Issues in Applied Coral Reef Biodiversity Valuation: Results for Montego Bay, Jamaica

World Bank Research Committee Project RPO# 682-22 "Marine System Valuation: An Application to Coral Reef Systems in the Developing Tropics"

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Abstract

The broad objective of this research is to assist policy makers in managing and protecting coral reefs by deriving improved estimates of coral reef economic benefits. While the research area of biodiversity valuation has grown significantly over the past decade, most research efforts dealing with valuation focus on terrestrial diversity; no methodical investigation has been made of marine biodiversity valuation issues.

The research includes an extensive review of existing biodiversity valuation studies, with a view to identifying appropriate methodological frameworks for marine biodiversity valuation. We generally endorse the use of a Total Economic Value approach, which includes, for example, direct use, indirect use, and non-use values; we underline, however, the need to recognize that such values are frequently non-additive. In addition, our classification framework recognizes three different methodological approaches to biodiversity valuation, which we characterize as Production Valuation, Utility Valuation and Rent Valuation methods. Each of these methods will use a different style of estimation approach, each will generally address a different type of policy problem, and each will generally result in a different empirical valuation. This research regards all of these methods as potentially useful and technically valid; while there are definite incorrect methods for valuation, there is no single correct method. Similarly, we would argue that economic value is dependent on the decision-making, institutional or policy context: there is thus no single biodiversity value that can be attached to any particular reef area. In this light, biodiversity valuation should be regarded primarily as an educational tool to assist policy-makers, and secondarily as a planning tool in formulating specific policies. Although economic theory might provide us with a basis for using benefit valuation in an optimizing framework (e.g., choosing optimal conservation levels or quality targets), we advise that this be done only with extreme caution; our results indicate that optimal policy choices are very sensitive to the chosen valuation methodology.

Empirical work for Montego Bay, Jamaica, commenced with an estimate of the net present value (NPV) of readily identified local uses using production valuation approaches; these provide a benchmark value for comparative purposes. Values estimated included tourism and recreation (NPV of US$315 million), fisheries (NPV of US$1.31 million) and coastal protection (US$65 million). The total NPV of US$381 million translates to approximately US$8.93 million per hectare net present value, or US$893,000/ha/yr on an annualized basis. This is based on an estimated coral reef area within Montego Bay of 42.65 ha.

Contingent valuation methods for the same area explored the relevance of lexicographic preferences – represented by “zero willingness to pay (WTP)” – on respondent preferences. These approaches are meant to address the consumer surplus, or individual utility, of coral reef improvement. The survey instrument was designed to capture the “non-use” benefits of marine biodiversity at Montego Bay, for both local Jamaican residents and for visitors. Expected WTP for coral reef improvement was US$3.24 per person in a sample of 1058 respondents (a similar study for Curaçao placed this at US$2.08 per person). But this value was heavily dependent on whether respondents believed that marine systems possessed inherent rights, or that humans had inherent duties to protect marine systems; such preferences would increase WTP by up to a factor of three. For typical population characteristics, and using typical visitor profiles, it is estimated that the Montego Bay biodiversity has a net present value of US$13.6 million to tourists and US$6.0 million to Jamaica residents. The total NPV of US$19.6 million translates to approximately $460,000/ha, or $46,000/ha/yr on an annualized basis.

The above values imply a net present value of approximately $400 million for the Montego

Bay reefs. At present, no institutional arrangements exist for capturing any values for biological prospecting, so this value may be taken as a lower bound estimate. While it is difficult to translate this into a marginal benefit function, best estimates for coral abundance and available substrate suggest that this is equivalent to a marginal benefit of US$10 million per % of coral abundance improvement. Related research on least-cost modeling of interventions suggested that up to a 20% increase in coral abundance may be achievable through using appropriate policy measures having a present value cost of US$153 million. The cost curve envelope generated by that research showed marginal costs rising from under $1 million per % of coral abundance to $29 million per % of coral abundance. Global optimization using the combined cost and benefit functions suggested an "optimal" improvement of coral reef abundance of 13%, requiring net expenditures of US$27 million, primarily in the areas of: installation of a sediment trap; waste aeration; installation of a sewage outfall; implementation of improved household solid waste collection; and implementation of economic incentives to improve waste management by the hotel industry. Sensitivity tests suggest that net economic benefits would need to increase by US$275 million or decrease by US$300 million for the coral quality target to vary from this by more than 2% (i.e., fall below 11% or above 15%). To justify the full expenditure (achieving a 20% coral reef improvement), would require additional benefits of some $660 million.

The impact of pharmaceutical bioprospecting values on this optimal value depends on a number of factors. Using typical cost estimates for Jamaica, and typical hit rates and end-use values, scenario analyses were conducted using a parametric model. These scenarios place marine bioprospecting values at about $7775 per species. This value is somewhat higher than typical estimates for terrestrial species, primarily because of somewhat higher success rates. Using base case estimates of ecosystem yields for the Montego Bay area, coupled with a hypothetical sampling program that would be consistent with National Cancer Institute standards for marine sampling, a base case value of $70 million is ascribed to the Montego Bay reefs; approximately $7 million would be realistically capturable by Jamaica under typical royalty regimes or sample rental arrangements. None of this value is captured under existing institutional arrangements.

The first differential of the bioprospecting benefit function is calculated to arrive at an ecosystem marginal "global price" of $530,000/ha or $225,000/% coral abundance. For Jamaica's share, the relevant "local planning price" computes to approximately $22,500/% coral abundance. Including this additional price within the optimization calculation does not affect the outcome: "optimal" improvement of coral reef abundance remains at 13%. The model demonstrates primarily the sensitivity of total and marginal values to ecosystem yield and institutional arrangements for capturing genetic prospecting value. For example, sensitivity analyses within a plausible range of species-area relationships generated global benefits for the Montego Bay reef of $54 to $85 million; reef prices ranged from $698,000/ha to $72,500/ha.

In conclusion, biodiversity valuation is best implemented within a specific policy context; choice of any given technique should be driven by specific policy questions or analytical issues. Most techniques still fail to adequately come to grips with issues of system complexity; these include issues such as non-linear ecological-economic linkages, interdependencies and redundancy in the species discovery process, cost interdependencies in the R&D process of bringing new products to market, and ecosystem yield in terms of species-area relationships for coral reef systems. Empirical studies demonstrate that optimal policy choices are frequently very sensitive to assumptions made regarding such issues. Substantial work also remains to be done in the area of risk analysis and industry structure.

Environmental valuation has often been described as an art rather than a science; if this is true, then coral reef biodiversity valuation may well best be described as magic.

Contents

Summary

WHY Value Marine Biodiversity?

Marine ecosystems are among the most diverse systems in the world. Their proper management will deliver a wide range of economic benefits to the local and the global economy. Coral reefs, in particular, generate a large number of direct local uses – such as fisheries and tourism – while also harboring biological products and information that are of increasing interest to the pharmaceutical and other industries. Some coral reef areas in the tropics are under particularly heavy pressure and are deteriorating; a recent World Bank report on coral reefs identified such ecosystems as the highest priority areas for conservation (Hatziolos *et al*. 1998). As such, marine biodiversity is potentially the most significant sustainable use of marine products, and valuing this biodiversity is of substantial research interest. While the research area of biodiversity valuation has grown significantly over the past decade, most research efforts dealing with valuation have focused on terrestrial diversity; no methodical investigation has been made of marine biodiversity valuation issues.

The broad objective of this research is to assist policy makers in managing and protecting coral reefs by deriving improved estimates of coral reef economic benefits. The key problem in this research is to adapt and refine available valuation methodologies so that they account for key coral reef characteristics. The research also identifies the not insignificant limitations to many of these methods.

This report summarizes the results of this research work, highlighting key methodological findings and lessons, as well as providing empirical results using various techniques of local use valuation, non-use valuation, and biological prospecting valuation. The lessons and results are cast in the context of policy choices that would face typical developing country management authorities.

WHAT is Biodiversity Valuation?

As a point of departure, this research basically asks, “What is a coral reef worth?” It is tempting to look for a single number – in terms of dollars or Euros or some local currency – that we can attach to a hectare of coral reef substrate, the same way we might attach a price to a barrel of apples. When the Cunard liner Royal Viking Sun hit a reef in the Gulf of Aqaba some years ago, Egyptian authorities sought US$23 million in damages for the loss of about 2000 square meters of coral reef (Sheppard 1996). The implied price of US$10,000 a square meter seemed remarkably high at the time – it would make reefs among the most valuable real estate in the world – but the case served to focus more attention on the "art" of economic valuation, rather than on the value itself.

