



Quantifying Coral Reef Ecosystem Services



SCIENCE

Quantifying Coral Reef Ecosystem Services

Peter P. Principe
Environmental Sciences Division
National Exposure Research Laboratory
Research Triangle Park, NC

Patricia Bradley
Atlantic Ecology Division
National Health and Environmental Effects Research Laboratory
Key West, FL

Susan H. Yee
William S. Fisher
Eric D. Johnson
Gulf Ecology Division
National Health and Environmental Effects Research Laboratory
Gulf Breeze, FL

Paula E. Allen
Environmental Sciences Division
National Exposure Research Laboratory
Las Vegas, NV

Daniel E. Campbell
Atlantic Ecology Division
National Health and Environmental Effects Research Laboratory
Narragansett, RI

National Exposure Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Research Triangle Park, NC 27711



Recycled/Recyclable

Printed with vegetable-based ink on paper that
contains a minimum of 50% post-consumer
fiber and is processed chlorine free.

Notice and Disclaimer

The U.S. Environmental Protection Agency through its Office of Research and Development funded the research described herein. It has been subjected to the Agency's peer and administrative review and has been approved for publication as an EPA document. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

This is a contribution to the EPA Office of Research and Development's Ecosystem Services Research Program, Coral Reefs Project.

The appropriate citation for this report is:

Principe P, Bradley P, Yee S, Fisher W, Johnson E, Allen P and Campbell D. 2011. Quantifying Coral Reef Ecosystem Services. U.S. Environmental Protection Agency, Office of Research and Development, Research Triangle Park, NC. EPA/822/T/33/428, Lcpwct{ 2014.

This document can be downloaded from EPA's website: www.epa.gov/research

Acknowledgements

This report was peer reviewed by Steve Jordan and Debbie Santavy of ORD's Gulf Ecology Division and Bob Leeworthy of the National Oceanic and Atmospheric Administration.

Cover photo credit: Charles LoBue, EPA Region 2.

Table of Contents

List of Figures.....	vi
List of Tables.....	vii

1 Coral Reefs: Introduction and Overview 1

1.1 Quantifying coral reef ecosystem services.....	1
1.2 Purpose and organization.....	5
1.3 Ecosystem services and economic benefits.....	5
1.4 Ecological integrity, ecological resilience, and biodiversity	8
1.4.1 Ecological integrity.....	8
1.4.2 Ecological resilience.....	9
1.4.3 Biodiversity	9
1.4.4 Insurance value	9
1.5 References.....	10

2 Coral Reefs: Tourism and Recreation 15

2.1 Describing the service	15
2.1.1 Definitions	15
2.1.2 Tourism and the economy.....	15
2.1.3 Tourism and recreation activities related to coral reefs.....	16
2.1.3.1 Recreational (scuba) diving	16
2.1.3.2 Snorkeling	17
2.1.3.3 Underwater photography.....	17
2.1.3.4 Recreational (sport) fishing.....	18
2.1.3.5 Viewing nature and wildlife.....	18
2.1.3.6 Beach sunbathing and swimming.....	19
2.1.3.7 Collecting objects (beachcombing).....	19
2.1.3.8 Surfing.....	19
2.1.4 Tourism and recreation: businesses.....	20
2.2 Necessary conditions for providing the service	20
2.2.1 Linkages among reef condition, reef structures, and reef functions with respect to delivery of the service	21
2.3 Measuring the service.....	22
2.3.1 Stony corals (scleractinians).....	23
2.3.2 Octocorals (gorgonians)	23
2.3.3 Sponges.....	23
2.3.4 Fishes	23
2.3.5 Mangroves and seagrasses.....	24
2.4 Valuing the service.....	24
2.4.1 Effect on production (EoP)	25
2.4.2 Financial analysis (FA)	25
2.4.3 Travel costs (TC).....	26
2.4.4 Contingent valuation method (CVM)	26
2.4.5 National scale valuation of tourism	26
2.4.6 National scale valuation of recreational fishing	27
2.4.7 Noneconomic human dimensions measures.....	27
2.4.7.1 Importance-satisfaction ratings	28
2.4.7.2 Expectancy-discrepancy analysis.....	28
2.4.7.3 Norm curves.....	28

2.4.7.4	<i>Emergy</i>	28
2.5	Reflections	28
2.6	Bibliography	31
Appendix 2-A: Studies quantifying tourism and recreation		39
3	Coral Reefs: Fish & Coral for Food, Aquaria, & Ornaments	43
3.1	Describing the service	43
3.1.1	Definitions	43
3.1.2	Benefits of coral reef fisheries	43
3.1.2.1	<i>Seafood</i>	43
3.1.2.2	<i>Live fish and coral for aquaria</i>	44
3.1.2.3	<i>Ornaments and jewelry</i>	44
3.2	Providing the service	44
3.2.1	Linkages among reef condition, reef structures, and reef functions with respect to delivery of fishes for aquaria and food	44
3.2.1.1	<i>Scleractinian corals</i>	44
3.2.1.2	<i>Reef structural complexity</i>	45
3.2.1.3	<i>Seascape connectivity</i>	45
3.2.2	Linkages among reef condition, reef structures, and reef functions with respect to provision of stony corals, black corals, and precious corals for aquaria stock and jewelry	46
3.3	Measuring the service	47
3.3.1	Fish	47
3.3.2	Stony corals	47
3.3.3	Reef structural complexity	47
3.3.4	Seascape mapping	47
3.3.5	Fisheries modeling	48
3.4	Valuing the service	48
3.5	Reflections	51
3.5.1	Threats to coral reef fisheries	51
3.5.2	Management options	51
3.5.2.1	<i>Essential fish habitat (EFH)</i>	51
3.5.2.2	<i>Marine protected areas (MPAs)</i>	51
3.5.3	Conclusions	52
3.6	Bibliography	53
4	Coral Reefs: Shoreline Protection	59
4.1	Defining the service	59
4.2	Providing the service	60
4.2.1	Presence of the reef	60
4.2.2	Reef attributes	60
4.2.3	Reef health	62
4.3	Measuring the service	62
4.3.1	Physical processes	62
4.3.2	Biological processes	62
4.3.3	Ecosystem service measures	63
4.3.4	Socioeconomic benefits	64
4.4	Valuing the service	64
4.5	Reflections	65
4.5.1	Improving current knowledge	65

4.5.2 Connecting biophysical processes and ecosystem services to socioeconomic benefits	66
4.6 Bibliography.....	69
Appendix 4-A: Studies quantifying shoreline protection	73
5 Coral Reefs: Natural Products	77
5.1 Natural products as sources and templates for pharmaceuticals, biochemicals, and biomaterials	77
5.1.1 Pharmaceutical uses of marine natural products	77
5.1.2 Marine natural products as structural templates for synthesis	83
5.1.3 Marine natural products as molecular probes.....	83
5.1.4 Nonpharmaceutical uses of marine natural products.....	84
5.2 Sustaining the presence of natural products in coral reef ecosystems.....	85
5.2.1 Ecological role and sources of secondary metabolites	86
5.3 Measuring and valuing the service	88
5.3.1 Specific examples	89
5.3.2 Possible approach	89
5.4 Reflections.....	90
5.5 Bibliography.....	90
Appendix 5-A: Marine pharmaceutical products	95
6 Coral Reefs: Summary	133
6.1 Lessons learned	133
6.2 Next steps.....	134
Coral Reefs: Glossary.....	137

List of Figures

Chapter 1

- Figure 1-1 U.S. jurisdictions with coral reefs. 3
a. The Atlantic Ocean, the Caribbean Sea, and the Gulf of Mexico
b. The Pacific Ocean
- Figure 1-2 Conceptual model of a coral reef ecosystem illustrating local effects of driving forces (urban development, industrial production, fishing, tourism), pressures (industrial effluent, sedimentation and erosion, over fishing, groundings), state (healthy coral reef on the left and degraded coral reef on the right), and impacts (loss of fish and coral species, conversion of reef habitat to rubble). 5
- Figure 1-3 Ecosystems provide services that, in turn, provide economic benefits. 6
- Figure 1-4 Ecological integrity as the overlap of physical, chemical, and biological integrity. 8

Chapter 2

- Figure 2-1 Annual diver certifications by the Professional Association of Dive Instructors (PADI). 17

Chapter 4

- Figure 4-1 Illustration of wave set-up and attenuation over a reef. 61
- Figure 4-2 Relationship of wave energy with increasing reef depth and width and with increasing reef friction. 61
- Figure 4-3 Reef influences on shorelines: salient and tombolo..... 64
- Figure 4-4 Conceptual diagram showing how reef attributes, and various physical or socioeconomic variables, can be used to determine various endpoints quantifying shoreline protection. 68

Chapter 5

- Figure 5-1 Phyletic distribution of 160 reviewed marine species from which potential antifouling natural products have been extracted. 85
- Figure 5-2 Marine phyla contributing secondary metabolites with pharmaceutical potential. 88
- Figure 5-3 Sources of 20 marine anticancer drugs in clinical trials or recently in clinical trials: reported versus predicted based on subsequent metagenomic analysis..... 88

List of Tables

Chapter 1

Table 1-1	Economic benefits provided by coral reefs	1
Table 1-2	Market and nonmarket value estimates for selected ecosystem services at local, state/regional, and national/international levels	2
Table 1-3	Areal extent estimates for potential shallow water coral reefs inside 10 fathom (18 m) and 100 fathom (183 m) depths and local populations that benefit from coral reefs	4
Table 1-4	Examples of the variety of ecosystem services valued by previous coral reef studies	7
Table 1-5	Estimated annual economic impact from coral reef ecosystem services at global, regional, national, and local levels	7

Chapter 2

Table 2-1	Economic impact of travel and tourism (2009 preliminary data)	15
Table 2-2	Features relevant to the perceived value of coral reefs	22
Table 2-3	Stony coral rapid bioassessment protocol coral condition indicators	24
Table 2-4	Methods used for valuing goods and services of coral reef ecosystems.....	25
Table 2-5	Final ecosystem services and supporting features for tourism and recreation	30

Chapter 3

Table 3-1	Benefits or amenities derived from fish production.....	43
Table 3-2	Important habitats for juveniles and adults of selected fish species	46
Table 3-3	Valuation methods.....	49
Table 3-4	Categories of values	50
Table 3-5	Final ecosystem services and supporting features for fish production	53

Chapter 4

Table 4-1	Measures that have been used to quantify shoreline protection	59
Table 4-2	Reef attributes that contribute to wave attenuation	60
Table 4-3	Measures used to quantify shoreline protection, and the major reef attributes, physical parameters, and socioeconomic parameters used to estimate that protection's value	63
Table 4-4	Estimated values of shoreline protection	65
Table 4-5	Final ecosystem services and supporting features for shoreline protection.....	67

Chapter 5

Table 5-1	Testing stages for new pharmaceuticals	78
Table 5-2	Status of marine-derived natural products in clinical trials or clinical use.....	79
Table 5-3	Number of candidate drugs reaching different stages of clinical trials.....	81
Table 5-4	Timeline of drug development and amount of raw material and pure product needed at each stage	82

Table 5-5	Marine biochemicals used as molecular probes.....	83
Table 5-6	Current and potential nonpharmaceutical uses for marine natural products	84
Table 5-7	Percentage of secondary metabolites with pharmaceutical potential from marine phyla	88
Table 5-8	Market value of pharmaceutical products	89
Table 5-9	Final ecosystem services and supporting features for natural products	90

Chapter 6

Table 6-1	Combined final ecosystem services and supporting features for coral reefs	134
-----------	---	-----

Coral Reefs: Introduction and Overview

1.1 Quantifying coral reef ecosystem services

Coral reefs have been declining during the last four decades as a result of both local and global anthropogenic stresses (MEA 2005). In response, governments, nongovernmental organizations (NGOs), and academia initiated numerous research efforts to elucidate the nature, causes, magnitude, and potential remedies for the decline. This work has led to the widely-held belief that the recovery of coral reefs is unlikely if public and private sector decisions that affect coral reefs continue to ignore the economic value of the goods and services provided by these ecosystems (MEA 2005). If this perception is correct, successful conservation will, in most instances, require that environmental benefits (or, ecosystem services) are routinely included in economic and social decisions (Pearce & Turner 1990; Pearce & Moran 1994; Daily et al. 1997; Turner et al. 2003; Chee 2004; Boyd & Banzhaf 2007; Turner 2010). However, this approach presupposes knowledge of what the ecosystem services are, what their magnitudes and values are, what ecosystem characteristics provide them, how those characteristics are affected by human activities, and how human activities may affect the future provision of ecosystem services. With this knowledge, decisionmakers could have access to a more complete characterization of the consequences of different policy options.

Table 1-1. Economic benefits provided by coral reefs

A. Direct extractive uses	B. Direct nonextractive uses
1. Commercial fishing 2. Subsistence fishing 3. Aquarium fish 4. Sport fishing 5. Coral jewelry 6. Pharmaceutical harvesting 7. Nonpharmaceutical harvesting	1. Scuba diving 2. Snorkeling 3. Boating 4. Pharmaceutical chemicals 5. Nonpharmaceutical natural products
C. Indirect uses	D. Nonuse values
1. Fish habitat 2. Nutrients 3. Reduced flooding 4. Less storm damage 5. Fewer deaths from storms & flooding 6. Reduced erosion from storms & flooding 7. Mangrove & seagrass protection 8. Sealife nursery protection 9. Global life support	1. Existence value 2. Cultural value 3. Option value 4. Quasi-option value 5. Bequest value 6. Instrumental value 7. Intrinsic value 8. Scientific value 9. Scarcity value

Source: Beaumont *et al.* 2008; Burke *et al.* 2008; Cesar 2002; Cesar & Chong 2005; David *et al.* 2007; Ghermandi *et al.* 2009; Moberg & Folke 1999; Naber *et al.* 2008; Nunes *et al.* 2009; Remoundou *et al.* 2009; Spurgeon 1992.

The ecosystem services in Table 1-1 are organized in categories normally used for valuation purposes. The services can also be organized according to their ecological role, an approach used in the Millennium Ecosystem Assessment (MEA 2005). The MEA used four categories: provisioning, regulating, cultural, and supporting. Coral reefs, with high species diversity and topographically complex habitat, are valued in all categories (McKinney 1998). *Provisioning services* include food (fish and invertebrates), materials for construction (sand and coral blocks), pharmaceutical and cosmetic compounds (bio-mining), jewelry, curios, and ornamental fish. *Regulating services* include land accretion and shoreline protection from waves and currents (which allows growth of seagrass and mangrove communities), and carbon sequestration. Major *cultural services* include recreation and tourism; in addition, coral reefs provide coastal communities an inherent sense of place. Sometimes less obvious are the *supporting services* of coral reefs, such as sand for beach formation, biological primary and secondary production, and biological diversity.

The economic value of some of these services (*e.g.*, commercial fishing) are established in markets, while others have nonmarket values for local, state/regional, and national/international segments of the population (Table 1-2).

Table 1-2. Market and nonmarket value estimates for selected ecosystem services at local, state/regional, and national/international levels [small (+), moderate (++), or high (+++)]

Ecosystem Service*	Sector	Local	State	National
Tourism	Market	+++	+	+
	Nonmarket	+	+++	+++
Recreation	Market	+	+	+
	Nonmarket	++	—	—
Commercial Fisheries	Market	+	++	++
	Nonmarket	—	—	—
Shoreline Protection	Market	—	—	—
	Nonmarket	++	++	++
Non-Use Existence Value	Market	—	—	—
	Nonmarket	++	++	++
Biodiversity	Market	++	+	+
	Nonmarket	+	+++	+++

* Tourism and recreation include snorkeling, diving, fishing, and viewing in reef areas; commercial fisheries include spiny lobsters, shrimp, finfish, and aquarium fish; shoreline protection is based on damage avoided from storms; nonuse existence value is based on what people are willing to pay to conserve coral reefs; biodiversity has both market value (*e.g.*, potential pharmaceutical products) and nonmarket value (existence value).

Source: EPA (2009)

An estimated 173,488 km² of coral reefs exist in U.S. jurisdictions widely distributed across the Pacific Ocean, western Atlantic Ocean, Caribbean Sea and Gulf of Mexico (Figure 1-1, Table 1-3) (Rohmann *et al.* 2005; Waddell 2005, p. 8). This is roughly the areal extent of the State of Florida. Nearly 12 million people in these jurisdictions directly benefit from shoreline protection, recreation, subsistence fishing, and sense of place provided by reefs. Some of them owe their livelihood to the services provided by coral reefs. Others worldwide benefit from tourism, commercial fishery harvests, pharmaceutical products, jewelry, and non-use services such as natural beauty and biodiversity. Many of these beneficiaries contribute to the success of non-governmental organizations (*e.g.*, The Nature Conservancy (TNC), Coral Reef Alliance, Reef Relief, Reef Environmental Education Foundation (REEF), and the World Wildlife Fund (WWF)) in raising money for protection of coral reefs, and in supporting actions by the U.S. Government to establish and fund the interagency Coral Reef Task Force, National Marine Sanctuaries, National Parks, local action strategies, and legislation (*e.g.*, Coral Reef Conservation Act) for protection of coral reefs.

There is an urgent need to manage coral reefs and coastal zones differently. Over the past two decades, there have been precipitous declines in coral reefs (Waddell & Clark 2008), despite their widely held status as highly valued and highly important ecosystems. An estimated 19% of the world's reefs have been lost in the last 30 years, 15% are threatened with loss by 2030, and another 20% with loss by 2050 (Wilkinson 2008). Many of the causes of this decline are well known. Stony corals (*Scleractinia* spp.), which provide the calcareous reef infrastructure, are suffering worldwide from massive bleaching (resulting from the loss of symbiotic algae) and higher than normal mortality. The most common trigger for bleaching events is elevated sea surface temperatures. Also at the global level, increasing seawater acidity from elevated atmospheric CO₂ is slowing the calcification processes responsible for coral growth and repair. At local scales (Figure 1-2), corals are under chronic assault from fishing and land use practices that release sediments, nutrients, toxic contaminants, and potentially pathogenic microorganisms into the reef environment.

The loss or impairment of coral reefs directly results in the reduction or loss of ecosystem services provided by the reefs to humans. When reef-building stony corals die, they become covered in algae and other organisms that eventually erode the remnant skeletons. Unfortunately, coral reefs are among the few marine environments to exhibit disturbance-induced phase shifts (akin to “tipping points”) in which lush, complex coral communities dominated by reef-building stony corals are transformed relatively quickly into “biologically impoverished wastelands overgrown with algae” (Bellwood *et al.* 2004; Work *et al.* 2008). As coral skeletons erode and crumble, reefs lose the highly complex ecological and physical architectures that provide shelter and resources for the uniquely abundant and diverse reef biota. The loss of the reefs' physical structure (such as that currently being experienced in the Caribbean) is referred to as “flattening” (*i.e.*, losing topographic complexity) (Alvarez-

Filipi *et al.* 2009). This term would also be appropriate to describe the loss of ecological structure and biodiversity that make these ecosystems so valuable to humans. Inevitably, these losses will adversely affect human well-being.

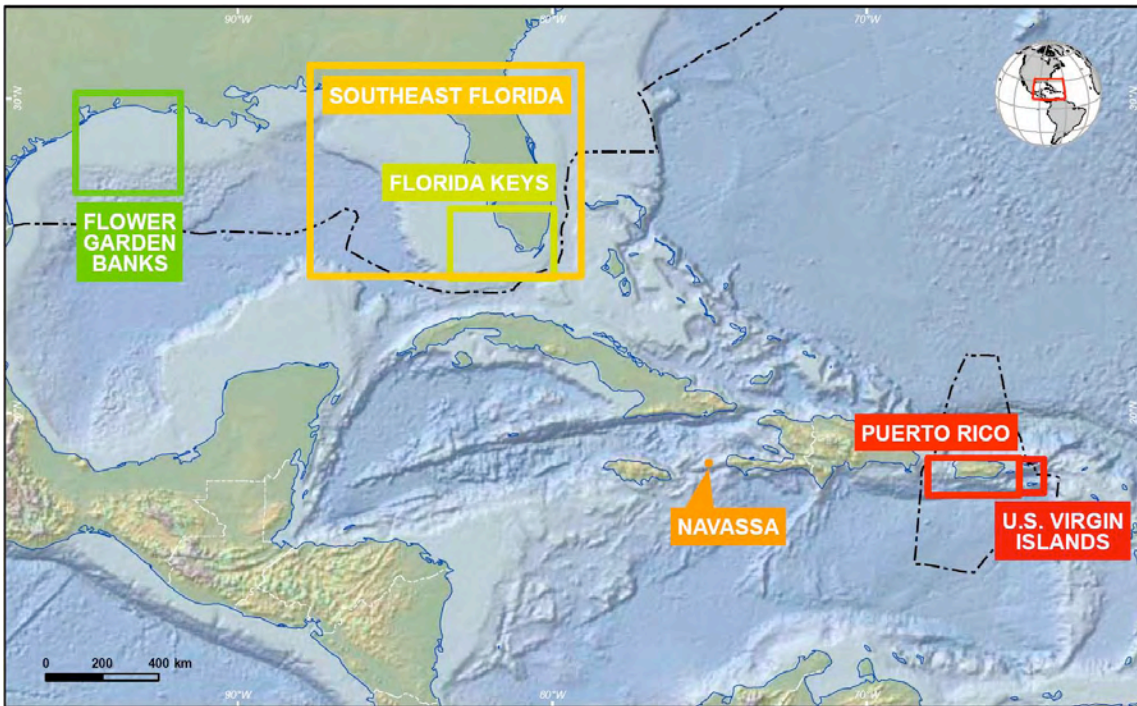


Figure 1-1a. U.S. jurisdictions with coral reefs. The Atlantic Ocean, the Caribbean Sea, and the Gulf of Mexico. (figure from Waddell & Clarke 2008, p. 10)

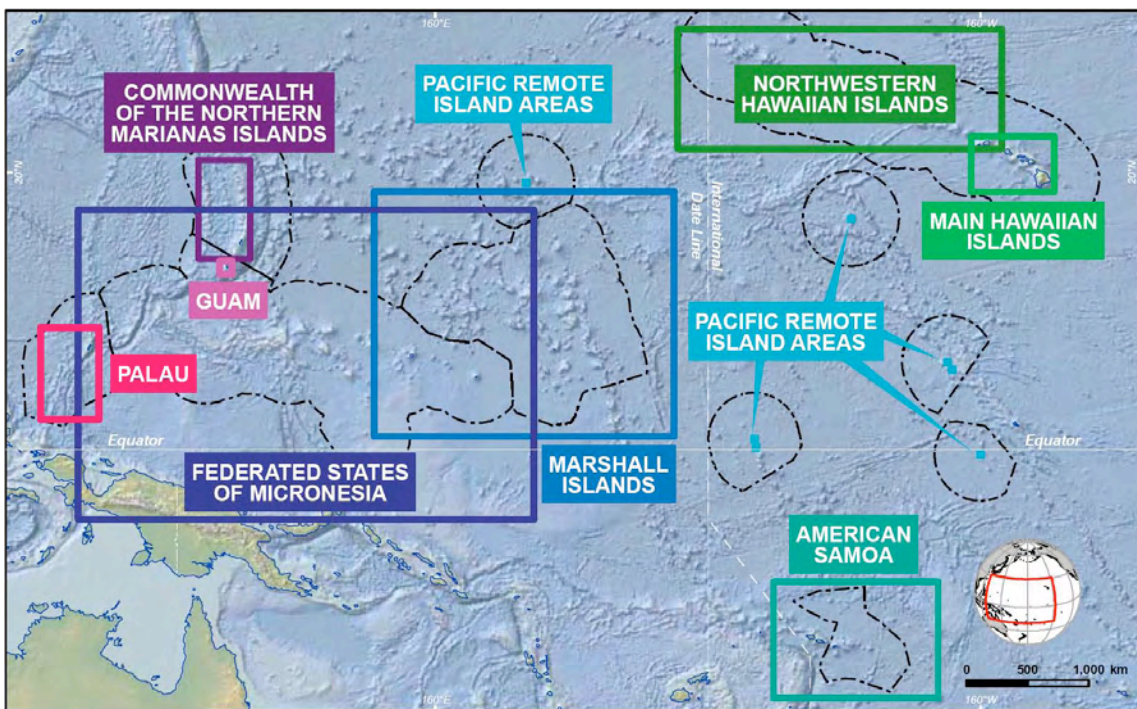


Figure 1-1b. U.S. jurisdictions with coral reefs. The Pacific Ocean. (Waddell & Clarke 2008, p. 12)

Table 1-3. Areal extent estimates for potential shallow water coral reefs inside 10 fathom (18 m) and 100 fathom (183 m) depths and local populations that benefit from coral reefs

U.S. Jurisdiction	Reef Area (km ²)		Population
	<10 fathoms ^a	<100 fathoms ^a	
Florida ^b	30,801	113,092	5,213,884 ^c
Puerto Rico ^d	2,302	5,501	3,971,020 ^e
U.S. Virgin Islands ^f	344	2,126	109,825 ^e
Navassa Island	3	14	0
Flower Gardens NMS ^g	0	164	0
Main Hawaiian Islands ^h	1,231	6,666	1,283,388 ⁱ
Northwestern Hawaiian Islands (NWHI) ^j	1,595	13,771	0
American Samoa ^k	55	464	65,628 ^e
Pacific Remote Islands ^l	252	436	100 ^e
Northern Mariana Islands (CNMI) ^m	124	476	86,616 ^e
Guam	108	276	178,430 ^e
Marshall Islands	13,456 ⁿ	13,456 ⁿ	64,522 ^e
Federated States of Micronesia	14,517 ⁿ	14,517 ⁿ	107,434 ^e
Palau	2,529 ⁿ	2,529 ⁿ	20,796 ^e
Total	67,317	173,488	11,774,315

a Areas estimated from NOAA nautical charts except for the Marshall Islands, the Federated States of Micronesia, and the Republic of Palau, which were estimated from Landsat satellite imagery of shallow waters (<15 m).

b Florida corals extend along the Atlantic Ocean coast of Florida to Jupiter Inlet, Florida and along the Gulf of Mexico coast of Florida to Tarpon Springs, Florida.

c 2007 estimate for five coastal counties: St. Lucie, Martin, Palm Beach, Broward, Miami-Dade and Monroe counties. Total population of Florida is 18,251,243 (Census Bureau 2010).

d Puerto Rico includes the islands of Puerto Rico, Desecheo, Culebra, Vieques, and Mona.

e Projected 2009 population (CIA 2010)

f The U.S. Virgin Islands includes the islands of St Thomas, St John, and St Croix.

g The NOAA nautical chart depicts only the 100 fathom depth curve for this location.

h The Main Hawaiian Islands includes the islands of Hawaii, Maui, Molokai, Lanai, Kahoolawe, Oahu, Kauai, and Niihau.

i 2007 estimate (Census Bureau 2010)

j The NWHI includes the islands and atolls of Nihoa, Necker, French Frigate Shoals, Gardner Pinnacles, Maro Reef, Laysan, Lisianski, Pearl and Hermes, Midway, and Kure. Numerous shallow-water seamounts, such as St. Rogatein Bank or Raita Bank, also are located in the NWHI.

k American Samoa includes the islands of Tutuila, Ofu, Olosega, Tau, Swains, and Rose Atoll.

l The Pacific Remote Islands include Howland, Baker, and Jarvis Islands, Palmyra, Johnston, and Wake Atolls, and Kingman Reef.

m The CNMI includes the islands of Rota, Aguijan, Tinian, Saipan, Farallon de Medinilla, Anatahan, Sarigan, Guguan, Alamagan, Pagan, Agrihan, Asuncion, Maug, and Farallon de Pajaros.

n Unpublished estimates of potential coral ecosystem area visible in Landsat satellite imagery. Area estimates generally include seafloor features visible in water 18–27 m (10–15 fathoms) deep. NOAA does not produce nautical charts of these locations.

Source: Rohmann *et al.* (2005); Waddell (2005, p. 8).

The Ecosystem Research Program (ESRP) is a concerted research effort within the U.S. Environmental Protection Agency (EPA) Office of Research and Development (ORD) to better incorporate consideration of ecosystem services in decision processes. The overall goal of the ESRP is to provide decision-makers information on the nature and magnitude of environmental benefits provided by ecosystems and the means to understand how policy or management choices will affect the provision of those benefits (*i.e.*, the nature and magnitude of the economic benefits [see Table 1-1 for a list of benefits and Table 1-2 for their relative magnitudes]).

Completion of research in the Coral Reef Project (CRP) is expected to advance the understanding of coral reef ecosystem services, how they are affected by human activities, and how management and policy decisions influence their delivery. If this

information is incorporated into public and private decision-making and the policy analyses that precede it, the resulting decisions will undoubtedly have a firmer scientific basis and a more inclusive consideration of the benefits provided by coral reef ecosystems. This report provides a review of previous studies of ecosystem services and economic benefits provided by coral reefs and how those ecosystem services are linked to characteristics (attributes) of the reef.

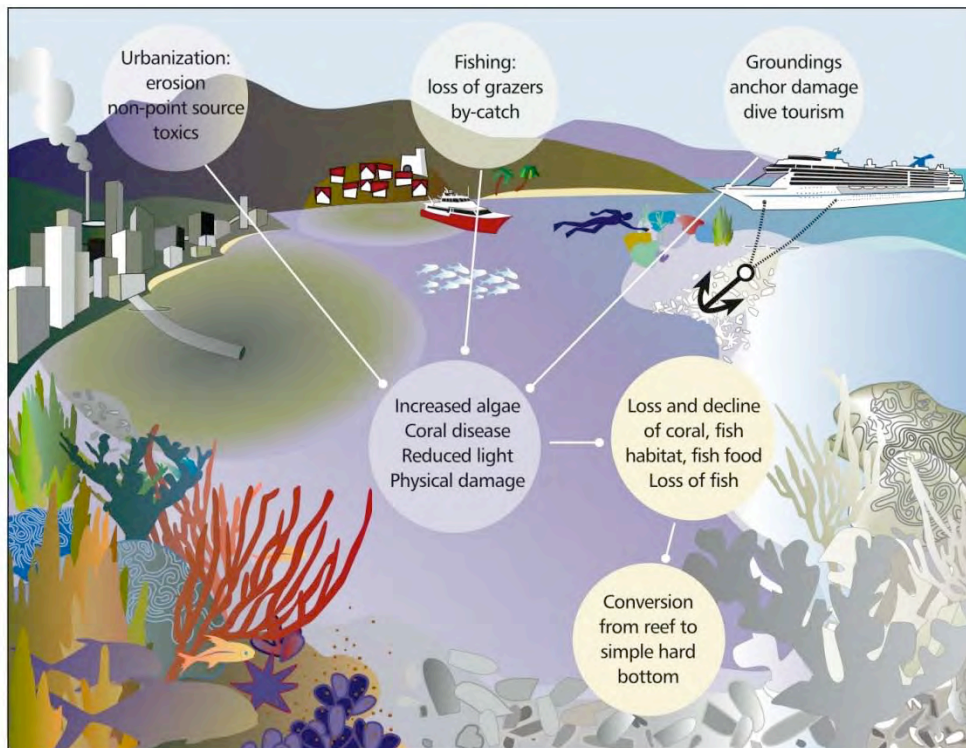


Figure 1-2. Conceptual model of a coral reef ecosystem illustrating local effects of driving forces (urban development, industrial production, fishing, tourism), pressures (industrial effluent, sedimentation and erosion, over fishing, groundings), state (healthy coral reef on the left and degraded coral reef on the right), and impacts (loss of fish and coral species, conversion of reef habitat to rubble). Adverse impacts reduce the natural benefits and value of coral reefs unless steps are taken to reduce pressures. (figure and caption from Bradley *et al.* 2010)

1.2 Purpose and organization

The purpose of this report is to provide an overview of the published literature with respect to three aspects of ecosystem services provided by coral reefs: (1) which services have been identified; (2) what, if any, methods were used to quantify the services; and, (3) what connections were identified between the services and the attributes of the reef. The goal is to lay the foundation for selecting research questions that, if answered, would fill gaps in our current understanding of the links between coral reef attributes and the delivery of services by the coral reef ecosystem. Ultimately, the goal is to identify coral reef indicators that can be used to estimate the quantity of ecosystem services being delivered by coral reef ecosystems and to predict the extent to which the current quantities are likely to change in the future.

1.3 Ecosystem services and economic benefits

There exists a certain imprecision prevalent in the current use of the term “ecosystem services”. Many authors tend to conflate “ecosystem services” and “economic benefits”, thereby creating a confusing logical muddle. In this report, ecosystem services are viewed as an ecological construct that creates wholly, or partially, the economic construct of economic benefits, which is the core of policymaking. Ecosystem services can always be quantified in physical terms (*e.g.*, kg of fish, board feet of lumber), but they are always linked to economic benefits, which are usually valued in monetary terms (*e.g.*, market value of fish catch or lumber). In the case of shoreline protection provided by coral reefs, the presence of the reef attenuates the energy contained in waves reaching the shoreline, and that attenuation reduces the wave-induced erosion of the shoreline and, during storms, the extent of near-shore flooding, damage to buildings and property, and danger to humans and livestock. The shoreline protection ecosystem service could be characterized as the amount of wave energy attenuation attributable to the presence of the reef, or in the case of a foregone ecosystem service, the increase in wave energy attributable to a diminishment of the reef’s size. The economic benefits from shoreline protection would be the value of the property, lives, and well-being preserved by the attenuation of the wave energy, or the value lost due to the increase in wave energy. However, the value of the economic

benefit is a function of how much erosion is prevented, how much property is protected, and how many human and livestock lives are saved. Transforming energy attenuation into a physical quantification of economic benefits should be a joint exercise for scientists and economists, with the former leading the conversion modeling and the latter leading the identification of the economic benefits to be quantified, but the subsequent valuation of the benefits would be the bailiwick of economists. To determine which ecosystem services are the most important for policymaking requires working backward from the economic benefits to identify the services that created those benefits (Figure 1-3).

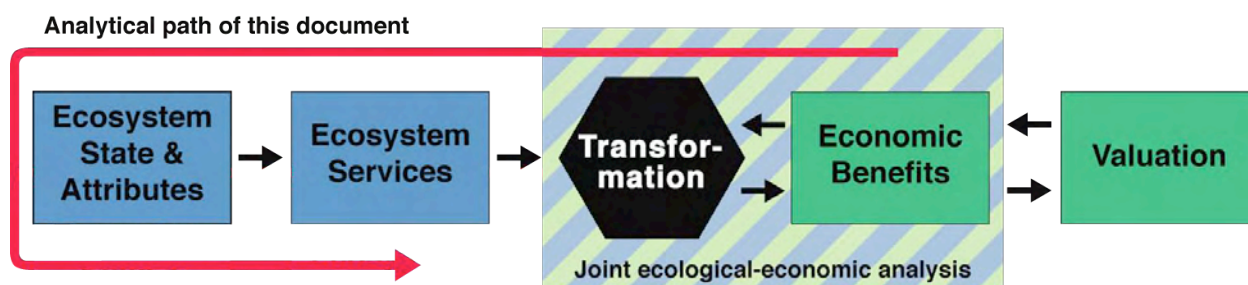


Figure 1-3. Ecosystems provide services that, in turn, provide economic benefits. Some services have a direct, one-to-one correspondence to benefits, but more commonly services have to be transformed, disaggregated, or combined to yield benefits. Services and many benefits can be quantified in physical terms; the value of benefits is usually estimated in monetary terms; services are not valued *per se*, but their importance can be inferred from the value of the benefits they create.

The journey traversed in creating this report, then, began by identifying the most valuable economic benefits arising from coral reefs, followed by an assessment of which ecosystem services contribute to those benefits. Subsequently, the literature was reviewed to find examples where these ecosystem services had been wholly or partially quantified and where the links between these services and coral reef attributes were investigated.

Identification and quantification of coral reef ecosystem services began in the 1980s (Hodgson & Dixon 1988; Mattson & DeFoor 1985; McAllister 1988; Munro & Williams 1985), followed in the early 1990s by the first unified estimates of the value of the economic benefits generated by those services. Numerous studies have estimated quantities and values for specific services and the derived benefits received from coral reefs, but fewer have done so for the whole range of coral reef services and benefits (see Pendleton [2008] and Conservation International [2008] for reviews; also see Table 1-1 references). In most cases, reefs are valued to determine or demonstrate the economic impact of a planned or implemented decision. The decision under consideration plays a role in what is quantified and how the services are valued. For example, one early coral reef study focused on the economic value of biodiversity, because the study area was an existing marine reserve established to protect biodiversity (Bakus 1983); another study approached valuation more broadly because it was intended to reinforce the creation of a Marine Protected Area in exchange for international debt reductions (David *et al.* 2007). The services valued can vary from study to study (Table 1-4), depending on the decision, the availability of information, and the expertise or insight of the authors.

Despite the wide variety of services that have been measured and valued, there are certain services that are almost always considered, because they make very significant contributions to the total economic value (TEV includes all direct and indirect use values plus all nonuse values). The values can be calculated at a global, regional, or local scale (Table 1-5).

The values reported in Table 1-5 suggest that the four most valuable economic benefits are: fisheries, natural products, shoreline protection, and tourism and recreation. This report examines each of these in a separate chapter.

Table 1-4. Examples of the variety of ecosystem services valued by previous coral reef studies

Study	Direct Use	Indirect Use	Nonuse
Spurgeon 1992	Fisheries, aquarium and curio trade, pharmaceutical, construction, tourism, research, education, social value	Biological support, physical protection, global life support, social services	Existence value, option value, intrinsic value
Berg <i>et al.</i> 1998	Tourism, mining, fishing	Coastal protection	Food security, biodiversity
Pet-Soede <i>et al.</i> 1999	Blast fishing, nondestructive fishing, tourism	Coastal protection	—
Burke <i>et al.</i> 2002	Tourism, recreation, fishing, blast fishing, poison fishing, mining	Coastal protection	Aesthetic, biodiversity
Cesar 2002	Live reef fish, mariculture, aquarium trade, pharmaceutical, tourism, recreation, research, education, aesthetic	Biological support (habitat), physical protection, carbon store	Future uses, new information, bequest value, existence value
Burke & Maidens 2004	Tourism, recreation, fishing	Coastal protection	—
MEA 2005	Food, medicines, cultural and amenity, aesthetic, recreational	Biodiversity, biological regulation, nutrient cycling, climate regulation, disease control, waste processing, flood protection, erosion control	—
Spurgeon 2006	Fisheries, tourism, recreation, mining,	Biodiversity, coastal protection, carbon storage	Intergenerational equity, existence value
Burke <i>et al.</i> 2008	Tourism, recreation, fishing	Coastal protection	—
Hicks <i>et al.</i> 2009	Fishery, cultural, research, aesthetic, recreational	Biological control, habitat/refuge, waste regulation, coastal protection	Bequest, option, and existence values

Table 1-5. Estimated annual economic impact from coral reef ecosystem services at global, regional, national, and local levels

Scale/Location	Tourism	Fisheries	Coastal Protection	Biodiversity	Carbon Storage	Ref.
Global	\$9.6 billion	\$5.7 billion	\$9.0 billion	\$5.5 billion	—	1
Caribbean	\$2.1 billion	\$0.3 billion	\$1.5 billion	—	—	2
Indonesia	\$103m	\$1.221 billion	\$314m	\$9m	—	7
Philippines	\$108m	\$620m	\$326m	\$10m	—	7
St. Lucia	\$160m–\$194m	\$0.5m–\$0.8m	\$28m–\$50m	—	—	6
Tobago	\$101m–\$130m	\$0.8m–\$1.3m	\$18m–\$33m	—	—	6
Turks & Caicos Islands	\$18.2m	\$3.7m	\$16.9m	\$4.7m	—	8
Jamaica Portland Bight	\$11m	\$19m	\$0.4m	\$18m	\$4m	3
Jamaica Montego Bay	\$315m	\$1.3m	\$65m	\$19.6m	—	4
Jamaica Montego Bay	\$400m	\$4m	\$65m	—	—	5

References:

- 1: Cesar *et al.* (2003) 2: Burke & Maidens (2004) 3: Cesar *et al.* (2000) 4: Ruitenbeek & Cartier (1999)
5: Gustavson (1998) 6: Burke *et al.* (2008) 7: Burke *et al.* (2002) 8: Carleton & Lawrence (2005)

Source: Partially adapted from Conservation International (2008).

1.4 Ecological integrity, ecological resilience, and biodiversity

Ecological integrity, resilience, and biodiversity are all concepts that portray slightly different aspects of ecosystem condition but convey the same sense that the attributes, processes, and functions of an ecosystem are all integral to the ecosystem itself and necessary for sustaining it as well as its continued provision of services. These concepts represent the “glue” (Pearce & Moran 1994, p. 22; Turner *et al.* 2000) of the properly functioning ecosystem, supporting the growth of reef-building corals for shoreline protection, the presence of unique and diverse species to attract tourists, the creation of potentially useful natural products, and the maintenance of habitat and nurseries for harvestable fish stocks. Assessing the extent to which an ecosystem possesses any of these concepts provides insight into the many elements and processes that we do not know, understand, and cannot otherwise measure. The development of concise, rigorous definitions and unambiguous metrics for these three attributes continues but remains unfinished.

In choosing which topics to cover in this report, considerable thought was given to the role of ecological integrity, ecological resilience, and biodiversity. Are these economic benefits, ecosystem services, or something else? How, or should, they be included in our analysis? In the end, we decided that they were natural features rather than ecosystem services or economic benefits (see the Definitions section at the bottom of Table 6-1, page 153), and consequently should not be included in this report.

1.4.1 Ecological integrity

The Millennium Ecosystem Assessment (MEA 2005) describes supporting services as “those that are necessary for the production of all other ecosystem services”, including soil formation, photosynthesis, primary production, and nutrient cycling, among others. Some have called these “biotic services” (Moberg & Folke 1999) or “fundamental services” (Holmlund & Hammer 1999). Although called services, these could otherwise be characterized as functions of the ecosystem that ensure ecosystem persistence and resilience, which are required for the sustainable delivery of services. The same characteristics of the reef ecosystem have also been called “regulation functions” (de Groot 1992) and “primary” or “glue” value of the ecosystem (Pearce & Moran 1994, p. 22; Turner *et al.* 2000). In many respects, these are all descriptions of ecological integrity, a concept that has evolved from the stated objective of the Clean Water Act (CWA): “The objective of this Act is to restore and maintain the chemical, physical, and biological integrity of the Nation’s waters.” (CWA 1972).

Although often debated, a generally accepted definition of ecosystem integrity is:

the capability of supporting and maintaining a balanced, integrated, adaptive community of organisms having a species composition, diversity, and functional organization comparable to that of natural habitat of the region (Frey 1975; Karr & Dudley 1981; Karr *et al.* 1986; Angermeier & Karr 1994).

Ecological integrity thus encompasses a variety of scales (genetic, taxonomic, ecological), elements (genes, species, populations, landscapes), processes (colonizations, mutations, extinctions), and a dynamic biology in terms of evolution and biogeography. Intended or not, the concept of ecological integrity appears to encompass the natural functions of an ecosystem that provide services. Ecological integrity is generally decomposed into the components described by the CWA—represented as the overlap of physical, chemical, and biological integrity (Figure 1-4). Yoder (1995) argues that the three components are not equal and that physical and chemical integrity are components of biological integrity. Regardless, many authors (*e.g.*, Turner *et al.* 2000) suggest that ecological integrity is a component that should be valued as an ecosystem service.

Healthy reefs maintain their structure and function and provide the supporting services that allow for the fulfillment of reasonable human needs through more direct provisioning of ecosystem services, such as shoreline protection, fisheries production, and recreational opportunities (McField & Richards Kramer 2007). A number of indicators have been proposed and monitored for assessing reef health (van Beukering & Cesar 2004; Healthy Reefs Initiative 2010).

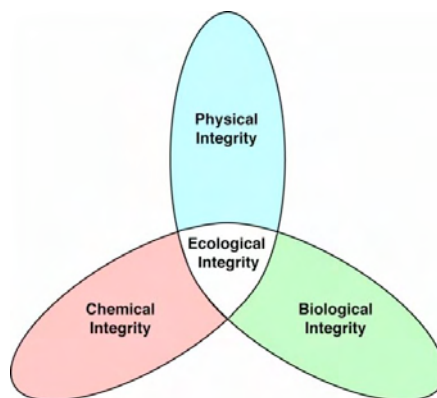


Figure 1-4. Ecological integrity as the overlap of physical, chemical, and biological integrity.

1.4.2 Ecological resilience

Ecological integrity is often equated with ecological health and ecological resilience. Although “health” is an anthropocentric concept, it implies that a stressed ecosystem is similar to a diseased individual. While use of the term is sometimes neither accurate nor precise (Ehrenfeld 1992), carefully structured definitions have been proposed using Energy Systems models (Campbell 2000). Ecological resilience—“the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks” (Walker *et al.* 2004; Folke 2006)—is a more potent concept. Moberg and Folke (1999) conclude that managing resilience is the key to maintaining delivery of ecosystem services. Clearly related to ecological integrity, resilience emphasizes the ecosystem’s capacity to buffer stress and reduce rates of system change. Hollings (1973) states that ecological resilience “determines the persistence of relationships within a system and is a measure of the ability of these systems to absorb changes of state variables, driving variables, and parameters, and still persist”. Ecosystem integrity and resilience are thus closely linked, but provide a few distinctions. Ecosystem integrity emphasizes a natural condition with implied stability, whereas resilience emphasizes stability with an implied natural condition.

In the case of resilience, more than one stable state can exist. When considering a single stable state, resilience is measured by the amount of time (after disturbance) required to return to the stable state (referred to as engineering resilience). When considering multiple stable states, resilience is measured by the amount of disturbance needed to shift the system to an alternative stable state (referred to as ecological resilience). This approach allows that an ecosystem can slide into a highly stable, but less desirable state—in fact, less desirable states are often extremely resilient and difficult to revert to desired conditions (Scheffer *et al.* 2000; Gunderson & Holling 2002; Walker *et al.* 2004). Reversion to a desired state is the goal of ecosystem restoration. Although ecosystem resilience is not usually considered an ecosystem service, it is similar to low ecosystem integrity in that a less desirable state is expected to provide fewer ecosystem services.

1.4.3 Biodiversity

Biodiversity is frequently cited as an ecosystem service (*e.g.*, Cesar 2002; CI 2008). Taken literally, biodiversity is simply taxa richness, which is not an ecosystem service but is an ecosystem attribute that can contribute to a variety of reef services. High biodiversity may contribute to ecological integrity, but there are many examples of natural systems with high integrity that do not exhibit high biodiversity. Biodiversity more likely plays a contributory role in ecological resilience—high species richness usually provides functional redundancy in the ecosystem, which increases resilience. If a keystone species is lost, another functionally redundant species may take its place, and the ecosystem persists in its original state.

1.4.4 Insurance value

While the preponderant view seems to be that ecological integrity, resilience, and biodiversity are not ecosystem services, a recent proposal by The Ecology and Economics of Biodiversity (TEEB) initiative combines the three concepts under the rubric of “insurance value”, which is defined as “the value of ensuring that there is no regime shift in the ecosystem with irreversible negative consequences for human wellbeing” (Pascual *et al.* 2010). A similar notion put forward by Balmford *et al.* (2008) is “infrastructure value”, which is the capacity of an ecosystem to maintain its provision of ecosystem services despite variability and disturbance.

The concept that ecosystem biodiversity and resilience provide insurance against a variety of uncertainties has been generally accepted for some time in the environmental economics literature. While this literature’s view of insurance value has been evolving over the past 20 to 30 years, the notion that insurance value is a distinct economic nonuse benefit that can be valued is not generally accepted, because of the difficulties described below. Generally speaking, the insurance value of ecosystems is considered part of option value and quasi-option value (Pearce & Moran 1994, pp. 19-21; Pearce 2001; Weikard 2001), but our limited understanding of ecological processes precludes our being able to be sufficiently certain of ecological outcomes to move from uninsurable uncertainty to insurable risk (Pearce & Pearce 2001; Turner *et al.* 2003; Barbier 2006; Turner 2010; Abson & Termansen 2011).

In the 1990s, Pearce and Moran (1994), Perrings (1995a; 1995b; 1998), Swanson *et al.* (1994), Turner (1992), and others began describing how biodiversity and resilience might have an insurance value analogous to crop insurance, and included it as an element of option value. They took care to distinguish between the insurable risk (the probability that a known adverse outcome might occur) and the uninsurable uncertainty (wherein neither the outcome nor the probability are known) (Perrings 1995b). That biodiversity and ecological resilience provided insurance in a more general sense was recognized, but the tangled complexity of the relationship between that insurance and those “natural features” was viewed as an almost insurmountable hurdle to its proper characterization (Pearce 2004). In the past five years, Baumgärtner and colleagues have developed a more generalized and rigorous definition of insurance value (Baumgärtner 2007; Baumgärtner & Quaas 2006; Quaas & Baumgärtner 2008; Baumgärtner & Strunz 2010), but the means to measure it as a distinct value not embedded in whole or in part within other use and nonuse benefits (specifically, option value and quasi-option value) remains to be defined. The importance of viewing insurance value (or the value of any ecosystem service) in terms of the value of a marginal change rather than a lump sum value is regularly emphasized (Pearce 1998; Toman 1998; Heal 2000; Pearce & Pearce 2001), and to properly assess the

value of marginal changes, ecological models must be able to predict the effect of small state changes (an ability that remains beyond our reach).

Even though our incomplete understanding of ecological functions and processes and our resulting inability to predict ecological outcomes prevent us from moving from uninsurable uncertainty to insurable risk, it may be that the inherent instability of ecosystems near thresholds (or, tipping points) may preclude a quantification of the insurance value. Though these limitations suggest that insurance value may be best characterized in qualitative terms (Fromm 2000), insurance value remains a powerful and tangible concept that should be included in any ecological assessment.

1.5 References

- Abson DJ and Termansen M. 2011. Valuing Ecosystem services in Terms of Ecological Risks and Returns. *Conservation Biology*, **25**(2):250-258.
- Alvarez-Filipi L, Kulvy NK, Gill JA, Côté IM and Watkinson AR. 2009. Flattening of Caribbean coral reefs: region wide declines in architectural complexity. *Proceedings of the Royal Society B*, **276**(1669):3019-3025.
- Angermeier PL and Karr JR. 1994. Biological Integrity versus Biological Diversity as Policy Directives. *BioScience*, **44**(10):690-697.
- Bakus GJ. 1983. The Selection and Management of Coral reef Preserves. *Ocean Management*, **8**(1982/83):305-316.
- Balmford A, Rodrigues ASL, Walpole M, ten Brink P, Kettunen M, Braat L and de Groot R. 2008. *The economics of biodiversity and ecosystems: scoping the science*. Cambridge (UK): European Commission (contract: ENV/070307/2007/486089/ETU/B2), 305 pp.
- Barbier EB. 2006. Valuing Ecosystem Services as Productive Inputs. Mimeo, University of Wyoming, 52 pp.
- Baumgärtner S. 2007. The Insurance Value of Biodiversity in the Provision of Ecosystem Services. *Natural Resource Modeling*, **20**(1):87-127 (Spring 2007).
- Baumgärtner S and Quaas MF. 2006. *The Private and Public Insurance Value of Conservative Biodiversity Management*. Working Paper Series in Economics, No. 33, Leuphana University of Lüneburg (Germany), 48 pp.
- Baumgärtner S and Strunz S. 2010. The economic insurance value of ecosystem resilience. Mimeo, Leuphana University of Lüneburg (Germany), 33 pp.
- Beaumont NJ, Austen MC, Mangi SC and Townsend M. 2008. Economic valuation for the conservation of marine biodiversity. *Marine Pollution Bulletin*, **56**(3):386-396.
- Bellwood DR, Hughes TP, Folke C and Nyström. 2004. Confronting the coral reef crisis. *Nature*, **429**(24 June):827-833.
- Berg H, Öhman MC, Troëng S and Lindén O. 1998. Environmental Economics of Coral Reef Destruction in Sri Lanka. *Ambio*, **27**(8):627-634.
- van Beukering PJH & Cesar HSJ. 2004. Ecological economic modeling of coral reefs: Evaluating tourist overuse at Hanauma Bay and Algæ Blooms at the Kihei Coast, Hawai'i. *Pacific Science*, **58**(2):243-260.
- Boyd J and Banzhaf S. 2007. What are ecosystem services? The need for standardized environmental accounting units. *Ecological Economics*, **63**:616-626.
- Bradley P, Fore L, Fisher W and Davis W. 2010. *Coral Reef Biological Criteria: Using the Clean Water Act to Protect a National Treasure*. Narragansett (RI): U.S. Environmental Protection Agency, Office of Research and Development, EPA/600/R-10/054, July 2010.
- Burke L, Greenhalgh S, Prager D and Cooper E. 2008. *Coastal Capital -- Economic Valuation of Coral Reefs in Tobago and St. Lucia*. Washington, DC: World Resources Institute, 66 pp.
- Burke L and Maidens J. 2004. *Reefs at Risk in the Caribbean*. Washington, DC: World Resources Institute, 80 pp.
- Burke L, Selig E and Spalding M. 2002. *Reefs at Risk in Southeast Asia*. Washington, DC: World Resources Institute, 76 pp.
- Campbell DE. 2000. Using Energy Systems Theory to Define, Measure, and Interpret Ecological Integrity and Ecosystem Health. *Ecosystem Health*, **6**(3):181-204.
- Carleton C and Lawrence KS. 2005. *Economic Valuation of Environmental Resource Services in the Turks and Caicos Islands*. Prepared for the Government of the Turks and Caicos Islands by Nautilus Consultants Ltd., Peebles (UK).
- Census Bureau. 2010. *State & County QuickFacts*. Washington, DC: U.S. Census Bureau. <<http://quickfacts.census.gov/qfd/>>
- Central Intelligence Agency (CIA). 2010. *The World Factbook*. Updated biweekly. <<https://www.cia.gov/library/publications/the-world-factbook/index.html>>
- Cesar HSJ. 2000. Coral reefs: their functions, threats and economic value. In: Cesar HSJ (ed), *Collected Essays on the Economics of Coral Reefs*. Kalmar (Sweden): Kalmar University, Department for Biology and Environmental Sciences/CORDIO, pp. 14-39.
- Cesar HSJ. 2002. *The biodiversity benefits of coral reef ecosystems: values and markets*. Paris: Organisation for Economic Co-operation and Development (OECD). ENV/EPOC/GSP/BIO(2001)5/Final, 29 March 2002, 37 pp.

- Cesar HSJ, Burke L and Pet-Soede L. 2003. *The Economics of Worldwide Coral Reef Degradation*. Cesar Environmental Economics Consulting, Arnhem, The Netherlands, 24 pp.
- Cesar HSJ and Chong CK. 2005. Economic Valuation and Socioeconomics of Coral Reefs: Methodological issues and three case studies. In: Ahmed M, Chong CK and Cesar HSJ (eds), *Economic Valuation and Policy Priorities for Sustainable Management of Coral Reefs. Second edition*. Penang (Malaysia): World Fish Center, pp. 14-40.
- Cesar HSJ, Öhman MC, Espeut P and Honkanen M. 2000. Economic Valuation of an Integrated Terrestrial and Marine Protected Area: Jamaica's Portland Bight. In: Cesar HSJ (ed), *Collected Essays on the Economics of Coral Reefs*. Kalmar (Sweden): Kalmar University, Department for Biology and Environmental Sciences/CORDIO, pp. 203-214.
- Chee YE. 2004. An ecological perspective on the valuation of ecosystem services. *Biological Conservation*, **120**(4):549-565.
- Clean Water Act (CWA). 33 USC 1251 *et seq.* 1972. Federal Water Pollution Control Amendments of 1972
- Conservation International (CI). 2008. *Economic values of coral reefs, mangroves, and seagrasses. A global compilation*. Arlington (VA): Conservation International, Center for Applied Biodiversity Science, 36 pp.
- Daily GC, Alexander S, Ehrlich PR, Goulder L, Lubchenco J, Matson PA, Mooney HA, Postel S, Schneider SH, Tilman D and Woodwell GM. 1997. Ecosystem Services: Benefits Supplied to Human Societies by Natural Ecosystems. *Issues in Ecology*, **1**(2):1-18.
- David G, Herrenschmidt J-B, Mirault E and Thomassin A. 2007. *Social and economic values of Pacific coral reefs*. Nouméa (New Caledonia): Coral Reef Initiatives for the Pacific (CRISP) Component 1A, Project 1A4 Integrated Coastal Management (GERSA), 44 pp.
- Ehrenfeld D. 1992. Ecosystem health and ecological theories. In: Costanza R, Norton RG, Haskell BD (eds), *Ecosystem Health*. Washington, DC: Island Press, pp. 135-143.
- Folke C. 2006. Resilience: The emergence of a perspective for social-ecological systems analyses. *Global Environmental Change*, **16**(3):253-267.
- Frey D. 1975. Biological integrity of water: an historical perspective. In: Ballentine RK and Guarraia LJ (eds), *The Integrity of Water*. Washington, DC: Environmental Protection Agency, pp. 127-139.
- Fromm O. 2000. Ecological Structure and Functions of Biodiversity as Elements of Its Total Economic Value. *Environmental and Resource Economics*, **16**(3):303-328.
- Ghermandi A, Nunes PALD, Portela R, Rao N and Teelucksingh SS. 2009. *Recreational, Cultural and Aesthetic Services from Estuarine and Coastal Ecosystems*. Venice: Fondazione Eni Enrico Mattei [FEEM], Nota di Lavoro 121.2009, 67 pp.
- de Groot RS. 1992. *Functions of Nature: evaluation of nature in environmental planning, management and decision making*. Groningen: Wolters, Nordhoff BV.
- Gunderson LH and Holling CS (eds). 2002. *Panarchy: understanding transformations in human and natural systems*. Washington, DC: Island Press, 513 pp.
- Gustavson KR. 1998. *Values Associated With the Use of the Montego Bay Marine Park*. World Bank Research Committee, Project #RPO 681-05. <<http://www.island.net/~hjr/LocalMBF.pdf>>
- Heal G. 2000. Valuing Ecosystem Services. *Ecosystems*, **3**(1):24-30 (January 2000).
- Healthy Reefs Initiative. 2010. *Report Card for the Mesoamerican Reef: An Evaluation of Ecosystem Health*. Washington, DC: Smithsonian Institution, 44 pp.
- Hicks CC, McClanahan TR, Cinner JE and Hills JM. 2009. Trade-Offs in Values Assigned to Ecological Goods and Services Associated with Different Coral Reef Management Strategies. *Ecology and Society*, **14**:10-27.
- Hodgson G and Dixon JA. 1988. Logging versus fisheries and tourism in Palawan. Honolulu: East-West Environment and Policy Institute, Occ. Paper 7.
- Holling CS. 1973. Resilience and stability of ecological systems. *Annual Review of Ecological Systems*, **4**:1-23.
- Holmlund CM and Hammer M. 1999. Ecosystem services generated by fish populations. *Ecological Economics*, **29**(2):253-268.
- Karr JR and Dudley DR. 1981. Ecological perspective on water quality goals. *Environmental Management*, **5**:55-68.
- Karr JR, Fausch KD, Angermeier PL, Yant PR and Schlosser IJ. 1986. *Assessing biological integrity in running waters: a method and its rationale*. Special publication 5. Urbana (Illinois): Illinois Natural History Survey, 28 pp.
- Mattson JS and DeFoor JA. 1985. Natural Resource Damages: Restitution as a Mechanism to Slow Destruction of Florida's Natural Resources. *Journal of Land Use and Environmental Law*, **1**(3):295-319.
- McAllister DC. 1988. Environmental, economic and social costs of coral reef destruction in the Philippines. *Galaxea*, **7**:161-178.
- McField M and Richards Kramer P. 2007. *Healthy Reefs for Healthy People: A Guide to Indicators of Reef Health and Social Well-being in the Mesoamerican Reef Region*. With contributions by M Gorrez and M McPherson. Washington, DC: Smithsonian Institution, 208 pp.

