Village Ecology and Economy of Giant Clams in Fiji: Restoration of a Cultural Resource

Giant clams total seven species in the Indo-West Pacific and are an integral part of village sustenance wherever they occur. Overharvest, coupled with slow growth and the accessibility of their habitat has reduced giant clam population from abundance to scarcity in many areas. Repopulation plans were encouraged in the 1970s by the development of culture techniques to grow giant clams from fertilized egg to a sub-adult size at which they could survive their natural predators on reefs.

Despite this advance, restoration projects for giant clams have remained stalled. Clam farms, established across the tropical Pacific in the 1980s, continue to operate but restoration goals are limited and successes are few. One reason for slow progress is the lengthy life cycle of clams. In Fiji they require 2-3 years of lab rearing, 1-2 years of cage enclosure, and 3-10 years of reef growth before reaching adulthood. Outplanted clams- those placed on reefs after farm rearing - are extremely vulnerable to poaching. If they are not protected from harvest, local fishers often find and consume them before they reach full size.

In this project, we combine basic biology of clam growth, new studies of the scale of clam populations, and new approaches to the sociology of enforcement to effect a new program of giant clam restoration. This model research will create a program which, if successful, can be exported widely to other Pacific locations. This program is poised for success because of the marine conservation infrastructure afforded by village participation in marine managed area programs, which can reduce, perhaps, the overwhelming enforcement costs that slowed clam restoration projects. New techniques in spatial ecology and dispersal monitoring provide the needed influx of key data for decision making. Finally, we will operationalize and test the effectiveness of a new clam protection mechanism that rewards individuals for the long-term protection of clams on their village reefs. This “clam rental” program is the marine equivalent of land leases in terrestrial conservation, and could revolutionize village approaches to protection of long-lived sedentary reef species.

The long farm-life of grown clams reduces production capacity and limits the number of clams that can be placed onto reefs. In the Fijian clam farm at Makogai, for example, one clam spawning produces enough young to fill 5 grow-out raceways for 4 years. The facility has about 20 active raceways, meaning that its yearly capacity is to grow-out the young from one spawning – approximately 500 juvenile clams. Of these, half may survive the cage-growing phase on the Makogai reef, making no more then 250 clams available a year for transfer to villages.

Once in village control, clams may not survive long. At the village of Naigani, for example, out planted clams were taken and eaten. Only three remain in front of the neighboring resort. Low delivery to villages, the long time for growth to adulthood, and traditionally poor area management has reduced successful Fijian gaint clam introductions to a few well-guarded areas, such as Jean Michelle Cousteau’s resort on Vanua Levu.

A shift in the nature of marine protection may signal an opportunity to restore giant clam populations. Fully protected marine reserves have been established throughout the Pacific under a coordinated Local Marine Managed Area program (LMMA). In Fiji, the FLMMA program has established over 177 areas comprising 400 KM^2 (5%) of reef area. These areas have higher levels of enforced protection, and may serve as the best recipients of giant clam juveniles for sub request grow-out. Although enforcement is still a serious problem in LMMA sites, the social and culture framework for area protection seems to afford the best chance for long-term clam survival. In fact, the Fijian clam farm at Makogai is only providing clams to well-established LMMA sites.

This strategy obviates a major shift in restoration strategy. Juvenile clams are best seen, not as meat animals themselves, but rather as the seed source for local village clam production by natural replenishment. Just as a gift of a few cattle or goats can not feed a village for long, but can re-establish a village livestock herd, a set of breeding giant clams in LMMAs may provide for breeding stock needed to replenish local village reefs so that a steady supply of giant clams becomes possible.

