation. Using a length–weight conversion factor developed in previous surveys (12% of whole weight, but variable depending on size; Gilbert *et al*., 2006), the flesh biomass was estimated at 354 ± 41 t, including 313 ± 37 t of clams >12 cm (Table 3).

Discussion

The two resource assessments were based on complementary but totally independent investigations. Despite the small size of the island and the lack of direct spatial overlap between the stations investigated, both programmes managed to characterize the island's clam populations consistently. General qualitative conclusions released from both programmes appeared similar and suggested similar management action, although the SPC programme had less clam-specific sampling effort.

Spatial coverage

The SPC sampling design required a broad-scale survey of many different reef zones (24 km linear distance of relevant habitat) along with discussions with local fishers to determine areas for subsequent reef-benthos transect stations. These RBt stations were sited at random within the areas identified, whereas the SPE/IRD survey covered sites selected through an image-driven sampling design. The SPE/IRD design therefore ensured that all habitats were sampled in a more systematic manner. However, the sampling did not include the fore-reef and reef-slope areas because of the lack of scuba infrastructure deployed for the survey, and the difficulty of using spectral signatures from remote-sensing imagery to map the habitat at >3 m deep.

Despite characterizing the fishery-resource location similarly, the SPC survey team did not assess comprehensively all the clam reefs. For instance, only one shallow-water transect station was completed at the more easterly reef, despite it being identified in the broad-scale survey as an area rich in clams. The SPE/IRD remote-sensing and habitat-based approach is reliant on the availability of high-spatial-resolution remote images and human capital, but is designed to avoid spatial gaps that would result in no-data areas when determining the status of the resource.

Density distribution and values

In understanding the number of clams present, both programmes gave a relatively consistent picture of station density for sampling. Both reported their highest and lowest densities in the same locations, but the larger, remotely-sensed driven, sampling effort of SPE/IRD was better able to define inter-habitat differences. This is important, if the goal of the survey is to provide scaled-up stock population estimates based on abundance by habitat.

In comparing the estimates of clam density in the more important fishing areas of the southwest, both programmes gave similar results; the SPC station average (±s.e.) of 2.4 ± 0.11 clams m^{-2} for five stations compared with 2.34 ± 0.63 clams m^{-2} for 17 SPE/IRD stations. However, the SPE/IRD sampling and approach allowed finer characterization across the critical southwest reefs within habitat bands (Table 3, Figure 6).