- McKinney ML. 1998. Is Marine Biodiversity at Less Risk? *Diversity and Distributions*, **4**(1):3–8.
- Millennium Ecosystem Assessment (MEA). 2005. Millennium Ecosystem Assessment Report - Ecosystems and Human Well-being: Current State and Trends Chapters 18 Marine Fisheries Systems & 19 Coastal Systems. In: Hassan RS and Ash N (eds), *Ecosystems and human well-being : Current State and Trends : Findings of the Condition and Trends Working Group*. Washington, DC: Island Press.
- Moberg F and Folke C. 1999. Ecological goods and services of coral reef ecosystems. *Ecological Economics*, **29**(2):215-233.
- Munro JL and Williams DMcB. 1985. Assessment and management of coral reef fisheries: biological, environmental, and socioeconomic aspects. Proceedings of the 5th International Coral Reef Congress. Tahiti. **4**:545-578.
- Naber H, Lange G-M and Hatzios ME. 2008. *Valuation of Marine Ecosystem Services: A Gap Analysis*. Washington, DC: The World Bank, 57 pp.
- Nunes PALD, Ding H and Markandya A. 2009. *The economic valuation of marine ecosystems*. Venice: Fondazione Eni Enrico Mattei [FEEM], Working Paper 329. <<http://www.bepress.com/feem/paper329/>>
- Organisation for Economic Co-operation and Development (OECD). 2002. *Handbook of biodiversity valuation: a guide for policy makers*. Paris: OECD. ENV/EPOC/GEEI/ BIO(2000)2/FINAL, 156 pp.
- Pascual U, Muradian R, Brander L, Gómez-Baggethun E, Martín-López B, Verma M, Armsworth P, Christie M, Cornelissen H, Eppink F, Farley J, Loomis J, Pearson L, Perrings C and Polasky S. 2010. *The economics of valuing ecosystem services of biodiversity*. Chapter 5 in: Kumar P (ed), *The Economics of Ecosystems and Biodiversity: Ecological and Economic Foundations*. London: Earthscan, 456 pp. (Chapter 5: 133 pp.)
- Pearce DW. 1998. Auditing the Earth: The Value of the World's Ecosystem Services and Natural Capital. *Environment*, **40**(2):23-28.
- Pearce DW. 2001. Valuing Biological Diversity: Issues and Overview. In: OECD, *Valuation of Biodiversity Studies. Selected Studies*. Paris: Organisation for Economic Co-operation and Development, Environment Directorate, pp. 27-44.
- Pearce DW. 2004. Environmental market creation: saviour or oversell?. *Portuguese Economic Journal*, **3**(2):115-144.
- Pearce DW and Moran D. 1994. *The Economic Value of Biodiversity*. In association with the Biodiversity Programme of IUCN – The World Conservation Union (IUCN). London: Earthscan Publications, 172 pp.
- Pearce DW and Pearce CGT. 2001. *The Value of Forest Ecosystems*. A Report to the Secretariat, Convention on Biological Diversity. Draft. February 2001, 59 pp.
- Pearce DW and Turner RK. 1990. *Economics of Natural Resources and the Environment*. Baltimore: The Johns Hopkins University Press, 378 pp.
- Pendleton L (ed). 2008. *The Economic and Market Value of Coasts and Estuaries: What's At Stake?* Washington, DC: Coastal Ocean Values Press, 135 pp.
- Perrings C. 1995a. Ecology, Economics and Ecological Economics. *Ambio*, **24**(1):60-64.
- Perrings C. 1995b. Biodiversity conservation as insurance. In: Swanson TM (ed), *The economics and ecology of biodiversity decline: The forces driving global change*. Cambridge (UK): Cambridge University Press, pp. 69-78.
- Perrings C. 1998. The economics of biodiversity loss and agricultural development in low income countries. Mimeo, University of York (UK), Environment Department, 26 pp.
- Pet-Soede C, Cesar HSJ and Pet JS. 1999. An economic analysis of blast fishing on Indonesian coral reefs. *Environmental Conservation*, **26**(2):83-93.
- Quaas MF and Baumgärtner S. 2008. Natural vs. financial insurance in the management of public-good ecosystems. *Ecological Economics*, **65**(2):397-406.
- Remoundou K, Koundouri P, Kontogianni A, Nunes PALD and Skourtos M. 2009. Valuation of natural marine ecosystems: an economic perspective. *Environmental Science & Policy*, **12**(7):1040-1051.
- Rohmann SO, Hayes JJ, Newhall RC, Monaco ME and Grigg RW. 2005. The area of potential shallow-water tropical and subtropical coral ecosystems in the United States. *Coral Reefs*, **24**(3):370-383.
- Ruitenbeek HJ and Cartier CM. 1999. Prospecting for marine biodiversity: a case study in Montego Bay, Jamaica. Chapter 13 in Turner K, Bateman I and Adger N (eds), *Economics of coastal and water resources: valuing environmental functions*. Dordrecht: Kluwer Academic Press, pp. 281-304.
- Scheffer M, Brock WA and Westley F. 2000. Mechanisms preventing optimum use of ecosystem services: an interdisciplinary theoretical analysis. *Ecosystems*, **3**:451–471.
- Spurgeon JPG. 1992. The economic valuation of coral reefs. *Marine Pollution Bulletin*. **24**(11):529-536.
- Spurgeon JPG. 2006. Time for a third-generation economics-based approach to coral management. Chapter 12 in: Côté IM and Reynolds JD (eds), *Coral Reef Conservation*. London: Zoological Society of London, Cambridge University Press, pp. 362-391.

- Swanson TM, Pearce DW and Cervigni R. 1994. *The Appropriation of the Benefits of Plant Genetic Resources for Agriculture: an Economic Analysis of the Alternative Mechanisms for Biodiversity Conservation*. Rome: Food and Agriculture Organization of the United Nations (FAO), Commission on Plant Genetic Resources. 127 pp.
- Toman M. 1998. Why not to calculate the value of the world's ecosystem services and natural capital. *Ecological Economics*, **25**(1):57-60.
- Turner RK. 1992. *Speculations on weak and strong sustainability*. Norwich (UK): University of East Anglia, The Centre for Social and Economic Research on the Global Environment (CSERGE), CSERGE Working Paper GEC 92-26, 41 pp.
- Turner RK. 2010. A Pluralistic Approach to Ecosystem Services Evaluation. Norwich (UK): University of East Anglia, The Centre for Social and Economic Research on the Global Environment (CSERGE), CSERGE Working Paper EDM 10-07, 16 pp.
- Turner RK, Brouwer R, Georgiou S and Bateman IJ. 2000. *Ecosystem functions and services: an integrated framework and case study for environmental valuation*. Norwich (UK): University of East Anglia, The Centre for Social and Economic Research on the Global Environment (CSERGE), CSERGE Working Paper GEC 2000-21, 32 pp.
- Turner RK, Paavola J, Cooper P, Farber S, Jessamy V & Georgiou S. 2003. Valuing nature: lessons learned and future research directions. *Ecological Economics*, **46**:496-510.
- U.S. Environmental Protection Agency (EPA). 2009. *Final Report on the Assessment of Services Derived from Coral Reef Ecosystems. Appendix A. Impact Focus Group, Coral Reefs Project, Ecological Services Research Program (ESRP)*. June 2009, 19 pp.
- Waddell JE (ed). 2005. *The State of Coral Reef Ecosystems of the United States and Pacific Freely Associated States: 2005*. NOAA Technical Memorandum NOS NCCOS 11. NOAA/NCCOS Center for Coastal Monitoring and Assessment's Biogeography Team. Silver Spring, MD, 522 pp.
- Waddell JE and Clarke AM (eds). 2008. *The state of coral reef ecosystems of the United States and Pacific Freely Associated States: 2008*. NOAA Technical Memorandum NOS CCOS 73. NOAA/NCCOS Center for Coastal Monitoring and Assessment's Biogeography Team. Silver Spring, MD, 569 pp.
- Walker B, Holling CS, Carpenter SR and Kinzig AP. 2004. Resilience, adaptability and transformability in social-ecological systems. *Ecology and Society*, **9**(2):5. <<http://www.ecologyandsociety.org/vol9/iss2/art5/>>
- Walker B, Pearson L, Harris M, Maler K-G, Li C-Z, Biggs R and Baynes T. 2010. Incorporating resilience in the assessment of inclusive wealth: an example from South East Australia. *Environmental and Resource Economics*, **45**:183-202.
- Weikard H-P. 2002. Diversity Functions and the Value of Biodiversity. *Land Economics*, **78**(1):20-27.
- Wilkinson C (ed). 2008. *Status of Coral Reefs of the World: 2008*. Townsville (Australia): Global Coral Reef Monitoring Network and Reef and Rainforest Research Center, 296 pp.
- Work TM, Aeby GS and Maragos JE. 2008. Phase Shift from a Coral to a Corallimorph-Dominated Reef Associated with a Shipwreck on Palmyra Atoll. *PLoS ONE*, **3**(8):e2989. doi:10.1371/journal.pone.0002989.
- Yoder CO. 1995. Policy issues and management applications for biological criteria. In: Davis WS and Simon TP (eds), *Biological Assessment and Criteria: Tools for water resource planning and decision making*. Boca Raton (FL): Lewis Publishers, pp. 327-343.

Coral Reefs: Tourism and Recreation

Tourism is one of the most important economic sectors worldwide and few environments are more important for tourism and recreation than coastal zones.
(Moreno & Amelung 2009)

2.1 Describing the service

2.1.1 Definitions

It is important to understand the terms “tourism” and “recreation”, particularly in the context of ecological economics.

Webster defines recreation as “refreshment of strength or spirits after work; also: a means of refreshment or diversion” (Merriam-Webster 2010). Recreational activities are enjoyed by both tourists and residents of a given geographic location. However, the common practice of economists is to differentiate between tourism and recreation based upon the source of demand.

Tourists: people who “travel to and stay in places outside their usual environment for more than twenty-four (24) hours and not more than one consecutive year for leisure, business and other purposes not related to the exercise of an activity remunerated from within the place visited” (UNWTO 1995).

Residents: people who live at a particular place for a prolonged period (Leeworthy 2002; Princeton WorldNet Glossary 2010a).

2.1.2 Tourism and the economy

Tourism is a significant sector of the global economy. According to the UN World Tourism Organization, tourism has become one of the largest and fastest growing economic sectors in the world—as much as 30% of the world’s exports of commercial services and 6% of overall exports of goods and services are due to tourism. Globally, tourism ranks fourth after fuels, chemicals, and automotive products in exports. For many developing countries, it is a main income source and the number one export category (UNWTO 2009).

According to Goeldner and Ritchie (2009), global travel and tourism in 2011 is expected to account for:

- \$7.0 trillion of economic activity
- 260 million jobs

The travel and tourism industry accounts for 24% of all U.S. service exports and 8% of total U.S. exports. Tourism is our nation’s third largest retail industry and the nation’s largest service export. There are currently more than 7m Americans employed directly in the travel industry, 9 million indirectly, for a total of over 16m jobs. In 29 states, tourism is the first, second, or third largest employer (Goeldner & Ritchie 2009; Table 2-1).

Congress passed “The Travel Promotion Act of 2009”, which highlights the importance of travel and tourism to our national economy. The act creates a public-private partnership—the Corporation for Travel Promotion—to help bring more international visitors to the United States (Sánchez 2010).

Table 2-1. Economic impact of travel and tourism (2009 preliminary data)

Travel expenditures*	\$704.4 billion
Travel-generated payroll	\$186.3 billion
Travel-generated tax revenue	\$113.0 billion
Travel trade surplus	\$22.0 billion
Travel-generated employment (direct)	7.4m jobs
Travel-generated employment (indirect)	9m jobs

* includes spending by domestic and international travelers in the U.S. on travel related expenses (i.e., transportation, lodging, meals, entertainment & recreation, and incidental items)

Source: Goeldner & Ritchie (2009); U.S. Travel Association (2010)

Tourism demand is strongly dependent on the economic conditions in major generating markets. Discretionary income is particularly dependent upon economic conditions. Tourism tends to account for a relatively large part of discretionary income, particularly in emerging economies. And most significantly, “the growth of international tourism arrivals significantly outpaces growth of economic output as measured in Gross Domestic Product (GDP)” (UNWTO 2010).

Marine tourism is the industry sector relevant to coral reef ecosystems. Orams (1999) provides a working definition for marine tourism: “Marine tourism includes those recreational activities that involve travel away from one’s place of residence and that have as their host or focus the marine environment (where the marine environment is defined as those waters that are saline and tide-affected).” This definition excludes business or work-related activities such as commercial fishing, shipping, oil exploration, and scientific research.

The definition includes activities that have as their focus the marine environment such as shore-based fishing, land-based whale-watching, or reef walking (Orams 1999). It also includes marine tourism development (accommodation, restaurants, food industry, and second homes) and the infrastructure supporting marine development (*e.g.*, retail businesses, marinas, and activity suppliers) (Hall 2001).

2.1.3 Tourism and recreation activities related to coral reefs

Coral-reef based tourism and recreation is a subset of marine tourism. Leeworthy and Wiley (2001) provide estimates for a comprehensive list of coastal and marine recreational uses. Recreational activities on or associated with coral reefs include:

- Scuba diving
- Snorkeling
- Underwater photography
- Recreational (sport) fishing
- Viewing nature and wildlife
- Beach sunbathing
- Surfing
- Collecting objects (*e.g.*, dead shells, fragments of corals, driftwood)

2.1.3.1 Recreational (scuba) diving

Scuba diving is a type of diving that uses Self-Contained Underwater Breathing Apparatus (SCUBA) equipment for the purpose of leisure and enjoyment.

The first documented underwater diving took place in 500 BC, when Scyllis demonstrated the practical use of breath-hold diving by performing military exploits for the King of Persia. In the 1600s, dive bells were invented, with air being pumped in from the surface. In the 19th century, Bert and Haldane researched the effects of water pressure on the body, and began to define safe limits for compressed air diving. Also in the 19th century, improvements in technology (*e.g.*, compressed air pumps, carbon dioxide scrubbers, regulators, etc.) made it possible for people to stay under water for long periods, although still using surface air (Martin 1997).

But it was not until the 20th century, with the invention of SCUBA, that recreational diving was really possible. Further developments in technology have reduced the cost of training and equipment. Swim fins, masks, dive computers and other scuba gear are available and affordable (Freeland 2010). Today, scuba diving is well regulated, with internationally governed training programs and a code of conduct (Basiron 1997).

Scuba diving has become a popular leisure activity and globally, there are many locations that derive significant income from scuba diving tourists. Recreational diving is an industry that is dependent upon the condition of the underwater resources. Certain types of features make an interesting dive, and most of these are found on coral reefs including:

- Wildlife at the site (*e.g.*, coral, sponges, fish, rays, mollusks, cetaceans, sharks and crustaceans).
- Complex topography of the site (*e.g.*, coral reefs, drop offs).
- Historical or cultural items at the site (*e.g.*, ship wrecks, aircraft) provide both historical value and form artificial habitats for marine fauna.
- Good underwater visibility. Poor visibility is caused by particles in the water, such as mud, sand and sewage.
- Temperature. Warm water diving is comfortable and convenient.

The growth in recreational scuba diving can be measured by analyzing the increase in Professional Association of Dive Instructors (PADI) diver certifications (Figure 2-1).

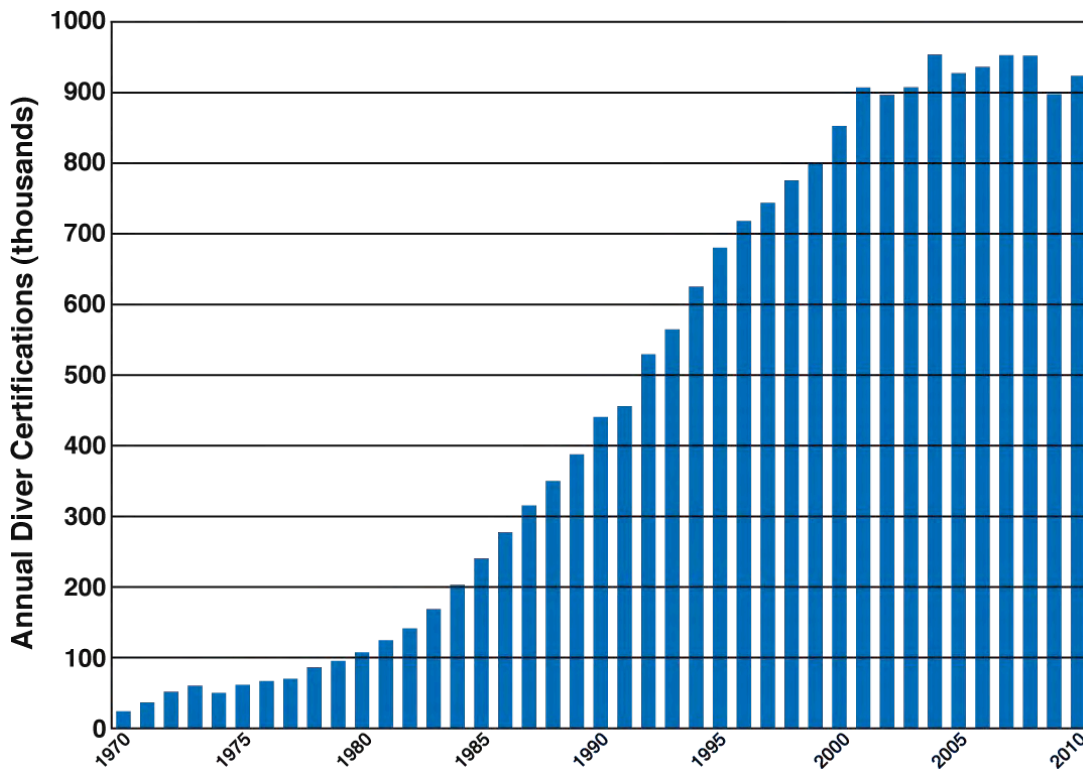


Figure 2-1. Annual diver certifications by the Professional Association of Dive Instructors (PADI).
Source: PADI 2011

2.1.3.2 Snorkeling

Snorkeling is the practice of swimming while equipped with a diving mask, a shaped tube called a snorkel, and fins. A wetsuit may also be worn in colder waters. Snorkel equipment allows the snorkeler to observe underwater attractions for extended periods of time with relatively little effort and minimal cost.

The earliest documented snorkeling dates back to 3000 BC, when sponge farmers in Crete used hollow reeds to allow them to breathe while diving under water (Snorkeling 2010). Leonardo da Vinci is credited with inventing the first modern snorkel, a hollow breathing tube attached to a leather diver's helmet. Advancements in plastic and rubber in the 20th century greatly improved the construction of snorkels, masks and fins.

While snorkeling is possible in almost any body of water, snorkelers prefer locations where there are minimal waves, warm water, and something particularly interesting to see near the surface. Coral reefs are particularly attractive to snorkelers because they:

- occur in calm, warm waters;
- are populated with visually attractive biota (e.g., corals, sponges, brilliantly colored fish, turtles);
- have clear waters providing high visibility;
- often have sunken ships and other historical artifacts nearby; and,
- may have designated snorkeling areas (reducing conflicts with boats and fishers).

2.1.3.3 Underwater photography

Underwater photography is the process of taking photographs while scuba diving, snorkeling, or swimming. The first documented underwater color photograph was taken off the Florida Keys in 1926 by Dr. William Longley and *National Geographic* staff photographer Charles Martin. Their equipment included cameras encased in waterproof housing and pounds of highly explosive magnesium flash powder for underwater illumination (*National Geographic* 2010).

Since then, underwater photography has evolved considerably. Today there are options that fit almost any budget, ranging from simple point-and-shoot disposable cameras to sophisticated single lens reflex (SLR) cameras (Gilbert & Alary 2010). Digital technology has further accelerated the evolution of underwater photography, eliminating the constraints associated with film (e.g., waiting to get film developed and toxic chemicals used in developing film). Today most underwater photographers are able to capture images digitally that would have been considered "ground breaking" in the film era (Yonover 2010).

The goal of underwater photography is to bring back an image that will inform, entertain or educate. Attributes that contribute to good underwater photographs include:

- Clear water. If the water is not clear, underwater pictures will not be either.
- Colorful fish, corals and other biota.

2.1.3.4 Recreational (sport) fishing.

Recreational fishing, fishing for pleasure or competition, is included as a component of tourism and recreation. Commercial fishing (*i.e.*, fishing for profit) and subsistence fishing (*i.e.*, fishing for survival) are covered in the following chapter on fishing.

Many common salt water game fish spend some portion of their lives in coral reef ecosystems including tarpon, shark, bonefish, permit, sailfish, marlin, bonito, pompano and mackerel. Historically, sport fishers, even if they did not eat their catch, almost always killed them to bring them to shore to be weighed or for preservation as trophies. To protect recreational fisheries, sport fishermen now often catch and release or tag and release, which involves fitting the fish with identity tags, recording vital statistics, and sending a record to a government agency.

Recreational fishing is governed by a variety of conventions, rules, licensing restrictions and laws that typically restrict sportfishing to hook, line, rod and reel rather than with nets or other aids.

Recreational fishing is big business, generating more than \$125 billion in economic output and more than one million American jobs. At nearly 40 million, more Americans fish than play golf (24.4 million) and tennis (10.4 million) combined. If fishing were ranked as a corporation, it would be 47 on the 2007 Fortune 500 list of America's largest companies based on total sales (Allen & Southwick 2008).

The recreational fishing industry consists of enterprises such as the manufacture and retailing of fishing tackle, the design and building of recreational fishing boats, and the provision of fishing boats for charter and guided fishing trips. The American Sportfishing Association (ASA) is the sportfishing industry's trade association, committed to looking out for the interests of the entire sportfishing community (ASA 2010).

While recreational fishing is possible in almost any body of water, sport fishermen prefer locations where there are minimal waves (calm water). Coral reefs are particularly attractive to recreational fishers because they:

- occur in calm waters;
- are found where the weather is generally hot and sunny; and,
- are populated with a wide diversity of fish species, including large, hard-fighting fish (tarpon, sailfish, sharks, mahi mahi).

2.1.3.5 Viewing nature and wildlife.

Nature and wildlife watching is the practice of observing nature and wildlife (*e.g.*, birds, dolphins, fish, manatees, turtles, whales) in their natural habitat. Viewing is performed with the naked eye or through a visual enhancement device like binoculars. The wildlife found in coral reefs and the adjacent seagrasses and mangroves are diverse and fascinating creatures. They range from the charming and intelligent dolphin to the gentle, slow-moving manatee.

Guidelines for responsible wildlife viewing have been developed by federal and state agencies and NGOs. These agencies support responsible wildlife viewing as a positive way to promote conservation and respect for the animals and the marine environment.

Wildlife viewing is a significant commercial activity. For example:

- Whale-watching is estimated to be worth up to \$2.1 billion per annum worldwide to whale watching operations, employing around 13,000 workers (Cisneros-Montemayor et al. 2010).
- Bird-watchers contributed \$36 billion per annum in the U.S. alone, and a fifth (20%) of all Americans identify themselves as birdwatchers (U.S. Fish & Wildlife Service 2006).

Wildlife viewing can be done on an individual basis or through organized tours with knowledgeable marine naturalists. Guided bird tours have become a major business with at least 127 companies offering tours worldwide (Wikipedia 2010a). Guided kayak nature tours are a popular way to view birds, manatees, fish, and other wildlife in mangroves adjacent to reefs.

Recreational wildlife viewing is an industry that is dependent upon the condition of the supporting habitat. Coral reefs and the adjoining mangroves and seagrasses are particularly attractive to wildlife viewers because they:

- occur in calm waters;
- are found where the weather is generally hot and sunny; and,
- are populated with a wide diversity of species, including birds, dolphins, fish, manatees, turtles, and whales.

2.1.3.6 Beach sunbathing and swimming.

Sunbathing on wide sandy beaches is a popular recreational activity. Sandy beaches are an important part of the attraction for major tropical and subtropical destinations, and many tourists spend at least some time at the beach. White, soft sandy beaches composed of coral and shell particles are a favorite. The contrast between white sand beaches and the emerald, light blue, and sparkling azure colors of tropical and subtropical sea waters is especially beautiful.

Coral reefs and mangroves play an important role in building and maintaining white sand beaches. Coral reefs serve as a sand source. The sand is made of limestone of recent biological origin (e.g., corals, foraminifera, calcareous algæ, mollusks, and crustaceans) (UNEP/GPA 2003). Production of sand results from two processes: wave erosion of the coral reefs and fish feeding on the coral and excreting coral sand (e.g., parrot fish, butterfly fish, and trigger fish).

However, not all beaches are made up of coral sand. Many Caribbean beaches are composed of sand derived from weathered rock, and others consist of a mixture of coral and terrigenous sands.

Reefs also reduce wave energy creating calm waters desirable for swimming. Many sunbathers spend some portion of their time swimming or wading in the water.

Attributes that contribute to good sunbathing beaches include:

- White coralline sands;
- Generally hot, sunny weather; and,
- Calm, warm waters

2.1.3.7 Collecting objects (beachcombing).

Beachcombing is the recreational activity of searching the beach and the intertidal zone for items that have washed in with the tide (e.g., corals, seashells, sponges, sea fans, fossils, pottery shards, artifacts, sea beans, sea glass, and driftwood).

Beachcombing provides the opportunity to achieve better emotional, physical and spiritual health at little or no financial cost (Ritterbush 2008, 2010).

Many beachcombers use knowledge of storms, geography, ocean currents, and seasonal events to determine the arrival and exposure of rare finds (LaMotte 2004; Robinson & Robinson 1995; McRee 2009). Beachcombers tend to focus on the area from just above the high tide line, usually marked by a row of seaweed and debris (wrack), down to the water's edge (McRee 2009).

Beachcombing equipment can be as simple as a bag or bucket to put the shells in and a shell identification guide. Many beachcombers also use a metal detector, which aids in locating jewelry, coins and artifacts buried in the sand. Beachcombers tend to be environmentally conscious and serve as stewards of the seashore (Ritterbush 2008).

Currently recognized beachcombing experts include: oceanographer Dr. Curtis Ebbemeyer (*Flotsametrics and the Floating World*); eco-educator Dr. Deacon Ritterbush (*A Beachcomber's Odyssey*); sea glass experts Richard LaMotte (*Pure Sea Glass*) and C.S. Lambert (*Sea Glass Chronicles*); geologist Margaret Carruthers (*Beach Stones*); shell specialists Chuck and Debbie Robinson (*The Art of Shelling*); and, zoologists Dr. Blair Witherington and Dawn Witherington, (*Florida's Living Beaches: A Guide for the Curious Beachcomber*) (Wikipedia 2010b).

Beaches adjacent to coral reefs are particularly attractive to beachcombers because they:

- provide unique, beautiful shells, corals, and sponges;
- often have wide sandy beaches;
- generally have hot and sunny weather; and,
- experience occasional tropical storms that bring in treasures.

2.1.3.8 Surfing.

Surfing is the sport of riding a surfboard toward the shore on the crest of a wave (Princeton WorldNet Glossary 2010b).

Ancient Polynesians (e.g., Hawaiians, Samoans, Tongans, Tahitians, and Māori) integrated surfing into their culture and considered surfing an art. Hawaiians referred to this art as *he'e nalu*, which translates into English as "wave sliding". Samoans call surfing *fa'ase'e* or *se'egalu* (Krämer 1994). The most skilled surfers were often members of the upper class, which included chiefs and warriors, who had access to the best waves (Young 1983).

In 1779, Lieutenant James King, the newly promoted captain of the HMS Discovery (following Captain James Cook's demise), devoted two full pages of the ship's log to a description of surfboard riding, as practiced by the locals at Kealahakua Bay on the Kona coast of the Big Island. His entry is the earliest written account of surfing (Marcus 2010). The sport was also recorded in print by Augustin Krämer, a 19th century German ethnologist, author, collector, and expert on Polynesian and Samoan culture.

European missionaries forbade or discouraged many Polynesian traditions including surfing. By the 20th century surfing had almost disappeared. Only a few Hawaiians continued to practice surfing and the art of crafting surfboards. In 1905, Duke

Kahanamoku and his friends created a surf club in the Waikiki area of Hawaii. Duke and his friends are credited for bringing surfing back to Hawaii and exposing the world to surfing. In 1907, Jack London went to Hawaii and was introduced to surfing by Alexander Hume Ford, an eccentric journalist and wanderer. London subsequently wrote *A Royal Sport: Surfing in Waikiki*, which included descriptions of Waikiki and Alexander Hume Ford. His story was published in the October 1907 edition of *The Lady's Home Companion* and again in 1911 as part of *The Cruise of the Snark*. In 1907, another member of the Waikiki surf club, George Freeth, introduced surfing to California. Duke Kahanamoku introduced surfing to Australia in 1915.

Until the 1960s only a small number of people were involved in surfing, mainly in Hawaii, Australia and California. The release of the movie *Gidget* moved surfing from an underground culture to a national fad. Since then, films about surfing have continued to play a part in the evolution of surfing.

Globally, there are over 10 million surfers. In the Indo-Pacific, the commercial surf tourism industry is strongly linked to the clothing, fashion, and entertainment industries, and marketed through specialist surfing magazines and surfing media (Buckley 2002).

Coral reefs and other shallow water formations (*e.g.*, rocks, sandbars, etc.) allow waves to break, thereby forming a surfable wave. Collectively, these breaks are known as surf breaks (Silimalis 2007). A reef break is a wave that breaks over a coral reef. When a coral reef is exposed to open ocean, there is potential for a fast and hollow wave. As the wave swell approaches from deep water, it hits the shallower reef, escalating in height before pitching and curling over the reef. The waves at Pipeline in O'ahu, Cloudbreak in Fiji, and Jaws in Maui are among the most famous and photographed reef-break waves. Experienced surfers are rewarded with a fast tubing ride on a ramp-like wave. Most surfing competitions take place on reef breaks (The Surfing Site 2010).

According to Baker (2007), the Caribbean has fewer surf breaks than the Pacific, but offers great surfing during winter and spring. The waves provide short powerful rides, sometimes sweeping over the coral reefs, creating demanding tubes. The best surfing conditions occur when Atlantic storms push through the Caribbean in late May through early September (hurricane season) and December through March (when Atlantic storms push through the Caribbean). When coral reefs are destroyed, waves may diminish, so preserving coral reefs is critical to preserve the sport of surfing (NOAA 1997).

2.1.4 Tourism and recreation: businesses

A diverse range of businesses forms the coral reef tourism industry. Those directly associated with coral reef tourism include small businesses such as charter fishing boat operators, sea kayak tours, and scuba diving instructors, etc. They also include moderate-sized private companies like coral reef dive-boat operators and large corporations such as those that manufacture and retail fishing tackle and recreational fishing boats. An even greater number of businesses are indirectly associated with coral reef tourism (*e.g.*, boat maintenance shops, coastal resorts, island ferry services, and artists). Government agencies monitor and manage coral reef tourism (*e.g.*, park authorities, fisheries control agencies, tourism marketing and promotion bodies, law enforcement agencies, and marine safety organizations). Nonprofit groups also form an important component of the industry (*e.g.*, clubs for scuba diving and fishing) (Orams 1999).

2.2 Necessary conditions for providing the service

Coral reefs are the most biologically diverse marine ecosystems on earth, rivaled only by tropical rainforests (Sebens 1994; Odum 1997). Coral reefs cover less than 0.1% of the ocean's surface (an area about half the size of France) but support about 25% of all marine species (Wilkinson 2004; Mulhall 2007).

Coral reefs occur in seas with very specific environmental and climatic conditions.

- Mainly in tropical and subtropical seas—between 30°N and 30°S latitudes.
- Warm ocean temperatures (68–82°F, or 20–28°C). Warm water flows along the eastern shores of major land masses.
- Generally at depths of less than 150 ft (46 m), where sunlight penetrates. Because reef-building corals have a symbiotic relationship with zooxanthellæ, a type of microscopic algæ, sunlight is necessary for these corals to thrive and grow.
- High salinity, low CO₂ concentration, and low acidity, facilitating precipitation of calcium from the water necessary to form a coral polyp's skeleton.
- Strong wave action. Waves carry food, nutrients, and oxygen to the reef, distribute coral larvæ, and prevent sediment from settling on the coral reef.
- Most corals grow on a hard substrate.

Coral reefs depend on the interaction of many species, including hard and soft corals, fish, sponges, crustaceans (including shrimp, lobsters, and crabs), echinoderms (including starfish, sea urchins, and sea cucumbers), sea turtles, and cetaceans. Hard and soft corals provide the structural habitat that supports this high abundance and diversity. Bryozoans encrust coral skeletons and reefs debris, cementing the reef structure. Fish, crabs, and lobsters find shelter in the reef structure and play a vital role in the reef's food web.

2.2.1 Linkages among reef condition, reef structures, and reef functions with respect to delivery of the service

The complex three-dimensional coral reef structure provides habitat for the high numbers and diversity of marine organisms that support tourism and recreation (Bradley *et al.* 2008; Fisher *et al.* 2007; Courtney *et al.* 2007; Cesar 2002; Wilkinson 2002; Done *et al.* 1996; Hoegh-Guldberg 1999; Muscatine 1980, 1990; Reaka-Kudla 1996; Sebens 1994; Sale 1991; Crossland *et al.* 1991; Sutton 1983; Loya 1972). Stony corals are the basic building blocks of the coral reef (Human & DeLoach 2002). Massive species (*e.g.*, *Montastrea* spp., *Diploria* spp.) and branching corals (*e.g.*, *Acropora* spp.) provide significant three-dimensional surface area that functions as essential habitat for fish and other reef-dwelling animals (Mumby & Steneck 2008; McField & Richards Kramer 2007; Moberg & Folke 1999). Tourism and recreation are, therefore, directly or indirectly dependent upon the reef-building corals (Moberg & Folke 1999).

Most reef-building corals have photosynthetic algæ (zooxanthellæ) that live in the coral tissue. The coral provides the zooxanthellæ with a protected environment and compounds they need for photosynthesis. The zooxanthellæ provide glucose, glycerol, and amino acids (the products of photosynthesis) that the coral uses to make proteins, fats, and carbohydrates, and produce calcium carbonate (Barnes 1987; Barnes & Hughes, 1999; Lalli & Parsons 1995; Levinton 1995; Sumich 1996). Zooxanthellæ also give stony corals their beautiful, bright coloration.

When stony corals become physically stressed, they expel their zooxanthellæ and the coral colony bleaches (Barnes & Hughes 1999; Lalli & Parsons 1995). This, in turn, results in a reduction of energy (in the form of various photosynthates) being provided to the host (Hoegh-Guldberg & Smith 1989; Brown 1997), and a subsequent loss of tissue biomass (Porter *et al.* 1989; Szmant & Gassman 1990; Fitt *et al.* 1993), coral skeletal deposition (Goreau & MacFarlane 1990), and fecundity (Szmant & Gassman 1990). Extended periods of coral bleaching can result in the coral's death.

Poor coral health may also adversely impact fish production. While overall abundance of reef fishes is correlated mainly with structural complexity of reefs (Jones & Syms 1998; Done 1999), several short-term studies have documented decreases in fish productivity, species richness, fish biomass, and potential yield (reef biocapacity) (Warren-Rhodes *et al.* 2003; Graham *et al.* 2006; Sano 2004) resulting from lost coral structural complexity. Over the long term, however, coral reef structure will reduce in complexity as corals die and bio-erode.

Coral reefs are part of a tropical marine “seascape that functionally links them with the adjacent tropical ecosystems (*i.e.*, mangrove forests and seagrass meadows)” (Mumby & Steneck 2008). This seascape mosaic: (McField & Richards Kramer 2007; Mumby *et al.* 2004)

- provides critical foraging areas, nurseries and refugia;
- provides physical and chemical buffering;
- facilitates energy and material flows; and,
- creates corridors for transient species.

For example, mangroves strongly influence the community structure of fish on neighboring coral reefs (Mumby *et al.* 2004), and also trap sediments, nutrients and pollutants, improving the water quality on nearby reefs (Grimsditch & Salm 2006). Seagrasses contribute nutrients to the coral reefs and produce colored dissolved organic matter (CDOMs), which can protect coral against bleaching by screening harmful solar radiation (Salm & West 2003).

Reef fish respond to this spatial mosaic, many showing pronounced associations with specific habitat types (Sale & Kritzer 2008). Coral reefs provide essential habitat for adult fish. The three-dimensional coral reef structure protects shorelines and creates calm waters necessary for seagrass meadows and mangrove forests to thrive. The rainbow parrotfish, grunts, barracudas, and several snapper species depend on these mangrove forests and seagrass beds for nursery habitat (McField & Richards Kramer 2007).

The tropical marine mosaic also supports “charismatic megafauna”, large animal species with widespread popular appeal (*e.g.*, manatees and dugongs, sea turtles, rays, sharks, and dolphins). Some of these species (*e.g.*, manatees and sea turtles) use a variety of habitats during different life stages (McField & Richards Kramer 2007).

Many of the attributes discussed above make coral reefs particularly attractive destinations for tourists. The warm, sunny weather, clear, calm waters, and wonderful species diversity and richness all contribute to this appeal. The desirability of these attributes for tourism and recreation has been well documented in the literature. For example, Pendleton (1994) points out that scuba divers look for high-quality coral reef habitats (as indicated by live coral coverage), coral and fish diversity, and water clarity. Leujack and Ormand (2007) reported that 51% of survey respondents were interested in both fish and corals, whereas 36.5% were only interested in fish and 5.2% only in corals, while another 5.2% stated that besides being interested in corals they also looked for other things on the reef. Uyarra *et al.* (2005) found that divers correctly perceived differences between sites in the condition of biological attributes such as:

- fish species richness;
- total number of fish schools;
- live coral cover;
- coral species richness; and,
- reef structural complexity.

Leeworthy *et al.* (2004) grouped survey respondents' preferences into three categories:

- natural resource attributes (e.g., clear water, amount of living coral, fish/biota diversity, megafauna, and beach quality);
- natural resource facilities (e.g., parks, shoreline access, marina facilities, mooring buoys, boat ramps); and,
- other facilities (parking, roads, rest rooms) and services.

Studies in Israel (Weilgus 2004) and Tobago (Beharry-Borg & Scarpa 2010) have documented the importance of water clarity, coral cover, and fish abundance for divers and snorkelers.

There are other factors that influence the selection of a tourism venue, including the availability of facilities and amenities (e.g., boats, dive shops, fishing guides, hotels and restaurants, etc.), the perceived "healthy" condition of the waters (e.g., lack of pollution, absence of debris), and even perceptions of crowding (Park *et al.* 2002; Beharry-Borg & Scarpa 2010). Inglis *et al.* (1999) and Leujack and Ormand (2007) documented the effect of perceived crowding on snorkelers' enjoyment. Table 2-2, below, summarizes some of the most important attributes that have been identified in the literature.

Table 2-2. Features relevant to the perceived value of coral reefs

Natural Features		Social Features
Biotic Features	Abiotic Features	
Species richness (coral, fish, sponges, etc.)	Warm ocean temperatures	Perceptions of crowding <ul style="list-style-type: none"> • # of divers/snorkelers • # of proximal boats
Variety of species characteristics (coral, fish, sponges, etc.) <ul style="list-style-type: none"> • colorful • large • rare 	Water clarity	Lack of pollution
Charismatic megafauna species diversity (birds, marine mammals, turtles)	Calm waters	Absence of debris
Coral health	White coralline sands	
3-dimensional reef structure	Proximity to deep ocean & waves	
Coral/macroalgæ ratio	Connectivity with the adjacent tropical ecosystems	

The coral reef tourism industry depends upon high-quality, pristine or undisturbed assets (Basiron 1997). Coral reef degradation directly impacts delivery of the tourism and recreation services (Cooper *et al.* 2009). For example, recreational fishing is extremely dependent upon the health of coral reefs since many marine game fish species (e.g., tarpon, groupers, snook, barracuda, and dolphin) utilize reef habitats for at least part of their life cycles (Bryant *et al.* 1998).

Recreational diving is especially sensitive to reef condition, and thus particularly vulnerable to degradation (Cooper *et al.* 2009). As an example, dive tourism in Zanzibar decreased by 20%, snorkeling in Sri Lanka declined substantially, and there was an estimated \$1.5m annual loss in tourism dollars in the town of El Nido, Philippines, after the mass bleaching and coral mortality of 1998 (Wilkinson *et al.* 1999; Cesar 2000; Bruno 2008). The relative cover of benthic habitats in an area may be indicative of snorkeling or swimming opportunities, with certain types of benthic habitats, such as patch reefs or *Montastrea*-dominated reefs, having greater recreational value than those dominated by seagrass or macroalgæ (Mumby *et al.* 2008).

2.3 Measuring the service

The recreational ecosystem services provided by coral reefs (the opportunity to dive, snorkel, and fish) have not been directly measured. However, there are surrogate measurements related to the natural features that support these ecosystem services that

can (and have) been measured. These could potentially serve as, or be combined into, multi-metric indicators of final ecosystem services.

A wide range of biological indicators have been developed and are documented in Jameson *et al.* (1998). Methods for monitoring stony corals, octocorals, fish, benthos, and sponges have been developed and tested by EPA.

2.3.1 Stony corals (*scleractinians*)

Stony corals (phylum Cnidaria, class Anthozoa, subclass Hexacorallia) build and maintain the physical infrastructure that supports all other organisms in the community (Fisher *et al.* 2007; Fisher *et al.* 2008). Stony corals constitute the basic framework and substrate for many other organisms that penetrate the skeletal mass (sponges, polychaetes, sipunculides, bivalves, and gastropods). The complex skeletal structure of stony corals also provides habitat for the high numbers and diversity of marine organisms that support fisheries and tourism (Crossland *et al.* 1991; Done *et al.* 1996; Hoegh-Guldberg 1999; Muscatine 1980, 1990; Reaka-Kudla 1996; Sebens 1994; Wilkinson 2002). Coral structures also protect coastal shorelines from wave and current erosion (Costanza *et al.* 1997; Pernetta 1992).

Because the health, growth, and recruitment of stony corals are crucial to reef sustainability and future benefits, these corals are often considered the primary indicator organisms for reef communities (Loya 1972; Brown 1988; Done 1997). Stony coral colony size is an extremely important attribute, because colony size determines the contribution of each colony and species to community habitat, biomass, photosynthetic activity, metabolism, and calcium carbonate deposition. Colony size is a major determinant of growth, reproduction, population dynamics and community interactions (Fisher 2007).

The stony coral rapid bioassessment protocol (RBP) (Fisher 2007) relies on three observations (colony identification, colony size, and proportion of live tissue), that can be combined in different ways to generate multiple indicators that characterize the value and sustainability of coral reefs. These indicators can be used to assess the capability of reefs to continue providing ecosystem services such as reef-based tourism and recreation (Table 2-3). Unique to the RBP is the ability to generate three-dimensional indicators that help to quantify the complex three-dimensional structure of the reef that is so important to providing the ecosystem services.

2.3.2 Octocorals (*gorgonians*)

Marine octocorals (phylum Cnidaria, class Anthozoa, subclass Octocorallia [aka Alcyonaria]) (including gorgonians, blue coral, soft corals, and sea pens) are sessile invertebrates that provide substantial spatially varied biogenic habitat for adult and juvenile fish and other invertebrates (Pugliese 1998; Lybolt 2003). Octocoral surface area and topographical heterogeneity are therefore extremely important attributes.

EPA has developed a method that can be performed in conjunction with stony coral monitoring to estimate the total three-dimensional surface area of octocorals on coral reefs. Divers classify marine gorgonians by colony morphology and measure their maximum height and diameter. Morphology-specific equations are used to calculate surface area. These indicators can be used to assess habitat availability for fish and macrobenthos.

The protocol may be supplemented to identify gorgonians by taxonomy and report adverse health conditions (*e.g.*, bleaching, disease, predation, etc.) These additional observations can be used to estimate additional indicators (gorgonian abundance, density, and richness) (Santavy *et al.* in review). These additional indicators could be used to assess features that would be attractive to divers and snorkelers.

2.3.3 Sponges

Marine sponges (phylum Porifera) provide habitat for fish and other invertebrates, cement and reinforce reef structure, contribute to nitrogen and carbon cycling through microbial symbionts, and efficiently filter sediment, algæ, and small organisms from the water column. Three-dimensional sponge area is the critical attribute that supports these services.

EPA has developed a method that can be used to estimate the three-dimensional surface area of marine sponges. Divers classify sponges by colony morphology, then measure height and maximum diameter. Dimensions are converted to surface area using a formula derived for each morphological type. If the necessary expertise is available, additional data collection can include taxonomic identification and adverse physical condition (*e.g.*, bleaching, disease, and predation). Such data will permit estimation of sponge abundance, density, surface area, and, if included in the protocol, taxa richness and physical condition (Santavy *et al.* in review).

2.3.4 Fishes

Reef fish are major components of coral reef ecosystems. The coral reef ecosystem is a very complex environment with many niches. Reef fish fill these niches, helping to sustain the balance of the reef. Reef fish also provide a readily available food source and are an important aspect of tourism and recreation (*e.g.*, sportfishing and diving/snorkeling).

Species diversity and richness are critical attributes that support these services. NOAA has developed and tested fish survey techniques that can be performed in conjunction with stony coral monitoring. Divers assess the species, numbers, and sizes of

all reef fishes within an underwater transect. This protocol is a noninvasive, timed, rapid assessment that takes approximately 30 minutes to complete (Menza *et al.* 2006). The fish are classified according to size categories. Visual data are used to estimate abundance, species richness, and biomass for the fish populations and different feeding guilds sampled. Although not yet included in the protocol, the visual data collection could be expanded to include indicators of fish color, which is an attribute of interest to divers and snorkelers.

2.3.5 Mangroves and seagrasses

Remote sensing provides an efficient way to track the change in the areal extent of mangrove forests and seagrass meadows over time. Landsat or other satellite images can be used to measure the extent and spatial patterns of coral reefs, seagrass meadows, and mangrove forests (McField & Richards Kramer 2007). The development of indicators that relate landscape composition and pattern attributes (including hydrology and transitional coastal systems) to coral reef condition is a new research area for EPA.

Table 2-3. Stony coral rapid bioassessment protocol coral condition indicators*

Abundance and Composition	
Abundance	number of colonies
Density	number of colonies per m ² sea floor
Relative species abundance	abundance of a particular species per total abundance
Species (taxa) richness	number of species occurring in a reef or region
Species frequency	proportion of sites where a species occurs
Species diversity	index of taxa richness and relative abundance
Protected species	richness and abundance of protected coral species
Community composition	relative richness or abundance of a species or groups of species with some discretionary biological or physical attribute (<i>e.g.</i> , tolerance)
Physical Status	
Colony surface area (CSA)	3D skeletal surface area of an entire colony (m ²)
Total surface area (TSA)	Σ CSA for all colonies at a transect, station or reef
3D total coral cover (3DTC)	TSA per m ² sea floor
Average colony surface area (AvCSA)	TSA / # colonies
Population structure	colony size distribution for a species compared to colony number or other attribute
Community structure	colony size distribution for all species compared to colony number or other attribute
Biological Condition	
Percent live tissue (%LT)	proportion of live coral tissue on each colony
Average percent live tissue (Av%LT)	Σ %LT / # colonies
Colony live surface area	live tissue on a colony (m ²) = (CSA × [%LT / 100])
Live surface area (LSA)	Σ colony live surface areas at a transect, station or reef (m ²)
3D live coral cover (3DLC)	LSA per m ² sea floor
Percent Live Surface Area (%LSA)	comparative ratio of live and total surface area = ([LSA / TSA] × 100)

* Indicators are derived from three core observations (colony identification, colony size, and proportion of live tissue) on stony coral colonies and can represent cumulative or average values for transects, stations, and reefs or for a particular species or group of species.

2.4 Valuing the service

Across the globe, nearly half a billion people are located within 100 km of a coral reef, and therefore, receive some benefit from the ecosystem services provided by coral reefs (Park *et al.* 2002). Local communities depend on coral reefs as an important source of employment, income, and tourism revenues (Ahmed *et al.* 2007). Consequently, tourism (and recreation) is one of the most commonly valued ecosystem services. Tourism (and recreation) is a direct, largely nonconsumptive use of coral

reef ecosystems. Sportfishing is largely catch and release, so we consider it to be nonconsumptive even though a portion of sportfishing remains consumptive.

There is a considerable body of literature on valuation of tourism and recreation in coral reef environments. Many different valuation methods have been developed, tested, and applied globally; however, the results are rarely comparable (Burke *et al.* 2008). Values for ecosystem services (UNEP-WCMC 2006) will vary according to:

- the location (e.g., reefs that are major tourist destinations will have a higher value in terms of diving and other reef-related activities than those where tourism has not been developed);
- the length of time being considered and whether a prediction for the future is involved (e.g., all reefs are potentially of value for diving tourism, but some may have no value at present);
- visitor responses to marginal changes in reef quality (e.g., some people are more sensitive to changes and will place a higher value on maintaining reef quality than those less sensitive to such changes); and,
- the method used and the assumptions made.

Table 2-4 below describes commonly used approaches to economic valuation and relates them to particular services. Approaches relevant to tourism and recreation are Travel Cost (TC), Effect on Production (EoP), Financial Analysis (FA), and Contingent Valuation Method (CVM). A brief description of some of these methods is given in the following sections.

Table 2-4. Methods used for valuing goods and services of coral reef ecosystems

Generally Applicable Methods
<ul style="list-style-type: none"> ▶ Using the change in conventional market value of goods and services that results from a change in the environmental resource <ul style="list-style-type: none"> • Change in Productivity / Effect of Production (EoP) • Change in Stock (houses, infrastructure, land) at Risk (SaR) • Loss of earnings / Human capital approach (HC) • Opportunity cost approach (OC) ▶ Using the value of direct expenditures (cost based) <ul style="list-style-type: none"> • Preventive expenditures (PE) • Compensation payments (CP) ▶ Using the observed market prices to analyze the current economic activity generated (Financial Analysis)
Potentially Applicable Methods
<ul style="list-style-type: none"> ▶ Using implicit or surrogate market values – indirect approaches <ul style="list-style-type: none"> • Property-value and other land-value approaches (PV) • Travel-cost approaches (YC) ▶ Using the magnitude of potential expenditures (cost based) <ul style="list-style-type: none"> • Replacement costs (RP) • Shadow-project costs (SPC)
Survey-Based Methods
<ul style="list-style-type: none"> ▶ Using surveys of individuals to elicit values <ul style="list-style-type: none"> • Contingent valuation method (CVM) – hypothetical markets and situations (Willingness-to-Pay [WTP] and Willingness-to-Accept [WTA])

Source: Cesar 2000

2.4.1 Effect on production (EoP)

EoP estimates the difference in value of productive output before and after the impact of a threat or a management intervention. The change in net profit (*i.e.*, effect on production) can be calculated and used as a proxy for the loss in tourism value. One challenge with this method is determining and modeling the relationship between the damage to an environmental resource and its corresponding impact on the production of the specified good or service. An example of EoP is the previously cited coral mortality in 1998 and loss of tourism revenues in Zanzibar, Sri Lanka, and the Philippines (Bruno 2008).

2.4.2 Financial analysis (FA)

FA uses observed current financial activities, revenues, costs, and financial flows in the economy from market-based uses of the reef (such as diving and snorkeling) to analyze the economic activity generated by use of an ecosystem good or service.

Data availability and quality vary considerably and have direct bearing on the statistical confidence of the resulting analysis. In addition, this approach will *underestimate* the tourism value of reefs, because it omits consumer surplus (the additional welfare a consumer enjoys beyond what he or she has paid for the service) (Cooper *et al.* 2009).

An example is the World Resources Institute (WRI) economic valuation of coral reefs in Tobago and St. Lucia (Burke *et al.* 2008). Using FA, Burke *et al.* (2008) valued direct and indirect economic impacts from visitor spending in 2006 associated with coral reefs in Tobago to range from \$101m to \$130m and in St. Lucia from \$160m to \$194m.

For both EoP and FA, it is important to calculate secondary (*i.e.*, indirect) impacts on the economy from spending by coral reef associated visitors. Economists estimate the magnitude of these *indirect* impacts using a tourism multiplier. A multiplier of 1.6, for example, represents 60 cents of additional impact for every \$1 in direct tourist expenditure. The size of the multiplier is influenced by the portion of goods and services used in the tourism sector that are produced domestically, such as linens, beverages, food, dive equipment, and construction materials. (Cooper *et al.* 2009).

2.4.3 Travel costs (TC)

TC uses the travel time or travel costs as a proxy “total entry fee”, and therefore, it is a measure of a person’s willingness to pay for visiting a particular tourist location. The further away people live from the location, the higher the costs. A demand curve can be developed and the associated consumers’ surplus can be determined. This surplus represents an estimate of the value of the environmental good in question (*e.g.*, the coral reefs).

An example of TC is given by Pendleton (1995), who used this method to estimate the economic value of the Bonaire Marine Park. Pendleton used marine park permit data to estimate the number of visitors from each state and county. This number was then divided by the population of the state or county to determine a visitation rate that was then regressed on travel costs, providing the demand curve for coral reef associated vacations to Bonaire. Pendleton was then able to calculate the annual value of Bonaire Marine Park at approximately \$19.2m.

2.4.4 Contingent valuation method (CVM)

CVM is used to obtain information on consumers’ preferences by asking people what they are willing to pay for a benefit (willingness to pay or WTP), or what they are willing to accept by way of compensation to tolerate a loss (willingness to accept or WTA). Analysts may use either a direct questionnaire/survey or experimental techniques in which subjects respond to different stimuli under controlled conditions. Analysts now use a combination of conjoint analysis (developed in the social psychology field) and multi-attribute utility theory (Adamowicz *et al.* 1998).

An example of a CVM is given by Spash (2000), who surveyed visitors to Montego Bay (Jamaica) and Curacao (Netherlands Antilles) to estimate the benefits of maintaining and improving coral reef biodiversity (a nonuse benefit). Respondents were willing to pay \$3.24 per person for Montego Bay and \$2.08 per person for Curacao to preserve coral reef biodiversity (Spash 2000). A weakness in applying CVM in this context is whether respondents believe that coral reefs possess inherent rights or that humans have a duty to protect coral reefs. Such preferences could increase WTP by up to a factor of three (Spash 2000).

Economists are now combining various approaches to achieve a more robust valuation. Park *et al.* (2002) developed a TC-CV model of demand for trips to the Florida Keys focusing on willingness to pay to preserve the current water quality and coral reef condition. The integrated model “incorporates key factors for establishing baseline amenity values for tourist dive sites, including perceptions of reef quality and dive conditions” (Park *et al.* 2002).

