polypropylene, which prevents fish from breaking the sausages off the headline. Although the 'sausages' are labour intensive to set up, they overcome the necessity of repeatedly cutting clumps of spat apart to prevent stunting. The BPOM farm has completely eliminated the use of lantern baskets, with spat going straight from the spat bag to the 'sausage' and then to the net panel. Trials are currently examining the most cost-effective number of spat in each 'sausage' pouch, and the optimum cleaning regime for these 'sausages', and for net panels with older oysters.

Experimental work on the BPOM farm is also looking at deep-water culture, as a means of reducing the amount of fouling on early-nursery animals. Trials have shown growth rates to be comparable between larger animals held on longlines below 25 m depth, and tended only every six months or more, compared with animals held on the usual sub-surface longline arrays, and cleaned at least every two months. There is far less fouling on the deep-cultured animals, and the type of fouling organisms is noticeably different. Deep culture could therefore reduce the demand for manpower on the farm both in adult grow-out and through all stages of the nursery.

It appears that the high degree of mixing in the well-flushed Marshall Island lagoons ensures that the deep-cultured animals are still supplied with sufficient food and water exchange. In earlier work, Sims (1990) had shown that animals cultured in deep water in Manihiki lagoon showed slower DVM (dorso-ventral measurement) growth, but comparable increases in shell thickness to shallow-water cultured animals, suggesting some food or other limitation in the more stagnant deep water. Recent hydrodynamic and water-quality studies (see Miles Anderson's article in this issue) have confirmed this depletion in the entrapped deep water of this highly enclosed lagoon.

Black Pearls Inc. is also collaborating with a Maryland naval engineering company, Band, Lavis, and Associates, on a US Department of Defence research grant (through the Center of Excellence for Research in Ocean Sciences, or CEROS), investigating the use of non-toxic antifouling coatings of nets and lines. Candidate coatings have been identified, and over the next year these will be applied to various materials, and tested on different pearl farms and at other aquaculture and naval sites.

Under another CEROS grant, BPI is pursuing some early encouraging results in the use of probiotic bacteria to improve growth and survival of pearl oyster larvae and spat, and of other aquaculture species in the hatchery and nursery using both surface seawater, and the nutrient-rich deep sea water available at Kona's Natural Energy Laboratory site.

The ecological sustainability of pearl farming in Manihiki lagoon, Northern Cook Islands

by Miles Anderson [1]

Introduction

Culture of the black-lipped pearl oyster, *Pinctada margaritifera*, in the Northern Group of the Cook Islands began in the mid 1980s. The Ministry of Marine Resources (MMR), with the assistance of international aid donors, has sponsored a series of projects and activities encouraging the reasonable further development and expansion of the Cook Islands' black pearl industry. An integral part of this effort recognises the sustainable use of natural resources as the key to long-term success of the industry.

In 1995 the Asian Development Bank, in concert with the MMR, awarded a technical assistance contract to RDA International Inc. to establish a Lagoon Ecology Monitoring and Management Project (LEMMP) in Manihiki, an atoll in the Northern Cook Islands. The project mobilised in March 1995 under the direction of Dan Cheney with the construction of an environmental research and training centre, the Manihiki Environmental Laboratory (MEL). Technical assistance was provided by Project Manager, Miles Anderson.

[1] Analytical Laboratories of Hawaii Inc. and RDA International

The project concluded in May 1997, and the MEL's operations were handed over to the MMR. This article provides a limited overview of the field work conducted during the course of the project, and reports some preliminary water-quality monitoring results.

Materials and Methods

Overview

The LEMMP work programme was broadly aimed at undertaking environmental assessment of Manihiki lagoon for the development of ecologically-sound pearl farming practices and policies to ensure that the lagoon is managed in a sustainable manner. A baseline survey was conducted and a long-term environmental monitoring programme was implemented that would supply the needed information to meet this goal.

Other surveys contributed to an estimate of carrying capacity for farming pearl oysters in Manihiki lagoon. Studies such as farmed oyster population dynamics, hydrodynamic surveys of water movement in the lagoon and surveys of oyster pathology were among these. A comprehensive study of the population dynamics of wild black-lipped oysters in the lagoon was undertaken in which assessment of size distribution, sex ratios, rates of recruitment, mortality and fecundity were made.

Surveys also quantified impacts to lagoon water quality and sediment as a result of oyster feeding and the generation of organic material from farmed oysters and fouling organisms associated with farming structures. Simple water-quality indicators were identified that reflect the seasonal stratification patterns of the lagoon water and were applied to recommend areas which are most appropriate for farming as well as those which would be most advantageous to dedicate as marine reserves. Also, on-land activities were identified that can affect lagoon water quality and were included in the final recommendations for long-term management of the pearl production industry in the lagoon.

