CHAPTER 12

Pearl Oysters

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I. INTRODUCTION

Two species of the pearl oyster genus *Pinctada* (Table I) are commercially significant to the South Pacific. The black-lip pearl oyster, *Pinctada margaritifera* (Linnaeus, 1758), ranges from Baja California to the eastern Mediterranean Sea (Jameson, 1901; George, 1978: Table II). Black-lip shell is fished throughout the region, and black pearls are cultured in French Polynesia, the Cook Islands, Fiji and Okinawa. *P. maxima* (Jameson, 1901), the gold-lip or silver-lip, ranges from Burma to Solomon Islands. It is cultured for white pearls in Australia and South-east Asia. Gold-lip has also been cultured at various times in Papua New Guinea, Solomon Islands, Palau and Tonga (George, 1978; Uwate, *et al.*, 1984). The two species are distinguishable by colour (Hynd, 1955); *P. margaritifera* has a black external shell surface and black non-nacreous border, where *P. maxima* is yellow, gold or silver.

The winged, or brown-lip pearl oyster, *Pteria penguin*, is fished for shell in Solomon Islands (Philipson, *unpubl. data*). It can produce half pearls, although early culture trials in Tonga were unsuccessful (Uwate, *et al.*, 1984). A smaller species, *Pinctada maculata* (Gould, 1850), is also found through the Pacific islands (Hynd, 1955) and is fished in some areas for the small, baroque natural pearls. The shell is of no value, however, and there is little potential for culture of the species. *P. albina* (Lamarck, 1819) is cultured in Shark Bay, Western Australia (Hancock, 1989) and *P. radiata* (Leach, 1814) culture is being tried on the Australian Great Barrier Reef. However the potential for culturing these species in the Pacific islands is not known.

II. LIFE HISTORY AND POPULATION BIOLOGY

HABITAT

P. margaritifera occurs in lagoons, bays and sheltered reef areas to around 40 m depth, but is most abundant just below low-water. Strong byssal threads attach the oyster to rocks or other oysters. *P. maxima* is occasionally found on reef flats but its greatest abundance is between 10 m and 60 m on the open shelf

Table I. Species of the pearl oyster genus *Pinctada*.

SPECIES	SYNONYMS	DISTRIBUTION
margaritifera (Linnaeus, 1758)	*cumingi* "Black-lip"	Indo-Pacific: from Mexico to Tanzania and Red Sea
maxima (Jameson, 1901)	*margaritifera* "Gold-lip" "Silver-lip"	Australia South East Asia P.N.G., Solomon Is.
maculata (Gould, 1850)	*pitcairnensis* *panasesae*	Pitcairn Is., Polynesia Central west Pacific, Indian Ocean, and Red Sea
fucata (Gould, 1850)	*vulgaris* *muricata* "Ceylon" "Lingah"	Ceylon, India, S.E. Asia Australia and Red Sea, Mediterranean[1]
fucata martensii (Dunker, 1872)	*muricata* "Akoya" "Japan Lingah"	Japan, Korea and China
radiata (Leach, 1814)		Arabian Gulf, Red Sea Mediterranean[2]
albina sugillata	*sugillata* *irradians* *fimbriata* *scheepmekeri* "Bastard pearl oyster"	Eastern and Northern Australia, S.E. Asia India
albina albina (Lamarck, 1819)	*imbricata* *carchariarium*	Shark Bay, West Australia
imbricata	*radiata* *fimbriata* *albina*	Carribean Americas Florida, Yucatan
chemnitzi (Philippi, 1849)		Australia, India China Sea and Japan
atropurpurea (Dunker, 1852)		India
anomioides (Reeve, 1857)		India
nigra	Dubious status	Red Sea
concinna	Dubious status	Japan
simizuensis	Dubious status	Japan

[1] Early Lessepsian migrant [2] More recent Lessepsian migrant

Table II. Sub-species of *P. margaritifera*.

SUB-SPECIES	DISTRIBUTION
typica (Linnaeus)	Ryukyus, Taiwan, Australia, Micronesia and Melanesia, including Fiji.
cumingi (Reeve)	Cook Islands French Polynesia
mazatlanica (Hanley)	Baja California Panama Bay
erythraensis (Jameson)	Red Sea
persica (Jameson)	Persian Gulf
zanzibarensis (Jameson)	East Africa, Madagascar, Seychelle Islands
galtsoffi (Bartsch)	Hawaiian Archipelago

areas of continents and large islands (Hynd 1955). *P. maxima* juveniles are anchored by byssal threads, but lose their attachment in later life.

Pearl oysters are non-selective filter-feeders (Mansour and Gabal, 1980; Nasr, 1984; Chellam, 1987; Jacob *et al.*, 1980). High turbidities may exclude *P. margaritifera* from closed lagoons or from areas of heavy terrestrial run-off. Temperature limits both species to warmer tropical regions.

