The restocking of sea cucumbers in the Pacific Islands[1]

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INTRODUCTION

Large invertebrates associated with coral reefs are an important source of food and income for coastal communities in the small island developing states (SIDS) of the Pacific (Wright and Hill, 1993; Richards, Bell and Bell, 1994; Dalzell, Adams and Polunin, 1996). Although the volume of these fisheries is low by world standards, they are of considerable economic importance to SIDS because the ratio of coastline to landmass is much greater than for continental countries (Adams, 1998). It is now evident, however, that the inshore invertebrate fisheries are not yielding their full potential. This is not due to lack of development. Rather, the problems facing these fisheries have been caused by overharvesting, with the result that in many places there are too few adults to replenish stocks regularly. In short, the natural supply of juveniles is often well below the carrying capacity of the coral reef habitats.

Part of the solution to the current lack of productivity from coral reefs in the Pacific is to raise awareness of the need to allow stocks to recover to productive levels, and to implement community-based management (Lam, 1998). However, improved awareness and protection will not necessarily result in rapid recovery of stocks, and will not deliver increased levels of production compared with historical catches. Both these outcomes are essential for the increased well-being of the rapidly growing human populations in the Pacific.

Aquaculture, in a variety of forms, is needed to redress the problem of low yields from inshore invertebrate fisheries in the Pacific (Bell, 1999a). Aquaculture can be used to increase productivity in three ways. First, cultured juveniles can be released into the wild to restore stocks to levels at which they provide substantial, sustainable yields. This process is known as "restocking".

Second, cultured juveniles can be released into the wild to increase stocks compared with historical, unexploited levels. This process is known as "stock enhancement"

1. Since this manuscript was submitted for publication in 2001, considerable progress has been made on methods for hatchery production of sandfish (*Holothuria scabra*), the techniques for releasing the cultured juveniles in the wild, and the ways to assess the potential benefit of restocking programmes to the sustainable management of fisheries for sea cucumbers. This progress has been documented in the recent publication by FAO entitled "Advances in sea cucumber aquaculture and management" A. Lovatelli, C. Conand, S. Purcell, S. Uthicke, J.-F. Hamel and A. Mercier (Eds.). FAO Fisheries Technical Paper 463, FAO, Rome, 2004, 425pp.

and is designed to overcome the common phenomenon of "recruitment limitation" (Doherty, 1999). This phenomenon occurs when the natural supply of juveniles fails to reach the carrying capacity of the habitat, even when there are great numbers of breeding adults. Recruitment limitation is the rule rather than the exception among tropical marine animals and arises for several reasons. For example, the floating (pelagic) larval stages of fish and shellfish may perish en masse in the plankton because of lack of suitable food, or be swept away from coral reefs by currents, thus preventing successful settlement. Mass mortality of larvae as a result of predation can also occur when they cease their pelagic phase and settle on coral reefs. The result of recruitment limitation is that (even unexploited) coral reef habitats do not produce as many valuable shellfish as they could. Stock enhancement seeks to redress this situation by supplying as many juveniles as the habitat can support (Munro and Bell, 1997; Doherty, 1999). Stock enhancement and restocking are not without pitfalls, however, and the factors that need to be considered for responsible implementation of such programmes, and transferring the technology to the Pacific, are described by Blankenship and Leber (1995), Munro and Bell (1997) and Bell (1999b).

Third, cultured juveniles can be grown in captivity to increase productivity independently from the management of wild fisheries. This process is usually referred to as "aquaculture" or "farming".

The imperative for SIDS in the Pacific is to apply aquaculture technology to the restocking of several invertebrate fisheries, and then to introduce sound management of the resources, so that increased yields can be made sustainably in the near future. In time, the same technology can also be used in stock enhancement programmes to ensure that maximum yields are obtained by overcoming recruitment limitation.

Although the way forward for SIDS is clear, they usually do not have the financial and human resources to develop the technology for restocking marine species. Instead, they need to rely on international and regional organizations to do this work on their behalf. They will also need to rely on donors to implement restocking programmes until the additional revenue from the increased catches can be levied to meet the cost of further restocking, or stock enhancement (Bell, 1999b).

The WorldFish Center, in collaboration with several partners, has begun the development of technology for restocking valuable coral reef invertebrates on behalf of Pacific Islands (see Lawrence, 1999, for details). To date, the research has focused on developing methods for the restocking of giant clams (Tridacnidae),trochus or topshell (*Trochus niloticus*) and sea cucumbers (Holothuroidea). The technology for propagating and restocking giant clams is now documented and widely available (see Munro, 1993a, 1993b; Lucas, 1994; Mungoa-Licuanan and Gomez,1996 and Bell, 1999c, for reviews), and the status of restocking programmes has been reviewed by Bell (1999c). The efforts to restock trochus through release of hatchery-reared juveniles are still at an early stage (Nash, 1993; Lee *et al.*, 1998), although adults have been introduced to more than 50 locations in the Pacific to create fisheries (Eldredge, 1994).

In this paper, we expand on our previous report (Battaglene and Bell, 1999) on the potential of tropical sea cucumbers for stock enhancement and focus on the need for, and progress of, methods for restocking sea cucumbers in the Pacific. We describe the fishery for bêche-de-mer (processed sea cucumbers), outline the rationale for restocking sea cucumbers, summarize the methods that have been developed and identify the work that remains to be done before responsible restocking methods will be available for dissemination to SIDS in the Pacific. Much of the research we refer to has been done in the Solomon Islands, but it can also be applied to any other SIDS in the region and Southeast Asia.

NATURE AND STATUS OF THE FISHERY FOR BÊCHE-DE-MER IN THE PACIFIC

The trade in bêche-de-mer (processed sea cucumbers) is one of the oldest and most widespread forms of commerce in the Pacific Islands (Conand and Byrne, 1993; Holland, 1994a). It is based on the demand for sea cucumbers in Asia, especially mainland China, where the boiled and dried body wall is prized for its aphrodisiac, curative and medicinal properties (Preston, 1993). The body and/or viscera of sea cucumbers are also eaten in Japan, the Republic of Korea and some Pacific Islands (Shelley, 1985; Yanagisawa, 1996), and variously used as food for livestock, production of fish poisons and antifungal agents (Preston, 1993). Although more than 1400 species of sea cucumbers have been described, trade is restricted to the 20–30 species that generally have thick body walls. Most of these species are found in the tropics (Conand and Byrne, 1993; Holland, 1994b; Rowe and Gates, 1995).

Fishing for bêche-de-mer has brought considerable benefits to SIDS in the Pacific because harvesting, processing and storage of sea cucumbers is easy and requires no specialized equipment or refrigeration (Preston, 1993). In several of these countries, bêche-de-mer provides the majority of revenue from non-finfish marine resources (e.g. Solomon Islands; Richards, Bell and Bell, 1994) and, for many coastal communities, it is one of the few sources of income. A striking example of the importance of sea cucumbers to Pacific Islands comes from the large, remote atoll of Ontong Java in the Solomon Islands. There, bêche-de-mer has been the major fishery and has provided the majority of cash income for the population (Holland, 1994a).

Other important features of the bêche-de-mer fishery in the Pacific Islands are that it causes little damage to the environment, and does not conflict with the subsistence food requirements of villagers (Holland, 1994b; Dalzell, Adams and Polunin, 1996).