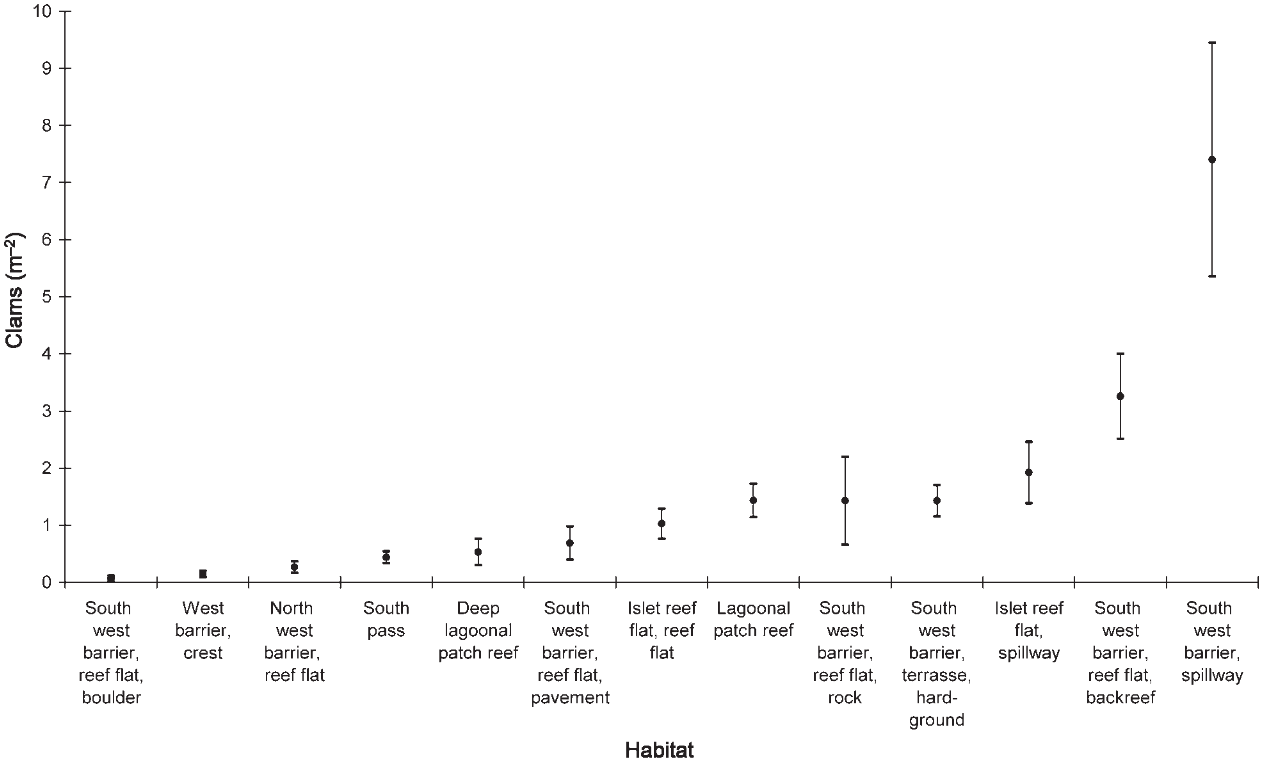

Figure 6. Clam density (mean ± 95% *CI*s) for each habitat class, mapped by the SPE/IRD.

The range of densities was smaller with the SPC than with the SPE/IRD surveys: average values for the latter reached levels of abundance as great as 8.25 clams m^{-2} compared with the 3.6 clams m^{-2} for the SPC. The higher value may be to some extent the result of the smaller scales employed for sampling and the larger sampling programme of SPE/IRD, which covered some areas of dense aggregation at a small scale, with replicates as little as 5 m long compared with the replicates of 40 m for SPC sampling. The greater size of the SPC sampling units increases the probability of sampling both inside and outside the clumps of individual clams, with the consequence that variations in counts would tend to be less (see review by Andrew and Mapstone, 1987). Moreover, the SPC 40-m transects were straight lines, placed across, or oblique to, environmental gradients, and not along reef edges where clam numbers are generally denser. Finally, Mapstone and Ayling (1998) showed how the mean densities from smaller sampling units are often higher because counting biases arise as a result of changes in search intensity. In this case, the search intensity for clams, especially for the smallest size classes (<3 cm shell length), was likely to be less intense for SPC surveying than for SPE/IRD surveying, so that part of the population was possibly underrepresented in the SPC results.

Sampling-unit size

The shallow reef-sampling strategy of SPC (six transects of 40 m^2 per RBt station) differs from the more adaptive design of SPE/IRD, in which the transect number is variable and the lengths of transects decrease in areas of higher clam density. The SPC survey found 40 m^2 transects to be practical for surveys across the Pacific, but it must be noted that the SPE/IRD method originated within French Polynesia, where some atolls have an extremely high clam density (Gilbert *et al.*, 2006). When the precision around the mean for both studies, based on subsets of stations covering ~2880 m^2, is examined, the s.e. for the SPE/IRD results bracketed those from the SPC stations. In detail, SPC's 12 RBT stations had an s.e. of 0.31, whereas SPE/IRD stations 1–48, 26–60, and 49–72 had s.e. values of 0.22, 0.29, and 0.36, respectively. This suggests that for comparable coverage, there is little to choose between the two protocols in generating an accurate estimate around the mean. In fact, the SPE/IRD system seems to be an innovative way of shortening transects in areas of high density. However preferable this adaptive design is when considering the time and cost implications of making longer transects, it must be noted that transects of variable length make ancillary analysis difficult for objectives that lie outside between-site variation analysis, so limits the use of the data at a smaller scale.