In general, the quest for determining a single coral reef price would be fraught with frustration. Serious well-researched attempts to value biodiversity have typically resulted in huge ranges of values. Policy makers might rightfully ask why scientists can not agree on a single number; they often interpret this lack of precision as bad science, bad analysis, bad data or – in less harsh terms – as scientific uncertainty. Unfortunately, the outcome is typically that little action is taken, that status quo policies remain in place, and that reefs further deteriorate.

But the reality is that it is not likely that we shall ever find a single "biodiversity value," and that analysts and policy makers must come to grips with that reality. It is somewhat like trying to nail a cream pie to a wall: it seems obvious what we want to accomplish, yet all attempts fail to consider every aspect needed to achieve the task. This reality arises from two simple observations: "biodiversity" means different things in different contexts; and, "value" means different things to different people. Before presenting our own empirical results, we shall expand on each of these notions.

What is Biodiversity?

Many complex and different meanings can be, and have been, ascribed to the term "biodiversity." Its scope of meaning seems to expand daily. In the Global Overlay Program of the World Bank, for example, many recent forest biodiversity valuation exercises include values associated with carbon sequestration to abate global climate change, even though biodiversity and climate change are the subjects of two quite distinct international conventions. One might rightfully ask, then, "If biodiversity valuation can include values for climate change, where does one draw the line in valuation?" The only way to answer this fully is to review the different meanings that one might attach to biodiversity. Again, we see that the different meanings can have different implications for valuation. Also, there are important similarities – and differences – among marine, terrestrial and coral reef biodiversity (Box S.1).

Box S.1
Marine, terrestrial, and coral reef biodiversity

Both marine and terrestrial systems are open. Organisms transport themselves across boundaries either under their own steam, or more often transport is provided by physical processes (e.g., wind, land bridges, or ocean currents.) But marine systems are relatively more open than terrestrial systems because water provides the dispersal medium. The majority of marine species distribute their larvae among the plankton via ocean currents. As a result, the recruitment line could cover hundreds of kilometers. In terrestrial systems, conversely, self-powered dispersal is limited; even species which rely on air for dispersal are only air-borne for a limited time. Given the differing patterns of dispersal in marine and terrestrial ecosystems, species endemism is a more common phenomenon on land than in the sea.

Marine ecosystems include coral reefs, intertidal zones, lakes, estuaries, and pelagic and deep ocean systems. The relative degree of species and ecosystem biodiversity in these systems depends on the physical characteristics of the particular system. In general, marine organisms exhibit more genetic diversity than terrestrial organisms; and terrestrial ecosystems exhibit more species diversity than marine systems. Marine systems have more higher-level taxonomic diversity than terrestrial environments: among all macroscopic organisms, there are 43 marine phyla and 38 terrestrial phyla; of the 33 animal phyla, 32 live in the sea and only 12 inhabit terrestrial environments (Reaka-Kudla 1995). However, in a coral reef, which is dominated by substrate, species and ecosystem biodiversity is relatively high; in the open pelagic ocean, where there is no substrate, diversity is relatively low.

Because of the existence of substrate, coral reef ecosystems and terrestrial ecosystems share similar structuring processes. Terrestrial ecosystems are dominated by substrate, biotic interactions, and the properties of air. Coral reef systems are similarly dominated by substrate and biotic interactions; but instead of air, they have to deal with the physical properties of water. By contrast, open ocean ecosystems, having no substrate, are dominated primarily by the properties of water. In coral reefs and terrestrial ecosystems – particularly rainforests – physical complexity, high species diversity, high functional diversity, and co-evolved species associations are biologically generated. To differing degrees, the biota control the structures of these systems. In open ocean pelagic ecosystems, with the absence of substrate, ecosystem structure is more the result of abiotic forces than biotic interactions.

Based on recorded species, fewer than 15 percent of currently named species are found in the ocean (Gaston 1996). However, coral reefs rank among the most diverse of all natural ecosystems, comparable to rainforests. The coral reef contains thousands of species interacting among themselves and abiotic conditions in a crowded marine environment. The result is many fine subdivisions of food and space resulting in high productivity, and efficient use of space. For example, symbiotic algae with coral polyps process the polyps' wastes thus improving recycling and nutrient retention. Also, diurnal and nocturnal fish species share their specific shelter sites.

The crowded and competitive conditions on coral reefs result in many types of interactions between species. One interaction well developed in the reef is antibiosis: the production by one organism of substances repulsive or fatal to another. These are the highly bioactive compounds investigated for various pharmaceutical properties: such as antiviral, antimicrobial, antitumor, and anticoagulant. These are used in the production of pharmaceuticals to treat viral and bacterial infections, cancers, and heart disease. Corals have also developed strategies to protect themselves from abiotic forces; for example, pigments protect the coral organism from harmful ultra-violet rays. These can be used for the production of sunscreens for humans.

The term biodiversity indicates a broad range of biotic phenomena ranging from the smallest unit studied – genetic diversity – to the earliest studied – species diversity – to the recently studied – ecosystem diversity. Within ecosystem diversity, both biotic and abiotic processes are studied as elements of functional, community and landscape diversity. When discussing the value of biodiversity, one should be clear about what the term connotes.

Genetic diversity refers to diversity *within* species – its total variety of genes. Different populations of the same species are not genetically identical; nor are individuals within the same population. Therefore, whereas the genetic diversity of a collection of species obviously declines with the extinction of a member species, it also declines with the extinction of a population of that species – a process known as genetic impoverishment. In the marine environment while some species extinction events have been documented, the loss of marine biodiversity comes primarily from genetic impoverishment.

Genetic diversity is important for adaptation: those species with high genetic diversity are better equipped to adapt to environmental changes. In agriculture, for example, genetic *uniformity* in a cultivated species renders that species vulnerable to climatic variations and disease. *Genetic resources*, a category of genetic diversity, refers to the actually or potentially useful characteristics and information contained in the genes and chemical substances of microbes, insects, plants, animals, and other organisms. Extracted from these organisms, genetic resources take the form of biomolecules, germplasm, enzymes and chemical compounds to be used for innovation in agriculture, horticulture, pharmaceuticals, and other types of chemical industries producing products ranging from skin care to industrial microbes for waste degradation.

Species diversity refers to diversity *among* species; it is the variety of different species within a collection of species. In the hierarchical system used to classify living things, species represents the lowest of the main taxa after kingdom (the highest), phylum, class, order, family, and genus. Estimates of the total number of species on earth range between 5 and 120 million; only about 1.8 million species have so far been described (Reaka-Kudla 1997).

Species diversity is important for ecosystem health. Ecosystem resilience is affected by the loss of its functional diversity (discussed below), which occurs with the extinction of functionally important species. Some species are functionally redundant meaning that should they be removed, there exist other species within the ecosystem that can assume their function. However, species which provide a critical structuring service in the ecosystem may not be replaceable, and their removal will change the structure of the system. For example, if a key predator is removed from an ecosystem, the dominant prey can then exclude its competitors thereby simplifying the ecosystem structure to a monoculture.

In terms of economic value, species diversity provides a breadth of consumptive opportunities in terms of current and future sources of food, nutrients, medicine, and construction materials. It also provides non-consumptive option and existence values. However, consumptive opportunities afforded by species diversity can become limited or less desirable, as a result of over-exploitation of certain species. For example, the over-harvest of top marine predators for human consumption is resulting in marine catches from lower trophic levels. Due to the over-harvesting of these top predators, humans are consuming different species that are further down the food chain; but as we move down the food chain, there are fewer potential species fit for human consumption.

Ecosystem diversity refers to the constituent biotic and abiotic elements and processes of an ecosystem, defined over a particular spatial and temporal scale from days and centimeters to millennia and thousand kilometers. The term includes the concepts of community, landscape, and functional diversity. Community diversity refers to species combinations and interaction, habitat pattern, relative abundance, distribution, population age structures, and trophic structure. Landscape diversity refers to the variety of spatial scales and patterns of species combinations across the landscape: the patchiness of the landscape. Functional diversity refers to the degree of niche subdivision, and the number and abundance of functionally distinct species filling the niches.

The maintenance of ecosystem diversity is important for the protection of genetic and species diversity contained within the system, and for the overall resilience of the system. Ecosystem resilience refers, in general, to its ability to absorb disturbances and renew itself. A disturbance can be defined as any phenomenon that causes organism mortality. Functional diversity is particularly important in maintaining ecosystem resilience. Research has shown that the more functionally diverse an ecosystem, the better equipped it is to recover from shocks.