All the data were mapped, and the resulting spatial analysis was made available through a small computerized geographic information system (GIS). This GIS then formed the basis of other surveys such as plankton studies correlating bivalve spawning, and timing and location of spat-collector placement. Analysis of other spatial data led to recommendations such as maximum farming density and the width of a recommended buffer between farms.

Farm impacts on water quality

Three aspects of this work addressed the question of the impact of pearl farm on the environment:

- The potential impact on water quality due to filter feeding by the farmed oysters was assessed using chlorophyll-a analysis.

- The potential for impact on sediments under the farm from accumulation of organic material and metabolic by-products from the farmed oysters and associated fouling organisms was surveyed using sediment-oxygen demand.

- A hydrodynamic survey evaluated the extent to which re-circulation might cause accumulative impacts on water quality.

Reduction in particulates due to oyster filter feeding

A survey was designed to study the impact on the ambient water resulting from its passage over a pearl oyster farm. The extent of removal of phytoplankton is effectively measured by analysis of chlorophyll-a. Since most suspended material is removed from the water as a result of filter feeding, the relative reduction of chlorophyll-a reflects the relative reduction of most of the particulate material in the water column.

The oyster density on four farms used in this survey was determined to be 0.13, 0.19, 0.48 and 0.70 oysters per square metre of surface area using the GIS. A single up-current site was selected as a reference station and three other stations were established on the down-current edge of the farm. Three more were established 100 metres and another three 200 metres down current of the farm. Three control stations were established in an area which was unaffected by farming activity. Water samples were collected at three depths (2, 6 and 20 metres) from each sample station. Current velocities of the water passing across the farms were estimated to be 1 to 5 centimetres per second using diver observation of the distance suspended particles move during a specific amount of time.

The reduction of chlorophyll-a was compared to farmed oyster density. A relative change in phytoplankton concentration after the water passed over the farm was calculated by assigning the up-current station a value of 100% and comparing the down-current stations at each depth.

Sediment oxygen demand

Organic material such as faeces and debris from farmed organisms and biofouling on farm lines, buoys and other farm structures, falls to the sea floor where it decomposes. As the intensity of farming increases, the amount of organic material which rains to the sea floor also increases. The effects of this decomposition on water quality has not been thoroughly studied but there may be some risk of nutrient enrichment in aerobic conditions, or pro-

duction of noxious compounds in anaerobic conditions. The extent of this impact was assessed by measuring the sediment oxygen demand (SOD), the net amount of oxygen which is exchanged as a result of the biological activity associated with the sediment. A survey was established to evaluate the extent to which SOD is altered in areas used for farming black-lipped pearl oysters.

A sample of sediment was collected from an area which was not used for oyster farming and was used as a control. Experimental samples were collected directly under longline farms of varying oyster density ranging from 0.13 to 1.0 oysters per square metre of surface area. The experiment was again conducted using sediment collected under a rack-culture area where oyster farming is far more intense. In areas used for rack culture, farmed oyster densities reach 25 oysters per square metre.

Two standard dilution curves which compared the weight of sediment used for inoculation with the reduction of oxygen in the SOD test were developed. Sediment collected under low-density longline culture was used to inoculate samples for one curve and sediment collected under rack culture was used for the second. The curves were used to select the optimum amount of inoculant that would produce reliable data for each case.

Hydrodynamic considerations

The exchange of water over a marine farm provides the mechanism by which nutrition is brought into the area and by-products are removed. For this reason, as an integral part of the LEMMP, a hydrodynamic survey was completed wherein these patterns were identified and quantified. This work was completed through a cooperative effort between the LEMMP and the South Pacific Applied Geoscience Commission (SOPAC).

A one-month study of hydrodynamic patterns in Manihiki Lagoon was completed. To carry out the surveys three vane-type current metres, a conductivity-temperature-depth probe and a boat-mounted acoustic doppler current profiler (ADCP) were deployed. A global positioning system was used to establish base station positions, position bathymetry and to navigate to ADPC sites.

Results

Reduction in particulates due to oyster filter feeding

Several patterns emerged. At the down current edge of the farm the water that passed above the farm but not through it showed little change (Table 1, Figure 1). The water that passed through the farm showed an approximate 40% decrease in phytoplankton at densities above 0.4 oysters per square metre.