Despite the importance of bêche-de-mer to coastal communities in the Pacific, production remained at low levels for much of this century as a result of previous overfishing, a trade embargo into China caused by the Sino-Japanese war, and later by trade restrictions from the Chinese communist government (Dalzell, Adams and Polunin, 1996). However, the re-entry of China into world trade during the 1980s resulted in a sharp increase in demand and supply of sea cucumbers (Conand and Byrne, 1993; Dalzell, Adams and Polunin, 1996; Conand, 1997). Prices for bêche-de-mer remained strong throughout this period because demand for bêche-de-mer is considered to be highly inelastic, or "insatiable" (Dalzell, Adams and Polunin, 1996). The ability of villagers and wholesalers to store bêche-de-mer for long periods also contributes to stability in the market, and has resulted in bartering of the product to circumvent trade barriers (Dalzell, Adams and Polunin, 1996).

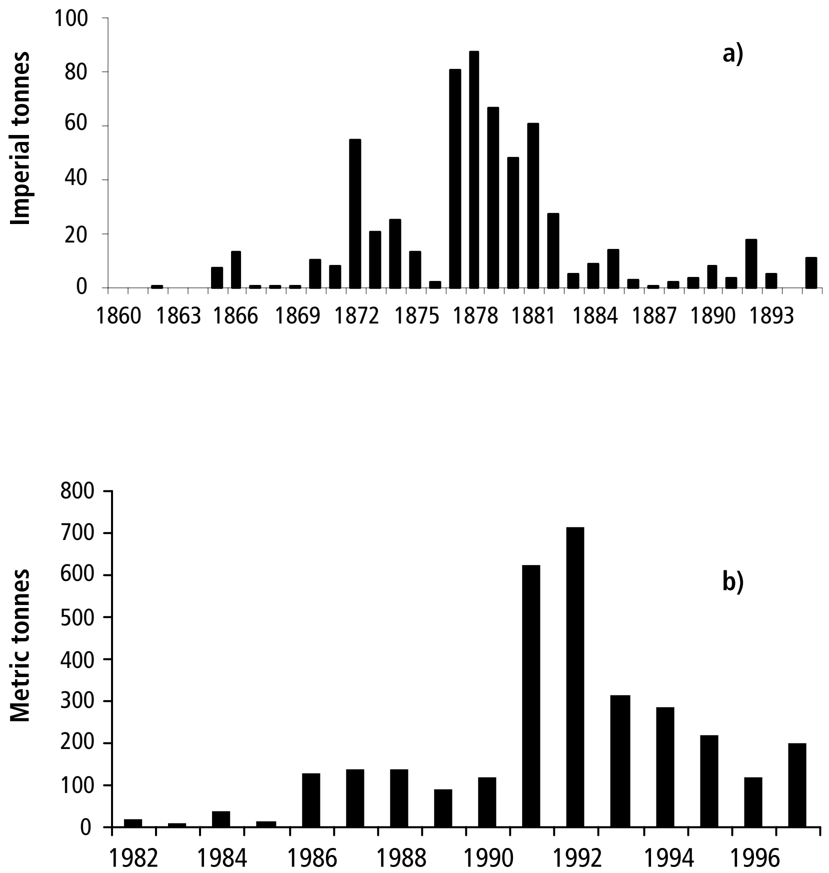
Total imports of bêche-de-mer into Hong Kong, Singapore and Taiwan Province of China from all sources were estimated to be 12 000 tonnes in 1994, valued at US$60 million (Conand and Byrne, 1993; Conand, 1997). Because of shrinkage during processing, 12 000 tonnes of bêche-de-mer represent a wet weight of ~120 000 tonnes. Despite the large volume of bêche-de-mer traded each year, accurate information on the species exploited, the tonnages harvested and the total value of bêche-de-mer exports from SIDS and other developing countries is difficult to obtain (Preston, 1993; Conand and Byrne, 1993). This is because catches are often poorly recorded, and because sea cucumbers can be difficult to identify to species level once processed into bêche-de-mer.

PRINCIPAL PROBLEMS WITH THE FISHERY

The major problem with the bêche-de-mer fishery in the Pacific is that it has followed a "boom and bust" cycle (Preston, 1993). In many places, the initial phase of exploitation reduced the resource to the point at which there was little capacity for replenishment. Indeed, it often took 3–4 decades before stocks of sea cucumbers recovered to levels at which profitable harvests were again possible. The long time frames needed for recovery of bêche-de-mer fisheries are related to the fact that sea cucumbers can be harvested to very low levels, and that there is often limited scope for replenishment from the nearest source of spawners as a result of the large distances and the relatively short larval after Bennett cycles. The boom and bust cycle has been repeated several times in some countries although, as mentioned previously, a trade embargo provided an extended period for recovery at one stage.

The fishery in the Solomon Islands provides a typical example of the long-term, cyclical nature of the bêche-de-mer industry. The historical records of bêche-de-mer exports from 1860 to 1895 provided by Bennett (1987) indicate a pulse of fishing that peaked in 1878 followed by rapid depletion of the resource (Figure 1a). Production of bêche-de-mer then remained at low levels for much of the twentieth century, in part owing to the disruptions of the Second World War. Fishing recommenced in earnest in the mid 1980s, with catches peaking in 1992 at 716 tonnes and then declining rapidly

FIGURE 1. Export of beche-de mer from the Solomon Islands from: a) 1854 to 1896 (after Bennett, 1987), and b) 1982 to 1997 (data from the Solomon Island Department of Fisheries and Marine Resources

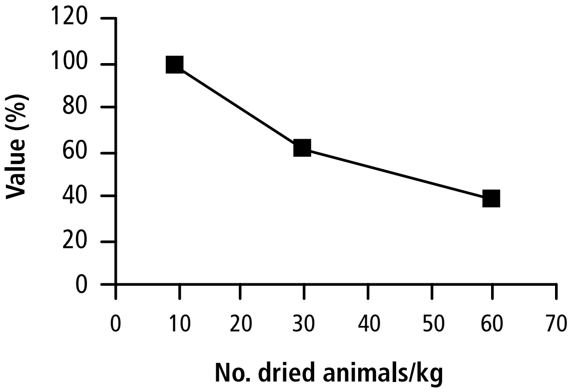


to 120 tonnes by 1996 (Figure b). A slight recovery in 1997 reflected the opening of waters off Bouganville on the western order of the Solomon Islands.

Richmond (1997) refers to a case of complete overexploitation of sea cucumbers from a relatively isolated location in the Pacific, where there was no recovery 50 years after intense harvesting. He reports that thousands of tonnes of commercially valuable sea cucumbers were exported from Chuuk (Truk) to Japan in the late 1930s, but that surveys in 1988 found only two individuals of one edible species. His interviews with local residents and fishermen confirmed that there have been no harvests of sea cucumbers in the intervening period.

The problems facing the bêche-de-mer fishery during the recent "boom" in the cycle were driven by the high prices being paid for valuable species, and the fact that coastal communities in SIDS often have few other options to derive income. Four general trends have emerged during the most recent harvesting cycle. First, high-value species have been fished heavily (Conand and Byrne, 1993; Dalzell, Adams and Polunin, 1996). The average wholesale price for these species is now around US$50/ kg, although price is highly variable depending on quality: premium prices are paid for large animals and the price for smaller specimens declines rapidly (Figure 2). The value of first-grade, i.e. large and well-processed, bêche-de-mer has more than doubled since 1993 (Conand, 1997). Second, the species composition of exports has changed: catches of high-value species are lower and more species are being exploited. The relatively low catch of high-value species has been particularly evident in the Solomon Islands and Fiji (Holland, 1994a; Dalzell, Adams and Polunin, 1996). Third, the mean size of many harvested species has declined (Dalzell, 1990; Holland, 1994b). Fourth, there has been a tendency for the development of centralized processing facilities that reduce the economic benefits to coastal villages and lead to localized resource depletion (Adams, 1992; Preston, 1993). Together, these four trends indicate that stocks of tropical sea cucumbers have once again been overfished.