The economic value of ecosystem diversity stems from its direct use values (recreation, research and education); its indirect values (biological support, physical protection); and its existence and option values. Direct use values are the most obvious because they enter the economy in some way; indirect values are generally less so because their economic value is not priced, or is hidden in production of some other good or service. The biological support provided by a coral reef, for example, can be considerable. The pelagic juvenile (larval) stages of reef organisms provide a food source to other ecosystems, as larvae drift on ocean currents, or as fish species migrate between their particular ecosystem and the reef. The reef is thereby supporting commercial fisheries both offshore and in nearby seagrass beds, lagoons, and mangroves. Seabirds also use the reef as a food source; and turtles feed and breed on the reef. On a global scale, coral reefs play a role in the global calcium and carbon balances. Coral reefs also provide physical protection to shorelines. The calcium carbonate skeletons of coral reef organisms form an effective barrier that dissipates wave energy. As a result, reefs protect coastlines from storms and currents thereby reducing coastal erosion.

What is “Value”?

Value, like beauty, is in the eye of the beholder. And differences in the perception of economic value are rife throughout the biodiversity valuation literature. Many different methodologies exist for attaching values, and these generally focus on some of the direct, indirect, and non-use values alluded to above. These are all different components of what economists often call the Total Economic Value (TEV). But even among these methods, there are differences of focus. Some methods may focus on the value to an end user, such as the ultimate value of a drug to a cancer patient. Other methods may focus on the share of income that is received by the licenser of a process or owner of a resource, such as a patent holder or a developing country institution. Still other methods focus on how biodiversity contributes to a given income generating process, such as through an artisanal fishery. In this research, we distinguish between these three types of methodologies, classifying them as production valuation, utility valuation, and rent valuation approaches (Table S.1). Many of the differences in values can be ascribed simply to the application of such different approaches. In our view, there is no correct or incorrect approach, as each of these methods will generally address a different policy or decision-making problem. A key lesson, however, is that the distribution of value, and the incidence of costs and benefits of resource use, often play a critical role in such decision making. As is often the case, it is not so much the size of the pie that is of interest, as how it is divided.

WHERE was the Research Done?

The main empirical focus of this study is in the Montego Bay Marine Park area on the north coast of Jamaica. Earlier related work also conducted cost-effectiveness analyses in the Maldives and in Curaçao; work in the area of contingent valuation was also conducted in Curaçao (Brown *et al*. 1996, Meesters 1995, Meesters *et al*. 1995, 1996, Rijsberman and Westmacott 1996, Westmacott and Rijsberman 1996).

The Montego Bay site (Figure S.1) was chosen for a number of reasons. Jamaica is itself committed to sustainable management of its biodiversity, having signed the Convention on

Table S.1
A system for classifying marine biodiversity valuation methodologies

	Biodiversity Production Valuation Methods	**Biodiversity Utility Valuation Methods**	**Biodiversity Rent Capture Valuation Methods**
Economic Basis	"Supply-Oriented"	"Demand-Oriented"	"Profit-Oriented"
Description	Values biodiversity within an economic production function.	Values biodiversity within an economic utility function.	Values biodiversity as a distribution of profits or value-added.
Valuation Target	Measures the contribution of biodiversity to the value of output in a produced good or service. Can estimate and isolate direct or indirect Use Values, including ecological functions or embedded information.	Measures the contribution of biodiversity to the utility of an individual or society. Can estimate aggregated Use and Non-use Values, including consumer's surplus.	Measures one or more components of the distribution of Use Values, focusing on captured rents, profits or value added. Can isolate value of embedded information.
Examples of Methods	Cobb-Douglas Production Function Linear Transforms Non-linear Transforms	Contingent Valuation Hedonic (quality-adjusted) Pricing 'Value of life' measures	Royalty evaluations Patent system evaluations Joint-venture evaluations
Examples of a Model	Q = Q{L,K,M,R,Ib} Q=drug production; L=labor; K=capital; M=materials; R=R&D effort; Ib=Biodiversity information content Value of biodiversity is marginal change in Q as Ib changes.	U=U{Y, C, Cb} U=individual or society's utility; Y=income level; C=consumption level; Cb=consumption or availability of biodiversity Value of biodiversity is marginal change in U as Cb changes.	Π=s{ΣPX} Π= profit or rent vector (n participants) s=revenue sharing transform P=price vector (m inputs/outputs) X=input/output vector Value of biodiversity is Π.
Examples of 'Terrestrial Biodiversity' Values	Estimates have been made of the expected value of rainforest species in the production of drugs or agricultural products. Typical values fall in the range of $1,000 to $10,000 per untested rainforest species.	Measures of the value of lives saved and avoided disease from single rainforest species (e.g., rosy periwinkle in cancer treatment) often far exceed $100 million.	Evaluations of revenue sharing through typical patent and joint-venture arrangements show low capture rates of biodiversity values in developing countries. Cameroon collects about $20 per untested rainforest species.

Biological Diversity on 6 January 1995. But foremost, recent political commitment in the region has resulted in the establishment of the Montego Bay Marine Park as a protected area that will be managed to promote sustainable reef-based tourism while still accommodating a local fishery. Originally under public jurisdiction, a bold experiment was undertaken when the park was transferred to private management in 1996. A group of concerned citizens, which formed the Montego Bay Marine Park Trust in 1992, obtained responsibility from the Government of Jamaica to manage the park under the authority of the Natural Resources Conservation Authority.

Moreover, impacts on the park are varied, ranging from over-fishing to pollution impacts from sedimentation, ocean dumping from cruise ships, and influx of nutrients through ground and surface water transport. The area is economically important, as it also supports a recently established free trade zone. From an ecological perspective, the area has been studied over a long period of time as there is continued interest in the precise extent and cause of reef degradation (O'Callaghan 1992, Hughes 1994, Sullivan and Chiappone 1994, Louis Berger 1995, Lapointe *et al*. 1997).

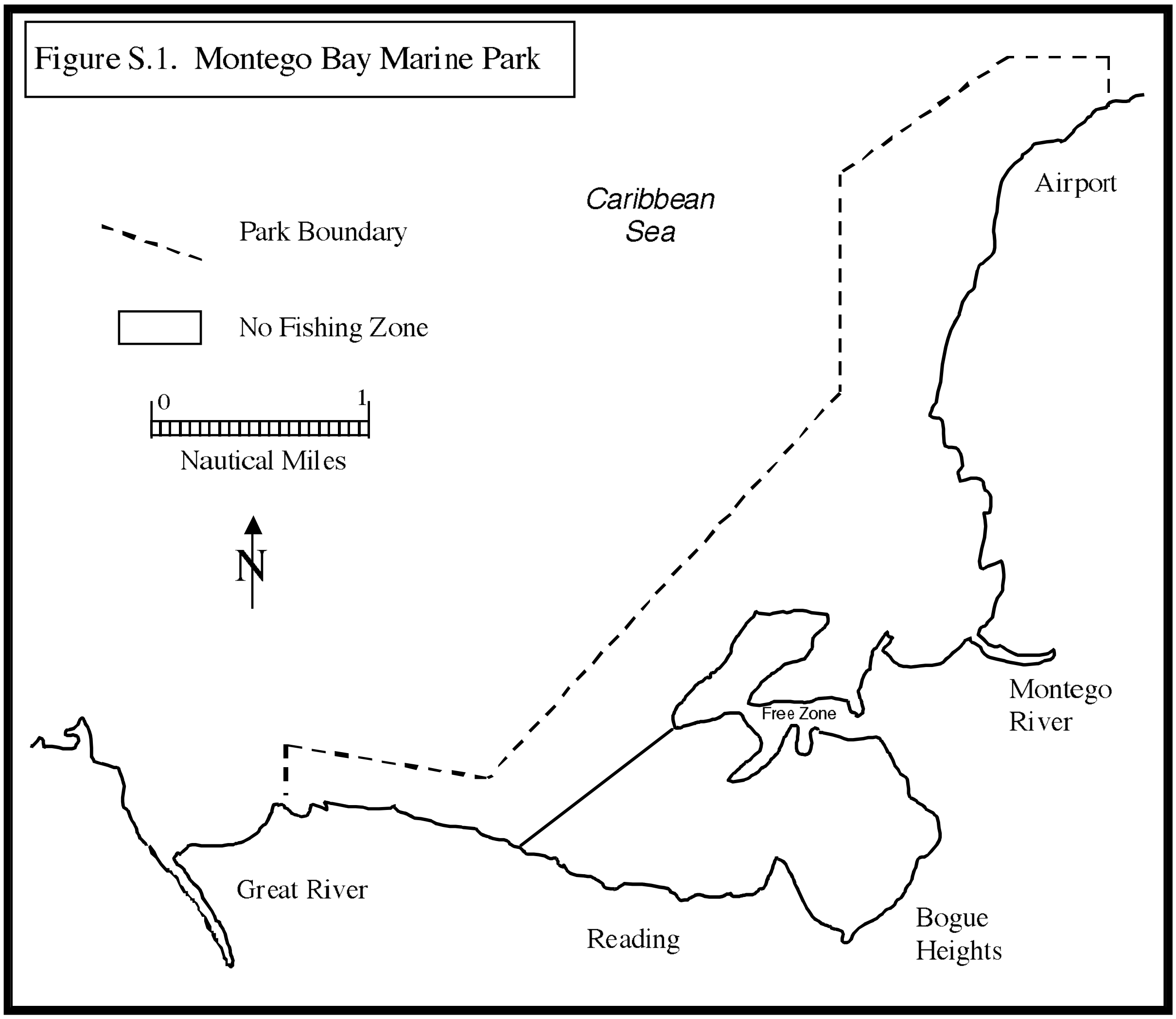

Figure S.1. Montego Bay Marine Park

HOW was the Research Done?