Table 1. Impact on water quality from farmed pearl oysters at the down-current edge from a farm, as a result of oyster feeding, showing the change of chlorophyll-a in water which has passed through and under the farm

	Down-current edge from farm		
Shell density	**2 metres**	**6 metres**	**20 metres**
0.13	7.87%	-0.83%	5.57%
0.19	8.33%	-1.52%	19.05%
0.48	16.67%	-42.67%	33.33%
0.70	9.26%	-40.67%	77.52%
Average	10.53%	-21.42%	33.87%

Table 2. Impact on water quality from farmed pearl oysters 100 metres down-current from a farm, as a result of oyster feeding, showing the reduced change of chlorophyll-a in water which has passed through and under the farm

	100 metres down-current from farm		
Shell density	**2 metres**	**6 metres**	**20 metres**
0.13	-7.92%	0.65%	6.80%
0.19	2.73%	1.67%	0.00%
0.48	9.50%	-4.67%	14.00%
0.70	-33.33%	-33.30%	10.00%
Average	-7.26%	-8.91%	7.70%

Table 3. Impact on water quality from farmed pearl oysters 200 metres down-current from a farm, as a result of oyster feeding, showing the ameliorated change of chlorophyll-a in water which has passed through and under the farm

	200 metres down-current from farm		
Shell density	**2 metres**	**6 metres**	**20 metres**
0.13	-8.47%	-4.76%	-3.84%
0.19	2.77%	2.73%	-0.20%
0.48	-4.11%	-4.68%	-5.88%
0.70	-7.41%	0.00%	7.04%
Average	-4.31%	-1.68%	-0.72%

However, the water that passed under the farm showed an increase in phytoplankton. At a farmed oyster density of 0.7 oysters per square metre, the increase in phytoplankton at the down-current edge was as high as 77% at the deep site. This increase is attributed to increased nutrient levels in the water as a result of metabolic by-products of oyster metabolism and that of other fouling organisms on the farm. Dissolved inorganic nutrient analysis was not available to this project, so this assumption was not tested.

One hundred metres down current from the farms, the impact had decreased significantly (Table 2) and 200 metres down current of the farm the impact was improved (Table 3, Figure 2).

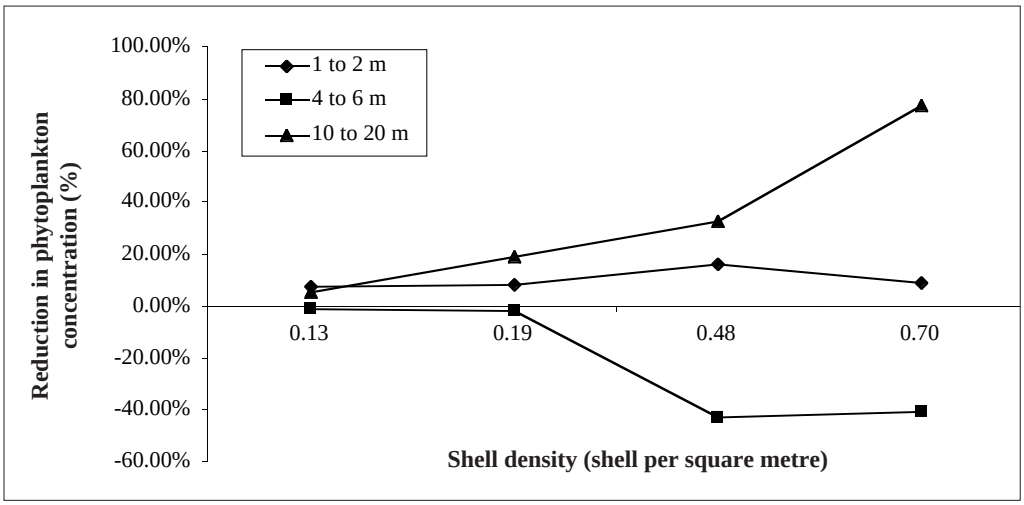

Figure 1: Change in phytoplankton as lagoon water passes over pearl oyster farms of four densities at three depths at the down-current edge of the farms

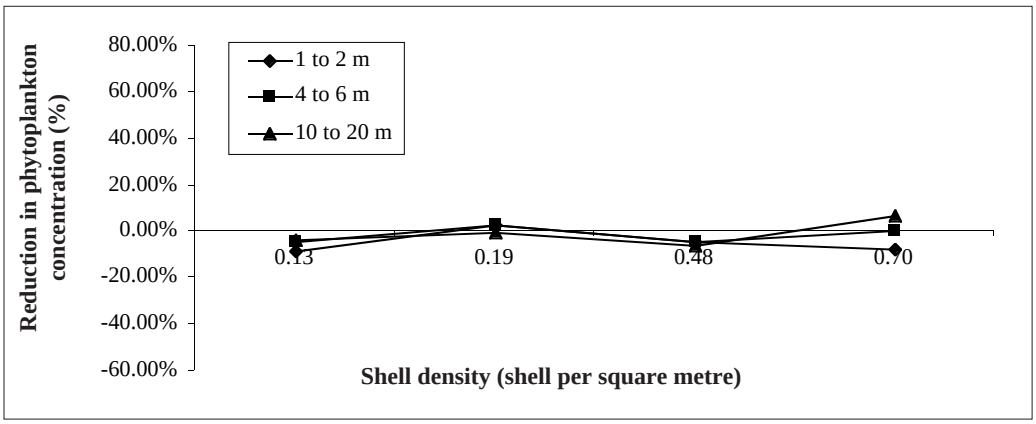

Figure 2: Change in phytoplankton as lagoon water passes over pearl oyster farms of four densities at three depths 200 metres down current from the farms