2.4.5 National scale valuation of tourism

Most countries maintain National Account Systems (NAS), which provide a complete and consistent conceptual framework for measuring the economic activity of a nation. NAS are derived from a wide variety of source data including surveys, administrative and census data, and regulatory data. Most countries have a national statistical office or central bank that compiles, integrates, harmonizes, and publishes the data. NAS include a number of aggregate measures (*e.g.*, gross domestic product [GDP], disposable income, savings and investment) and other information (*e.g.*, input-output tables that show how industries interact with each other in the production process).

In the United States, the Bureau of Economic Analysis (BEA) is responsible for the national account. BEA prepares and publishes a variety of economic statistics on U.S. industries, including the annual industry accounts and the benchmark input-output accounts. U.S. industries are defined according to the North American Industry Classification System (NAICS) (BEA 2010).

The North American Industry Classification System (NAICS) was cooperatively developed by the United States, Canada, and Mexico, and it uses a production-oriented conceptual framework that groups establishments into industries based on the activity in which they are primarily engaged. Corporate entities using similar raw material inputs, similar capital equipment, and similar labor are classified in the same industry. NAICS is based on the product that is being produced (*e.g.*, accommodation services) rather than who is consuming the product (*e.g.*, a tourist or a local resident).

Tourism is not designated as an industry in NAICS. Measuring the economic contributions of tourism presents a twofold challenge:

1. the “Tourism Industry” is actually made up of parts of many industries; and,
2. tourism is traditionally measured and understood from the demand side (*i.e.*, what are visitors spending?), while industries are properly measured from the supply side (*i.e.*, what is being produced?).

To properly value tourism in a manner consistent with the other economic accounts, the World Tourism Organization and the United Nations developed the Tourism Satellite Account (TSA) standard (Sacks 2004). “Satellite accounts provide a framework linked to the central accounts and which enables attention to be focused on a certain field or aspect of economic and social life in the context of national accounts; common examples are satellite accounts for the environment, or tourism, or unpaid household work” (OECD 2010).

The BEA develops the U.S. Travel and Tourism Satellite Accounts (TTSA), based on the benchmark input-output accounts and consistent with the integrated annual industry accounts. BEA methods used to prepare the TTSA are consistent with the methods used to estimate GDP, national income, and other national economic measures. The BEA (2010) characterizes the TTSA in the following way:

The TTSA presents a detailed picture of travel and tourism activity and its role in the U.S. economy. These accounts present estimates of expenditures by tourists, or visitors, on 24 types of goods and services. The accounts also present estimates of the income generated by travel and tourism and estimates of output and employment generated by travel and tourism-related industries. The accounts are updated annually and have been expanded to provide quarterly estimates of the sales of goods and services to travelers and employment attributable to those tourism sales.

Several states are now developing their own TTSA (Alaska, Delaware, Hawaii, New Jersey, North Carolina, Rhode Island, South Carolina, and Virginia) (Aydin 2008). There has also been interest in developing a TTSA for Florida (Ayden 2008; Florida Tax Watch News 2007).

2.4.6 National scale valuation of recreational fishing

The Sustainable Fisheries Act of 1996 (PL 104-297) and the Magnuson-Stevens Fishery Conservation and Management Reauthorization Act of 2007 (PL 109-479) both amend the Fishery Conservation and Management Act of 1976 and are incorporated into 16 U.S.C. 1801. Together, they mandate collection of detailed information on marine recreational fishing. Since 1981, the National Marine Fisheries Service (NMFS) has conducted an annual survey of marine recreational fisheries covering all fishing modes (private/rental boat, party/charter boat, and shore) and including estuarine and brackish water. A variety of survey methods are used, including:

- a coastal household telephone survey (CHTS);
- a telephone survey of for-hire fishing vessel operators (FHS); and,
- a field intercept survey of angler fishing trips.

Additional information is also obtained from State or regional logbook programs and is used to supplement survey data to produce more robust catch and effort estimates (NOAA 2009).

An additional source of information on recreational fishing can be obtained from the U.S. Fish and Wildlife Service’s National Survey of Fishing and Hunting (NSFH), which collects economic information about recreational saltwater fishing at five-year intervals. The NSFH canvasses the U.S. population by telephone and conducts personal interviews with a subsample to obtain statistically reliable results at the State level.

2.4.7 Noneconomic human dimensions measures

Economic values are contingent on income and wealth and, therefore, cannot capture the full value of ecosystem services. Human values (*e.g.*, social, political, cultural, spiritual) can also be measured. Several key concepts (importance, satisfaction, and expectation) can be measured using survey techniques.

- Importance refers to how a consumer would rate various attributes of the service. Important attributes would presumably figure heavily in choices among alternatives (Alpert 1980).
- Satisfaction is the consumer’s fulfillment response received from a service (Myers & Alpert 1968). Satisfaction is influenced by the consumer’s perceptions of experienced quality, service quality, price, and other factors (Loomis et al. 2008a).
- Expectation is what the consumer believes is most likely to happen. An expectation may or may not be realistic. Expectations may significantly condition perceptions of experiences or services.

2.4.7.1 Importance-satisfaction ratings.

Martilla and James (1977) first described the concept of importance-satisfaction when considering people's demands for goods and services. Importance-satisfaction involves rating certain attributes of the service on their importance to the rater and on satisfaction with the service. Connecting importance-satisfaction ratings to a conceptual model of economic demand and value allows for interpretation of the satisfaction ratings as "indicators" of demand and value for particular ecosystem attributes/ecosystem services. Importance-satisfaction ratings are widely used to assess the demand for outdoor recreation (Guadagnolo 1985; Richardson 1987; Joppe *et al.* 2001; Tonge & Moore 2007) and have recently been used to assess demand for tourism and recreation associated with coral reefs (Johns *et al.* 2003a, 2003b; Leeworthy & Bowker 1997; Leeworthy & Wiley 1996/1997; Leeworthy *et al.* 2004).

2.4.7.2 Expectancy-discrepancy analysis.

Expectancy-discrepancy theory suggests that satisfaction is a measure of how closely a consumer's desired experiential outcome is to that consumer's perceived reality once the activity takes place (Vroom 1964; Porter & Lawler 1968). When perceptions meet or exceed expectations, consumers tend to be more satisfied (Manning 1999). Two consumers may receive the same service at the same time and place, but experience very different satisfaction levels due to their expectations. Expectancy-discrepancy analysis was used by Loomis *et al.* (2008a, 2008b, 2008c) in their valuation of recreational fishing, diving, and snorkeling in the Florida Keys.

2.4.7.3 Norm curves.

Social norms are the rules of behavior that coordinate interactions within a society or group. Normative theory involves identifying the standards that individuals and groups use to evaluate behavior and social/environmental conditions. Jackson (1965) developed a methodology — return-potential curves — to measure norms. The methodology involves using stakeholder surveys to measure respondent normative evaluations of varying levels of indicators. The personal norms of individuals can then be aggregated to test for the existence of social norms. Social norm curves (Manning *et al.* 1999) can be used to determine the level at which indicator values shift from acceptable to unacceptable conditions.

Normative theory and methods have been used to formulate standards of quality for outdoor recreation, including issues related to crowding (Shelby 1981; Heberlein *et al.* 1986; Whitaker & Shelby 1988; Patterson & Hammitt 1990; Williams *et al.* 1991; Vaske *et al.* 1986; Manning *et al.* 1996; Jacobi & Manning 1999), ecological impacts at campsites (Shelby *et al.* 1988), and wildlife management practices (Vaske & Donnelly 1988). Researchers have begun using photographs and videos to represent levels of impacts (Vaske *et al.* 1996; Manning *et al.* 1999). Visual representations can be used to effectively "tell a story" and resonate well with stakeholders.

2.4.7.4 Emergy.

Emergy analysis is another way to quantify ecosystem services. Odum (1996) defined emergy as "the available solar energy used up directly and indirectly to make a service or product". After converting energies of different kinds to the same kind of energy (*i.e.*, solar joules, sej) by multiplying each by the appropriate emergy per unit factor (sej/J), the value of an ecological or economic product or service is determined by summing the inputs. Emergy has units of solar emjoules denoting that it is an accumulation of available energy used in the past. The emergy of an ecosystem product, such as fish, can be converted to a monetary value by dividing by the emergy to dollar ratio of the economy in which the item was sold. The emergy to money ratio is the total emergy flows supporting an economy divided by the dollar flow of the GDP of the economy. Emdollars then redistribute the monetary flow of the system in proportion to the emergy flows, thereby assigning each item the portion of the total buying power in the system attributable to it based on its emergy relative to the emergy of all other products and services in the system's economy including those not counted by economic measures. Emdollar values can be compared to dollar values of the same item to determine the unvalued work of nature that was required for an item compared to the human services required for the same item.

2.5 Reflections

There is considerable variation in the way coral reef based tourism and recreation is defined, measured, and valued. Generally, existing definitions are incomplete and not rigorously developed. Linking the attributes to the ecosystem service should be a step towards standardization. While there are regional differences as to which sectors are operative and at what level, if we develop an appropriate classification framework, that variability should not matter.

We have a fundamental understanding of the factors that affect delivery of the tourism and recreation ecosystem service. We need to improve our understanding of the cumulative and synergistic effects of multiple stressors in both a spatial and temporal context. The application of landscape ecology approaches and metrics to understand coral reef ecosystem functions and to assess the impacts of a variety of management activities (both terrestrial and aquatic) may contribute significantly to our understanding.

We also need to develop, test, and refine indicators that are sufficiently sensitive to distinguish the effects of human disturbance from those of natural variability and that can serve as quantitative estimates of services provided. Ecological models can help to

illustrate and quantify relationships among environmental and ecological reef elements and can be used to investigate thresholds for reef persistence and sustainable delivery of services.

Better understanding of consumer preferences vis-à-vis the attributes would be helpful.

- The colloquial literature, including marketing materials, may reflect what people are actually looking for from their tourism experience but does not quantify its value.
- NOAA has done a fairly comprehensive analysis of consumer preferences for the Florida Keys National Marine Sanctuary, although the survey questionnaire could be refined somewhat based upon the attributes work.
- We need the same type of statistically valid information for USVI and Puerto Rico.

From a valuation perspective, the Tourism Satellite Accounts could contribute significantly towards the valuation of coral reef ecosystem services, if refined both from a scale perspective (need to have state or finer scale TSAs), and in a manner that can link them directly to reef-based tourism (need to be able to separate out tourism associated with the coral reef from nonreef-based tourism). If the consumer preference surveys are properly designed, they could help quantify the latter and fill in the gaps with nonmarket values.

Throughout this chapter, we have been using the commonly used term “tourism and recreation” as the ecosystem service. However, more precise terminology is needed to facilitate the interaction between ecological assessment and economic valuation of changes in ecosystem goods and services (Munns personal communication). One approach would be to distinguish between final and intermediate ecosystem services (Boyd & Banzhaf 2007; Daily & Matson 2008). Final ecosystem services are the components of nature, directly enjoyed, consumed, or used to yield human well-being. These are described in units upon which accounting systems and valuation can be based. Intermediate ecosystem services are the components of nature that are not directly enjoyed, consumed or used to yield human well-being, but that are important for the production of final ecosystem services. Final ecosystem services are the units upon which valuation will be based. It is also important to understand intermediate services, because their relationship to final services is of great importance in understanding, assessing, predicting and managing final services and the human well-being provided (Ringold *et al.* 2009). Clearly differentiating between final ecosystem services and intermediate ecosystem services precludes “double counting” (Boyd 2008).

Within “tourism and recreation” there is a suite of final ecosystem services. We are defining these as “opportunities”, since the ecosystem does not actually provide tourism and recreation, but rather provides the opportunity for humans to enjoy recreational experiences. We have identified the following final ecosystem services:

- Recreational fishing opportunity
- Recreational diving/snorkeling opportunity
- Recreational underwater photography opportunity
- Recreational surfing opportunity
- Opportunity to view nature and wildlife
- Opportunity to sunbath and swim at the beach
- Opportunity to collect objects (beachcombing)

Ecosystem production functions describe the relationship between intermediate ecosystem services and final ecosystem services. The intermediate ecosystem services that support tourism and recreation include:

- Production of benthic and aquatic prey for consumption by recreational fish
- Coral reef formation and maintenance
- Maintenance of water quality
- Maintenance of reef breaks
- Maintenance of biological integrity and biodiversity
- Sand production

Table 2-5 illustrates the ecosystem services (final and intermediate), as well as those features that support them. The table serves to help address the following question: *What biophysical metrics directly facilitate the integration of biophysical measurement, analysis, and models with analyses of the social and economic benefits derived from ecosystem goods and services?*

Table 2-5. Final ecosystem services and supporting features for tourism and recreation

Ecosystem Service(s)		Natural Features	Social Values	Complementary Goods & Services	Ecosystem-Derived Benefits	Potential Indicators of Final Ecosystem Service(s)
Final (FES)	Intermediate					
Tourism & Recreation						
Recreational Fishing Opportunity	Production of benthic and aquatic prey for consumption by recreational fish	Fish diversity and abundance	Desirability of fish species and size for rod-and-reel catches	Adequate infrastructure (boats, marinas, etc.)	Revenues from tourism and recreation activities	Abundance of catchable snappers and groupers
Recreational Diving/Snorkeling Opportunity	Coral reef formation & maintenance; maintenance of water clarity; production of benthic and aquatic prey for consumption by recreational fish	Coral diversity, abundance and health; fish diversity and abundance; water clarity	Desirability of coral reef for recreation based on physical appearance (color, visibility, etc.)	Access to reef, safe swimming conditions, adequate infrastructure (hotels, dive boat operators, etc.)	Revenues from tourism and recreation activities	Taxa richness, size and density of reef organisms
Recreational Underwater Photography Opportunity	Coral reef formation & maintenance; maintenance of water clarity; production of benthic and aquatic prey for consumption by recreational fish	Coral diversity, abundance and health; fish diversity and abundance; water clarity	Desirability of coral reef for recreation based on physical appearance (color, visibility, etc.)	Access to reef, safe swimming conditions, adequate infrastructure (hotels, dive boat operators, etc.)	Revenues from tourism and recreation activities	Taxa richness, size and density of reef organisms
Recreational Surfing Opportunity	Reef breaks	3-D reef structure	Desirability based on wave size and speed	Access to reef, adequate infrastructure (hotels, board shops, etc.)	Revenues from tourism and recreation activities	3-D structure and proximity to deep ocean
Opportunity to View Nature and Wildlife	Biological integrity	Biodiversity (birds, marine mammals, turtles)	Desirability of species (rarity, size)	Access to reef and adequate infrastructure (boats, tour guides)	Revenues from tourism and recreation activities	Taxa richness, presence of specific species
Opportunity to Sunbath and Swim at the Beach	Water quality, shoreline protection, sand production	White coralline sands; calm waters	Desirability of coralline sand beach for sunbathing (size, cleanliness, appearance)	Access to beach	Revenues from tourism and recreation activities	Areal extent of beach, color of beach, water temperature, days of sunshine, beach trash
Opportunity to Collect Objects (Beachcombing)	Water quality	Wide sandy beaches, biodiversity, occasional storms	Desirability of walking on beach and of finding beautiful & unusual objects	Access to beach	Revenues from tourism and recreation activities	Areal extent of beach, frequency of storms, proximity of reef, taxa richness of invertebrates

Definitions (proposed by the Ecosystem Services Research Program and currently under discussion by the Program)

- **Final Ecosystem Service** – Output of ecological functions or processes that directly contributes to social welfare or has the potential to do so in the future (broadly based on Boyd & Banzhaf [2007]).
- **Intermediate Ecosystem Service** - Output of ecological functions or processes that indirectly contributes to social welfare or has the potential to do so in the future.
- **Natural Features** – The biological, chemical, and physical attributes of an ecosystem or environment.
- **Social Values** – The social attributes that influence economic demand for an ecosystem service.
- **Complementary Goods & Services** - Inputs (usually built infrastructure or location characteristics) that allow a good or service to be used by complementing the ecological condition. For example, complementary goods and services that allow the presence of fishable fish to become an opportunity for recreational fishing will include aspects of site accessibility, such as road access, available parking and the presence of a fishing pier, all of which make fishing at the site possible and enhance enjoyment of the activity.
- **Ecosystem-Derived Benefits** - The contribution to social welfare of ecosystem goods and services. In the ESRP, the term applies specifically to net improvements in social welfare that result from changes in the quantity or quality of ecosystem goods and services attributable to policy or environmental decisions.
- **Indicator of Final Ecosystem Service** – Biophysical feature, quantity, or quality that requires little further translation to make clear its relevance to human well-being (*i.e.*, “public-friendly” measurement)

2.6 Bibliography

- Adamowicz W, Boxall P, Louvierre J, Swait J and Williams M. 1998. Stated Preference Methods for Valuing Environmental Amenities. In: Bateman I and Willis K (eds). *Valuing Environmental Preferences: Theory and Practice of the Contingent Valuation Method in the US, EU and Developing Countries*. London: Oxford University Press, pp. 460-479.
- Adamowicz W, Louvierre J and Swait J. 1998. *Introduction to Attribute-Based Stated Choice Methods*. Report submitted to Research Valuation Branch, Damage Assessment Center, National Oceanic and Atmospheric Administration (NOAA), US Department of Commerce, Silver Spring, MD.
- Ahmed M, Umali GM, Ching CK, Rull MF and Garcia MC. 2007. Valuing recreational and conservation benefits of coral reefs - The case of Bolinao, Philippines. *Ocean & Coastal Management*, **50**:103-118.
- Allen T and Southwick R. 2008. *Sportfishing in America: An Economic Engine and Conservation Powerhouse*. American Sportfishing Association (ASA).
- Alpert MI. 1980. Unresolved Issues in Identification of Determinant Attributes. *Advances in Consumer Research*, **7**:83-88.
- American Sportfishing Association (ASA). 2010. American Sportfishing Association – Leading the Way for Fishing’s Future. <<http://www.asafishing.org/>>
- Andersson JEC. 2007. The recreational cost of coral bleaching - A stated and revealed preference study of international tourists. *Biological Economics*, **62**:704-715.
- Aydin N. 2008. The Need for Tourism Satellite Account: A Florida Case Study: More Basic Estimating Methods Reach Only the Tip of the Iceberg. *Applied Research in Economic Development*, **5**(3):37-47.
- Baker CP. 2007. Surf’s Up. In: *Costa Rica, 6th Edition*. Moon Handbooks.
- Barnes R. 1987. *Invertebrate Zoology*. Fort Worth: Harcourt Brace Jovanovich College Publishers, 783 pp.
- Barnes R and Hughes R. 1999. *An Introduction to Marine Ecology*. Oxford (UK): Blackwell Science Ltd. pp. 131-133.
- Barton DN. 1994. *Economic Factors and Valuation of Tropical Coastal Resources*. Bergen (Norway): University of Bergen, Center for Studies of Environment and Resources, SMR-Report 14/94, 128 pp.
- Basiron MN. 1997. Marine Tourism Industry – Trends and Prospects. Paper presented at the National Seminar on the Development of Marine Tourism Industry in South East Asia at Langkawi (25-28 September 1997).
- Beharry-Borg N and Scarpa R. 2010. Valuing quality changes in Caribbean coastal waters for heterogeneous beach visitors. *Ecological Economics*, **69**:1124-1139.
- van Beukering PJH & Cesar HSJ. 2004. Ecological economic modeling of coral reefs: Evaluating tourist overuse at Hanauma Bay and Algae Blooms at the Kihei Coast, Hawai’i. *Pacific Science*, **58**(2):243-260.
- van Beukering PJH, Sarkis S, McKenzie E, Hess S, Brander L, Roelfsema M, Looijenstijn-van der Putten L & Bervoets T. 2010. *Total Economic Value of Bermuda’s Coral Reefs. Valuation of Ecosystem Services*. van Beukering Consulting, Amsterdam.
- Bhat MG. 2003. Application of non-market valuation to the Florida Keys marine reserve management. *Journal of Environmental Management*, **67**:315-325.
- Boyd J. 2008. *Counting Nonmarket, Ecological Public Goods*. Resources for the Future, Washington, DC.
- Boyd J and Banzhaf S. 2007. What are ecosystem services? The need for standardized environmental accounting units. *Ecological Economics*, **63**:616-626.
- Bradley P, Davis W, Fisher W, Bell H, Chan V, LoBue C and Wiltse W. 2008. Biological Criteria for Protection of U.S. Coral Reefs. *Proceedings of the 11th International Coral Reef Symposium*, Ft. Lauderdale, Florida, 7-11 July 2008.
- Brown BE. 1988. Assessing environmental impacts on coral reefs. In: *Proceedings of the 6th International Coral Reef Symposium*, **1**:71-80.
- Brown BE. 1997. Coral bleaching: causes and consequences. *Coral Reefs*, **16**:S129-S138.
- Bruno J. 2008. Coral reefs and climate change. In: Cleveland CJ (ed). *Encyclopedia of Earth*. Washington, DC: Environmental Information Coalition, National Council for Science and the Environment. [First published in *The Encyclopedia of Earth*, 2007.12.19; Last revised 2008.08.26.] <http://www.eoearth.org/article/Coral_reefs_and_climate_change> Accessed 2010.07.11.
- Bryant D, Burke L, McManus J and Spalding M. 1998. *Reefs at Risk: A Map Based Indicator of Threats to the World’s Coral Reefs*. Washington, DC: World Resources Institute.
- Buckley R. 2002. Surf Tourism and Sustainable Development in Indo-Pacific Islands. I. The Industry and the Islands. *Journal of Sustainable Tourism*, **10**(5):405-424.
- Bureau of Economic Analysis (BEA) US Department of Commerce. 2010. *Industry Economic Accounts*. <<http://www.bea.gov>>
- Burke L, Greenhalgh S, Prager D and Cooper E. 2008. *Coastal Capital – Economic Valuation of Coral Reefs in Tobago and St. Lucia*. Washington, DC: World Resources Institute.

- Cesar HSJ. 2000. *Impacts of the 1998 Coral Bleaching Event on Tourism in El Nido, Philippines*. U.S. Department of State, East Asia and Pacific Environmental Initiative (US-EAP-EI)/Coastal Resources Center, University of Rhode Island, Narragansett, RI.
- Cesar HSJ. 2000. Coral Reefs: Their Functions, Threats and Economic Value. In: Cesar HSJ (ed). *Collected Essays on the Economics of Coral Reefs*. Kalmar (Sweden): Kalmar University, Department for Biology and Environmental Sciences/CORDIO.
- Cesar HSJ. 2002. *The biodiversity benefits of coral reef ecosystems: Values and markets*. Paris: Organisation for Economic Co-operation and Development, Working Party on Global and Structural Policies, Working Group on Economic Aspects of Biodiversity. <<http://www.cbd.int/doc/external/oecd/oecd-coral-reefs-2002-en.pdf>>
- Cesar HSJ, van Beukering PJH, Payet R & Grandourt E. 2004. *Evaluation of the socio-economic impacts of marine ecosystem degradation in the Seychelles*. Cesar Environmental Economics Consulting, Arnhem (The Netherlands).
- Christiernsson A. 2003. *An economic valuation of the coral reefs at Phi Phi Island*. Luleå University of Technology. Masters thesis.
- Cisneros-Montemayor AM, Sumaila UR, Kaschner K and Pauly D. 2010. *The Global Potential for Whale Watching*. Vancouver: University of British Columbia, Fisheries Centre, Working paper # 2010-05.
- Cooper E, Burke L and Bood N. 2009. *Coastal Capital: Belize, The Economic Contribution of Belize's Coral Reefs and Mangroves*. WRI Working Paper. Washington DC: World Resources Institute, 53 pp. <<http://www.wri.org/publications>>
- Costanza R, D'Arge R, de Groot R, Farber S, Grasso M, Hannon B, Limburg K, Naeem S, O'Neill R, Paruelo J, Riaslein RG, Sutton P and van den Belt M. 1997. The value of the world's ecosystem services and natural capital. *Nature*, **387**:253-260.
- Courtney LA, Fisher WS, Raimondo S, Oliver LM and Davis WP. 2007. Estimating 3-dimensional colony surface area of field corals. *Journal of Experimental Marine Biology and Ecology*, **351**(1-2):234-242.
- Crossland CJ, Hatcher BG and Smith SV. 1991. Role of coral reefs in global ocean production. *Coral Reefs*, **10**(2):55-64.
- Daily GC and Matson PA. 2008. Ecosystem services: from theory to implementation. *Proceedings of the National Academy of Sciences (PNAS)*, **105**:9455-9456.
- Davis D & Tisdell C. 1996. Economic management of recreational scuba diving and the environment. *Journal of Environmental Management*, **48**:229-248.
- Dixon JA, Scura LF & van't Hof T. 2000. *An economic and ecological analysis of the Bonaire Marine Park*. <<http://www.nacri.org/greylit/dixon-et-al-2000-econanalysisbonaire.pdf>>
- Done TJ. 1997. Decadal changes in reef-building communities: implications for reef growth and monitoring programs. In: *Proceedings of the 8th International Coral Reef Symposium*, **1**:411-416.
- Done TJ. 1999. Coral community adaptability to environmental change at the scales of regions, reefs, and reef zones. *American Zoologist*, **39**:66-79.
- Done TJ, Ogden JC and Wiebe WJ. 1996. Biodiversity and ecosystem function of coral reefs. In: Mooney HA, Cushman JH, Medina E, Sala OE and Schulze ED (eds). *Functional Roles of Biodiversity: a Global Perspective*. Chichester (UK): Wiley Press, pp. 393-429.
- Fedler AJ & Hayes C. 2008. *Economic impact of recreational fishing for bonefish, permit and tarpon in Belize for 2007*. Gainesville (FL): Human Dimensions Consulting and Friends of Turneffe Atoll.
- Fisher WS. 2007. Stony Coral Rapid Bioassessment Protocol. U.S. Environmental Protection Agency. EPA/600/R-06/167.
- Fisher WS, Davis WP, Quarles RL, Patrick J, Campbell JG, Harris PS, Hemmer BL and Parsons M. 2007. Characterizing Coral Condition Using Estimates of Three-dimensional Colony Surface Area. *Environmental Monitoring and Assessment*, **125**:347-360.
- Fisher WS, Fore LS, Hutchins A, Quarles RL, Campbell JG, LoBue C and Davis WS. 2008. Evaluation of stony coral indicators for coral reef management. *Marine Pollution Bulletin*, **56**:1737-1745.
- Fitt WK, Spencer HJ, Halas J, White MW and Porter JW. 1993. Recovery of *Montastrea annularis* in the Florida Keys after the 1987 Caribbean "bleaching event". *Coral Reefs*, **12**:57-64.
- Florida Tax Watch News. 2007. Tourism's Impact on Florida May be Greater than We Know: Tourism Satellite Accounts Can Provide the Answer. <www.FloridaTxWatch.org>
- Freeland S. 2010. The History of Scuba Diving. <<http://ezinearticles.com/?The-History-of-Scuba-Diving&id=315991>>
- Gilbert M and Alary D. 2010. Photo 101: Part 1. Of underwater photography history and prerequisites. <http://divemag.com/divermag/archives/dec96/gilbert1_dec96.html>
- Goeldner CR and Ritchie JRB. 2009. *Tourism: Principles, Practices, Philosophies*, 11th Edition. Hoboken (NJ): John Wiley & Sons, Inc., 648 pp.
- Goreau TJ and MacFarlane AH. 1990. Reduced growth rate of *Montastrea annularis* following the 1987-1988 coral bleaching event. *Coral Reefs*, **8**:211-215.
- Graham NAJ, Wilson SK, Jennings S, Polunin NVC, Bijoux JP and Robinson J. 2006. Dynamic fragility of oceanic coral reef ecosystems. *Proceedings of the National Academy of Science (PNAS)*, **103**(22):8425-8429.

- Grimsditch GD and Salm RV. 2006. *Coral Reef Resilience and Resistance to Bleaching*. Gland (Switzerland): International Union for the Conservation of Nature (IUCN), 52 pp.
- Guadagnolo F. 1985. The importance-performance analysis: an evaluation and marketing tool. *Journal of Park and Recreation Administration*, **3**(2):13-22.
- Hajkowicz S. 2006. Multi-attributed environmental index construction. *Ecological Economics*, **57**:122-139.
- Hall CM. 2001. Trends in ocean and coastal tourism: the end of the last frontier? *Ocean & Coastal Management*, **44**:601-618.
- Heberlein TA, Alfano GE and Ervin LH. 1986. Using a social carrying capacity model to estimate the effects of marina development at the Apostle Islands National Lakeshore. *Leisure Sciences*, **8**(3):257-274.
- Hoegh-Guldberg O. 1999. Climate change, coral bleaching and the future of the world's coral reefs. *Marine Freshwater Research*, **50**(8):839-866.
- Hoegh-Guldberg O and Smith GJ. 1989. The effect of sudden changes in temperature, light and salinity on the population density and export of zooxanthellæ from the reef corals *Stylophora pistillata* Esper. and *Seriatopora hystrix* Dana. *Journal of Experimental Marine Biology and Ecology*, **129**:279-303.
- Humann P and Deloach N. 2002. *Reef Coral Identification: Florida Caribbean Bahamas*. Jacksonville (FL): New World Publications,.
- Inglis GJ, Johnson VI and Ponte F. 1999. Crowding norms in marine settings: a case study of snorkeling on the Great Barrier Reef. *Environmental Management*, **24**:369-381.
- Jackson J. 1965. *Standard Characteristics of Norms*. *Current Studies in Social Psychology*. New York: Holt, Rinehart and Winston, pp 301-309.
- Jacobi C and Manning R. 1997. *Applying the Visitor Experience and Resource Protection Process to Acadia National Park Carriage Roads: A Summary of Research and Decision-Making*. U.S. National Park Service Technical Report NPS/NESO-RNR/NRTR/98-5.
- Jameson SC, Erdmann MV, Gibson Jr. GR and Potts KW. 1998. Development of biological criteria for coral reef ecosystem assessment. *Atoll Research Bulletin*, **450**:1-102.
- Johns GM, Leeworthy VR, Bell FW and Bonn MA. 2003a. *Socioeconomic study of reefs in southeast Florida*. Final Report October 19, 2001, as revised April 18, 2003, from Hazen and Sawyer to Broward County, Palm Beach County, Miami-Dade County, Monroe County, Florida Fish and Wildlife Conservation Commission, and National Oceanic and Atmospheric Administration. <<http://marineeconomics.noaa.gov/Reefs/02-01.pdf>>
- Johns GM, Leeworthy VR, Bell FW and Bonn MA. 2003b. *Socioeconomic study of reefs in southeast Florida. Technical Appendix to Final Report*. October 19, 2001, as revised April 18, 2003, from Hazen and Sawyer to Broward County, Palm Beach County, Miami-Dade County, Monroe County, Florida Fish and Wildlife Conservation Commission, and National Oceanic and Atmospheric Administration. <<http://marineeconomics.noaa.gov/Reefs/PDFs/Tech/TechApp.pdf>>
- Jones GP and Syms C. 1998. Disturbance, habitat structure and the ecology of fishes on coral reefs. *Australian Journal of Ecology*, **23**:287-297.
- Joppe M, Martin DW and Waalen J. 2001. Toronto's Image As a Destination: A Comparative Importance-Satisfaction Analysis by Origin of Visitor. *Journal of Travel Research*, **39**:252-260.
- Krämer A. 1994. *The Samoa Islands Vol 1*. Honolulu: University of Hawaii Press.
- Lalli CM and Parsons T. 1995. *Biological Oceanography: An Introduction*. Oxford: Butterworth-Heinemann Ltd. pp. 220-233.
- LaMotte R. 2004. *Pure Sea Glass*. Chestertown (MD): Chesapeake Sea Glass Publishing.
- Leeworthy VR. 2002. Economic impact of tourist and resident uses of coastal resources in the Florida Keys: Survey methods and impact assessment methodology. In: Letson D and Milon JW (eds), *Florida Coastal Environmental Resources*, Florida Sea Grant SGR 124.
- Leeworthy VR and Bowker JM. 1997. *Nonmarket economic user values of the Florida Keys/Key West*. Silver Spring (MD): National Oceanic and Atmospheric Administration and Athens (GA): U.S. Forest Service. <<http://marineeconomics.noaa.gov/SocmonFK/publications/97-30.pdf>>
- Leeworthy VR and Wiley PC. 1996. *Importance and satisfaction ratings by recreating visitors to the Florida Keys/Key West*. Silver Spring (MD): National Oceanic and Atmospheric Administration, 23 pp. <<http://marineeconomics.noaa.gov/SocmonFK/publications/96-27.pdf>>
- Leeworthy VR and Wiley PC. 1997. *A socioeconomic analysis of the recreation activities of Monroe County residents in the Florida Keys/Key West*. Silver Spring (MD): National Oceanic and Atmospheric Administration. <<http://marineeconomics.noaa.gov/SocmonFK/publications/97-18.pdf>>
- Leeworthy VR and Wiley PC. 2001. *National Survey on Recreation and the Environment 2000. Current Participation Patterns in Marine Recreation*. Silver Spring (MD): National Oceanic and Atmospheric Administration.

- Leeworthy VR, Wiley PC and Hospital JD. 2004. *Importance-Satisfaction Ratings Five-year Comparison, SPA & ER Use, and Socioeconomic and Ecological Monitoring Comparison of Results 1995-96 to 2000-01*. Silver Spring (MD): National Oceanic and Atmospheric Administration, 67 pp.
- Leujak W and Ormond RFG. 2007. Visitor Perceptions and the Shifting Social Carrying Capacity of South Sinai's Coral Reefs. *Environmental Management*, **39**(4):472-489.
- Levinton JS. 1995. *Marine Biology: Function, Biodiversity, Ecology*. New York: Oxford University Press, pp. 306-319.
- Loomis DK, Anderson LE, Hawkins C and Paterson SK. 2008a. *Understanding Coral Reef Use: Recreational Fishing in the Florida Keys by Residents and Non-Residents During 2006-2007*. Amherst: University of Massachusetts, Amherst. HDMCE Analysis Series 2008-1-001.
- Loomis DK, Anderson LE, Hawkins C and Paterson SK. 2008b. *Understanding Coral Reef Use: Snorkeling in the Florida Keys by Residents and Non-Residents During 2006-2007*. Amherst: University of Massachusetts, Amherst. HDMCE Analysis Series 2008-1-002.
- Loomis DK, Anderson LE, Hawkins C and Paterson SK. 2008c. *Understanding Coral Reef Use: SCUBA Diving in the Florida Keys by Residents and Non-Residents During 2006-2007*. Amherst: University of Massachusetts, Amherst. HDMCE Analysis Series 2008-1-003.
- Loya Y. 1972. Community structure and species diversity of hermatypic corals at Eilat, Red Sea. *Marine Biology*, **13**(2):100-123.
- Lybolt MJ. 2003. Count or Pointcount: Is Percent Octocoral Cover an Adequate Proxy for Octocoral Abundance? Masters Thesis. Department of Biological Oceanography, College of Marine Science, University of South Florida.
- Lynch TP, Melling L, Hamilton R, Macready A & Feray S. 2004. Conflict and impacts of divers and anglers in a marine park. *Environmental Management*, **33**(2):196-211.
- Manning R, Lawson S and Frymier L. 1999b. Navigating the confluence of two streams of social research: Contingent valuation and normative standards. *Human Ecology Review*, **6**(1):35-48.
- Manning RE, Line D and Hof M. 1996. Social carrying capacity of natural areas: Theory and application in the national parks. *National Areas Journal*, **16**(2):118-127.
- Manning RE. 1999a. *Studies in outdoor recreation: Search and research for satisfaction* (2nd ed.). Corvallis: Oregon State University Press.
- Marcus B. 2010. *From Polynesia, with Love – The History of Surfing from Captain Cook to the Present*. <<http://www.surfingforlife.com/history.html>>
- Martilla JA, James JC. 1977. Importance-performance analysis. *Journal of Marketing*, **41**(1):77-79.
- Martin L. 1997. *Scuba Diving Explained: Questions and Answers on Physiology and Medical Aspects of Scuba Diving – A Brief History of Diving, From Antiquity to the Present*. Lakeside Press. <<http://www.lakesidepress.com/>>
- McField M and Richards Kramer P. 2007. *Healthy Reefs for Healthy People: A Guide to Indicators of Reef Health and Social Well-being in the Mesoamerican Reef Region*. With contributions by M Gorrez and M McPherson. Washington, DC: Smithsonian Institution. 208 pp. <http://www.toniparras.com/stories/Healthy_Reef_24_complete-1.pdf>
- McRee D. 2009. Beachcombing and Shelling. VisitFlorida.com. <<http://www.visitflorida.com/articles/beach-combing-and-shelling>>
- Menza C, Ault J, Beets J, Bohnsack J, Caldwell C, Christensen J, Friedlander A, Jeffrey C, Kendall M, Luo J, Monaco M, Smith S and Woody K. 2006. *A Guide to Monitoring Reef Fish in the National Park Service's South Florida / Caribbean Network*. NOAA Technical Memorandum NOS NCCOS 39, 169pp.
- Merriam-Webster. 2010. Dictionary. <<http://www.merriam-webster.com/dictionary/recreation>>
- Moberg F and Folke C. 1999. Ecological goods and services of coral reef ecosystems. *Ecological Economics*, **29**:215-233.
- Moreno A and Amelung B. 2009. Climate Change and Coastal & Marine Tourism: Review and Analysis. *Journal of Coastal Research*, **56**:1140-1144.
- Mulhall M. 2007. Saving rainforests of the sea: An analysis of international efforts to conserve coral reefs. *Duke Environmental Law and Policy Forum*, **19**:321-351.
- Mumby PJ and Steneck RS. 2008. Coral reef management and conservation in light of rapidly evolving ecological paradigms. *Trends in Ecology & Evolution*, **23**(10):555-563.
- Mumby PJ, Broad K, Brumbaugh DR, Dahlgren CP, Harborne AR, Hastings A, Holmes KE, Kappel CV, Micheli F and Sanchirico JN. 2008. Coral Reef Habitats as Surrogates of Species, Ecological Functions, and Ecosystem Services. *Conservation Biology*, **22**:941-951.
- Mumby PJ, Edwards AJ, Arias-Gonzalez JE, Lindemann KC, Blackwell PG, Gall A, Gorczynska MI, Harborne AR, Pescod CL, Renken H, Wabnitz CCC and Llewellyn G. 2004. Mangroves enhance the biomass of coral reef fish communities in the Caribbean. *Nature*, **427**:533-536.

- Muscatine L. 1980. Productivity of zooxanthellae. In: Falkowski PG (ed). *Primary Productivity in the Sea*. New York: Plenum Press, pp. 381-402.
- Muscatine L. 1990. The role of symbiotic algae in carbon and energy flux in reef corals. In: Dubinsky Z (ed). *Coral Reefs*. Amsterdam: Elsevier. Ecosystems of the World 25, pp. 75-87.
- Myers JH and Alpert MI. Determinant Buying Attitudes: Meaning and Measurement. *Journal of Marketing*, **32**:13-20.
- National Geographic. 2010. Milestones in Underwater Photography. <http://photography.nationalgeographic.com/photography/photos/milestones-underwater-photography/#hogfish_1428_600x450.jpg>
- National Oceanic and Atmospheric Administration (NOAA). 1997. The Wave of the Future: Surfing and Coral Reef Conservation. NOAA's Reporter's Coral Reef Tip Sheet, May 26, 1997 – Week 21.
- National Oceanic and Atmospheric Administration (NOAA), National Marine Fisheries Service. 2009. *Fisheries of the United States 2008*. Silver Spring (MD). <<http://www.st.nmfs.noaa.gov/st1/publications.html>>
- Odum EP. 1997. *Ecology*. Sinauer Associates Inc.
- Orams M. 1999. *Marine Tourism – Development, Impacts, and Management*. New York: Routledge, 136 pp.
- Organisation for Economic Co-operation and Development (OECD). 2010. *Glossary of Statistical Terms*. <<http://stats.oecd.org/glossary/detail.asp?ID=2385>>
- Park T, Bowker JM and Leeworthy VR. 2002. Valuing snorkeling visits to the Florida Keys with stated and revealed preference models. *Journal of Environmental Management*, **65**:301-312.
- Parsons GR & Thur SM. 2007. Valuing changes in the quality of coral reef ecosystems: a stated preference study of scuba diving in the Bonaire National Marine Park. Working Paper Series, Department of Economics, Alfred Lerner College of Business & Economics, University of Delaware.
- Patterson ME and Hammitt WE. 1990. Backcountry encounter norms, actual reported encounters, and their relationship to wilderness solitude. *Journal of Leisure Research*, **22**(3):259-275.
- Pendleton LH. 1994. Environmental quality and recreation demand on a Caribbean coral reef. *Coastal Management*, **22**:399-404.
- Pendleton LH. 1995. Valuing coral reef protection. *Ocean and Coastal Management*, **26**:119-131
- Pernetta JC. 1992. Impacts of climate change and sea level rise on small island states. *Global Environmental Change*, **2**:19-31.
- Porter JW, Fitt WK, Spero HJ, Rogers CS and White MW. 1989. Bleaching in reef corals: Physiological and stable isotopic responses. *Proceedings of the National Academy of Sciences*, **86**:9342-9346.
- Porter L and Lawler E. 1968. *Managerial Attitudes and Performance*. Homewood (IL): Dorsey Press.
- Princeton WorldNet Glossary. 2010a. Residents. <<http://wordnetweb.princeton.edu/perl/webwn?s=resident>>
- Princeton WorldNet Glossary. 2010b. Surfing. <<http://wordnetweb.princeton.edu/perl/webwn?s=surfing>>
- Professional Association of Dive Instructors (PADI). 2011. Worldwide Corporate Statistics 2010. <<http://www.padi.com/padi/en/footerlinks/padistatistics.aspx>>
- Public Law (PL) 104-297. 1996. *The Sustainable Fisheries Act*.
- Public Law (PL) 109-479. 2007. *Magnuson-Stevens Fishery Conservation and Management Reauthorization Act*.
- Pugliese R. 1998. *Final Habitat Plan For The South Atlantic Region*. Charleston (SC): South Atlantic Fishery Management Council.
- Reaka-Kudla ML. 1996. The global diversity of coral reefs: A comparison with rain forests. In: Reaka-Kudla, ML Wilson DE and Wilson EO (eds). *Biodiversity II: Understanding and Protecting our Natural Resources*. Washington, DC: Joseph Henry Press, Chapter 7, pp. 83-108.
- Richardson SL. 1987. An importance-performance approach to evaluating communication effectiveness. *Journal of Park and Recreation Administration*, **5**(4):71-83.
- Ringold P, Boyd J, Landers D and Weber M. 2009. *Report from the Workshop on Indicators of Final Ecosystem Services for Streams*. U.S. Environmental Protection Agency, EPA/600/R-09/137.
- Ritterbush D. 2010. Dr. Beachcomb. <<http://www.drbeachcomb.com/profile.html>>
- Ritterbush SD. 2008. *A Beachcomber's Odyssey, Vol. I: Treasures from a Collected Past*. Ritz Dotter Publishers.
- Robinson C and Robinson D. 1995. *The Art of Shelling*. Old Squan Village Publishing, 184 pp.
- Sacks A. 2004. The Alaska Tourism Satellite Account: A Comprehensive Analysis of the Economic Contribution of Travel & Tourism. Global Insight.
- Sale PF. 1991. *The Ecology of Fishes on Coral Reefs*. San Diego: Academic Press, 754 pp.
- Sale PF, Jacob P and Kritzer JP. 2008. Connectivity: What it is, how it is measured, and why it is important for management of reef fishes. In: Grober-Dunsmore R and Keller BD (eds). *Caribbean connectivity: Implications for marine protected area*

- management*. Proceedings of a Special Symposium, 9-11 November 2006, 59th Annual Meeting of the Gulf and Caribbean Fisheries Institute, Belize City, Belize. Marine Sanctuaries Conservation Series ONMS-08-07. Silver Spring (MD): U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Office of National Marine Sanctuaries, pp. 16-30.
- Salm RV and West JM. 2003. Enhancing coral reef survival in a changing climate: Additional marine protected area guidelines. In: The Nature Conservancy and Partners (TNC) (2004) *R2- Reef resilience: Building resilience into coral reef conservation; Additional tools for managers: Coral bleaching*. Volume 2.0. CD ROM Toolkit. Honolulu: The Nature Conservancy.
- Samonte-Tan G, White AT, Tercero MA, Diviva J, Tabara E & Caballes C. 2007. Economic Valuation of Coastal and Marine Resources: Bohol Marine Triangle, Philippines.
<http://www.oneocean.org/download/db_files/SamonteTan_White%202007_Economic%20valuation%20coastal.pdf>
- Sánchez F. 2010. Under Secretary of Commerce for International Trade Francisco Sánchez Remarks to the Washington International Trade Association. 2010.05.19. <<http://trade.gov/press/speeches/2010/sanchez-060210.asp>>
- Sano M. 2004. Short-term effects of a mass coral bleaching event on a reef fish assemblage at Iriomote Island, Japan. *Fisheries Science*, **70**:41-46. doi: 10.1111/j.1444-2906.2003.00768.x
- Santavy DL, Courtney LA, Fisher WS, Quarles RL and Jordan SJ. In review. *Estimating the surface area of marine gorgonians and sponges in the field*.
- Sebens KP. 1994 Biodiversity of Coral Reefs: What are we losing and why? *American Zoology*, **34**:115-133.
- Shelby B. 1981. Encounter norms in backcountry settings: Studies of three rivers. *Journal of Leisure Research*, **13**:129-138.
- Shelby B, Vaske JJ and Harris R. 1988. User standards for ecological impacts at wilderness campsites. *Journal of Leisure Research*, **20**(3):245-256.
- Silmalis L. 2007. Surf break names recognised. *The Daily Telegraph*, April 08, 2007.
- Snorkeling. 2010. Snorkeling History. <<http://www.snorkeling.info/snorkeling-history/index.html>>
- Sorice MG, Oh C & Ditton R. 2007. Managing scuba divers to meet ecological goals for coral reef conservation. *Ambio*, **36**(4):316-322.
- Spash CL. 2000. Assessing the Benefits of Improving Coral Reef Biodiversity: The Contingent Valuation Method, In: Cesar HSJ (ed), *Collected Essays on the Economics of Coral Reefs*. Kalmar (Sweden): Kalmar University, Department for Biology and Environmental Sciences/CORDIO, 242 pp.
- Spurgeon J, Roxburgh T, O’Gorman S, Lindley R, Ramsey D & Polinin N. 2004. Economic valuation of coral reefs and adjacent habitats in American Samoa. Final Report. JacobsGIBB Ltd., 157 pp.
- Sumich JL. 1996. *An Introduction to the Biology of Marine Life; Sixth Edition*. Dubuque (IA): Wm. C. Brown, pp. 255-269.
- Sutton M. 1983. Relationship between reef fishes and coral reefs. In: *Perspectives on coral reefs*, Hatcher BG, Barnes DJ and Clouston B. (eds). Townsville (Australia): Australian Institution of Marine Science, pp. 248-252.
- Szmant AM and Gassman NJ. 1990. The effects of prolonged “bleaching”, on the tissue biomass and reproduction of the reef coral *Montastrea annularis*. *Coral Reefs*, **8**:217-224.
- Tapswan S & Asafu-Adjaye J. 2008. Estimating the economic benefit of scuba diving in the Similan Islands, Thailand. *Coastal Management*, **36**(5):431-442.
- The Surfing Site. 2010. Surfing 101. <<http://www.thesurfingsite.com/Surf-Conditions.html>>
- Tonge J and Moore SA. 2007. Importance-satisfaction analysis for marine-park hinterlands: A Western Australian case study. *Tourism Management*, **28**(3):768-776.
- United Nations Environment Program – World Conservation Monitoring Center (UNEP-WCMC). 2006. *In the front line: shoreline protection and other ecosystem services from mangroves and coral reefs*. Cambridge (UK): UNEP-WCMC, 33 pp.
- United Nations Environment Program – Global Programme of Action for the Protection of the Marine Environment from Land-Based Activities (UNEP/GPA). 2003. *Diagnosis of the Erosion Processes in the Caribbean Sandy Beaches*. Report prepared by the Environmental Agency, Ministry of Science, Technology and Environment, Government of Cuba. March.
- United Nations World Tourism Organization (UNWTO). 1995. *Collection of Tourism Expenditure Statistics*. Technical Manual No. 2, p. 14.
- United Nations World Tourism Organization (UNWTO). 2009. *Tourism Highlights, 2009 Edition*.
- United Nations World Trade Organization (UNWTO). 2010. Tourism and the world economy.
<<http://www.unwto.org/facts/eng/economy.htm>> Accessed 2010.06.25.
- U.S. Fish & Wildlife Service. 2006. Birding in the United States: A Demographic and Economic Analysis. Addendum to the 2006 National Survey of Fishing, Hunting, and Wildlife-Associated Recreation. Report 2006-4.
- U.S. Travel Association. Economics of Travel and Tourism. Updated 2010.05.06.
<<http://www.ustravel.org/sites/default/files/page/2009/09/EconomicImpactofTravelandTourism2009.pdf>>

- Uyarra MC, Cote IM, Gill JA, Tinch RRT, Viner D and Watkinson AR. 2005. Island-specific preferences of tourists for environmental features: Implications of climate change for tourism-dependent states. *Environmental Conservation*, **32**(1):11-19.
- Vaske J, Donnelly M and Petruzzi J. 1996. Country of origin, encounter norms, and crowding in a frontcountry setting. *Leisure Sciences*, **18**:161-176.
- Vaske JJ and Donnelly MP. 1988. Normative evaluations of wildlife management. Paper presented at the Annual Congress of the National Recreation and Park Association. Indianapolis, IN.
- Vaske JJ, Graefe AR, Shelby B and Heberlein T. 1986. Backcountry encounter norms: Theory, method and empirical evidence. *Journal of Leisure Research*, **18**(3):137-153.
- Vroom V. 1964. *Work and Motivation*. New York: John Wiley & Sons.
- Warren-Rhodes K, Sadovy Y and Cesar HSJ. 2003. Marine ecosystem appropriation in the Indo-Pacific: A case study of the live reef fish food trade. *Ambio*, **32**:481-488.
- Westmacott S, Cesar HSJ, Pet-Soede L & Lindén O. 2000. Coral Bleaching on the Indian Ocean: Socioeconomic Assessment of Effects, In: Cesar HSJ (ed) *Collected Essays on the Economics of Coral Reefs*. Kalmar (Sweden): Kalmar University, Department for Biology and Environmental Sciences/CORDIO, pp. 94-106.
- Whittaker D. and Shelby B. 1988. Types of norms for recreation impacts: Extending the social norm concept. *Journal of Leisure Research*, **20**(4):261-273.
- Wielgus J. 2004. General protocol for calculating the basis of legal claims for damages caused by vessel groundings in Eilat. Israel Nature and National Parks Protection Authority, Jerusalem. Available in ReefBase.
- Wielgus J, Chadwick-Furman NE, Zeitouni N & Shechter M. 2003. Effects of coral reef attribute damage on recreational welfare. *Marine Resources Economics*, **18**:225-237.
- Wikipedia. 2010a. Birdwatching. <<http://en.wikipedia.org/wiki/Birdwatching>>
- Wikipedia. 2010b. Beachcombing. <<http://en.wikipedia.org/wiki/Beachcombing>>
- Wilkinson CR. 2002. *Status of Coral Reefs of the World: 2002*. Townsville (Australia): Australian Institution of Marine Science.
- Wilkinson CR. 2004. *Status of Coral Reefs of the World: 2004 Volume 1*. Townsville, Australia: Australian Institution of Marine Science.
- Wilkinson CR, Lindén O, Cesar HSJ, Hodgson G, Rubens J and Strong AE. 1999. Ecological and socioeconomic impacts of 1998 coral mortality in the Indian Ocean: An ENSO impact and a warning of future change. *Ambio* **28**:188-196.
- Williams DR, Roggenbuck JW and Bange SP. 1991. The effects of norm-encounter compatibility on crowding perceptions, experience and behavior in river recreation settings. *Journal of Leisure Research*, **23**:154-172.
- Williams ID & Polunin N. 2002. Differences between protected and unprotected reefs of the western Caribbean in attributes preferred by dive tourists. *Environmental Conservation*, **27**(4):382-391.
- Yonover J. 2010. Underwater Photography Tips. <<http://www.coral.org/node/4039>>
- Young N. 1983. *The History of Surfing*. Angourie (NSW, Australia): Palm Beach Press, 224 pp.

Appendix 2-A

Studies quantifying tourism and recreation

The following table lists studies and the endpoint they used to quantify tourism and recreation. Also included are the biological reef attributes and the physical and socioeconomic variables used to estimate that endpoint. The method and location of the studies are also given.

Reef attributes	Physical variables	Socioeconomic variables	Method	Location	Citation
<i>Final Ecosystem Service: Recreational Diving/Snorkeling Opportunity</i>					
Coral cover			Survey questionnaire	Bolinao, Philippines	Ahmed <i>et al.</i> (2007)
Coral bleaching; coral cover; fish species composition (preference for more colorful reef fish)			Survey questionnaire	Zanzibar & Mafia	Andersson (2007)
Coral cover, abundance of fish	Coastline development on shoreline, water clarity, plastic debris, risk of contracting ear infection by swimming in polluted water	number of boats, presence of MPA, number of snorkelers, fee	Survey questionnaire	Tobago	Beharry-Borg & Scarpa (2010)
Coral biodiversity, coral cover, fish biodiversity, fish stock, algae cover			Model	Kihei Coast, Hawaii	van Beukering & Cesar (2004)
“Pristine” coral reef condition; coral diversity; fish diversity and abundance	Water clarity	Swimming restrictions; payment vehicle	Two survey questionnaires – tourist exit survey and tourist operator survey; face-to-face interviews of 400 households for recreational fishing; three focus groups	Bermuda	van Beukering <i>et al.</i> (2010)
Fish abundance, coral health	Water clarity		Survey questionnaire and pictures of alternative scenarios	Florida Keys	Bhat (2003)
Coral reef and coral health			Survey questionnaire	Seychelles	Cesar <i>et al.</i> (2004)
Coral quality			Survey questionnaire	Phi Phi Islands, Thailand	Christiernsson (2003)
		Perceptions of crowding (social carrying capacity), ease of access	Summary article		Davis & Tisdell (1996)
Coral diversity	Water clarity	Number of divers per site per year	Survey questionnaire & photo analysis	Bonaire	Dixon <i>et al.</i> (2000)
Diversity of colorful marine life	Water clarity	Clean and odor-free water; crowd-free experience	Survey questionnaire	Great Barrier Reef, Australia	Hajkowicz (2006)
Amount of live coral, fish and sea life diversity, fish abundance	Water clarity	Access and availability of facilities	Survey questionnaire	Florida Keys	Leeworthy & Wiley (1996)

Reef attributes	Physical variables	Socioeconomic variables	Method	Location	Citation
<i>Final Ecosystem Service: Recreational Diving/Snorkeling Opportunity (con't)</i>					
Amount of live coral, fish and sea life diversity, fish abundance	Water clarity	Access and availability of facilities	Survey questionnaire	Florida Keys	Leeworthy & Wiley (1997)
Amount of live coral, fish and sea life diversity, fish abundance	Water clarity (visibility)	Access and availability of facilities	Survey questionnaire	Florida Keys	Leeworthy <i>et al.</i> (2004)
Coral health, fish abundance, large fish, coral cover		Perceptions of crowding (social carrying capacity), knowledge of ecosystem, experience snorkeling	Self-administered questionnaires	South Sinai, Egypt	Leujak & Ormond (2007)
Species richness, density and average size of organisms				Jervis Bay, Australia	Lynch <i>et al.</i> (2004)
Health of corals	Current WQ		Survey questionnaire	Florida Keys	Park <i>et al.</i> (2002)
Species diversity (fish and corals), percent coral cover	Visibility (water clarity)	Dive tag price	Survey questionnaire	Bonaire National Marine Park	Parsons & Thur (2007)
Percent coral cover			Model	Roatán, Honduras	Pendleton (1994)
Coral reef biodiversity (inferred from other study)			Interviews (survey) of municipal fishers, gleaners, seaweed farmers, and tourism business operators	Bohol Marine Triangle, Philippines	Samonte-Tan <i>et al.</i> (2007)
Amount of marine life		number of divers at a site at any one time	Survey questionnaire	Worldwide ?	Sorice <i>et al.</i> (2007)
Coral biodiversity			In-person interviews using open-ended elicitation questions	Jamaica & Curacao	Spash (2000)
Coral growth	Access to reef, safe swimming conditions, water quality	Adequate infrastructure (hotels, dive boat operators, etc.)		American Samoa	Spurgeon <i>et al.</i> (2004)
Aesthetic beauty of dive site (not defined further)			Survey questionnaire	Similan Islands, Thailand	Tapsuwan & Asafu-Adjaye (2008)
Coral diversity, abundance and health; fish diversity and abundance	Warm temperatures, clear waters, beach characteristics	Low health risks	Survey questionnaire	Bonaire & Barbados	Uyarra <i>et al.</i> (2005)
Coral bleaching, "marine life"			Questionnaire; four different surveys, secondary data sources	Indian Ocean (Tanzania/Kenya & Maldives/ Sri Lanka)	Westmacott <i>et al.</i> (2000)
Abundance and diversity of corals and fish	Water clarity (visibility)	Entrance fee	Video of alternative diving sites; survey questionnaire	Eilat, Israeli Red Sea	Wielgus <i>et al.</i> (2003)

Reef attributes	Physical variables	Socioeconomic variables	Method	Location	Citation
<i>Final Ecosystem Service: Recreational Diving/Snorkeling Opportunity (con't)</i>					
Abundance and variety of fishes, number of “unusual”, and number of “large” fish			Interview	Jamaica	Williams & Polunin (2002)
<i>Final Ecosystem Service: Recreational Fishing Opportunity</i>					
Target sportfishing species (bonefish, permit, tarpon)			Survey questionnaire	Belize	Fedler & Hayes (2008)
Target sportfishing species abundance and diversity		Clean and odor-free water; crowd-free experience	Survey questionnaire	Great Barrier Reef, Australia	Hajkowicz (2006)
Target sportfishing species (80 fish and invertebrate species)				Jervis Bay, Australia	Lynch <i>et al.</i> (2004)
<i>Final Ecosystem Service: Beach Recreation Opportunity</i>					
Quality of beaches			Survey questionnaire	Florida Keys	Leeworthy & Wiley (1996)
Quality of beaches			Survey questionnaire	Florida Keys	Leeworthy & Wiley (1997)
Quality of beaches			Survey questionnaire	Florida Keys	Leeworthy <i>et al.</i> (2004)
<i>Final Ecosystem Service: Wildlife Viewing Opportunity</i>					
Large wildlife (manatees, whales, dolphins, sea turtles)			Survey questionnaire	Florida Keys	Leeworthy & Wiley (1997)

Coral Reefs: Fish & Coral for Food, Aquaria, & Ornaments

All oceans are affected by humans to various degrees, with overfishing having the most widespread and dominant direct impact on food provisioning services that will affect future generations
(MEA 2005)

3.1 Describing the service

3.1.1 Definitions

A fishery is an entity engaged in harvesting fish, which is typically defined in terms of the people involved, species or type of fish, area of water or seabed, method of fishing, class of boats, purpose of the activities or a combination of these identifiers (FAO 2010).