In addition to extensive literature reviews and careful implementation of conventional research methods, there has been extensive participation throughout the research process in a number of areas to gather information, get stakeholder input, and check output. Workshops and meetings have been held at the study site to receive feedback on the research methodology, analytical issues, and interim output. A six step consultative approach was used that has better enabled the team to check information with the academic, private, public, NGO, and consultant community. First, the team elicits participant views and reactions through interviews and roundtable discussions. Second, participants and affected groups take part in work sessions, generally limited in the number of participants. The third and fourth steps are workshops so that the views and reactions of participants can be taken into account in the final report; one workshop occurs before a draft final report is prepared, and a second workshop occurs before the final report is completed. The fifth step involves questionnaires as a way of eliciting participant views. The sixth and final step provides for the distribution of documents or reports.

Phase I empirical work benefited greatly from participation of local stakeholders and participants. Contingent valuation survey pretests were conducted with the cooperation of the Montego Bay Marine Park Trust, which was active both in the design and implementation of the pretest. Indeed, Park T-shirts were given as gifts to all respondents in the pretest. In addition, preliminary study results have been presented and reviewed locally in Montego Bay during a workshop and seminar in February 1997. Similar seminars were held in February 1998 and February 1999.

The research has also had ongoing interactive feedback in the policy making environment. While there is an existing management plan for the area, it is under constant review. Modeling workshops associated with this research have focused government officials and Montego Bay Marine Park managers on critical water quality and fisheries issues and shaped action plans in the new park management plan. These include: (i) a new park zoning plan (with mooring and demarcation buoy programs); (ii) a watershed management program; (iii) alternative income programs for fishermen; (iv) merchandise, user fee and ecotourism programs for revenue generation; (v) education programs for school children and the community; (vi) volunteer and public relations programs; (vii) enhanced enforcement to protect fisheries resources from poaching; and, (viii) research and monitoring programs to evaluate the recovery of the ecosystem and track the success of park programs.

Socioeconomic Lessons

In valuation, the distribution and incidence of physical and social impacts is important. Rapid ecological assessments have provided a cost-effective means to gain necessary biological information to assist with management strategies. Similarly, rapid socioeconomic assessments offer a means of quickly and efficiently evaluating the social and economic basis of the various user groups whose activities are affecting or affected by coral reef management efforts. But because of the relative infancy of research considering the socioeconomic context of reef management, there is a lack of research on developing rapid quantitative and qualitative techniques for assessing both the social and economic bases of reef uses.

To complement the economic analysis work, a methodology was developed for conducting rapid socioeconomic assessments of coral reef user groups (Bunce and Gustavson 1998). This methodology was applied to the three primary user groups of Montego Bay Marine Park – fishers, watersports operators, and hoteliers – during a six-week field period in January and February 1998. The utility of this methodology was demonstrated by considering the management implications of these findings for Montego Bay Marine Park.

Through document and database analysis, interviews with individuals representative of their user group, and participation in and observation of user activities, data on the following socioeconomic variables were collected: (i) characteristics of the user groups' activities; (ii) characteristics of the user groups themselves; and, (iii) users' perceptions of reef management. Scoping meetings and telephone surveys were also conducted with representative individuals from each user group to discuss major concerns regarding future management of the Montego Bay Marine Park, specific actions proposed by the users to address these concerns, and the role of each user group in the future management of the Park.

Analysis of the socioeconomic background of the user groups highlighted several socioeconomic factors with management implications, specifically: (i) patterns of use; (ii) the level of dependence on the resource; (iii) the cultural value of reef activities; (iv) ethnicity; (v) relations within and among user groups; (vi) the nature of indirect links to the Montego Bay community; (vii) the level of awareness and concern for the resource; (viii) relations with the

Box S.2
Recommended guiding principles for Montego Bay reef management arising from rapid socioeconomic assessment

A rapid socioeconomic assessment methodology was developed and implemented in 1998, resulting in several guiding principles for reef management in Montego Bay Marine Park:

1. *Greater awareness* of the Park and *concern* over the deterioration of the reefs are critical building blocks for long-term compliance and support. To build trust in the Park's abilities, the Park needs to increase the visibility of its goals, and particularly its programs and services that are beneficial to the users (e.g., the mooring system, retraining programs for fishermen).
2. *Marketing the Park and providing incentives* will promote the perception of the Park as an asset to the users. The Park needs to provide direct links between reef conservation and business revenues by marketing support of the Park as an environmentally friendly means of attracting tourists.
3. *User group involvement* in the Park must be changed in nature to actively include the full range of users in the planning process, in the development of programs (e.g., representation on advisory boards) and in the implementation of programs (e.g., assistance with monitoring programs).
4. *Community resource management* of the Park should evolve as a target in which all user groups can participate. Currently, the reefs are managed under an almost entirely open access regime. There needs to be a shift in the users' perception of the reefs such that each user group feels it has an interest in effective management, and that their long-term interests are protected.
5. *Intersectoral coordination* needs to be recognized as an important component of developing an effective, comprehensive reef management program. By building relations between user groups through the existing networks, the users can begin to work together and with the Park to maximize the range of available resources, minimize duplication, and ensure complementary and cooperative programs as part of a comprehensive effort toward reef management.

Source: Bunce and Gustavson (1998).

Montego Bay Marine Park; and, (ix) the nature and extent of resources of use to management efforts. The management implications of these socioeconomic factors provided several guiding principles for reef management in Montego Bay Marine Park (Box S.2).

Institutional Lessons

Institutional arrangements – through revenue-sharing agreements, royalties or public policies – refer to the mechanisms through which developing countries might share in the benefits of commercial development of their marine resources. While such arrangements are common for hydrocarbon, mining or fisheries resources, they are novel in the realm of biodiversity. The notion that countries such as Jamaica can integrate use of marine genetic resources into coastal zone planning, through using such arrangements, is a relatively new one. Certain international treaties empower government under international law to enact such regulations. But such arrangements form a critical, and necessary, link in transferring genetic resource values to developing countries. The nature of the arrangements, and their enforceability, will more often than not be a determining factor in whether biodiversity values are captured locally.[1]

To explore this distributional dimension of economic value, an institutional study was undertaken in Jamaica by Putterman (1998). The study provides an assessment of Jamaican institutions with expertise relevant to the management of marine genetic resources, and makes policy recommendations intended to enable Jamaica to capture the maximum value created by commercial research and development of marine genetic resources.

Currently there are no Jamaican policies to regulate access to genetic resources, or even to recognize these as valuable material. The NRCA Act of 1991 does give authority to the Natural Resources Conservation Authority to regulate the use of natural resources, as well as the authority to require permits for various kinds of prescribed uses; but genetic resources uses are not specified. Overall, there is some anxiety in Jamaica over the absence of mechanisms to ensure that Jamaica shares in the benefits of genetic resources utilization (especially when foreign private companies are involved). But there is also a good appreciation for the value of private investment in genetic resources development as a tool for economic development and biodiversity conservation. Policy development should include mechanisms for regulating access to genetic resources, establishing novel rights to property and traditional knowledge, developing prior informed consent procedures, and creating a national benefit-sharing formula.

In addition, the study explored some specific mechanisms for capturing economic values. Optimally, the government of Jamaica would require all research contracts and Material Transfer Agreements to incorporate up-front or guaranteed compensation in exchange for the transfer of genetic resources samples. Also, some contingent compensation would be forthcoming through royalties or profit sharing. It is not recommended that the government of Jamaica impose an access fee on private companies seeking genetic resources research material. Because of the highly competitive nature of natural products sourcing, arbitrary access fees would increase the cost of Jamaican genetic resources and would likely price these resources out of the market.