Lagoon water quality influences sizes, growth rates, and shell colour and quality in *P. margaritifera* (Galtsoff, 1933; Anon, 1956c; Ranson, 1957; Domard, 1962; Service de la Peche, 1970). Strong currents also promote faster shell growth (Kent, 1890; 1893; Galtsoff, 1933; Kafuku and Ikenoue, 1983).

REPRODUCTION

P. maxima and *P. margaritifera* generally reach maturity at two years of age. Initially, the majority are males, but protandric sex changes usually result in an even sex ratio by the fourth or fifth year (Millous, 1977).

Temperature is the main influence on sexual development and spawning patterns (Tranter, 1958b; Millous, 1980; M. Coeroli, *pers. comm.*). Spawning is usually not limited to distinct seasons and protracted spawnings may occur throughout the year. The period of greatest spawning intensity for *P. maxima* is summer (Tranter, 1958b). *P. margaritifera* usually exhibits two periods of maximum spawning (Tranter, 1958a; Coeroli *et al.*, 1982). Marked seasonal temperature changes produce more discrete spawnings in higher latitudes.

RECRUITMENT

The planktonic larval stage in *P. margaritifera* may extend to four weeks (Coeroli *et al.*, 1982), but it is somewhat shorter (around three weeks) in *P. maxima*. The larvae are obligate planktotrophs after one or two days. *P. margaritifera* and *P. maxima* larvae have relatively narrow physiological tolerances. Larvae settle out onto suitable available substrate, but retain some motility before beginning to secrete byssal threads.

Age-fecundity patterns, density-dependent effects, and larval and juvenile survival rates are not well understood. Larval drift patterns are difficult to predict, and wind-driven eddies may cause highly patchy spat-falls in enclosed lagoons. Spat-collector records for *P. margaritifera* (Coeroli *et al.*, 1982; Cabral *et al.*, 1985; Sims, *unpubl. data*), and observations of wild stocks (*e.g.*: Hornell, 1914; Alagarswami, 1977) suggest that recruitment fluctuates from year to year. Crossland (1957), however, obtained consistently high *P. margaritifera* spatfalls, throughout the year, over a 14-year period on collectors in the Red Sea.

GROWTH

Growth rates vary markedly among individuals, and among locations (Chellam, 1978; Yoo *et al.*, 1985; Sims, 1990b). Representative von Bertalanffy parameters are around K = 0.52, and L_∞ = 155 mm for cultured *P. margaritifera* (Sims, 1990 b). L_∞ is between 200 mm and 250 mm for *P. maxima* (Sagara and Takemura, 1960; R. Dybdahl, *pers. comm.*).

The rapid initial growth results in shell diameters between 100-120 mm after two years in *P. margaritifera* (Coeroli *et al.*, 1982; Sims, 1990b) and 100-160 mm for *P. maxima* (Sagara and Takemura, 1960; R. Dybdahl, *pers. comm.*). Subsequent growth consists mainly of increasing shell thickness, with the oyster continuing to secrete nacre (the pearl material) throughout its life.

Growth rings have been found in shell sections of *P. maxima* from north Western Australia (R. Dybdahl, *pers. comm.*), where there is a marked annual temperature variation. Rings have not been found in shells from other locations or in other pearl oysters (Hynd, 1955; Chellam, 1978; Sims, 1990b).

MORTALITY

Pearl oysters suffer greatest mortalities as larvae and immediately after settlement. Predation in the plankton is high, and many spat are carried by currents away from suitable benthic habitats. Juvenile predation produces skewed or bimodal size-frequencies (Galtsoff, 1933; Sims, 1989). The large growth processes in juvenile *P. maxima* and *P. margaritifera* are for protection from predators (Crossland, 1911) and are less pronounced in the smaller, faster-growing *Pinctada* species.

Predation by fish, octopii and gastropods is the main cause of natural mortality (M) in adults (Herdman, 1903; Shipley and Hornell, 1904; Allen, 1906; Crossland, 1911; 1957; Reed, 1966; Intes, 1984). Intes (1984) used M = 0.1 - 0.2 as an approximation for *P. margaritifera*, with a life-span of up to fifteen years. Sims (1990b) estimated natural mortality of *P. margaritifera* at 0.11.

Shell borers include sponges (*Cliona* sp.), bivalves (*Lithophaga* spp.) and polychaetes (*Polydora* spp.) (Coeroli, 1983; Reed, 1966; Crossland, 1957). *Polydora* infested 75 per cent of *Pinctada margaritifera* cultured in Palau (Takahashi, 1937). Older oysters are more prone to borer attack, but regular shell cleaning can reduce the problem on farms (Mohammad, 1972; 1976).

III. THE FISHERIES

PEARL SHELL FISHERIES

P. margaritifera and *P. maxima* are the largest species in the genus, with thick nacreous shells (Mother-of-Pearl, or MOP). Pacific Islanders traditionally used pearl shell for fish hooks, tools and ornaments (Hedley, 1899; Beaglehole and Beaglehole, 1938; Skinner, 1935; Macgregor, 1935; Buck, 1932). Today it is used in jewelry and the button industry.