Tridacna maxima population size structure and fishery management

In French Polynesia until 2007, only clams >12 cm could be collected from the wild and held. As sizes are recorded systematically by sampled habitat, it is also possible for SPE/IRD to compute and compare the commercial stock by number and weight of individual clams, and this provides a habitat-explicit fine assessment of the harvestable stock. Differences in the proportion of shell length of the legal size classes compared with easily visible, pre-legal year classes collected by both groups are relevant to understanding fishing pressure and can be adopted as a status measure (a trigger point), when deciding on when management

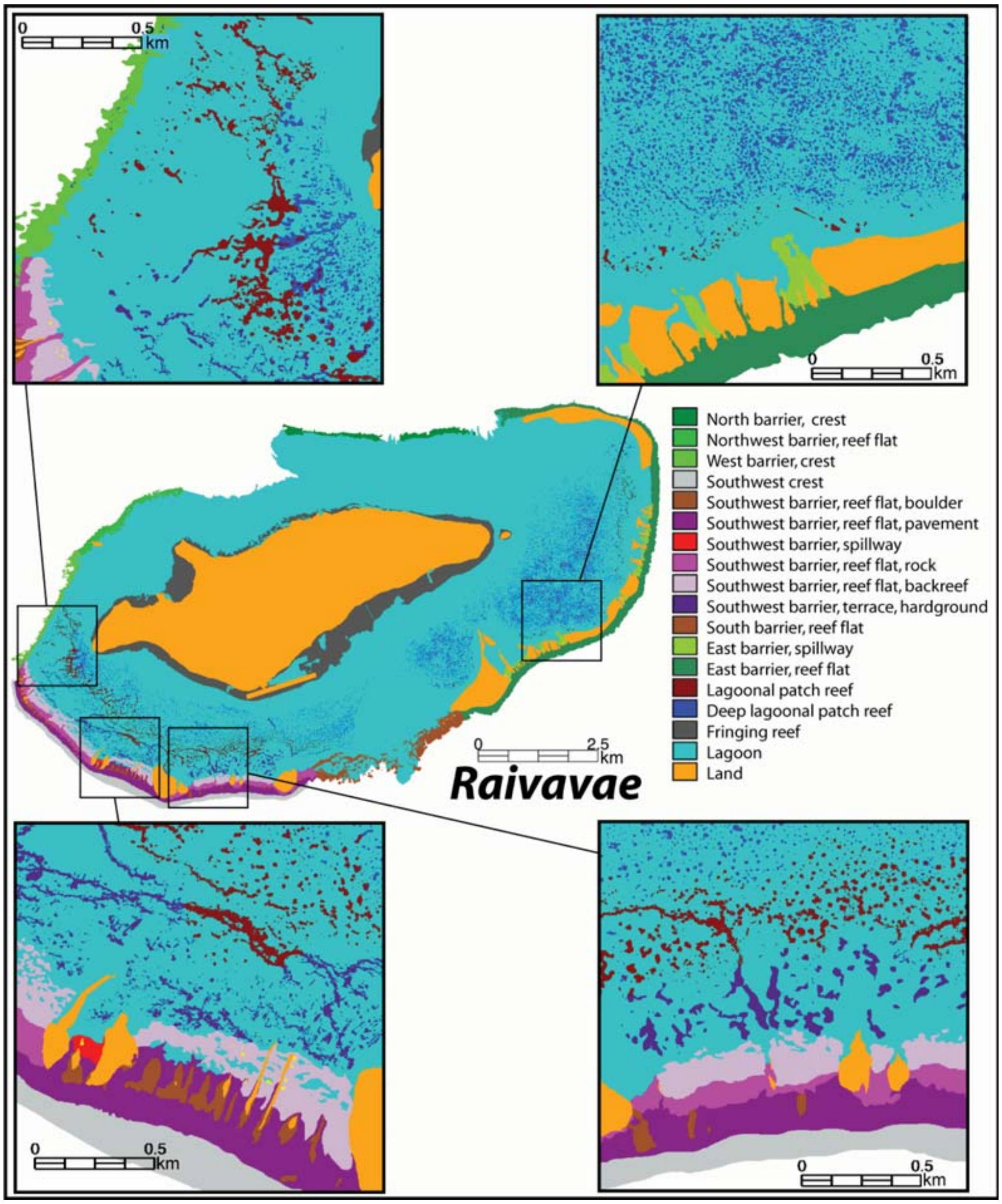

Figure 7. Habitat map, and hence clam-density map (see Figure 6 for values), resulting from Quickbird satellite-image interpretation. Enlargements show different configurations of habitats around the island.

intervention is necessary. Such data are also useful to managers when they assess the period required for stock recovery, if rotational management is applied.

A full range of lengths for *T. maxima* was recorded in both the SPC and the SPE/IRD surveys. Although the maximum length of *T. maxima* at Raivavae (∼23 cm shell length) was the third smallest of 16 countries and territories targeted by SPC (no clams in Nauru), the average length of the elongate clam was 4.5 cm longer, reflecting the mass of the larger legal-sized clams in the population at Raivavae. As at Tubuai, the average size of *T. maxima* at Raivavae was larger than that recorded in atoll lagoons of French Polynesia (Gilbert *et al.*, 2006), and similar to recordings from atoll lagoons in the Cook Islands and Samoa (Chambers, 2007; Green and Craig, 1999). Compared with the other four sites surveyed by SPC in French Polynesia, the average length of clam at Raivavae was 5.2 cm longer (SPC PROCFish/C, unpublished data).

Comparison of population size structure between the two programmes yields valuable insight. Sampling of clam lengths was three times greater by SPE/IRD (Gilbert *et al.*, 2006) than by SPC, and although this level of sampling yields a smoother histogram of shell length, it is time-consuming in the field and may yield little in the way of clear modal peaks associated with year-class recruitment. This is partly because *T. maxima* is one of the slowest growing of all species of giant clam, and year classes tend to become obscured after year 3. In the SPE/IRD study, some 1% of the population was ≤2 cm long, whereas in the SPC surveys, with their larger sampling units, this percentage was only reached by clams ≤4 cm long. The slightly larger average size determined in the SPC study

Table 3. Details per habitat of clam population size and biomass.