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[1] The Convention on Biological Diversity highlights the "sovereign rights" of Parties over genetic resources (Articles 3 and 15.1), stating that governments have the right to regulate access to these resources on "mutually-agreed terms" (Article 15.4) and with "prior informed consent" (Article 15.5). Other relevant provisions include access to technology, including proprietary technology and biotechnology (Articles 16 and 19), and knowledge pertaining to traditional uses of genetic resources (Article 8j). The UN Convention on the Law of the Sea highlights the rights of member States to grant or withhold consent for marine scientific research, stating that consent can be withheld if the research is of direct significance for the exploration and exploitation of natural resources, whether living or non-living (Articles 246.3 and 246.5a). Finally, the Trade-Related Intellectual Property subagreement (TRIPs) to the World Trade Organization (WTO) Agreement calls for Parties to adopt a wide range of intellectual property rights regimes, including patents, plant breeders rights, and trade secrets.

Box S.3
Recommendations for Jamaican genetic resources policy

Policy recommendations intended to incorporate the management of marine genetic resources into integrated coastal zone management planning in Jamaica are developed by Putterman (1998). The recommendations are intended to allow Jamaica to fulfill obligations under the Biodiversity Convention and the Convention on the Law of the Sea, guaranteeing benefit-sharing while avoiding large disincentives to private sector investment. Key components of genetic resources policy include the following:

1. *Regulate Access Up-Front with Permits and Contracts.* Because there are no internationally recognized protocols on rights to genetic resources and traditional knowledge, it is necessary to define rights to these resources by contract before samples are collected. The NRCA, or possibly the Ministry of Commerce and Technology, would be appropriate regulatory agencies. It is highly recommended that private parties be allowed to negotiate draft research contracts independently. These draft contracts would be submitted to the regulatory agency for review along with the collecting permit application. A multi-disciplinary Genetic Resources Advisory Authority, with expertise in scientific matters, contract law, community rights and business development, would convene to review draft contracts.
2. *Establish Sui Generis (Novel) Rights to Tangible Property and Traditional Knowledge.* To define who has the right to negotiate genetic resources research contracts, it will be necessary to create rights to both the tangible and intangible (intellectual property) manifestations of these. Tangible property includes the physical embodiment of genetic resources and value-added research material. Intellectual property here refers mainly to traditional knowledge. A modification of industrial trade secrets laws, which Jamaica is required to develop under the WTO Agreement, is recommended for creating rights to this knowledge. *It is strongly recommended that the government of Jamaica refrain from nationalizing genetic resources rights*. This creates the possibility of establishing community rights; local resource tenure systems have been successful in creating local incentives for sustainable resource management.
3. *Develop Prior Informed Consent Procedures.* To give the legal owners of rights to genetic resources and traditional knowledge a means to control use of these resources, it will be necessary to devise a Prior Informed Consent mechanism to be used in the negotiation of "mutually-agreed terms." At the national level, establishing a Genetic Resources Advisory Authority would be sufficient to ensure Prior Informed Consent of the government of Jamaica. There is a critical role for NGOs in facilitating Prior Informed Consent decisions by local communities. Requiring foreign researchers to obtain Prior Informed Consent directly from each and every local stakeholder may act to strongly discourage foreign direct investment. A more user-friendly method would be to require a local research partner organization to obtain a Certificate of Prior Informed Consent from the government, certifying that research material has been obtained with adequate Prior Informed Consent from local stakeholders. Foreign researchers would then merely have to ensure that domestic partners present an approved Certificate of Prior Informed Consent.
4. *Create a National Benefit-Sharing Formula.* To ensure fair and equitable distribution of income from genetic resources utilization, a national formula to convert a portion of this income into public goods is necessary. An existing formula would simplify genetic resources negotiations. An ideal revenue-sharing arrangement would allow domestic research partners such as private companies, NGOs (including those managing National Parks), and local communities to keep a portion of their income to maintain incentives for private investment and innovation. The remainder of genetic resources income would be set aside for broader uses (e.g., protected area management across Jamaica.) Developing a set of guidelines or fixed percentages, through defining these national set-asides on genetic resources income, would streamline the permit approval process; set-aside percentages could be recorded directly on the genetic resources permit.

Source: Putterman (1998).

Also, it is recommended that the government of Jamaica encourage the development of local value-added research services. These could provide inventoried biodiversity samples – or advanced research material derived from these samples – directly to private industry for a fee. Sample rental fees can be in the form of monetary compensation, which would be designed to recover the full costs of collection and processing. Note that value-added genetic resources research material is difficult to obtain. Marine genetic resources in particular are prized for the complex structures and novel biological activities of chemicals and enzymes derived from them. Jamaican organizations offering these types of material would give Jamaica a clear competitive advantage over other countries.

Valuing the Obvious – Local Uses

Empirical work for Montego Bay, Jamaica, commenced with an estimate of the net present value (NPV) of readily identified local uses using production valuation approaches; these can be regarded as a benchmark value for comparative purposes. Initial priority-setting and valuation estimates done by Huber and Ruitenbeek (1997) in association with local stakeholders was subsequently refined and updated by Gustavson (1998) through identifying specific direct and indirect uses during a site visit in January and February 1998. Direct local use values were estimated on an annual basis for two broad categories of uses: nearshore fisheries and tourism. Indirect use values associated with coastal protection were also estimated. These local uses of the Park waters were identified as the most significant during the final study site application, as well as being of the highest policy priority. Other uses considered were aquarium trade, mariculture, coral crafts, non-coral crafts, and coral sand extraction; all of these were of negligible value.

Tourism services include accommodations, food and beverage service, entertainment (including independent watersports and attractions), transportation, shopping, and other miscellaneous services. NPV estimates associated with tourism in Montego Bay range from US$210 million (using a 15% discount rate) to US$630 million (using a 5% discount rate); at a 10% discount rate the value is US$315 million. In contrast to some other recreational valuation studies on larger coral reef areas (Driml 1999), we here attribute this entire value to the availability and maintenance of the intact coral reef. This is therefore the value at risk, to the extent that it would all be lost if the coral reef resource were totally degraded.

Fishing in the waters of the Montego Bay Marine Park is artisanal, and largely subsistence in nature. Trap, net and hand line fishing occur off of canoe-type vessels, launching from any one of five landing beaches in the area; in addition, there are numerous spear fishers using Park waters. The NPV estimate associated with fishing is US$1.31 million at a 10% discount rate. This assumed a shadow value of labor of 75% of the market wage; the fishery value is in fact negative if one assumes full market rates.

The value of coastal protection is estimated from the value of land that is vulnerable to erosion; this represents approximately 100 hectares (250 acres). Assuming this area to be vulnerable to erosion along the approximately 34 kilometers (21 miles) of shoreline within the Montego Bay Marine Park boundaries means that approximately the first 30 meters (100 feet) of shoreline property are at risk of erosion should the protective function of the coral reefs be compromised. The NPV of the total amount of land at risk of erosion, based on this area, is estimated to be US$65 million.

The total NPV of US$381 million translates to approximately US$8.93 million per hectare, or US$893,000/ha/yr on an annualized basis. Allocation to reef area corresponds to an estimated available coral substrate area within the Montego Bay Marine Park of 42.65 hectares.

The value for the direct uses represents what would typically be considered to be producer surplus or rent. In other words, it is the difference between the total revenues taken in through the use of the coral reefs, and the total economic costs associated with operating the activity. Of great interest to the management authorities of the Montego Bay Marine Park, as well as to managers of any coastal marine system, is to capture at least a portion of this rent to pay for the necessary management, and potential enhancement, of the resource. The current efforts of the Montego Bay Marine Park to implement user fees should be encouraged. An independent administration of a program of rent capture that ultimately varies at least according to the level of use and the type of business (assuming that there is a certain level of per use rent capture associated with a particular activity) will help ensure that the funds are accessible by management authorities.

Valuing the Less than Obvious – Biodiversity Non-use

Contingent valuation methods (CVM) are meant to address the consumer surplus, or individual utility, associated with coral reef improvement. Such methods explore the willingness to pay

(WTP) by respondents, for given changes in reef quality. Specifically, a survey instrument was designed to capture the non-use benefits of marine biodiversity at Montego Bay, for both local Jamaican residents and for visitors. Coral reef conservation benefits were valued in monetary terms to identify various economic and demographic characteristics of this valuation and its determinants.