FIGURE 2. Percentage change in prices paid for beche-de-mer (sandfish) of different sizes (data from exporters in Singapore and Holland, 1994a)



CURRENT MANAGEMENT PRACTICES

The premium prices paid for large specimens mean that sea cucumber fisheries need to be managed in a way that maximizes the economic return per recruit through regulations that provide for sustainable harvests comprising large individuals. However, it has not been easy to establish the scientific basis for such management. In particular, the large number of species of sea cucumbers now being targeted, and the remote and artisanal nature of fisheries for bêche-de-mer, make it expensive to collect the data on catch-per-unit-effort, growth and mortality that are normally used to manage marine fisheries on a sustainable basis (Shelley, 1985; Conand and Byrne, 1993; Lokani, 1995). Consequently, the only data on species composition and size frequency of wild stocks in many countries are those provided by exporters (Adams, 1992; Holland, 1994a; Lokani, 1995).

Even if it was possible for SIDS to obtain the resources needed to collect the necessary data, the length and weight of sea cucumbers are not easy to measure: individuals retain water and sediment to varying degrees. Modal progressions in growth are also difficult to interpret because many sea cucumbers are capable of asexual reproduction by binary fission, and evisceration and shrinkage when stressed (Preston, 1993; Reichenbach, Nishar and Saeed, 1996). In addition, there are no established tagging methods or ageing techniques for sea cucumbers (Preston, 1993).

One country (the Kingdom of Tonga) has overcome many of the difficulties involved in managing the restoration of an ongoing fishery simply by implementing a long-term prohibition on the export of bêche-de-mer to allow recovery of stocks to productive levels. In most other places in the Pacific, however, management, or recommendations for management, of the bêche-de-mer fishery have been based on scant knowledge of the size at sexual maturity for the numerous species, and measures aimed broadly at preventing "recruitment" and "growth" overfishing (Adams, 1992; Holland, 1994a, 1994b; Lokani, 1995). These measures include size limits, prohibition on collection using compressed air and the use of closed seasons and marine protected areas.

The management measures referred to above have been of limited success. The fact that small bêche-de-mer fetch drastically reduced prices should mitigate against the need for size limits, but this has not been the case (Shelley, 1988; Adams, 1992; Holland, 1994b). Unfortunately, recommendations regarding the need for size limits have not always been adopted by fisheries departments, or those with responsibility for stocks under customary marine tenure arrangements. Rather, fishers have often preferred to catch sea cucumbers at a small size to obtain some cash now instead of waiting to maximize returns. Restrictions on the use of scuba are common and were designed to ensure that sea cucumbers have sanctuary in deeper water so that they can maintain effective breeding populations (Adams, 1992). However, deep-water sanctuaries are of limited benefit to species inhabiting shallow water (<20 m), or in areas of very clear water where free divers have devised methods for collecting at depths >30 m (Holland, 1994a). Closed seasons appear to be working well only in areas with strong traditions and customs. There is little doubt that marine reserves could provide sanctuary for breeding populations, and a source of recruits for nearby areas that remain open to fishing. The major question here, however, is the time required for recovery of stocks. The monitoring of a Marine Conservation Area of 83 km^2 at the Arnavon Islands, Solomon islands, which was dedicated to protect large invertebrates, indicates that replenishment of sea cucumbers is likely to take more than ten years (Lincoln Smith *et al.*, 2000).

An all-encompassing problem, however, is that SIDS often lack the financial and human resources to enforce management regulations. The diverse social and coastal tenure systems of many Pacific Islands also complicate the application of regulations (Conand and Sloan, 1989; Lokani, 1995; Aswani, 1997).

RATIONALE FOR RESTOCKING

Even if SIDS can implement sound management practices for sea cucumber stocks, there are two reasons why the measures described above are unlikely to result in highly productive bêche-de-mer fisheries in the near future. These two reasons have been mentioned in the preceding sections: they are the long timeframes required for restoration of depleted fisheries, and recruitment limitation of restored fisheries.

There is now general recognition that the fastest way to restore the productivity of severely depleted sea cucumber fisheries for the benefit of the coastal communities in the Pacific may well be to rebuild the stocks by releasing cultured juveniles, and to combine this intervention with other forms of management that will protect the released animals until they, and their progeny, replenish the population to a level at which it can be managed sustainably. At that point, stock enhancement can also be evaluated as a means of maximizing the productivity in locations where there is recruitment limitation.

To date, most research on restocking of tropical sea cucumbers has focused on the sandfish, *Holothuria scabra*. This is because of the fortuitous coincidence that it is relatively easy to rear in captivity, and it is the most valuable species worldwide (Conand and Byrne, 1993). The sandfish also has several other attributes that make it particularly suitable for stock enhancement (Battaglene and Bell, 1999). In particular, it is sedentary, it inhabits inshore areas such as seagrass beds, mangroves, inner-reef flats and estuaries (Hamel *et al.*, 2001), and it can occur at very high densities, e.g. 13 500, 6 000 and 2 562 per ha, for Papua New Guinea, New Caledonia, and the Torres Strait, respectively (Shelley, 1985; FAO, 1990; Lokani *et al.*, 1996). These attributes increase the probability of monitoring restoration programmes successfully, simplify access and ownership issues, and provide for high levels of production. In addition, sandfish feed low in the food chain – they burrow in mud and sand and process organic matter, bacteria, diatoms, cyanophyceans and foraminiferans (Wiedemeyer, 1992; Mercier, Battaglene and Hamel, 1999). This means that the release of cultured sandfish is unlikely to have an impact on other fisheries species. By contrast, sandfish are believed to play a beneficial role through the bioturbation of sediments (Hammond, 1982; Massin, 1982; Wiedemeyer, 1992; Mercier, Battaglene and Hamel, 1999).

METHOD OF RESTOCKING SANDFISH

The method being developed for the restocking of sandfish involves the propagation of juveniles in hatcheries for release in the wild. Other methods for restocking sea cucumbers have been proposed, including collection, rearing and transplantation of postlarvae; induced fission; and translocation of adults. However, these methods are not suitable for the large-scale restocking of sandfish. Collection of wild juveniles is not practical because they are difficult to find, even though the settlement habitat of postlarvae has now been identified (Mercier, Battaglene and Hamel, 2000; Hamel *et al.*, 2001). In addition, their abundance is likely to be limited as a result of overfishing, and methods for collecting them at settlement would still involve the use of aquaculture facilities for grow-out. Induced fission is not considered to be an option as it only works for a few generally lower-value species of sea cucumbers and is a slow and labour-intensive way to increase numbers (but see Reichenbach, Nishar and Saeed, 1996). Finally, the translocation of adults would only be effective where their propagules are retained, and at best would benefit some localities at the expense of others. The methods that have been developed for the propagation of juvenile sandfish are described in detail by James *et al.* (1994), Battaglene (1999), Battaglene, Seymour and Ramofafia (1999) and Pitt (2001). A summary of these methods is set out below, together with a description of the research that remains to be done to scale-up the production of juveniles needed for restocking programmes.

Collection and induction of broodstock

Like many other species of tropical sea cucumbers, sandfish can be difficult to hold in captivity. Reduced feeding, weight loss and poor gonad development are often reported for animals kept in tanks. Consequently, it is common practice to use individuals caught from the wild for broodstock. However, transport of the animals to the hatchery can pose problems. In particular, rapid changes in water temperature, salinity and pressure should be avoided because these stresses can cause evisceration and premature spawning of ripe individuals. Packing 20 individuals in separate plastic bags within a single insulated box has proved to be an effective method of transporting sandfish for periods of up to 10 h by small plane (Battaglene *et al.*, 2002).