	Clam population (number of individuals, top line), and biomass (g, bottom line)		
Habitat	**Total (mean ± 95% CI)**	**≥12 cm (mean ± 95% CI)**	**Proportion of the stock (%)**
Southwest barrier, reef flat, backreef	2 473 463 ± 564 064 95 608 307 ± 21 803 132	1 427 967 ± 325 643 80 899 043 ± 18 448 737	30.3 27.0
East barrier, reef flat	1 617 938 ± 419 444 65 718 276 ± 17 037 188	936 843 ± 242 873 56 951 323 ± 14 764 392	19.8 18.5
Lagoon patch reef	753 169 ± 153 803 34 744 451 ± 7 095 079	509 598 ± 104 064 31 376 764 ± 6 407 372	9.2 9.8
Southwest barrier, reef flat, rock	691 491 ± 372 817 28 890 578 ± 15 576 347	436 328 ± 235 246 25 435 184 ± 13 713 372	8.5 8.2
Deep-lagoon patch reef	651 315 ± 287 292 52 013 699 ± 22 943 042	577 779 ± 254 856 51 344 700 ± 22 647 948	8.0 14.7
Southwest barrier, reef flat, pavement	599 874 ± 254 278 24 355 994 ± 10 324 152	414 728 ± 175 797 22 276 470 ± 9 442 672	7.4 6.9
Southwest barrier, terrace, hard ground	500 789 ± 95 627 17 642 987 ± 3 368 968	270 468 ± 51 647 14 583 576 ± 2 784 767	6.1 5.0
East barrier, spillway	358 251 ± 100 241 6 785 815 ± 1 898 722	85 365 ± 23 886 4 101 667 ± 1 147 677	4.4 1.9
South barrier, reef flat	307 338 ± 73 357 18 217 250 ± 4 348 219	207 795 ± 49 598 16 996 056 ± 4 056 737	3.8 5.1
Northwest barrier, reef flat	85 339 ± 32 158 5 651 435 ± 2 129 610	67 410 ± 25 402 5 426 948 ± 2 045 017	1.0 1.6
Southwest barrier, spillway	71 566 ± 19 815 1 875 007 ± 519 146	27 466 ± 7 605 1 398 318 ± 387 162	0.9 0.5
West barrier, crest	39 181 ± 14 809 2 040 693 ± 771 297	26 773 ± 10 119 1 907 369 ± 720 906	0.5 0.6
Southwest barrier, reef flat, boulder	10 874 ± 8 678 939 348 ± 749 630	9 666 ± 7 714 907 197 ± 723 973	0.1 0.3
All habitats	8 160 588 ± 911 175 354 483 842 ± 41 610 095	4 998 187 ± 577 598 313 604 615 ± 37 688 895	– –

can be explained potentially by the search-intensity factors alluded to above, the smaller size classes (<3 cm shell length) being under-represented in larger transect designs (Mapstone and Ayling, 1998). Additionally, a settlement event could be implicated because the SPE/IRD study was made more than 1.5 years after the SPC study, so the latter survey may have recorded growth of juvenile *T. maxima* that had recently settled but were not picked up by the SPC survey in year classes 1 and 2. *T. maxima* in the Pacific grow an average of 2.35 cm year^{-1}; the average size of a 2-year-old clam has been noted as 2–5 cm shell length (McMichael, 1974; McCoy, 1980; Munro and Heslinga, 1983). Both these factors may help to explain the differences in average clam length noted between the two studies compared here.

Importantly, both studies suggested a similar stock structure, with a dominance of legal shell-size classes (>12 cm shell length), but few large clams (> 18 cm shell length). Otherwise, the less intense level of shell-length measurement conducted by the SPC shows results consistent with the SPE/IRD survey, and the question of adapting sampling by the SPE/IRD will certainly be addressed if new surveys on similar sites are proposed to monitor possible changes in community structure.

Habitat maps and fishery management

The SPE/IRD mapping delivers precise delineation of clam information according to habitat boundaries (Figure 7) and allows for more spatially explicit management of clams based on habitat, something not possible at the same level of precision with the SPC protocol. Such functionality is useful if managers wish to map particular points of interest (e.g. no-take areas) related to habitat. For instance, it has been found recently that some parts of Raivavae lagoon have clams which can induce symptoms of Paralytic Shellfish Poisoning when ingested (T. Darius, pers. comm.). Therefore, habitat-scale mapping for the giant-clam fishery of Raivavae should incorporate fishers and managers and be aligned with the research goals needed to link the fishery to environmental gradients. One needs to consider, however, the material and staff required to define such habitats, which vary greatly between island groups, even within French Polynesia, and are likely to vary with time if an ongoing monitoring programme was to be implemented (Gilbert *et al.*, 2006).

SPC surveys, although designed to be flexible and not incur the costs of remote-sensing, may benefit from establishing first-order stock estimates if sampling was combined with habitat maps. *A posteriori* mapping of survey data (under SPE/IRD protocols) could be tried for sites where sufficient remote-sensing data are available, and sufficient habitat zones have been sampled. It is unlikely that the results will be sufficient for the optimal development of population estimates for many sites because of the non-exhaustive spatial scaling of the information, but the collection of density data across similar habitats in the region may offer useful comparisons for specific resource distributions. The use of satellite imagery would provide a more objective estimate of the representivity of the sampling zone and assist with some scaling estimates for SPC observations if it was delivered for a few key species groups, e.g. the giant clam.