Table S.2
Predicted willingness to pay –
Montego Bay coral reef conservation*

	P(>0)	E(WTP)
Sample Means – All	65.77%	3.24
Sample Means – Typical Local	68.49%	3.75
Sample Means – Typical Tourist	62.51%	2.73
Locals with Moral Duties/Rights	70.72%	4.26
Locals with No Moral Duties/Rights	52.37%	1.66
Tourists with Moral Duties/Rights	64.22%	2.98
Tourists with No Moral Duties/Rights	45.17%	1.17

* P(>0) is probability of non-zero bid; E(WTP) is expected WTP in US$.

Source: Spash, van der Werff ten Bosch, Westmacott and Ruitenbeek (1998).

Although CVM is well-developed and routinely used in assessing environmental benefits, the current study involved several areas of innovation. Coral reef quality had previously been neglected by valuation work with most developing country CVM studies focusing on other issues (such as water quality) or on specific urban locations. More significantly from a research perspective, the study undertaken for this research by Spash *et al*. (1998) addressed the existence of lexicographic preferences as one of a number of outstanding methodological questions associated with biodiversity valuation requiring further attention. The methodological problems associated with lexicographic preferences – which occur when a respondent refuses to assign a value to conservation – occur both at the survey stage and at the data reduction and interpretation stage. At the survey stage, responses typically show up as zeros, and surveys must be designed to probe further into such responses and attempt to link them to some form of preference structure associated, for example, with perceptions of rights or duties of marine animals. At the interpretation stage, data analysis is confounded by a large number of excluded data (with the high number of zeros), which still may provide useful information; usual methods of bid curve analysis relying on averages or bid distributions are inadequate in such circumstances. These methodological challenges were overcome by careful design of a questionnaire that permitted probing of respondents and through the adoption of econometric maximum likelihood estimation techniques for analysing the bid functions.

Expected WTP for coral reef improvement was US$3.24 per person in a sample of 1058 respondents (Table S.2); a similar study for Curaçao placed this at US$2.08 per person. But this value was heavily dependent on whether respondents believed that marine systems possessed inherent rights, or that humans had inherent duties to protect marine systems; such preferences would increase WTP by a factor of two to three in Jamaica. Based on these values, for typical population characteristics, and using typical visitor profiles, it is estimated that the Montego Bay biodiversity has a net present value of US$13.6 million to tourists and US$6.0 million to Jamaica residents. The total NPV of US$19.6 million translates to approximately $460,000/ha, or $46,000/ha/yr on an annualized basis.

Valuing the Subtle – Biological Prospecting

A comprehensive review was undertaken of methods and models relevant to bioprospecting benefit valuation (Cartier and Ruitenbeek 1999). The goal of the review was to identify issues and potential models that have been considered in the valuation of terrestrial bioprospecting, and adapt these to a situation of marine bioprospecting. Particular attention was paid to *pharmaceutical* bioprospecting issues. The resultant model is used in an exploratory fashion to derive benefit values for pharmaceutical bioprospecting at Montego Bay.

The literature review highlighted a number of factors that have tended to be crucial in the derivation of values in terrestrial bioprospecting valuation models (Table S.3). These issues include: (i) estimation of gross vs. net economic values; (ii) estimation of private vs. social returns; (iii) capture of rent shares by local governments; (iv) estimation of average vs. marginal returns, and the role of redundancy and substitutability in each of these; and, (v) treatment of complexity through interdependence of discoveries and ecosystem yields.

The estimating model for Montego Bay bioprospecting focuses on a model of average social net returns, using localized cost information for Jamaica, and benefit values and success rates based on proprietary information for marine-based pharmaceutical products in the Caribbean. As with the other models reviewed (Table S.3), the approach essentially reflects an estimate of social value based on private behavior; similarly, the model excludes explicit calculation of option values. The institutional costs associated with rent capture are estimated for Montego Bay but are found to be small in relation to overall costs and benefits; they are at most US$230,000 in present value terms.

Table S.3. Comparative summary of pharmaceutical bioprospecting models

	Farnsworth & Soejarto (1985), Principe (1989ab), Pearce & Puroshothaman (1992ab)	Aylward (1993)	Mendelsohn & Balick (1995,1997)	Simpson, Sedjo & Reid (1996), Simpson & Sedjo (1996ab), Simpson & Craft (1996)	Artuso (1997)	Solow et al. (1993), Polasky & Solow (1995)	Ruitenbeek & Cartier (1999)
Model Attributes							
Analytical Specification Only						✔	
Terrestrial System Application	✔	✔	✔	✔	✔		
Marine System Application							✔
Policy Applications							
Education & Awareness	✔						
National Level Policies	✔	✔	✔		✔		✔
Private Profitability Analysis		✔		✔	✔		
Site Specific Planning				✔		✔	✔
General Economic Attributes							
Gross Economic Value	✔						
Net Economic Value		✔	✔	✔	✔	✔	✔
Private Costs	✔	✔	✔	✔	✔	✔	✔
Social Costs (including Institutional)		✔			✔	✔	✔
Time Delays		✔	✔	✔	✔	✔	✔
Average Species Value	✔	✔	✔		✔	✔	✔
Marginal Species Value				✔		✔	
Average Habitat Value		✔	✔		✔	✔	✔
Marginal Habitat Value				✔	✔	✔	✔
Specific Model Parameters							
Discovery Process Stages (Hit Rates)	**1**	**1**	**1**	**1**	**9**	**1**	**3**
Discovery Process Stages (Costs)	**1**	**1**	**1**	**1**	**9**	**1**	**1**
Revenue Sharing Treatment	■	■		✔	■	✔	✔
Redundancy/Interdependency				✔	■	✔	
Ecosystem Yield (Species-Area Relationship)				✔	✔	✔	✔
"Price Function" (Once Differentiable Value)				✔	✔	✔	✔
Industry Structure/Behavior						■	
Risk Preference/Aversion Behavior					■		■

✔ Explicitly Relevant or Incorporated

■ Treated Qualitatively or Partially

20-Mar-99

The adopted model uses some of the concepts incorporated in the terrestrial bioprospecting valuation models and builds on these for the marine environment by explicitly introducing parameters relating to *rent distribution* and complexity, as reflected by *ecosystem yield*. Sensitivity analyses demonstrated that these two parameters are likely to have the most significant impact on captured values, and on planning problems. Rent distribution is introduced as a policy variable, while ecosystem yield is a composite measure of species and sample yield potentially available from the Montego Bay reef. We derive likely estimate ranges for ecosystem yield based on typical species-area relationships postulated in the island biogeography literature (Simberloff and Abele 1976, Quammen 1996, Reaka-Kudla 1997). Finally, the results are once differentiated to derive a marginal benefit function, which relates value to coral reef abundance or area, and can be interpreted as our estimate of coral reef "price" that would be applied within a planning framework.

Using typical cost estimates for Jamaica, and using typical hit rates and end-use values, scenario analyses were conducted using a parametric model. These scenarios typically place marine bioprospecting values in the neighborhood of $2600 per sample, or $7775 per species. The per species values are somewhat higher than typical estimates for terrestrial species; primarily because of higher demonstrated success rates in terms of product development. Success rates are generally somewhat better than those for terrestrial sampling programs; the implied rates within our model are of the order of 1:30,000.

Translating these values to a system such as Montego Bay will depend on the specific bioprospecting program and the ecosystem yield of samples and species. The bioprospecting program is designed as one that might typically follow National Cancer Institute (NCI) protocols (Colin 1998), which would realize comprehensive sampling over a period of approximately 16 years. Estimates for ecosystem yield generate a result that there are about 18,000 target species available for sampling at the Montego Bay area of 42 hectares; this is based on a derived result that incorporates known reef area, expert assessments of reef quality, and a standard species-area relationship for marine organisms of the form $S=cA^z$. In the reference case we take z=0.265, but a plausible range for this parameter of z=0.2 to z=0.3 yields confidence limits for the target range of species of 10,600 to 47,400. Consistent with other findings, we assume each species yields on average three testable samples, each of which may in turn be assayed for multiple targets.

Using base case estimates of ecosystem yields for the Montego Bay area, coupled with a hypothetical sampling program that would be consistent with NCI standards for marine sampling, a base case value of $70 million is ascribed to the Montego Bay reefs; approximately $7 million would be realistically capturable by Jamaica under typical royalty regimes or sample rental arrangements. None of this value is captured under existing institutional arrangements.

The base case value of $70 million corresponds to equilibrium coral abundance levels of 43% on available substrate; ecosystem model predictions set this as a long-term equilibrium in the event of no additional stresses on the reef. Where current economic growth places new stresses on the reef, a predicted “degradation” to approximately 25% is set as a comparative case. Under this case, the global value of the reef would be $66 million: a loss of about $4 million.

