Economics of Coral Reef Restoration

James P. G. Spurgeon & Ulf Lindahl

ABSTRACT

This chapter provides an introduction to the economics of coral reef restoration. A comparison of coral restoration schemes from four countries indicates that costs can vary from some US$ 13,000 per ha to over a hundred million US$ per ha. However, it also reveals that cost estimates in the literature are not readily comparable, and that many cost components of restoration are ignored. Little work has been conducted into the potential benefits of coral restoration. This issue is briefly considered with reference to the case studies. The chapter suggests that a benefit–cost analysis approach should be used more often to help assess the justification for coral reef restoration and to improve the efficiency of any such expenditure. It is clear that a greater understanding of the economics and biology of coral reef restoration is required, as well as consideration of alternative management options, before being able to determine with confidence whether coral reef restoration really is an effective use of available funds.

1. INTRODUCTION

Coral reefs throughout the world are being degraded (Birkeland 1997). Related to this is an increasing interest in, and perceived need for coral reef restoration. Numerous attempts at restoring coral reefs are currently being undertaken (NCRI 1999), and a few useful guidelines (Miller et al. 1993) and reviews of the literature (Edwards and Clark 1998) are available. However, a fundamental question is whether coral restoration is actually an appropriate use of funds to maintain and enhance the world's valuable remaining coral reefs?

Resources and funds available for coral reef conservation are without doubt limited. Benefit–cost analysis (BCA) is a decision-aiding tool that can help select the most efficient means of achieving maximum economic returns from using a country's resources (i.e. labour, capital and natural resources). As is further explained in in the overview essay by Cesar in this monograph (pp. 14–39), this technique involves the identification, valuation and comparison of all economic costs and benefits that relate to a particular use of resources, such as a coral restoration scheme. If all factors are fully accounted for, the scheme with the greatest ratio of benefits to costs can generally be considered the preferred option.

This chapter provides an introduction to the economics of coral reef restoration. Using five coral restoration case studies, it gives an overview of restoration costs and benefits. To conclude, an assessment is made of the potential application of benefit–cost analysis and other decision-making tools to evaluate the usefulness of coral reef restoration.

2. THREATS TO CORAL REEFS

Various mechanisms, both natural and human-induced, commonly degrade and destroy coral reefs. For the purposes of this review, the mechanisms are classified into two categories by the nature of their impact on the reef framework. First are those mechanisms that cause direct structural damage, where the corals and other sessile biota are crushed, dislodged or removed. This occurs from incidents such as: storms; ship groundings; destructive fishing practices; coral quarrying; and careless diving.

These impacts can flatten the three-dimensional relief of the reef and create rubble and shifting sediment. The latter may prevent the recruitment of corals and cause further destruction through wave-induced movement and abrasion (Alcala & Gomez 1987, Fox et al. 1999, Harriott et al. 1997). Ship-groundings can also shatter the underlying reef rock, resulting in secondary damage if boulders are dislodged during storms (Miller et al. 1993).

Second, are the more insidious chemical, biological and physical impacts such as: toxic and thermal pollution; lower salinity; eutrophication; sedimentation; and biotic changes (e.g. diseases and crown-of-thorns starfish infestation). Their origin is generally less direct and may be difficult to determine. These disturbances can cause coral mortality or reduced growth, but will initially leave a structurally intact reef framework, which may disintegrate slowly (Sano et al 1987) or can be recolonised.

3. CORAL RESTORATION OBJECTIVES AND TECHNIQUES

The field of coral reef restoration encompasses a wide range of objectives and techniques. Indeed, the term 'restoration' is commonly used as an umbrella term for several forms of human interference or 'manipulation' of coral habitats, as is the case in this chapter. Coral habitat manipulation includes:

- 'restoration' of a damaged reef back, as nearly as possible, to its original condition, for example in terms of its biological diversity, structure, functions and aesthetic quality;
- 'rehabilitation' (or partial restoration) of a damaged reef, whereby the original characteristics and qualities are either partially replaced, or are replaced by an alternative set, perhaps with emphasis on certain functions such as fish habitat or coast protection.
- 'creation' is also possible under certain conditions, whereby corals are either directly introduced, or conditions are altered to enable corals to grow, in areas previously devoid of coral (Bowden-Kerby 1996; Oren & Benayahu 1981; Bouchon et al. 1981; Van Treeck & Schumacher 1999).

Restoration, rehabilitation and creation of coral reefs are increasingly being used and experimented with as a means of managing and conserving coral reefs, and helping to make up for the many threats to them. As is summarised by Edwards and Clark (1998), the techniques have been used for.

i) aiding recovery following various physical, chemical and biological damages;
ii) moving of corals threatened by development and pollution; and
iii) enhancing coral habitats for tourism and fisheries.

For the purposes of this review, coral restoration techniques used to achieve the above objectives can be categorised into three main methods. Each is briefly outlined below, and can either be carried out independently or in conjunction with each other:

- Fixing the substrate. This may include clearing and consolidating loose rubble, and stabilising or filling cracks and hollows (Fox et al. 1999; Hudson & Diaz 1988; NOAA 1999)
- Installing artificial reefs. A range of artificial structures can be placed on the seabed to provide a suitable surface for natural and human induced coral attachment. Structures include concrete blocks and mattresses (Clark & Edwards 1995; Fitzharding & Bailey-Brock 1989; and Harriott & Fisk 1988) and using electrolytically accreted carbonate on chicken wire (Van Treeck & Schumacher 1999).
- Transplanting corals. Corals can be relocated and fixed to the substrate using glue, nails or wire, or simply left to attach naturally (Auberson 1982;

Birkeland et al. 1979; Bowden-Kerby 1996; 1999a; 1999b; Clark & Edwards 1995; Guzmán 1991; Harriott & Fisk 1988; Kaly 1995 Maragos 1974; Yap et al. 1992).