Proposals for managing the Raivavae clam fishery

Not included here is the complementary understanding of clam fishing collected by both SPC and SPE/IRD from fisher questionnaires, which gives an overview of catches and the use of resources (e.g. Kronen *et al.*, 2006). Such questionnaires and the ongoing monitoring of clam-meat exports to Tahiti suggest that at least ~30 t of flesh left the island in 2006. As this represents some 10% of the estimated stock of available clams (>12 cm) from SPE/IRD assessments, evidence-based decision-making for management purpose becomes more pressing and suggests that ongoing monitoring and active controls are warranted.

Based on all SPC observations, the SPC study reached several conclusions at the end of the in-water survey.

(i) The mid-lagoon, patch-reef areas, and especially the shallow-water back reef of Raivavae were highly suitable habitat for the elongated clam *T. maxima*. Clams were not present on all reefs, but densities in the southwest of the lagoon were exceptional for a high-island, open-lagoon environment (Figure 4).

(ii) *Tridacna maxima* displayed a full range of size classes (Figure 5), including the young clams representative of successful spawning and recruitment. The number of large clams in the stock supports an assumption that clam stocks are only marginally impacted by fishing pressure, though clams >22 cm shell length were rare.

(iii) Although no sustainability issues were identified, and the current rate of exploitation presents no critical threat to commercial-fishing sustainability in the short term, a management plan designed to rest certain areas is needed. According to local custom, a system of rotational closures, introduced with local consultation, could operate over variable periods, depending on the state of the reef, i.e. its condition and location, but the system would need to take into account the growth rate, and therefore the time to maturity, of clams. Rotational closures are proposed because clams are relatively slow-growing (~6–8 years old when at their legal size of 12 cm), and recruitment is likely to proceed in pulses, with good years and poor years.

The SPE/IRD concluded the following after their in-water survey.

(i) The spatial distribution of the stock is irregular, and the densities varied greatly between habitats (Figures 6 and 7). Concentrations were highest on the southwest barrier reef and patch reefs, and in several spillways between barrier-reef islets (Figure 7). Clams were not present on all reefs and were absent from fringing reefs and the northern barrier reef. These patterns compare with those found on Tubuai, the only other high island investigated with similar methods, but their generalization to other islands and archipelagos warrants further local investigation.

(ii) *Tridacna maxima* was present at a full range of size classes (Figure 5). This reflects the stock dynamics of past years and indicates a balanced population, with successful spawning but spatio-temporally erratic recruitment. Juveniles, for example, are in many parts of the lagoon, but not everywhere.

(iii) The estimated stock (8.16 ± 0.91 million clams, representing 354 ± 41 t biomass) and its commercial fraction (4.99 ± 0.57 million clams, 313 ± 37 t) do not call for emergency management action. However, if fishers target high-density, shallow aggregations of clams, then the impact on reproductive potential and recruitment could escalate (Orensanz *et al.*, 2006). Therefore, a management plan designed to rest certain high-density areas is required for longer-term management because any increase in fishing pressure attributable to the demand from the Tahiti markets, or concentrated effort in one area, may affect sustainability. Actions could involve implementation of no-take areas such as at Tatakoto Atoll (Gilbert *et al.*, 2005), and as contained in proposed co-management plans by the IRD to SPE for the lagoons of Tatakoto, Fangatau, and Tubuai.

Succinctly, therefore, the general qualitative conclusions of both programmes appear to be similar and to point in the same management direction, even with the less clam-specific effort of the SPC programme.