Although a fish in the strictest sense is an aquatic vertebrate with fins, the term fisheries is used more broadly, to include mollusks, crustaceans, or any other aquatic animals (and in a few cases, aquatic plants) that are harvested. These include, but are not limited to, oysters, scallops, conch, squid, octopus, lobster, shrimp, and kelp.

Fisheries are most often associated with food production, but harvest of aquatic organisms can be for other purposes, such as for sale as live aquarium fish, bait, or fish meal for agriculture. Other uses include harvest of shells and skeletons for curios and jewelry (Table 3-1).

Food production from coral reefs includes both fish and invertebrate organisms that are harvested on the reef or spend at least a portion of their life cycle on the reef and are harvested elsewhere.

Food products are derived from commercial fishing (for profit), subsistence fishing (for survival), or recreational fishing (for pleasure). Because the benefit of recreational (sport) fishing is pleasure, it is discussed in the Tourism and Recreation section. Artisanal fishing is a term that usually describes traditional harvesting techniques (e.g., rod and tackle, spear, throw-net) that are more likely to represent a small-scale, low-intensity (usually subsistence) fishery. Although coastal fisheries in many parts of the world are mostly artisanal, some dominate the catches of some species or particular year/size classes.

Table 3-1. Benefits or amenities derived from fish production

- Seafood for human consumption (fish & invertebrates)
- Live fish and coral for aquariums (Chan & Sadovy 2000)
- Shells and skeletons for ornamental art and jewelry
- Recreational fishing for pleasure (Brander *et al.* 2007; NOAA 2009)
- Human health and well-being (Olsen *et al.* 1984; WHO 2010)
- Fish meal and oil for livestock and aquaculture feed

3.1.2 Benefits of coral reef fisheries

3.1.2.1 Seafood.

The most commonly described and most highly valued benefit of coral reef fisheries is food for human sustenance. In general, humans are obtaining their protein from fish, both marine and freshwater, in ever-increasing numbers. After the remarkable increase in both marine and inland capture of fish during the 1950s and 1960s, world fisheries production has leveled off since the 1970s. This leveling of the total catch follows the general trend of most of the world's fishing areas, which have apparently reached their maximum potential for fisheries production, because the majority of stocks have been fully exploited. Therefore, it is very unlikely that substantial increases in total catch will be possible in the future.

The total food fish supply and hence consumption has been growing at a rate of 3.6% per year since 1961, while the world's population has been expanding at 1.8% per year. The proteins derived from fish, crustaceans, and mollusks account for between 13.8% and 16.5% of the animal protein intake of the human population. The average apparent global per capita consumption increased from about 9 kg per year in the early 1960s to 16 kg per year in 1997, nearly doubling in 40 years (FAO 2002). Currently, two-thirds of the total food fish supply is obtained from capture fisheries in marine and inland waters, while the remaining one-third is derived from aquaculture.

Typically, fish provide about 20–30 kcal per person per day. In a few countries, such as Iceland, Japan, and some small island states, where there are few alternative proteins or the people have a strong preference for fish, fish can contribute up to 180 kcal per person per day. Fish proteins are essential in the diet of some densely populated countries where the total protein intake level is low. Worldwide, about a billion people rely on fish as their main source of animal protein. Dependence on fish is usually higher in coastal than in inland areas. About 20% of the world's population derives at least 20% of its animal protein intake from fish, and some small island states depend almost exclusively on fish. Artisanal coral reef fisheries provide an inexpensive source of protein and employment where few alternatives exist (Burke & Maidens 2004). For example, Seychelles has one of the highest per capita consumption rates of fish in the world (65 kg per year) with 900–1,000 artisanal fishers fishing full-time at 35 landing sites (Cesar et al. 2004).

The current annual global harvest from tropical reef fisheries has been estimated at six million metric tons (Polunin & Roberts 1996). Some scientists have estimated that worldwide coral reefs could produce a sustainable fisheries yield of 20m–35m metric tons per year (Crossland et al. 1991; Hatcher et al. 1987); however, Birkelund (1997) argues that coral reefs cannot or should not sustain such large fisheries yields.

3.1.2.2 Live fish and coral for aquaria.

Another specialized coral reef fishery is the collection of live fish and coral for aquaria (Livengood & Chapman 2007). The United States is the single largest importer of ornamental fish in the world, but the European Union is the largest market for ornamental fish (FAO 1996–2005; Chapman 2000). Estimates of the magnitude and value of the aquaria fishery vary widely. Livengood and Chapman (2007) estimate the value of ornamental fish and invertebrates imported into different countries worldwide at \$278m. Chan and Sadovy (2000) conducted a survey of marine aquarium shops in Hong Kong and estimated that close to a million individual coral reef fish enter the aquarium trade annually with an average value of about HK\$60 (~\$8) per fish. Bruckner (2005) estimated the market to be 14m–30m fish per year, with an import value of \$28m–\$44m.

3.1.2.3 Ornaments and jewelry.

Species of “precious coral” such as red and pink corals (Family Coralliidae), black corals (Order Antipatharia) and gold corals (Family Parazoanthidae) have historically been harvested from many parts of the world for high end jewelry and beads (Hourigan 2008; Grigg 1984, 1989). It has been estimated that precious coral catch reached roughly 450 tons per year in the 1980s and has now declined to roughly 50 tons per year (Oceana 2010). The United States and the European Union proposed thirty-one species of the family Coralliidae (*Corallium* spp. and *Paracorallium* spp.) for inclusion in the Convention on International Trade in Endangered Species (CITES) Appendix II (Oceana 2010). However, the measure failed to reach the two-thirds majority at the 2010 CITES conference in Doha, Qatar (ENS 2010).

3.2 Providing the service

3.2.1 Linkages among reef condition, reef structures, and reef functions with respect to delivery of fishes for aquaria and food

Almost a third of the world's marine fish species are found on coral reefs (Moberg & Folke 1999). Reefs provide essential habitat for adult fish, and their physical structure creates quiet water areas necessary for seagrass and mangrove nurseries. Valued open water commercial fish such as groupers, snappers, grunts, and barracuda spend critical life stages on the reef and in the reef-seagrass-mangrove system (Mumby et al. 2004, 2008; Mumby 2004; Dorenbosch et al. 2004). Some reefs in the Pacific and Indian Oceans are extremely rich in species (Tibbetts 2004); for example, Pereira (2000) lists 794 species in 93 families of reef-associated fishes that live in Mozambique waters.

3.2.1.1 Scleractinian corals.

Coral reefs are composed of a physical infrastructure that provides essential fish habitat. The infrastructure is constructed by reef-building scleractinians, or “stony corals”. These corals are distinguished by their ability to secrete an extracellular calcium carbonate (aragonite) skeleton, which in most cases forms a solid, relatively permanent reef structure. To form the skeleton, scleractinians rely on symbiotic algæ to produce energy for skeletal growth through photosynthesis. Capturing the energy from sunlight is one reason that stony corals are usually found in shallow, transparent waters. The durability of stony coral skeletons provides an enduring reef habitat that allows the evolution of complex reef communities that include harvestable fish and invertebrates. Dahl (1973, p. 240) stated:

The production, occupation, and destruction of surface area are, therefore, basic reef processes, and the balance between them is an essential aspect of the reef ecosystem. The efficient production of surface is a primary function of many reef organisms, and the control of surface by secondary occupants is a basic competitive force and a major determinant of reef communities.

Scleractinians provide enormous reef surface area. Although slow-growing by most standards, scleractinian corals can live for hundreds of years, and some species can grow to the size of an automobile (WS Fisher, personal communication).

In the Caribbean, the dominant, large reef-building corals are in the *Montastraea* genus, which includes *M. cavernosa* and three closely related species (*M. annularis*, *M. faveolata*, and *M. franksii*) that are often referred to as the *Montastraea* complex.

Montastraea colonies are often found on the fore-reef and appear particularly critical to the biodiversity of fish and invertebrates and for maintaining the structure, function, and flow of reef services (Mumby *et al.* 2008; Beets & Friedlander 1998). The Caribbean acroporid species, *Acropora palmata* and *A. cervicornis* are also relatively large and are highly branched, which provides additional surface area and greater reef complexity. Unfortunately, these species are vulnerable to elevated water temperatures that would result from climate warming and white-band disease (Aronson & Precht 2001). Because of enormous losses suffered by acroporids in the last three decades, both of these critical species are listed as threatened. As might be expected, healthy stony corals appear to be critical to productive fisheries. Fish productivity, species richness, fish biomass, and potential yield have all been reported to decrease with a decline in stony coral health (Warren-Rhodes *et al.* 2003).

Mumby *et al.* (2008) used 11 classes of reef habitat as surrogates for species, functions, and ecosystem services and found that one-fourth to one-third of benthic invertebrates and fish occurred in the *Montastraea*-dominated fore-reefs, which consistently had the highest richness, the highest number of processes, and the most services. Yet only 10% of fish species functional classes were unique to any one habitat. Functional classes of fish were an effective surrogate for total fish and benthic species richness, and the representation of species or functional classes ensured inclusion of all processes and services in the design of a reserve network. This research suggests that using the number of fish functional groups as a proxy indicator for benthic richness may be helpful in managing reef functions, services, and biodiversity for maintaining the resilience of reefs.

3.2.1.2 Reef structural complexity.

The physical structure of reef habitat influences the biodiversity and ecosystem functions of a reef community (Alvarez-Filip *et al.* 2009). In general, more complex habitats facilitate species coexistence through niche partitioning and provision of spatially delineated refuge from predators (Beets & Friedlander 1998; Bruno & Bertness 2001). Physical structures influence the spaces that are inhabited by organisms by defining volume, orientation, accessibility, water residence time, and food availability, among other factors (Scheffers *et al.* 2003). The rich diversity of coral reefs rests partly in the provision of habitable surface area and partly in the variability of that surface area.

There has been a widespread decline in the health of coral reefs that has reduced the amount and complexity of the available habitat for fish. A potential consequence of this decline, referred to as “reef flattening” (Alvarez-Filip *et al.* 2009), is the loss of species richness and abundance of reef fishes and invertebrates (Gratwicke & Speight 2005; Idjadi & Edmunds 2006; Wilson *et al.* 2007).

For coral reefs, there appears to be a strong positive correlation of habitat complexity to fish species richness (Walker *et al.* 2009; Pittman *et al.* 2007). Rugosity (an indicator of habitat complexity) has, therefore, been used successfully in the Virgin Islands as an index of fish diversity and in data-poor areas may be used to spatially assess where areas of high fish species richness may occur. Studies on the recruitment behavior of epibenthic communities have also shown that substrate irregularity may encourage the diversity of initial substrate colonizers, which may result in higher diversities later in succession (Breitburg 1985). Habitat complexity, especially appropriately-sized holes or cover for a particular species, provide shelter from predators (Hixon & Beets 1993; Roberts & Ormond 1987; Friedlander & Parrish 1998; Aguilar-Perera & Appeldoorn 2008).

3.2.1.3 Seascape connectivity.

Along with coral reefs, seagrass meadows and mangrove forests combine in a complex and dynamic mosaic that provides critical foraging areas, nurseries, and refugia for fish and invertebrates (Christensen *et al.* 2003; Aguilar-Perera & Appeldoorn 2007; McField & Richards Kramer 2007). Some commercially important species and threatened species, such as the rainbow parrot fish, utilize mangroves exclusively as nursery habitat, and the biomass of other fish is significantly increased when mangrove habitat is available (Mumby *et al.* 2004, 2008; Meynecke *et al.* 2008). Functional dependency of some fish on specific habitats, like the mangrove-dependent rainbow parrotfish, can also make them more vulnerable to extinction (Mumby *et al.* 2004). Proximity to seagrass and mangrove nursery habitat and the connectivity of reefs with nursery habitat has been measured using a variety of landscape connectivity metrics (Dorenbosch *et al.* 2004; Meynecke *et al.* 2008; Mumby 2006; Edwards *et al.* 2010).

Recent studies have directly compared the value of seagrass and mangrove habitats with the value of other possible shallow water habitats (Dorenbosch *et al.* 2006). Nagelkerken *et al.* (2000) used a visual survey technique to evaluate the importance of mangroves, coral reefs, and seagrasses as habitat for juvenile fishes in Bonaire. Their study showed that all three habitats were important nursery areas, but for different species. A similar study in the Indo-Pacific (Dorenbosch *et al.* 2006) documented ontogenetic shifts from juvenile habitats (seagrasses and mangroves) towards adult habitats (coral reefs). In a multi-year study in La Parguera, Puerto Rico, Pittman *et al.* (2010) found a high degree of multi-habitat use, with size-dependent ontogenetic habitat shifts. The importance of different habitats for juveniles and adult fishes is shown in Table 3-2.

Table 3-2. Important (x) habitats for juveniles and adults of selected fish species
☒ indicates the most important habitat for juveniles

Species	Juveniles			Adults			Study Location	Ref.
	Seagrass	Mangrove	Coral Reefs	Seagrass	Mangrove	Coral Reefs		
<i>Acanthurus chirurgus</i> (doctorfish)	☒	—	x	—	—	x	Bonaire	N
<i>Chaetodon capistratus</i> (foureye butterflyfish)	x	☒	—	—	—	x	Bonaire	N
<i>Cheilinus undulatus</i> (humphead wrasse)	☒	—	—	—	—	x	Indian Ocean	D
<i>Hæmulon flavolineatum</i> (French grunt)	☒	x	x	—	—	x	Bonaire	N
<i>Hæmulon plumieri</i> (white grunt)	☒	x	x	—	—	x	Puerto Rico	P
<i>Hæmulon sciurus</i> (bluestriped grunt)	☒	x	—	—	—	x	Bonaire	N
<i>Lutjanus apodus</i> (schoolmaster snapper)	x	☒	—	—	x	x	Puerto Rico	P
<i>Lutjanus griseus</i> (gray snapper)	x	☒	—	—	x	—	Bonaire	N
<i>Lutjanus mahogoni</i> (mahogany snapper)	x	☒	x	—	x	x	Puerto Rico	P
<i>Lutjanus synagris</i> (lane snapper)	x	☒	☒	—	—	—	Puerto Rico	P
<i>Ocyurus chrysurus</i> (yellowtail snapper)	☒	—	—	—	—	x	Bonaire	N
<i>Scarus guacamaia</i> (rainbow parrotfish)	—	☒	—	—	—	x	USVI	P
<i>Sparisoma radians</i> (bucktooth parrotfish)	x	x	—	x	x	—	Indian Ocean	D
<i>Sparisoma viride</i> (stoplight parrotfish)	☒	—	x	—	—	x	Puerto Rico	P
<i>Sphyræna barracuda</i> (great barracuda)	x	☒	—	x	x	x	Bonaire	N

References: D: Dorenbosch *et al.* (2006) N: Nagelkerken *et al.* (2000) P: Pittman *et al.* (2010)

Source: Partially adapted from Nagelkerken *et al.* (2000).

3.2.2 Linkages among reef condition, reef structures, and reef functions with respect to provision of stony corals, black corals and precious corals for aquaria stock and jewelry

Corals collected for the aquarium and jewelry industries generally are rare, slow-growing, long-lived species (USFWS 2011). According to the Global Marine Aquarium Database (GMAD), there are 61 species of soft corals and 140 species of stony corals collected for aquaria (Wabnitz *et al.* 2003). Of the approximately 220 species of precious corals (those used in the jewelry industry), only about 16 are commercially important (Hanfee 1997). Precious corals are found in deeper water (250–1600 feet depth) and include red and pink corals, black corals, gold corals and bamboo corals (Tsounis *et al.* 2010).

Coral condition is an important characteristic of corals collected for both the aquarium and jewelry industries. Corals collected for the aquaria trade must be healthy enough to survive collection and transport. Precious corals must be healthy enough that their skeletons can be formed into jewelry. It is not known how structural complexity or seascape connectivity relate to corals for aquaria stock and jewelry.

3.3 Measuring the service

3.3.1 Fish

A number of indicators of fisheries production are directly monitored as attributes of reef condition, including fish abundance, fish size, conch abundance, lobster abundance, and the biomass of commercially important species (McField & Richards Kramer 2007; Healthy Reefs Initiative 2010). Reef fish surveys are one method of measuring the available fish biomass. A variety of standardized methods has been developed and implemented (Bohnsack & Bannerot 1986; McField & Richards Kramer 2007; Schmitt & Sullivan 1996; Pattengill-Semens & Semens 2003). Divers swim along transects, estimating the number and size ranges of fish species. Several metrics that can be used as indicators of stock status can be derived from the data (*e.g.*, species abundance, density, size structure, and frequency-of-occurrence; total fish biomass; commercially significant fish biomass) (Ault *et al.* 1998; Paddack *et al.* 2009; McField & Richards Kramer 2007). Paddack *et al.* (2009) conducted a meta-analysis of reef fish density obtained from 48 studies covering 318 reefs across the Caribbean and found that overall reef fish density has been declining significantly for more than a decade, at rates that are consistent across all subregions of the Caribbean basin (6%–22.7% per year and in three of six trophic groups). There appears to be a considerable lag-time between degradation of coral reef habitat and the decline of fish populations; however, a consistent significant decline across several trophic groups and among both fished and nonfished species indicates that Caribbean fishes have begun to respond negatively to habitat degradation (Paddack *et al.* 2009).

Fishery-dependent population estimates can also be developed using catch data (*e.g.*, the National Marine Fisheries Service (NMFS) headboat catch and effort data). The NMFS data provide total numbers of individual fish in the catch as well as total weight in the catch by species by year (Ault *et al.* 1998).

3.3.2 Stony corals

Despite the fact that more stony corals (greater abundance) and larger corals provide greater habitat for fish and invertebrates (Beets & Friedlander 1998), few studies are available that directly measure coral surface area. Most commonly, stony coral studies measure “live coral cover”, which reflects only a 2-dimensional planar area viewed from above the coral. The planar approach is convenient but does not account for colony height, which can vary widely, and cannot be used to estimate colony surface area (quantity of habitat). The concept of 3-dimensional (3D) colony surface area has been explored (Dahl 1973; Szmant-Froelich 1985; Roberts & Ormond 1987; Babcock 1991; Alcala & Vogt 1997; Bak & Meesters 1998), but only recently have 3D colony surface area methods been developed for use in applied field studies (Fisher 2007; Fisher *et al.* 2007; Fisher *et al.* 2008; The Nature Conservancy 2010).

3.3.3 Reef structural complexity

The structural complexity of reefs is determined by size, shape, and juxtaposition. Complexity refers not only to the surface area but also to the size variability of spaces, which provide different habitats for organisms with different sizes and behaviors. A complexity index (Aronson *et al.* 1994) and a similar rugosity index (NOAA 2008) are calculated from comparison of the length of a chain to the distance covered by the chain when draped over a coral reef (Risk 1972; Rogers *et al.* 1982; Connell & Jones 1991). Despite the intention to measure multiple aspects of reef complexity, this approach only measures the cumulative height of coral colonies on a reef, which is only one component of complexity. Since reef height reflects greater surface area, this is a useful measurement for predicting habitat availability. Another component of complexity, however, is variability in spaces, which is created by corals of different sizes and holes or caves in coral structures. In a recent study, Fisher *et al.* (2008) calculated the coefficient of variation of colony size to reflect this component of complexity. Others have developed tools to estimate holes and caves in coral structures (Scheffers *et al.* 2003). While all of these approaches are useful, no truly comprehensive method has yet been presented to indicate reef complexity.

3.3.4 Seascape mapping

Despite the fact that the earliest landscape ecology studies of marine systems had their beginnings in the classic works of Levins (1969) and Levin and Paine (1974), it is only within the last decade or so that we have seen a significant increase in the application of landscape ecology principles to seascapes. Early work concentrated on mapping habitats and understanding reef functions and processes (Dierssen *et al.* 2003; Kvernevik *et al.* 2002). Even though this work continues, there has been recent growth in the availability of spatial data from GIS (geographic information system) and remote sensing technologies, which are necessary to map coral reef habitats (Phinn *et al.* 2008). This, in combination with survey and monitoring data of reef attributes, has led to methods that increase the data resolution needed to make meaningful observations at more local scales (Harbourne *et al.* 2006).

These developments have also inspired work on spatially explicit modeling and mapping of fish distributions and fish production (and service provisioning) on reefs (Pittman *et al.* 2010; Pittman *et al.* 2007; Mumby *et al.* 2008; Purkis *et al.* 2008). Although mapping of services is in its infancy, trade-offs in managing services result in changes in the location or scale of the beneficiaries (*e.g.*, local fisheries or jobs versus global tourists), which we are only beginning to understand (Hodgson & Dixon 2000). The connectivity of coral reef fish habitat and nursery habitat is important to fish production, so methods for mapping

these habitats at finer scales and methods to measure the connectivity of habitat used throughout the life cycles of fishes is increasingly important in making land use and other management decisions.

3.3.5 Fisheries modeling

Ecopath is a trophic structure model that simulates ecological processes in complex food webs, while *Ecosim* allows the simulation of scenarios to maximize benefits under different management regimes and allows evaluation of tradeoffs for different decisions. Combined socioeconomic and ecologic process models such as *EwE* (*Ecopath* with *Ecosim*) have been used to evaluate fisheries management alternatives. Examples include managing a resource to optimize biodiversity or habitat for at-risk species, or optimizing social values in terms of fisheries jobs (Cheung & Sumaila 2008). *Ecopath* was used by Pauly *et al.* (2000) to document the structural changes in global fisheries. By looking at all historic data and estimating the trophic level of each species, Pauly *et al.* (2000) estimated that top predators are being lost and that the average catch is lower in the food chain today than in the past. This approach might be useful at a more local level to determine sustainable levels of harvest.

Another program, *Marxan*, is a model used to design marine protected areas (MPAs). The model incorporates an optimization algorithm for finding spatially cohesive sites that meet specified criteria, such as biodiversity (Smith *et al.* 2002).

Jordan *et al.* (2008) demonstrated an approach that links production at the scale of habitat patches to large-scale delivery of the ecosystem service (edible fish). This framework may be used to model habitat effects for use in predicting and managing coral reefs and other coastal habitats, to identify sources of uncertainty and data gaps to improve the precision and accuracy of predictions, and to demonstrate the potential for large-scale effects of multiple small-scale decisions on delivery of ecosystem services.

3.4 Valuing the service

Coral reef associated fisheries encompass both direct and indirect values (van Beukering *et al.* 2010). Most of the research on the value of ecosystem services has focused on direct use values (*e.g.*, consumption for food, marine ornamentals) or indirect use values (*e.g.*, habitat provisioning, cultural and recreational importance).

Fisheries agencies often use the annual ex-vessel value (*i.e.*, the gross value paid to commercial fishermen for their harvest). For example, in 2000 the annual ex-vessel value of commercial fisheries associated with U.S. coral reefs was estimated at over \$137.1m (NOAA 2001). The ex-vessel value is an incomplete value of the fishery: it does not include the value added by processors and vendors; it does not reflect the value of future catches; and, it does not reflect the uncertainty surrounding the ability to obtain a comparable income in the future. For more complete fisheries valuation, economists estimate either the present value (PV) or the net present value (NPV) of the fishery (Cheung & Sumaila 2008; Costanza *et al.* 1989). PV represents a series of future cash flows expressed in today's dollars. NPV is a method used in evaluating investments; the NPV of all cash outflows (such as the cost of the investment) and cash inflows (returns) is expressed in today's dollars. Both PV and NPV use a discount rate (*i.e.*, the rate at which society as a whole is willing to trade off present for future benefits) to calculate the value.

Data on the trade of marine ornamentals is, at best, qualitative. Collectors are generally small-scale fishermen working alone or in small groups, using artisanal equipment (Wabnitz *et al.* 2003). CITES covers some marine ornamentals (including all species of stony corals) and provides some trade data. National governments also produce statistics regarding the export or import of marine ornamentals. A few countries report the actual number of specimens exported (*e.g.*, Singapore and the Maldives). More precise data can be obtained by interviewing collectors (Cesar *et al.* 2002), but this has not been done at a global scale.

For indirect use values (habitat provisioning) researchers may have derived a value for the resource by first identifying a management scenario (MPA, No-Take Areas, incentive programs, etc.) from which they determined what the expected increase in fish production and its value would be (opportunity cost methods). The value of fisheries has also included attempts to calculate the Total Economic Value (TEV) of reefs, which includes fish production (Spurgeon 1992; Cesar 2002), but difficulties arise when trying to sum nonuse and use values. Random utility models are most often used in valuation of recreational fishing (Bockstael *et al.* 1989; McConnell *et al.* 1995). Many of these methods, except for determination of the present monetized value of fish for food consumption, use contingent valuation methods to determine what people are willing to pay, accept, or volunteer for the service (Table 3-3).

Cesar (2000), Moberg and Folke (1999), and Spurgeon (1992) provide excellent reviews on problems coral reefs face and on what types of values and valuation methods should be used for valuing different benefits (Table 3-4). Stressors have been translated into "disservices" for the purposes of valuation. For example, Cesar *et al.* (1997) used a quasi-option value approach to evaluate the costs (potential losses due to the threat) and benefits of overfishing.

Table 3-3. Valuation methods

1. Stated preference
<p>Uses surveys to determine WTP (willingness to pay) or WTA (willingness to accept) or WTV (willingness to volunteer one's services for fundraising, etc.)</p> <p>a. Discrete or Dichotomous Choice Method</p> <p>A good or service (or change in a good or service) is presented to samples of individuals. Randomly assigned dollar amounts are presented, and individuals in the sample group choose their preferred amount. This is consistent with how choices are made in markets and helps the analyst to derive estimates of economic value.</p> <p>b. Choice Methods – Multi-Attribute Utility Theory</p> <p>This method uses conjoint-type analysis to yield changes in total economic value or changes in preference rankings for changes in attributes.</p>
2. Revealed preference
<p>a. Travel Cost Method</p> <p>Uses the distance one has to go and the cost involved to assess value (<i>e.g.</i>, bird watching)</p> <p>b. The value of time spent traveling, or the opportunity cost of travel time</p> <p>c. Opportunity cost</p> <p>The value of the best alternative to a given choice, or the value of resources in their next best use. In regard to time, the opportunity cost of time spent on one activity is the value of the best alternative activity that the person might engage in at that time.</p> <p>d. Random utility modeling</p> <p>A version of the travel cost method that is often used for recreational fishing.</p>
3. Cost/benefit analysis
4. Damage cost avoided, replacement costs, substitutes
5. Hedonic pricing
<p>The hedonic pricing method is used to estimate economic values for ecosystem or environmental services that directly affect market prices. It is most commonly applied to variations in housing prices that reflect the value of local environmental attributes (<i>e.g.</i>, housing values of Wisconsin lake front property increases with greater water clarity). It can be used for estimating the economic benefit of environmental quality, including air pollution, water pollution, or noise environmental amenities, such as aesthetic views or proximity to recreational sites.</p>
6. Costless choice method
Dixon & Sherman (1990)
7. Total consumer surplus
<p>Consumer surplus is the difference between the total amount that consumers are <i>willing and able to pay</i> for a good or service (indicated by the demand curve) and the total amount that they actually do pay (<i>i.e.</i>, the market price for the product). An example might be the cost savings in property tax relief to individuals who place conservation easements on their properties (these are deed restrictions that landowners voluntarily place on their land to protect important resources). The total consumer surplus is simply the sum of all the consumer surpluses for each individual good purchased.</p>
8. Direct cost
For example, research expenditures by the Smithsonian Institution surveying coral reefs in Belize
9. Change in productivity approach
Difference in value of the biologically supported economic activity in situations with and without the reef (can use fish production and yield estimates with and without MPA, or production on degraded versus undegraded reefs)
10. Percentage dependence technique
The value of the supported activity multiplied by an estimate of the percentage dependence of the activity on the reef's presence
11. Replacement cost
For example, cost of installing artificial coastal defenses to replace reef protection function or fish production (<i>e.g.</i> , artificial reefs)

12. Option price
Option value (benefit received by retaining the option of using a resource in the future by protection or preserving it today) plus expected consumer surplus (the measure of the <i>welfare</i> that people gain from the consumption of goods and services, or a measure of the benefits they derive from the exchange of goods).
13. Bioeconomic models
In this approach, both supply and demand are estimated. Production functions relating natural system attribute inputs along with capital, labor and energy inputs are estimated and cost curves and the supply curve are estimated. Demand curves for the good or service are also estimated. The outputs are changes in consumer's surplus, producer's surplus, and a special part of producer's surplus—economic rent (ER) or the amount of profit over and above a normal return to investment. ER is a measure of welfare for the fisheries where no one pays a price for the fish.
14. Total economic value (TEV)
TEV is an aggregation of consumer's surplus, producer's surplus/economic rent (CS, PS/ER). This includes use and nonuse/passive economic use values (both direct and indirect). These values are used in Benefit-Cost Analysis (BCA), damage assessments and restorations.
15. Value transfer
From meta-analysis of valuation studies (Brander <i>et al.</i> 2007)
16. Noneconomic human dimensions measures
(A more extensive discussion of these measures is provided in section 2.4.7 of this report.)
a. Importance-satisfaction ratings
b. The value of time spent traveling, or the opportunity cost of travel time
c. Opportunity cost
The value of the best alternative to a given choice, or the value of resources in their next best use. In regard to time, the opportunity cost of time spent on one activity is the value of the best alternative activity that the person might engage in at that time.
d. Random utility modeling
A version of the travel cost method that is often used for recreational fishing.

Source: except where noted, from Spurgeon (1992), Moberg & Folke (1999), and Cesar (2000).

Table 3-4. Categories of values

Direct use value
▶ Extractive value (<i>e.g.</i> , fisheries, coral for jewelry)
▶ Nonextractive value (<i>e.g.</i> , scuba diving)
Indirect use value
▶ Habitat that supports fish
▶ Nutrients
▶ Shoreline protection
▶ Global life support
Nonuse values
▶ Existence value (<i>i.e.</i> , value attributable to the presence of the reef, whether used or not)
▶ Option value (<i>i.e.</i> , potential future direct or indirect used, such as bioprospecting)
▶ Bequest value (<i>i.e.</i> , value of preserving for future generations)
▶ Intrinsic value (<i>i.e.</i> , innate value without reference to humans)

Source: Spurgeon (1992); Cesar (2000).

Income derived from fishing is another important benefit. Surveys conducted by Cinner *et al.* (2008) found that fishers from poorer households would be less likely to exit a severely declining fishery. They suggest that wealth generation and employment opportunities targeted at the poorest fishers would help reduce fishing effort in overfished areas (Cinner *et al.* 2008).

3.5 Reflections

3.5.1 Threats to coral reef fisheries

Global landings of fish have been in serious decline since the mid-1980s (Pauly *et al.* 2005). Overfishing has been identified as one of the major causes of reef ecosystem decline in recent decades, because the loss of harvested fish species changes the structure and functioning of reef systems (Jackson *et al.* 2001; MEA 2005; Pauly *et al.* 2000; Burke & Maidens 2004) and reduces reef resilience to natural disturbances (Hughes *et al.* 2003). While the loss or reduction of specific functional groups (*e.g.*, herbivores) through overfishing may reduce the size of harvestable fish stocks, overfishing of keystone herbivores like parrot fish and surgeon fish completely alter reef dynamics. Their loss substantially increases growth of macroalgae and can cause a phase shift in the reef system from coral to algal dominance (Hughes *et al.* 2003; Pandolfi *et al.* 2003; Burke & Maidens 2004).

Many tropical fish species (*e.g.*, groupers and snappers) form large spawning aggregations once or twice a year. The fish that come to these aggregations are the oldest and largest individuals in the population (Coleman *et al.* 2000; Domeier & Colin 1997; Beets & Friedlander 1998; Smith 1972). These aggregations are easily targeted by fishermen, and intensive fishing during spawning can quickly deplete a population (Burke & Maidens 2004; Beets & Friedlander 1998). Removing the largest individuals from the population decreases spawning potential and reduces larval recruitment, since larger animals produce more eggs (McField & Richards Kramer 2007; Roberts & Hawkins 2000). There is also evidence that spawning-site fidelity is a learned behavior, and when heavy fishing at aggregation sites removes the experienced fish, new recruits are unable to locate the aggregation site (Coleman *et al.* 2000; Warner 1990; Clark & Tracey 1993; Sadovy & Eklund 1999).

Destructive fishing methods pose another threat to coral reefs and to sustainable fish populations. Cyanide fishing (using cyanide to stun reef fish for collection of live fish for the aquarium trade); blast fishing (using explosives to kill or stun reef fish); muroami netting (nets that are weighted and dropped repeatedly onto coral); and gleaning (digging through reefs with steel tools in search of abalone and invertebrates) have significant impacts on the reef structure, connectivity of the reef with other habitats, and community structure of nontarget species (Pauly *et al.* 2000; Cesar 2002).

3.5.2 Management options

The American Fisheries Society (AFS) supports conservative management of reef fishes to avoid rapid overfishing and stock collapse (Coleman *et al.* 2000). Two management approaches (essential fish habitat and marine protected areas) can be combined to help maintain fish populations at sustainable levels.

3.5.2.1 Essential fish habitat (EFH).

The EFH provision of the 1996 Sustainable Fisheries Act (PL 104-297 1996) amended the habitat provisions of the Magnuson Act (now called the Magnuson-Stevens Act) to require the National Marine Fisheries Service (NMFS), the Fishery Management Councils, and Federal agencies to protect, conserve, and enhance essential fish habitat. Congress defined EFH as “those waters and substrate necessary to fish for spawning, breeding, feeding or growth to maturity.” Additionally, EFH that is determined to be particularly important to the long-term productivity of populations of one or more managed species, or to be particularly vulnerable to degradation, can be identified as “habitat areas of particular concern” (HAPC) to help provide additional focus for conservation efforts (Duval *et al.* 2004).

EFH can account for spatial and temporal variation in the distribution of life history stage, seasonal and geographic distributions, abundance, and interactions with other species. However, the regulations governing EFH designation do not provide for temporal designation (*i.e.*, a habitat is EFH all year long). Fisheries management plans now include a description and identification of EFH, a description of potential threats (including how different fishing methods affect EFH), and actions to conserve and enhance habitat (EPA 2005).

Spawning aggregations are potential EFH, since they are concentrated production sites and can be predictable in space and time (Lindemann *et al.* 2000). EFH can also be identified by correlating benthic habitat variables with the distribution, abundance, and size of reef fishes (Pattengill-Semmens & Semmens 2003). NOAA’s Biogeography Program has produced benthic habitat maps of most U.S. coral reefs. These data have been used to identify and map structural habitats used by fish species at different life stages (Recksiek *et al.* 2001). The goal is to develop predictive habitat affinity models for selected fish species that will support location of essential fish habitat.

3.5.2.2 Marine protected areas (MPAs).

MPAs or no-take areas (NTAs) may provide the best protection against overfishing (Hughes *et al.* 2003), so it is not unexpected that a large body of literature is focused on optimization of MPA system design and the ecosystem service benefits that they provide (Roberts & Polunin 1993; Trexler & Davis 2000; Cesar 2000; Pendleton 1995; Arias-Gonzalez *et al.* 2004; Roncin *et al.* 2008; Stelzenmüller *et al.* 2008). Protected areas are an effective management tool, because “if well enforced they change human behavior”, and in actuality, it is human behavior and not the resource that is managed (Hughes *et al.* 2003). Reserves in the Mexican Caribbean generally have a greater number of species, higher organism density, and larger-sized herbivores than unprotected reefs (Nuñez-Lara *et al.* 2003; Arias-Gonzalez *et al.* 2004).

But estimates of the no-take area needed to be effective may be economically prohibitive in the short term despite the increasing probability of the future collapse of the industry and the system as a whole. For example, Hughes *et al.* (2003) point out that ecological modeling studies indicate that at least 30% of the world's coral reefs should be NTAs to ensure the sustainability of exploited fish stocks. While this may seem extreme, Moberg and Ronnback (2003) point out that it is most likely more cost effective to try to preserve ecosystem functioning than to restore or replace ecosystems when they have been degraded or lost.

The quantitative associations between fish populations and their habitats is a key issue in determining EFH and establishing MPAs and NTAs that protect fish and the fisheries. These must incorporate concepts of targeted fish species, life history stages, age structure, genetic diversity of the stock, community structure, and physical habitats (Recksiek *et al.* 2001; Roberts *et al.* 1993; Coleman *et al.* 2000; Murray *et al.* 1999). While precise corridors of connectivity between habitats are not yet fully understood, MPAs that encompass areas of connected habitats (*e.g.*, coral reefs, seagrass meadows, mangroves forests) may best protect fisheries (Pittman *et al.* 2010; Mumby *et al.* 2004; Lindemann *et al.* 2000).

MPAs may also address other management concerns, such as how to allocate ecosystem services among user groups. The Florida Keys National Marine Sanctuary (FKNMS) is using no-take areas and other marine zoning methods to resolve conflicts between users.

3.5.3 Conclusions

Fisheries are fairly well defined, but measurements and valuation are incomplete and vary widely. Attributes associated with fishing have been identified, and scientists have begun to link those with fish production. Spatial and temporal analysis of fish populations and their use of various habitats has advanced considerably in recent years.

Linking the attributes to ecosystem services (not just fish production) (Table 3-5) and conducting valuation studies will further advance the science. Fish production is an ecological endpoint, a necessary part of the realization of benefits (amenities, goods, or services) to people. The benefits can be thought of as ecosystem service endpoints for which there are values. Valuation places a monetary or nonmonetary value on these benefits by establishing a relationship between the inputs (physical, biological, socioeconomic factors) and the output (benefit). This relationship may be defined by a model, statistical equation, function, or conceptual model.

Often the methods available to value a service, benefit, amenity, or stock, dictate how the benefits are described. The same benefit may have very different inputs depending on the scale of analysis, the area under investigation, the focus of the research (individual type of fish, what people in a particular area value most highly, the availability of certain tradeoffs, etc.). As we suggest in Chapter 1, it may be helpful to distinguish between ecological services (which are expressed in physical units) and economic benefits (which are expressed in monetary units). Some researchers have derived ways to combine the monetary and nonmonetary benefit values of a system to compare purely economic values with the value of the system as a whole (Odum 1996).

Ecological models can be used to illustrate and quantify relationships among environmental and ecological reef elements and to investigate thresholds for reef persistence and sustainable delivery of services. This information can be applied in the development of EFH and MPAs, with the ultimate goal of a sustainable fishery.

Table 3-5. Final ecosystem services and supporting features for fish production

Ecosystem Service(s)		Natural Features	Social Values	Complementary Goods & Services	Ecosystem-Derived Benefits	Potential Indicators of Final Ecosystem Service(s)
Final (FES)	Intermediate					
Fishing						
Seafood Products (fish, shellfish, algae harvested)	Biological integrity	Fish diversity and abundance; coral health; seascape connectivity; and structural complexity	Desirability of species based on taste	Adequate infrastructure (boats, marinas, etc.)	Revenue from commercial seafood fisheries	Abundance of commercially desirable fish species
Aquarium Products (live fish & coral taken)	Biological integrity	Coral diversity, abundance and health; fish diversity and abundance; seascape connectivity; and structural complexity	Desirability of species for aquaria based on physical appearance (color, size, etc.), rarity		Revenue from sales of aquarium fish and coral	Species abundance and diversity of target populations
Material Removed for Curios and Jewelry	Biological integrity	Coral diversity, abundance and health; water clarity	Aesthetic values and artistic inspiration	Diving and boating infrastructure	Revenue from sales of curios and jewelry	Species abundance and diversity of target populations

Definitions (proposed by the Ecosystem Services Research Program and currently under discussion by the Program)

- **Final Ecosystem Service** – Output of ecological functions or processes that directly contributes to social welfare or has the potential to do so in the future (broadly based on Boyd & Banzhaff [2007]).
- **Intermediate Ecosystem Service** - Output of ecological functions or processes that indirectly contributes to social welfare or has the potential to do so in the future.
- **Natural Features** – The biological, chemical, and physical attributes of an ecosystem or environment.
- **Social Values** – The social attributes that influence economic demand for an ecosystem service.
- **Complementary Goods & Services** - Inputs (usually built infrastructure or location characteristics) that allow a good or service to be used by complementing the ecological condition. For example, complementary goods and services that allow the presence of fishable fish to become an opportunity for recreational fishing will include aspects of site accessibility, such as road access, available parking and the presence of a fishing pier, all of which make fishing at the site possible and enhance enjoyment of the activity.
- **Ecosystem-Derived Benefits** - The contribution to social welfare of ecosystem goods and services. In the ESRP, the term applies specifically to net improvements in social welfare that result from changes in the quantity or quality of ecosystem goods and services attributable to policy or environmental decisions.
- **Indicator of Final Ecosystem Service** – Biophysical feature, quantity, or quality that requires little further translation to make clear its relevance to human well-being (*i.e.*, “public-friendly” measurement)

3.6 Bibliography

- Aguilar-Perera A and Appeldoorn RS. 2007. Variation in juvenile fish density along the mangrove-seagrass-coral reef continuum in SW Puerto Rico. *Marine Ecology Progress Series*, **348**:139-148.
- Aguilar-Perera A and Appeldoorn RS. 2008. Spatial distribution of marine fishes along a cross-shelf gradient containing a continuum of mangrove-seagrass-coral reefs off southwestern Puerto Rico. *Estuarine, Coastal and Shelf Science*, **76**:378-394.
- Alcala, MLR and Vogt H. 1997. Approximation of coral reef surfaces using standardized growth forms and video counts. In *Proceedings of 8th International Coral Reef Symposium*, **2**:1453-1458.
- Alvarez-Filip L, Kulvy N, Gill JA, Isabelle M and Watkinson AR. 2009. Flattening of Caribbean coral reefs: region wide declines in architectural complexity. *Proceedings Royal Society B*, **276**(1669):3019-3025.
- Arias-Gonzalez JE, Nunez-Lara E, Gonzalez-Salas C and Galzin R. 2004. Trophic models for investigation of fishing effect on coral reef ecosystems. *Ecological Modelling*, **172**:197-212.
- Aronson RB and Precht WF. 2001. White-band disease and the changing face of Caribbean coral reefs. *Hydrobiologia*, **460**:25-38.
- Aronson RB, Edmund PJ, Precht WF, Swanson DW and Levitan DR. 1994. Large-scale, long-term monitoring of Caribbean coral reefs: simple, quick, inexpensive techniques. *Atoll Research Bulletin*, **421**:1-19.
- Ault JS, Bohnsack JA and Meester GA. 1998. A retrospective (1979-1996) multispecies assessment of coral reef fish stocks in the Florida Keys. *Fishery Bulletin*, **96**(3):395-414.
- Babcock RC. 1991. Comparative demography of three species of scleractinian corals using age-and size-dependent classifications. *Ecological Monographs*, **61**:225-244.
- Bak RPM and Meesters EH. 1998. Coral population structure: the hidden information of colony size-frequency distributions. *Marine Ecology Progress Series*, **162**:301-306.
- Beets J and Friedland A. 1998. Evaluation of a conservation strategy: a spawning aggregation closure for red hind, *Epinephelus guttatus*, in the U.S. Virgin Islands. *Environmental Biology of Fishes*, **55**:91-98.
- van Beukering PJH, Sarkis S, McKenzie E, Hess S, Brander L, Roelfsema M, Looijensstijn-van der Putten L & Bervoets T. 2010. *Total Economic Value of Bermuda's Coral Reefs. Valuation of Ecosystem Services*. van Beukering Consulting, Amsterdam.
- Birkeland C. 1997. Symbiosis, fisheries and economic development on coral reefs. *Trends in Ecology & Evolution*, **12**:364-367.

- Bockstael NE, McConnell KE and Strand IE. 1989. A Random Utility Model for Sportfishing: Some Preliminary Results for Florida. *Marine Resource Economics*, **6**:245-260.
- Bohnsack JA and Bannerot SP. 1986. *A stationary visual census technique for quantitatively assessing community structure of coral reef fishes*. Miami (FL): National Oceanic and Atmospheric Administration, Southeast Science Fisheries Center. NOAA Technical Report NMFS 41, 15 pp.
- Brander LM, van Beukering PJH and Cesar HSJ. 2007. The recreational value of coral reefs: A meta-analysis. *Ecological Economics*, **63**:209-218.
- Breitbart DL. 1985. Development of a subtidal epibenthic community: factors affecting species composition and the mechanisms of succession. *Oecologia*, **65**:173-184.
- Bruckner AW. 2005. The importance of the marine ornamental reef fish trade in the wider Caribbean. *Revista de Biología Tropical*, **53**(1): 127-138.
- Bruno JF and Bertness MD. 2001. Habitat modification and facilitation in benthic marine communities. In: Bertness MD, Gaines SD and Hay ME (eds), *Marine Community Ecology*. Sunderland (MA): Sinauer. pp. 201-218.
- Burke L and Maidens J. 2004. *Reefs at Risk in the Caribbean*. Washington, DC: World Resources Institute, 80 pp.
- Cesar H, van Beukering PJH, Pintz S and Dierking J. 2002. *Economic valuation of the coral reefs of Hawaii*. Cesar Environmental Economics Consulting, The Netherlands.
- Cesar HSJ, van Beukering PJH, Payet R and Grandourt E. 2004. *Evaluation of the socio-economic impacts of marine ecosystem degradation in the Seychelles*. Cesar Environmental Economics Consulting, Netherlands, 96 pp.
- Cesar HSJ (ed). 2000. *Collected Essays on the Economics of Coral Reefs*. Kalmar (Sweden): Kalmar University, Department for Biology and Environmental Sciences/CORDIO.
- Cesar HSJ. 2002. Coral Reefs: Their Functions, Threats and Economic Value. In Cesar H. (ed.), *Collected Essays on the Economic Value of Coral Reefs*, Kalmar (Sweden): Kalmar University, Department for Biology and Environmental Sciences/CORDIO, pp. 14-39.
- Cesar HSJ, Lundin C, Bettencourt S and Dixon J. 1997. Indonesian coral reefs: An economic analysis of a precious but threatened resource. *Ambio*, **26**(6):345-350.
- Chan TTC and Sadovy Y. 2000. Profile of the Marine Aquarium Fish Trade in Hong Kong. *Aquarium Sciences and Conservation*, **2**:197-213.
- Chapman FA. 2000. Ornamental fish culture, freshwater. In: Stickney RR (ed), *Encyclopedia of Aquaculture*. New York: John Wiley & Sons, pp. 602-610.
- Cheung WWL and Sumaila UR. 2008. Trade-offs between conservation and socio-economic objectives in managing a tropical marine ecosystem. *Ecological Economics*, **66**:193-210.
- Christensen JD, Jeffrey CFG, Caldwell C, Monaco ME, Kendall MS and Appeldoorn RS. 2003. Cross-Shelf Habitat utilization patterns of Reef Fishes in Southwestern Puerto Rico. *Gulf and Caribbean Research*, **14**(2):9-27.
- Cinner JE, Daw T and McClanahan TR. 2008. Socioeconomic Factors that Affect Artisanal Fishers' Readiness to Exit a Declining Fishery. *Conservation Biology*, **23**(1):124-130.
- Clark MR and Tracey DM. 1993. Changes in a population of orange roughy, *Hoplostethus atlanticus*, with commercial exploitation on the Challenger Plateau, New Zealand. *Fishery Bulletin*, **92**:236-253.
- Coleman FC, Koenig CC, Huntsman GR, Musick JA, Eklund AM, McGivern JC, Chapman RW, Sedberry GR and Grimes CB. 2000. Long-lived Reef Fishes: The Grouper-Snapper Complex. *Fisheries*, **25**(3):14-20.
- Connell SD and Jones GP. 1991. The influence of habitat complexity on postrecruitment processes in a temperate reef fish population. *Journal of Experimental Marine Biology and Ecology*, **151**:271-294.
- Costanza R, Farber SC and Maxwell J. 1989. Valuation and management of wetland ecosystems. *Ecological Economics*, **1**:335-361.
- Crossland CJ, Hatcher BG, Smith SV. 1991. The role of coral reefs in global carbon production. *Coral Reefs*, **10**:55-64.
- Dahl AL. 1973. Surface area in ecological analysis: quantification of benthic coral-reef algae. *Marine Biology*, **23**:239-249.
- Dierssen HM, Zimmerman RC, Leathers RA, Downes TV and Davis CO. 2003. Ocean color remote sensing of seagrass and bathymetry in the Bahamas Banks by high-resolution airborne imagery. *Limnology and Oceanography*, **48**:444-455.
- Dixon JA and Sherman PB. 1990. *Economics of Protected Areas: A new look at benefits and costs*. Washington, DC: Island Press, 251 pp.
- Domeier ML and Colin PL. 1997. Tropical reef fish spawning aggregations: defined and reviewed. *Bulletin of Marine Science*, **60**(3):698-726.
- Dorenbosch M, Grol MGG, Nagelkerken I and van der Velde G. 2006. Seagrass beds and mangroves as potential nurseries for the threatened Indo-Pacific humphead wrasse, *Cheilinus undulatus* and Caribbean rainbow parrotfish, *Scarus guacamaia*. *Biological Conservation*, **129**:277-282.
- Duval MA, Rader DN and Lindeman KC. 2004. Linking habitat protection and marine protected area programs to conserve coral reefs and associated back reef habitats. *Bulletin of Marine Science*, **75**(2):321-334.
- Edwards AJ (ed). 2010. *Reef Rehabilitation Manual*. St. Lucia (Australia): Coral Reef Targeted Research and Capacity Building for Management Program (CRTR), 166 pp. <<http://www.gefcoral.org/Publications/ReefRehabilitationManual.aspx>>

- Environmental News Service (ENS). 2010. CITES Leaves Trade in Precious Corals Unrestricted. March 22, 2010. <<http://www.ens-newswire.com/ens/mar2010/2010-03-22-01.html>>
- Fisher WS, Davis WP, Quarles RL, Patrick J, Campbell JG, Harris PS, Hemmer BL and Parsons M. 2007. Characterizing Coral Condition Using Estimates of Three-dimensional Colony Surface Area. *Environmental Monitoring and Assessment*, **125**:347-360.
- Fisher WS, Fore LS, Hutchins A, Quarles RL, Campbell JG, LoBue C and Davis WS. 2008. Evaluation of stony coral indicators for coral reef management. *Marine Pollution Bulletin*, **56**:1737-1745.
- Fisher WS. 2007. *Stony Coral Rapid Bioassessment Protocol*. U.S. Environmental Protection Agency. EPA/600/R-06/167.
- Food and Agriculture Organization of the United Nations (FAO). 1996-2005. *FAO Yearbooks 1996 to 2005, Fishery Statistics, Commodities*, Volumes 83-97. Rome.
- Food and Agriculture Organization of the United Nations (FAO). 2002. *State of the World Fisheries and Aquaculture*. Rome.
- Food and Agriculture Organization of the United Nations (FAO). 2010. *Fisheries Glossary*.
<<http://www.fao.org/fi/glossary/default.asp>>
- Friedlander AM and Parrish JD. 1998. Habitat characteristics affecting fish assemblages on a Hawaiian coral reef. *Journal of Experimental Marine Biology and Ecology*, **224**:1-30.
- Gratwicke B and Speight MR. 2005. Effects of habitat complexity on Caribbean marine fish assemblages *Marine Ecology Progress Series*, **292**:301-310.
- Grigg RW. 1984. Resource Management of Precious Corals: A Review and Application to Shallow Water Reef Building Corals. *Marine Ecology*, **5**(1):57-74.
- Grigg RW. 1989. Precious coral fisheries of the Pacific and Mediterranean. In: Caddy JF (ed), *Marine Invertebrate Fisheries: Their Assessment and Management*. San Francisco: John Wiley, pp. 637-645.
- Hanfee F. 1997. *Trade in Corals*. FAO Regional Workshop on the Conservation and Sustainable Management of Coral Reefs.
<<http://www.fao.org/docrep/x5627e/x5627e0r.htm>>
- Harborne AR, Mumby PJ, Micheli F, Perry CT, Dahlgren CP, Holmes KE, Brumbaugh DR and Alan JS. 2006. The Functional Value of Caribbean Coral Reef, Seagrass and Mangrove Habitats to Ecosystem Processes. *Advances in Marine Biology*, **50**:57-189.
- Hatcher BG, Imberger J, Smith SV. 1987. Scaling analysis of coral reef systems: An approach to problems of scale. *Coral Reefs*, **5**:171-181.
- Healthy Reef Initiative. 2010. *Report Card for the Mesoamerican Reef: An Evaluation of Ecosystem Health*. Washington, DC: Smithsonian Institution, 44 pp.
- Hixon MA and Beets JP. 1993. Shelter characteristics and Caribbean fish assemblages: Experiments with artificial reefs. *Bulletin of Marine Science*, **44**:881-892.
- Hodgson G and Dixon JA 2000. El Nido Revisited: Ecotourism, Logging and Fisheries, In: Cesar HSJ (ed), *Collected Essays on the Economics of Coral Reefs*. Kalmar (Sweden): Kalmar University, Department for Biology and Environmental Sciences/CORDIO.
- Hourigan T. 2008. *Deep Water Connections*, **6**(1). (NOAA Fisheries Management Service)
<<http://www.nmfs.noaa.gov/habitat/habitatprotection/pdf/coral/Deep%20Sea%20Corals-habitat%20connections.pdf>> Accessed 2010.07.02.
- Hughes TP, Baird AH, Bellwood DR, Card M, Connolly SR, Folke C, Grosberg R, Hoegh-Guldberg O, Jackson JBC and Kleypas J. 2003. Climate change, human impacts, and the resilience of coral reefs. *Science*, **301**:929-933.
- Idjadi JA and Edmunds PJ. 2006. Scleractinian corals as facilitators for other invertebrates on a Caribbean reef. *Marine Ecology Progress Series*, **319**:117-127.
- Jackson JBC, Kirby MX, Berger WH, Bjorndal KA, Botsford LW, Bourque BJ, Bradbury RH, Cooke R, Erlandson J, Estes JA, Hughes TP, Kidwell S, Lange CB, Lenihan HS, Pandolfi JM, Peterson CH, Steneck RS, Tegner MJ and Warner RR. 2001. Historical Overfishing and the Recent Collapse of Coastal Ecosystems. *Science*, **293**:629-637.
- Labrosse P, Letourneur Y, Kulbicki M and Paddon JR. 2000. Fish stock assessment of the northern New Caledonian lagoons: 3 – Fishing pressure, potential yields and impact on management options. *Aquatic Living Resource*, **13**:91-98
- Levin SA and Paine RT 1974. Disturbance, patch formation, and community structure. *Proceedings of the National Academy of Sciences*, **71**:2744-2747.
- Levins R. 1969. Some demographic and genetic consequences of environmental heterogeneity for biological control. *Bulletin of the Entomological Society of America*, **15**:237-240
- Lindeman KC, Pugliese R, Waugh GT and Ault JS. 2000. Developmental patterns within a multispecies reef fishery: management applications for essential fish habitats and protected areas. *Bulletin of Marine Science*, **66**(3):929-956.
- Livngood EJ and Chapman FA. 2007. *The Ornamental Fish Trade: An Introduction with Perspectives for Responsible Aquarium Fish Ownership*. Gainesville: University of Florida, IFAS Extension FA 124.
- McConnell KE, Strand IE and Blake-Hedges L. 1995. Random Utility Models of Recreational Fishing: Catching Fish Using a Poisson Process. *Marine Resource Economics*, **10**(3):247-261.