Sediment oxygen demand

Sediment collected under the farm which supports an oyster density of 1.0 oyster per square metre or less, produced no significant reduction in oxygen when inoculating a standard BOD bottle with as much as 50 grams of sediment. A 40% reduction in dissolved oxygen was measured when 10 grams of sediment collected from under the rack-culture area was used as an inoculant.

Hydrodynamic considerations

It was found that in prevailing trade wind conditions, the upper 27 metres of water in Manihiki Lagoon (the area used for farming black-lipped pearl oysters) exchanges with the open ocean approximately every 60 days and water currents rarely exceed 8 cm per second. This slow exchange and low current velocity is characteristic of closed or semi-closed lagoons.

Discussion

In the last decade, spatial data analysis has become a powerful technique for examining, understanding and displaying environmental relationships in complex data sets. The ability to identify ecological patterns in the context of hydrodynamic, chemical, biological and physical oceanographic properties has improved through the ability to attach data to maps displaying geophysical and man-made features.

The work carried out in Manihiki utilised this enhanced interpretive capability in the process of meeting the goals of the project. Combined with routine data-collection methods, spatial data management facilitated the development of the LEMMP in which ecologically sound black-lipped pearl oyster farming practices were identified to ensure that the industry is managed in a sustainable manner.

The results of the data presented in this paper show that in Manihiki Lagoon, given the prevailing hydrodynamic regime and farmed oyster density at or below 0.7 oysters per square metre, the impacts of the primary productivity and water quality were ameliorated 200 metres down current from the farm. It has also been shown that no discernible impacts existed in the oxygen demand associated with the sediment under a pearl oyster farm wherein farming intensity is maintained at these low levels. In developing a management plan, these data were used to recommend a 200-metre buffer zone between farms and an optimum farmed-oyster density.

When applying the results of this work to estimate the risk of environmental impact from pearl oyster farming in other areas, including other lagoons, hydrodynamic regime must be a primary consideration. Closed and semi-closed lagoons, open lagoons, bays and estuaries, sheltered coasts and open coasts progressively experience more water exchange and thus the risk of detrimental impact to water quality resulting from any perturbation is lessened respectively.

The study in Manihiki Lagoon exemplifies a situation in which the probability of degradation to water quality is exceptionally high due to the low rate of exchange of lagoon water with the open ocean. Therefore, the information presented in this report can be applied with significant margin when comparing it to environments typified by hydrodynamic regimes in which the rate of water exchange is greater.

This discussion represents only a small portion of the surveys that were addressed during the two-year field study. Subsequent to the completion of the LEMMP, the MEL continues to collect water quality and other data on a routine basis. The data is periodically reviewed for long-term trends that contribute to fine tuning the management strategies as the pearl production industry in Manihiki Lagoon matures.

New ACIAR-funded pearl oyster project: pearl oyster resource development in the Pacific Islands

by Paul Southgate [1]

The Australian Centre for International Agricultural Research (ACIAR)-funded project 'Pacific Island Pearl Oyster Resource Development' ran from June 1993 to June 1996 with a further period of bridging finance between July 1996 and March 1997 (see *Pearl Oyster Information Bulletin*, 9: 6-8, 1996).

This project, which focused on the pearl oyster resources of Kiribati, involved James Cook University (JCU) as the commissioned organisation, collaborating with the Ministry of Environment and Natural Resource Development in Kiribati, the ICLARM Coastal Aquaculture Centre (ICLARM-CAC) in the Solomon Islands, Fiji Fisheries and the Secretariat of the Pacific Community (SPC).

The major objectives of the Project were:

- to assess the natural stocks of pearl oysters in Kiribati and Fiji and the rates of spat-fall of blacklip pearl oysters in the atoll lagoons of Kiribati.
- to develop appropriate low-technology methods for hatchery and nursery culture of blacklip pearl oysters.
- to improve the yield of gem-quality and average-quality pearls through better bead insertion and oyster management practices.

During the Project, appropriate hatchery and nursery techniques were developed for *P. margaritifera* and a pilot-scale hatchery was constructed in

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