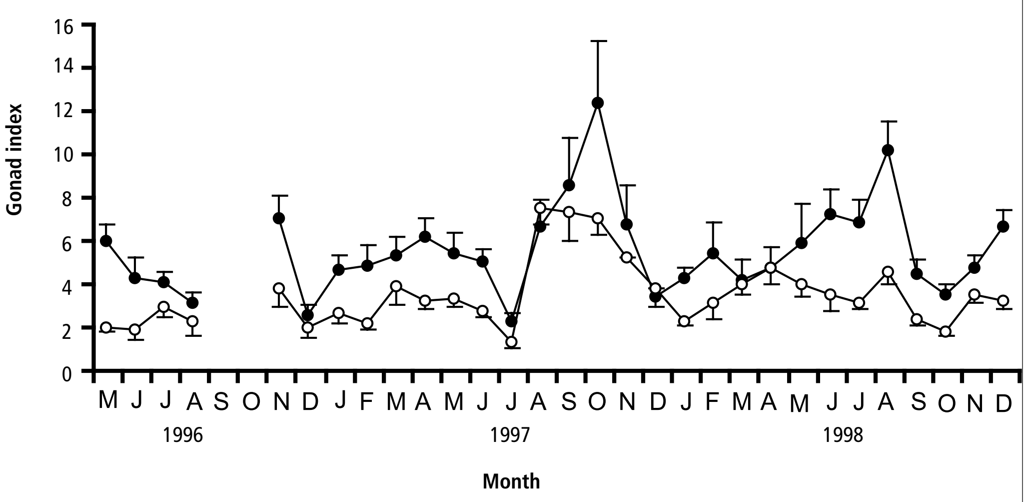
Thermal stimulation is the most commonly used method for inducing sandfish to spawn: temperatures are typically raised by 3–5 °C for 1 h. Spawning success depends on seasonal maturity and lunar periodicity. The natural reproductive cycle of sandfish has been studied in Australia, New Caledonia, Papua New Guinea and the Solomon Islands (Harriot, 1980; Conand, 1993; Ramofafia, unpublished data).

In general, this species has a biannual peak in gonadosomatic index, indicating that there are two main spawning periods each year. However, closer to the equator, e.g. in the Solomon Islands, a proportion of the population appears to spawn all year round (Figure 3). Indeed, in the Solomon Islands, it was possible to induce the production of ripe eggs each month, although the proportion of individuals that shed gametes varied from 10 percent to 50 percent. Overall, it was easiest to spawn sandfish in September, and males were easier to spawn than females.

The addition of a commercially available powdered algal product, *Schizochytrium* sp., Algamac-2000 (Bio-Marine, Hawthorne, CA, the United States) has also been used to induce sandfish to spawn: 100 g of blended Algamac is added to 1000 litres of static seawater for 1 h. However, live phytoplankton is not an effective spawning stimulant, despite the fact that phytoplankton blooms stimulate spawning in some temperate species (Hamel and Mercier, 1996a). A combination of thermal stimulation and addition of Algamac dried algae is recommended for induction of spawning in *Holothuria scabra*.

Despite the past difficulties in maintaining sandfish in tanks, it is now possible to condition this species in captivity. Battaglene *et al.* (2002) held sandfish in 4000-litre fiberglass tanks for over six months in the Solomon Islands. Spontaneous spawning occurred in >60% of animals held in tanks to which shrimp pellets were added to

FIGURE 3. Variation in gonadosomatic index of sandfish, *Holothuria scabra*, from Solomon Islands (after Ramofafia and Battaglene, unpublished data)



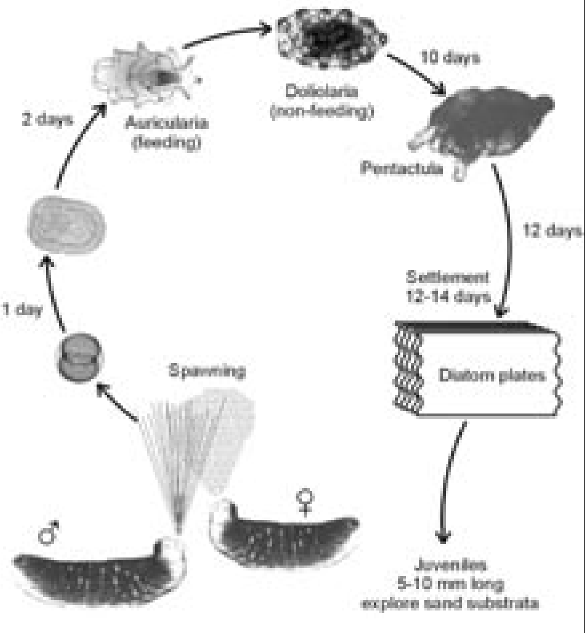
promote bacterial food production. Spawning peaked in October and continued until January when the experiment was terminated. There was also some evidence to suggest that spawning may be influenced by lunar periodicity. Ultimately, it may be possible to achieve out-of-season spawning by holding broodstock in tanks in which the temperature and photoperiod is controlled (as is practised for a number of marine fish and molluscs).

The onset of spawning in sandfish is usually preceded by rolling and agitated movements. Males typically lift half their bodies off the substrate during spawning, releasing sperm continuously for up to 3 h, whereas females spawn in a series of short powerful bursts. Females produce an average of 1.9 million eggs, but this can vary greatly among individuals. The eggs should be fertilized at a sperm density of 10 000–100 000 per ml as higher concentrations of sperm increase the incidence of deformities in holothurian larvae (YSFRI, 1991; Ito, 1995; Hamel and Mercier, 1996b). The fertilized eggs are incubated for 24 h in 250-litre tanks with conical bottoms at 28 ± 2 °C.

Larval rearing and grow-out of juveniles for restocking

As a result of several years of research by the WorldFish Center in the Pacific, and more recently in Viet Nam, methods for the larval rearing of sandfish, and grow-out of juveniles, are now fairly routine. The larval cycle is relatively short, at 14 days, and involves three separate larval stages: auricularia, doliolaria and pentaculae (Figure 4). The auricularia is the larval feeding stage and, provided adequate food is supplied, the larvae become non-feeding doliolaria during a short transition stage before settling as pentactulae (Battaglene, 1999; Pitt, 2001). Feeding of larvae with micro-algae commences on the second day after hatch at 20 000 cells/ml and gradually increases to 40 000 cells/ml after 14 days. Larvae survive and grow best on a combined diet of *Rhodomonas salina* (a red alga with a large cell size, 8–12 µm) and *Chaetoceros muelleri* (diatom, 5– to 8 µm excluding spines). However, if facilities for growing algae are limited, then the best all round choice appears to be *Chaetoceros muelleri* as it is tolerant of high temperatures and is relatively easy to grow.