- McField M and Richards Kramer P. 2007. *Healthy Reefs for Healthy People: A Guide to Indicators of Reef Health and Social Well-being in the Mesoamerican Reef Region*. With contributions by M Gorrez and M McPherson. Washington, DC: Smithsonian Institution. 208 pp. <http://www.toniparras.com/stories/Healthy_Reef_24_complete-1.pdf>
- Meynecke JO, Lee SY and Duke NC. 2008. Linking spatial metrics and fish catch reveals the importance of coastal wetland connectivity to inshore fisheries in Queensland, Australia. *Biological Conservation*, **141**:981-996.
- Millennium Ecosystem Assessment (MEA). 2005. Millennium Ecosystem Assessment Report - Ecosystems and Human Well-being: Current State and Trends Chapters 18 Marine Fisheries Systems & 19 Coastal Systems. In: Hassan RS and Ash N (eds), *Ecosystems and Human Well-Being: Current State and Trends: Findings of the Condition and Trends Working Group*. Washington, DC: Island Press.
- Moberg F and Rönnbäck P. 2003. Ecosystem services of the tropical seascape: interactions, substitutions and restoration. *Ocean and Coastal Management*, **46**:27-46.
- Moberg F and Folke C. 1999. Ecological goods and services of coral reef ecosystems. *Ecological Economics*, **29**:215-233.
- Mumby PJ. 2006. Connectivity of reef fish between mangroves and coral reefs: Algorithms for the design of marine reserves at seascape scales. *Biological Conservation*, **128**:215-222.
- Mumby PJ, Broad K, Brumbaugh DR, Dahlgren CP, Harborne AR, Hastings A, Holmes KE, Kappel CV, Micheli F and Sanchirico JN. 2008. Coral Reef Habitats as Surrogates of Species, Ecological Functions, and Ecosystem Services. *Conservation Biology*, **22**:941-951.
- Mumby PJ, Edwards AJ, Arias-González JE, Lindeman KC, Blackwell PG, Gall A, Gorczynska MI, Harborne AR, Pescod CL, Renken H, Wabnitz CCC and Llewellyn G. 2004. Mangroves enhance the biomass of coral reef fish communities in the Caribbean. *Nature*, **427**(6974):533-536.
- Mumby, PJ and Steneck, RS. 2008. Coral reef management and conservation in light of rapidly evolving ecological paradigms. *Trends in Ecology & Evolution*, **23**(10):555-563.
- Murray SN, Ambrose RF, Bohnsack JA, Botsford LW, Carr MH, Davis GE, Dayton PK, Gotshall D, Gunderson DR, Hixon MA, Lubcheco J, Mangel M, MacCall A, McArdle DA, Ogden JC, Roughgarden J, Starr RM, Tegner MJ and Yoklavich MM. 1999. No-take reserve networks. *Fisheries*, **24** (11):11-25.
- National Oceanic and Atmospheric Administration (NOAA). 2001. *Fisheries of the United States 2000*. <<http://www.nmfs.gov/st1/fus/fus00/2000-fus.pdf>>
- National Oceanic and Atmospheric Administration (NOAA). 2009. *Fisheries of the United States 2008*. Silver Spring, MD. <<http://www.st.nmfs.noaa.gov/st1/publications.html>>
- National Oceanic and Atmospheric Administration (NOAA). 2008. *Detailed Methods for Characterization and Monitoring of Coral Reef Ecosystems and Associated Biological Communities*. NOAA Center for Coastal Monitoring and Assessment. <http://ccma.nos.noaa.gov/ecosystems/coralreef/reef_fish/protocols.html>
- Núñez-Lara E, Arias-González EJ and Pierre L. 2005. Spatial patterns of Yucatan reef fish communities: Testing models using a multi-scale survey design. *Journal of Experimental Marine Biology and Ecology*, **324**(2):157-169.
- Oceana 2010. *Precious Corals and CITES*. <http://na.oceana.org/sites/default/files/CITES_English_Coral_Fact_Sheet.pdf>
- Odum HT (ed). 1996. *Environmental Accounting: Emergy and Environmental Decision Making*. New York: John Wiley.
- Olsen DA, Nellis DW and Wood RS. 1984. Ciguatera in the Eastern Caribbean. *Marine Fisheries Review*, **46**:13-18.
- Paddock MJ, Reynolds JD, Aguilar C, Appeldoorn RS, Beets J, Burkett EW, Chittaro PM, Clarke K, Esteves R, Fonseca AC, Forrester GE, Friedlander AM, García-Sais J, González-Sansón G, Jordan LKB, McClellan DB, Miller MW, Molloy PP, Mumby PJ, Nagelkerken I, Nemeth M, Navas-Camacho NVC, Reyes-Nivia MC, Robertson DR, Rodríguez-Ramírez A, Salas E, Smith ID, Wormald CL, Watkinson AR and Côté IM. 2009. Recent region-wide declines in Caribbean reef fish abundance. *Current Biology*, **19**:590-595.
- Pandolfi JM, Bradbury RH, Sala E, Hughes TP, Bjorndal KA, Cooke RG, McArdle D, McClenachan L, Newman MJH., Paredes G, Warner RR and Jackson JBC. 2003. Global Trajectories of the Long-Term Decline of Coral Reef Ecosystems. *Science*, **301**:955-958.
- Pattengill-Semmens CV and Semmens BX. 2003. Conservation and Management Applications of the REEF Volunteer Fish monitoring program. *Environmental Monitoring and Assessment*, **81**:43-50.
- Pauly D, Christensen V, Froese R and Palomares ML. 2000. Fishing down aquatic food webs. *American Scientist*, **88**:46-51.
- Pauly D, Watson R and Alder J. 2005. Global trends in world fisheries: impacts on marine ecosystems and food security. *Philosophical Transactions of the Royal Society B*, **360**:5-12.
- Pendleton LH. 1995. Valuing coral reef protection. *Ocean and Coastal Management*, **26**:119-131.
- Pereira MAM. 2000. Preliminary Checklist of Reef-associated Fishes of Mozambique. Maputo: Ministério para a Coordenação da Acção Ambiental (MICOA), Centro de Desenvolvimento Sustentável das Zonas Costeiras (Xai-Xai), Mozambique Coral Reef Management Programme (MCRMP). 28 pp. <<http://www.zonascosteiras.gov.mz/IMG/pdf/2000.7%20full%20text.pdf>>
- Phinn S, Roelfsema C, Dekker A, Brando V and Anstee J. 2008. Mapping seagrass species, cover and biomass in shallow waters: An assessment of satellite multi-spectral and airborne hyper-spectral imaging systems in Moreton Bay (Australia). *Remote Sensing of Environment*, **112**:3413-3425.

- Pittman SJ, Christensen JD, Caldow C, Menza C, Monaco ME. 2007. Predictive mapping of fish species richness across shallow-water seascapes in the Caribbean. *Ecological Modelling*, **204**:9-21.
- Pittman SJ, Hile SD, Jeffrey CFG, Clark R, Woody K, Herlach BD, Caldow C, Monaco ME and Appeldoorn R. 2010. *Coral reef ecosystems of Reserva Natural de La Parguera (Puerto Rico): Spatial and temporal patterns in fish and benthic communities (2001-2007)*. NOAA Technical memorandum NOS NCCOS 107.
- Polunin NVC and Roberts CM. (1996) *Reef Fisheries*. London: Chapman and Hall, 477 pp.
- Public Law (PL) 104-297. 1996. *The Sustainable Fisheries Act*.
- Purkis SJ and Kohler KE. 2008. The role of topography in promoting fractal patchiness in a carbonate shelf landscape. *Coral Reefs*, **27**:977-989.
- Recksiek CW, Murphy BR, Appeldoorn RS and Lindeman KC. 2001. Integrating fish fauna and habitat assessments: A fundamental step in developing fishery reserve design criteria. Proceedings of the 52nd Gulf and Caribbean Fisheries Institute. *GCFI*, **52**:654-666.
- Risk MJ. 1972. Fish diversity on a coral reef in the Virgin Islands. *Atoll Research Bulletin*, **153**:1-6.
- Roberts CM and Pulunin NVC. 1993. Marine Reserves: Simple Solutions to Managing Complex Fisheries? *Ambio*, **22**:363-368.
- Roberts CM and Hawkins JP. 2000. *Fully-protected marine reserves: A guide*. WWF Endangered Seas Campaign, 1250 24th Street, NW, Washington, DC, and Environment Department, University of York, York, UK.
- Roberts CM and Ormond RFG. 1987. Habitat complexity and coral reef fish diversity and abundance on Red Sea fringing reefs. *Marine Ecology Progress Series*, **41**:1-8.
- Rogers CS, Suchanek TH and Pecora F. 1982. Effects of Hurricanes David and Frederic (1979) on a coral reef in St. John USVI. *Marine Ecology Progress Series*, **78**:189-199.
- Roncin N, Alban F, Charbonnel E, Crec'hriou R, de la Cruz Modino R, Culioli J-M, Dimech M, Goñi R, Guala I, Higgins R, Lavissee E, Direach LL, Luna B, Marcos C, Maynou F, Pascual J, Person J, Smith P, Stobart B, Szelianszky E, Valle C, Vaselli S and Boncoeur J. 2008. Uses of ecosystem services provided by MPAs: How much do they impact the local economy? A southern Europe perspective. *Journal for Nature Conservation*, **16**:256-270.
- Sadovy Y and Eklund A. 1999. *Synopsis of biological data on the Nassau grouper, Epinephelus striatus (Bloch 1792), and the jewfish, E. itajara (Lichtenstein 1822)*. NOAA Technical Report NMFS 146 and FAO Fish. Synop. 157.
- Scheffers SR, de Goeij J, van Duyl FC and Bak RPM. 2003. The cave-profiler: A simple tool to describe the 3-D structure of inaccessible coral reef cavities. *Coral Reefs*, **22**:49-53.
- Schmitt EF and Sullivan KM (1996). Analysis of a volunteer method for collecting fish presence and abundance data in the Florida Keys. *Bulletin of Marine Science*, **59**(2):404-416.
- Smith CL. 1972. A spawning aggregation of Nassau grouper, *Epinephelus striatus*. *Trans. American Fisheries Society*, **101**:257-261.
- Smith Q, McKinney J, Komoroske L and Pettersen, L (2002). *Dominica Coral Reef Status 2002: Assessment of the sea urchin Diadema antillarum, reef fishes, and algal cover*. ITME Research Reports **12**:1-2.
- Spurgeon JPG. 1992. The Economic Valuation of Coral Reefs. *Marine Pollution Bulletin*, **24**:529-536.
- Stelzenmüller V, Maynou F, Bernard G, Cadiou G, Camilleri M, Crec'hriou R, Criquet G, Dimech M, Esparza O, Higgins R, Lenfant P and Pérez-Ruzafa Á. 2008. Spatial assessment of fishing effort around European marine reserves: Implications for successful fisheries management. *Marine Pollution Bulletin*, **56**:2018-2026.
- Szmant-Froelich, A. 1985. The effect of colony size on the reproductive ability of the Caribbean coral *Monastrea annularis* (Ellis and Solander). *Proceedings 5th International Coral Reef Congress*, **4**:295-300.
- The Nature Conservancy (TNC). 2010. *Florida Reef Resilience Program*. <<http://www.nature.org/wherework/northamerica/states/florida/preserves/art17499.html>> Accessed September 2010.
- Tibbetts J. 2004. Delving Deeper into the Sea's Bounty. *Environmental Health Perspectives*, **112**(8):472-481.
- Trexler JC and Davis TJ. 2000. Can marine protected areas restore and conserve stock attributes of reef fishes? *Bulletin of Marine Science*, **66**:853-873.
- Tsounis G, Rossi S, Grigg R, Santangelo G, Bramanti L & Gili J. 2010. The exploitation and conservation of precious corals. *Oceanography and Marine Biology: An Annual Review*, **48**:161-212.
- U.S. Environmental Protection Agency (EPA). 2005. *Reviewing Environmental Impact Statements for Fishery Management Plans*. Office of Federal Activities. Washington, DC.
- U.S. Fish and Wildlife Service (USFWS). 2011. *Coral Trade*. <<http://www.fws.gov/news/coral.html>>
- Wabnitz C, Taylor M, Green E and Razak T. 2003. *From Ocean to Aquarium*. Cambridge (UK): UNEP-WCMC, 64 pp.
- Walker BK, Jordan LKB and Spieler RE. 2009. Relationship of Reef Fish Assemblages and Topographic Complexity on Southeastern Florida Coral Reef Habitats. *Journal of Coastal Research*, **53**:39-48.
- Warner RR. 1990. Resource assessment versus tradition in mating-site determination. *American Nature*, **135**:205-217.
- Warren-Rhodes K, Sadovy Y and Cesar HSJ. 2003. Marine Ecosystem Appropriation in the Indo-Pacific: A Case Study of the Live Reef Fish Food Trade. *Ambio*, **32**:481-488.
- Wilson SK, Graham NAJ and Polunin NVC. 2007. Appraisal of visual assessments of habitat complexity and benthic composition on coral reefs. *Marine Biology*, **151**:1069-1076.

World Health Organization (WHO). 2010. *Global and regional food consumption patterns and trends*.
<http://www.who.int/nutrition/topics/3_foodconsumption/en/index5.html> Accessed 2010.07.02.

Coral Reefs: Shoreline Protection

4.1 Defining the service

Coral reefs form natural barriers along the coast, protecting coastlines from erosion, flooding, and storm damage (UNEP-WCMC 2006; WRI 2009). In general, the term “shoreline protection” refers to the ability of reefs to attenuate offshore wave energy, providing sheltered nearshore waters, and protecting coastlines from erosion, flooding, and storm damage. Shoreline protection has been defined in various ways, including intermediate biophysical ecosystem services endpoints that are indirectly relevant to human well-being, final ecosystem services endpoints that are directly relevant to human well-being, or ecosystem-derived benefits that provide social value (Table 4-1; Wainger & Boyd 2009). However, far greater progress has been made in advancing our understanding of wave energy attenuation than in linking that attenuation to the provision of ecosystem services. The key to quantifying shoreline protection is to understand the links between reef attributes, physical processes, and benefits relevant to society.

Table 4-1. Measures that have been used to quantify shoreline protection

Ecological processes
<i>Physical processes</i>
• Reduction in wave energy, velocity, or height
<i>Biological processes and structures</i>
• Damage to coral reefs by hurricanes and storm events
• Presence of seagrasses or mangroves
• Fish density and species composition
Ecosystem services
• Rates of beach or shoreline erosion
• Shoreline geography
• Wave set-up during extreme events
• Coastal inundation during extreme events
Socioeconomic benefits
• Reduced property damage or loss of life during extreme events
• Dollar value of avoided damages during extreme events
• Dollar value to build artificial wave breaks

Categories derived from Wainger & Boyd 2009

The physical properties of wave attenuation have been measured and modeled in studies of numerous locales worldwide, including the Caribbean (Lugo-Fernandez *et al.* 1998), Australia (Hardy & Young 1996), and Hawaii (Gerritsen 1981). Ocean waves traveling over coral reefs experience significant attenuation of energy, height, and velocity (Wolanski 1994; Gourlay & Colleter 2005; Lowe *et al.* 2005). Wave attenuation by coral reefs has biological consequences for the reef itself as well as inshore ecosystems:

- shelter is provided to nearshore coral from damaging effects of hurricanes (Woodley *et al.* 1981);
- low-energy environments are created that are favorable to the growth of highly valued wetlands, including seagrasses and mangroves (Birkeland 1985); and,
- recruitment and nursery habitats (mangroves and seagrasses) for fish are protected (DeMartini *et al.* 2009).

Shoreline protection has also been quantified using metrics that are more directly relevant to humans. Wave energy moderation provided by reefs can greatly influence the geography of the coastline (Black & Andrews 2001) and reduce the rate of shoreline erosion (Frihy *et al.* 2004). The value of such ecosystem services is often underappreciated until expensive beach restoration (Riopelle 1995) or artificial breakwaters are needed to protect eroding beaches (Berg *et al.* 1998; Talbot & Wilkinson 2001). Reefs also play an important role in mitigating coastal flooding caused by natural hazards, such as large storms, hurricanes or cyclones, and tsunamis, which can cause immense property damage and loss of human life (Sudmeier-Rieux *et al.* 2006).

Quantifying shoreline protection in terms of hazard mitigation is challenging and often anecdotal. Although hurricanes or cyclones occur worldwide, much of the information on coastal flooding, property damage, and loss of life comes from examining the effects of reefs in mitigating tsunami damage in Asian countries (UNEP-WCMC 2006). Recent extreme events undoubtedly color the interpretations of shoreline protection, as do regional differences in geography, coastal development, and frequency of storm events (WRI 2009).

4.2 Providing the service

4.2.1 Presence of the reef

The scientific evidence for shoreline protection by coral reefs is largely anecdotal and observational, quantified by various physical, biological, and social endpoints with and without the presence of reefs (Table 4-1). The presence of coral reefs has long been known to provide wave-sheltering and protection to the coastline, with locals utilizing calm waters for navigation routes, fishing, and recreation (UNEP-WCMC 2006). The presence of reefs is associated with:

- the inshore presence of seagrasses and mangroves (Birkeland 1985; Ogden & Gladfelter 1983; Short et al. 2007);
- a reduction in offshore wave energy reaching the shoreline (Lugo-Fernandez et al. 1998);
- reduced rates of shoreline erosion (Hayden et al. 1978); and,
- reduced property damage and loss of life during extreme events (EJF 2005; UNEP-WCMC 2006).

Furthermore, the presence of certain reef types or species (*e.g.*, patch reef, *Acropora* spp., or *Montastraea* spp.) has also been used to characterize the relative magnitude of wave energy attenuation (Mumby et al. 2008).

4.2.2 Reef attributes

Beyond the presence or absence of a reef, key attributes such as reef height, width, and topography (see Table 4-2) need to be monitored to provide a more detailed understanding of wave energy attenuation.

The contribution of reef attributes to the hydrodynamic processes governing wave energy attenuation by coral reefs have been extensively modeled and studied with field observations (Monismith 2007). The general idea is that incoming waves break at the face of the reef, causing an initial increase in water level within the surf zone, which pushes waves over the reef flat as they travel to shore (Figure 4-1). Offshore wave height and propagation over the reef will determine the height of waves reaching the shore, typically quantified by the wave set-up (the increase in water level above the still water level) and wave run-up (the height along the beach that water reaches due to incoming waves).

Table 4-2. Reef attributes that contribute to wave attenuation. Definitions are a synthesis of those used in literature (see Appendix 4-A; also Figure 4-1 and Glossary)

Attribute	Definition
Presence of reef	indicates whether or not an offshore reef is present near the coastal area of interest.
Reef continuity	the extent to which the reef is uninterrupted or unfragmented in distribution; namely, the absence of large gaps such as those due to degradation or coral mining.
Reef depth	the distance from the ocean surface to the top of the reef; may be an assumed or fixed value in simulation models, or an average value from field observations for the reef in question.
Reef distance	the distance between the reef crest at the seaward edge of the reef and the edge of the shoreline; essentially, the width of the lagoon; may be an assumed or fixed value in simulation models, or an average value from field observations for the reef in question.
Reef height	the distance from the top of the reef to its base; may be an assumed or fixed value in simulation models, or an average value from field observations for the reef in question.
Reef roughness	the bottom drag coefficient (which characterizes friction); may be approximated in field studies by variability in colony height, or other measures of topography, along the reef flat; may be estimated indirectly by fitting models to data on wave energy attenuation.
Reef slope	the angle, from gradual to steep, of the reef front where offshore waves are first encountered; may be an assumed or fixed value in simulation models, or an average value from field observations for the reef in question.
Reef type	describes the general structure of the reef and its relationship to the shoreline, including fringing reefs that border the shoreline, barrier reefs that are separated from shore by a deep lagoon, atoll reefs that form a circular barrier around an island, and patch reefs that are small, isolated reef outcrops.
Reef width	the length of the reef flat, the flat expanse of reef from where offshore waves first crest over the reef to the edge closest to the shoreline; may be an assumed or fixed value in simulation models, or an average value from field observations for the reef in question.

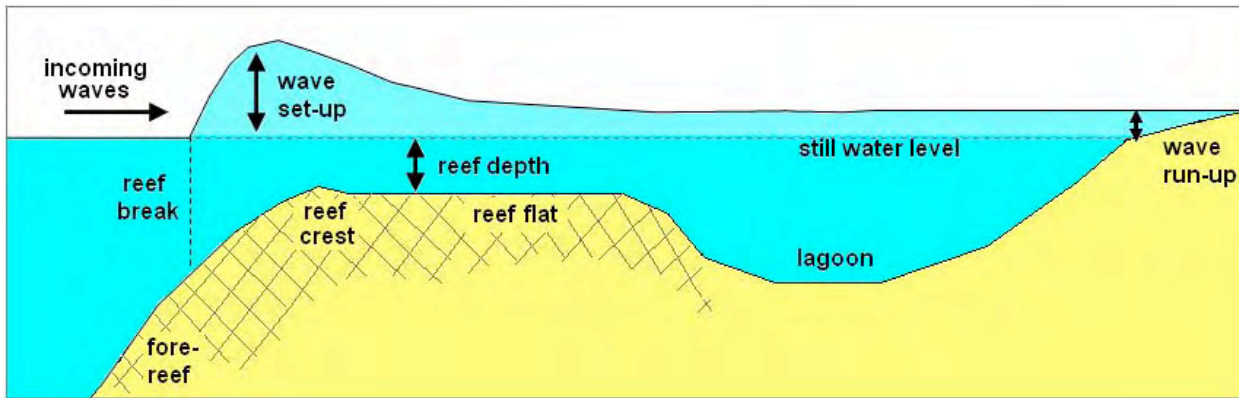


Figure 4-1. Illustration of wave set-up and attenuation over a reef (redrawn from Monismith [2007]).

Coral reefs reduce offshore wave energy primarily in two ways: (1) the steep gradient from deep water to shallow causes the wave to break at the reef crest; and, perhaps more importantly, (2) the increased bottom friction along the reef flat creates drag (Wolanski 1994; Lowe *et al.* 2005). Reef depth is perhaps the simplest single attribute that can be related to wave attenuation (Gourlay 1994; Barbier *et al.* 2008). Reef area, reef slope, and distance from shoreline are additional key attributes derived from field (Young 1989; Hardy & Young 1996; Brander *et al.* 2004) and modeling studies (Tait 1972; Gourlay & Colleter 2005). In general, wave energy attenuation decreases with increasing reef depth across the reef flat, with greater energy being attenuated as reef width increases (Figure 4-2; Kunkel *et al.* 2006), such that broad, shallow reefs provide the greatest attenuation. Tidal variations in water depth and initial offshore wave height can also influence the degree of wave energy attenuation (Madin *et al.* 2006).

Modeling studies indicate that friction across the reef surface is a strong determinant of the degree of wave energy attenuation, as can be seen in Figure 4-2 (Sheppard *et al.* 2005; Kunkel *et al.* 2006). Drag coefficients used to quantify reef friction in simulation models are often calibrated by comparing model outcomes to field data. These coefficients indicate that coral reefs exert ten times more drag than sandy bottoms (Tait 1972; Roberts *et al.* 1975; Lugo-Fernandez 1998; Reidenbach *et al.* 2006). Measurements of *in situ* reef friction are challenging to obtain. Field estimates of reef roughness based on the standard deviation of reef height have provided values similar to model-calibrated estimates of reef friction (Lowe *et al.* 2005). Other methods for estimating reef roughness have been used, including draping chains over reefs along a transect to generate a linear measure of surface topography. There are as yet no standard methods for deriving wave energy attenuation from field measurements of reef roughness (Monismith 2007).

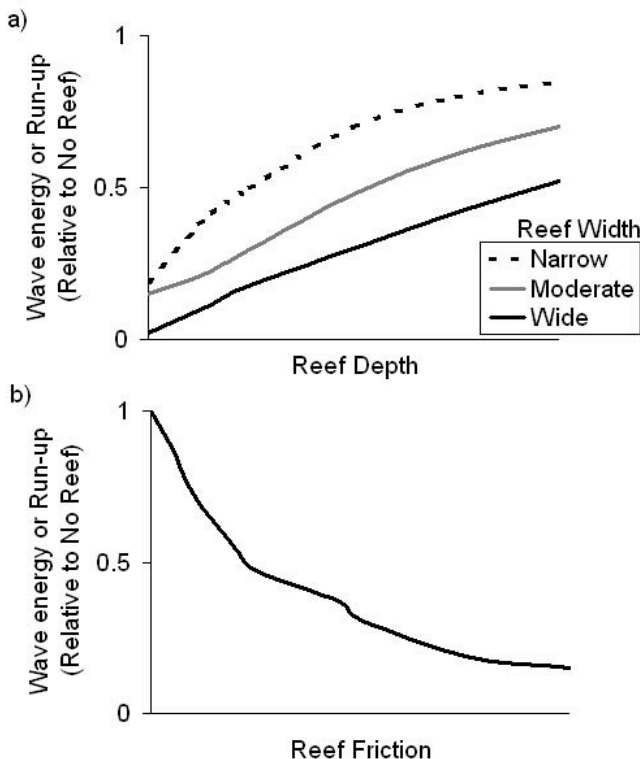


Figure 4-2. Relationship of wave energy with increasing reef depth and width (top) and with increasing reef friction (bottom) (derived from Sheppard *et al.* [2005] and Kunkel *et al.* [2006])

4.2.3 Reef health

The health of a coral reef is an important determinant of wave attenuation. Degraded reefs have diminished roughness, and model simulations indicate the reduction in reef friction reduces the reef's attenuation of wave energy (Figure 4-2; Kunkel *et al.* 2006; Sheppard *et al.* 2005). A reduction in reef friction of approximately 50% could produce a doubling of wave energy reaching the shores behind those reefs. Dead corals on degraded reefs break or disintegrate easily under wave action, resulting in reduced reef height and roughness and, consequently, in reduced attenuation of wave energy. In general, the degree of shoreline protection afforded by reefs during storms reflects a balance between the reef's attenuation of wave energy and the damage inflicted on the reef itself by that storm event (Lacambra *et al.* 2008).

Reef continuity is another important indicator of shoreline protection (WRI 2009). Damage to reefs from coral mining, in which large sections of coral are harvested to provide blocks for construction, can accelerate rates of beach erosion and require expensive beach restoration (Riopelle 1995). Fragmented reefs can allow high energy tsunami waves to reach the shoreline (Nott 1997) and may intensify flooding (Fernando *et al.* 2005; Chatenoux & Peduzzi 2005). Furthermore, sections of degraded reef that have been invaded by macroalgae may afford less protection than reefs with a high abundance of large stony coral species (Mumby *et al.* 2008).

Shoreline protection may be devalued by as much as 80%–90% when reefs are degraded (Burke & Maidens 2004). For valuation purposes, reefs are assumed to retain their protective capacity until coral cover (living tissue) loss exceeds 25%, after which the value of coastal protection declines linearly with increasing loss of coral (Cesar 1996; Pet-Soede *et al.* 1999). The most extreme degradation leads to loss of reefs, which can have severe consequences for property damage and human life in the case of extreme hazard events (Sudmeier-Rieux *et al.* 2006).

4.3 Measuring the service

Shoreline protection has been quantified in numerous ways that vary in their relevance to human well-being (Table 4-3). Natural features, including reef attributes and physical variables, have been translated into metrics of shoreline protection using anecdotal information, statistical relationships, and mechanistic models. Estimates of coastal protection also depend on socioeconomic variables.

4.3.1 Physical processes

Incoming waves encountering the steep gradient at the reef front causes the waves to break, producing a sudden increase in wave amplitude that diminishes (or attenuates) as the residual wave energy moves toward shore (Figure 4-1). Numerous field, laboratory, and modeling studies have looked at physical endpoints of shoreline protection in terms of reductions in wave energy, wave height, or wave velocity from offshore to the shoreline (reviewed in Gourlay & Colleter [2005], Sheppard *et al.* [2005], and Monismith [2007]; see Table 4-3). Field studies have measured as much as a 68%–95% reduction in wave energy as waves travel over the reef flat (Roberts *et al.* 1975; Gerritsen 1981; Young 1989; Lugo-Fernandez *et al.* 1998; Brander *et al.* 2004). Tidal variations in reef depth will produce variations in the degree of wave energy attenuation. At high tide, waves within the normal range may be reduced only slightly by the reef, whereas at low tide all waves may effectively be blocked (Madin *et al.* 2006). Attenuation of wave energy and height are essential for understanding the height of wave inundation on the shore, referred to as wave run-up, which also has been modeled (Kunkel *et al.* 2006). Wave run-up may be a potential indicator of damage from flooding, and physical models can be used to translate reductions in wave height into flood hazard maps, depending on the slope and porosity of the shoreline (FEMA 2007).

4.3.2 Biological processes

Shoreline protection by coral reefs has also been quantified through the health and survival of highly valued biological components in near-shore areas and along the coast. For example, the presence of outer reefs can shelter nearshore coral from damaging effects of hurricanes (Woodley *et al.* 1981). The protection afforded by coral reefs also creates low-energy environments favorable to the growth of seagrasses or mangroves in coastal wetlands (Ogden & Gladfelter 1983; Birkeland 1985; Short *et al.* 2007; Sheaves 2009). Reefs reduce the vulnerability of wetlands to damage and vegetative loss during hurricane events (Fourqurean & Rutten 2004). Wetlands themselves provide numerous ecosystem services (Mumby *et al.* 2008) and in many regions are more important for coastal protection than the presence of reefs (EJF 2005; Cochard *et al.* 2008). Reefs appear to serve as a first line of defense by diffusing wave energy and protecting coastal wetlands, thereby enhancing the protective value of those wetlands. Whether there exists a synergistic relationship between wave energy attenuation by reefs and shoreline protection by mangrove and seagrass wetlands has not been studied.

Table 4-3. Measures used to quantify shoreline protection, and the major reef attributes, physical parameters, and socioeconomic parameters used to estimate that protection's value (see Appendix 4-A for details)

Measures	Reef Attribute	Physical Variables	Socioeconomic Variables
Physical processes			
Reduction in wave energy, velocity, or height in appropriate units	Reef depth, width, slope, roughness, distance to shore	Offshore wave energy & height; Tidal depth	
Biological processes			
Damage to coral by hurricanes (e.g., prevalence of broken coral)	Presence of outer reef; Reef depth, width, slope	Hurricane path	
Presence of seagrasses or mangroves (e.g., area)	Presence of reef; Gap in reef		
Fish density & species composition	Presence of reef	Water motion; Wind or wave exposure	
Ecosystem services			
Rates of shoreline erosion (e.g., distance or volume lost per year)	Presence of reef; Reef depth	Wave energy; Beach elevation & sediment grain size	
Shoreline geography (e.g., presence of salients & tombolos, change in shoreline position)	Reef width; Distance from shoreline	Wave height and period	
Wave set-up during extreme events	Presence of reef; Reef depth, width, slope, & roughness	Offshore wave energy, height, & amplitude	
Coastal inundation during extreme events (e.g., decrease in area inundated)	Presence or area of reef; Gap in reef;	Distance from hazard event; Slope of coastline;	
Socioeconomic benefits			
Decrease in property damage or loss of life during extreme events	Presence of intact reefs		
Value of avoided damages	Presence of reef; Reef type, continuity, & distance from shore	Coastal geography; Storm height & frequency	Property values
Replaces need for costly artificial breakwaters or beach replenishment	Presence of reef		Breakwater costs; Restoration costs

Reductions in wave energy by reefs may also provide prime wave-sheltered habitat for larval fish and enhance local recruitment. Lower water velocities and reduced wave exposure are associated with high juvenile fish densities (Burgess *et al.* 2007; DeMartini *et al.* 2009). Fish assemblages in wave-sheltered reefs often have different species than exposed habitats, including small fish species whose locomotion and foraging activities may be inhibited in fast-moving water (Fulton & Bellwood 2005). Increased fish abundance would likely increase fishing and tourism services, something that has been discussed anecdotally (UNEP-WCMC 2006) but not linked directly to the physical processes of wave energy attenuation.

4.3.3 Ecosystem service measures

Physical hydrodynamic processes associated with coral reefs affect the geography, appearance, and stability of the shoreline. The strength and pattern of waves reaching the beach determine rates of beach erosion and shapes the contours of the shoreline (Hayden *et al.* 1978). Models have been developed to predict rates and patterns of shoreline changes under a variety of wave conditions (Frihy *et al.* 2004). Assuming the edge of the shoreline may change by an average of 0.4 meters per year in unprotected areas, an example of a quantitative measure of an ecosystem service is given in Berg *et al.* (1998), who estimated that 1 km² of reef, protecting 5 km of shoreline along the coast of Sri Lanka could prevent a loss of 2,000 m² of land per year. The presence of reefs can also influence the contour of the shoreline through the creation of salients (bell-shaped extensions of the shoreline toward the reef) and tombolos (shoreline extensions connecting to offshore sandbars) (Figure 4-3). The size of

these shoreline extensions depends on the width of nearby reefs and reef distance offshore (Black & Andrews 2001). Coral reefs also play a role in replenishing sandy beaches and islands as corals and other calcified organisms break down after death (UNEP-WCMC 2006).

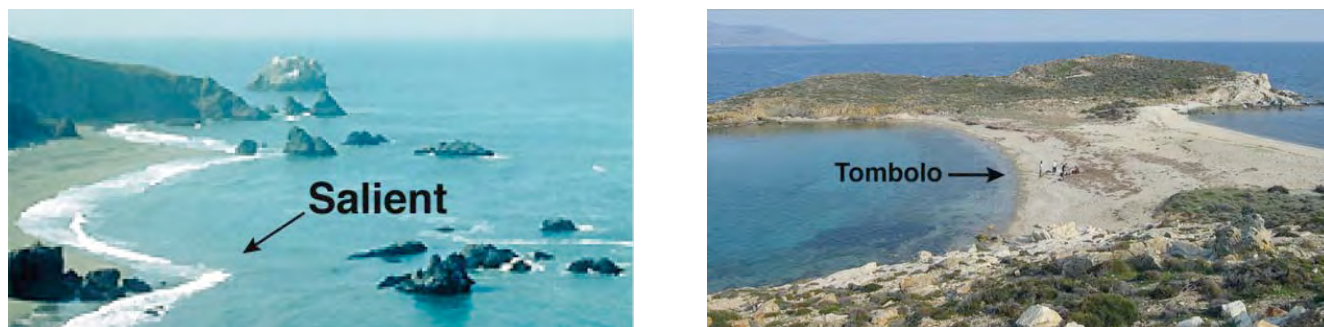


Figure 4-3. Reef influences on shorelines: salient (left) and tombolo (right).

(photo credits: salient – California State Parks [2011]; tombolo – Tim Bekaert [2005])

Reductions in wave energy or wave height by coral reefs have clearer socioeconomic relevance when connected to wave run-up or coastal flooding during storm or extreme hazard events. Numerous studies that have examined wave run-up during tsunami events suggest that, while there is some evidence of reduced flooding in areas behind reefs (Fernando *et al.* 2005), channelized or fragmented reefs may actually accelerate movement of tsunami waves to the coastline (Nott 1997; Chatenoux & Peduzzi 2007). Modeling studies indicate the buffering ability of reefs is largely dependent on the state of reef health (Kunkel *et al.* 2006). In other observational studies, however, reefs appeared to have little protective value, and tsunami inundation was largely determined by wave height and coastal topography (Baird *et al.* 2005). Coral reefs may be more effective at buffering normal wave action or storm events than tsunamis, which have longer wavelengths and larger wave amplitudes (Cochard *et al.* 2008).

4.3.4 Socioeconomic benefits

The value of reefs in shoreline protection is often underappreciated until quantified in terms of human lives, property damage, or economic costs. Anecdotally, the presence of reefs is linked to diminished property damage and loss of life during hurricanes (Whittingham *et al.* 2003) or tsunamis (Liu *et al.* 2005; WI 2005; UNEP 2005; EJF 2005; UNEP-WCMC 2006). In one study of a tsunami's effects, areas protected by reefs experienced wave heights of only 2–3 m with inundation extending only 50 m inland with no loss human life (Fernando *et al.* 2005). In contrast, just 3 km to the north where there was no coral reef to protect the shore, the same tsunami resulted in a 10 m wave that flooded 1.5 km inland and killed 1,700 people. This evidence is largely anecdotal, however, and there is some question as to whether reefs substantially reduce coastal inundation during tsunami events (Baird *et al.* 2005; Cochard *et al.* 2008).

Although shoreline protection can be a significant contributor to the total economic value of coral reefs, it is largely underestimated by decision-makers, except during times of crisis. A few studies (see below) have attempted to place a dollar value on coastal protection by reefs, either in terms of expected damages or beach/shoreline replacement costs due to reef degradation (Chong 2005).

4.4 Valuing the service

There are many coral reef studies estimating costs of reef restoration, fisheries value, or recreational value, but only a few studies have looked at the economic value of shoreline protection (Chong 2005; Table 4-4). One approach to valuing coastal protection is to estimate defensive expenditures required to replace the loss of the reef. When reefs are severely degraded, they may need to be replaced with artificial breakwaters that may cost \$10m per linear kilometer to construct (Wells & Edwards 1989; Weber 1993; Berg *et al.* 1998; Talbot & Wilkinson 2001). In other cases, expensive beach and shoreline restoration is needed as a consequence of lost coral reefs (Riopelle 1995).

Another approach to estimating the economic value of coastal protection is to estimate the damages avoided due to the presence of the reef. In a study of Indonesian Reefs, Cesar (1996) estimated the monetary value of damage avoided based on the value of three types of coastal development: (1) the value of agricultural production (\$820 per km coastline); (2) the cost of replacing homes and road infrastructure (\$50,000 per km coastline); and, (3) hotel expenditures toward maintaining beaches (\$1,000,000 per km coastline). These values, or similarly derived values, have been used to value damages avoided due to the presence of reefs in Bermuda (Beukering *et al.* 2010), the Philippines (White *et al.* 2000), throughout the Caribbean (Burke & Maidens 2004), southeast Asia (Burke *et al.* 2002), and worldwide (Cesar *et al.* 2003).

The economic value of coral reefs depends on more than just the presence of the reef. Reliable economic estimates require knowledge of biological, physical, and socioeconomic factors that influence the provision of and need for coastal protection

(WRI 2009). First, the value of shoreline protection will depend on whether the coastal area is vulnerable to erosion or storm damage, namely low-lying lands near the coast. Second, coastal vulnerability is determined by the physical stability of the shoreline (including coastal geomorphology and geology, elevation, and vegetation) and the potential for storm surges (including offshore wave energy and hurricane frequency). Third, reef attributes such as distance from shore, reef continuity, and type of reef determine the protective capability of the reef. Fourth, the amount and value of coastal development will determine the potential value of protection. All of these factors must be considered when estimating the potential economic damages resulting from the loss of reefs. This approach has been used to estimate the value reef coastal protection throughout the world as ranging from \$0.3 billion to \$2.2 billion (Burke *et al.* 2002; Burke & Maidens 2004). Coastal development, sedimentation, pollution, overfishing, and climate change can severely degrade reefs, reducing their protective ability by an estimated 80–90%, with a potential net loss of benefits associated with shoreline protection on the order of \$140m to \$420m per year in the Caribbean (Burke & Maidens 2004).

Table 4-4. Estimated values of shoreline protection (modified from Chong 2005)

Location	Total Value	Study
Americas		
Bermuda	\$266m	Beukering <i>et al.</i> 2010
Caribbean	\$720m	Cesar <i>et al.</i> 2003
Caribbean	\$700m–\$2,200m	Burke & Maidens 2004
USA	\$172m	Cesar <i>et al.</i> 2003
Asia		
Australia	\$629m	Cesar <i>et al.</i> 2003
Indian Ocean	\$1,595m	Cesar <i>et al.</i> 2003
Indonesia	\$314m	Burke <i>et al.</i> 2002
Japan	\$268m	Cesar <i>et al.</i> 2003
Philippines	\$326m	Burke <i>et al.</i> 2002
SE Asia	\$5,047m	Cesar <i>et al.</i> 2003
Pacific	\$579m	Cesar <i>et al.</i> 2003
Sri Lanka	\$30m	Berg <i>et al.</i> 1998
World	\$9,009m	Cesar <i>et al.</i> 2003
Values per kilometer of shoreline		
Caribbean		
<i>Low development</i>	\$2,000–\$20,000	Burke & Maidens 2004
<i>Medium development</i>	\$30,000–\$60,000	Burke & Maidens 2004
<i>High development</i>	\$100,000–\$1,000,000	Burke & Maidens 2004
Indonesia		
<i>Remote areas</i>	\$820	Cesar 1996
<i>Some construction</i>	\$50,000	Cesar 1996
<i>Major infrastructure</i>	\$1,000,000	Cesar 1996
Philippines	\$5,000–\$25,000	White <i>et al.</i> 2000
Maldives	\$10,000,000	Talbot & Wilkinson 2001

4.5 Reflections

Final ecosystem services for shoreline protection are summarized in Table 4-5. Natural features, including reef attributes and physical variables, contribute to biophysical processes that provide ecosystem services, such as wave energy attenuation. These natural processes directly benefit humans by reducing shoreline erosion and protecting coastlines from inundation during extreme events. Social values, such as the desirability of coastal housing or the attractiveness of sandy beaches, influence the demand for shoreline protection. Complementary goods and services, such as the availability, intensity, and location of coastal development or the absence of constructed breakwaters, influence the opportunity to take advantage of shoreline protection. The existence of constructed breakwaters, including rubble mounds and artificial reefs, can also diminish the demand for shoreline protection by natural reefs.

4.5.1 Improving current knowledge

Physical models of wave energy attenuation are based on relatively simple physical assumptions, so field validation of mathematical models of wave energy attenuation would improve our ability to characterize the degree of protection provided

under different conditions (Monismith 2007). Furthermore, the reef is generally treated as a single object, rather than a living community. Although some models have attempted to connect reef roughness to wave energy attenuation (Sheppard *et al.* 2005; Kunkel *et al.* 2006), there is little understanding of how reef attributes, such as species composition or skeletal calcification rates, contribute to wave attenuation, or how growth, reproduction, and survival contribute to sustainable shoreline protection.

Our understanding of the social benefits of shoreline protection is largely derived from anecdotal evidence, but it could be improved with more quantitative or statistical studies relating property damage or loss of life to reef attributes and physical properties of the coastline. Furthermore, studies of flooding or potential damage during extreme events are largely tied to tsunamis (UNEP-WCMC 2006). Less is known about the extent to which reefs reduce hurricane damage, but the protection provided by reefs may result from buffering wave energy rather than reducing inundation (Cochard *et al.* 2008).

The presence of reefs is associated with providing wave-sheltered environments for mangroves and seagrasses (Birkeland 1985), yet there is little understanding of how subtle changes in reef integrity may impact these neighboring systems. Furthermore, wetlands themselves are important for coastal protection and their protective ability may be enhanced by the presence of reefs as a first line of defense (EJF 2005). However, the potential synergistic relationship between reef shoreline protection and the provision of wetland ecosystem services is not well understood.

Few studies have attempted to quantify or value indirect consequences of shoreline protection by reefs (Chong 2005). Direct consequences of storm events, hurricanes, and tsunamis include loss of lives, housing, and buildings. These direct losses can have long-lasting reverberations as the affected society becomes vulnerable to disease epidemics or economic instability (Cochard *et al.* 2008). The potential value of shoreline protection will depend on the likelihood of such indirect consequences, and the potential for the local economy to rebound from disasters. Historical data on disease outbreaks, economic losses, and time to economic recovery for post-hurricane or post-tsunami economies might suggest which societies are particularly vulnerable to a loss of shoreline protection. The current lack of consideration of indirect consequences is an oversight that may lead decision makers to underestimate the potential value of shoreline protection.

4.5.2 Connecting biophysical processes and ecosystem services to socioeconomic benefits

For biophysical endpoints to be relevant to humans, they must connect to an ecosystem service or social benefit (Wainger & Boyd 2009). Ideally, our ability to quantify shoreline protection in socially relevant endpoints requires that we characterize two relationships in quantitative terms: (1) that between reef attributes and the physical environment; and, (2) that between the physical environment and ecosystem services, including their social benefits (Figure 4-4). Natural features of the environment, including attributes of the reef and physical attributes of offshore waves, affect physical ecosystem processes, such as attenuation of wave height or energy. Attenuation of wave energy by reefs leads to protection from shoreline erosion or flooding, but the degree of protection will depend on physical variables, such as coastal geography, vegetation, and the frequency of storm events. Humans derive benefits from shoreline protection through reductions in property damage or loss of life, but the value of protection will depend on socioeconomic factors, such as the degree of coastal development and property values (WRI 2009). Wave energy attenuation can also indirectly benefit humans by providing wave-sheltered habitats for fish or protecting wetlands, which themselves provide ecosystem services.

The quantitative relationships between reef attributes and shoreline protection and between physical processes and socioeconomic benefits are poorly understood. Models of wave energy attenuation are reasonably adept at accounting for the impacts of reef attributes such as height, width, slope, and roughness (Lowe *et al.* 2005; Sheppard *et al.* 2005; Kunkel *et al.* 2006). However, our understanding of the socioeconomic benefits, such as the prevention of property damage or loss of life, is largely anecdotal, based solely on the presence or absence of a reef (UNEP-WCMC 2006). Further research and modeling efforts are needed to provide useful quantifications of these relationships.

Table 4-5. Final ecosystem services and supporting features for shoreline protection

Ecosystem Service(s)		Natural Features	Social Values	Complementary Goods & Services	Ecosystem-Derived Benefits	Potential Indicators of Final Ecosystem Service(s)
Final (FES)	Intermediate					
Shoreline Protection						
Protection from shoreline erosion	Decreased erosion in kg/ha/y Reduction in wave energy, velocity, or height Presence of reef	Reef height, width, slope, & roughness	Reef continuity Offshore wave energy & wave height Tidal depth	Beach elevation, sediment grain size Attractiveness of sandy beaches	Desirability of housing near water Absence of constructed breakwaters Higher property values	Opportunity to use beaches (see Chapter 2) % reduction in rates of shoreline erosion due to presence of reef
Protection from coastal inundation during extreme events area in hectares protected Reduction in wave set-up, or storm surge Presence of reef	Reef height, width, slope, roughness	Reef continuity Wave energy	Distance from hazard event	Slope of coastline	Frequency & intensity of extreme events Past history of extreme events Absence of constructed breakwaters	Location, intensity, and value of coastal development Lower insurance rates

Definitions (proposed by the Ecosystem Services Research Program and currently under discussion by the Program)

- **Final Ecosystem Service** – Output of ecological functions or processes that directly contributes to social welfare or has the potential to do so in the future (broadly based on Boyd & Banzhaf [2007]).
- **Intermediate Ecosystem Service** - Output of ecological functions or processes that indirectly contributes to social welfare or has the potential to do so in the future.
- **Natural Features** – The biological, chemical, and physical attributes of an ecosystem or environment.
- **Social Values** – The social attributes that influence economic demand for an ecosystem service.
- **Complementary Goods & Services** - Inputs (usually built infrastructure or location characteristics) that allow a good or service to be used by complementing the ecological condition. For example, complementary goods and services that allow the presence of fishable fish to become an opportunity for recreational fishing will include aspects of site accessibility, such as road access, available parking and the presence of a fishing pier, all of which make fishing at the site possible and enhance enjoyment of the activity.
- **Ecosystem-Derived Benefits** - The contribution to social welfare of ecosystem goods and services. In the ESRP, the term applies specifically to net improvements in social welfare that result from changes in the quantity or quality of ecosystem goods and services attributable to policy or environmental decisions.
- **Indicator of Final Ecosystem Service** – Biophysical feature, quantity, or quality that requires little further translation to make clear its relevance to human well-being (*i.e.*, “public-friendly” measurement)

One possible approach for linking reef attributes with socioeconomic benefits of shoreline protection would be to integrate socioeconomic metrics into physical process models. Wave attenuation by reefs has been fairly well characterized in laboratory experiments, field observations, and models (as reviewed in Gourlay & Colleter [2005], Sheppard *et al.* [2005], and Monismith [2007]), and it has been connected to shoreline changes using predictive models (Frihy *et al.* 2004). However, for all intents and purposes, there are no studies connecting changes in wave energy or height to potential loss of life or property damage. The Reefs at Risk shoreline protection index (WRI 2009), which is used to calculate the damage prevention provided by reefs, indirectly accounts for a number of physical processes by considering key reef attributes related to wave attenuation. In addition to reef distance from shore, Reefs at Risk includes reef type as a proxy for reef depth and slope, and reef degradation as a proxy for bottom friction. However, these factors are combined into a single index reflecting shoreline stability and fail to capture more subtle changes in reef topography or species composition that may influence wave energy attenuation.

Bayesian probabilistic networks could be useful for characterizing the complex relationships between reef attributes and probabilistic characterizations of exposure, damage, and cost (Cochard *et al.* 2008). Physical models of wave energy attenuation that permit subtle changes in reef height, slope, width, and friction, combined with the physical properties of the coastline and local climate, could be the basis for developing predictive models for the probability of flooding or shoreline erosion. These could then be tied to socioeconomic factors, such as the degree of coastal development, to predict the probability of property damage, loss of life, or a variety of indirect consequences. Such models could reflect the uncertainty associated with largely anecdotal information and could be updated as probabilistic characterizations of relationships or physical process models are improved.

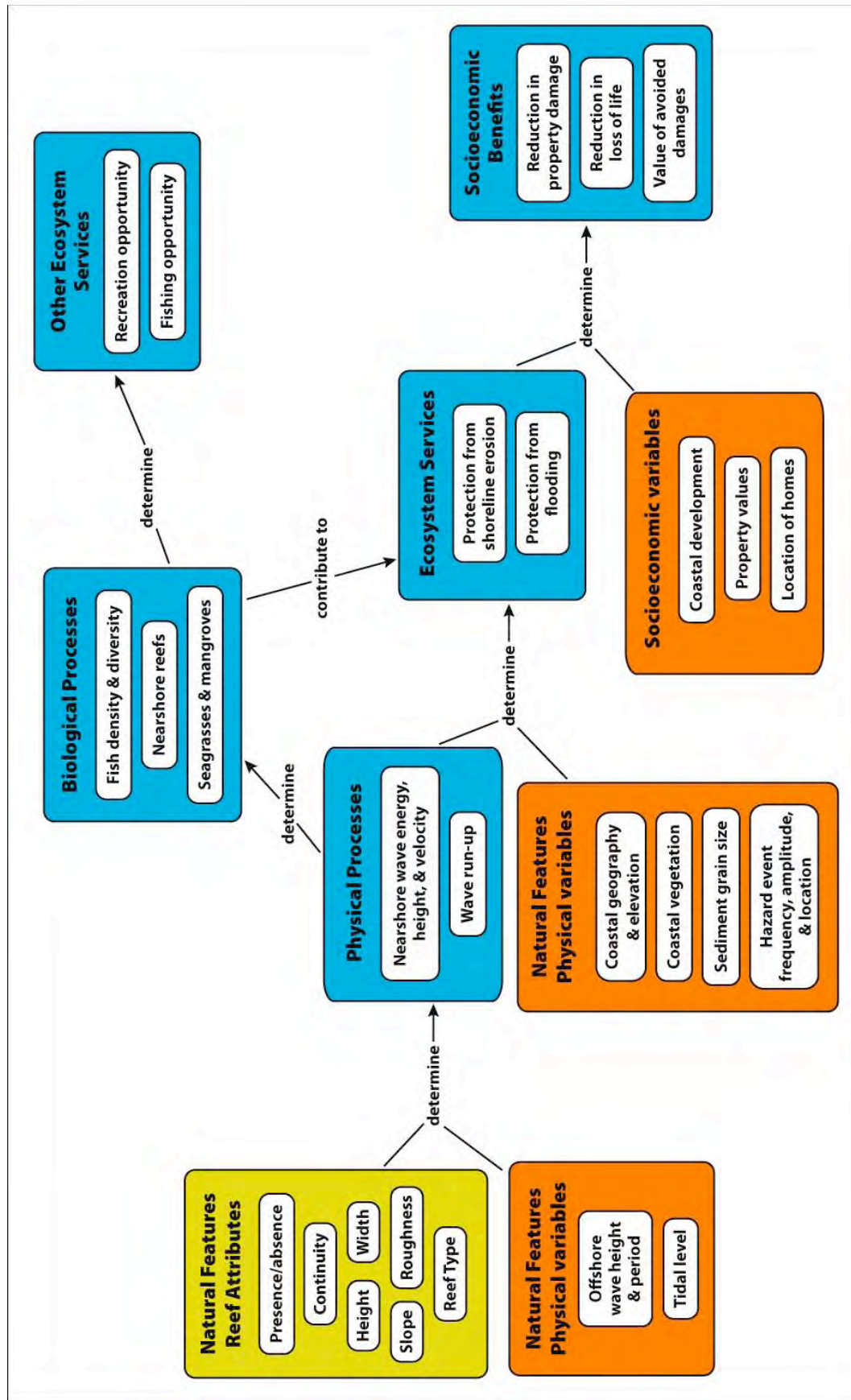


Figure 4-4. Conceptual diagram showing how reef attributes (yellow), and various physical or socioeconomic variables (orange), can be used to determine various endpoints quantifying shoreline protection (blue).

4.6 Bibliography

- Baird AH, Campbell SJ, Anggoro AW, Ardiwijaya RL, Fadli N, Herdiana Y, Kartawijaya T, Mahyiddin D, Mukminin A, Pardede ST, Pratchett MS, Rudi E and Siregar AM. 2005. Acehnese reefs in the wake of the Asian Tsunami. *Current Biology*, **15**:1926-1930.
- Barbier EB, Koch EW, Silliman BR, Hacker SD, Wolanski E, Primavera J, Granek EF, Polasky S, Aswani S, Cramer LA, Stoms DM, Kennedy CJ, Bael D, Kappel CV, Perillo GME and Reed DJ. 2008. Coastal ecosystem-based management with nonlinear ecological functions and values. *Science*, **319**:321-323.
- Bekaert T. 2005. <http://en.wikipedia.org/wiki/File:Tombolo_Paximadhi_Eboea.jpg> Accessed 2011.08.09.
- Berg H, Ohman M, Troeng S and Linden O. 1998. Environmental Economics of Coral Reef Destruction in Sri Lanka, *Ambio*, **27**(8):627-634.
- van Beukering PJH, Sarkis S, McKenzie E, Hess S, Brander L, Roelfsema M, Looijensstijn-van der Putten L & Bervoets T. 2010. *Total Economic Value of Bermuda's Coral Reefs. Valuation of Ecosystem Services*. van Beukering Consulting, Amsterdam.
- Birkeland C and Grosenbaugh D. 1985. *Ecological interactions between tropical coastal ecosystems*. Nairobi: United Nations Environment Programme (UNEP), Regional Seas Reports and Studies, vol. 73, 71 pp.
- Black K and Andrews C. 2001. Sandy shoreline response to offshore obstacles: Part 1. Salient and tombolo geometry and shape. *Journal of Coastal Research*, **29**:82-93.
- Brander RW, Kench PS and Hart D. 2004. Spatial and temporal variations in wave characteristics across a reef platform, Warraber Island, Torres Strait Australia. *Marine Geology*, **207**:169-184.
- Burgess SC, Kingsford MJ and Black KP. 2007. Influence of tidal eddies and wind on the distribution of presettlement fishes around One Tree Island, *Great Barrier Reef Marine Ecology Progress Series*, **341**:233-242.
- Burke L and Maidens J. 2004. *Reefs at Risk in the Caribbean*. Washington, DC: World Resources Institute, 80 pp.
- Burke L, Selig E and Spalding M. 2002. *Reefs at Risk in Southeast Asia*. Washington, DC: World Resources Institute, 76 pp.
- California State Parks. 2011. <http://www.parks.ca.gov/?page_id=22804> Accessed 2011.08.05.
- Cesar H. 1996. *Economic Analysis of Indonesian Coral Reefs*. Washington, DC: The World Bank, 103 pp.
- Cesar H, Burke L and Pet-Soede L. 2003. *The Economics of Worldwide Coral Reef Degradation*. Arnhem (Netherlands): Cesar Environmental Economics Consulting.
- Chatenoux B and Peduzzi P. 2007. Impacts from the 2004 Indian Ocean Tsunami: Analysing the potential protecting role of environmental features. *Natural Hazards*, **40**:289-304.
- Chong J. 2005. *Protective values of mangrove and coral ecosystems: A review of methods and evidence*. Gland (Switzerland): International Union for the Conservation of Nature (IUCN).
- Cochard R, Ranamukhaarachchi SL, Shivakoti GP, Shipin OV, Edwards PJ and Seeland KT. 2008. The 2004 tsunami in Aceh and Southern Thailand: A review on coastal ecosystems, wave hazards, and vulnerability. *Perspectives in Plant Ecology, Evolution, and Systematics*, **10**:3-40.
- DeMartini EE, Zgliczynski BJ, Boland RC and Friedlander AM. 2009. Influence of wind-wave exposure on the distribution and density of recruit reef fishes at Kure and Pearl and Hermes Atolls, Northwestern Hawaiian Islands. *Environmental Biology of Fishes*, **85**:319-332.
- Environmental Justice Foundation (EJF). 2005. *Mangroves: Nature's Defence against Tsunamis. A report on the impact of mangrove loss and shrimp farm development on coastal defences*. London: Environmental Justice Foundation.
- Federal Emergency Management Agency (FEMA). 2007. *Guidelines and specifications for flood hazard mapping partners*. <http://www.fema.gov/plan/prevent/fhm/gs_memos.shtm> Accessed 2011.09.01.
- Fernando HJS, Mendis SG, McCulley JL and Perera K. 2005. Coral poaching worsens tsunami destruction in Sri Lanka. *EOS Transactions*, **86**:301-304.
- Fourqurean JW and Rutten LM. 2004. The impact of Hurricane Georges on soft-bottom back reef communities: Site- and species-specific effects in South Florida seagrass beds. *Bulletin of Marine Science*, **75**:239-257.
- Frihy OE, El Ganaini MA, El Sayed WR and Iskander MM. 2004. The role of fringing coral reef in beach protection of Hurghada, Gulf of Suez, Red Sea of Egypt. *Ecological Engineering*, **22**:17-25.
- Fulton CJ and Bellwood DR. 2005. Wave-induced water motion and the functional implications for coral reef fish assemblages. *Limnology and Oceanography*, **50**:255-264.
- Gerritsen F. 1981. *Wave attenuation and setup on a coastal reef*. Honolulu: University of Hawaii, Look Laboratory, Technical Report 48, 416 pp.
- Gourlay MR. 1994. Wave transformation on a coral reef. *Coastal Engineering*, **23**:17-42.
- Gourlay MR and Colleter G. Wave-generated flow on coral reefs: An analysis for two dimensional horizontal reef-tops with steep faces. *Coastal Engineering*, **52**:353-387.