In developed commercial fisheries, or fisheries centred on a controlled species (giant clam is CITES Appendix II protected) with noted variation in genetic structuring across relatively small scales (Laurent *et al.*, 2002), SPE/IRD data may be considered more appropriate for management, especially when managers wish to predetermine harvest quotas. However, in small-scale inshore fisheries in the Pacific, it could be argued that the simpler, lower-cost approach of monitoring the health of the main fishing areas, coupled with adaptive management, might be preferable, because there are generally few resources available for more complex assessment and timely re-assessment. Additionally, enforcement of any spatially relevant harvest plans would be unachievable, and historical experience shows that once such population estimates have been made, they are difficult to displace if they are not updated regularly. Consequently, they tend to remain a fixture for decades, even when the condition of stocks alters markedly. Management of the clam fisheries of Raivavae (and French Polynesia) should ensure that there is ongoing monitoring to understand the changing dynamics of the stock in relation to fishing pressure. Such considerations, as well as SPC and SPE/IRD recommendations, need to be accounted for in the final decisions that the authorities of French Polynesia will take to manage the resources of giant clams at Raivavae. This will allow careful management and ensure that their exceptional status is maintained.

Conclusions

The SPC sampling strategy couples invertebrate and fish surveys for a range of species with related socio-economic sampling. Datasets have now reached the point where they can be analysed to seek indicators of fishery status across these disciplines for fisheries of importance in the Pacific Islands. Subsequent analysis by both programmes will allow precise positioning of Raivavae in the context of French Polynesian islands (SPE/IRD), and Pacific Islands (SPC) trends in general. In the Pacific Ocean area overall, Raivavae has an exceptionally rich population of clams based on SPC observations, although it does not equal those reported from the closed atolls surveyed by SPE/IRD in Eastern Tuamotu (Fangatau, Reao, Pukarua, Napuka, or Tatakoto), where densities as great as 500 clams m^{-2} have been recorded (Gilbert *et al*., 2005).

The comparison of the SPC and SPE/IRD in-water surveys was the focus of this study. Despite their specificities and differences in scope, the conclusions converged in terms of the status of the clam resource at Raivavae. This is important. In terms of the strengths of the two sampling protocols in making an assessment of clam-fishery status, the small discrepancies in the results are to be expected considering the different sampling design, effort, and time-lag between studies. From the comparison of the two protocols being used at the same site, lessons can be learned and further rationalization proposed for future surveys of Pacific Ocean islands and atolls.

Acknowledgements

This SPE/IRD study was funded by the Government of French Polynesia (Contrat de Développement Etat-Territoire, phase 2), under an agreement between the Ministry of Fisheries and IRD for the SPE/IRD survey. SPC work was supported by the European Union and Pacific Island Governments under the PROCFish/C programme. We thank Frederic Faana, Auguste Faatuarai, and Yann Pareau for assistance in the field, and the mayor, city council, and inhabitants of Raivavae for their hospitality and support.

References

Andréfouët, S. 2008. Coral reef habitat mapping using remote sensing: a user vs. producer perspective. Implications for research, management and capacity building. Journal of Space Science, 52: 113–129.

Andréfouët, S., Chauvin, C., Spraggins, S., Torres-Pulliza, D., and Kranenburg, C. 2005b. Atlas des récifs coralliens de Polynésie française. Report IRD/Service de la Pêche de Polynésie, Nouméa. 38 pp. + 86 Plates.

Andréfouët, S., Gilbert, A., Yan, L., Remoissenet, G., Payri, C., and Chancerelle, Y. 2005a. The remarkable population size of the endangered clam *Tridacna maxima* assessed in Fangatau Atoll (Eastern Tuamotu, French Polynesia) using *in situ* and remote sensing data. ICES Journal of Marine Science, 62: 1037–1048.

Andrew, N., and Mapstone, B. 1987. Sampling and the description of spatial pattern in marine ecology. Oceanography and Marine Biology: an Annual Review, 25: 39–90.