FIGURE 4. The larval cycle of cultured sandfish (*Holothuria scabra*)

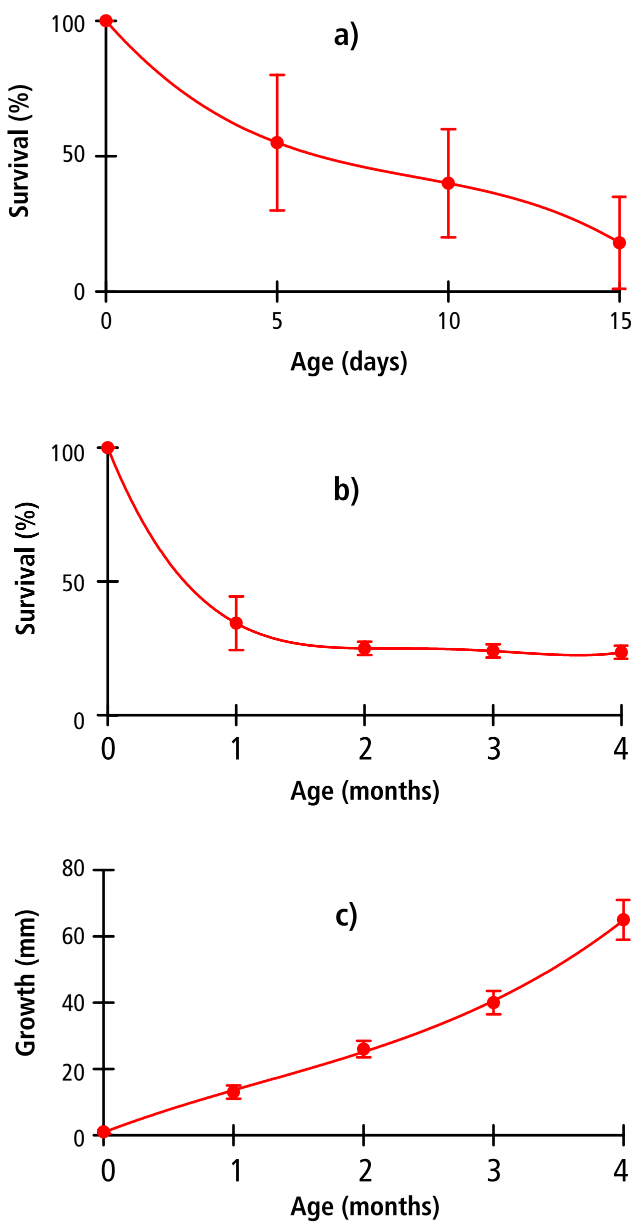


In general, there is a negative relationship between stocking density of larvae and survival to settlement. The optimal stocking density in static tanks, with water temperatures ranging from 26 to 29° C, is around 0.5 larvae/ml. Survival to settlement has been variable, ranging from <1 percent to 35 percent. Mortality is greatest at first feeding, and at settlement (Figure 5a and 5b). Preliminary experiments suggest light intensity should be kept at around 400 lux on the water surface. There is considerable scope for improving the survival of larvae and, as techniques are refined, survival to settlement will hopefully reach the 80–90 percent currently achieved with *Stichopus japonicus* in Japan (Ito and Kitamura, 1997; Yanagisawa, 1998).

The pentactulae larval stage of sandfish are settled on fibreglass plates that have been "conditioned" in seawater for 4–10 days outdoors under direct sunlight. Conditioning provides a bacterial film and fine coating of epiphytes and diatoms that stimulates metamorphosis and settlement of sandfish. Algamac is also added from day 10 at 1.0 g/1 000 litres as a potential settlement cue and source of food for newly settled pentactulae. Newly settled juveniles attach firmly to settlement surfaces and then have to be detached so that they can be moved from indoor larval rearing tanks to outdoor nursery tanks. This is done using a 0.5–1 percent (wt/ wt)solution of potassium chloride (Battaglene and Seymour, 1998).

There is a critical period of high mortality for newly settled juveniles within the first month of culture (Figure 5b). To combat this mortality, it is better to rear juveniles on plates rather than on hard substrata during the initial stages of outdoor culture. Once the juveniles reach a size of 20 mm, which takes an average of six weeks after settlement (Figure 5c), survival stabilizes and they can be transferred to tanks with a substratum of sand. Diatoms and epiphytic algae are the most important sources of food for cultured juveniles up to 50 mm in length and addition of powdered algae does not improve growth or survival except at high densities. Growth rates for juveniles average 0.5 mm/day (±0.03 SE) and 0.2 g/ day (±0.02 SE) for the first two months after settlement. Sandfish juveniles reared in production tanks of 3 000 litres are an average size of 65 mm (Figure 5c) and 18 g three months after settlement, i.e. a total age of four months. Growth is density dependent, however, and slows when densities reach ~ 225 g/m². This is equivalent to 15 individuals of 15 g/m².

FIGURE 5. Survival of cultured sandfish (*Holothuria scabra*) during the 15 days following hatching (a), and following settlement (b). Growth of sandfish juveniles during the first four months following settlement is also shown (c)



In summary, larval sandfish can be produced using standard marine hatchery technology, and the juveniles can be grown-out to sizes that appear to be suitable for release in the wild in 3–4 months with little or no addition of food to tanks. The development of these methods holds great promise for restocking programmes. The challenges now are to scale-up the production of juveniles to provide the tens to hundreds of thousands of individuals needed for rebuilding stocks, and to develop ways of releasing these juveniles into the wild with high rates of survival.

Scaling-up the production of juveniles

This is perhaps the most challenging part of the work remaining to be done. Unlike most fish and molluscs used in aquaculture, sandfish cannot be reared in the water column; rather, they must be associated with the substratum. At stocking densities that do not inhibit growth, a large surface area of tanks or ponds (not including hatchery facilities and settlement systems) is required to culture the great numbers of juveniles needed for effective restocking programmes. For example, a restocking programme designed to release 2 million juveniles would require more than 13 ha of grow-out ponds. Unless a cheaper way of mass-producing the juveniles can be found, there is a considerable risk that the expense involved will be a deterrent to development agencies interested in assisting SIDS with restocking sandfish.

One possible way of defraying these costs would be to combine the culture of sandfish with shrimp, thereby saving the costs of constructing and managing rearing ponds. This may be a possibility for farms dedicated to rearing *Penaeus monodon* because juvenile sandfish juveniles are one of the few species of sea cucumbers that can tolerate a reduction in salinities as low as 20 ppt (Mercier, Battaglene and Hamel, 1999). Otherwise, farms raising shrimp in normal seawater (35 ppt), e.g. those in New Caledonia for *Litopenaeus stylirostris*, may be suitable. In addition to producing a second crop for purchase by development agencies, such co-culture may also have other advantages for the shrimp farmers. These potential benefits stem from the burrowing and feeding behaviour of sandfish. Burrowing by sandfish may help to mobilize nutrients from the sediment into the water column, improving the normally low productivity of ponds early in the shrimp production cycle. The feeding and burrowing behaviour of sandfish may also help assimilate excess nutrients and bacteria towards the end of the production cycle, when eutrophication of pond water is a common problem.

Assessment of the potential for combined culture of sandfish and shrimp cannot proceed, however, until experiments are completed to determine whether there are any deleterious interactions between shrimp and sandfish. This is a possibility because *H. scabra* has sapponins in the body wall (Sotheeswaran, personal communication) that are toxic to some fish. It will also be important to perform experiments in tanks and ponds to determine whether the shrimp prey on the sandfish. The WorldFish Center and partners have undertaken some investigations of interactions between sandfish and *Penaeus monodon* in the Socialist Republic of Viet Nam, and are preparing to perform similar research involving *L. stylirostris* in New Caledonia. If deleterious interactions do not occur, methods for the development of combined culture of sandfish and shrimp in ponds will be investigated. In the event that there are damaging interactions between sandfish and shrimp, there may still be considerable scope for reducing the cost of growing-out sandfish by rearing them in the flooded drains between shrimp ponds.

An alternative to ponds, with or without shrimps, for rearing cultured juveniles for restocking programmes would be the farming methods already developed in

India and Indonesia (FAO, 1988; Daud *et al.*, 1993; Muliani, 1993; James, 1994, 1996). There, sandfish are grown-out in rectangular meshed cages anchored to the mud by wooden poles. According to James *et al.* (1994), cages need to be cleaned regularly and replenished with new substrate in order to obtain good survival and growth. Farmed juveniles are also fed various waste products, including chicken manure and the bottom sludge from prawn farming ponds. However, such methods would make it difficult to mass-produce the very large numbers of individuals needed for restocking programmes. They would also be vulnerable to vandalism, poaching and damage by storms.