But will breeding clams in an LMMA help re-supply local village reef areas? Or will the eggs and larvae of these brood stocks drift so far that they only serve to add to the island-wide population of clam larvae? The answer to this question is crucial for development of clam restoration plans in LMMAs. If clam larvae drift island-wide, then adult clams in LMMAs will not produce local benefits, but will require local resources in the form of constant protection. The socio-economic cost of this protection may be too high unless national resources are made available. By contrast, if larvae settle close to the adults that produced them, then clams protected in LMMAs will produce local benefits that may pay for the effort involved in local protection. These two aspects of clam restoration- the spatial scale of dispersal (and the spatial scale of local benefit), and the village cost of enforcement need to be understood in order for the balance of gain vs. cost to be calculated. In addition, the growth rate, spawning ecology, and ecological interaction of the giant clams in Fiji need to be known so that reef grow-out protocols that minimize time to maturity and maximize larvae production can be established.

A proposal to generate this information would have three major parts: 1) Dispersal scale studies: What are the scales of larval dispersal for giant clams in Fiji? Do local clams generate a local “settlement cloud”? Over what scale is this cloud seen? 2) Micro-spatial ecology of giant clam growth and reproduction: What environmental attributes enhance clam growth? What biological and physical features result in high survival and growth? Is growth density dependent? Is spawning frequency or fertilization success density dependent? Can large clams in fished areas been moved into LMMAs to immediately increase protected stocks? 3) What enforcement efforts are needed to protect clams within LMMAs? What monetary or time costs do these efforts require? What social mechanism will work best to reduce poaching? What national or regional resources are needed or are available to augment local village-level efforts?

A clam-LMMA proposal would entail teams of Fijian researchers and outside collaborators to address each of these questions in detail. The major research endeavors and deliverables will require development in consultation with partner groups at the village, agency and national level in Fiji, plus outside researchers, but the broad outlines might include the following elements.

I. Dispersal scale:

Is there a measurable recruitment cloud surrounding local concentrations of giant clams adults? There are two known concentrations of giant clam adults in Fiji- one in the bay in front of the Makogai clam farm where ~40 adult *Tridacna gigas* and ~50 *T. aquamosa* and *T. derasa* are housed between spawnings. The two villages on Makogai reportedly consume small clams, suggesting the clams within the bay are a local seed source. To test this, we would survey the fringing reef around Makogai to test if juvenile clam density was related to either distance from the clam farm or to prevailing currents from the bay around the island. Currents could be measured by diluted dye studies, drift card studies and interviews with villagers. Local village snorkelers could form a part of the survey team, led by students from University of the South Pacific (USP). Spatial patterns of harvest intensity might complicate this patter because the villages are distant from the farm. Interviews with villagers as to the areas from which they derive the most clam harvest will be conducted to address this variable. *(Deliverable: likelihood that local brood stock will significantly enhance local clam population.)*

A second concentration of adult clams is at Jean-Michelle Cousteau's resort on Vanua Levu. A similar survey effort there could be undertaken, though the influence of village collecting will be less.

A) Measuring the dispersal cloud of clam larva.

Using the brood stock of the clam farm, 100 million clam larvae will be produced in a single spawning of 10 *T. gigas* following seratonin injection following standard farm protocols. The spawning could take place anytime from March – August. Following fertilization the eggs will be tagged with tetracycline and pumped into a large reservoir and boated to a recipient reef site. The reef flat south of Naigani village could be an appropriate recipient site since it is partially enclosed, about ½ sq km, has been the site of local clam harvest and is of local interest as a clam restoration LMMA. The ultimate site will be chosen in consultation with USP researchers who have long term monitoring efforts underway in various areas.

The fertilized eggs will be added to the recipient site on a slack low tide, along with a standard amount of fluorescent dye used commonly for dye-dilution studies in oceanography. 15 minutes later, plankton tows will be down by snorkel in a previously marked grid around the release site. The grid will be oriented depending on prevailing currents, with more stations downstream. The 10x10 grid spacing will be 50m. The grid will be sampled at ¼, ½, 1, 2, 6, and 12 hours and every 12 hours thereafter for 12 days. The plankton samples will be inspected with a UV light for tetracycline-tagged clam larvae and the number of larvae recorded in order to chart the flow of the larval cloud within and out of the area.