Capolsini, P., Andréfouët, S., Rion, C., and Payri, C. 2003. A comparison of Landsat ETM+, SPOT HRV, Ikonos, ASTER and airborne MASTER data for coral reef habitat mapping in South Pacific islands. Canadian Journal of Remote Sensing, 29: 187–200.

Chambers, C. 2007. Pasua (*Tridacna maxima*) size and abundance in Tongareva Lagoon, Cook Islands. SPC Trochus Information Bulletin, 13: 7–12.

English, S., Wilkinson, C., and Baker, V. 1997. Survey Manual for Tropical Marine Resources. Australian Institute of Marine Science, Townsville. 390 pp.

Friedman, K., Pakoa, K., Kronen, M., Chapman, L., Sauni, S., Vigliola, L., Boblin, P., *et al.* 2008. Vanuatu country report: profile and results from survey work at Paunangisu village, Moso Island, Uri and Uripiv islands and the Maskelyne Archipelago (July to December 2003). Secretariat of the Pacific Community Noumea, New Caledonia. 216 pp. +175 pp. of Appendices.

Gilbert, A., Andréfouët, S., Yan, L., and Remoissenet, G. 2006. The giant clam *Tridacna maxima* communities of three French Polynesia islands: comparison of their population sizes and structures at early stages of their exploitation. ICES Journal of Marine Science, 63: 1573–1589.

Gilbert, A., Planes, S., Friedman, K., and Remoissenet, G. 2007. First observation of the giant clam *Tridacna squamosa* in French Polynesia: a species range extension. Coral Reefs, 26: 229.

Gilbert, A., Yan, L., Remoissenet, G., Andréfouët, S., Payri, C., and Chancerelle, Y. 2005. Extraordinarily high giant clam density under protection in Tatakoto Atoll (Eastern Tuamotu Archipelago, French Polynesia). Coral Reefs, 24: 495.

Green, A., and Craig, P. 1999. Population size and structure of giant clams at Rose Atoll, an important refuge in the Samoan archipelago. Coral Reefs, 18: 205–211.

Kronen, M., Sauni, S., Magron, F., and Fay-Sauni, L. 2006. Status of reef and lagoon resources in the South Pacific—the influence of socio-economic factors. *In* Proceedings of the 10th International Coral Reef Symposium, CD-ROM, pp. 1185–1193. Ed. by Y. Suzuki, T. Nakamori, M. Hidaka, H. Kayanne, B. E. Casareto, K. Nadaoka, H. Yamano, *et al.* Japanese Coral Reef Society, Okinawa, Japan.

Laurent, V., Planes, S., and Salvat, B. 2002. High variability of genetic pattern in giant clam (*Tridacna maxima*) populations within French Polynesia. Biological Journal of the Linnean Society, 77: 221–231.

McCoy, J. L. 1980. Biology, exploitation and management of the giant clam (Tridacnidae) in the Kingdom of Tonga'. Fisheries Bulletin Tonga, 1. 61 pp.

McMichael, D. F. 1974. Growth rate, population size and mantle coloration of the small giant clam *Tridacna maxima* (Roding), at One Tree Island, Capricorn Group, Queensland. Proceedings of the Second International Coral Reef Symposium, 1: 241–254.

Mapstone, B., and Ayling, A. M. 1998. An investigation of optimum methods and unit sizes for the visual estimation of abundances of some coral reef organisms. Great Barrier Reef Marine Research Authority Research Publication, 47. 75 pp.

Munro, J. L., and Heslinga, G. A. 1983. Prospects for the commercial cultivation of giant clams (Bivalvia: Tridacnidae). Proceedings of the Gulf and Caribbean Fisheries Institute, 35: 122–134.

Orensanz, J. M., Parma, A. M., Turk, T., and Valero, J. 2006. Dynamics, assessment and management of exploited natural populations. *In* Scallops: Biology, Ecology and Aquaculture, 2nd edn, pp. 765–868. Ed. by S. Shumway, and G. J. Parsons. Elsevier, Amsterdam.

doi:10.1093/icesjms/fsp148