Commercial fisheries for black-lip shell have flourished periodically throughout its range. The most productive lagoons are in the Tuamotu-Gambier Archipelago of French Polynesia and the northern Cook Islands. Black-lip shell is also produced in notable quantities in Solomon Islands, Fiji, and Papua New Guinea (Table III).

Methods: Free-diving is still the main method used in most Pacific fisheries. Shot-lines are used in Polynesia to aid descent and ascent, allowing some divers to reach 40 m (Sims, 1989). Hard-hat and hookah diving machines were once widely used, but their use is now generally proscribed.

Markets: The South Pacific and Australia provide perhaps one quarter of all MOP, including trochus shell (Philipson, 1989). Worldwide annual production of MOP from pearl oysters is around 1,200 tonnes (*ibid.*).

Table III. Annual pearl shell exports (in tonnes) from the South Pacific and South-east Asia.

	YEAR							
COUNTRY	1980	1981	1982	1983	1984	1985	1986	1987
Cook Islands	11	35	46	34	111	106	91	114
French Polynesia	22	19	27[1]					
Solomon Islands	7	9	26	20	46	17	38	39
Fiji	13	35	7	11	13	10	12	23
Palau/FSM	10	-	-	3	2	3	11	-
Papua New Guinea	8	5	1	13	6	4	5	16
Indonesia	555	770	601	585	449	323	388	
Philippines	381	278	252	292	245	99	137	

[1] Data from Intes and Coeroli (1985): no data available beyond 1982. All other data from Philipson (1989).

Annual pearl shell production from the South Pacific region is valued in excess of US$1 million. The value of pearl shell has increased over the past decade. Black-lip shell from Solomon Islands, for example, has increased from US$741 per tonne in 1981 to US$5,531 per tonne in 1989 (Skewes, 1990). The long-term prospects for continued high returns are good, with the limited supply making price declines unlikely.

Expanded production of button blanks within the region could double the value of shell exports as most shell is currently exported unprocessed (Philipson, 1989). In addition, some potential exists for export of dried pearl oyster meat to the South-east Asian market.

PEARL CULTURE

Natural pearls are rare in *P. margaritifera* and *P. maxima*, but both species produce large cultured pearls. Pearl culture developments have wide-ranging benefits to farmers, island communities and national economies, yet require minimal capital or technical support. In the Cook Islands, one local family began spat-collecting and shell culture in 1982. By 1990 there were more than 100 local farms on Manihiki alone (Sims, 1990a).

Pearls are the ideal export commodity: they are non-perishable, shipping costs are negligible, and lucrative markets are well established.

Methods: Pearl culture was first developed by the Japanese early this century (Matsui, 1957; George, 1978; Hollyer, 1984). The general principles of culture and grafting were first "kept in absolute secrecy" (Wada, 1953 in George, 1969), but have since become more widely known (Tranter, 1957; George, 1969; 1978; Mizuno, 1983; Coeroli and Mizuno, 1985). Techniques for spat collection and culture have been described for *P. maxima* (George, 1978; Dybdahl and Rose, 1986), and *P. margaritifera* (Crossland, 1957; Reed, 1962, for the Red Sea; and Service de la Pêche, 1970, Coeroli *et al.*, 1984, and Sims, 1988a and c, for Polynesia). (Also *P. fucata martensii*, in Kafuku and Ikenoue, 1983, and Hollyer, 1984; and *P. fucata*, in Alagarswami, 1987).

Black-lip culture techniques for the Pacific were first developed in French Polynesia. Spat-collectors consist of bundles of local hardwood, nylon rope, gauze or plastic sheet strung on sub-surface lines (Fig.s 1 and 2). Juveniles are also collected from wild stocks by diving. Adults are placed in panel-net pockets, or drilled and tied to lines. These are then suspended from platforms on the bottom, or from floating rafts or buoy-lines (Fig. 3).

First seedings occur around two years of age. The pearls are harvested after 18 months or 2 years, when the nacre coating on the bead is around 2 mm thick. Individual oysters may be reseeded and can produce up to 3 pearls during their life. Experienced Japanese technicians generally provide best results, and are still used widely throughout the industry.

Markets: Current annual production from the Australian and French Polynesian culture industries is valued respectively at over US$70 million and US$40 million (based on Japanese import values, 1989: Table IV). The Cook Islands industry is currently worth US$4 million annually.

Demand for pearls is increasing. Black pearl values could further improve as expanded production increases product awareness.

IV. RESEARCH PRIORITIES

Prevention of overfishing and evaluation and development of pearl culture are priorities for most Pacific islands countries with pearl oyster stocks (see Table III). Routine survey techniques are required, and spat-collector and growth trials need to be conducted.