On day 8, a grid of passive larval collectors will be place evenly throughout the study site. These cylindrical collectors will be placed on the bottom. Modeled after open water elation collectors, they employ a solution of formalin in a high-density layer at eh bottom to immobilize settling larvae. They will be collected and larvae counted under UV after day 15 in order to chart the settlement cloud generated from the larval release experiment.

The data set will consist of a time series of larval abundances for 12 days along with final larval settlement densities for the clam cohort. One pilot experiment will be conducted in 2007; thereafter it will be repeated as often as practical-up to 6 times per year in different release locations.

(*Deliverable: scale of larval dispersal and decision-making tool for likely local benefits of local brood stock)*

B) Genetic connectivity.

The above two experiments can measure local ecological retention of clam larvae over short (km) spatial scales, but can not establish patterns of connectivity over longer scales appropriate to island-wide or nation-wide movement. To accomplish this we will analyze genetic difference among *T. derasa* and *T. squamosa* populations collected nation-wide. An initial collection under a CI LMMAs work plan by Paul Barber has already been made. Genetic characterization using moderately variable microsatellite SNPsters will compare populations at 1, 10, and 100 km scales. Expansion of the data set would be best accomplished by local collaboration with LMMA operators trained to collect biopsies. *(Deliverable: map of likely connections across Fiji archipelego and limits of ability of brood stock to enhance settlement.)*

C) Surrogate dye studies

Fluorescent dye released during the clam larval addition will be monitored during that study by collecting water samples at every time point and grid point used in plankton samples. Data on dye concentration will be collected using a USP fluorometer, and used to construct a time series of dye dispersion. This cloud can be compared to the larval cloud. If water and larval movement patterns are similar then future dispersion studies can be conducted with dye alone. If water and larvae move differently, then the comparison in this experiment will help create a model with which dye studies can be used to infer larval movement. Our expectation is that larvae will tend to move less then dye – but a demonstration of this has never been attempted.

Once this relationship between dye and larval movement has been established, dye studies can be used to understand the level of predicted larval retention in current and proposed LMMA sites. Because the dye studies will originate at USP, this institution will be able to replicate and analyze the results at times and in settings best suited to local management. In particular, these studies plus the replicated larval releases may be able to answer the question of whether successful LMMAs are those that naturally retain larvae, or whether, these LMMAs are successful because they favor survival of larvae transported from else where. *(Deliverable: protocol to estimate larval retention rate for an LMMA)*

II. Ecology of growth and reproduction:

A) Mapping of giant clams for longitudinal growth and survival inside and outside targeted LMMA sites:

We would map the position of all clams larger then 5 cm. Discovery would be accomplished by local village research aids who would mark live clams with flagging tape. Other village researchers would establish the GPS coordinates of each clam, and number it by discoverer. A third team would measure each clam, note its depth, substrate, and the percent cover of benthos within a circle of 5 m, and count average fish density in the vicinity. Light levels will be recorded using sensors developed for fish tagging.

Maps will be made in *tabu* areas under village restrictions and in adjacent areas open to fishing. The area surveyed will vary depending on village participation but at least 100 clams should be part of each mapping exercise inside and outside *tabu* areas.

Clams will be re-visited 3 and 6 months later and re-measured along with benthic cover and fish densities. Afterward, all clam and habitat data will be gathered every 6 months. New clams in the area can be added to the study by offering a bounty for their live discovery. After one year and then annually thereafter, data will be used to determine what significant biological or physical features of the environment correlate with giant clam growth and survival. This information will show the best local environment for clams, an answer that may vary from village to village. Size dependent growth and survival data will be used to build a demographic model of giant clam populations. This model will be able to answer the question "How many clams of size x need to be added to the reef so that an adult clam of size y is likely to result?" This is a key question that may largely determine whether restoration of a spawning stock of clams is feasible in a particular area. *(Deliverable: optimal habitat village by village to grow clams plus estimate of time and stocking density needed to produce clam brood stock.)*

B) Spawning ecology:

Single giant clams can reproduce because they are hermaphrodites. However sperm are released before eggs, and it may be the case that a solitary animal has low self-fertilization. It also may be true that self-fertilized eggs are less fit. As a result, successful fertilization may require groups of spawning adults. To test this, spawning trials would be conducted with brood stock gathered from village reefs such as that in Dravuni, Kadavu where clam abundance is high. Adult clams will be gathered in groups of 1, 3, 5 and 10 and induced to spawn with seratonin injections. Fertilization success will be monitored by capturing eggs with plankton net, washing off ambient sperm with seawater and scoring percent developing eggs at 1 hour, 6 hours and 24 hours. In other free spawning animals, too much sperm generates polyspermy that kills embryos, so a decline in developing embryos at the highest clam density is a possibility. This experiment will probably be current dependent and will be repeated at slack, moderate, and strong current conditions. *(Deliverable: optimal density to raise brood stock to enhance fertilization.)*

C) Density dependent growth:

If clams are brought together for culture and spawning does this decrease their growth rate? Clams are so rare that the experiments described in (A) are unlikely to be able to detect density dependent growth. To accomplish this, experimental clam areas will be constructed with different densities. Half of the clams marked in section (A) in non-LMMAs will be moved after one year of monitoring to adjacent LMMAs and placed in the environment that the first year's work suggests is optimum. (The other half will continue to be monitored as described in A). They will be placed in groups of 1, 2, 5, and 10 spaced as closely together as possible. Subsequent growth and survival will be monitored every 6 months to test for density dependence. *(Deliverable: Optimum density to raise clams on village reefs.)*

III. Social economies of clam protection

The major value of giant clam culture on reefs is the low maintenance required for this important cultural and dietary resource. Clams require no exogenous feeding, and their ability to use sunlight as food -- in partnership with their algal symbionts – allows them to grow well even in low-nutrient coral reef settings. Harvest of clams is straightforward – requiring only gathering from shallow reef areas. It is in the protection of these long-lived animals that major social costs are seen.

Clam growth requires years. Maturity is reached in 5-10 years in the common reef species, but large adult size is not achieved until 10-20 years of age. In Fiji, farm grow-out over five years brings a clam to about 5-10 cm. in shell width. Maturity and adult size thus require continuous protection of clams for an additional 5-15 years. During this time, any poacher can find and kill a clam, wasting all the effort put into its husbandry. On the other hand, social structure and traditions may decrease the likelihood of poaching in certain areas under specific circumstances.

A successful clam restoration project must understand the costs and benefits of protecting clams during their adult lives. Our work will explore these costs in three complementary enforcement regimes that vary with respect to their reliance on 1) traditional *tabu*, 2) economies of scale in LMMAs, and 3) novel market-driven instruments designed to facilitate entrepreneurial resource protection.

First, the products of sections I and II of this project will provide a growth/survival schedule for giant clams and the time required for growth. The question posed in this section of the proposal is: What costs are associated with clam protection for this period of time?

Costs are likely to be different for different compliance systems, as will be their effectiveness. Effectiveness is measured as a decline in mortality of protected clams compared to unprotected clams. Costs will be measured in ways dependent on the protection method.

A) Village *tabu* system:

Currently villages can declare certain species *tabu* – off limits to hunting. Such systems have been a traditional source of local management, but the large amount of time needed for clam growth and the difficulty in policing a *tabu* system has resulted in very little success in clam restoration projects around the Pacific. Areas in Fiji under this type of management – if any – are expected to have low enforcement cost but little effectiveness.

B) Marine Managed Areas:

Inside LMMAs, all species are protected, and the cost of protection is therefore spread out over all the benefits of all the species. However giant clams require special enforcement. Their population numbers are so few that concerted effort by a small number of people for only a short time is necessary to remove a good fraction of a clam population. As a result, 24-hour envorcement is probably needed. The same is true in LMMAs in the Philippines, where protection of LMMA resources -- fish as well as invertebrates – is so important that a local warden keeps night watch.