RELEASE STRATEGY

In tandem with the development of methods for the cost-effective mass-production of sandfish 3–6 months of age, it is critical to determine how to release the juveniles in a way that ensures they survive to maturity in high proportions. As a prelude to the development of optimal release strategies, there has been a concerted effort to learn about the ecology of juvenile sandfish (reviewed by Hamel *et al.*, 2001).

It is now evident that recently settled juveniles occur on seagrass leaves in the wild, and that the pentactulae settle preferentially on seagrass leaves, possibly using chemical detection (Mercier, Battaglene and Hamel, 2000). Newly-settled juveniles remain on the seagrass leaves for about a month, then migrate to sand at around 6 mm in length (Mercier, Battaglene and Hamel, 2000), where they are initially cryptic. However, once they reach 10–40 mm in length, they start to display diel burrowing behaviour, emerging close to sunset and burrowing around sunrise (Mercier, Battaglene and Hamel, 1999). The recent research has also shown that juveniles of all sizes demonstrate a strong selectivity for organically rich sediments with a mean grain size of 0.4 mm, and are tolerant of salinities as low as 20 ppt (Mercier, Battaglene and Hamel, 1999). In general, juvenile sandfish can inhabit a range of shallow sandy inshore areas, suggesting that it may be possible to release them effectively in a number of habitats.

Based on what we now know about the ecology of sandfish, the lessons from restocking a temperate species of sea cucumber in Japan (Yanagisawa, 1996, 1998), and the stock enhancement of other species (Blankenship and Leber, 1995), the following factors have potential to affect the survival of released sandfish: method of transport to the release site, size at release, type of substrate, timing of releases (both within the diurnal cycle and seasonal), stocking density, abundance of predators and availability of food.

To date, there have only been short-term field experimentss to examine one of these factors: release habitat. Dance, Lane and Bell (2003) released juvenile cultured sandfish, with a mean size of 35 mm, on soft substrata near mangrove–seagrass and lagoonal coral reef flat habitats in the Western Province of the Solomon Islands. Mean survival at the mangrove–seagrass sites was 95–100 percent 1 h after release and approximated 70 percent three days later. At the coral reef flat sites, however, mean survival was as low as 37.5 percent 1 h after release and total loss occurred in two of the three releases within 48 h. The mortality was a result of predation by fish (Balistidae, Labridae, Lethrinidae and Nemipteridae). Dance, Lane and Bell (2003) also demonstrated that survival of juvenile sandfish was improved significantly by releasing them within a cage of 8-mm mesh, but did not continue the experiments for long enough to determine whether high rates of predation occurred for larger individuals in the coral habitat once the cages were removed. They concluded that, for the two habitats they studied, only the mangrove–seagrass areas should be considered for release of juvenile sandfish. They also suggested that release at night, to coincide with the time sandfish emerge during their diel burrowing cycle, and short-term use of protective cages, should be investigated to improve survival in that habitat.

The WorldFish Center is now assessing the effects of the factors listed above on the survival of juvenile cultured sandfish released into the wild. The research is being carried out in the zones of the lagoon in New Caledonia where sandfish are distributed commonly (Conand, 1989) in collaboration with the Secretariat of the Pacific Community (SPC), the Provinces and Government of New Caledonia and the French Research Institute for Exploitation of the Sea (IFREMER).

GENETIC RESOURCE MANAGEMENT

The programme to develop methods for restocking sandfish in the Pacific is paying special attention to the need to describe the genetic structure of stocks in the region, and the need to produce and release juveniles in a way that maintains the genetic diversity of these stocks. The work on stock structure has been the initiative of the Australian Institute of Marine Science (AIMS) with support from the WorldFish Center. To date, the analysis has been limited to quantifying the genetic affinities of sandfish at several inshore locations along the tropical coast of eastern Australia, and from two locations in the Solomon Islands. However, plans are in place to broaden the scope of the study to include Papua New Guinea, New Caledonia and several sites in Southeast Asia.

Although the extent of the sampling for the analysis of stock structure has been limited, some important results have already emerged. In particular, gene flow between populations from different locations on the east coast of Australia is significantly restricted (Uthicke and Benzie, 1999). Moreover, one of the two populations in the Solomon Islands is more closely related to a population in Australia than it is to the other one in the Solomon Islands, even though the two populations in the Solomon Islands are only about 20 km apart (S. Uthicke, personal communication). Other important findings from the study are that there were no significant differences between individuals from shallow and deep water, or between black and brown colour morphs, at the same general location in Australia (Uthicke and Benzie, 1999).

On the basis of the distinct structuring of sandfish stocks in the Pacific revealed by the above-mentioned study, juveniles used in field experiments to develop optimal release strategies will only be released in the same general area where the broodstock were collected. Other measures advocated to conserve the genetic diversity of sandfish stocks during field experiments and pilot-scale restocking projects will include:

(1) use of a minimum of 30 broodstock for each spawning;

(2) regular replacement of all broodstock and;

(3) release of multiple cohorts at the same site.

One problem that has emerged with these measures is that even when large numbers of broodstock are used, the effective spawning size for sandfish is low: as few as 10 percent of induced animals shed gametes. However, taken together over time, the measures listed above should greatly reduce the risk of altering the gene pool as the production and release of numerous cohorts, each with different gene frequencies, will build a released stock with gene frequencies approximating the wild population (Munro and Bell, 1997 and references therein). In other cases where this approach has been used, the resulting gene frequency of all cultured individuals combined is a close approximation to that of the wild stock (e.g. Bartley and Kent, 1990).

HEALTH MANAGEMENT

Few problems have arisen with diseases during the propagation and grow-out of sandfish but there is always a risk of transferring pathogens to the wild through the release of cultured juveniles. The only significant incidence of disease during the production of seven cohorts of sandfish in Solomon Islands between 1997 and 1999 was the loss of one tank of three-month-old sandfish to skin peeling disease. The cause of this disease is thought to be ciliated protozoans brought on by overcrowding (Yanagisawa 1998). There is no known treatment for skin peeling disease but it does not appear to be highly contagious and can be avoided through good husbandry practices.

We recommend the following quarantine procedures prior to release of juveniles:

1. removal of damaged or sick animals during the culture period;
2. placement of sandfish in tanks with hard surfaces, flow-though seawater and aeration for 48 h prior to release to evacuate intestines of sand. There should also be regular removal of sand and faecal material from the tanks during this period;
3. examination of a subsample of sandfish for external parasites and diseases prior to release;
4. removal of any algae or invertebrates associated with sandfish harvested from quarantine tanks to avoid translocation of other organisms to the wild.

The main "health" management problems facing the production of sandfish are likely to be the control of predators and competitors of the larvae, rather than the treatment of diseases per se. For example, copepods multiply in tanks receiving unfiltered water and cause mortality of the larvae by depleting food resources. The copepods can be removed with regular applications of Trichlorophos at 0.5–1 ppm for 8 h or Dipterx at 2 ppm for 2 h (James *et al.*, 1994; Ito, 1995; Yanagisawa, 1996; Ito and Kitamura, 1997). Alternatively, copepod infestations can be prevented by routine filtering of seawater with 5 µm nominal filters, and regular transfer of juveniles to clean tanks.

MONITORING AND EVALUATION

Although no large-scale releases of sandfish in the Pacific to rebuild wild stocks have yet occurred, some thought has already gone into two of the components that will be required for effective monitoring and evaluation of restocking. These components are the development of methods for measuring the success of releasing cultured juveniles, and estimates of the potential economic gains from a national restocking project.

Measures of success

There are two options for measuring the success of programmes for restocking sandfish. One involves the use of a genetic marker to identify the proportion of the rebuilt stock derived from released cultured animals; the other is based on large-scale sampling to compare abundances of sandfish at sites with and without releases.