SURVEY METHODS

Earlier surveys were usually conducted by test fishing, with highly subjective results. Refinement of SCUBA and hookah survey methods has permitted objective assessment of stocks of *P. margaritifera* in Polynesian lagoons (Intes and Coeroli, 1982; Intes *et al.*, 1986; Sims, 1989; 1990b), and *P. maxima* in Australia (Penn and Dybdahl, 1988; K. Colgan, *pers. comm.*). Densities, distribution, and age- or size-structure of populations and descriptions of associated benthic assemblages and bottom-types are among the primary objectives of most surveys.

Objective surveys can provide baseline measures of abundance, but permanent survey sites are needed for monitoring stock changes. Objective surveys are inappropriate for regularly determining sustainable harvest quotas. Results are inherently imprecise because of the wide variability in densities between randomly selected sites (Sims, 1989, 1990b). Permanent sampling sites remove the between-site variability, but both fishing and recruitment remain highly patchy. Large sample areas are therefore needed to detect changes in abundance, particularly under moderate fishing pressures, or over short periods.

GROWTH STUDIES

Shell dimensions: Shell diameter (dorsoventral measurement, or D.V.M.) is a simple measure to use in the field and is a good indicator of growth performance. Coeroli and Mizuno (1985) validated the use of D.V.M. in comparative culture trials by relating shell growth to pearl nacre deposit rate and value. Although heel depth usually increases linearly with time, it is also affected by environmental influences (Sims 1990b). Both D.V.M. and heel depth vary within the same age-class, even when cultured under identical conditions.

Growth trials: Tagging in mark-remeasure growth studies is easy for pearl oysters: shells are drilled as for culture, and the tags tied through the hole. Underwater glues do not stick well to the smooth exterior shell surface. Theft and predation can cause problems in growth trials, but protected areas, co-operative farmers, enlightened officials and public education can all minimise losses.

Growth is often underestimated in tagging trials because of the high frequency of non-nacreous border loss. Negative growth may occur in individuals or with small sample sizes, probably due to grazing or predatory fish breaking the shell border. Exclusion experiments are difficult because restricted water movement may cause slower growth (Nicholls, 1931).

Linear increments can only be used to compare growth between trials for single age-classes. For oysters of unknown or mixed ages, confidence limits and significant differences for von Bertalanffy growth parameters and Φ' (Pauly and Munro, 1984) have been determined by comparing Ford-Walford plots (Sims, 1990b). Use of the Beverton-Holt model of optimum yield-per-recruit is validated by the observance of the cube law of length and weight (Galtsoff, 1931; Coeroli, 1983; Fig. 3, in Sims, 1990b).

Table IV. Annual pearl imports by Japan from the South Pacific and South-east Asia (US$'000)[1]

COUNTRY	YEAR 1988	1989
French Polynesia	24,900	40,700
New Caledonia[2]	1,860	491
Cook Islands	0	444
Papua New Guinea	1,442	0
Tonga	155	0
Australia	45,400	71,350
Indonesia	8,450	11,560
Philippines	5,100	3,800

[1] Source: *Weekly Pearl* Newspaper (Japanese), No. 1159, 2 March, 1990.
[2] Probably all re-exported from French Polynesia.

POPULATION DYNAMICS

Permanent survey sites are best for long-term monitoring of stocks. Catch data can be extrapolated to give fishing mortalities, but real measures of natural mortality and recruitment require survey sites set up in protected areas.

The patchy patterns of spat-falls across lagoons and over time make it difficult to predict the best times and locations for collector deployments. Collector trials are useful in lagoons of unknown potential but research should otherwise simply document results from commercial collectors. Suitable collector materials have already been identified (Coeroli *et al.*, 1984), and further developments are probably best left to the initiative of farmers.

Under normal conditions, larger, more fecund oysters should maintain an even sex ratio in the wild. Pearl implantation may disrupt the normal reproductive development of oysters (M. Coerloi, *pers. comm.*), and the degree and pattern of protandry may vary for different situations.

FISHING IMPACTS AND PRODUCTION

Sustainable yields for the Tuamotu-Gambier atolls in French Polynesia have been estimated using approximations of original abundances (Intes, 1984). Effort and fishing power are difficult to quantify, however, making production records, catch-per-unit-effort and test-fishing data all poor indicators of virgin abundance.

Knowledge of the distribution of fishing effort and impacts is useful for establishing reserves or closed areas. Effort is always difficult to quantify as catch rates vary widely among individual divers and among sites. Diver-hour is probably the best unit. Mandatory logbooks (in licensed fisheries) or creel census surveys can be used where divers are less willing to disclose catch information.

There is usually no attenuation of fishing effort (and oyster densities or sizes) away from villages because of the high value of the catch. Where free-dive fishing is heavy, shell densities and diameters generally increase with increasing depth. Heavier fishing also produces smaller average sizes over successive years (Sims, 1990b).