In addition, there is growing interest among scientists to use sexually recruited corals for reef rehabilitation through 'coral ranching'. Coral larvae can be reared in aquaria (Sammarco et al. 1999) or collected from slicks occurring after mass spawning events (Heyward et al. 1999). After some time in tanks or ponds, the coral larvae can be released on the target area, where they are held in place by net enclosures (Heyward et al. 1999) or by naturally occurring eddies (Sammarco et al. 1999) until they settle. These techniques are quite distinct from the other methods and are not covered further.

4. CORAL RESTORATION COSTS

The main economic cost components associated with coral restoration schemes can be split into capital and operational costs. The economic cost of resource inputs such as labour and materials are generally measured in terms of their 'opportunity cost'. This is defined as the value of that resource in its next best alternative use. Market prices can generally be used as a basis for opportunity costs, although they often need adjusting to allow for market distortions (e.g. government subsidies and taxes).

When comparing the cost of alternative options it is important to consider 'whole-life' costs. These are costs incurred from the outset of the initiative throughout the expected life of the scheme. Although various uncertainties may affect future scheme costs, adequate predictions can be made.

4.1 Capital Costs

Capital costs include both pre-construction and construction costs. Pre-construction costs include initial feasibility studies, site surveys, objective setting, and planning and design of the restoration. Construction costs are those needed to carry out the main restoration scheme itself, and include costs for substrate preparation, equipment, labour, materials, stock and transport. Two other types of associated cost that should be accounted for at this stage are the 'opportunity costs' of using the site and any donor site impacts. These are discussed in Section 4.4 .

4.2 Operational Costs

Once a scheme has been undertaken, it could be left entirely to the elements to succeed or fail. However, there will often be a case for continued operational involvement comprising elements of scheme management, maintenance and monitoring. Again these will include costs such as materials, equipment, staff wages, expenses and general administration costs.

Management may be required to minimise possible interference from, for example, destructive fishing methods, divers and natural disturbances at the site. Maintenance may be needed to repair damages to any newly installed structures, or to re-attach dislodged transplanted corals following rough weather. Monitoring is essential to assess the success of the restoration scheme, and enables appropriate and timely corrective management and maintenance measures to be taken.

Operational costs will be highly variable depending on the nature of the scheme and site specific factors. Few studies highlight and reveal the likely costs involved. However, Miller et al. (1993) do provide an indication of costs for 25 different types of coral restoration monitoring activities. Costs are shown to range from between US$ 5,000–100,000 for each activity although it is not clear as to how large an area these costs relate to.

4.3 Labour costs

An important component of capital and operational costs are costs for supervision, training and labour (i.e. actually undertaking the restoration). Individuals involved can range from expensive experienced professional personnel, to fishermen and voluntary recreational divers or students who may accept minimal or no payment. Since restoration is frequently labour intensive, particularly transplanting and relocating corals, unit price labour costs have a major bearing on overall costs.

Supervision and training of labour should always be carried out with the participation of an experienced biologist. The selection of suitable species, source populations and target areas, and the application of appropriate methods requires a thorough understanding of ecological processes, practical field experience and in many cases some systematic experimentation. Even the simplest methods for coral transplantation using unattached staghorn coral (Bowden-Kerby 1999b) requires that participating workers are trained and supervised, at least in the initial phase.

4.4 Other Associated Costs

The 'opportunity cost' of using a site (i.e. the value of using it for its next best alternative use) should be considered. This value will usually be small since there are few alternative uses for coral reefs. However, exceptions include instances where construction materials and land are scarce, and reefs consequently have a high value for coral mining or for land reclamation, as may be the case for some remote islands.

Another commonly overlooked coral restoration cost is the damage caused to the 'donor' or 'source' populations. Removal and relocation of coral colonies or fragments from healthy sites to degraded areas can effectively redistribute some of the damage to the donor site. Careful consideration is even needed as to the overall balance of effects prior to collecting and transplanting unattached fragments created by storms or bio-erosion. As some corals reproduce mainly through fragmentation (Highsmith 1982), the collection of these propagules may interfere with a critical step in the natural colonisation/rejuvenation process. The negative impacts to the donor site should always be fully considered and must not outweigh the transplantation benefits.

In circumstances where intraspecific competition for space occurs between adjacent coral branches, for example in some areas of dense coral cover, selective harvesting of coral branches may not significantly reduce the overall coral growth rate at the donor site. Each individual case therefore needs to be examined in light of appropriate ecological and economic theory.

5. CASE STUDIES

A simple comparison of the costs of past attempts at coral restoration reveals the potential magnitude and significant variation of costs involved. This section briefly summarises five such cases.