Genetic markers provide a possible tool for measuring the success of restocking programmes because they allow the progeny of released cultured animals to be identified across generations. Genetic tags can be created by breeding programmes that confer distinctive, inherited morphology or by screening and selecting broodstock with rare alleles (Munro and Bell, 1997 and reference therein). In the case of sandfish, one such potential genetic marker can be identified easily: a significant proportion (from 10 to 60 percent) of cultured individuals are black, even when the broodstock is composed completely of "brown" morphs. However, there are some reasons why it may not be practical to use the black morph as a genetic marker. These reasons are: 1) Black adults are not common in the wild, perhaps because they are more conspicuous and harvested in greater proportions than the brown morph, which means that it may be difficult to collect sufficient black individuals for responsible broodstock management; 2) the pattern of inheritance for the black morph is unknown and thus, even if only black individuals are used in restocking programmes, there is no guarantee that their progeny will be black, or that black individuals will be produced in high proportions when black morphs interbreed with wild brown stock; 3) brown cultured juveniles would not be suitable for experimental restocking programmes. The last of these problems is only a short-term concern as, once the effectiveness of restocking has been demonstrated, there will be no necessity to mark individuals and both colour morphs can be used for releases. The other concerns would also be eliminated if sufficient numbers of wild black adults could be accumulated for responsible broodstock management, and the black morph had a very high rate of inheritance. However, the probability of overcoming these problems cannot be determined without several years of effort and research.

The other means of creating a genetic marker, by selecting broodstock with rare alleles, is more suited to situations in which the breeding animals can be kept in captivity and managed so that the rare alleles can be included in each cohort used for restocking. In the case of sandfish, where there is reliance on the use of wild broodstock, the identification of rare alleles in each batch of animals collected for spawning, and their subsequent detection to ascertain the contribution of released animals to the restored stock, would be too complicated and expensive. Further problems with this method are that the rare alleles may be deleterious to the fitness of released sandfish and, if so, this lack of fitness would be passed on to the remnant wild stock through introgression of genes during inbreeding between cultured animals (or their progeny) and wild individuals.

The time and cost required to identify effective and safe genetic tags for released sandfish, compared with the relative ease of counting sedentary sandfish in shallow water, promotes the use of sampling methods to measure the success of restocking programmes. The technique we advocate is based on the work of Underwood (1992, 1995) and depends on sampling the abundance of sandfish in the populations(s) to be restocked, and those at several unstocked (control) sites, on several occasions before and after the release of juveniles. In this case, the "after" sampling would be done once the population had been given sufficient time to recover to fishable levels (i.e. the time needed for several generations). Significantly greater abundances at restocked sites than at control sites at such times can then be attributed unequivocally to restocking, rather than to the effects of other processes influencing recruitment.

Economic analysis

The initiatives to restock sandfish in the Pacific have been based on the fact that the price for first-grade bêche-de-mer is inelastic, and the general assessment that the costs of restoration should not exceed the value of the additional production in the long term. The exact information needed to calculate whether the gains from restocking will exceed the costs will not be available until the research has been completed. This information includes: the cost of producing and releasing cultured juveniles and protecting them from fishing until robust populations are established; the survival, reproductive success and longevity of the released sandfish; the level of sustainable harvests possible each year after stocks are replenished; and the area and carrying capacity of habitat suitable for sandfish. For evaluation of subsequent stock enhancement programmes to overcome recruitment limitation, the additional information needed is simply the difference between the cost of producing and releasing juveniles and the value of the additional production.

The bêche-de-mer fishery in the Solomon Islands provides an indication of the benefits and costs of using restocking or stock enhancement to manage the resource. Throughout much of the 1980s, harvests of bêche-de-mer from the Solomon Islands were steady at about 150 tonnes per annum (Figure 1b) but, according to one of the principal exporters, the catches included only a small component of sandfish because of previous overfishing of this valuable species. Consequently, there is much potential to increase the yield of sandfish from the numerous large lagoons surrounding the high islands that comprise the nation. However, even if the increase in production was limited to 50 tonnes of bêche-de-mer, the value of the additional catch would be up to US$2.5 million because first-grade sandfish currently fetches a retail price of US$50/ kg. Approximately 25 percent of this additional revenue (i.e. US$625 000) would be expected to end up in the hands of artisanal fishers. The costs of releasing and protecting the number of juveniles needed to restore the spawning biomass of sandfish to the level at which regular additional annual harvests of 50 tonnes were possible is unknown, but may not be much more than the release of a few large, genetically diverse cohorts in close succession, provided there is widespread compliance with the necessary prohibition on fishing during the restoration period.

The option of producing and releasing enough juveniles every year to increase catches by 50 tonnes in a stock enhancement programme would be more expensive, but is still estimated to be viable. For example, we estimate that the cost of producing juvenile sandfish is around US$0.25 each in some countries, and that the release of 2 million juveniles would result in the harvest of an additional 50 tonnes. This is based on the fact that there are 10 sandfish/kg of first grade bêche-de-mer, and that the average rate of survival in other restocking programmes worldwide is 25 percent (Munro and Bell, 1997). Thus, the annual cost of producing the juveniles required to increase yields by 50 tonnes is estimated to be US$500 000. If correct, this would result in a net added value to the fishers for each release of US$625 000, equivalent to a 25 percent return on investment.

The estimate of US$0.25 per animal is conservative and based on our experience in producing juvenile sandfish of 20 mm in length. However, the price should decline significantly with further research and economies of scale. In Japan, it costs about US$0.04 to produce a juvenile *Stichopus japonicus* (Yanagisawa, 1998). This is an appropriate comparison because, in 1996, the Sea Farming Centres in Japan released a total of 2 557 000 *S. japonicus*, with an average size of 9 mm (range 1–120 mm).

As mentioned previously, the artisanal fishers in the Pacific are not in a position to organize or pay for hatcheries to restock sandfish. This will have to be done on their behalf by development agencies. It is vital, however, that such support is maintained until stocks are rebuilt and managed to produce sustainable yields because the national governments do not have the resources to complete such programmes if support is withdrawn prematurely (Bell, 1999b).