Although pearl shell traders are often reluctant to provide production data, they can be a good source of information for village- or island-based fisheries. Estimates of the percentage of stocks fished each year can be calculated from this data when it is used in conjunction with surveys. Customs and export data can also be useful, providing that information such as the island of origin and weight of shell by grade is included.

V. DEVELOPMENT AND MANAGEMENT

PEARL OYSTER STOCK MANAGEMENT

Early pearl shell fisheries regulations throughout the Pacific were based largely on "guesswork" and "arbitrary" closures (Russell, 1958, p 58; and Anon, 1960). Overfishing was often justified by claims of better growth rates and improved shell quality at lower abundances (Anon, 1956a; Anon, 1956b; Anon, 1959; Noakes, 1959; Powell, 1960; Anon, 1961). In some cases, black-lip stocks have been fished to below self-sustaining levels and have not recovered since (*e.g.* Suwarrow Atoll, Cook Islands: Sims, 1989; and Kiritimati Atoll, Kiribati: Sims, *et al.*, 1989).

As growth overfishing should not be the major concern, management should ensure protection of broodstocks and continuing recruitment. Reserve areas, quotas, and other restrictions on effort should be applied rather than minimum size limits.

Permanent reserves: Permanent reserve areas are clearly beneficial. Dense aggregations of large, highly fecund oysters ensure continual recruitment to wild stocks and spat collectors. Spawnings are more synchronised and fertilization rates are higher. Reserves should be located in areas of high natural densities

Figure 1. A spat collector line in Manihiki, Cook Islands, weighed down by a heavy spatfall of *P. margaritifera*. Photo: Neil Sims.

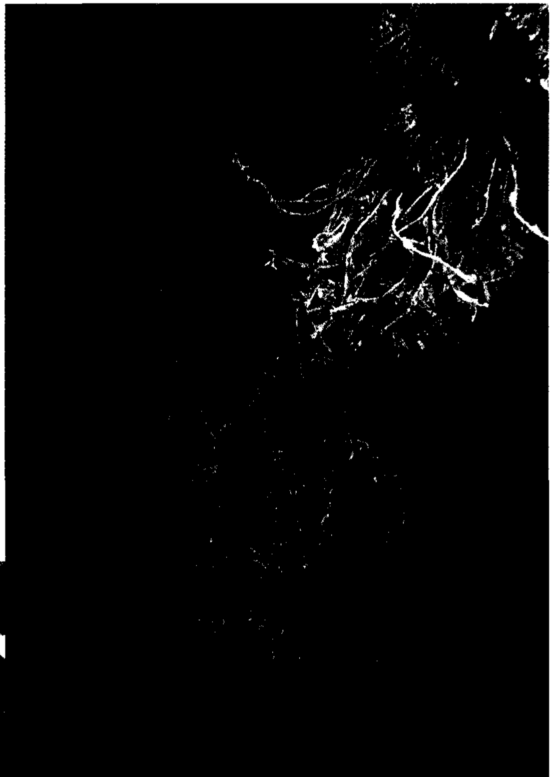

Figure 2. A single collector from the same spat line. Photo: Neil Sims.