Unlike fish, however, clams can be stocked at high density. This suggests a strategy of high density placement on carefully guarded reefs. One critical question is whether growth decreases at these high densities and whether the enforcement cost decrease per clam at high density is enough to offset any potential ecological consequences of crowding, or the attractive danger to poachers of creating too good a clam resource. Are there thresholds of abundance or size above which clams suffer increases in mortality? [*need density dependent growth as in IIc*].

Also needed are summaries of enforcement methods for LMMAs in Fiji and an estimate of their cost in person-hours. Are there village governance structures more conducive to effective enforcement? Do LMMAs enjoying high enforcement see a decrease in clam mortality? Are there examples of good LMMA enforcement? What do these examples have in common across villages? [*need survey of LMMAs for enforcement investment, need mortality of clams in different LMMAs*].

C) Individual-based enforcement incentives:

Lastly, we propose a novel enforcement mechanism ideally suited to clam protection that may prove a useful model for other long-lived sedentary species – clam rental. Modern GPS and tracking devices allow accurate mapping of individual clams – much of the ecological work described above depends on this. Individuals in villages could be encouraged to find and mark a set of giant clams on their village reefs. A per-person and a per-family limit would help assure equal distribution among people. Once found, they could be marked with a permanent magnetic ID tag, genotyped with diagnostic DNA tools to assure individual continuity, and entered on a permanent map of the village reef. For clams that survived a given six month period, the ‘owners’ will be paid a rental to be determined by an LMMA panel. Protection will be entirely up to the individual owners. This entrepreneurial approach to conservation has roots in efforts to purchase development right of land and buy back excess fishing boats. It has the major advantage of being easily expandable as a program and can be a paid for in perpetuity with a suitable endowment. Long-lived sedentary species can all be protected this way, from large coral heads to territorial seahorses, to collections of garden eels. However, cost and effectiveness o this novel program are completely unknown and need to be evaluated.

Experimental program:

The main goal of this work is to measure the cost and effectiveness of a variety of different enforcement efforts in giant clam growth on Fijian reefs. The first goal will be to summarize enforcement efforts at 177 LMMA sites through surveys of 1) enforcement plans, 2) village costs in person-hours and expenses, and 3) perceived effectiveness. These studies must be integrated with current LMMA efforts through dialogue.

From this survey, we will identify a set of five LMMAs with low enforcement protocols and ten with high enforcement protocols. Into each of these 15 LMMAs we will place 100 giant clams either gathered from surrounding reef areas or procured from the clam farm at Makogai. Where these clams will come from is not yet clear – one possibility is to move them from inaccessible areas of the reef. Local discussion will be needed to obtain the clams needed here. Once transplanted, clams will be monitored as in the ecological experiments above to measure mortality and growth. Among the 10 LMMAs with high enforcement, clams will be placed widely distributed across the LMMA at five of the sites. In the other five, clams will be clustered in as small a reef area as practical. This will allow comparison of effectiveness in three treatments: areas with low enforcement, diffuse areas with high enforcement, and concentrated areas with high enforcement. Transplantation, marking, and monitoring of clams can be accomplished with a team of locals from each village and outside logistical help from the Principal Investigators. Funds for monitoring and to defray enforcement costs will be required in each village. Differences in village governance structure or geography may make comparisons in an experimental approach difficult.

Lastly, the above results will be compared to the mortality experienced by clams protected under the experimental entrepreneurial conservation scheme. At five villages up to 100 clams will be identified by villagers from reefs under village jurisdiction. Initially, perhaps ten clams per individual or family might be a reasonable limit, though such limits are likely to need local discussion.

Once identified, each clam will be mapped, labeled, and electronically tagged to assure its identity and its size measured. Each six months, the locations of each clam will be re-censussed, the electronic tags read, and each animal remeasured. For each clam that survives the six month interval, the individual who had found the clam and placed it into the map system will be paid a six-month rental amount. Rental rates need discussion with LMMA staff in order to set a fair price that is low enough to have few negative social consequences within villages, but high enough to spark enforcement efforts by individuals.

After two years, the data on survivorship, growth, and cost for all three major experiments described here will be compared.