- Hardy TA and Young IR. 1996. Field study of wave attenuation on an offshore coral reef. *Journal of Geophysical Research*, **101**:14311-14326.
- Hayden BP, Dolan R, Hoffman S and Robinson A. 1978. Shoreline erosion in a reef-beach system. *Environmental Management*, **2**:209-218.
- Kono T and Tsukayama S. 1980. Wave transformation on reef and some consideration on its application to field. *Coast Engineering Journal*, **23**:45-57.
- Kunkel CM, Hallberg RW and Oppenheimer M. 2006. Coral reefs reduce tsunami impact in model simulations. *Geophysical Research Letters*, **33**:L23612.
- Lacambra C, Spencer T and Moeller I. 2008. Literature Review: Tropical coastal ecosystems as coastal defences. In: *The Role of Environmental Management in Disaster Risk Reduction and Climate Change Adaptation*, Tannay (Switzerland): ProAct Network, pp. 1-15.
- Liu PL-F, Lynett P, Fernando H, Jaffe BE, Fritz H, Higman B, Morton R, Goff J and Synolakis C. 2005. Observations by the International Tsunami Survey Team in Sri Lanka. *Science*, **308**:1595.
- Lowe RJ, Falter JL, Bandet MD, Pawlak G, Atkinson MJ, Monismith SG and Koseff JR. 2005. Spectral wave dissipation over a barrier reef. *Journal of Geophysical Research*, **110**(4):C04001.
- Lugo-Fernandez A, Roberts HH and Wiseman WJ. 1998. Tide effects on wave attenuation and wave set-up on a Caribbean coral reef. *Estuarine and Coastal Shelf Science*, **47**:385-393.
- Madin JS, Black KP and Connolly SR. 2006. Scaling water motion on coral reefs: From regional to organismal scales. *Coral Reefs*, **25**:635-644.
- Monismith, S. G. 2007. Hydrodynamics of Coral Reefs. *Annual Reviews of Fluid Mechanics*, **39**:37-55.
- Mumby PJ, Broad K, Brumbaugh DR, Dahlgren CP, Harborne AR, Hastings A, Holmes KE, Kappel CV, Micheli F and Sanchirico JN. 2008. Coral reef habitats as surrogates of species, ecological functions, and ecosystem services. *Conservation Biology*, **22**:941-951.
- Nott J. 1997. Extremely high-energy wave deposits inside the Great Barrier Reef, Australia: Determining the cause – tsunami or tropical cyclone. *Marine Geology*, **141**:193-207.
- Ogden JC and Gladfelter EH. 1983. Coral reefs, seagrass beds and mangroves: their interactions in the coastal zones of the Caribbean. Paris: UNESCO Reports in Marine Science, vol. 23, 133 pp.
- Pet-Soede C, Cesar HSJ and Pet JS. 1999. An economic analysis of blast fishing on Indonesian coral reefs. *Environmental Conservation*, **26**:83-93.
- Reidenbach MA, Monismith SG, Koseff JR, Yahel G and Genin A. 2006. Boundary layer turbulence and flow structure over a fringing coral reef. *Limnology and Oceanography*, **51**:1956-1968.
- Riopelle JM. 1995. *The Economic Valuation of Coral Reefs: A case study of West Lombok, Indonesia*. Thesis, Dalhousie University, Halifax, Canada.
- Roberts HH, Murray SP and Suhayda JN. 1975. Physical processes in a fringing reef system. *Journal of Marine Research*, **33**:233-260.
- Sheaves M. 2009. Consequences of ecological connectivity: The coastal ecosystem mosaic. *Marine Ecology Progress Series*, **391**:107-115.
- Sheppard C, Dixon DJ, Gourlay M, Sheppard A and Payet R. 2005. Coral mortality increases wave energy reaching shores protected by reef flats: Examples from the Seychelles. *Estuarine Coastal and Shelf Science*, **64**:223-234.
- Short F, Carruthers T, Dennison W and Waycott M. 2007. Global seagrass distribution and diversity: A bioregional model. *Journal of Experimental Marine Biology and Ecology*, **350**:3-20.
- Sudmeier-Rieux K, Masundire H, Rizvi A and Rietbergen S (eds). 2006. *Ecosystems, Livelihoods and Disasters: An integrated approach to disaster risk management*. Gland (Switzerland) & Cambridge (UK): International Union for the Conservation of Nature (IUCN).
- Tait RJ. 1972. Wave set-up on coral reefs. *Journal of Geophysical Research*, **77**:2207-2211.
- Talbot F and Wilkinson C. 2001. *Coral Reefs, Mangroves and Seagrasses: A Sourcebook for Managers*. Townsville (Australia): Australian Institute of Marine Science, ISBN 0-642-32208-2, 193 pp.
- United Nations Environment Programme (UNEP). 2005. *Indonesia: Preliminary Damage and Loss Assessment, December 26, 2004 Natural Disaster*. Nairobi: United Nations Environment Programme, Consultative Group on Indonesia January 19-20, 2005, Technical Report. <<http://www.unep.org/tsunami>>
- United Nations Environment Programme (UNEP) World Conservation Monitoring Centre (WCMC). 2006. *In the front line: Shoreline protection and other ecosystem services from mangroves and coral reefs*. Cambridge (UK): UNEP-WCMC, Biodiversity Series, vol. 24, 33 pp.

- Wainger LA and Boyd JW. 2009. Valuing ecosystem services. In: McLeod K and Leslie H (eds), *Ecosystem-Based Management for the Oceans*. Washington, DC: Island Press, pp. 92-111.
- Weber P. 1993. Reviving the coral reefs. In: Brown, LR (ed), *State of the World*. New York: W.W. Norton, pp. 42-60.
- Wells S and Edwards A. 1989. Gone with the waves. *New Scientist*, (1690):47-51.
- Wetlands International (WI) – Indonesia Programme. 2005. Tsunami of Aceh and North Sumatra, 26 December 2004. <<http://www.wetlands.or.id>>
- White AT, Ross M and Flores M. 2000. Benefits and Costs of Coral Reef and Wetland Management, Olango Island, Philippines. In: Cesar HSJ (ed), *Collected Essays on the Economics of Coral Reefs*. Kalmar (Sweden): Kalmar University, Department for Biology and Environmental Sciences/CORDIO.
- Whittingham E, Campbell J and Townsley P. 2003. *Poverty and Reefs*. DFID-IMM-IOC/UNESCO, 260 pp.
- Wolanski E. 1994. *Physical Oceanographic Processes of the Great Barrier Reef*. Boca Raton (Florida): CRC Press. ISBN: 0-8493-8047-2, 195 pp.
- Woodley JD, Chornesky EA, Clifford PA, Jackson JBC, Kaufman LS, Knowlton N, Lang JC, Pearson MP, Porter JW, Rooney MC, Rylaarsdam KW, Tunnicliffe VJ, Wahle CM, Wulff JL, Curtis ASG, Dallmeyer MD, Jupp BP, Koehl MAR, Neigel J and Sides EM. 1981. Hurricane Allen's Impact on Jamaican Coral Reefs. *Science*, **214**:749-755.
- World Resources Institute (WRI) 2009. *Value of Coral Reefs & Mangroves in the Caribbean. Economic Valuation Methodology v3.0*. Washington, DC: World Resources Institute, 22 pp.
- Young IR. 1989. Wave transformation over coral reefs. *Journal of Geophysical Research*, **94**:9779-9789.
- Young IR and Hardy TA. 1993. Measurement and modelling of tropical cyclone waves in the Great Barrier Reef. *Coral Reefs*, **12**:85-95.

Appendix 4-A

Studies quantifying shoreline protection

The following table lists studies and the endpoints they used to quantify shoreline protection. Also included are the biological reef attributes and the physical and socioeconomic variables used to estimate that endpoint. The method and location of the studies are also given.

Ecosystem Service Endpoint	Reef Attributes	Physical Variables	Socioeconomic Variables	Method	Location	Citation
<i>Physical processes</i>						
wave height	reef top water depth			Statistical analysis	Australia	Barbier <i>et al.</i> 2008
% change in wave height	distance to beach; variation in reef topography; reef depth	low or high tide		Field study	Australia	Brander <i>et al.</i> 2004
change in wave height	presence of reef	wave height, water level		Field study	Hawaii	Gerritsen 1981
wave energy reaching shore	reef depth & slope	wave height, water depth		Laboratory study & model	Australia	Gourlay 1994
shore wave energy; wave "set-up"; wave velocity	reef top water depth (reef height); reef friction; reef slope; width of reef flat (distance from shore)	offshore wave height & period		Model	Australia	Gourlay & Colleter 2005
wave height and period; wave spectra; wave breaking	distance along reef flat from reef front; depth over reef flat	wave height		Field study	Australia	Hardy & Young 1996
wave attenuation, spectra	presence of reef flat	tidal level		Field and laboratory studies	Japan	Kono & Tsukayama 1980
change in wave height; rate of wave dissipation	reef roughness (standard deviation in reef height); presence of reef flat; presence of fore reef	fore reef wave height, wave frequency, seawater density, etc.		Model & field study	Hawaii	Lowe <i>et al.</i> 2005
wave set-up; wave spectra	presence of reef crest, reef flat, lagoon	tide level		Field Study validation of Tait's model	Caribbean	Lugo-Fernandez <i>et al.</i> 1998
loss of wave height, velocity, and acceleration	distance from reef crest; model-calibrated reef friction parameter	wave height, period; tide level		Field validation of model	Australia	Madin <i>et al.</i> 2006
wave energy dissipation	presence of mangroves, sea grass, patch reef, <i>Acropora</i> , algal, gorgonians, or <i>Montastraea</i>			Field study & literature review	Caribbean	Mumby <i>et al.</i> 2008
wave energy dissipation spectra over range of frequencies	presence of reef crest, reef flat			Field study	Caribbean	Roberts <i>et al.</i> 1975
% offshore energy reaching the shore	reef top water depth (reef height); reef friction; reef slope; width of reef flat (distance from shore); relative area of live, dead, eroded coral, sand, rubble, seagrass, or algal turf	offshore wave height & period		Model	Indian Ocean	Sheppard <i>et al.</i> 2005

Ecosystem Service Endpoint	Reef Attributes	Physical Variables	Socioeconomic Variables	Method	Location	Citation
Physical processes (con't)						
reduction in wave height	presence of reef front, reef flat; distance from reef front; depth at reef crest; fore reef slope	offshore wave height & period; beach slope		Model	Hawaii	Tait 1972
wave dynamics; hydrodynamic processes	reef slope, height, depth	offshore wave height & period		Model	Australia	Wolanski 1994
wave attenuation; wave spectra; area of influence	presence of reef flat, fore reef; reef flat water depth; reef area	incident wave height		Field study	Australia	Young 1989
Biological processes processes						
damage to coral by hurricane	reef profile (depth, slope, & shelf width); presence of reef crest			Model	Jamaica	Woodley <i>et al.</i> 1981
low energy environment favorable for growth of mangroves and seagrasses	presence of reef			Anecdotal (review)	Caribbean & Pacific	Birkeland 1985
loss of seagrass vegetation	presence of reef; gap in reef			Field observations	Florida	Fourqurean & Rutten 2004
low energy environment favorable for growth of mangroves and seagrasses	presence of reef			Workshop summary	Caribbean	Ogden & Gladfelter 1983
presence of mangroves	presence of reef flats			Review, anecdotal	Global	Sheaves 2009
presence of seagrasses	presence of reef	wave sheltered		Mapping, anecdotal	Global	Short <i>et al.</i> 2007
presettlement fishes	presence of reef	tidally generated eddies		Field study	Australia	Burgess <i>et al.</i> 2007
larval fish densities	presence of reef	wind/wave exposure		Field study	Hawaii	DeMartini <i>et al.</i> 2009
fish assemblages	sheltered reef vs. wave-exposed fore-reef	water motion (flow velocity & rates of direction change)		Field study	Australia	Fulton & Bellwood 2005
Ecosystem services						
shift in shoreline due to erosion	hydrographic profile of seabed composition [reef face vs. sand], reef depth	waves (height, direction, period), current, sediment (grain size), water depth		Model	Egypt	Frihy <i>et al.</i> 2004
beach sand erosion	presence of reef	wave energy (height & period of waves at beach); beach elevation; height of sand deposition; beach elevation; sediment grain size		Field study	U.S. Virgin Islands	Hayden <i>et al.</i> 1978
formation of salients and tombolos	ratio of length of reef along shoreline to distance of reef from undisturbed shoreline; completely submerged	wave climate		Statistical analysis	Australia	Black & Andrews 2001

Ecosystem Service Endpoint	Reef Attributes	Physical Variables	Socioeconomic Variables	Method	Location	Citation
<i>Ecosystem services (con't)</i>						
tsunami run-up relative to no reef	depth and width of reef flat; width of lagoon (offshore distance to the reef); bottom drag coefficient ("reef health"); presence, width, and location of a gap	tsunami wavelength and amplitude		Model	Indian Ocean	Kunkel <i>et al.</i> 2006
reduction in wave height during cyclone	presence of reef			Field study and model	Australia	Young & Hardy 1993
coastal flooding	% coral protection; % seagrass; % mangrove; reef orientation	distance from tsunami fault line, sea bed depth 10 km offshore, length of slope		Statistical analysis	Indian Ocean	Chatenoux & Peduzzi 2007
tsunami height & inundation; tsunami damage (structures destroyed, deaths)	presence of reef or gap in reef			Observational	Sri Lanka	Fernando <i>et al.</i> 2005
coastal flooding	reef profile (depth, slope, & shelf width); reef continuity; reef area; reef topography; terrace width; species distribution, geometry, & ecology; species at reef front more resistant	extreme storm events; distance from hurricane event		Review	Global	Lacambra <i>et al.</i> 2008
tsunami run-up, height	gap in reef			Observational	Sri Lanka	Liu <i>et al.</i> 2005
tsunami movement to coast	gaps in reef				Australia	Nott 1997
tsunami wave run-up	presence of reef			Review	Global	UNEP-WCMC 2006
Coastal inundation during extreme events	presence of reef	coastal bathymetry		Observational	Indonesia	Baird <i>et al.</i> 2005
probability of indirect or direct consequences due to damage from exposure (p[C _{ID} D,EX])	presence of reef; fragmentation of reef (size & orientation of channels); seagrass or mangrove vegetation structure; orientation to coastline; vegetation relation to landscape morphology; presence of rivers	source distance & coastal geomorphology; type of coastline; profile of coastline; seabed depth; distance to tsunami source; coastline orientation; probability of geologic event	location of human inhabitants relative to hazard & vegetation	Framework	Indian Ocean	Cochard <i>et al.</i> 2008
<i>Socioeconomic benefits</i>						
human deaths & loss of property	presence of intact reefs			Review	Indian Ocean	EJF 2005
damage to human lives & livelihoods	presence of reefs			Review	Global	Sudmeier-Rieux <i>et al.</i>
damage to human lives & livelihoods	absence of reefs			Observational	Indonesia	UNEP 2005
loss of human life	presence of reefs			Observational	Indonesia	WI 2005
loss of village	presence of reef	cyclone		Observational	India	Whittingham <i>et al.</i> 2003
avoided damages				Economic analysis	SE Asia	Burke <i>et al.</i> 2002

Ecosystem Service Endpoint	Reef Attributes	Physical Variables	Socioeconomic Variables	Method	Location	Citation
<i>Socioeconomic benefits (con't)</i>						
length of coastline within 2 km of mapped coral reef	presence of healthy coral reef; presence of degraded coral reef	length of coastline		Economic analysis	Caribbean	Burke & Maidens 2004
avoided damages	reef loss		level of shoreline development	Economic analysis	Indonesia	Cesar 1996
avoided damages				Economic analysis	Worldwide	Cesar <i>et al.</i> 2003
avoided property damage due to presence of reef	coral reef locations, "role of coral reefs"	coastal profile, susceptible flood zones, shoreline stability, storm regime	historical property damage, property values	Economic analysis	Bermuda	Beukering <i>et al.</i> 2010
dollar value of coastal protection	presence of reef			Economic analysis	Philippines	White <i>et al.</i> 2000
dollar value of coastal protection	coral loss			Economic analysis	Indonesia	Pet-Soede <i>et al.</i> 1999
relative contribution of reefs to shoreline stability	reef type; reef continuity; reef distance from shore	wave energy; hurricane frequency; coastal geology & elevation; coastal vegetation		Economic analysis	Caribbean	WRI 2009
cost of replacement breakwaters				Economic analysis	Sri Lanka	Berg <i>et al.</i> 1998
cost to restore eroded beach	damage to reef due to mining			Economic analysis	Indonesia	Riopelle 1995
cost to replace with concrete breakwaters	presence of reefs			Case Study	Maldives	Talbot & Wilkinson 2001
cost of replacement artificial reef	reef loss			Observational	Maldives	Weber 1993
eroding coastline	presence of undamaged reefs	breakwaters	presence of low lying homes, cost to repair breakwaters	Observational	Maldives	Wells & Edwards 1989

Coral Reefs: Natural Products

The flora and fauna of coral reef ecosystems are the source for a large number of pharmaceuticals and biochemicals and the inspiration for a wide variety of chemical and structural models. This chapter describes some of these natural products, the ecological forces that create them, and how they can be quantified as an ecosystem service.

5.1 Natural products as sources and templates for pharmaceuticals, biochemicals, and biomaterials

Relative to their terrestrial counterparts, marine ecosystems are latecomers as sources and templates of pharmaceuticals, biochemicals, and other biomaterials. This tardiness is mainly due to their inaccessibility, especially as compared to the easy availability of terrestrial flora and fauna. Consequently, there is no indigenous medicine tradition to draw upon, because there are so few instances (southern China being one) where marine species were used for medicinal purposes (Fenical 1996).

However, advances in undersea technology in the past few decades have gradually opened up marine ecosystems to more systematic exploration. This exploration has revealed marine ecosystems to be complex and species-rich with a vast array of predator-prey relationships that, coupled with the challenges of living in an aqueous medium, have resulted in a myriad of secondary metabolites¹ with extraordinarily complex, and hitherto unseen, structures (Fenical 1997; Gerwick 2008). From 1977–1987, the first decade of intensive marine exploration, about 2,500 previously unknown metabolites were reported (Newman *et al.* 2000). Among the relatively small percentage of marine biochemicals that have been isolated, identified, and tested are pharmaceuticals, nutraceuticals, cosmetics, food additives, antifouling agents, adhesives, and physical and chemical templates in a variety of fields.

5.1.1 Pharmaceutical uses of marine natural products

Natural products have long been used for medicinal purposes. India's use of plants for medicinal treatment dates back over 5,000 years and has become codified in the Ayurveda, which contains over 8,000 herbal remedies. This same system of treatment is still used in over 14,000 dispensaries in India today. During the period in which the Ayurveda was created, a Chinese emperor was describing 365 herbal remedies, including ginseng, opium (the source of codeine and morphine), and ephedra (the source of ephedrine). During the subsequent millennium, the Assyrians listed 250 medicinal plants, and the Sumerians recorded 1,000 plants with medicinal properties (Huxley 1984). A Chinese herbal pharmacopoeia written about 2,000 years ago describes the use of marine seaweeds for medicinal purposes (Bowling *et al.* 2007).

More recently, from 2000 to 2006, about 50% of small molecule² new chemical entities³ were natural products or based on natural products (Newman & Cragg 2007). From 1981 through mid-2006, 63% of all new chemical entities were natural products or based on natural products (Newman & Cragg 2007; Cragg & Newman 2009). However, over 50% of marketable pharmaceutical products are consistently natural products or based on natural products (NRC 1999, p. 73), and half of all cancer drug research is devoted to marine natural products (Fenical 1996). Further, about 50% of the drugs introduced from 1994 to the present are either natural products or based on natural products (Harvey *et al.* 2010).

There are over 10,000 marine biochemicals with potentially useful pharmacological properties, and Appendix 5-A lists over 200 of them, showing their biological source, geographic location, chemical name and structure, the nature of their biological activity, and their approval status, where applicable. There were 36 marine-derived natural products that were in clinical trials (Table 5-1) or approved for use as of 2006 (Table 5-2), and 20 or more that were in the preclinical stage of testing (Simmons *et al.* 2005; Wijffels 2007).

¹ A secondary metabolite is a substance produced by an organism that seemingly has no direct role in the organism's metabolism, though they are often produced via pathways that are derived from primary metabolic pathways. It is believed that they are created because they confer some evolutionary advantage, particularly in nonmotile organisms. Most often secondary metabolites are used by the organism in intraspecies or interspecies interactions usually related to defense or signaling (*e.g.*, for reproduction) (NRC 1999, pp. 74-75; Croteau *et al.* 2000, pp. 1250-1, 1316; Seigler 2002, p. 3; Wink 2003).

² "In the fields of pharmacology and biochemistry, a small molecule is a low molecular weight organic compound which is by definition not a polymer. The term small molecule, especially within the field of pharmacology, is usually restricted to a molecule that also binds with high affinity to a biopolymer such as protein, nucleic acid, or polysaccharide and in addition alters the activity or function of the biopolymer. The upper molecular weight limit for a small molecule is approximately 800 Daltons which allows for the possibility to rapidly diffuse across cell membranes so that they can reach intracellular sites of action. In addition, this molecular weight cutoff is a necessary but insufficient condition for oral bioavailability." (Wikipedia 2010)

³ A new chemical entity is a drug that contains no active moiety that has been approved by the FDA (21CFR314.108).

Table 5-1. Testing stages for new pharmaceuticals

Trial Stage	Nature of Testing
Preclinical	<i>in vitro</i> tests and <i>in vivo</i> animal model tests for preliminary dose ranging, efficacy, toxicity, and pharmacokinetic evaluation
Phase 0	instituted by FDA in 2006; single, subtherapeutic dose; 10–15 human subjects; on-going evaluation of phase’s usefulness, ethics, and claimed benefits (to save money and to speed up the approval process)
Phase I	normally, first stage of human testing; trials assess the drug’s safety, tolerability (including maximum tolerable dose), pharmacokinetics (effects of drug), and pharmacodynamics (metabolism of drug); 20–100 healthy volunteers or patients with the target disease
Phase II	continues evaluation of the drug’s safety in larger groups of subjects (200–300 patients with the target disease); evaluation of the drug’s efficacy, optimal dosing regimen, and side effects; often double-blind tests versus placebo
Phase III	multicenter trials involving hundreds or thousands of subjects; trials attempt to establish the drug’s efficacy <i>vis-à-vis</i> current best practice and an overall risk-benefit ratio in a demographically diverse sample of patients with the target disease; usually drug versus standard treatment
Phase IV	post-approval monitoring of large populations of patients taking the drug; may evaluate drug’s usefulness in treating diseases other than the original target

Source: University of Pittsburgh (2002); Wikipedia (2011).

Table 5-2. Status of marine-derived natural products in clinical trials or clinical use

Compound Name	Source	Status (Disease)	Comment
Abyssomicin C	actinobacterium (<i>Verrucosipora maris</i>)	Phase I (antibiotic)	
ACV1 (aka α-conotoxin)	mollusk (cone snail) (<i>Conus victoriae</i>)	Phase I (analgesic)	Metabolic Pharma (Australia)(06/2006); conotoxin Vc1.1
Acyclovir (aka Zovirax®)	sponge (<i>Cryptothetya crypta</i>)	Clinically available (antiviral)	Synthetic analog of arabinose nucleotides; antiviral used to treat herpes infections; King Pharmaceuticals discontinued marketing in June 2001, possibly due to superior alternatives
Aplidine † (aka plitidepsin, Aplidin®)	tunicate (<i>Aplidium albicans</i>)	Phase II (cancer)	Dehydrodidemnin B; synthetic analog
Ara-A (aka vidarabine, Vira-A®)	sponge (<i>Cryptothetya crypta</i>)	FDA approved in 1976 (antiviral)	Synthetic analog of arabinose nucleotides; antiviral used primarily for ophthalmic infections
Ara-C † (aka cytarabine, Cytosar-U®, DepoCyt®, Tarabine PFS®)	sponge (<i>Cryptothetya crypta</i>)	Clinically available; FDA approved in 1969; Phase I/II (cancer)	Approved by FDA in 1969; first marine anticancer drug; synthetic analog of arabinose nucleotides; sold by Pharmacia & Upjohn
AZT (aka Retrovir®, zidovudine)	sponge (<i>Cryptothetya crypta</i>)	Clinically available (antiviral)	Synthetic analog of arabinose nucleotides; first drug licensed for treatment of HIV; sold by GlaxoSmithKline
Bryostatin 1 †	bryozoan (<i>Bugula neritina</i>)	Phase I/II (cancer); Phase II (Alzheimer's)	Now in combination therapy trials; licensed to GPC Biotech by Arizona State Univ.
Cematodin † (aka LU103793)	mollusk (sea hare) (<i>Dolabella auricularia</i>) cyanobacterium (<i>Symploca</i> sp.)	Phase I/II (cancer)	Synthetic analog of dolastatin 15; some positive effects in melanoma; studies discontinued in 2004
Contulakin-G (aka CGX-1160)	mollusk (cone snail) (<i>Conus geographus</i>)	Phase I (analgesic); Phase II late 2005	Cogentix and Elan Corporation (Ireland)
Diazepinomicin (aka ECO-4601)	actinobacterium (<i>Micromonospora</i> sp.)	Phase I (antibiotic, cancer)	Ecopia BioSciences (Canada)
Discodermolide †	sponge (<i>Discodermia dissoluta</i>)	Phase I (cancer)	Licensed to Novartis by Harbor Branch Oceanographic Institution; studies may have been discontinued in 2005
DMXB (aka GTS-21, DMXB-A)	marine worm	Phase II (Alzheimer's, schizophrenia)	Licensed to Taiho by the Univ. of Florida
Ecteinascidin 743 † (aka trabectedin, Yondelis®)	tunicate (<i>Ecteinascidia turbinata</i>)	Phase II/III (cancer) in 2003- 2005; approved by EMA* for treatment of soft tissue sarcoma	Licensed to Ortho Biotech (J&J/Janssen Pharmaceuticals); PharmaMar currently makes and sells Yondelis® in Europe
Eribulin † & Eribulin mesylate (aka E7389, Halaven®)	sponges (<i>Halichondria okadai</i> , <i>Axinella</i> sp., <i>Phakellia carteri</i> , & <i>Lissodendoryx</i> sp.) (or possibly their symbiotic ⁴ bacteria)	Phase II/III (cancer); FDA approved for late-stage breast cancer in 2010.	Eisai's synthetic halichondrin B derivative; breast, prostate, & nonsmall cell lung cancer (NSCLC) cancers
Hemiasterlin † (aka E7974)	sponges (<i>Hemiasterella minor</i> , <i>Auleta</i> sp., <i>Cymbastela</i> sp., & <i>Siphonochalina</i> sp.)	Phase I (cancer)	Eisai's synthetic analog of hemiasterlin; being tested against colorectal cancer
IPL-576,092 (aka HMR-4011A)	sponge (<i>Petrosia contignata</i>)	Phase II (anti-asthmatic) successfully completed	Derived from contignasterol; Inflazyme Pharma

⁴ Symbiosis is a close relationship between two or more organisms of different species. There are four forms: amensalism, commensalism, mutualism, and parasitism: amensalism is when one species is harmed while the other is unaffected; commensalism is when one species benefits while causing little or no harm to the other; mutualism is when both species benefit from the relationship; and, parasitism is when one species benefits and the other is harmed. We use symbiosis throughout this chapter, because the exact nature of the relationship is often unknown or unspecified.

Table 5-2. (continued)

Compound Name	Source	Status (Disease)	Comment
IPL-512,602 (aka AVE 0547)	Synthetic analog	Phase II (anti-asthmatic)	Derived from IPL576,092; with Aventis; no further data as of 08/2005
IPL-550,260	Synthetic analog	Phase I (anti-asthmatic)	Derived from IPL576,092; with Aventis; no further data as 08/2005
Irvalec® † (aka elisidepsin , PM02734)	mollusk (sea slug) (<i>Elysia rufescens</i>) green algae (<i>Bryopsis</i> sp.)	Phase II (cancer)	Synthetic analog of kahalalide F created to insure sufficient supply; licensed to PharmaMar by Univ. of Hawaii
KRN-7000 † (aka α-GalCer , α-galactosylceramide)	sponge (<i>Agelas mauritianus</i>)	Phase I/II (cancer)	An agelasphin derivative
LAF-389 †	sponge (<i>Jaspis</i> sp.)	Phase I (cancer)	Synthetic analog of bengamide B; may have been withdrawn in 2006
LBH-589 (aka Faridak® , panobinostat)	<i>Psammaplysilla</i> spp. (sponge)	Phase III (cancer)	Synthetic analog of psammaplin; with Novartis
Marizomib † (aka salinosporamide A & NPI-0052)	actinobacterium (<i>Salinispora tropica</i>)	Phase I (cancer)	Proteasome inhibitor; Nereus Pharma
Neovastat † (aka Æ-941)	shark	Phase II/III (cancer)	Defined mixture of <500 kDa from cartilage; anti-angiogenic; possibly withdrawn March 2007
NVP-LAQ824 † (aka dacinostat)	Synthetic combination of three natural products	Phase I (cancer)	Derived from psammaplin, trichostatin, and trapoxin structures; possibly withdrawn in 2006
Plinabulin † (aka NPI-2358)	fungus (<i>Aspergillus</i> sp.)	Phase I/II (cancer)	Synthetic analog of marizomib; selective tumor vascular disrupting agent (VDA)
Pseudopterოსins	gorgonian (sea whip) (<i>Pseudopterogorgia elisabethae</i>)	Phase II (anti-inflammatory)	Used in Estée Lauder's Resilience skin cream
Soblidotin † (aka auristatin PE & TZT-1027)	mollusk (sea hare) (<i>Dolabella auricularia</i>) cyanobacteria (<i>Symploca hydroides</i> <i>Lyngbya majuscula</i>)	Phase III (cancer)	Synthetic derivative of dolastatin 10; no positive effects found in Phase II trials, but appears to be effective in combination therapy with vinca alkaloids and bryostatin
Spisulosine (aka ES-285)	mollusk (arctic surf clam) <i>Spisula polynyma</i> (aka <i>Mactromeris polynyma</i>)	Phase I (cancer)	<i>Rho</i> -GTP inhibitor
Squalamine † (aka Evizon™)	shark (spiny dogfish) (<i>Squalus acanthias</i>)	Phase II (cancer & macular degeneration)	Anti-angiogenic activity is basis for its use to treat both cancer and wet form age-related macular degeneration; Evizon™ is the name used for the ophthalmic formulation
Synthatodin † (aka ILX651 , tasidotin)	mollusk (sea hare) (<i>Dolabella auricularia</i>) cyanobacteria (<i>Symploca</i> sp.)	Phase I/II (cancer)	Synthetic analog of dolastatin 15; for melanoma, breast, and nonsmall cell lung cancer (NSCLC)
Taltobulin † (aka HTI-286)	sponges (<i>Hemiassterella minor</i> , <i>Auletta</i> sp., <i>Cymbastela</i> sp. & <i>Siphonochalina</i> sp.)	Phase I/II (cancer)	A synthetic analog of hemiassterlin; studies may have been discontinued in 2005
Trodsuquimine (aka MSI-1436)	shark (spiny dogfish) (<i>Squalus acanthias</i>)	Phase I (diabetes treatment; weight loss)	Genaera started Phase I in 2007 and reported promising results in 2009. Shortly after, Genaera was dissolved, and trodsuquimine was sold to Ohr Pharmaceuticals; current status unknown
Zalypsis® † (aka PM1004)	mollusk (nudibranch) (<i>Jorunna funebris</i>)	Phase II (cancer)	A synthetic analog of jorumycin, safracin B, & saframycin B; made by PharmaMar
Ziconotide (aka Prialt®)	mollusk (cone snail) (<i>Conus magus</i>)	Clinically available (neuropathic pain)	Licensed by Elan to Warner Lambert; approved by FDA in Dec 2004; also approved by EMA*; chronic use does not result in tolerance

* EMA: European Medicines Agency

† The 20 anticancer products used as a basis for the charts in Figure 5-3.

Source: primarily Fenical (2006), Simmons & Gerwick (2008), and Mayer *et al* (2010). Also Baerga-Ortiz (2009), Butler (2005), Dumez *et al.* (2007), Glaser (2007), Gross & König (2006), Gullo *et al* (2006), Hunt & Vincent (2006), Lam (2006), Nereus (2010), Newman & Hill (2006), Sashidhara *et al* (2009), UN (2007, pp. 26-27), and Yuan *et al* (2006).

Identifying the optimum process of drug discovery has been the subject of a fairly contentious debate over the past three decades. Although natural products have long been the primary source of new drugs, the difficulty of finding biologically active chemicals, isolating and testing them, and then maintaining a steady supply of the chemical's source created an impetus in the pharmaceutical industry to turn to synthetic combinatorial chemistry, which was later coupled with high-throughput screening methods. The allure of *de novo* synthesis of new drugs induced most pharmaceutical firms to shift resources from natural products research to combinatorial chemistry, and many firms shuttered their natural products research entirely. However, despite large investments in combinatorial chemistry, it has yielded only one new drug that has been approved for use (Nexavar® [aka sorafenib] in 2005) (Newman & Cragg 2007). Müller *et al.* (2004) show that natural products are much more likely than combinatorial chemistry products to yield a drug approved for clinical use (Table 5-3).

Table 5-3. Number of candidate drugs reaching different stages of clinical trials

	Natural Products (Secondary Metabolites)	Combinatorial Chemistry (Synthesized Chemicals)
Available for study	200	5,000 – 10,000
Preclinical	200	200
Phase I trials	>>10	10
Clinical use	>>1	~1

Source: Müller *et al.* (2004).

The situation is nicely explained by Firm (2003):

In contrast to the chemists, organisms use enzymes instead of chemical reagents to bring about chemical transformations. The crucial advantage of using enzymes in biosynthetic sequences is that enzymes can bring about specific structural changes to very specific sites in a complex molecule. This facility of microbes and plants to make structurally complex molecules with relative ease means that humans inevitably find it hard to manufacture natural products.

The difficulty of creating new pharmaceuticals using only combinatorial chemistry was made abundantly clear by GlaxoSmithKline's announcement that a six-year effort to discover broad-spectrum antibiotics failed because of the limited chemical diversity of their synthetic screening libraries (Williams 2008). The best strategy may be to combine these two approaches by seeking bioactive chemical structures from natural sources and then optimizing those structures⁵ via combinatorial chemistry. By acknowledging the prominent role of natural products in drug discovery, this joint discovery-then-optimization strategy may highlight the importance of preserving marine biochemicals.

Despite its potential, marine drug discovery faces some difficult challenges, not the least of which is acquiring a sufficient quantity of the marine source material to allow extraction of a testable quantity. While the quantities of end product may seem small, steps in the development of the end product require much more raw material, and the quantity of source material needed rapidly escalates as the chemical proceeds through the discovery and testing process (Table 5-4). A vivid example of how much source material is required is that of bryostatin. For the initial clinical trials, 13,000 kg of *Bugula neritina* were collected and processed using large-scale chromatographic techniques, yielding 18 g of bryostatin 1 (about 1.4 mg per kg or 1.4 ppm) (Newman & Cragg 2004). Such small yields are not uncommon: the concentration of halichondrin B in *Lissodendoryx* spp. is ~0.4 mg per kg, and of halistatin in sponges is 8.8 µg per kg (Molinski *et al.* 2009). It seems likely that these secondary metabolites appear in such minute quantities because of their extremely potent biological activity (Gerwick 2008).

In some rare instances, a bioactive chemical can be used directly as a drug and can be obtained in quantities sufficient for therapeutic use. Ziconotide (Prialt®), a toxin from *Conus* snails, is such a rarity; it was the first "direct from the sea" approved drug (Donia & Hamann 2003; Newman & Cragg 2007). For terrestrial sources of pharmaceutical natural products, cultivation of the drug's source to produce marketable quantities is usually feasible, but there has been little success in attempts to cultivate marine sources to produce such quantities (Donia & Hamann 2003). As a result, chemical synthesis of the natural product is often the only available option for producing sufficient quantities of the bioactive chemical. Even so, synthesis is not always an option, as succinctly stated by Donia and Hamann (2003):

Unfortunately, the structural complexity of marine molecules, which suggests novel mechanisms of action and high selectivity, has also resulted in few economically feasible strategies for total chemical synthesis.

⁵ It is often the case that an effective dose of a bioactive natural product is either too toxic or produces unacceptable side effects. These undesirable effects can usually be reduced by selectively modifying the chemical structure of the natural product (Newman *et al.* 2000). For example, salicylic acid from willow trees was acylated to form acetylsalicylic acid (aspirin), which is less irritating to the gastrointestinal tract than the natural product.

Table 5-4. Timeline of drug development and amount of raw material and pure product needed at each stage

Stages	Length of Stage (approx.)	Raw Material Needed	Pure Chemical Needed
Collection of field samples & bioactivity screening	1–2 years	~0.1–1 kg	—
Identification, isolation, & purification of bioactive compound	1–2 years	~1–5 kg	1–10 µg
Determination of chemical structure			1–10 mg
Identification of mechanism of action and potential for synthesis			1–10 g
Preclinical trials	2–4 years	>5 kg (could be >10,000 kg)	100 g
Clinical trials	4–6 years		

Source: Koehn & Carter (2005); Hunt & Vincent (2006).

A steady progression of advances in chemical synthesis methods combined with the joint discovery-then-optimization strategy described above may make more of these syntheses economically feasible. It is worth noting that even when synthesis is achieved, the synthetic product may not have the same structure and biological activity as the natural product. Pettit and Taylor (1996) report an instance where the natural product (stylopeptide 1), despite seeming to be pure based on all physicochemical measurements, was in fact in association with a halistatin-like polyether compound that was a highly active anticancer agent. The presence of this polyether eluded the usual physical, chromatographic, and NMR tests and could only be detected using biological methods. As a result, synthetic stylopeptide 1 had none of the biological activity attributed to the natural product even though the two were structurally identical (Newman & Cragg 2004).

Although marine microbes⁶ have long been considered a likely and potentially significant source of bioactive chemicals (Fenical 1982; Kaul & Daftari 1986; Franco & Coutinho 1991; Fenical 1993), recent discoveries suggest that their importance could exceed expectations. Initially, marine microbes were viewed as likely counterparts to terrestrial microbes, which are the source of many antibiotics. However, in the past decade, it has become apparent that many of the bioactive chemicals attributed to higher order flora and fauna (*e.g.*, sponges and nudibranchs) are in fact created by symbiotic microorganisms (often algae, actinomycetes, cyanobacteria, or fungi) (Donia & Hamann 2003; Leeds *et al.* 2006; Wase & Wright 2008).

Marine microbes represent a surprisingly large amount of biomass: they can account for more than 60% of a sponge's wet weight (Wilkinson [1978] as cited by Bowling *et al.* [2007]). In total, marine prokaryotes (bacteria and archaea) outnumber their terrestrial counterparts; Whitman *et al.* have estimated that there are about 3.67×10^{30} prokaryotic cells in marine ecosystems (give or take a few billion), and that there are about 305 Pg of carbon in these cells.

Marine microbes demonstrate a surprising degree of host specificity, both with respect to different species in the same location and to the same species in different locations. Of the 100 bacterial species found on three nearby sessile organisms, only two were common to all three (Longford *et al.* [2007] as cited by Penesyan *et al.* [2010]). Further, the microbial community found in the coral *Montastraea franksi* had almost no overlap with the microbes found in the surrounding seawater (Rohwer *et al.* [2001] as cited by Penesyan *et al.* [2010]).

Despite their great potential as sources of new drugs or structural templates, marine microbes pose a considerable challenge, because fewer than five percent of them can be grown in standard laboratory or industrial conditions. To overcome this problem, it may be possible to use metagenomic techniques to move the section of the microbe's genome responsible for creating the bioactive chemical into the genome of a microbe that is already used in large-scale fermentation processes (Donia & Hamann 2003). However, many microbes will not produce the bioactive compounds of interest if they are not in contact with their symbiont host (Wijffels 2007), so a means must be devised to replace the biochemical signaling between microbe and host that activates the transferred genetic sequence. It seems likely that metagenomic techniques could solve this problem, but it has yet to be demonstrated. Although it has great promise and has already been successfully used, metagenomics is still early in its development, and it would be imprudent to depend on it exclusively. As pointed out by Udworthy *et al.* (2008, p. 521), metagenomics has its drawbacks (including cost and complexity) and has had its failures (discodermolide). Metagenomics is probably best seen as one of the arrows in the quiver rather than the only arrow.

⁶ The term “microbe” is used throughout this chapter to refer collectively to unicellular or colonial microorganisms, including bacteria, fungi, archaea, or protists.

5.1.2 Marine natural products as structural templates for synthesis

The many unique chemical structures found in marine species provide templates that can be used in the synthesis of new drugs and for insight into structural possibilities. One of the more significant contributions to medicinal chemistry was the discovery that sugars other than ribose or deoxyribose were constituents of naturally occurring nucleosides. This discovery resulted from the isolation of spongouridine and spongothymidine from marine sponges in the early 1950s, and it heavily influenced drug development for the next 30 years. According to Newman *et al.* (2000):

These two compounds can be thought of as the prototypes of all of the modified nucleoside analogues made by chemists that have crossed the antiviral and anti-tumor stages since then. Once it was realized that biological systems would recognize the base and not pay too much attention to the sugar moiety, chemists began to substitute the 'regular pentoses' with acyclic entities, and with cyclic sugars with unusual substituents. These experiments led to a vast number of derivatives that were tested extensively as antiviral and anti-tumor agents over the next thirty plus years...such structures evolved in the (then) Wellcome laboratories, leading to AZT and, incidentally, to Nobel Prizes for Hitchens and Elion, though no direct mention was made of the original arabinose-containing leads from natural sources.

5.1.3 Marine natural products as molecular probes

Molecular probes are chemicals that are used to explore and elucidate biochemical structures and processes at the cellular and molecular levels. A great many marine biochemicals that are biologically active but unusable as drugs are used extensively as molecular probes (some examples are shown in Table 5-5). Marine neurotoxins, including tetrodotoxin, saxitoxin, conotoxin, and lophotoxin, have been used with great success to advance our understanding of a wide variety of receptors and ion channels in the operation of nervous systems. "The importance of molecular probes in resolving the complexities of diseases and cellular processes has often outweighed any value that they would have as commercial drugs." (NRC 1999, p. 79)

Table 5-5. Marine biochemicals used as molecular probes

Chemical	Use	Reference
adociasulfate-2	selectively inhibits the intracellular molecular motor protein kinesin	NRC 1999; Brier <i>et al.</i> 2006
brevitoxin	sodium channel inhibitor in nerves and muscle	Al-Sabi <i>et al.</i> 2006; Karunasagar & Karunasagar 2008
conotoxins	calcium channel inhibitor (ω -conotoxins); block voltage-gated sodium channels (μ - & μ O-conotoxins); delay inactivation of sodium channels (δ -conotoxins); potassium channel inhibitor (κ -conotoxins); inhibits norepinephrine transporter (χ -conopeptides); nicotinic acetylcholine receptor (α -conotoxins); blocks type 3 serotonin receptors (σ -conotoxins); inhibits α_1 -adrenergic receptor (ρ -conopeptides); inhibits NMDA receptor (conantokins); vasopressin receptor agonist (conopressins); neurotensin receptor agonist (contulakins)	NRC 1999; Layer & McIntosh 2006; Lewis 2009
jaspamide (jasplakinolide)	selective binding agent to the intracellular actin network	Senderowicz <i>et al.</i> 1995; Saito 2009; Robinson <i>et al.</i> 2010
latrunculin A	selective binding agent to the intracellular actin network; used to explore the role of phospholipase A ₂ in inflammation	Matthews <i>et al.</i> 1997; Amagata <i>et al.</i> 2008 Karunasagar & Karunasagar 2008
lophotoxin	irreversible nicotinic receptor antagonist	Fusetani & Kem 2009
manoalide	selective inhibitor of the inflammation enzyme phospholipase A ₂	Glaser & Jacobs 1986; Yasuhara-Bell <i>et al.</i> 2006
okadaic acid	potent and selective inhibition of phosphatases	NRC 1999
saxitoxin	inhibits calcium, potassium, & sodium channels in nerves and muscles	Hay & Fenical 1996; NRC 1999; Al-Sabi <i>et al.</i> 2006
swinholid A	selective binding agent to the intracellular actin network; severs F-actin filaments; binds G-actin filaments	Bubb <i>et al.</i> 1995; Saito 2009
tetrodotoxin	inhibits calcium, potassium, & sodium channels in nerves and muscles	Hay & Fenical 1996; NRC 1999; Al-Sabi <i>et al.</i> 2006; Fusetani & Kem 2009

5.1.4 Nonpharmaceutical uses of marine natural products

Marine natural products have a wide variety of nonpharmaceutical uses, both as products and as templates or sources of insight that may lead to innovative new products (Table 5-6). Perhaps the largest and most economically significant use at this time is in antifouling coatings. In a review of the literature, Chambers *et al.* (2006) found that potential antifouling products had been found in 160 marine species from a wide variety of phyla (Figure 5-1).

Table 5-6. Current and potential nonpharmaceutical uses for marine natural products

Source	Use	Reference
algae	cultured for production of jet fuel	Guardian 2010
algae (green) (<i>Chlamydomonas reinhardtii</i>)	surrogate production of drugs	Rasala <i>et al.</i> 2010
algae (green, cryptophyte)	more efficient light-harvesting in photosynthesis	Collini <i>et al.</i> 2010
annelid (sandcastle worms) (<i>Phragmatopoma californica</i>)	medicinal glues and adhesives that function under water	Fountain 2010
cnidarian (corals) (<i>Porites</i> spp.) echinoderm (various)	highly interconnected microporous structures of calcium carbonate (<i>aka</i> aragonite from corals) or calcite (from echinoderms) used as hard tissue prostheses, cardiovascular material, and tracheal prostheses	White & White 2002
echinoderm (brittle stars) (<i>Ophiocoma wendtii</i>)	development of biomimetic compound lenses that minimize optical aberrations while maximizing focal length or field of view	Lee & Szema 2005
fish (sharks)	shark-skin textured material stops bacterial growth	Sharklet Technologies 2010
fish (sharks)	shark-skin textured surface improves fuel economy by reducing drag	Bhushan 2009
fish (zebrafish) (<i>Danio rerio</i>)	gene expression activation to repair and replace damaged cardiac cells damaged	Jopling <i>et al.</i> 2010; Kikuchi <i>et al.</i> 2010
fish (zebrafish) (<i>Danio rerio</i>)	use of zebrafish model to identify genes and proteins that promote melanoma	Ceol <i>et al.</i> 2008; Ceol <i>et al.</i> 2011; White <i>et al.</i> 2011
mammal (dolphin) (<i>Tursiops truncatus</i>)	genetic pathway for controlling blood sugar levels	Venn-Watson & Ridgway 2007
mollusk (abalone) (<i>Haliotis</i> spp.)	nacre (the inside lining of abalone shells) is a template for tough, lightweight structural coatings for buildings and airplanes	Mayer 2005
mollusk (mussels) (<i>Mytilus californianus</i> , <i>M. galloprovincialis</i>)	medicinal glues and adhesives that function under water	Messersmith 2010 Harrington <i>et al.</i> 2010
mollusk (mussels) (<i>Mytilus edulis</i>)	medicinal glues that bonds to living tissue and adheres in wet environments; used to repair human fetal membranes	Benedict 2002 Bilic <i>et al.</i> 2010
mollusk (scaly-foot snail) (<i>Crysmallon squamiferum</i>)	unique shell structure (fortified with iron sulfide) in a deep-sea snail found near hydrothermal vents will improve helmets & body armor	Yao <i>et al.</i> 2010
porifera (sponge) (<i>Agelas</i> spp.)	ageliferin renders previously resistant bacterial biofilms susceptible to antibiotics	Huigens <i>et al.</i> 2008
tunicate	cellulose from ascidians has a nanoscale structure that can be used to structurally align skeletal muscle tissue grown in the laboratory	Dugan <i>et al.</i> 2010
tunicate (ascidian) (<i>Pegea confoederata</i>)	the most efficient filter feeders may help remove carbon from ocean surface water thereby limited CO ₂ to atmosphere	Sutherland <i>et al.</i> 2010

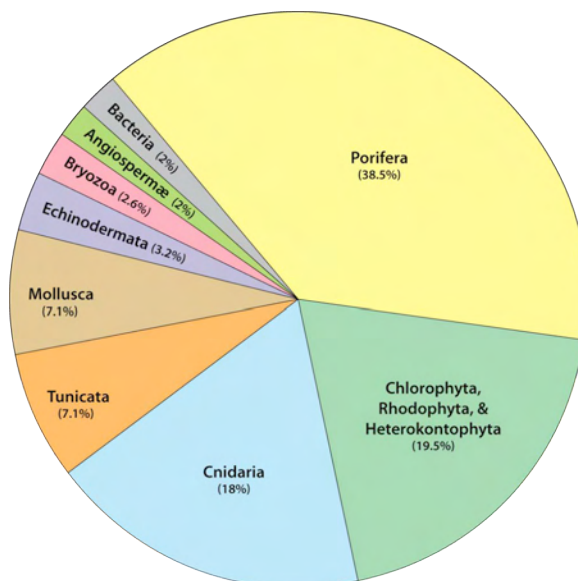


Figure 5-1. Phyletic distribution of 160 reviewed marine species from which potential antifouling natural products have been extracted (figure adapted from Chambers *et al.* 2006)

5.2 Sustaining the presence of natural products in coral reef ecosystems

Maintaining the richly diverse cornucopia of marine natural products requires some understanding of the dynamic ecosystems that drive their creation. Two of the contributing factors are the great diversity of marine life and the density of that life in the marine environment. Of the approximately 35 phyla, every phylum but one has marine species (NRC 1999, p. 74; Davidson & Erwin 2006). In 1999, the NRC (*loc. cit.*) stated that the 200,000 marine species that had been described to that point represented “a small percentage of the total number of species that have yet to be discovered and described.” Bouchet (2006) gives a range of 230,000–275,000 marine species, with 1,300–1,500 new species being identified every year. The First Census of Marine Life (CoML 2010, p. 11) states that as of 2010, experts believe that there are about 244,000 cataloged marine species and that this number will rise to about 250,000 in the next few years. However, the CoML goes on to state that the consensus of the CoML scientists is that at least a million marine species are likely to exist. In other words, for every marine species that has been identified, three more species are yet to be discovered.

Coral reefs are thought to have the highest species density of any marine ecosystem, with some areas having about 1,000 species per square meter (Donia & Hamann 2003). This combination of high species diversity and high species density leads to the profusion of secondary metabolites, with over 18,000 unique chemical structures having been identified (Gerwick 2008, p. 428). This may be just the tip of the iceberg. A metagenomic analysis of 1,800 species (primarily unicellular) found in seawater samples collected from the Sargasso Sea near Bermuda predicts more than six million proteins, more than double the number that have been identified (Yooseph *et al.* 2007; Cragg & Newman 2009). Hunt and Vincent (2006) have attempted to map the global distribution of previously unknown marine biochemicals, but the resulting map may better represent the location and frequency of natural product explorations than where novel chemicals are to be found.

The species numbers just described do not include microorganisms⁷. This is practical but may be somewhat misleading, because many of the natural products of pharmaceutical interest apparently originate in microorganisms. With respect to marine microorganism diversity, the NRC (1999, p. 78) stated, “Most of the Earth’s microbial diversity is found in the ocean.” While some can be found in both terrestrial and marine ecosystems, many taxonomic classes of microorganisms exist only in the sea, including ones that have adapted to a variety of extreme environments, such as hypersaline conditions, enormous hydrostatic pressures, hydrothermal vent temperatures, and high-sulfur environments. Based on what is known from the small areal extent that has been surveyed, it is estimated that several million marine microorganism species exist (Gerwick 2008, p. 427). The CoML (2010, p. 12) research has led to a hundredfold increase in estimates of the number of marine microbe genera and to an estimate that there may be as many as a billion types of marine microbes.

The adaptability of microorganisms may be the reason why different populations of the nearly ubiquitous bryozoan *Bugula neritina* yield very different amounts of bryostatins, a family of potential anticancer drugs. The few *B. neritina* populations that

⁷ It should be noted that only microbes that are protists (eukaryotes) are organized into species. Prokaryotes (including bacteria and archaea) are organized by kind, or phylotype (CoML 2010, p. 12).

produce detectable concentrations of the bryostatins are spatially scattered and are at depths greater than 9 m. A metagenomic analysis showed that the symbiotic microorganisms (*Candidatus Endobugula sertula*) from *B. neritina* harvested at greater than 9 m varied by 8% in its mitochondrial carboxylase I sequences from those harvested at less than 9 m (Newman & Cragg 2004). This suggests a pitfall for simplistic or insufficiently informed conservation strategies: implementing a conservation strategy for *B. neritina* (had one been needed) that preserved the wrong populations would have resulted in losing the potential anticancer benefits of the bryostatins (Hay & Fenical 1996).

A healthy reef with high biodiversity may increase the probability that any given species could be the source of a marketable product. As such, the probability of a bioprospecting discovery may be represented as directly proportional to the state of the reef (van Beukering & Cesar 2004). Certain benthic habitats may foster greater sponge diversity and abundance (Mumby *et al.* 2008), which, in turn, may foster the development of secondary metabolites with pharmaceutical potential by the sponges and their symbiont microorganisms.

5.2.1 Ecological role and sources of secondary metabolites

The flora and fauna inhabiting marine ecosystems are confronted with a very complex and stressful environment, and the biochemical adaptations made in response to those stresses have resulted in a vast trove of natural products with unprecedented structural complexity. Marine ecosystems have existed far longer than terrestrial ecosystems—thereby providing greater opportunity for evolutionary adaptation (*e.g.*, cyanobacteria have existed for about 3.5 billion years [Gerwick 2008, p. 428]). The immersion of marine species exposes them to attack by predators and pathogens to a much greater degree than in terrestrial ecosystems. Space is also a significant stressor, though it might not seem so given the oceans' expanse. The shallow coastal zones and infrequent seamounts (places where sunlight can be a useful source of energy) constitute a relatively small area, within which competition can be intense. In particular, sessile organisms not only need room to grow, but they need to prevent other sessile organisms from growing on top of them (Pawlik 1993).

Marine flora and fauna have adapted to the stresses inherent in their complex ecosystems by creating highly unusual and complex secondary metabolites. Faulkner (2000) provides a concise explanation of how these complex biochemicals came to be:

It is probable that chemical defense mechanisms evolved with the most primitive microorganisms but have been replaced in many more advanced organisms by physical defenses and/or the ability to run or swim away and hide. Sessile, soft-bodied marine invertebrates that lack obvious physical defenses are therefore prime candidates to possess bioactive metabolites. If it is assumed that secondary metabolites evolved from primary metabolites in a random manner, any newly produced secondary metabolite that offered an evolutionary advantage to the producing organism would contribute to the survival of the new strain. The specific evolutionary pressures that led to chemically rich organisms need not be defined but the longer the period of evolution, the more time the surviving organism has had to perfect its chemical arsenal. Sessile marine invertebrates have a very long evolutionary history and have had ample opportunity to perfect their chemical defenses.

In creating these chemical defenses, marine organisms use chemicals and pathways that are distinctly different than their terrestrial counterparts (Hay & Fenical 1996). Secondary metabolites are usually associated with immobility, so in terrestrial ecosystems they are most often found in plants. In marine ecosystems, secondary metabolites occur more widely both because both plants and animals (along with their symbiotic microbes) may be sessile and because of the high rate of predation (Hay & Fenical 1996). Interestingly, it is usually the case that more is known about the effect of a secondary metabolite on human cellular biochemistry than its function in the species from which it was isolated (NRC 1999, pp. 74–75).