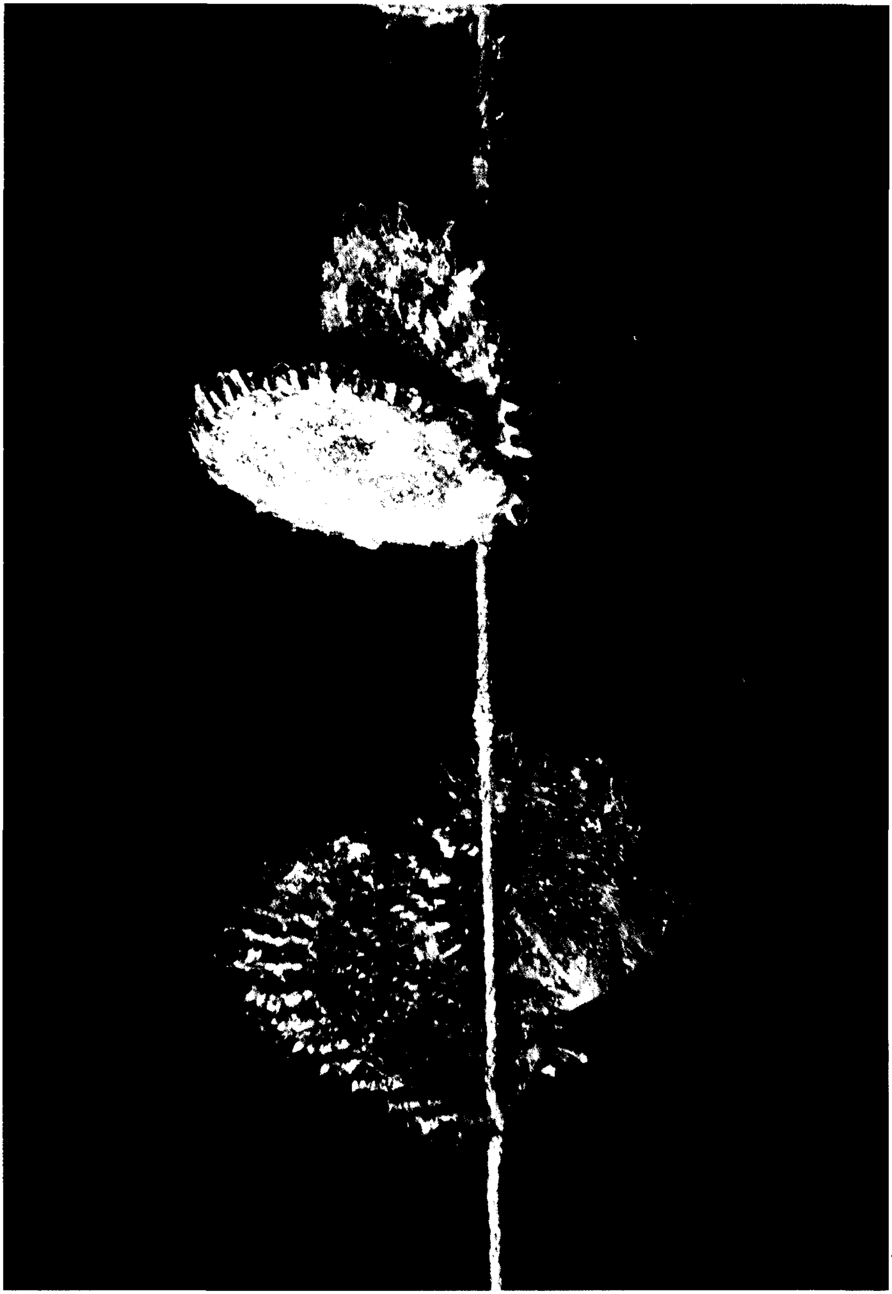

Figure 3. Long-line culture of black-lip pearl oysters in Manihiki, Cook Islands. Photo: Neil Sims.

and close to villages to allow constant community surveillance. Reserves should preferably be on the windward side of lagoons: Millous (1977) found higher reproductive activity there in Takapoto, French Polynesia, and the retention of larvae within the lagoon is improved.

Although protected areas have been widely used in traditional fisheries and are more readily incorporated into modern management (Sims, 1990c), they have not always been supported by divers or island communities. A breeding reserve in Manihiki, Cook Islands, has been ineffectively enforced because the benefits to the stock were not apparent to the local community. While densities increased in French Polynesian reserves over the short-term, recruitment to wild stocks or spat-collectors did not increase (M. Coeroli, *pers. comm.*). Reserves only reach full reproductive potential, with maximum fecundities and densities, after many years. Benefits from periodic closed seasons and rotational closures are therefore limited and long-term or permanent closures are preferable.

The main objection to reserves is usually that dense older shells will foster infestations of 'worms' and other borers. Borers are rarely host-specific, however, and there has been no evidence of increased prevalence in the shell catch due to proliferation of oysters in reserve areas.

Harvest seasons and quotas: Harvest seasons and quotas can be used to restrict effort, but are often applied arbitrarily. The logistical and manpower requirements make annual pre-harvest surveys on each island an impractical way to determine harvest durations or quotas. Seasons or quotas can be set in advance, using production data and standing stock figures from earlier surveys, but conservative estimates of abundance and sustainable yield should be used. Predicted catch rates should allow for unforseen increases in shell price or number of divers causing rapid increases in effort.

Enforcement of harvest quotas and seasons is invariably difficult. Actual catches may far exceed quotas due to hoarding of shell or poor monitoring.

Rotational closures have been used throughout French Polynesia (Alexander, 1902; Intes, 1984) and in Penrhyn, Cook Islands (Sims, 1989). In French Polynesia, harvests were rotated among islands. Rotations cause less economic detriment than total closures, but are of less benefit to the stock. Fishing effort is concentrated, rather than reduced.

Live shell quotas limit the taking of stocks for farms in French Polynesia (Intes, 1984) and gradual reductions in quotas have encouraged greater reliance on spat-collectors (M. Coeroli, *pers. comm.*). Farm numbers are also limited by individual quotas in Western Australia, primarily to protect wild stocks (Dybdahl and Rose, 1986; Malone *et al.*, 1988).

Size limits: Although minimum size limits have been used extensively in pearl shell fisheries, their benefits have not been demonstrated. Limits for *P. margaritifera* have been set at 120 and 132 mm in the Cook Islands and 130 mm for most of French Polynesia. *P. maxima* size limits are 115 mm in Torres

Strait (Yamashita, 1986) and 120 mm in north Western Australia (Dybdahl and Rose, 1986). However, theoretical optimum size at first harvest may be as small as 110 mm D.V.M. (Sims, 1990b) because of the high juvenile mortalities in the wild, slow shell weight growth and heavy fouling of older shells. Protection of small oysters is also of little benefit to reproductive capacities because of their slow, protandric development and lower fecundity.