The past decade has seen numerous coral reef restoration schemes undertaken in the United States, many in an attempt to rectify damages occurring to corals following ships running aground. The M/V Elpis, a 150 m cargo freighter, hit a reef in the Florida Keys National Marine Sanctuary (FKNMS) in 1989. Under the National Marine Sanctuaries Act, the National Oceanic and Atmospheric Administration (NOAA) were authorised to recover costs and damages to pay for site restoration. Funds of US$ 1.66 million (1991 prices) were awarded to restore 2,605 m^2 of totally destroyed reef and 468 m^2 of partially destroyed reef. The restoration involved removing debris, stabilising the reef substrate, importing new substrate, transplanting corals and sponges, and monitoring of the results (NOAA 1997). Extrapolating the costs based on 0.3 ha damage gives an overall cost of US$ 5.5 million/ha. This value is calculated merely as a means of indicative comparison and ignores potential economies of scale.

When the R/V Columbus Iselin ran aground and destroyed 345 m^2 of reef in FKNMS in 1994 (NOAA 1999), the ship's owner paid US$ 3.76 million in natural resource damages. The rehabilitation included removal of debris, reinforcement and rebuilding to prevent further disintegration of the cracked reef, and transplantation of reef biota to the impacted site. The objectives were to restore, to the extent practicable, the pre-existing habitat, structure and depth of the site. Some money was also used for compensatory restoration and grounding prevention elsewhere in the Sanctuary. A simple extrapolation gives a cost per hectare of over US$ 100 million.

Edwards and others (Edwards et al. 1994; Clark & Edwards 1995; 1999) evaluated different options to rehabilitate sections of reef in the Maldives previously destroyed by coral mining. This was attempted by stabilising the substrate, use of artificial reefs and through coral transplants. Costs (in 1994 prices) ranged from

US$ 0.4 million/ha for deployment of anchored chain link fencing, to US$ 1 million/ha for concrete (Armourflex) mattresses, and up to US$ 1.6 million/ha for the use of one cubic metre concrete blocks.

The objective of the study was to evaluate the effectiveness of alternative methods of rehabilitating former coral reefs to help protect the shoreline from erosion and to provide fish habitat. The enhancement of reef functions was to be provided directly through the influence of the installed structures and indirectly by providing substrate for coral recruitment. The costs only relate to construction and installation of artificial structures placed on barren reefs. The estimates exclude pre-construction studies, transplantation and subsequent monitoring or other associated costs.

Kaly (1995) compared methods of enhancing coral cover using different coral transplantation techniques on tourist damaged coral reefs on the Great Barrier Reef, Australia. She examined two methods of attachment, one using epoxy cement, the other using nails and cable ties. Increasing the natural density of corals on one hectare of hard substrate by 10% was found to cost roughly US$ 40,000 (1995 prices) for either method. The estimated costs only included labour (diving) and materials used for the re-attachment. The costs did not include time for obtaining the corals or monitoring or damages to the donor sites.

Lindahl (1998) studied methods to rehabilitate degraded coral reefs through transplantation of staghorn (*Acropora*) corals in Tanzania. The methods can potentially be used to restore or enhance coral cover to provide fish habitat and coastal protection, and improve the attractiveness of the site for tourists. The study demonstrated that coral fragments can be successfully collected and relocated in low to moderately exposed shallow areas without scuba-diving and with only minimal attachment. Based on the 1998 research results, it is predicted that an initial 10% coral cover might, over a six year period, attain a cover of 60–80%, even on an unconsolidated substrate. Assuming transplantation of 2.5 kg of corals per m^2 on a site three km from the donor population and five km from the nearest inhabited island, the costs would be about US$ 7,000/ha. The operation is estimated to take nine people, including a supervising marine biologist, around 5 months to complete. Costs include transportation of labour and corals by boat, but exclude an initial one-time pre-construction cost of US$ 6,000 for surveys, planning and training of the staff. Subsequent monitoring costs need only cost around US$ 200 per year for a basic coral and fish survey, for a six year period.

6. DISCUSSION OF CASE STUDY COSTS

It is first worth pointing out a few problems encountered in assessing and comparing the case study costs. Firstly, no detailed costings for coral restoration schemes are generally available in the literature. Secondly, there is no standard approach to accounting for and documenting the costs. Thirdly, the conversion of costs for different sized restoration schemes to a comparable unit area invites significant inaccuracies due to economies of scale and the effect of start up costs. Fourthly, the type of corals involved and the target coral cover may vary significantly between schemes. And finally, the overall success of the schemes over time is not always clear, and the results are not always available.

However, what is evident is that potential coral restoration costs can vary enormously, ranging from the equivalent of around US$ 13,000 to US$ >100,000,000 per hectare. Some of the more influential factors affecting restoration costs in the case studies are highlighted in table 1 on next page. See Spurgeon (in press) for a more detailed list of factors affecting coral restoration costs. The most critical factor seems to be the extent of construction works required, whether for substrate preparation or installation of artificial reefs, or both. The general cost of labour is also influential, particularly when time consuming diving is needed to carefully attach transplanted corals. Furthermore, when greater funds are available for restoration initiatives, more costly options are considered and undertaken. This is particularly true when compensation funds are available to finance restoration initiatives.

Table 1. Comparison of restoration costs and key factors affecting costs.