The very nature of secondary metabolites (*i.e.*, as biochemicals produced specifically to interact with biological processes) makes them more attractive to natural product chemists and far more likely than a randomly chosen organic structure to be biologically active. As Faulkner (2000) points out,

Chemical defense mechanisms cannot be directly equated with potential biomedical activity, but it is remarkable how well the two correlate in reality. This could be explained by the fact that targets of the chemical defenses, primary metabolites such as enzymes and receptors, are highly conserved compared with secondary metabolites.

Simmons & Gerwick (2008, p. 433) describe four distinctive characteristics of marine secondary metabolites:

From the species studied to date, it is clear that marine organisms have been subject to unique adaptive pressures and utilize rather different strategies for producing secondary metabolites compared to their terrestrial counterparts. In some cases, seasoned organic chemists look at the structures of metabolites produced by marine life and characterize them as bizarre, unlike anything found from the land environment. Alternatively, some marine metabolites are of exceptional complexity representing true milestones of human achievement in the characterization of their convoluted multicyclic, and three-dimensional structures, such as maitotoxin... Coupled to the uniqueness of their physical structure are their biological properties, which can be exquisitely potent against some cellular targets. Indeed, some of the most potent natural toxins on the planet derive from marine life... Perhaps even more important than potency is the fact that some of these marine metabolites exert their pharmacological activities through interactions at novel drug sites, such as

enzymes or receptors not targeted by any current pharmaceutical agent. Hence, the real possibility exists that entirely new drug classes will be discovered that have novel structures and new sites of action...

The potency of marine natural products is probably attributable to their inevitable dilution in seawater; that is, the chemical must be sufficiently powerful to overcome the dilution that will take place en route to its target and still have the desired effect (Newman & Cragg 2004). A fifth distinctive characteristic of marine secondary metabolites is the relatively high frequency with which they incorporate chlorine or bromine in their chemical structure, probably resulting from the easy availability of the halogens in seawater (Gerwick 2008, p. 428). It may also be that the toxicity often conferred by halogenation served to provide an evolutionary advantage.

Historically, marine macroorganisms⁸, particularly sponges and seaweeds from tropical waters, were thought to be the greatest source of these secondary metabolites (Gerwick 2008, p. 428). However, several different lines of inquiry have led to the understanding that the source is often one of the multitude of symbiotic microorganisms associated with the macroorganism. Probably the first evidence of this was the discovery of identical secondary metabolites in different species of macroorganisms. In some cases, this was a matter of macroorganisms ingesting the same species of microorganism. However, in other cases the association is symbiotic. Metagenomic analyses have confirmed that the symbiotic microorganisms, not the macroorganisms, possessed the genetic sequences capable of producing the biologically active secondary metabolites in question. It is fascinating that these microorganisms produce secondary metabolites not for their protection, *per se*, but for the protection of their symbiont macroorganisms, suggesting a lengthy co-evolution that may also include sophisticated biochemical signaling between the species (*e.g.*, the bacteria that grow on fish eggs protect the eggs from fungal infection) (Fisher 1983a; Fisher 1983b; Fisher & Clark 1983).

This state of affairs creates several difficulties. The first is that the identification of threatened or endangered ecosystems or species routinely focuses on macroorganisms. The obvious importance of the symbiotic relationship between marine macroorganisms and microorganisms clearly emphasizes the necessity of adopting a holistic perspective towards ecosystem protection, since ecosystems are similar to organisms in that their well-being requires preservation of the whole, not merely a few of the attractive parts (*e.g.*, charismatic megafauna).

The second difficulty is that a macroorganism species growing in different geographic locations may well have quite different symbiont microorganism populations. This possibility complicates strategies for both marine bioprospecting and ecosystem protection. A third difficulty is that culturing symbiont microorganisms apart from their hosts has been very difficult, and even when such cultures do succeed, they often do not produce the desired active natural products. Pharmaceutical screening is consequently more complicated, because it is necessary to analyze the microbial genome, identify and extract the likely sequences used to create the secondary metabolites, and insert those sequences into a culturable microorganism. If a sufficient amount of the secondary metabolite has been isolated from natural sources, another alternative would be to identify the chemical structure for synthesis. Unfortunately, synthesizing these complex secondary metabolites is unlikely to be feasible either with respect to time or cost early in the screening process.

The macroorganisms that have been found with potentially useful secondary metabolites (whether originating from the macroorganism or its symbiotic microorganisms) are predominantly from the phylum Porifera (sponges) (Figure 5-2 and Table 5-7). This observation results from an examination of the U.S. National Cancer Institute's Developmental Therapeutics Program and its Natural Product Extract Cancer Screening Database⁹, which appears to have been last updated in 2003. The database contains the results of 236,335 cancer screens for 4,335 marine natural products, 472 from marine plants and 3,863 from marine invertebrates. The predominance of sponges most likely results from several factors. Sponges tend to be fairly prominent and discrete, making them visible and easy to collect. Also, from the earliest marine biochemical research, sponges had developed a reputation for being excellent sources of biologically active chemicals. This may have led researchers to preferentially collect sponges for evaluation. Sponges appear to be a good starting point for investigating symbiotic microorganisms, because those microorganisms can account for greater than 60% of a sponge's wet weight (Bowling *et al.* 2007).

Simmons and Gerwick (2008) used metagenomic analysis to clarify the sources of 20 marine anticancer products (marked in Table 5-2 with a †) currently in clinical trials (Figure 5-3). The current view is that only 20% of these anticancer products (or the natural templates on which they are based) are produced by macroorganisms and that fully 80% are produced by symbiotic microorganisms. Of course, as noted above, if the macroorganisms are not present to host the microorganisms, the microorganisms will not produce the biologically active secondary metabolites.

⁸ A macroorganism is an organism that can be seen with the naked eye.

⁹ available at http://dtp.nci.nih.gov/docs/cancer/natural_products/natural_products_data.html (accessed 2010.08.19)

Figure 5-2. Marine phyla contributing secondary metabolites with pharmaceutical potential
(adapted from Hunt & Vincent [2006])

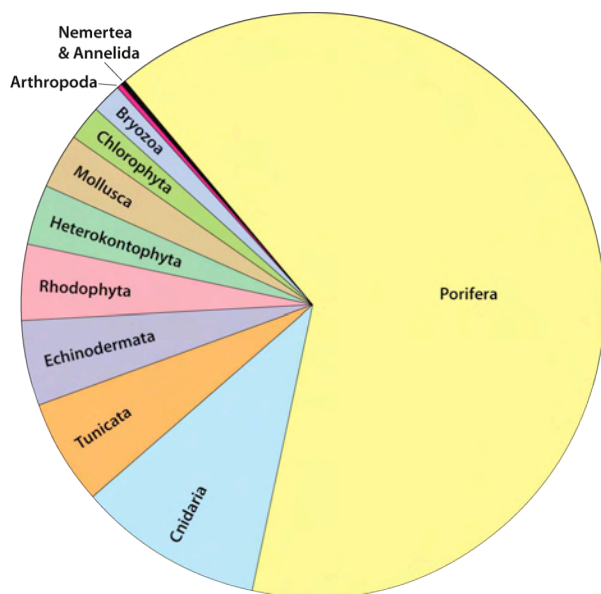


Table 5-7. Percentage of secondary metabolites with pharmaceutical potential from marine phyla
(percentages estimated from Figure 1 in Hunt & Vincent [2006])

Phylum	Phylum Members Include	Percentage of Secondary Metabolites
Porifera	sponges	64.7%
Cnidaria	corals, jellyfish, sea anemones	10.1%
Tunicata	tunicates (ascidians)	6.0%
Echinodermata	starfish, sea urchins	4.7%
Heterokontophyta	brown algae, seaweeds	3.4%
Mollusca	nudibranchs, snails, squid	3.1%
Chlorophyta	green algae	1.8%
Bryozoa	colonial filter feeders	1.7%
Arthropoda	barnacles, crabs, shrimp	0.3%
Nemertea & Annelida	worms	0.2%

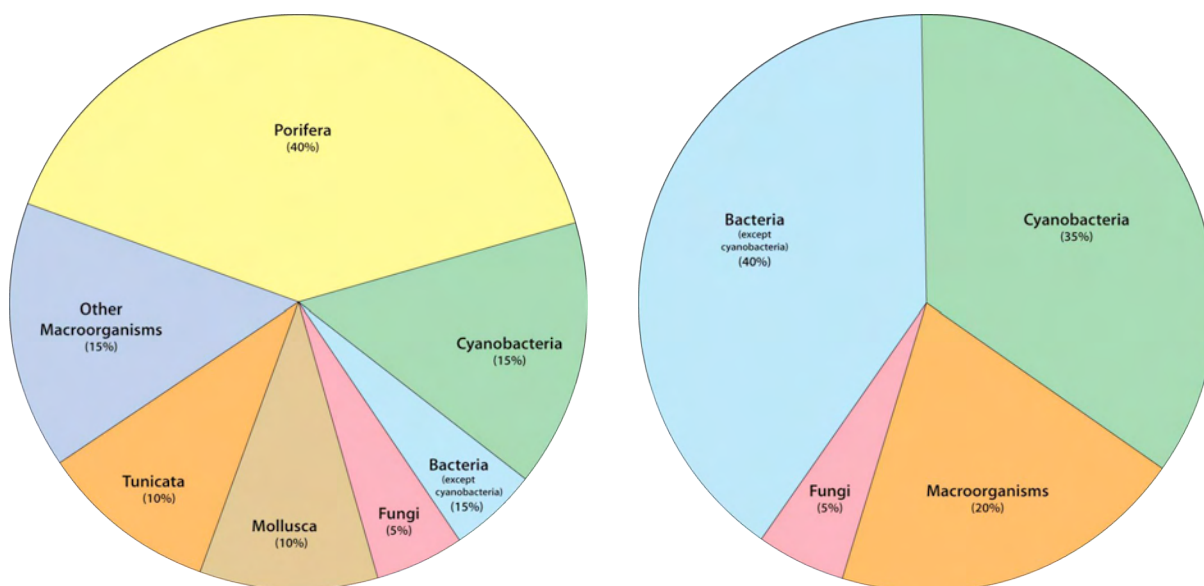


Figure 5-3. Sources of 20 marine anticancer drugs in clinical trials or recently in clinical trials (see Table 5-2): reported (left) versus predicted based on subsequent metagenomic analysis (right)
(adapted from Simmons & Gerwick [2008])

5.3 Measuring and valuing the service

The provision of natural products by marine ecosystems has not been assessed in the same manner as the other ecosystem services discussed in this document, probably because this ecosystem service, being of a distinctly different nature, does not lend itself to commonly employed assessment and valuation methods. For example, there is no easy or straightforward method for estimating either the number of natural products that could be developed or their value. Developing an ecosystem service assessment, particularly for pharmaceutical products, would be greatly impeded by the reticence of companies to discuss their methods, the status of their investigations and clinical trials, or even the specific products being investigated. Given these significant hurdles, it is not especially surprising that there appear to be no reported estimates of the value, or potential value, of marine natural products. There are rare instances where a product's sales may be given for a single year, but such examples

tend to be treated (even by authors) as throwaway factoids, rather than reliable data. Creating a list of potential products, such as Table 5-2, requires a wide-ranging review of many journal articles, reports, and web pages, because the information has not been compiled, and the lists that are available are inevitably incomplete and quickly outdated by new developments.

5.3.1 Specific examples

There are few well-documented market values for marine pharmaceutical products. Part of the problem is that there are not very many marine pharmaceutical products currently in commercial production. Another aspect of the problem is that the pharmaceutical industry tends not to make sales and profit figures available that are disaggregated by year or product. When figures are made available, they tend to be provided in ways that make comparisons difficult, if not impossible. In 2005 in the *British Medical Journal*, the following estimates were given:

The annual profits from a sea sponge compound used to treat herpes, for example, are between \$50m and \$100m (£27m and £55m; €41m and €81m), and cancer fighting agents derived from marine organisms are worth \$1bn (Cole 2005).

The herpes drug is almost certainly acyclovir (*aka* Zovirax®) (see Table 5-2 and Appendix 5-A [listed as acycloguanosine in the Anti-infectives section]).

Another approach is to consider the value of relatively new drugs not of marine origin to gain some sense of the market potential for new marine drugs (Table 5-8).

Table 5-8. Market value of pharmaceutical products

Product	Market Segment	Sales
Avastin®	cancer	\$2.7billion/yr
Herceptin®	cancer	\$1.3 billion /yr
Prezista®	HIV	\$25m (est. for 2006) \$181m (est. for 2007)
all products	antibiotics	\$5 billion
Lipitor®	cholesterol-lowering	\$13.6 billion (2006)
Retrovir® (AZT)	HIV	\$23m (2005)
Zovirax®	antiviral (herpes)	~\$237m (2006)

Source: UN (2007)

5.3.2 Possible approach

One approach that could be used to approximate the potential value of marine natural products in the pharmaceutical industry would be to rely on assumed values for the following parameters:

- 1. the number of marine species**
for megafauna, the number of species is likely to be about 250,000 (as discussed above), but it will be more difficult to estimate the number of species of microorganisms (the estimates discussed above come with great uncertainty);
- 2. the probability that any given species could be the source of a marketable pharmaceutical product**
estimates of this probability vary for terrestrial species, but it appears that the per species probability may be considerably higher for marine species;
- 3. the expected value of a product's revenue**
revenue estimates have been difficult to find (particularly revenue projections), but in the past decade, there has been more independent research in this area;
- 4. the expected cost of a product's development**
research costs have always been difficult to estimate, primarily because pharmaceutical companies consider them to be competitively important and so rarely release them except in the most aggregated forms. However, research on these costs has resulted in numerous journal articles in the past decade, particularly by DiMasi and colleagues at the Tufts Center for the Study of Drug Development (*e.g.*, DiMasi 2001a; DiMasi 2001b; Grabowski *et al.* 2002; DiMasi *et al.* 2003; Adams & Brantner 2006; DiMasi & Grabowski 2007; DiMasi *et al.* 2010); and,
- 5. the expected value of a product's nonmarket benefits**
the nonmarket benefits are usually the most difficult to estimate and the most difficult on which to reach consensus. These benefits will vary depending on: (a) the disease(s) a drug will be used to treat; (b) the treatment regime (short-term vs. long-term consumption); (c) the number of expected users; and, (d) the age distribution of the user population. Several difficult choices have to be made in arriving at an estimate,

including the value of human well-being (including quality of life), the value of life extensions, the value of palliative treatments, the value of a life saved, and whether the value of life depends on the age of the person saved.

This approach has been used to estimate the potential pharmaceutical value of terrestrial plant biodiversity (Principe 1987; Principe 1996). However, such global values are not very useful for assessments and management of specific marine locales and do not provide the marginal values necessary for a proper economic assessment (Simpson *et al.* 1996; Simpson & Craft 1996; Craft & Simpson 2001).

5.4 Reflections

In considering the coral reef ecosystem and which of its attributes contribute to the creation of the ecosystem services provided by natural products, it seems that one must inevitably conclude that these services are not so easily categorized. This results from the services being exclusively created by the ecosystem as a whole; a single attribute is not responsible for the provision of the service. The services provided by the natural products also do not lend themselves to a disaggregated perspective, as is possible, for example, in shoreline protection. Consequently, the table of final ecosystem services and supporting features (Table 5-9) is a brief one.

Marine natural products possess several characteristics that make them compellingly attractive for pharmaceutical purposes. First, the structural complexity of marine secondary metabolites is far greater than from terrestrial sources. Second, marine-derived compounds seem to possess a far higher probability of success than the one in ten thousand expected from traditional sources of potential pharmaceuticals (Principe 1987; Principe 1996). Third, marine-derived compounds have demonstrated biological activity against a wide variety of diseases, afflictions, and pathogens. Fourth, only a small percentage of marine secondary metabolites have been investigated for pharmacological use to date, so there remains an extremely large pool of marine biochemicals to investigate for pharmaceutical use. The utility for humans from marine-based pharmaceuticals is potentially so large that its economic value could surpass that of all other coral reef benefits combined. Consequently, the estimation of this utility will be a vital, if not determinative, element of analyses conducted to support policy decisions that affect the health and integrity of coral reefs.

Even once one gets past the stage of gaping, touristic wonder when viewing the complex structures and strategies created by the denizens of marine ecosystems, the tremendous potential of marine natural products to benefit humans remains mind-numbingly large. Unfortunately, what also remains is the discouraging possibility that the degradation or destruction of coral reef ecosystems will result in these being mind-numbingly large *foregone* benefits. This outcome could be forestalled if the potential benefits of marine natural products could be better characterized and quantified, and this should be one of the goals of the ESRP research program.

Table 5-9. Final ecosystem services and supporting features for natural products

Ecosystem Service(s)		Natural Features	Social Values	Complementary Goods & Services	Ecosystem-Derived Benefits	Potential Indicators of Final Ecosystem Service(s)
Final (FES)	Intermediate					
Pharmaceuticals from natural products						
Marketable natural product or a template that results in a marketable product	Unique biologically active secondary metabolite	Shallow, marine biodiverse, species-dense ecosystem	Desirability of good health and well-being	Pharmaceutical research programs for both field collection and laboratory analysis	Increased revenues from pharmaceuticals; increased health and well-being	Species density, biological integrity, sponge diversity, rare species

5.5 Bibliography

- Adams CP and Brantner VV. 2006. Estimating the Cost of New Drug Development: Is It Really \$802 Million? *Health Affairs*, **25**(2):420-428.
- Al-Sabi A, McArthur J, Ostroumov V and French, RJ. 2006. Marine Toxins That Target Voltage-gated Sodium Channels. *Marine Drugs*, **4**(3):157-192.
- Alexander J. 2002. Comparison of Clinical Trial Phases. Research Coordinator Orientation, University of Pittsburgh. <http://www.clinicalresearch.pitt.edu/docs/comparison_of_clinical_trial_phases.pdf> Accessed 2011.03.28.
- Amagata T, Johnson TA, Cichewicz RH, Tenney K, Mooberry SL, Media J, Edelstein M, Valeriote FA and Crews P. 2008. Interrogating the Bioactive Pharmacophore of the Latrunculin Chemotype by Investigating the Metabolites of Two Taxonomically Unrelated Sponges. *Journal of Medicinal Chemistry*, **51**(22):7234-7242.
- Baerga-Ortiz A. 2009. Biotechnology and Biochemistry of Marine Natural Products. *Marine Biotechnology*, **28**(3):251-257.
- Benedict C. 2002. The Commercialization of a Biopolymer Extracted from the Marine Mussel, *Mytilus edulis*. In, National Research Council (NRC), *Marine Biotechnology in the Twenty-First Century*. Washington, DC, pp. 69-74.

- van Beukering PJH & Cesar HSJ. 2004. Ecological economic modeling of coral reefs: Evaluating tourist overuse at Hanauma Bay and Algae Blooms at the Kihei Coast, Hawai'i. *Pacific Science*, **58**(2):243-260.
- Bhushan B. 2009. Biomimetics: lessons from nature—an overview. *Philosophical Transactions of the Royal Society*, **367**(1893):1445-1486.
- Bilic G, Brubaker C, Messersmith PB, Mallik AS, Quinne TM, Haller C, Done E, Gucciardo L, Zeisberger SM, Zimmermann R, Deprest J and Zisch AH. 2010. Injectable candidate sealants for fetal membrane repair: Bonding and toxicity in vitro. *American Journal of Obstetrics and Gynecology*, **202**(1):85.e1-85.e9.
- Bouchet P. 2006. The magnitude of marine biodiversity. In: C.M. Duarte (ed), *The exploration of marine biodiversity: Scientific and technical challenges*. Madrid: Fundacion BBVA, pp. 31-64.
- Bowling JJ, Kochanowska AJ, Kasanah N and Hamann MT. 2007. Nature's bounty – drug discovery from the sea. *Expert Opinion Drug Discovery*, **2**(11):1505-1522.
- Brier S, Carletti E, DeBonis S, Hewat E, Lemaire D and Kozielski F. 2006. The Marine Natural Product Adociasulfate-2 as a Tool To Identify the MT-Binding Region of Kinesins. *Biochemistry*, **45**(51):15644-15653.
- Bubb MR, Spector I, Bershadsky AD and Korn ED. 1995. Swinholid A is a microfilament disrupting marine toxin that stabilizes actin dimmers and severs actin filaments. *Journal of Biological Chemistry*, **270**(8):3463-3466.
- Butler MS. 2005. Natural products to drugs: natural product derived compounds in clinical trials. *Natural Products Reports*, **22**:162-195.
- Census of Marine Life (CoML). 2010. *First Census of Marine Life 2010. Highlights of a Decade of Discovery*. Washington, DC: Census of Marine Life International Secretariat, 68 pp.
- Census of Marine Life (CoML). <<http://www.coml.org/about>> Accessed 2010.08.24.
- Ceol CJ, Houvras Y, Jane-Valbuena J, Bilodeau S, Orlando DA, Battisti V, Fritsch L, Lin WM, Hollmann TJ, Ferré F, Bourque C, Burke CJ, Turner L, Uong A, Johnson LA, Beroukhim R, Mermel CH, Loda M, Ait-Si-Ali S, Garraway LA, Young RA and Zon LI. 2011. The histone methyltransferase SETDB1 is recurrently amplified in melanoma and accelerates its onset. *Nature*, **471**(24 March):513-517.
- Ceol CJ, Houvras Y, White RM, and Zon LI. 2008. Melanoma Biology and the Promise of Zebrafish. *Zebrafish*, **5**(4):247-255.
- Chambers LD, Stokes KR, Walsh FC and Wood RJK. 2006. Modern approaches to marine antifouling coatings. *Surface & Coatings Technology*, **201**(2006):3642-3652.
- Cole A. 2005. Looking for new compounds in sea is endangering ecosystem. *British Medical Journal*, **330**:1350 (published 9 June 2005 – web only). <<http://www.bmj.com/content/330/7504/1350.5.full>> Accessed 2010.09.16.
- Collini E, Wong CY, Wilk KE, Curmi PMG, Brumer P and Scholes GD. 2010. Coherently wired light-harvesting in photosynthetic marine algae at ambient temperature. *Nature*, **463**(4 February):644-647.
- Craft AB and Simpson RD. 2001. The Value of Biodiversity in Pharmaceutical Research with Differentiated Products. *Environmental and Resource Economics*, **18**(1):1-17.
- Cragg GM and Newman DJ. 2009. Nature: A vital source of leads for anticancer drug development. *Phytochemistry Reviews*, **8**(2):313-331.
- Croteau R, Kutchan TM and Lewis NG. 2000. Natural Products (Secondary Metabolites). In, Bob B. Buchanan, Wilhelm Gruissem, and Russell Jones (eds.), *Biochemistry & Molecular Biology of Plants*. Rockville, MD, American Society of Plant Physiologists, Chapter 24, pp. 1250-1318.
- Davidson EH and Erwin DH. 2006. Gene Regulatory Networks and the Evolution of Animal Body Plans. *Science*, **311**(5762):796–800.
- DiMasi JA. 2001a. New drug development in the United States from 1963 to 1999. *Clinical Pharmacology & Therapeutics*, **69**:286-296.
- DiMasi JA. 2001b. Risks in new drug development: Approval success rates for investigational drugs. *Clinical Pharmacology & Therapeutics*, **69**:297-307.
- DiMasi JA, Feldman L, Seckler A and Wilson A. 2010. Trends in risks associated with new drug development: Success rates for investigational drugs. *Clinical Pharmacology & Therapeutics*, **87**:272-277.
- DiMasi JA, Hansen RW and Grabowski HG. 2003. The price of innovation: New estimates of drug development costs. *Journal of Health Economics*, **22**:151-185.
- DiMasi JA and Grabowski HG. 2007. The Cost of Biopharmaceutical R&D: Is Biotech Different? *Managerial and Decision Economics*, **28**:469-479.
- Donia M and Hamann MT. 2003. Marine natural products and their potential applications as anti-infective agents. *The Lancet Infectious Diseases*, **3**(6):338-348.
- Dugan JM, Gough JE and Eichhorn SJ. 2010. Directing the Morphology and Differentiation of Skeletal Muscle Cells Using Oriented Cellulose Nanowhiskers. *Biomacromolecules*, **11**(9):2498–2504.
- Dumez H, Gall H, Capdeville R, Dutreix C, van Oosterom AT and Giaccone G. 2007. A phase I and pharmacokinetic study of LAF389 administered to patients with advanced cancer. *Anticancer Drugs*, **18**(2):219-225.
- Faulkner DJ. 2000. Marine pharmacology. *Antonie van Leeuwenhoek*, **77**:135-145.
- Fenical W. 1982. Natural Products Chemistry in the Marine Environment. *Science* **215**(4535):923–928.

- Fenical W. 1993. Chemical Studies of Marine Bacteria: Developing a New Resource. *Chemical Reviews* **93**:1673–1683.
- Fenical W. 1996. Marine biodiversity and the medicine cabinet: The status of new drugs from marine organisms. *Oceanography* **9**(1):23–27.
- Fenical W. 1997. New pharmaceuticals from marine organisms. *Trends in Biotechnology*, **15**(Nov):339–341.
- Fenical W. 2006. Marine Pharmaceuticals. Past, Present, and Future. *Oceanography*, **19**(2):111–119.
- Firn RD. 2003. Bioprospecting – why is it so unrewarding? *Biodiversity and Conservation*, **12**:207–216.
- Fisher WS. 1983a. Eggs of *Palaemon macrodactylus*: II. Association with aquatic bacteria. *The Biological Bulletin*, **164**(2):201–213.
- Fisher WS. 1983b. Eggs of *Palaemon macrodactylus*: III. Infection by the fungus, *Lagenidium callinectes*. *The Biological Bulletin*, **164**(2):214–226.
- Fisher WS and Clark WH Jr. 1983. Eggs of *Palaemon macrodactylus*: I. Attachment to the pleopods and formation of the outer investment coat. *The Biological Bulletin*, **164**(2):189–200.
- Fountain H. 2010. Studying Sea Life for a Glue That Mends People. *The New York Times*, April 12, 2010.
<<http://www.nytimes.com/2010/04/13/science/13adhesive.html>> Accessed 2010.04.14.
- Franco CMM and Coutinho LEL. 1991. Detection of Novel Secondary Metabolites. *Critical Reviews in Biotechnology*, **11**(3):193–276.
- Fusetani N and Kem W. 2009. Marine Toxins: An Overview. In: Fusetani N and Kem W (eds), *Marine Toxins as Research Tools*. 187 Progress in Molecular and Subcellular Biology, Marine Molecular Biotechnology 46. Berlin: Springer-Verlag, pp. 1–44.
- Gerwick WH. 2008. Marine Remedies. In: Walsh PJ, Smith SL, Fleming LE, Solo-Gabriele HM and Gerwick WH (eds), *Oceans and Human Health. Risks and Remedies From the Seas*. San Diego: Academic Press. ISBN 978-0-12-372584-4. Chapter 21, pp. 425–429.
- Glaser KB. 2007. HDAC inhibitors: Clinical update and mechanism-based potential. *Biochemical Pharmacology*, **74**(5):659–671.
- Grabowski HG, Vernon J and DiMasi JA. 2002. Returns on research and development for the 1990s new drug introductions. *Pharmacoeconomics*, **20**(S3):11–29.
- Gross H and König GM. 2006. Terpenoids from marine organisms: Unique structures and their pharmacological potential. *Phytochemistry Reviews*, **5**:115–141.
- Guardian 2010. <<http://www.guardian.co.uk/environment/2010/feb/13/algae-solve-pentagon-fuel-problem>> Accessed 2010.02.13.
- Gullo VP, McAlpine J, Lam KS, Baker D and Petersen F. 2006. Drug discovery from natural products. *Journal of Industrial Microbiology and Biotechnology*, **33**:523–531.
- Harrington MJ, Masic A, Holten-Andersen N, Waite JH and Fratzl P. 2010. Iron-Clad Fibers: A Metal-Based Biological Strategy for Hard Flexible Coatings. *Science*, **328**(5975):216–220 (2010.04.09).
- Harvey AL, Clark RL, Mackay SP and Johnston BF. 2010. Current strategies for drug discovery through natural products. *Expert Opinion Drug Discovery*, **5**(6):559–568.
- Hay ME and Fenical W. 1996. Chemical ecology and marine biodiversity: Insights and products from the sea. *Oceanography*, **9**(1):10–20.
- Huigens RW III, Ma L, Gambino C, Moeller PDR, Basso A, Cavanagh J, Wozniak DJ and Melander C. 2008. Control of bacterial biofilms with marine alkaloid derivatives. *Molecular BioSystems*, **4**(6):614–621.
- Hunt B and Vincent ACJ. 2006. Scale and Sustainability of Marine Bioprospecting for Pharmaceuticals. *Ambio*, **35**(2):57–64.
- Huxley A. 1984. *Green Inheritance: The World Wildlife Fund Book of Plants*. London: Collins/Harvill.
- Jopling C, Sleep E, Raya M, Martí M, Raya A and Belmonte JCI. 2010. Zebrafish heart regeneration occurs by cardiomyocyte dedifferentiation and proliferation. *Nature*, **464**(7288):606–611 (2010.03.25).
- Karunasagar I and Karunasagar I. 2008. Marine Biotechnology: A Natural Biorefinery Source of Marine Products and By-products for Human Welfare. *Asian Biotechnology and Development Review*, **10**(1–2):89–102.
- Kaul PN and Daftari P. 1986. Marine pharmacology: Bioactive molecules from the sea. *Annual Review of Pharmacology and Toxicology*, **26**(1):117–142.
- Kikuchi K, Holdway JE, Werdich AA, Anderson RM, Fang Y, Egnaczyk GF, Evans T, MacRae CA, Stainier DYR and Poss KD. 2010. Primary contribution to zebrafish heart regeneration by *gata4*⁺ cardiomyocytes. *Nature*, **464**(7288):601–605 (2010.03.25).
- Koehn FE and Carter GT. 2005. The evolving role of natural products in drug discovery. *Nature Reviews Drug Discovery*, **4**(3):206–220.
- Lam KS. 2006. Discovery of novel metabolites from marine actinomycetes. *Current Opinion in Microbiology*, **9**:245–251.
- Layer RT and McIntosh JM. 2006. Conotoxins: Therapeutic Potential and Application. *Marine Drugs*, **4**(3):119–142.
- Lee LP and Szema R. 2005. Inspirations from Biological Optics for Advanced Photonic Systems. *Science*, **310**(5751):1148–1150 (2005.11.18).
- Leeds JA, Schmitt EK and Krastel P. 2006. Recent developments in antibacterial drug discovery: Microbe-derived natural products – from collection to the clinic. *Expert Opinion Investigational Drugs*, **15**(3):211–226.
- Lewis RJ. 2009. Conotoxins: Molecular and Therapeutic Targets. In: Fusetani N and Kem W (eds). *Marine Toxins as Research Tools*. 187 Progress in Molecular and Subcellular Biology, Marine Molecular Biotechnology 46. Berlin: Springer-Verlag, pp. 45–65.

- Longford SR, Tujula NA, Crocetti GR, Holmes AJ, Holmstrom C, Kjelleberg S, Steinberg PD and Taylor MW. 2007. Comparisons of diversity of bacterial communities associated with three sessile marine eukaryotes. *Aquatic Microbial Ecology*, **48**:217-229.
- Mathews JB, Smith JA and Hrnjez BJ. 1997. Effects of F-actin stabilization or disassembly on epithelial Cl⁻ secretion and Na-K-2Cl cotransport. *American Journal of Physiology*, **272**(1 Pt. 1):C254-C262.
- Mayer AMS, Glaser KB, Cuevas C, Jacobs RS, Kem W, Little RD, McIntosh JM, Newman DJ, Potts BC and Shuster DE. 2010. The odyssey of marine pharmaceuticals: A current pipeline perspective. *Trends in Pharmacological Sciences*, **31**(6):255-265.
- Mayer G. 2005 Rigid Biological Systems as Models for Synthetic Composites. *Science*, **310**(5751):1144-1147 (2005.11.18).
- Messersmith PB. 2010. Holding On by a Hard-Shell Thread. *Science*, **328**(5975):180-181 (2010.04.09).
- Molinski TF, Dalisay DS, Lievens SL and Saludes JP. 2009. Drug development from marine natural products. *Nature Reviews Drug Discovery*, **8**(1):69-85.
- Müller WEG, Schröder HC, Wiens M, Perovic-Ottstadt S, Batel R and Müller IM. 2004. Traditional and Modern Biomedical Prospecting: Part II—the Benefits. Approaches for a Sustainable Exploitation of Biodiversity (Secondary Metabolites and Biomaterials from Sponges). *Evidence-based Complementary and Alternative Medicine*, **1**(2):133-144.
- Mumby PJ, Broad K, Brumbaugh DR, Dahlgren CP, Harborne AR, Hastings A, Holmes KE, Kappel CV, Micheli F and Sanchirico JN. 2008. Coral Reef Habitats as Surrogates of Species, Ecological Functions, and Ecosystem Services. *Conservation Biology*, **22**:941-951.
- National Research Council (NRC). 1999. *From Monsoons to Microbes. Understanding the Ocean's Role in Human Health*. Washington, DC: National Research Council, Commission on Geosciences, Environment, and Resources, Ocean Studies Board, Committee on the Ocean's Role in Human Health. ISBN 0-309-06569-0. 166 pp.
- Nereus Pharmaceuticals. 2010. Nereus Pharmaceuticals Completes Enrollment of Phase 2 ADVANCE Clinical Trial of Plinabulin in Non-Small Cell Lung Cancer [News Release]. <http://www.nereuspharm.com/news_06222010.shtml> Accessed 2010.08.11.
- Newman DJ and Cragg GM. 2004. Marine natural products and related compounds in clinical and advanced preclinical trials. *Journal of Natural Products*, **67**(8):1216-1238.
- Newman DJ and Cragg GM. 2007. Natural Products as Sources of New Drugs over the last 25 Years. *Journal of Natural Products*, **70**(3):461-477.
- Newman DJ, Cragg GM and Snader KM. 2000. The Influence of Natural Products upon Drug Discovery. *Natural Products Reports*, **17**:215-234.
- Newman DJ and Hill RT. 2006. New drugs from marine microbes: The tide is turning. *Journal of Industrial Microbiology and Biotechnology*, **33**:539-544.
- Pawlik JR. 1993. Marine Invertebrate Chemical Defenses. *Chemical Reviews*, **93**(5):1911-1922.
- Penesyan A, Kjelleberg S and Egan S. 2010. Development of Novel Drugs from Marine Surface Associated Microorganisms. *Marine Drugs*, **8**:438-459.
- Pettit GR and Taylor SR. 1995. Synthesis of the Marine Sponge Cycloheptapeptide Stylopeptide 1. *Journal of Organic Chemistry*, **61**(7):2322-2325.
- Principe PP. 1987. *The Value of Biological Diversity Among Medicinal Plants*. ENV/ECO/87.8. Organization for Economic Cooperation and Development (OECD), Environment Directorate, Group of Economic Experts, Paris. April 1987. 67 pp.
- Principe PP. 1996. Monetizing the Pharmacological Benefits of Plants. In: Balick MJ, Elisabetsky E and Laird S (eds), *Medicinal Resources of the Tropical Forest: Biodiversity and Its Importance to Human Health*. New York. Columbia University Press, Chapter 14, pp. 191-218.
- Rasala BA, Muto M, Lee PA, Jager M, Cardoso RMF, Behnke CA, Kirk P, Hokanson CA, Crea R, Mendez M and Mayfield SP. 2010. Production of therapeutic proteins in algae, analysis of expression of seven human proteins in the chloroplast of *Chlamydomonas reinhardtii*. *Plant Biotechnology Journal*, **8**(6):719-733.
- Robinson SJ, Morinaka BI, Amagata T, Tenney K, Bray WM, Gassner NC, Lokey RS and Crews P. 2010. New Structures and Bioactivity Properties of Jaspakinolide (Jasplamide) Analogues from Marine Sponges. *Journal of Medicinal Chemistry*, **53**(4):1651-1661.
- Rohwer F, Breitbart M, Jara J, Azam F and Knowlton N. 2001. Diversity of bacteria associated with the Caribbean coral *Montastraea franksi*. *Coral Reef*, **20**:85-91.
- Saito S. 2009. Toxins Affecting Actin Filaments and Microtubules. In: Fusetani N and Kem W (eds), *Marine Toxins as Research Tools*, 187 Progress in Molecular and Subcellular Biology, Marine Molecular Biotechnology 46. Berlin: Springer-Verlag, pp. 187-219.
- Sashidhara KV, White KN and Crews P. 2009. A Selective Account of Effective Paradigms and Significant Outcomes in the Discovery of Inspirational Marine Natural Products. *Journal of Natural Products*, **72**(3):588-603.
- Seigler DS. 2002. *Plant Secondary Metabolism*. Norwell (MA): Kluwer Academic Publishers, 2nd printing. ISBN 0-412-01981-7.

- Senderowicz AM, Kaur G, Saina E, Lang C, Inman WD, Rodriguez J, Crews P, Malspeis L, Grever MR, Sausville EA and Duncan KKK. 1995. Jaspilakinolide's inhibition of the growth of prostate carcinoma cells in vitro with disruption of the actin cytoskeleton. *Journal of the National Cancer Institute*, **87**(1):46-51.
- Sharklet Technologies, Inc. <<http://www.sharklet.com>> Accessed 2010.09.16.
- Simmons TL, Andrianasolo E, McPhail K, Flatt P and Gerwick WH. 2005. Marine natural products as anticancer drugs. *Molecular Cancer Therapeutics*, **4**(2):333-342.
- Simmons TL and Gerwick WH. 2008. Anticancer Drugs of Marine Origin. In: Walsh PJ, Smith SL, Fleming LE, Solo-Gabriele HM and Gerwick WH (eds), *Oceans and Human Health. Risks and Remedies From the Seas*. San Diego: Academic Press, ISBN 978-0-12-372584-4, Chapter 22, pp. 431-452.
- Simpson RD and Craft AB. 1996. *The Social Value of Using Biodiversity in New Pharmaceutical Product Research*. Discussion Paper 96-33. Washington, DC: Resources for the Future, 46 pp.
- Simpson RD, Sedjo RA and Reid JW. 1996. Valuing Biodiversity for Use in Pharmaceutical Research. *Journal of Political Economy*, **104**(1):163-185.
- Sutherland KR, Madina LP and Stocker R. 2010. Filtration of submicrometer particles by pelagic tunicates. *Proceedings of the National Academy of Sciences*, **107**(34):15129-15134.
- Uduary DW, Kalaitzis JA and Moore BS. 2008. Emerging Marine Biotechnologies. Cloning of Marine Biosynthetic Gene Clusters. In: Walsh PJ, Smith SL, Fleming LE, Solo-Gabriele HM and Gerwick WH (eds), *Oceans and Human Health. Risks and Remedies From the Seas*. San Diego: Academic Press, ISBN 978-0-12-372584-4, Chapter 26, pp. 507-524.
- United Nations (UN). 2007. An Update on Marine Genetic Resources: Scientific Research, Commercial Uses and a Database on Marine Bioprospecting. United Nations informal Consultative Process on Oceans and the Law of the Sea. Eighth Meeting. New York, 25-29 June 2007.
- Venn-Watson S and Ridgway SH. Big brains and blood glucose: Common ground for diabetes mellitus in humans and healthy dolphins. *Comparative Medicine*, **57**(4):390-395.
- Walther A, Bjurhager I, Malho J-M, Pere J, Ruokolainen J, Berglund LA and Ikkala O. 2010. Large-Area, Lightweight and Thick Biomimetic Composites with Superior Material Properties via Fast, Economic, and Green Pathways. *Nano Letters*, **10**(8):2742-2748.
- Wase NV and Wright PC. 2008. Systems biology of cyanobacterial secondary metabolite production and its role in drug discovery. *Expert Opinion Drug Discovery*, **3**(8):903-929.
- White RA and White EW. 2002. Uniform Microporous Biomaterials Prepared from Marine Skeletal Precursors. In: National Research Council (NRC), *Marine Biotechnology in the Twenty-First Century*. Washington, DC, pp. 80-83.
- White RM, Cech J, Ratanasirintra-woot S, Lin CY, Rahl PB, Burke CJ, Langdon E, Tomlinson ML, Mosher J, Kaufman C, Chen F, Long HK, Kramer M, Datta S, Neuberger D, Granter S, Young RA, Morrison S, Wheeler GN and Zon LI. 2011. DHODH modulates transcriptional elongation in the neural crest and melanoma. *Nature*, **471**(24 March):518-522.
- Whitman WB, Coleman DC and Wiebe WJ. 1998. Prokaryotes: The unseen majority. *Proceedings of the National Academy of Science*, **95**:6578-6583.
- Wijffels RH. 2007. Potential of sponges and microalgae for marine biotechnology. *Trends in Biotechnology*, **26**(1):26-31.
- Wikipedia. 2010. <http://en.wikipedia.org/wiki/Small_molecule> Accessed 2010.07.08.
- Wikipedia. 2011. <http://en.wikipedia.org/wiki/Clinical_trials> Accessed 2011.03.28.
- Williams PG. 2008. Panning for chemical gold: marine bacteria as a source of new therapeutics. *Trends in Biotechnology*, **27**(1):45-52.
- Wink M. 2003. Evolution of secondary metabolites from an ecological and molecular phylogenetic perspective. *Phytochemistry*, **64**(1):3-19.
- Yao H, Dao M, Imholt T, Huang J, Wheeler K, Bonilla A, Suresh S and Ortiz C. 2010. Protection mechanisms of the iron-plated armor of a deep-sea hydrothermal vent gastropod. *Proceedings of the National Academy of Sciences*, **107**(3):987-992.
- Yasuhara-Bell J, Yang Y, Barlow R, Trapido-Rosenthal H and Lu Y. 2010. *In vitro* evaluation of marine-microorganism extracts for anti-viral activity. *Virology Journal*, **7**:182-192.
- Yooseph S, Sutton G, Rusch DB, Halpern AL, Williamson SJ, Remington K, Eisen JA, Heidelberg KB, Manning G, Li W, Jaroszewski L, Cieplak P, Miller CS, Li H, Mashiyama ST, Joachimiak MP, van Belle C, Chandonia J-M, Soergel DA, Zhai Y, Natarajan K, Lee S, Raphael BJ, Bafna V, Friedman R, Brenner SE, Godzik A, Eisenberg D, Dixon JE, Taylor SS, Strausberg RL, Frazier M and Venter JC. 2007. The Sorcerer II Global Ocean Sampling Expedition: Expanding the Universe of Protein Families. *PLoS Biology*, **5**(3): 0432-0466.
- Yuan G, Wahlqvist ML, He G, Yang M and Li D. 2006. Natural products and anti-inflammatory activity. *Asia Pacific Journal of Clinical Nutrition*, **15**(2):143-152.


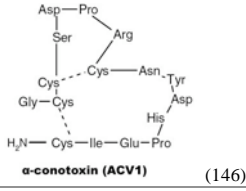

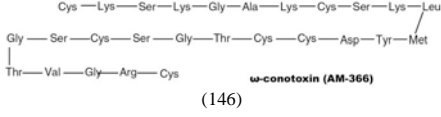

Appendix 5-A


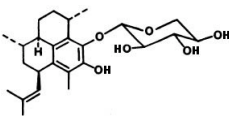
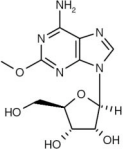

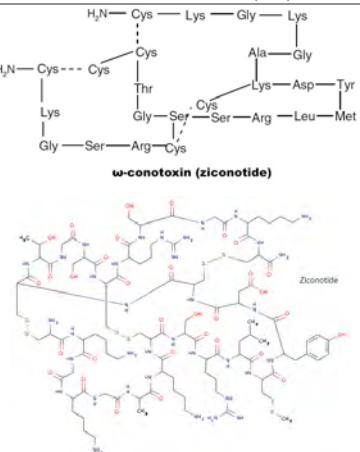
Marine pharmaceutical products

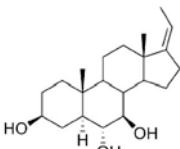
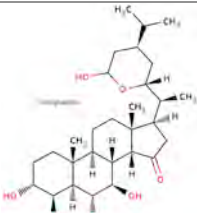
This table contains a small subset of the marine biochemicals possessing biological activity that have been investigated as potential pharmaceutical products or as molecular probes for exploring biochemical pathways and reactions. The biochemicals are grouped into the following categories:

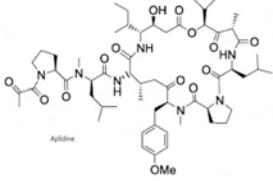
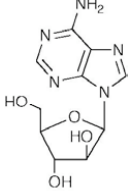
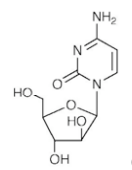
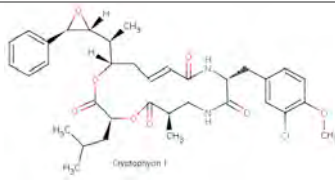
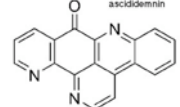

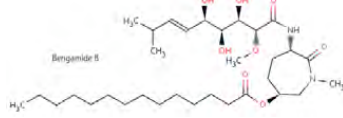

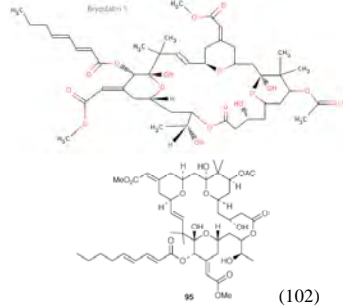
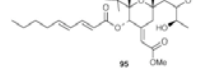
- Analgesic drugs
- Antiasthmatic drugs
- Anticancer drugs
- Antidiabetic drugs
- Anti-infective drugs
- Cardiac & circulatory system drugs; Anti-angiogenesis drugs
- Immunological drugs
- Molecular probes
- Neurological drugs
- Templates

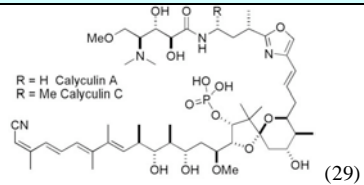

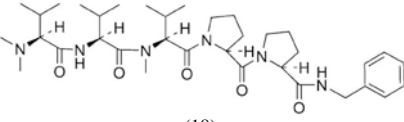
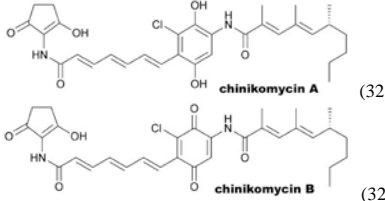
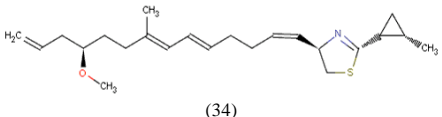
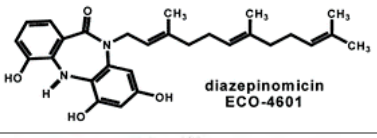
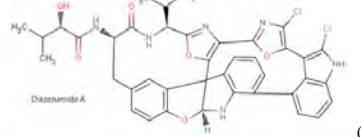
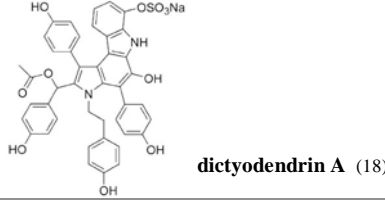

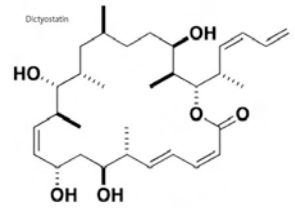
Some of the chemicals have duplicate entries if they have multiple uses.

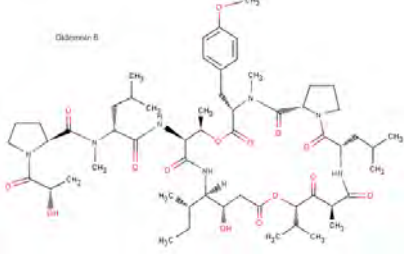
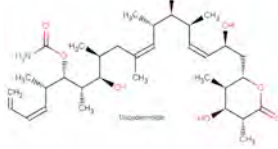

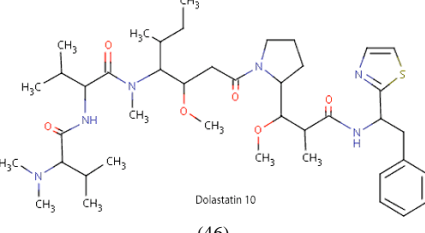

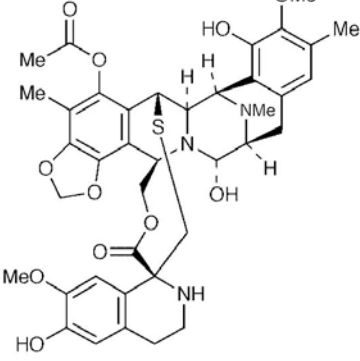

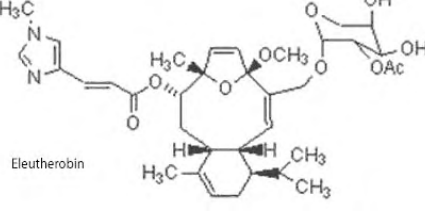
Analgesic drugs				
Chemical	Source	Uses & Status	Structure	Citations
conantokin G	mollusk (cone snail) (<i>Conus geographus</i>) Indo-Pacific 	analgesic & anti-seizure; 17-amino-acid competitive antagonist of N-methyl-D- aspartate (NMDA) receptors; Phase I trials discontinued	precursor amino acid sequence shown at (128, Figure 2, p. 275)	1,2,18 photo:3
α -conotoxin Vc1.1 (ACV1)	mollusk (cone snail) (<i>Conus victoriae</i>) Australia, Japan	α -conotoxins inhibit the postsynaptic acetylcholine receptor; preclinical studies	 α -conotoxin (ACV1) (146)	18,146
χ -conotoxin MR1A/B	mollusk (cone snail) (<i>Conus</i> sp.) Indo-Pacific	χ -conotoxins selectively inhibit the activity of neuronal noradrenaline transporter; preclinical studies		4,18
ω -conotoxin CVID (AM-336)	mollusk (cone snail) (<i>Conus catus</i>) Indo-Pacific 	ω -conotoxins inhibit voltage- activated entry of calcium into the presynaptic membrane, inhibiting the release of acetylcholine; preclinical studies	 ω -conotoxin (AM-336) (146)	18,146 photo: 5
contulakin G (CGX-1160)	mollusk (cone snail) (<i>Conus geographus</i>) Indo-Pacific 	a 16-amino acid peptide with an O-glycosylated threonine residue; a neurotensin agonist; Phase I trials		6,18 photo: 3
Thr 10-contulakin G (modified toxin)	mollusk (cone snail) (<i>Conus</i> sp.) Indo-Pacific	preclinical studies		7,8,18

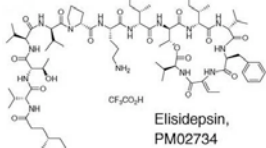
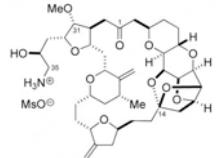
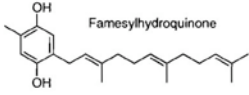
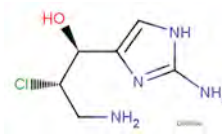
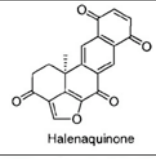
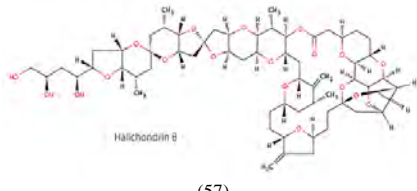
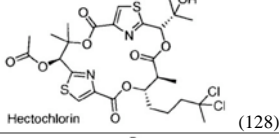
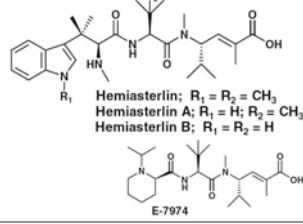
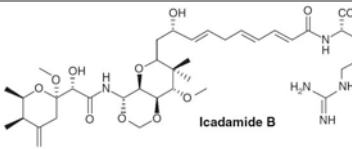
Analgesic drugs				
Chemical	Source	Uses & Status	Structure	Citations
pseudopterosins (including methopterosin, a derivative)	gorgonian (sea whip) (<i>Pseudopterogorgia elisabethae</i>) Caribbean 	arthritis, anti-inflammation, & analgesic; affect the arachidonic acid cascade; inhibit synthesis of eicosanoids, (locally functioning hormone-like substances) in specific white blood cells; pharmacologically distinct from other NSAIDs & their MOA seems novel; preclinical; sold as a cosmetic anti-wrinkle cream by Estee Lauder under the name	 pseudopterosin A (9)	9,10,24,25 photo: 11
spongosine (2-metoxyadenosine)	sponge (<i>Tectitethya crypta</i>) (synonym: <i>Cryptotethya crypta</i>) Caribbean	analgesic; neuropathic & inflammatory pain	 spongosine (146)	146
ziconotide (Prialt®)	mollusk (cone snail) (top: <i>Conus geographus</i> , bottom: <i>Conus magus</i>) Indo-Pacific 	inhibits N-type voltage-dependent calcium channels to short-circuit neurotransmitter release in nerves that transmit pain signals; the precisely targeted MOA effectively blocks pain while still allowing the rest of the nervous system to function properly; the effect of ω -conotoxin M VII A is 100 to 1000 times that of morphine; FDA approval in December 2004; licensed to Warner Lambert	 ziconotide (13)	12,13,14, 18,102,106, 146 photos: 3 (top) 15 (bottom)


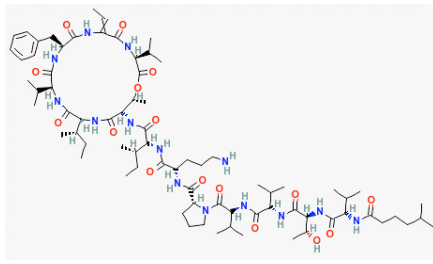
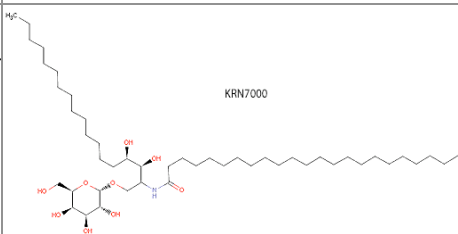

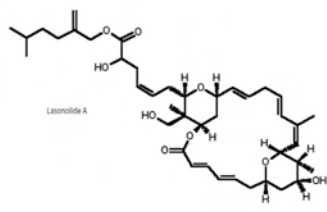
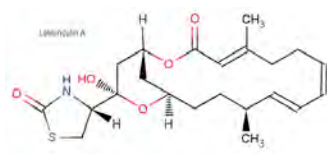
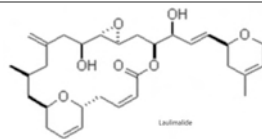

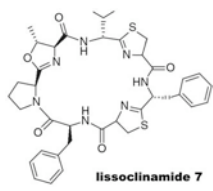
Antiasthmatic drugs				
Chemical	Source	Uses & Status	Structure	Citations
IPL-576,092 (HMR-4011A) IPL-550,260 IPL-512,602 (contignasterol derivatives)	sponge (<i>Neopetrosia contignata</i>) (synonym: <i>Petrosia contignata</i>) Indonesia	antihistamine & antiasthmatic; IPL-576,092 completed Phase II trials successfully (by Inflazyme Pharma); IPL-512,602 in Phase I trials (by Avantis); IPL-512,602 in Phase II trials (by Avantis)	 IPL-576,092 (18)	16,18
contignasterol	sponge (<i>Neopetrosia contignata</i>) (synonym: <i>Petrosia contignata</i>) Indonesia	antihistamine & antiasthmatic	 (16)	16,18

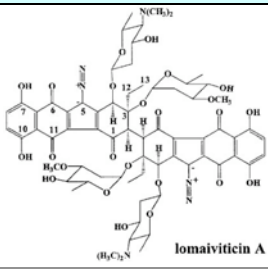

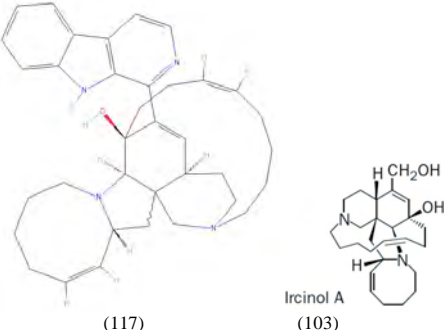
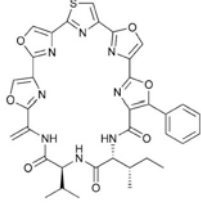
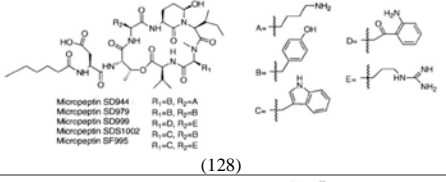
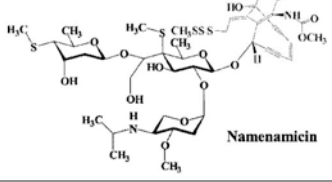