Enforcement of size limits has always been difficult. Divers are often unsupportive, perceiving that stocks are overfished when abundance decreases, not when sizes decrease. Juveniles are often "banked" until they attain minimum legal size, or undersized shell is crushed and sold as fragments.

Size limits are also not workable where juveniles are taken for farm stocks. In French Polynesia, a smaller limit of 11 cm is set in Takapoto lagoon (the chief source of spat), compared with 13 cm elsewhere. Size limits apply only to MOP shell in Western Australia (Dybdahl and Rose, 1986). Larger oysters also cannot be taken for MOP on the main pearling grounds south of Broome (R. Dybdahl, *pers. comm.*). Similar maximum size limits could provide some protection to broodstocks, as in trochus fisheries (Bour *et al.*, 1982; Sims, 1985; 1988b), but again they would be difficult to enforce.

Gear limits: *P. margaritifera* broodstocks in deep water can be protected by the prohibition of diving machines, hookah rigs and SCUBA gear. Restriction to free-diving also maximises employment; an important consideration for island economies. Gear restrictions are impractical in *P. maxima* fisheries, as hookah rigs are used exclusively.

Gear limits by themselves are not sufficient protection for black-lip stocks. Despite widespread claims of unfished *P. margaritifera* stocks beyond 40 m (Gug, 1957; Hynd, 1960; Domard, 1962; Intes, 1982), there is no evidence of natural reserves of abundant, large oysters below the range of free-divers (Intes and Coeroli, 1982; Intes *et al.*, 1986; Sims, 1989).

STOCK ENHANCEMENT

Early spat-collection and cultivation trials were intended primarily to preserve natural stocks through decreasing fishing pressure, increasing settlement success and reducing juvenile mortality (Ranson, 1955; 1957; Crossland, 1957; Hynd, 1960; Reed, 1962).

Spat from collectors can be used to re-establish over-exploited stocks or supplement stocks in reserve areas. Remaining adults can also be aggregated in protected areas to enhance reproductive efficiency. Stock enhancement may be especially useful in open lagoons, where planktonic larval losses and predation are heavy.

Introductions should be used to reseed depleted stocks only where other enhancement methods have proven unsuccessful. Broodstock aggregation and spat collector programmes are more beneficial in the long term. Continual transshipments to pearl farms in other lagoons may be commercially viable, but should be carefully controlled (see "oyster transshipments" below).

Transshipments aiming to establish self-sustaining wild stocks in new areas are not likely to be successful. There are no records of introduced pearl oysters becoming established in islands where they were not previously common. With such a long larval stage, pearl oysters were widely dispersed, and stocks became established in all lagoons with suitable habitats. It is therefore unlikely that introductions can overcome the natural limits to distributions.

PEARL OYSTER CULTURE ISSUES

Culture industries in Japan, Australia and French Polynesia have all suffered from over production and overcrowding resulting in heavy mortalities (George, 1978; Hollyer, 1984; Dybdahl and Pass, 1985). Many of the causes, such as disease and pollution, can be improved by better farm management. Overfishing is also still a problem where farms rely on wild stocks. Spat collectors (as in French Polynesia) and hatchery production (as in Japan) can alleviate these pressures.

Disease control: Persistent, heavy mortalities among pearl farm stocks have occurred in most culture industries, severely limiting profitability. Disease and pollution problems have plagued the Japanese industry since 1962, with over-production resulting in "very high mortalities" and "low quality pearls" (George, 1978, p 41; Hollyer, 1984). Recurring disease problems have accompanied the Australian and French Polynesian culture developments. Stressed or diseased oysters result in low retention rates and poor quality pearls. In addition, mortalities produce greater pressures on wild stocks. In French Polynesia mortalities have spread to wild *P. margaritifera* and other bivalve populations (*e.g. P. maculata, Tridacna maxima* and *Spondyllus* spp., M. Coeroli, *pers. comm.*).

The causal organisms and nature of pearl oyster diseases are still poorly defined. The marine bacteria, *Vibrio harveyi* was identified as a pathogenic agent in *P. maxima* in north-western Australia (Pass *et al.*, 1987). Bacteria (possibly *Vibrio alginolyticus* or *Benecka vulnifica*) are also associated with mortalities in *P. margaritifera* in French Polynesia (Coeroli, 1983), but these may be secondary infections.

Onset of disease is associated with stressing of the pearl oysters, through either transportation from collection site to farm, thermal shock during transshipment, overcrowding of oysters on farms, careless handling practices or the grafting operation itself. Oyster stresses are often linked to overcrowded conditions (Dybdahl and Pass, 1985; Reed, 1985, Lowe, 1986; Pass *et al.*, 1987). Matsui (1958, p. 526) noted that "the continuous use of the same ground often causes a serious decline in...production (and) quality", but that the removal of faecal deposits beneath farms helped recovery.