Case Study Location	Cost (US$ 000/ha)	Significant construction works scuba divers	Attachment of corals by	High labour rates	Availability of large funds
Florida	5,500–>100,000	√	√	√	√
Maldives	400– 1,600	√	–	–	√
Australia	40	–	√	√	–
Tanzania	13	–	–	–	–

In the case of the Florida coral restoration schemes (NOAA 1997; 1999), significant costs were incurred. Key factors affecting costs were the severe structural damage caused by the ship groundings; the risk of significant secondary wave-induced damage; the depth and exposure of the sites; the objective of restoring biological diversity and aesthetic quality as far as possible to the pre-disturbance situation; and the luxury of significant sums of money available to fund it. As highlighted in table 1, these factors resulted in the choice of expensive and technically challenging construction works being carried out by well paid scuba-diving personnel. The simplistic extrapolation of scheme costs to costs per ha is a little misleading, since there would probably be significant economies of scale.

In the Maldives case (Edwards et al. 1994; Clark & Edwards 1995, 1999) the high costs were incurred due to the expensive construction and placement costs for the artificial concrete structures. These structures were considered necessary on the degraded 'mined' reefs due to the lack of suitable places for coral to recruit naturally on the rough and loose remaining substrate. These costs were particularly high given the remoteness of the Maldives and local costs for construction material. Although transplanting corals was undertaken as part of the study, costs estimates are not included in the above costs.

Transplantation of corals is sometimes considered when natural recruitment fails as a consequence of scarcity of larvae or unfavorable conditions at the site, such as unstable substrate, algal overgrowth or siltation. The need to attach transplanted corals to the substrate in order to prevent dislodgement due to water movements is a fundamental problem that has prompted several experiments and feasibility studies during the last few decades. Attachment is often labour intensive and time consuming and generally requires SCUBA diving.

In the Maldives, coral transplantation and monitoring of the same required considerable effort (330 man-hours to transplant 500 coral colonies onto 50m^2 of armourflex and 114 man-hours for each monitoring). However, it is worth noting that within 2.5 years of the transplants, 40–60% had died or been ripped off by wave action (Clark & Edwards 1999). On the other hand, natural coral recruits onto the stable concrete surface were relatively successful.

In the Great Barrier Reef study (Kaly 1995), the relatively low costs (US$ 40,000/ha) reflect the lack of need for substrate preparation or use of artificial structures. This immediately reduces the magnitude of costs significantly. The major cost component was the time required by scuba divers plus minor costs for glue and nails. Kaly found that one diver could transplant 125 coral fragments per day, excluding time allowed to get to the site. In order to express these results in terms of area cover, one can translate the given maximum linear dimensions of the fragments of around 5–10 cm to an area of 30 cm^2 per piece. This means that one diver could create 10% coral cover over 3.75 m^2 per day.

The relatively high costs for coral restoration techniques have thus prompted research into 'low-tech' methods that may be more suitable in developing countries. One ideal has become to develop a coral restoration scheme that could be used on a large-scale without the need for artificial structures, scuba diving or expensive coral attachment materials. However, such an approach does bring two important restrictions on its potential applicability. Firstly, without scuba diving, the depth limit for collection and placement of corals is between 5 and 10 metres. Secondly, without careful attachment of the corals, only protected or moderately exposed areas can be rehabilitated.

The study in Tanzania (Lindahl 1998) is one attempt to assess the feasibility of such low-tech methods. The estimated costs (US$ 13,000/ha) are based on a hypothetical full-scale rehabilitation effort. In order to keep costs down, the project was developed with the idea of involving local fishermen as the main labour force. The short period of training needed is included in the costs. Most of the cost covers travel and wages for a foreign consultant. As soon as the know-how has been transferred to Tanzanian marine biologists, these costs would be substantially reduced for each new project. The per unit cost for areas greater than one ha would be much lower due to economies of scale and shared start-up costs.

In comparison to Kaly's work, the corresponding area of transplanted coral using Lindahl's approach would be 10% cover on 33 m^2 per person per day. This is almost ten times the area covered. It is calculated as an average for all labour involved in the rehabilitation work, including the in-boat travel time to the site and to and from the donor site. However, its limitations regarding suitable locations must be recognised.

Similar methods as those studied by Lindahl have been used for several years in the South Pacific, with promising results (Bowden-Kerby 1996, 1999a, 1999b). Here, the rehabilitation work builds on volunteer participation by the local fishing community. This obviously has important implications for low-tech reef rehabilitation in developing countries. However, it deserves mentioning that even a volunteer worker comes with a cost. The opportunity cost would be the value of the useful work that this person could have done elsewhere if he/she had not volunteered for this particular project.

With the exception of Florida, none of the case studies include costs for site management, maintenance or monitoring in their estimations. The need for, and extent of, management, maintenance and monitoring of coral restoration schemes will depend on the technique used and various site-specific factors. In the Tanzanian case, these costs are all likely to be small since the corals should not need further assistance once placed in position.

None of the case studies listed above have included site opportunity costs or costs for damage to the donor site. Only in the case of the Maldives are there likely to be significant opportunity costs of using the site. However, given the lack of additional building material in the area the options for using the site for land reclamation is perhaps limited. The lack of valuation of impacts to donor sites is related to the general difficulty in, and lack of, coral valuation studies.

7. CORAL RESTORATION BENEFITS

As discussed in the overview essay by Cesar in this monograph (pp. 14–39), coral reefs provide a vast array of benefits to mankind in the form of goods (products), services (functions) and non-use values. Few of the goods and services are traded in the market-place, and they rarely have readily observable monetary or economic values. However, as indicated in the overview essay, appropriate economic valuation techniques are available to estimate the value of corals, and studies have shown coral reefs to have considerable economic value, particularly when utilised on a sustainable basis.