Also, the first differential of the benefit function is calculated to arrive at an ecosystem marginal “global price” of $530,000/ha or $225,000/% coral abundance. For Jamaica’s share, the relevant “local planning price” computes to approximately $22,500/% coral abundance. The model demonstrates the sensitivity of total and marginal values to ecosystem yield and institutional arrangements for capturing genetic prospecting value. For example, sensitivity analyses within the plausible range of species-area relationships generated global benefits for the Montego Bay reef of $54 to $85 million; reef prices ranged from $698,000/ha to $72,500/ha.

The relatively low “price”, and the apparently small drop in benefits from significant coral reef degradation, underlines the importance of the ecosystem yield. In effect, two factors contribute to this result. First, because of the non-linear relationship between species and area, a decrease in coral abundance does not translate one to one into a decrease in species or available samples. Second, the loss in available samples is not experienced immediately; annual sampling constraints under a sustainable program under NCI standards at Montego Bay would yield approximately 3300 samples annually. The economic effect of these “lost samples” is therefore discounted substantially, and would consequently have less of an impact on current management decisions.

Detailed sensitivity results are shown in Table S.4. In particular, we note:

- ecosystem values, in terms of prices that would enter a planning function for land allocation and investment decisions, are most sensitive to assumptions regarding ecosystem yield.
- an appropriate risk mitigation strategy for Jamaica would likely involve some combination of a net profit share ($\alpha > 0$) and modest sample fee. Such a strategy would guaranty captured

Table S.4. Model results for marine pharmaceutical bioprospecting valuation – Montego Bay. Parametric assumptions relate to z-factor within species(S)-area(A) relationship $S=cA^z$, a contingent net profit share (α) and a fixed sampling feel level f ($/sample). Model solves for total samples (N) available at Montego Bay and the typical length (T) of sampling program that would be required to harvest these. Economic calculations relate to the expected net present value of the program to the world (NPV_G) and to Jamaica (NPV_J). A first differential of the function yields a global "price" (P_G) and Jamaican "price"(P_J) for coral reefs that could be applied within a planning framework equating marginal benefits to marginal costs.

Case	z	α	f ($)	N	T (yr)	PV_G (MM$)	PV_J (MM$)	P_G ($/%)	P_J ($/%)
Base Case Scenario at 43% Coral Abundance									
Reference*	0.265	10%	0	53,660	16.3	$70.09	$7.01	225,614	22,561
High z	0.3	10%	0	31,763	9.6	$54.46	$5.45	297,516	29,752
Low z	0.2	10%	0	142,099	43.1	$84.61	$8.46	30,901	3,090
Fee Only	0.265	0%	250	53,660	16.3	$70.09	$6.76	225,614	21,763
High z	0.3	0%	250	31,763	9.6	$54.46	$5.25	297,516	28,699
Low z	0.2	0%	250	142,099	43.1	$84.61	$8.16	30,901	2,981
Blended Revenue Shares	0.265	8%	50	53,660	16.3	$70.09	$6.96	225,614	22,402
High z	0.3	8%	50	31,763	9.6	$54.46	$5.41	297,516	29,541
Low z	0.2	8%	50	142,099	43.1	$84.61	$8.40	30,901	3,068
High R&D Cost	0.265	10%	0	53,660	16.3	$17.64	$1.76	56,783	5,678
[R/C Ratio=1.1:1]	0.265	0%	250	53,660	16.3	$17.64	$6.76	56,783	21,763
	0.265	8%	50	53,660	16.3	$17.64	$2.76	56,783	8,895
Low Hit Rate	0.265	10%	0	53,660	16.3	$25.02	$2.50	80,525	8,052
[1:80,000]	0.265	0%	250	53,660	16.3	$25.02	$6.76	80,525	21,763
	0.265	8%	50	53,660	16.3	$25.02	$3.35	80,525	10,795
Unconstrained**	0.265	10%	0	53,660	1.0	$139.07	$13.91	1,054,202	105,420
High z	0.3	10%	0	31,763	1.0	$82.32	$8.23	699,475	69,948
Low z	0.2	10%	0	142,099	1.0	$368.27	$36.83	2,145,937	214,594
Institutional***	0.265	10%	0	53,660	16.3	$70.09	$6.96	225,614	22,561
Degradation Scenario at 25% Coral Abundance									
Reference z	0.265	10%	0	46,477	14.1	$66.12	$6.61		
High z	0.3	10%	0	26,994	8.2	$49.37	$4.94		
Low z	0.2	10%	0	127,492	38.6	$84.06	$8.41		

*Uses study result hit rates of 1:30,000 and Sales:R&D Cost Ratio of 1.5:1. Prices P_G and P_J may be converted to $/ha basis by dividing by 0.4265.
** Assumes all samples are collected and subjected to preliminary screening immediately (in 1 year).
*** Includes institutional overheads of central government agencies.

values of the same order as those expected in the reference case, but would reduce exposure to hit rate uncertainties, product marketing uncertainties, and ecosystem dynamics.

- results are sensitive to sampling constraints. If it were realistic to assume that all relevant sampling and screening could be done immediately, the present value would double in the reference case.
- the impacts of the incremental institutional costs – for operating a national program consistent with the recommendations in Box S.3 – are minimal.

Table S.5
Summary of valuation results – Montego Bay coral reef

	Benefit	Price*	
	NPV (MM$)	MM$/%	MM$/ha
Tourism/Recreation	315.00	7.33	17.18
Artisanal Fishery	1.31	0.03	0.07
Coastal Protection	65.00	1.51	3.54
Local Non-use	6.00	0.24	0.56
Visitor Non-use	13.60	0.54	1.28
Subtotal	400.91	9.65	22.63
Pharmaceutical Bioprospecting (Global)	70.09	0.23	0.53
Total (Global)	471.00	9.88	23.16
Pharmaceutical Bioprospecting (Jamaica)	7.01	0.02	0.05
Total (Jamaica)	407.92	9.67	22.68

* Marginal benefits shown at typical current reef conditions.

Summing Up the Values – Towards a Benefit Function

As a final step, one can aggregate the economic values into a total value and a net marginal benefit (price) function for the Montego Bay reef (Table S.5). The use of such values requires making a number of further assumptions about the sensitivity of the individual values to reef quality. As seen with the bioprospecting values, the total value of the reef was relatively high ($70 million) but changes in reef quality within the planning range (of approximately 20% to 50% coral abundance) did not have a large effect on this value.

As no specific linkage models are available for the other values estimated, we make a number of simplifying assumptions for demonstration purposes. In general, as a reference case, we assume a linear relationship between reef quality and value for all values other than bioprospecting. In effect, this places a fixed price for these other uses and functions, and is likely to over-estimate price in some instances, while potentially underestimating in others. For erosion, for example, a degraded reef will still provide some limited erosion benefit for some time; an average price assuming a linear relationship will thus overstate the marginal benefit. For tourism, however, small changes in quality may have disproportionately larger impacts on arrivals if there is a perception that the reef is substantially degraded (to a degree, this occurred about ten years ago in Montego Bay after some highly publicized but overstated reports of massive degradation decreased diver visits there). In the case of the non-use values, the contingent valuation survey explicitly included a degradation scenario, hence the end-points were well established (they represented a 25% degradation) but the nature of the function between these end-points is somewhat uncertain.

Given these assumptions, it is clear that the total benefit attributable to the reef in its current condition is approximately $470 million, and that every 1% change in abundance is likely to generate a marginal benefit of approximate $10 million. Most of the value, and change in value, is attributable to the tourism resource; coastal protection and non-use benefits are next in terms of planning importance. The relative impacts of fisheries and bioprospecting on planning prices are negligible, especially if one considers only the capturable values to Jamaica.

We juxtapose these marginal benefit calculations against a marginal cost function for the Montego Bay reef, as generated by a fuzzy logic based ecological-economic model (Ruitenbeek *et al*. 1998, Annex A). This related research on cost effectiveness modeling of interventions suggested that up to a 20% increase in coral abundance may be achievable through using appropriate policy measures having a present value cost of US$153 million. The cost curve envelope generated by that research showed marginal costs rising from under $1 million per % of coral abundance to $29 million per % of coral abundance. Global optimization using the combined cost and benefit functions suggested an "optimal" improvement of coral reef abundance of 13%, requiring net expenditures of US$27 million, primarily in the areas of: installation of a sediment trap; waste aeration; installation of a sewage outfall; implementation of improved household solid waste collection; and implementation of economic incentives to improve waste management by the hotel industry. Sensitivity tests suggest that net economic benefits would need to increase by US$275 million or decrease by US$300 million for the coral quality target to vary from this by more than 2% (i.e., fall below 11% or above 15%). To justify the full expenditure (achieving a 20% coral reef improvement), would require additional benefits of some $660 million.