Depletion of phytoplankton in surface waters may impose limits on farm capacities (Intes, *unpubl. m.s.*), but is unlikely to be the principal cause of ongoing mortalities. The boom in farming in Takapoto, French Polynesia, produced an estimated 1,000 per cent increase in demands on surface water primary production (*ibid.*). Unexploited stocks of *P. margaritifera* would have also been concentrated in the shallows, however, with presumably similar impacts on phytoplankton levels.

Carrying capacities for *Pinctada* spp. are difficult to model (Dybdahl and Rose, 1986) because of the many unknown physiological and ecological parameters. Further study of pearl oyster feeding and filtration rates is required (see Mansour and Gabal, 1980; Nasr, 1984; Jacob, *et al.*, 1980), but is not a priority for the Pacific islands.

Farm management practices: Mortalities can be prevented by careful transshipment, stocking and handling practices (Coeroli, 1983; Dybdahl and Pass, 1985; Pass *et al.*, 1987), but are difficult to control once established. Losses were substantially reduced in Australia following the adoption of new farming procedures (Pass *et al.*, 1987). Most farms in Polynesia are now shifting from banks and fixed platforms to long-lines, with lower densities, better circulation, and limited detrital build-up on the underlying lagoon floor. Survivorship there has consequently improved (M. Coeroli, *pers. comm.*).

Oyster Transshipments: Transshipments between islands should be carefully controlled to limit the spread of diseases. Oysters stressed by transshipment are more likely to succumb to disease-causing pathogens (Dybdahl and Pass, 1985; Pass *et al.*, 1987). The disease problems in French Polynesia appear to have been spread among the atoll lagoons by commercial shipments of spats from Takapoto (Reed, 1985).

Transshipments should also protect genetic identities of different lagoons (Blanc, 1983; Blanc *et al.*, 1985; Wada, 1986a and b; Wada, 1987). The diversity among lagoon stocks is increasingly significant for selective breeding trials (Wada, 1987), as hatchery techniques are further developed. Fast-growing oysters could be bred for preferred pearl colours and greater resistance to disease and implantation stresses. Transshipments should therefore be over the smallest possible distances and in one direction only.

Farm stocks: Pearl farms require continual supplies of oysters from either divers, spat collectors, or hatcheries.

Diving: Where stocks are already overfished for MOP, farming produces further declines. The expansion of farming in Manihiki, Cook Islands, was accompanied by an 18 per cent decrease in stock abundance over one year (Sims, 1990b). Catch quotas are still the main limit to growth in the Australian industry (Malone, *et al.*, 1988). Fishing for farm stocks has been gradually phased out in French Polynesia, however, encouraging greater use of spat collectors.

Spat collectors: *P. margaritifera* culture in the South Pacific has developed largely due to successful spat collection. The required materials are inexpensive and readily available, and the methods are simple. Settlements average 50 spat per bundle for hardwood brush collectors (*Pemphis acidula*: AQUACOP, 1982) and reach over 300 per collector for optimum locations and materials (Coeroli, 1983). Over 80 per cent of farm spat were taken by collectors in French Polynesia in 1988 (M Coeroli, *pers. comm.*) and spat collectors will work in any lagoon with natural stocks.

Collectors for *P. maxima* have been less successful, with heavy fouling often occuring (Rand Dybdahl, *pers. comm.*). Spat which settled showed poor survival and growth (Dybdahl and Rose, 1986).

Hatchery culture: Commercial hatcheries for *P. maxima* are reported from Torres Strait, Western Australia, Indonesia, Japan and the Philippines. *P. margaritifera* hatcheries provide sufficient stocks for three black pearl farms in Okinawa (M. Yamaguchi, *pers. comm.*). Although the technology is still largely proprietary, some recent successes with black-lip larval culture have been reported (Alagarswami, *et al.*, 1989). A hatchery in French Polynesia is now consistently producing 300,000 black-lip spat per year (M. Coeroli, *pers. comm.*).

The physiological and nutritional requirements of the larvae and their long planktonic period make pearl oysters difficult hatchery subjects. Logistical and maintenance problems may make large-scale pearl oyster hatcheries impractical on isolated atolls. Where these constraints can be overcome, small hatcheries could provide spat for farm culture and for reseeding depleted stocks.

Farming and grafting research: As with hatchery developments, advances in farming or grafting techniques are usually considered proprietary. These refinements are best left to private farmers. Demonstration of the correlation between the pearl quality and shell growth (Mizuno, 1983; Coeroli and Mizuno, 1985) allows farming sites and husbandry methods to be evaluated using simple growth trials (*e.g.* Yoo *et al.*, 1986; Sims, 1990b).

Despite the expense of hiring experienced technicians, the more reliable results justify their employment in developmental farming stages. It is difficult to obtain training for local seeding technicians, and this should only be a priority in Pacific Islands after farming is well established.

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