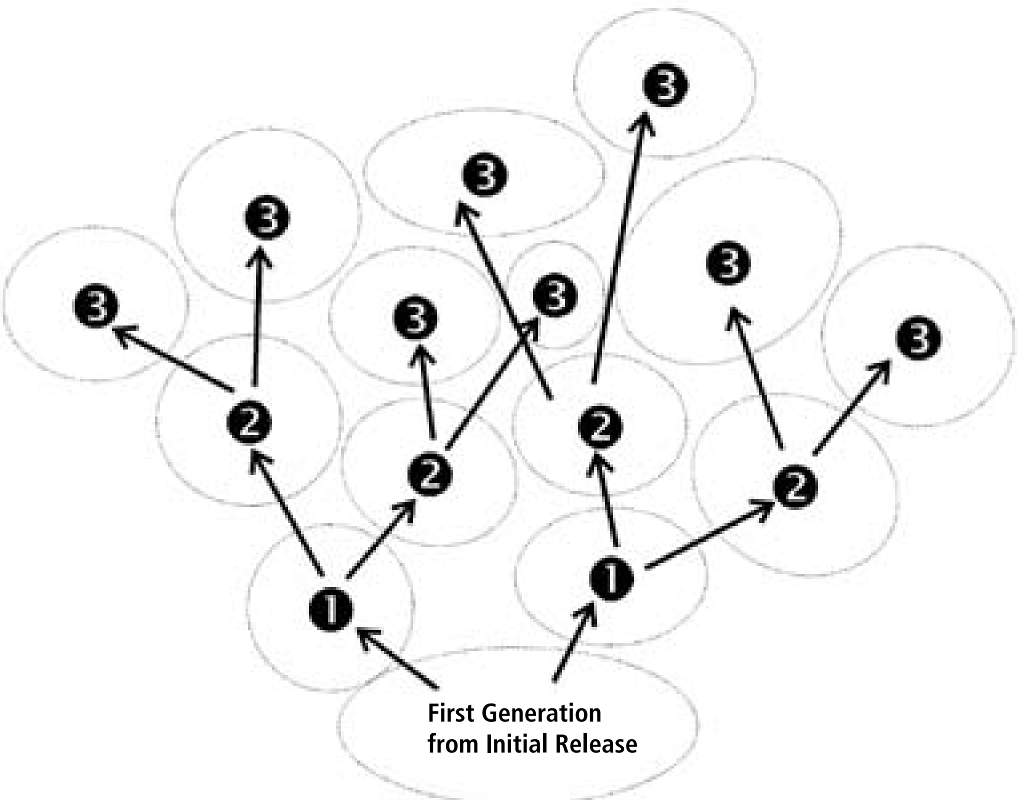
SPECIFIC MANAGEMENT REQUIRED FOR RESTOCKING

The range of management measures described earlier will need to be refined to ensure that restored sandfish stocks do not suffer recruitment and growth overfishing once the fishery is reopened. Prior to these measures, however, two specific types of management are needed for restocked populations of sandfish. The first task is to provide complete protection for the released individuals and the remnant wild stock until they and their progeny have replenished the population to the point at which substantial harvests can be sustained each year. This requires a well-policed moratorium on the capture and export of sandfish.

The second task is to manage the releases of sandfish so that all suitable habitat is colonized as quickly as possible. Where there is a single genetic stock and a large production facility, this can be done through multiple releases of juveniles at numerous points. However, in some Pacific Islands, there is likely to be discrete structuring of sandfish stocks and/or limited capacity to produce cultured juveniles. In such situations, the available resources may only be able to produce enough juveniles for releases at one area for each discrete stock. If so, dispersal of sandfish to all suitable habitat would be facilitated by translocation of a portion of the progeny produced at the restocked area to depleted areas within the range of the stock. Figure 6 provides an example of the gains that could be made through a well-managed translocation programme of this nature: 14 depleted areas could receive sandfish within three generations if two translocations of progeny were made from each area where spawning occurred.

The conditions that need to be met for translocations to be a responsible means of augmenting restocking programmes are: (i) the initial release has to be large and genetically diverse, (ii) sufficient juveniles need to be translocated each time to provide a genetically diverse and effective spawning biomass, (iii) the area where the progeny

FIGURE 6. Scheme for the translocation of sandfish from restocked to depleted areas to distribute juveniles to all suitable habitat. Numbers refer to the generation derived from an initial release of cultured animals. Broken lines denote area of larval dispersal of progeny of restocked sandfish



will occur can be defined, and (iv) the progeny are not transferred across stock boundaries. Owing to problems associated with achieving mass-spawning of sandfish in hatcheries, the first of these conditions may be difficult to achieve. However, it is most important that the initial release is genetically diverse because the gene frequencies will be translocated to all other areas. This may necessitate the release and spawning of several cohorts at the initial release site before translocations begin.

Whether direct hatchery releases or initial releases followed by translocations are used to rebuild the fishery, effective restocking of sandfish in the Pacific will also depend on close cooperation with fishing communities. As customary marine tenure is widespread in many Pacific countries, it will be important to ensure that all groups in control of suitable habitat for sandfish eventually receive juveniles to restock their areas. This consideration will be met by the aim to supply all suitable habitat with juveniles; however, the reality will be that some areas will receive juveniles before others. Clearly, it will aid social harmony if all communities are informed about the process, and the rationale, for the progressive distribution of juveniles. This will be particularly important where it is necessary to use translocation of progeny from one area to another.

The need to work with communities is not limited to the period required for rebuilding of the stock: communities will also be responsible for management of sandfish stocks once exports are permitted and so will need information about how best to sustain catches. There will also be the need for cooperation among communities in setting levels of catch because mismatches will occur between the distribution of a discrete stock and the area under the tenure of a community, such that effective management will depend on a unified approach by several communities. Regular communication with all communities during the rebuilding phase about the merits of the restocking programme, and the management measures that should be applied once the fishery reopens, will greatly enhance the likelihood of successful and cooperative community-based management of sandfish stocks.

SUMMARY AND CONCLUSIONS

Restocking with hatchery-reared juveniles has great potential to help Pacific Islands break the long-term "boom and bust" cycle of the bêche-de-mer fishery. The main benefit of restocking is that it provides a way to "fast-track" the restoration of stocks to the point where they can be managed for sustainable yields.

There are four steps to delivering the benefits promised by restocking: (1) development of methods for the mass-production of juveniles, (2) learning how to release the cultured sandfish in the wild so that they survive in high proportions, (3) protecting the released sea cucumbers until stocks are replenished and (4) managing the restored stocks to obtain sustainable harvests of first-grade bêche-de-mer (i.e. large individuals). The same technology used for restocking can then be applied to supplement the yields of restored stocks by releasing cultured juveniles in stock enhancement programmes to overcome recruitment limitation. This would allow the production of sandfish to approach the carrying capacity of the habitat.

Although the way to restore and manage the fishery for sea cucumbers in the Pacific is now apparent, only some of the technology and procedures needed to achieve these goals are currently in place. Furthermore, the research has been confined largely to just one species, sandfish (*Holothuria scabra*). The major challenges remaining for restocking of sandfish are: learning how to scale-up the rearing techniques to produce the hundreds of thousands of juveniles needed to have an impact on the abundance of stocks; developing effective strategies for releasing cultured juveniles in the wild; and assessing the economic viability of restocking. In all three cases, however, there is cause for optimism. If research underway to investigate the potential for co-culture of sandfish and shrimp is successful, the mass-production of juvenile sandfish may be possible as a by-crop of shrimp farming. Otherwise, it should be possible to mass-produce sandfish in dedicated ponds, albeit at greater cost. There is no obvious impediment to the development of release strategies, nor are there any apparent reasons why it cannot be done in a responsible way. For example, guidelines are in place for the management of broodstock to maintain genetic diversity, the risk of introducing diseases to conspecifics and other species appears to be low, and the fact that sandfish are low in the food chain means that there should be little or no impact on other fisheries species. Preliminary estimates also indicate that restocking should be economically viable in terms of returns to artisanal fishermen, although we hasten to point out that such an evaluation cannot be done thoroughly until the necessary research has been completed.

The key to harnessing the potential benefits of restocking sandfish is support for the programmes from regional/international research organizations, fishing communities, governments and development agencies. The regional/international research organizations need to complete the development of cost-effective methods for restocking sandfish so that this tool is ready for application throughout the Pacific. The fishing communities need to be prepared to forego catches until the stocks are rebuilt, and then to comply with the advice and/or regulations designed to ensure that yields of high value can be obtained each year.

Governments must provide the framework for this process by implementing a moratorium on the export of sandfish until the stocks recover, applying a total export quota based on sustainable yields when the fishery is reopened and ensuring that there is compliance with these laws. Finally, as most governments in the Pacific do not have the financial or human resources to produce the very large numbers of juveniles required to replenish stocks, support is needed from development agencies for restocking programmes. They could also assist by contributing to the costs of developing the measures needed for sustainable management of the restored fishery.

Overall, the prospects for restocking sandfish look particularly promising and every effort should be made to bring this potential management tool to the attention of fishing communities, governments and development agencies so that they stand ready to support and implement restocking programmes as soon as the full suite of methods required becomes available.

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