No coral restoration studies, including the five case studies, appear to have included an economic benefit assessment. This lack is probably due to lack of awareness of the capabilities of the techniques coupled with the difficulties and costs often involved in such assessments. It is perhaps time that this deficiency is reversed. Environmental valuation studies need not be excessively expensive.

Many factors affect the magnitude of benefits that coral restoration schemes potentially give rise to (Spurgeon, in press). Bearing this in mind, the following observations can be made with respect to economic benefits relating to the case studies. Recreation benefits will be highest in Florida due to the popularity of the site, the relatively small area of the overall Sanctuary and the extensive nature of the restoration scheme. Fishery benefits will generally be greater where artificial structures provide additional voids and surface area for organisms to use. The potential benefits from pharmaceutical uses in such circumstances are relatively unknown as yet. There is potentially considerable benefit from most coral restoration schemes in terms of research and education.

Installation of artificial structures will speed the process of the coral area forming a wave absorbing structure, thus providing improved coastal protection. As for fisheries, the extent of biological support may be somewhat related to the provision of voids, surface area and coral cover. Finally, non-use values and intrinsic values are even more complex to evaluate. The magnitude of non-use value is likely to be related to factors such as the extent to which the sites' overall coral reef integrity is maintained by the restoration and the uniqueness of the site. Similar factors will apply for intrinsic values, although it can be argued that the more a site's naturalness is interfered with, the less the intrinsic value.

8. DECISION-MAKING FOR CORAL RESTORATION

8.1 Decision-making tools

As its science and application develops, there will be more opportunities and requirements to undertake coral restoration in the future. However, as this chapter has demonstrated, there are numerous types of reef impact and various restoration techniques available. How does one decide what action to take, which restoration method to use and to what extent? Will it be money well spent? Several alternative decision-making tools could be used to go some way towards answering these questions.

Least-cost analysis (LCA) is a simple but powerful way of identifying the least cost way of achieving certain environmental objectives (Dixon et al. 1988). If there is an overriding decision that something must be done to achieve a certain level of improvement, then LCA can determine the cheapest method. Related to this is cost-effectiveness analysis (CEA) (Dixon et al. 1988; Ruitenbeek et al. 1999). This technique adds an additional level of complexity by comparing different thresholds of improvement and their associated costs. For example, CEA could determine the most cost-effective level of coral cover to restore to. Both techniques are commonly and best used when there is no doubt over the need and objectives for a scheme, (i.e. the 'safe minimum standard' approach).

Multi-criteria analysis (MCA) can help select a preferred scheme option by scoring, weighting and prioritising a series of different objective criteria (Korhonen et al. 1992; Fernandes et al. 1999). The criteria should be selected, scored and weighted through a comprehensive stakeholder analysis coupled with appropriate expert opinions. The preferred option is effectively the scheme that gets the most points.

The US government has developed a method known as habitat equivalency analysis (HEA) for assessing the appropriate extent to which damaged habitats should be restored to, or compensated for (Unsworth and Bishop 1994; Milon and Dodge, in press). This approach combines biological and economic information, particularly relating to the timing of lost biological functions. There are various problems associated with this approach, as highlighted by Milon and Dodge (2000).

Although LCA, CEA, MCA and HEA are valid and useful option appraisal techniques, they are all incapable of addressing whether or not coral restoration schemes are money well spent. Cost-benefit analysis (CBA), on the other hand, potentially can.

CBA compares all scheme costs and benefits occurring over the duration of the scheme. In theory, if his is carried out properly, based on Total Economic Values (TEV; see the overview essay by Cesar in this monograph, pp. 14–39), it is possible to determine if a coral restoration scheme provides a good economic return. It could also help select the preferred means of restoration (i.e. the one method generating the best benefits relative to the costs incurred).

However, as with LCA, CEA and MCA, there is little evidence in the literature that CBA has been applied to coral restoration decision-making. A major difficulty in conducting a CBA is clearly the valuation of scheme benefits. Such limitations are significant, although major methodological advances are being made with respect to valuing environmental benefits in general, as well as for coral reefs. As greater efforts are made to undertake and understand coral reef valuations, this issue will become less of a problem. The cost of undertaking valuation studies is also perhaps seen as prohibitive. However, as more are carried out over time, the relative cost of such exercises will fall, particularly if the concept of 'benefit transfer' (see the overview essay by Cesar, pp. 14–39) is used and adopted appropriately.

A major advantage of using CBA over the other decision-making tools is that if used properly, it is the best way of determining how best to use any available funds for coral management. For example, if a ship were to run aground on a coral reef, a damage assessment could reveal a value for compensation either based on the value of lost coral benefits or the cost of restoring the reef (Spurgeon 1999). CBA could then be applied to determine if that money is best spent in restoring the reef or in providing other improved management or protection from other potential damages. The chances are that expensive restoration schemes are unlikely to be the best use of resources except possibly on extremely well managed reefs in popular visitor locations.

8.2 Assessing restoration costs and benefits over time

When using LCA, CEA, HEA and CBA, economic theory requires the use of 'discounting' (see the overview essay by Cesar, pp. 14–39) to bring all future sums of money into equivalent present day values. Consequently, capital costs are usually equal to or close to their actual cost, whilst future management, monitoring and maintenance costs are reduced to lower present day values. In decision-making analysis, this process thus favours schemes where costs are staggered and spread over long periods.