It is notable that the inclusion or exclusion of pharmaceutical bioprospecting values from this analysis does not have an effect on this planning outcome. Even if a strict linear relationship were applied and 100% of the bioprospecting value were capturable by Jamaica, the resultant price ($70 million per 43% coral = $1.6 million/%) would not be adequate to justify improvements beyond those stated above.

Summary and Conclusions

This project has looked at biodiversity valuation in general, with a view to considering the different methods that may be relevant to applied marine biodiversity valuation. Methods relating to direct and indirect uses and functions are among the best developed, and techniques are readily transferred to coral reef systems. Methods relating to non-use values are also available, although they are complicated by methodological issues such as lexicographic preferences.

Of greatest research interest, however, is the field of biological prospecting valuation. Models for terrestrial systems have evolved considerably over the past decade, although none have yet been applied to marine systems. Also, bioprospecting model development in the literature has tended to be isolated in two distinct areas: agriculture and pharmaceuticals. While both have similar foundations in the modeling of the value of applied research (Evenson and Kislev 1976), distinct literatures have developed in agricultural and pharmaceutical modeling development. This has arisen because of different technical aspects of bioprospecting in these fields, as well as different policy concerns.

From a technical perspective, bioprospecting values are derived somewhat differently in agriculture and pharmaceuticals. In both cases, the actual *value* associated with biodiversity is closely tied to the type of information provided, as opposed to any particular material good (Swanson 1996). In the case of pharmaceuticals, this information provides a stock of ideas that can be used to synthesize key compounds, often establishing new products and markets (WCMC 1994a). In the field of plant genetic resources, however, the information itself provides direct genetic information that can be introduced into other economic species or crops which already have a market (WCMC 1994b).

Efforts in agricultural valuation have been driven by policy questions that address issues such as food security, farm incomes, and efficient research methods in a market where end products (such as food crops) are dominated by open competition (Evenson *et al*. 1998). Much of the research work in agricultural prospecting is funded through public institutions and international agencies. In agriculture, modeling has addressed distributional concerns related to the improvement of farm level incomes, and the social benefits arising from incorporating traits in improved crop varieties (see Smale 1995, 1998, Smale *et al*. 1995). Also, it has often focused on the valuation of genetic traits and optimization of the search paths for finding economically useful traits within large samples (often maintained in *ex situ* collections) (e.g., Gollin and Smale 1998).

By contrast, the pharmaceutical bioprospecting literature was, initially, dominated by policy concerns relating to the *in situ* conservation of wild genetic resources (e.g., "drugs from the rainforest"). The intensely private – and often seemingly monopolistic – nature of new drug patenting and development, coupled with long testing periods, has meant that institutional questions frequently dominate discussions relating to valuation. Most models remain relatively deterministic; only more recently have concerns such as optimal research paths entered the pharmaceutical bioprospecting literature (Artuso 1998). Moreover, the role of ecosystem and habitat conservation and their potential yields of "new" species adds a dimension that is often absent from discussions in the agricultural bioprospecting literature.

In the case of marine systems, the issues are further complicated by ownership concerns and the perceived system yield of useful information. Management and ownership of marine and near-offshore resources is a problematic topic in most jurisdictions, and the entire discipline of Integrated Coastal Zone Management (ICZM) is targeting such problems through what are by and large institutional reforms and interventions. Also, on balance, marine systems are receiving greater scrutiny for new sources of drugs while bioprospecting for useful maricultural traits is limited (Henkel 1998). For example, in early 1999, more than 30 drugs derived from marine species were under preclinical investigations by private and public research organizations, and by the National Cancer Institute (Mestel 1999).

The marine bioprospecting valuation approach we take in this study falls primarily into the realm of deterministic models relating to pharmaceutical development. These attempt to infer social values from intensely private behavior. The model we develop, like its counterparts, makes no explicit calculation of option value. It does, however, provide insights into issues of value related to marine environments, focusing on issues such as marine product success rates, institutional revenue sharing issues, and ecosystem yield. We encourage further research that looks into such issues in greater depth, and extends models to bioprospecting for other marine products, such as mariculture. In that respect, future modeling efforts are likely to borrow more extensively from both the agricultural and the pharmaceutical literature.

We maintain, however, that no single terrestrial bioprospecting valuation model should be preferred over the others; each has a different policy application. In pharmaceutical bioprospecting, the early models of gross economic value had an important role to play for education and awareness policies, although they may be less useful for management and specific planning. The next generation of models, those relating to net economic values, taught us that we need to pay greater attention to the allocation and calculation of costs within the biological prospecting process. This has distributive implications, such as through the incidence of benefits and costs to the private sector vs. society at large, as well as efficiency considerations, such as whether it in fact makes economic sense to undertake biological prospecting. In particular, the average cost models showed us how sensitive economic values can be to technical parameters (such as success rates) and to economic variables, such as royalty rates or R&D costs.

But even these models fail to tell the whole picture, or answer all of the relevant economic policy questions. From a system planning perspective, we are constantly reminded that we must pay attention to the complexity inherent in biological and ecological systems, as well as within the discovery process itself (Brown and Goldstein 1984, Solow *et al*. 1993, Polasky and Solow 1995). One manifestation of this is the potential for interdependence of probabilities within the discovery process; an example of this was illustrated by Simpson *et al*. (1996) in their treatment of "redundancy" to show that the value of the marginal species is in fact quite low when such complexities are considered. Another manifestation of this complexity arises at the policy planning stage when trying to transfer "$/species" values to some tract of ecosystem such as rainforest. In such cases, the yield of species by the ecosystem is typically non-linear, and the first differential of this relationship must be estimated before allocative decisions about optimal levels of conservation can be made. Again, this issue was touched upon by Simpson *et al*. (1996), as well as by Artuso (1997), and their findings illustrate the sensitivity of valuation results to assumptions relating to ecosystem yields.

As another example of the complexity and interdependence issue, none of the models have adequately grappled with differentiating among the *intended reasons* for bioprospecting. It is normally assumed that we are looking for new products and new discoveries that will somehow cure all of our worst maladies. In fact, however, some of the bioprospecting is oriented to looking for new – but cheaper – sources of existing materials. In that respect, bioprospecting is akin to mineral or oil exploration … we know what we are looking for and are simply looking for a cheaper source. In this case, redundancy is not an issue; indeed, redundancy may be a positive rather than a negative factor in valuation.

To date, no single model has provided all of the answers. At best, they provide some indication of value, and what that value is sensitive to within a given policy context. There remain substantial limitations to valuation techniques. When designing a new model, or choosing among the existing ones, one must therefore pay attention to the particular policy issues or analytical issues one wishes to address. For marine products, these issues can be quite different than those related to terrestrial products. While any single valuation will generally be a useful policy input, it should normally be regarded as just one among many potential inputs to such a policy making exercise. It is no accident that wider reliance is also being made on multi-criteria analyses, with valuation as one component of that analysis. Adger *et al*. (1999) demonstrate how such MCA techniques can be of particular use in marine park planning applications where there are often a large number of stakeholders, having a wide variety of interests and objectives.

Further, we would submit that the overall focus on valuation has perhaps distracted analysts from more pressing institutional and socioeconomic concerns. Valuation results consistently show that institutional arrangements between developing countries and the rest of the world are critical components of capturing value and of mitigating risks associated with uncertain economic and ecosystem conditions. Yet local institutional capacity remains weak in Jamaica, as it does in most developing countries. Also, both the economic theory of resource utilization and the social realities arising out of extensive stakeholder participation consistently demonstrate that we must move rapidly towards decentralized and communal management of coral reef resources. Failure to do so will likely rapidly dissipate, or totally eliminate, any notional values we might attach to these resources. But this decentralization is often fettered by a bureaucratic malaise that resists such change, as well as other vested interests in maintaining the status quo. It is incumbent on analysts to assist opinion leaders in overcoming such constraints.

In closing, we might be reminded of two principles in particular, developed as a result of extensive interdisciplinary consultations initiated in 1992 by the Marine Mammal Commission:[2]

> Principles for the conservation of wild living resources. …
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> Principle II. The goal of conservation should be to secure present and future options by maintaining biological diversity at genetic, species, population and ecosystem levels; as a general rule neither the resource nor other components of the ecosystem should be perturbed beyond natural boundaries of variation. …
>
> Principle V. The full range of knowledge and skills from the natural and social sciences must be brought to bear on conservation problems.
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> (Mangel *et al*. 1996).

When dealing with ecosystems, these principles essentially mean "exercise precaution; work together." The same principles, it seems to us, should apply to biodiversity valuation.

[2] The full set of Principles and its discussion appears in Mangel *et al.* (1996) and in Perrings (1997).