Just as the timing of scheme costs is important in CBA, so too is the timing of scheme benefits. The later that benefits accrue, the less value they effectively have in a CBA calculation. This process of discounting thus discriminates against projects that generate benefits slowly over time.

The rate at which coral restoration benefits accrue depends on the form of restoration scheme and the type of impact that caused the loss in the first place. This point is illustrated here using two simple graphical representations to display the effect of alternative restoration methods under two different types of impact.

Depending on the cause and nature of an impact, degraded coral reefs can recover to a degree naturally within a decade provided that the reef is spared from chronic disturbances like eutrophication, overfishing, siltation or frequent storms, and if the substrate and physical environment allow recolonisation of corals (Connell 1997). If there are surviving corals with a vegetative/fragmenting mode of reproduction on the damaged site, the time for natural recovery may be even shorter (Highsmith 1982). However, major physical damage to reefs, for example through ship groundings on spur-and-groove formations, can take 100 to 150 years before pre-impact coral cover and species diversity fully recovers (Precht 1998).

When considering whether or not to restore or rehabilitate a coral reef the natural recovery rate should be predicted and compared with the enhanced restoration recovery rate. Ideally the coral recruitment and growth patterns should be known for the site, as well as the influential underlying ambient parameters, such as pollution, sedimentation, turbidity, etc.

Figure 1 on next page shows the potential loss of benefits (i.e. the value of lost products and services) from a hypothetical short-term direct physical impact (see section 2) such as a ship grounding. The scenario assumes an instant loss of coral structure at the time of impact, and an eventual full natural recovery. The combined areas of A, B, C, D and E represent the total loss of benefits without any form of restoration.

Area E represents the benefit from fixing the substrate and clearing rubble, thereby preventing further

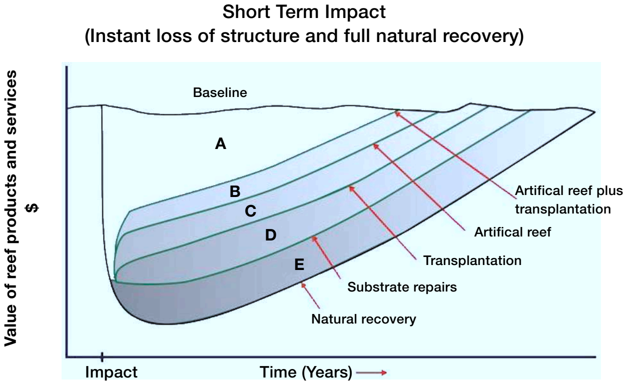

Figure 1. Flow of restoration benefits following a sudden physical impact.

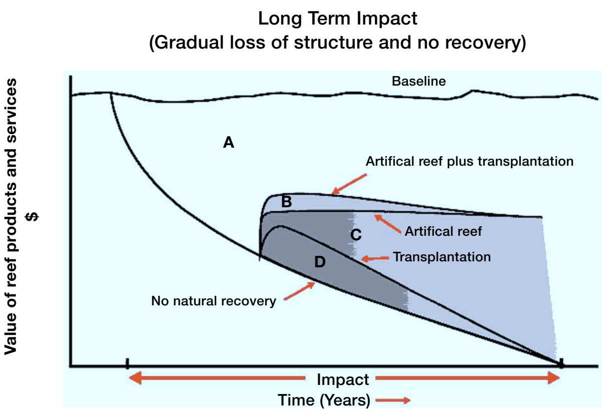

Figure 2. Flow of restoration benefits following a long term insidious impact.

secondary damages. Area D represents the potential benefit from transplanting corals. Areas C and D represent the benefits from installing an artificial reef, and area B, C, and D represents a combined scheme of artificial reef and transplantation. Area A is effectively the remaining damages, or 'interim losses' in natural resource damage assessments. It should be noted that the relative size of each area is not based on any detailed calculations.

Figure 2 illustrates the effects of restoration following gradual deterioration of a coral reef from a long-term insidious impact (see Section 2) such as that resulting from chronic pollution. It clearly highlights the futile attempt at transplanting corals whilst the cause of the impact is still occurring. Area D represents the level of benefits from transplanting corals. Although benefits initially accrue with the new corals in place, benefits soon tail-off as the new corals are no better equipped to deal with the recurring form of impact. Provision of an artificial structure on the other hand does yield permanent benefits, as represented by area C. The benefits will primarily be those associated with the coastal defence and habitat functions of the new artificial reef structure. If the structure is of sufficient interest, recreational benefits may also accrue to divers and snorkellers.

The graphs show the importance of understanding the conditions at the site, the cause of degradation, and how the level of benefits can relate to different restoration methods. Clearly, there is little point restoring a coral reef if the underlying cause of degradation is still present (i.e. an ongoing insidious impact), although installing some form of artificial reef structure under such circumstances may possibly be worthwhile.

9. CONCLUSIONS AND RECOMMENDATIONS

The five coral restoration case studies have shown that various forms of coral restoration exist, the costs of which vary significantly for a number of reasons. Within the growing literature on coral restoration, few studies go into adequate detail on the costs involved, and those that do, generally ignore some costs and resource implications altogether. There is a need for more studies to assess and communicate coral restoration cost estimates using a universally accepted format for presenting the full scheme costs.

Coral restoration schemes potentially provide a wide range of economic benefits, particularly from enhanced recreation, fisheries and coastal defence. Although valuation techniques capable of estimating coral restoration benefits do exist, no such valuations appear in the literature. Without a slightly more detailed benefit assessment it is difficult to predict with any certainty whether or not benefits accruing from the case study restorations outweighed the scheme costs. Considerable additional research is needed in this important subject.

Decision-making with respect to coral restoration is potentially facilitated with the use of various analytical tools. Cost-benefit analysis is perhaps the most complicated and demanding of the techniques, but its potential value far exceeds that of the alternative techniques. Its power lies in its potential ability to improve decision-making through helping determine the best use of limited funds. CBA can help select the overall optimum coral reef management option from an economic perspective whilst taking into account technical, environmental and social aspects.

Coral restoration may not always be the most appropriate or efficient way to enhance damaged coral reefs. Alternative options representing better value for money may include improved management of the reef and methods of reducing other reef damaging activities (e.g. pollution, fishing and recreational activities). Indeed, prevention may well be more cost-effective than cure. The allocation of some of the damage claims after grounding accidents in the FKNMS to prevent further groundings elsewhere in the sanctuary, as in the Columbus Iselin case, may thus be a good investment as well as being part of a viable long term management strategy.

ACKNOWLEDGEMENTS

We would like to thank Al Edwards and Susan Clark for providing additional data on their coral reef rehabilitation and restoration efforts, and Herman Cesar, for the encouragement and opportunity to write this paper. In addition we thank all the reviewers.

REFERENCES

Alcala, A. C., & Gomez, E. D., (1987) "Dynamiting Coral Reefs for Fish: A Resource-Destructive Fishing Method". In Salvat, B., (ed.) *Human Impacts on Coral Reefs: Facts and Recommendations*. Antenne Museum, French Polynesia, pp. 51–60.

Auberson, B., (1982) "Coral transplantation: an approach to the reestablishment of damaged reefs". *Kalikasan, Philippinean Journal of Biology*, Vol. 11, pp.158–172.

Birkeland, C., Randall, R. H., & Grimm, G., (1979) *Three methods of coral transplantation for the purpose of re-establishing a coral community in the thermal effluent area at the Tanguisson power plant*. Technical Report no. 60, University of Guam, USA.

Birkeland, C., (ed.) (1997) *Life and Death of Coral Reefs*. Chapman & Hall, New York.

Bouchon, C., Jaubert, J., & Bouchon-Navaro, Y., (1981) "Evolution of a semi-artificial reef built by transplanting coral heads". *Tethys*, Vol. 10, pp. 173–176.

Bowden-Kerby, A., (1996) "Coral transplantation in sheltered habitats using unattached colonies and cultured colonies". *Proceedings of the 8th International Coral Reef Symposium, Panama,* Vol. 2, pp. 2063–2068.

Bowden-Kerby, A., (1999a) "The Johnny Coral Seed Approach to Coral Reef Restoration: New Methodologies Appropriate for Lower Energy Reef Areas". Presented at NCRI International Conference on Scientific Aspects of Coral Reef Assessment, Monitoring and Restoration [location?].

Bowden-Kerby, A., (1999b) "The Community Coral Reef Initiative: coral reef restoration in rural Pacific settings". Presented at the International Conference on Scientific Aspects of Coral Reef Assessment, Monitoring and Restoration. April 14–16 1999, F.t Lauderdale, Florida, National Coral Reef Institute.

Clark, S., & Edwards, A. J., (1995) "Coral transplantation as an aid to reef rehabilitation: evaluation of a case study in the Maldive Islands". *Coral Reefs*, Vol. 14, pp. 201–213.

Clark, S., & Edwards, A. J., (1999) "An evaluation of artificial reef structures as tools of marine habitat rehabilitation in the Maldives". *Aquatic Conservation*. 9 (1): 5–21.

Connell, J. H., (1997) "Disturbance and recovery of coral assemblages". In: *Proc. 8:th Int. Coral Reef Symp.* Panama, pp. 9–22.

Connell, J. H., Hughes, T. P:, & Wallace, C. C., (1997) "A 30-year study of coral abundance, recruitment and disturbance at several scales in space and time". *Ecological Monographs* 7 (4): pp 461–488

Dixon, J. A., Carpenter, R. A., Fallon, L. A., Sherman P. B., & Manipomoke, S., (1988) *Economic Analysis of the Environmental Impacts of Development Projects*. Earthscan Publications Ltd. UK.

Edwards, A., Clark. S., & Brown, B., (1994) *Rehabilitation of Degraded Reefs Using Artificial Reef Blocks*. Report to UK Overseas Development Administration (R4533), London, UK.

Edwards, A., & Clark. S., (1998) "Coral Transplantation: A Useful Management Tool or Misguided Meddling?". *Marine Pollution Bulletin*, Vol. *37*, No. 8–11, pp. 474–487.

Fernandes L., Ridgley. M. A., & van't Hof, T., (1999) "Multiple criteria analysis integrates economic, ecological and social objectives for coral reef managers". *Coral Reefs* 18:393–402.

Fitzharding, R. C., & Bailey-Brock, J. H., (1989) "Colonization of artificial reef materials by corals and other sessile organisms". *Bulletin of Marine Science*, Vol 44, pp. 567–579.
Fox, H. E., Caldwell, R. L., & Pet, J. S., (1999) "Enhancing Coral Reef Recovery After Destructive Fishing Practices in Indonesia". Presented at the International Conference on Scientific Aspects of Coral Reef Assessment, Monitoring and Restoration, F.t Lauderdale, USA, National Coral Reef Institute, April 14–16.
Guzmán, H. M., (1991) "Restoration of coral reefs in pacific Costa Rica". *Conservation Biology*, Vol 5, pp.189–195.
Harriott, V. J., & Fisk, D. A., (1988) *Accelerated regeneration of hard corals: a manual for coral reef users and managers.* Technical Memorandum 16, Great Barrier Reef Marine Park Authority.
Harriott, V. J., Davis, D., & Banks, S. A., (1997) "Recreational Diving and Its Impact in Marine Protected Areas in Eastern Australia". *Ambio*, Vol. 26 (3), pp 173–179.
Heyward, A. J, Rees, M., & Smith, L. D., (1999) "Coral spawning slicks harnessed for large-scale coral culture". Presented at the International Conference on Scientific Aspects of Coral Reef Assessment, Monitoring and Restoration. April 14–16 1999, F.t Lauderdale, Florida, National Coral Reef Institute.
Highsmith, R. C., (1982) "Reproduction by fragmentation in corals". *Mar. Ecol. Prog. Ser. 7,* 207–226.
Hudson, J. H., & Diaz, R., (1988) "Damage survey and restoration of M/V Wellwood grounding site, Molasses Reef, Key Largo National Marine Sanctuary". *Proceedings of the 6th International Coral Reef Symposium*, *Australia*, Vol. 2, pp. 231–236.
Kaly, U. L., (1995) *Experimental test of the effects of methods of attachment and handling on the rapid transplantation of corals.* Technical Report No. 1, CRC Reef Research Centre, Townsville.
Korhonen, P., Moskowitz, H., & Wallenius, J., (1992) "Multiple criteria decision support — a review". *Europ J Opera Res,* Vol. 63, pp. 361–375.
Lindahl, U., (1998) "Low-Tech Rehabilitation of Degraded Coral Reefs through Transplantation of Staghorn Corals". *Ambio*, Vol. 27, No. 8 [pp]
Maragos, J. E., (1974) *Coral transplantation: a method to create, preserve and manage coral reefs.* UNIHI-SEAGRANT-AR-74-03, CORMAR-14, University of Hawaii, USA.
Milon J. W., & Dodge, R. E., (in press) "Applying Habitat Equivalency Analysis for Coral Reef Damage Assessment and Restoration". *Bulletin of Marine Science*.
Miller, S. L., McFall, G. B., & Hulbert, A. W., (eds.) (1993) *Guidelines and recommendations for coral reef restoration in the Florida Keys National Marine Sanctuary*. National Undersea Research Center, University of North Carolina at Wilmington, USA.
NCRI (1999) *International Conference on Scientific Aspects of Coral Reef Assessment, Monitoring and Restoration*. April 14–16 1999, Ft Lauderdale, Florida, National Coral Reef Institute.
NOAA (1997) "Elpis Coral Reef Restoration". http://www-orca.nos.noaa.gov/darp/seregion/elpis.htm
NOAA (1999) Web page: http://www.sanctuaries.nos.noaa.gov/special/columbus/project.html
Oren, U., & Benayahu, Y., (1997), "Transplantation of juvenile corals: a new approach for enhancing colonization of artificial reefs". *Marine Biology*, Vol. 127, pp. 499–505.
Precht, W., (1998) "The art and science of reef restoration". *Geotimes* 43: 16–20.
Ruitenbeek J., Ridgely, M., Dollar, S., & Huber, R., (1999) "Optimization of economic policies and investment projects using a fuzzy logic based cost-effectiveness model of coral reef quality: empirical results for Montego Bay, Jamaica". *Coral Reefs* 18: 381–392.
Sammarco, P. W., Brazeau, D. A., & Lee. T. N., (1999) "Enhancement of reef regeneration processes: Supplementing coral recruitment processes through larval seeding". Presented at the International Conference on Scientific Aspects of Coral Reef Assessment, Monitoring and Restoration. April 14–16 1999, Ft Lauderdale, Florida, National Coral Reef Institute.
Sano, M., Shimizu, M., & Nose, Y., (1987) "Long-term Effects of Destruction of Hermatypic Corals by *Acanthaster planci* Infestation on Reef Fish Communities at Iriomote Island, Japan". *Marine Ecology Progress Series*, Vol 37, pp.191–199.
Spurgeon, J. P. G., (1999) "Economic Valuation of Damages to Coral Reefs". *Coral Reefs: Marine Wealth Threatened*. Conference organised by National University of Mexico. Cancun, Mexico 1999.
Spurgeon, J. P. G., (in press) "Improving the Economic Effectiveness of Coral Restoration". *Bulletin of Marine Science.*
Unsworth R., & Bishop, R. C., (1994) "Assessing natural resource damages using environmental annuities". *Ecological Economics* Vol 11 pp. 35–41.
Van Treeck, P., & Schumacher, H., (1999) "Mass Diving Tourism — A New Dimension Calls for New Management Approaches". *Marine Pollution Bulletin*, Vol. 37, pp. 499–504.
Yap, H. T., Alino, P. M., & Gomez, E. D., (1992) "Trends in growth and mortality of three coral species (Anthozoa: Scleractinia), including effects of transplantation". *Marine Ecology Progress Series*, Vol. 83, pp. 91–101.