Anticancer drugs				
Chemical	Source	Uses & Status	Structure	Citations
aplidine (total synthetic of dehydrodidemnin B) (Aplidin®)	tunicate (<i>Aplidium albicans</i>) Mediterranean	anticancer; differs chemically from didemnin B and the other didemnins only in the structure of its side chain; MOA is unclear; a multifactorial apoptosis inducer; Phase II trials underway for various cancers; PharmaMar	 (17)	17,18
Ara-A (vidarabine, Vira-A®) (derived from spongouridine & spongothymidine)	sponge (<i>Tectithya crypta</i>) (synonym: <i>Cryptotethya crypta</i>) Caribbean	antiviral & anticancer; clinical use	 (102)	18,19,102
Ara-C (Cytosar-U®, DepoCyt®, Tarabine PFS®, cytarabine, 1-β-D-arabinosylcytosine) (derived from spongouridine & spongothymidine)	sponge (<i>Tectithya crypta</i>) (synonym: <i>Cryptotethya crypta</i>) Caribbean	antiviral & anticancer; clinical use	 (102)	18,19, 102,103
arenastatin A (cryptophycins)	sponge (<i>Dysidea arenaria</i>) Palau Islands	anticancer; tubulin interactive agent; Phase I trials; synthetic derivative licensed to Lilly by Univ. of Hawaii; withdrawn in 2002	 (20)	18,20
ascididemnin	tunicate (<i>Leptoclinides</i> sp.) Central Pacific	anticancer; reductive DNA-cleaving agents; preclinical studies	 (18)	18,21
azaspiracid-1	algæ	anticancer; shows toxicity to lymphocytes & neuroblastoma cells		128
bengamide derivative; LAF-389	sponge (<i>Jaspis</i> sp.) Fiji 	anticancer & antihelminthic; methionine aminopeptidase (Met-AP1) inhibitor; licensed to Novartis; withdrawn from Phase I trials in 2002; LAF-389 is a synthetic bengamide B derivative; Phase I trial may have been suspended in 2006	 (22)	18,22 photo: 23
bistratene	tunicate	anticancer; induces cell-cycle arrest in G ₀ /G ₁ & G ₂ /M		128
bryostatins 1	bryozoan (<i>Bugula neritina</i> [photo]) (chemical possibly from commensal bacterium [<i>Endobugula sertula</i>]) worldwide 	anticancer; inhibits leukemia via immunostimulation & binding to the receptor, protein kinase C (PKC), displacing tumor promoting phorbol esters that bind to the same place; seems to enhance other drugs but not effective by itself; Phase II trials; in combination therapy trials in 2004; licensed by Arizona State Univ to GPC Biotech., which stopped development in 2003	 (27)  (102)	18,24,25,26, 27,102 photo: 28

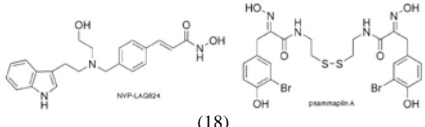

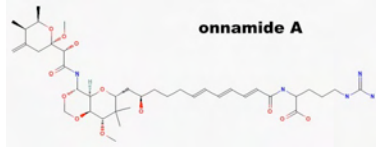
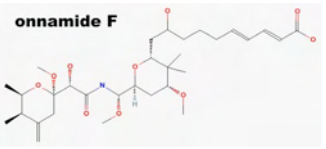
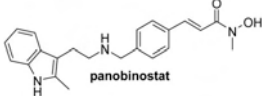

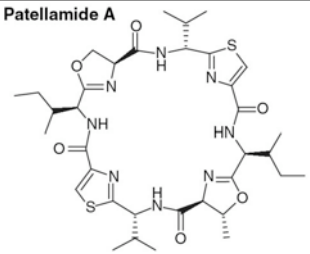
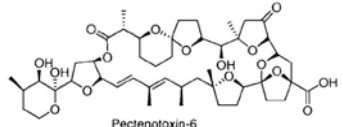
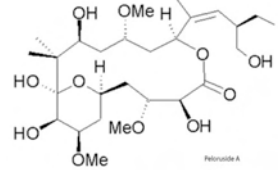

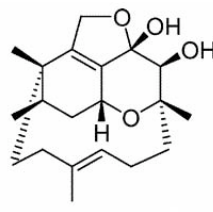
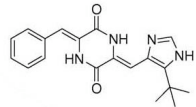
Anticancer drugs				
Chemical	Source	Uses & Status	Structure	Citations
calyculin A & calyculin C	sponge (<i>Discodermia calyx</i>)	anticancer; strong serine/threonine protein phosphatase inhibitors	 <p>(29)</p>	30
cematodin (synthetic derivative of dolastatin 15) (LU-103793)	sea hare (<i>Dolabella auricularia</i> [photo]) (chemical possibly from commensal cyanobacteria [<i>Symploca hydroides</i> & <i>Lyngbya majuscula</i>]) Indian Ocean 	anticancer; Phase II trials for malignant melanoma, metastatic breast cancer & non-small-cell lung cancer; Phase II trials for melanoma, breast, & NSCLC; appears to stabilize melanoma & breast cancers; increase in QoL for NSCLS	 <p>(18)</p>	18,44 photo: 31
chinikomycin A & chinikomycin B (chlorine-containing manumycin derivatives)	sediment actinobacterium (<i>Streptomyces</i> sp.) China	anticancer; antitumor activity against several cancer lines	 <p>chinikomycin A (32) chinikomycin B (32)</p>	32
coscinosulfate	sponge	anticancer; cell cycle regulation		128
curacin A	cyanobacterium (<i>Lyngbya majuscula</i>) Caribbean	anticancer; antimetabolic activity; tubulin interactive compound; preclinical; synthetic derivatives with better solubility being evaluated	 <p>(34)</p>	18,24,25, 33,34
diazepinomicin (ECO-4601)	actinobacterium (<i>Micromonospora</i> sp.)	antibiotic & anticancer; Phase I trials (antibiotic & anticancer)	 <p>diazepinomicin ECO-4601 (35)</p>	35,36
diazonamide	ascidian (<i>Diazona angulata</i>) Phillipines	anticancer; inhibits microtubule assembly, arresting the process of cell division; preclinical studies; synthesized & new structure elucidated	 <p>Diazonamide A (37)</p>	18,37
dictyodendrins	sponge (<i>Dictyodendrillia verongiformis</i>) Japan	anticancer; telomerase inhibitors; has shown 100% inhibition; preclinical studies	 <p>dictyodendrin A (18)</p>	18
dictyostatin	sponge (<i>Spongia</i> sp.) Caribbean 	anticancer; inhibits the growth of human cancer cells; active against certain Taxol-resistant tumors; MOA appears to be prevention of the breakdown of tubulin during mitosis (like Taxol); preclinical studies	 <p>(38)</p>	38 photo: 126

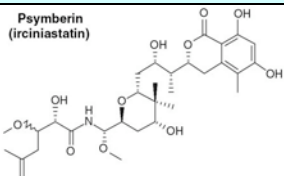

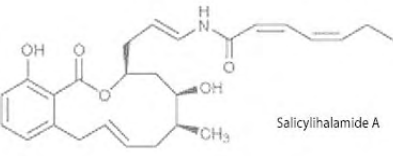
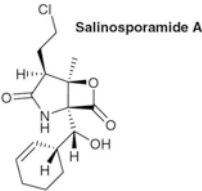
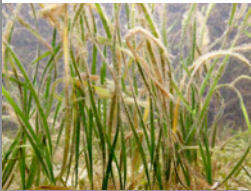
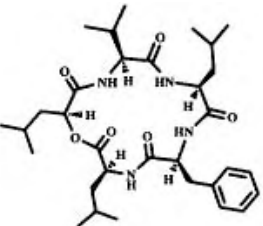

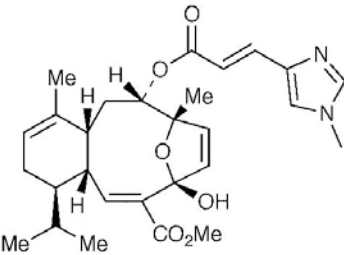
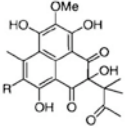
Anticancer drugs				
Chemical	Source	Uses & Status	Structure	Citations
didemnin B	tunicate (<i>Trididemnum solidum</i>) Caribbean	anticancer & antiviral interrupts protein synthesis in target cells by binding noncompetitively to palmitoyl protein thioesterase; cytotoxic for lymphomas, some leukemias & melanomas; antiviral for herpes simplex and several others; Phase II trials showed significant toxicity at efficacious doses; dropped in middle 1990s	 (41)	18,24,39,40,41
discodermolide	deep-water sponge (<i>Discodermia dissoluta</i>) Caribbean	anticancer & immunosuppressive; tubulin polymer stabilizer (like taxol); essentially arresting cells at a specific stage in the cell cycle and halting cell division; Phase I trials; licensed to Novartis by Woods Hole; may be used in combination with Taxol	 (43)	24,25,42,43
dolastatin 10	sea hare (<i>Dolabella auricularia</i>) (chemical possibly from commensal cyanobacteria [<i>Symploca hydroides</i> & <i>Lyngbya majuscula</i>]) Indian Ocean 	anticancer; mitotic inhibitor; interferes with tubulin formation & thereby disrupt cell division by mitosis; binds to tubulin at the vinca/peptide region, the target for several structurally complex natural products, including hemisterlin; cytotoxic for B-16 and LOX melanomas; no positive effects in Phase II trials, but may find use in combination drug therapy with vincas or bryostatins; many derivatives made synthetically (see next entries)	 (46)	18,24,25,44,45,46 photo: 31
ecteinascidin 743 (trabectedin, ET-743, Yondelis®)	tunicate (Caribbean sea squirt, a mangrove ascidian) (<i>Ecteinascidia turbinata</i>) Caribbean 	anticancer; cytotoxic for several types of cancer; binds to target cell DNA & inhibits cell division, leading to apoptosis; induces apoptosis only during active gene transcription, which is much more frequent in cancer cells; keeps tumors from becoming resistant to chemotherapy by interfering with the gene that produces P-glycoprotein, a membrane protein that enables drug resistance; Phase I trials showed effectiveness against advanced-stage breast, colon, ovarian and lung cancers, melanoma, mesothelioma and several types of sarcoma; Phase II/III trials in 2003; licensed by Ortho Biotech (J&J); partial synthesis from microbial metabolite; approved by EC for soft tissue sarcoma	 (102)	18,24,25,44,47,48,49,102 photo: 50
eleutherobin (related to sarcodicytins)	alcyonarian (<i>Eleutherobia</i> sp.) gorgonian (<i>Eunicella stricta</i>) coral (<i>Erythropodium caribaeorum</i> [photo]) W. Australia, Caribbean (<i>E. caribaeorum</i>) 	anticancer; mimics paclitaxel's activity against tubulin; synthesized and derivative structures created	 (51)	18,51,102 photo: 52


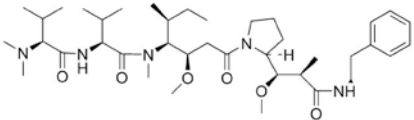
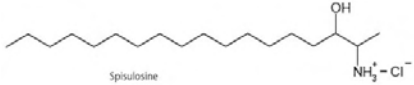

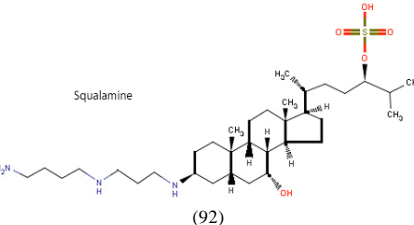
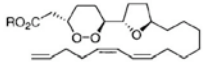
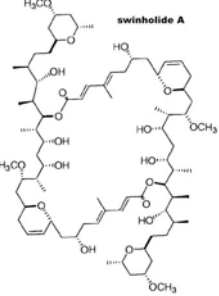

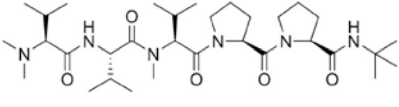
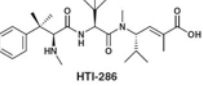
Anticancer drugs				
Chemical	Source	Uses & Status	Structure	Citations
elisidepsin (Irvalec [®] , PM02734)	sacoglossan sea slug (<i>Elysia rufescens</i>) that grazed on green macroalgae (<i>Bryopsis pennata</i>) Pacific	Synthetic analog of kahalalide F created to insure sufficient supply; licensed to PharmaMar by Univ. of Hawaii; Phase II trials	 Elisidepsin, PM02734 (53)	53
eribulin & eribulin mesylate (E7389, Halaven [®])	sponge (<i>Halichondria okadai</i> , <i>Axinella</i> sp., <i>Phakellia carteri</i> , & <i>Lissodendoryx</i> sp.) Japan, W. Pacific, Eastern Indian Ocean, & New Zealand	Eisai's synthetic halichondrin B derivative; breast, prostate, & non-small cell lung cancer (NSCLC) cancers; Phase II/III trials; FDA approved for late- stage breast cancer in 2010	 Eribulin (mesylate salt) (E7389) (54)	18,44,54
farnesylhydro- quinone	fungus	anticancer & antimalarial	 Farnesylhydroquinone (128)	128
giroline	sponge (<i>Pseudaxinyssa cantharella</i>) (synonym: <i>Cymbastela</i> <i>cantharella</i>) New Caladonia	anticancer; inhibits protein synthesis at termination the process rather than at the initiation or chain elongation steps like other known inhibitors; Phase I trials discontinued due to hypertension	 (55)	18,55
halenaquinone	sponge	anticancer; induces apoptosis	 Halenaquinone (128)	128
halichondrin B	sponge (<i>Halichondria okadai</i> , <i>Axinella</i> sp., <i>Phakellia carteri</i> , & <i>Lissodendoryx</i> sp.) Japan, W. Pacific, Eastern Indian Ocean, & New Zealand	anticancer; binds tubulin at a site close to the so-called vinca site and altered tubulin depolymerization; in clinical trials; see eribulin	 Halichondrin B (57)	24,25,56,57
hectochlorin	bacterium	anticancer; inhibits cell growth; induces actin polymerization	 Hectochlorin (128)	128
hemiasterlin (hemiasterlin analog E-7974)	sponge (<i>Hemiasterella minor</i> , <i>Auleta</i> sp., <i>Siphonochalina</i> sp., <i>Cymbastela</i> sp.) South Africa	anticancer; cytotoxic, anti-tubulin; mitotic inhibition occurs through binding to tubulin at the vinca/peptide region in a manner similar to dolastatin and the vinca alkaloids; Phase II trials; licenses to Wyeth by Univ. of British Columbia; a closely related chemical, E7974, from Eisai is currently in Phase I trials	 Hemiasterlin; R ₁ = R ₂ = CH ₃ Hemiasterlin A; R ₁ = H; R ₂ = CH ₃ Hemiasterlin B; R ₁ = R ₂ = H E-7974 (both 44)	18,44,58
hermitamide A & hermitamide B	cyanobacterium (<i>Lyngbya majuscula</i>) Papua New Guinea	anticancer;		114
icadamides	sponge (<i>Leiosella</i> sp.) Phillipines	anticancer, antiviral, & immunostimulant	 Icadamide B (106)	59,106

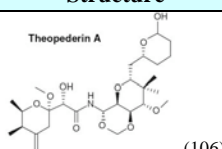
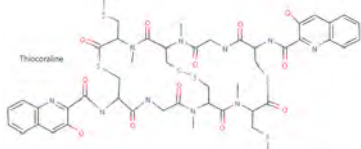

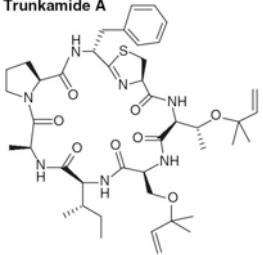
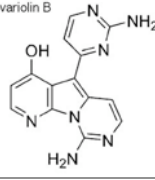
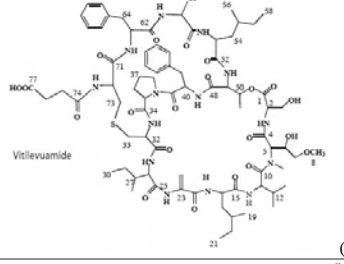
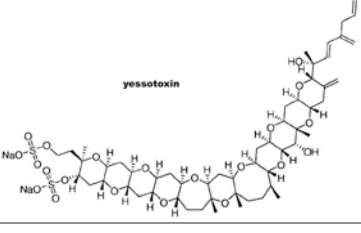

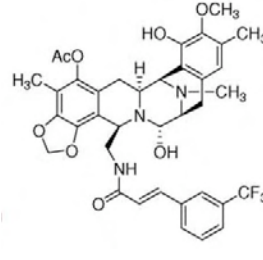
Anticancer drugs				
Chemical	Source	Uses & Status	Structure	Citations
kahalalide F (revised structure) (see elisidepsin, above)	sacoglossan sea slug (<i>Elysia rufescens</i>) that grazed on green macroalgae (<i>Bryopsis pennata</i>) Hawaii 	anticancer; disrupts lysosome [def] membranes within certain target cells, thereby initiating apoptosis (programmed cell death); inhibits gene expression related to DNA replication & cell proliferation; Phase II trials for NSCLC, melanoma & androgen-independent prostate cancer; also being studied for use on androgen-resistant prostate cancer, liver cancer, & advanced solid tumors; licensed to PharmaMar by U. Hawaii	 (61)	18,44,60,61 photo: 60
KRN-7000 (α -GalCer, α -galactosyl- ceramide) (agelasphin derivative)	sponge (<i>Agelas mauritiana</i>) Red Sea, Indian Ocean	anticancer; stimulates lymphocytic proliferation under certain conditions; appears to stimulate the production of natural killer T (NKT) cells in the body; Phase I trial showed effects with patients having high levels of NKT cells. Phase II trial ongoing	 (62)	18,62
lasonolides	deep-water sponge (<i>Forcepia</i> sp.) Gulf of Mexico 	anticancer & antifungal; kills cancer cells in a different way than most other cancer drugs; the exact mode of action is not yet fully understood, and is an area of active research; preclinical studies	 (63)	63 photo: 64
latrunculins	sponge (<i>Latrunculia magnifica</i>) Red Sea	cytotoxic actin-active agent; disrupts actin polymerization, microfilament organization, etc; cell shape, cytokinesis, and microfilament-mediated processes such as fertilization and early development are altered; preclinical; early tests show low in vivo activity; may require novel drug delivery strategies; also used as a probe for studying the role of actin in maintaining cell shape	 (65)	18,65
laulimalide	sponge (<i>Cacospongia mycofijiensis</i>) Pacific	anticancer; microtubule stabilizer; activity profiles are clearly different than other microtubule-binding agents such as paclitaxel; preclinical studies	 (66)	18,66
lissoclinamide 7	commensal bacterium found on tunicate (<i>Lissoclinum</i> sp.) Indo-West Pacific (photo: <i>Lissoclinum patellum</i>) 	anticancer	 lissoclinamide 7 (106,67)	67,106 photo: 68



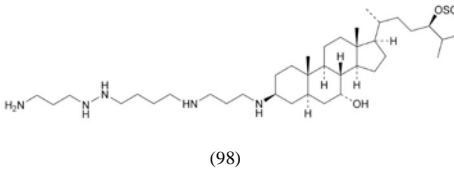
Anticancer drugs				
Chemical	Source	Uses & Status	Structure	Citations
lomaivitin A	commensal bacterium (<i>Micromonospora lomaivitiensis</i>) found on tunicate Fiji	anticancer; potent DNA damaging activity	 lomaivitin A (69)	69
makaluvamines	sponge (<i>Zyzya fuliginosa</i>) Indo-West Pacific	anticancer; cytotoxic through inhibition of DNA topoisomerase II		70,114
manzamine A & Ircinol A (its likely biogenic precursor, which lacks the β -carboline moiety)	sponges (<i>Haliclona</i> sp., <i>Pachypellina</i> sp.) with commensal bacterium (<i>Micromonospora</i> sp.) Indo-Pacific (photo: <i>Haliclona sarai</i>) 	antitumor, antimalarial, anti-infective, antituberculosis, antitoxoplasmosis, & antineurogenic inflammation; has shown activity against malaria, tuberculosis, HIV, and other inflammatory diseases; preclinical studies	 (117) Ircinol A (103)	103,117 photo: 71
mechercharmycin A	sediment actinobacterium (<i>Thermoactinomyces</i> sp.) Palau	anticancer; active against lung cancer & leukemia cell lines; a patent claims cytotoxicity	 (32)	32
micropeptins	bacterium	anticancer; inhibition of trypsin & chymotrypsin	 (128)	128
namenamicin	commensal bacterium found on tunicate (<i>Polysyncraton lithostrotum</i>) Australia, New Zealand	antitumor & antibiotic; the enediyne moiety is very reactive with DNA, making these chemicals extremely cytotoxic for all cells & among the most potent antitumor agents known	 Namenamicin (72)	72
Neovastat (Δ E-941) (a derivative of shark cartilage extract; not a specific mono-molecular compound, Δ E-941 is a defined standardized liquid extract comprising the <500 kDa (kilodaltons, a unit of mass) fraction from shark cartilage)	shark (photo: <i>Carcharhinus amblyrhynchos</i>) 	anticancer; inhibits the binding of Vascular Endothelial Growth Factor (VEGF) to its receptors; normally, VEGF binds to target endothelial receptors & directs the profusion of new capillaries to nourish the tumor; by blocking the receptor sites, Δ E-941 preempts the formation of the new blood supply; Phase II & III trials for renal carcinoma and NSCLC	a mixture	18 photo: 73

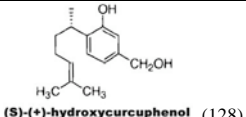
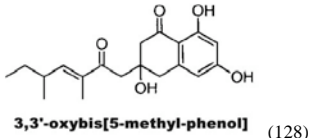
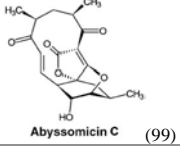
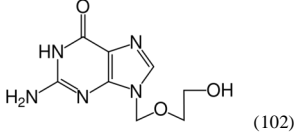
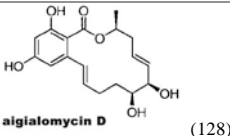
Anticancer drugs				
Chemical	Source	Uses & Status	Structure	Citations
NVP-LAQ824 (dacinostat) (synthetic using structures from psammaplin, trichostatin, & trapoxin)	sponge (<i>Psammaplysilla</i> [also found in a 2-sponge association of <i>Poecillastra</i> sp. & <i>Jaspis</i> sp.]) Indo-West Pacific	antibiotic, anti-tumor, DNA methyltransferase inhibitor; extremely potent histone deacetylase (HDAC) inhibitor; Phase I trial for hematologic malignancies	 (18)	18,74
onnamide A onnamide F	sponges (<i>Theonella</i> sp. and <i>Trachycladus lavipirulifer</i>) Okinawa, Australia (photo: <i>Theonella cylindrica</i>) 	anticancer, antifungal, & anthelmintic	 (75)  (76)	75,76, 114,128 photo: 77
panobinostat (LBH-589, Faridak®)	sponge (<i>Psammaplysilla</i> spp.) Indo-West Pacific	anticancer; synthetic analog of psammaplin; with Novartis; Phase III	 (78)	78
patellamides	commensal bacterium found on tunicate (<i>Lissoclinum patella</i>) Indo-West Pacific 	anticancer; cytotoxic; patellamides B, C, & D appear to reverse multidrug resistance	 (106)	79,80,106 photo: 68
pectenotoxin-6	algæ	anticancer; induces F-actin depolymerization	 (128)	128
peloruside A	sponge (<i>Mycale hentscheli</i>) New Zealand	anticancer; appears to bind tubulin and arrests target cell development at the G2-M transition stage of the cell cycle, triggering apoptosis (cell suicide) before mitosis can begin; preclinical studies	 (81)	18,81
phomactins	fungus (<i>Phoma</i> sp.) found on shell of crab (<i>Chionoecetes opilio</i>) Japan 	anticancer; platelet activating factor (PAF) antagonists	 (82)	83 photo: 84
plinabulin (NPI-2358)	fungus (<i>Aspergillus</i> sp.)	anticancer; synthetic analog of marizomib; selective vascular disrupting agent (VDA); Phase I/II	 (53)	53


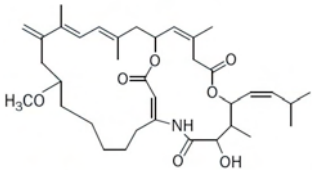

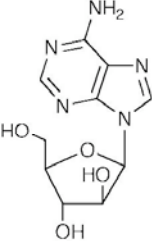
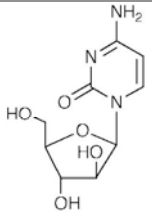
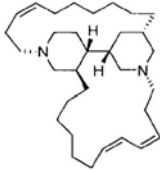
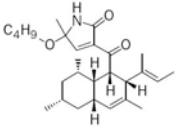
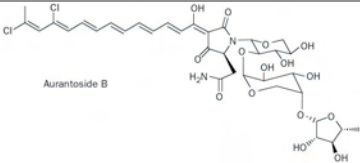
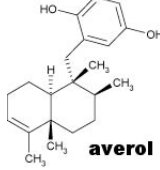
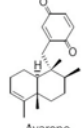
Anticancer drugs				
Chemical	Source	Uses & Status	Structure	Citations
psymberin (irciniastatin)	sponges (<i>Psammocinia</i> sp. & <i>Ircinia ramosa</i>) Indo-West Pacific	anticancer; showed extremely potent toxicity toward several cancer cell lines ($>10^4$ more potent than usually observed))	 <p>(106)</p>	85,106
salicylilalimides	sponge (<i>Haliclona</i> sp.) Indo-Pacific (photo: <i>Haliclona sarai</i>) 	anticancer & anti-osteoporosis; first marine Vo-ATPase inhibitor (Vo- ATPases are eukaryotic enzymes whose principal role is to pump hydrogen ions across cell vacuolar membranes); may mediate bone resorption; preclinical studies	 <p>Salicylilalimide A (86)</p>	18,86,87 photo: 71
saliniketal A & saliniketal B	actinobacterium (<i>Salinispora arenicola</i>) worldwide	chemopreventive		
salinosporamide A (NPI-0052, marizomib)	actinobacterium (<i>Salinispora tropica</i>) tropics	antibiotic & cytotoxin; very potent proteasome inhibitor; A & B inhibited colon cancer cells in vitro; A was extremely potent against NSCLC, CNS, & breast cancer lines; in Phase I trials with Nereus Pharma	 <p>Salinosporamide A (44)</p>	32,44
sansalvamide	fungus (<i>Fusarium</i> sp.) found on seagrass (<i>Halodule wrightii</i>) western tropical Atlantic & Gulf of Mexico 	anticancer; selective cytotoxicity towards colon & melanoma cell lines	 <p>(88)</p>	88,114 photo: 89
sarcodicytin (related to eleutherobins & eleuthosides)	alcyonarians (soft corals) (<i>Sarcodictyon roseum</i> [photo], <i>Eleutherobia aurea</i> , & <i>Bellonella albiflora</i>) Mediterranean 	anticancer; tubulin interactive agent; synthetic combinatorial research using base structures of sarcodicytins & eleutherobins; preclinical testing of derivatives	 <p>(102)</p>	18,86,102 photo: 90
sculezonone A & sculezonone B	bacterium	anticancer; inhibits DNA polymerase	 <p>Sculezonone A R=H Sculezonone B R=OH (128)</p>	128

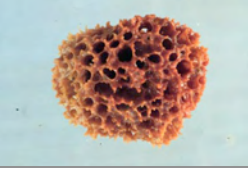
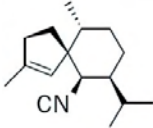
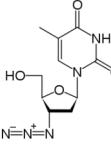
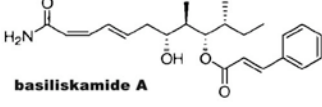
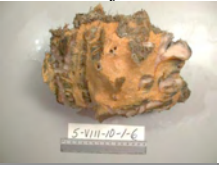
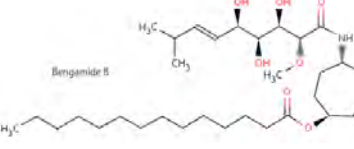

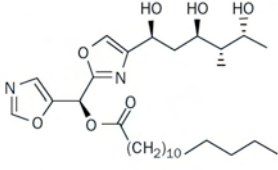
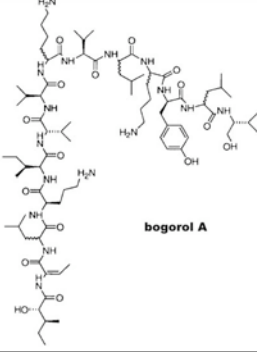
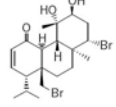
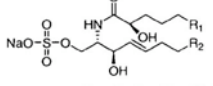
Anticancer drugs				
Chemical	Source	Uses & Status	Structure	Citations
soblidotin (auristatin PE, TZT-1027) (synthetic analog of dolastatin)	sea hare (<i>Dolabella auricularia</i>) (chemical possibly from commensal cyanobacteria [<i>Symploca hydroides</i> & <i>Lyngbya majuscula</i>]) Indian Ocean 	anticancer; exhibits potent antivascular effects in addition to antitubulin activity; Phase III trials; Phase II trials showed no positive results when used alone, but it appears to be effective in combination therapy with vinca alkaloids and bryostatin	 (18)	18,44 photo: 31
spisulosine (ES-285)	Arctic surf clam (<i>Spisula polynyma</i>) North Atlantic, North Pacific, Arctic Seas, Japan	anticancer; <i>Rho</i> -GTP inhibitor; appears to alter cell morphology: treated cells appear to lose actin stress fibers, (bundles of actin filaments that appear & disappear in response to mechanical stimuli); Phase I trials	 (91)	18,91
squalamine (ophthalmic formulations are called Evizon™)	spiny dogfish (<i>Squalus acanthias</i>) Northwest Atlantic 	anticancer, antiangiogenic, & antibiotic; broad spectrum antibiotic; also shows anti- angiogenic activity and may be useful to treat wet-form age-related macular degeneration; Phase II trials for nonresponding solid tumors as part of combination therapy and for advanced ovarian cancer as primary treatment; Phase III trials for wet macular degeneration show significant activity	 (92)	18,44, 92,103 photo: 93
stolonoxides	tunicate	anticancer; mitochondrial respiratory chain inhibition	 Stolonoxide A R=H Stolonoxide A methyl ester R=CH3 (128)	128
swinholid A	sponge	anticancer; facilitates outflow in eye	 (128)	128
synthadotin (ILX 651, tasidotin) (3 rd gen. derivative of dolastatin 15)	sea hare (<i>Dolabella auricularia</i>) (chemical possibly from commensal cyanobacteria [<i>Symploca hydroides</i> & <i>Lyngbya majuscula</i>]) Indian Ocean 	anticancer; orally-active 3 rd generation analog; Phase I/II trials for melanoma, breast, NSCLC; licensed by Ilex from BASF Pharma	 (18)	18,44,46 photo: 31
Taltobulin (HTI-286) (hemiasterlin analog)		Phase I/II trials	 HTI-286 (44)	44

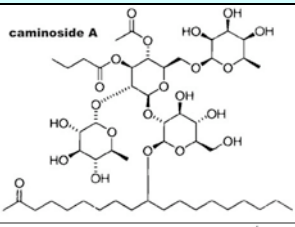
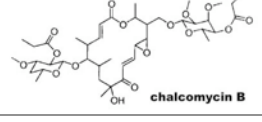

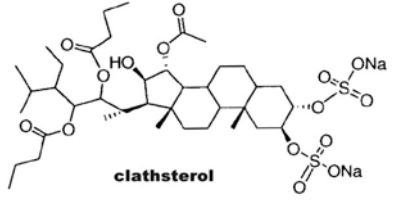
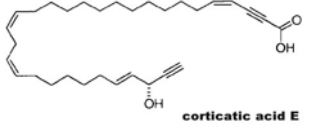
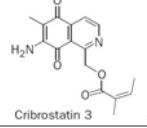
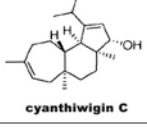
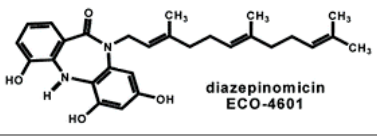
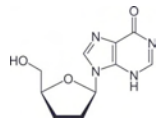
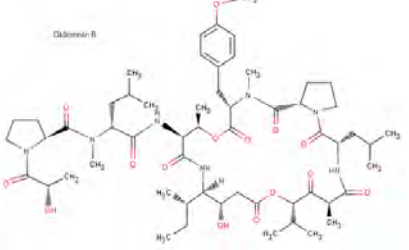
Anticancer drugs				
Chemical	Source	Uses & Status	Structure	Citations
theopederins	sponge (<i>Theonella swinhoei</i>) Indo-Pacific	anticancer	 <p>Theopederin A (106)</p>	106
thiocoraline	actinobacterium (<i>Micromonospora marina</i>)	anticancer; DNA polymerase α inhibitor; preclinical studies	 <p>Thiocoraline (94)</p>	18,94
trunkamide	commensal bacterium found on tunicate (<i>Lissoclinum patella</i>) Indo-West Pacific 	anticancer; has specific & unusual activity against the multidrug-resistant UO31 renal cell line	 <p>Trunkamide A (106)</p>	80,106 photo: 68
variolins	Antarctic sponge (<i>Kirkpatrickia variolosa</i>) Antarctic	anticancer; Cdk inhibitors; preclinical studies	 <p>variolin B (18)</p>	18
vitilevuamide	tunicates (<i>Didemnum cuculiferum</i> & <i>Polysyncrator lithostrotum</i>) [photo] Australia, New Zealand	anticancer; inhibits tubulin polymerization & can arrest the cell cycle in the G2/M phase; tubulin binding & inhibition occurs at a different site on the tubulin molecule than used by dolastatin 10, colchicine, & the vinca alkaloids; preclinical studies	 <p>Vitilevuamide (95)</p>	18,95
yessotoxin	algae	anticancer; lymphocyte homeostasis modulation	 <p>yessotoxin (128)</p>	128
Zalypsis® (PM1004)	nudibranch (<i>Jorunna funebris</i>) Western Indian Ocean, Red Sea 	anticancer; synthetic analog of jorumycin, safracin B, & saframycin B; made by PharmaMar; Phase II trials	 <p>(53)</p>	53 photo: 96

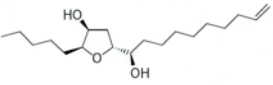
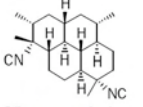
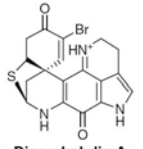
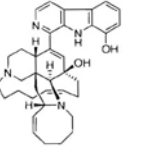
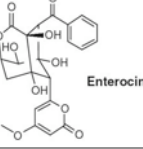

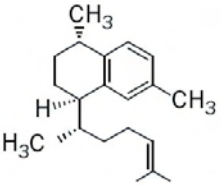

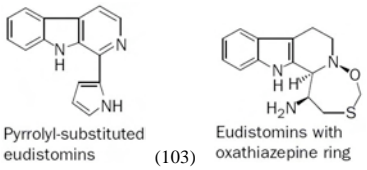
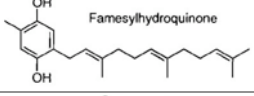
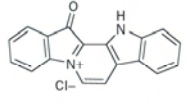
Antidiabetic drugs				
Chemical	Source	Uses & Status	Structure	Citations
insulin	European spotted dogfish (<i>Scyliorhinus canicula</i>) & hammerhead shark (<i>Sphyrna lewini</i> [photo]) North Atlantic, Indian Ocean, Red Sea 	antidiabetic; high affinity binding to human insulin receptor; although markedly different than human insulin the binding sites for the human receptor in the same location	<div> A Chain GIVDHCCHNTCSLYDLEGYCNDQ B Chain LPSQHLGSHLVETLYFVCGQKGFYYVPKI </div> Insulin - AA sequence from insulin of the hammerhead shark (128)	128 photo: 97
trodosquemine (MSI-1436)	spiny dogfish (<i>Squalus acanthias</i>) worldwide 	antidiabetic; causes fat-specific weight loss; Phase I trials had very promising results; Genaera started Phase I in 2007 and reported promising results in 2009. Shortly thereafter, Genaera was dissolved, and trodosquemine was sold to Ohr Pharmaceuticals; current status unknown	 (98)	92,98 photo: 93


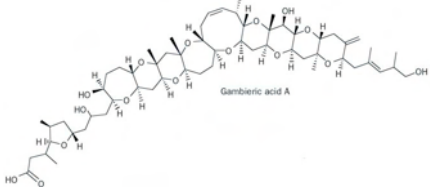

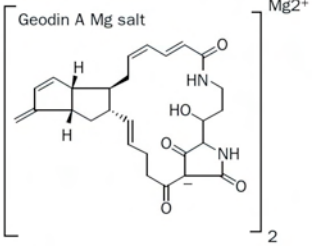

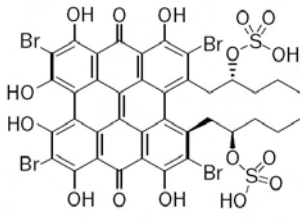
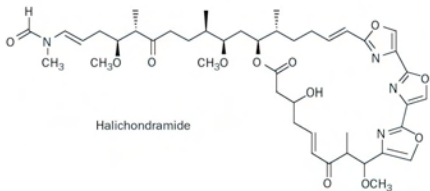
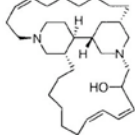
Anti-infective drugs				
Chemical	Source	Uses & Status	Structure	Citations
(S)-(+)-15-hydroxy-curcuphenol	sponge (<i>Didiscus oxeata</i>) Jamaica	antimalarial; <i>P. falciparum</i> inhibition	 (128)	128
3,3'-oxybis[5-methyl-phenol]	fungus (<i>Keissleriella</i> sp.)	antifungal; <i>C. albicans</i> , <i>T. rubrum</i> & <i>A. niger</i> inhibition	 (128)	128
abyssomicin C	actinobacterium (<i>Verrucosipora maris</i>)	antibiotic; inhibits biosynthesis of p-aminobenzoate (pABA), a pathway not found in humans; Phase I trials	 Abyssomicin C (99)	99,100,101
Acyclovir (ACV, acycloguanosine, Zovirax®) (derived from spongouridine & spongothymidine)	sponge (<i>Tectitethya crypta</i>) (synonym: <i>Cryptotethya crypta</i>) Caribbean	antiviral; Acyclovir differs from previous nucleoside analogues in that it contains only a partial nucleoside structure: the sugar ring is replaced by an open-chain structure; clinical use	 (102)	102
aigialomycin D	mangrove fungus (<i>Aigialus parvus</i> BCC 5311) tropics	antimalarial; <i>P. falciparum</i> inhibition	 (128)	128


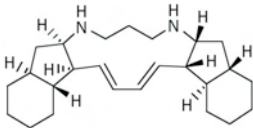
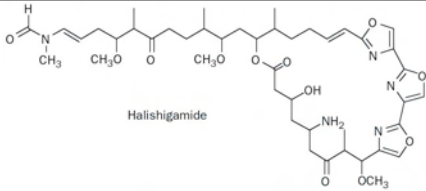
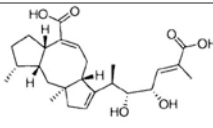
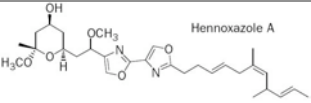
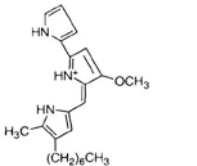
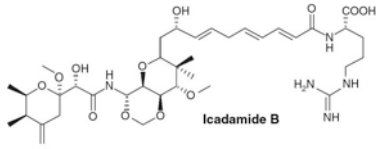
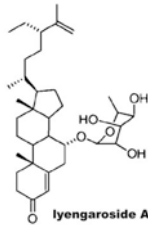
Anti-infective drugs				
Chemical	Source	Uses & Status	Structure	Citations
amphilactams	sponge (<i>Amphimedon sp.</i>) Australia (photo: <i>A. queenslandica</i>) 	antiparasitic	 Amphilactam D (103)	103 photo: 104
Ara-A (vidarabine, Vira-A®) (derived from spongouridine & spongothymidine)	 gorgonian (<i>Eunicella cavolinii</i>) Mediterranean	antiviral & anticancer; clinical use	 (102)	18,19, 105,102 photo: 105,
Ara-C (Cytosar-U®, DepoCyt®, Tarabine PFS®, cytarabine, 1-β-D- arabinosylcytosine) (derived from spongouridine & spongothymidine)	sponge (<i>Tectithya crypta</i>) (synonym: <i>Cryptothya crypta</i>) Caribbean	antiviral & anticancer; clinical use	 (102)	18,19, 102,103
arenosclerins (similar to haliclonacyclamine)	sponge (<i>Arenosciera brasiliensis</i>) Brazil	antibacterial	 arenosclerin A (128)	128
ascosali- pyrrolidinone A	green algæ (<i>Ulva sp.</i>) with commensal fungus (<i>Ascochyta salicorniæ</i>) worldwide	antiparasitic	 Ascosalipyrrolidinone A (103)	103
aurantoside B	sponge (<i>Siliquariaspongia japonica</i>) Japan	antifungal	 Aurantioside B (103)	103
avarol	sponge (<i>Dysidea avara</i>) Mediterranean	antibiotic & anticancer; Cytostatic agent with potent antileukemic activity both <i>in vitro</i> & <i>in vivo</i> (mice); antibacterial & antifungal activities for a limited range of microbes; inhibits HIV-1 reverse transcriptase	 avarol (107)	106,107
avarone	sponge (<i>Dysidea avara</i>) Mediterranean	antiviral	 Avarone (103)	103


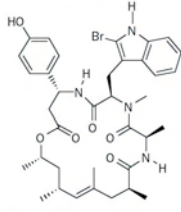

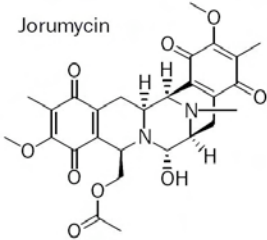

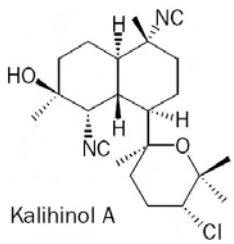
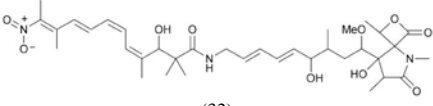
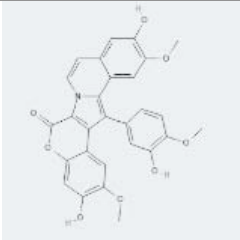

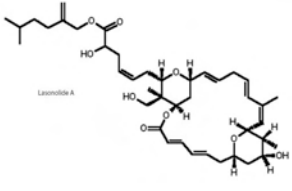
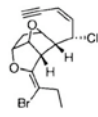
Anti-infective drugs				
Chemical	Source	Uses & Status	Structure	Citations
axisonitrile-3	sponge (<i>Acanthella klethra</i>) Australia 	antituberculosis	 Axisonitrile-3 (103)	103 photo: 108
azidothymidine (AZT, zidovudine, Retrovir®) (derived from spongouridine & spongothymidine)	sponge (<i>Tectitethya crypta</i>) (synonym: <i>Cryptotethya crypta</i>) Caribbean	antiviral; reverse-transcriptase inhibitor; clinical use	 (109)	18,19,102 106,109
basiliskamide A & basiliskamide B	bacterium (<i>Bacillus laterosporus</i>)	antifungal; <i>C. albicans</i> & <i>A. fumigatus</i> inhibition	 basiliskamide A (128)	128
bengamide derivative	sponge (<i>Jaspis</i> sp.) Fiji 	anticancer & antihelminthic; methionine aminopeptidase (Met-AP1) inhibitor; licensed to Novartis; withdrawn from Phase I trials in 2002	 Bengamide B (22)	18,22 photo: 23
bengazole A	sponge (<i>Jaspis</i> sp.) Fiji 	antifungal	 Bengazole A (103)	103 photo: 23
bogorol A	bacterium (<i>Bacillus</i> sp.)	antibacterial; inhibits antibiotic-resistant <i>S. aureus</i> & enterococci	 bogorol A (128)	128
bromosphaerone	red algæ (<i>Sphaerococcus coronopifolius</i>) Atlantic coast of Morocco	antibiotic	 Bromosphaerone (103)	103
calyceramides A–C	sponge (<i>Discodermia calyx</i>) Japan	antiviral; neuraminidase inhibition	 Calyceramide A R ₁ = C ₁₀ H ₂₂ R ₂ = C ₁₂ H ₂₆ Calyceramide B R ₁ = C ₉ H ₂₀ R ₂ = C ₁₃ H ₂₈ Calyceramide C R ₁ = C ₁₁ H ₂₄ R ₂ = C ₁₁ H ₂₄ (128)	128


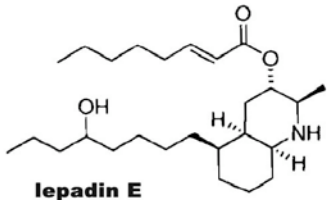
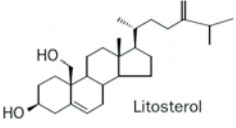

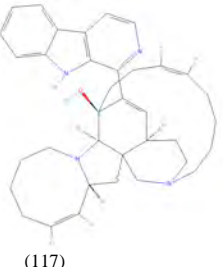
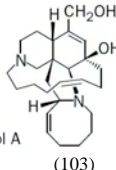
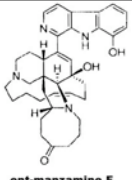
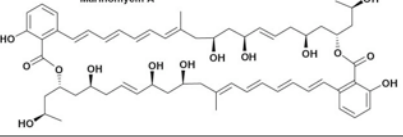
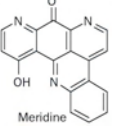
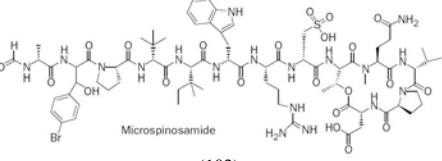
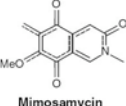
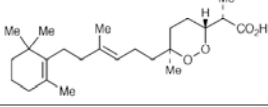
Anti-infective drugs				
Chemical	Source	Uses & Status	Structure	Citations
caminoside A	sponge (<i>Caminus sphaericonia</i>) Caribbean, Brazil	antibacterial; inhibits antibiotic-resistant <i>S. aureus</i> & enterococci	 (128)	128
chalomycin B	actinobacterium (<i>Streptomyces</i> sp.)	antibacterial; inhibits antibiotic-resistant <i>S. aureus</i>	 chalomycin B (128)	128
clathsterol	sponge (<i>Clathria</i> sp.) Red Sea 	antiviral; HIV reverse transcriptase inhibition	 clathsterol (128)	128 photo: 110
corticatic acid A & corticatic acid B	sponge (<i>Petrosia corticata</i>) Western Pacific	antifungal; <i>C. albicans</i> & <i>A. fumigatus</i> inhibition; selective GGTase 1 inhibition (enzyme is involved in fungal cell wall biosynthesis)	 corticatic acid E (128)	128
cribrostatin 3	sponge (<i>Cribrochalina</i> sp.) worldwide	antibiotic & anticancer	 Cribrostatin 3 (103)	103
cyanthiwigin C	sponge (<i>Myrmekioderma rea</i>) (synonym: <i>Myrmekioderma styx</i>) Jamaica	antituberculosis	 cyanthiwigin C (128)	128
diazepinomicin (ECO-4601)	actinobacterium (<i>Micromonospora</i> sp.)	antibiotic & anticancer; Phase I trials (antibiotic & anticancer)	 diazepinomicin ECO-4601 (35)	36
dicynthaurin	tunicate (<i>Halocynthia aurantium</i>) North Pacific	antibacterial; gram negative & gram positive inhibition	ILQKAVLDCLKAAGSSLSKAAITAIYNKIT dicynthaurin (128)	128
didanosine (2',3'-dideoxy- inosine, ddI, DDI) (derived from spongouridine & spongothymidine)	sponge (<i>Tectitethya crypta</i>) (synonym: <i>Cryptotethya crypta</i>) Caribbean	antiviral; clinical use	 (102)	102
didemnin B	tunicate (<i>Trididemnum solidum</i>) Caribbean	anticancer & antiviral interrupts protein synthesis in target cells by binding noncompetitively to palmitoyl protein thioesterase; cytotoxic for lymphomas, some leukemias & melanomas; antiviral for herpes simplex and several others; Phase II trials showed significant toxicity at efficacious doses; dropped in middle 1990s	 (41)	18,24, 39,40,41,41

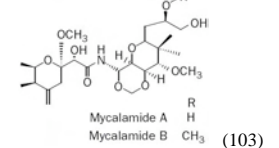
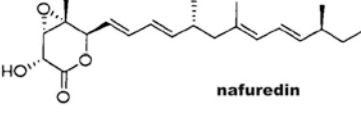
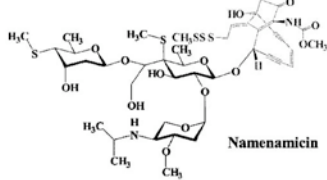
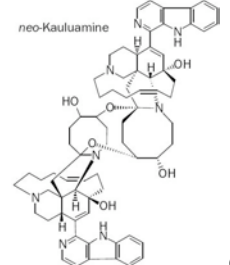

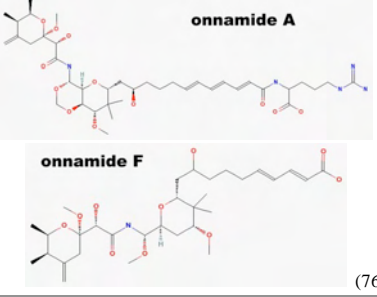
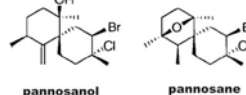
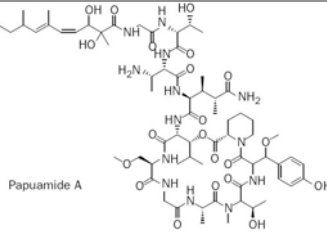
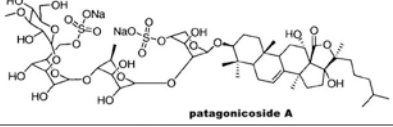
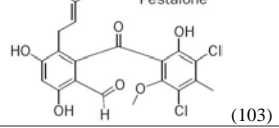
Anti-infective drugs				
Chemical	Source	Uses & Status	Structure	Citations
dihydroxytetrahydrofuran	brown algæ (<i>Notheia anomala</i>) Australia	antiparasitic; <i>in vivo</i> tests did not duplicate <i>in vitro</i> success, probably because drug is strongly hydrophobic	 Trans-dihydroxytetrahydrofuran (103)	103
di-isocyano-adociane	sponge (<i>Pipestela hooperi</i>) (synonym: <i>Cymbastela hooperi</i>) Australia	antimalarial	 Diisocyanoadociane (103)	103
discorhabdins	sponges (<i>Latrunculia</i> sp.) New Zealand	antibacterial, antifungal, & antitumor	 Discorhabdin A (106)	106,111
ent-8-hydroxy-manzamine A	sponge Indo-Pacific	antimalarial; <i>P. berghei</i> inhibition	 ent-8-hydroxymanzamine (128)	128
enterocin	actinobacterium (<i>Streptomyces maritimus</i>)	antibiotic & antiviral	 Enterocin (106)	106,112
ergorgiaene & 7-hydroxy-ergorgiaene	gorgonian (sea whip) (<i>Pseudopterogorgia elisabethae</i>) Caribbean 	antituberculosis	 Ergorgiaene (103)	12,103 photo: 11
eudistomins	shallow water tunicate (<i>Eudistoma</i> sp.) Caribbean 	antiviral; Four types of eudistomins: unsubstituted, pyrrolyl-substituted, pyrrolinyl-substituted, & tetrahydro-β-carbolines	 Pyrrolyl-substituted eudistomins (103) Eudistomins with oxathiazepine ring (103)	103 photo: 113
farnesylhydroquinone	fungus	anticancer & antimalarial	 Farnesylhydroquinone (128)	128
fascaplysin	sponge (<i>Fascaplysinopsis</i> sp.) Indo-West Pacific	antifungal	 Fascaplysin (103)	103

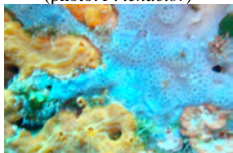
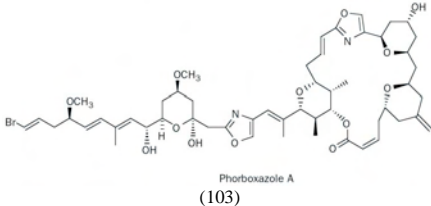
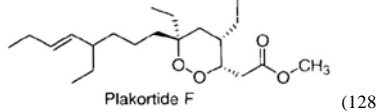

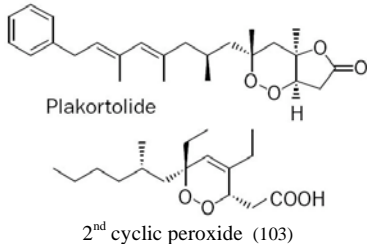
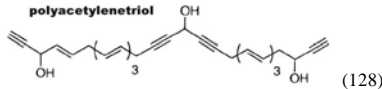
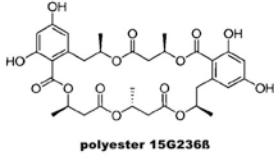

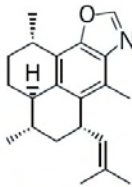

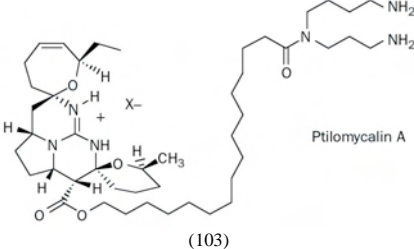
Anti-infective drugs				
Chemical	Source	Uses & Status	Structure	Citations
fumiquinazoline	epiphytic fungus (<i>Acremonium</i> sp.) on tunicate (<i>Ecteinascidia turbinata</i>) Caribbean 	antifungal		114 photo: 50
gambieric acids	dinoflagellate (<i>Gambierdiscus toxicus</i>) Central Pacific, Gulf of Mexico	antifungal	 (103)	103
geodin A Mg salt	sponge (<i>Geodia</i> sp.) Australia 	antiparasitic	 (103)	103 photo: 115
gymnochrome D	stalked crinoid (sea lily) (<i>Neogymnocrinus richeri</i>) (synonym: <i>Gymnocrinus richeri</i>) New Caledonia 	antiviral	 Gymnochrome D (103)	103 photo: 116
halichondramide	sponge (<i>Halichondria</i> sp.) Indo-West Pacific	antifungal & antimalarial	 Halichondramide (103)	103
haliclona-cyclamines (similar to arenosclerins)	sponge (<i>Arenosclera brasiliensis</i>) Brazil	antibacterial	 haliclona-cyclamine E (128)	128

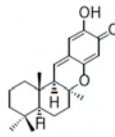
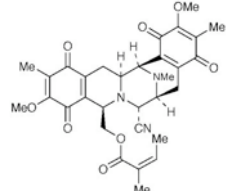
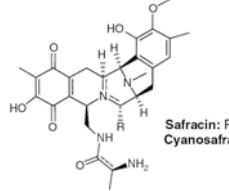
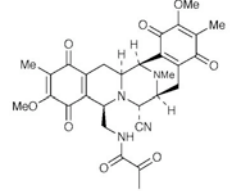
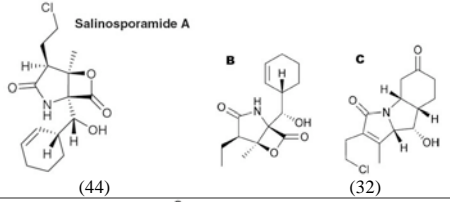
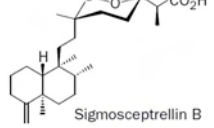

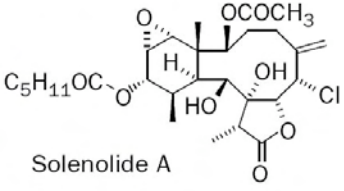
Anti-infective drugs				
Chemical	Source	Uses & Status	Structure	Citations
haliclonadamine	sponge (<i>Haliclona</i> sp.) Indian Ocean (photo: <i>Haliclona sarai</i>) 	antifungal	 Haliclonadamine (103)	117 photo: 71
halishigamide A	sponge (<i>Halichondria</i> sp.) Indo-West Pacific	antifungal	 Halishigamide (103)	103
halocidin	tunicate (<i>Halocynthia aurantium</i>) Northern Pacific	antibacterial; inhibits antibiotic-resistant <i>S. aureus</i> & MDR-resistant <i>P. aeruginosa</i>	WLNALLHHGLNCAKGVLA ALLHHGLNCAKGVLA Two amino acid sequences (one 18-unit & one 15-unit) joined by a disulfide bond between a cysteine residue in each unit halocidin (128)	128
halorosellinic acid	fungus (<i>Halorosellinia oceanica</i> BCC 5149) Thailand	antimalarial; <i>P. falciparum</i> inhibition	 halorosellinic acid (128)	128
hennoxazole A	sponge (<i>Polyfibrospongia</i> sp.) Indo-Pacific	antiviral	 Hennoxazole A (103)	103
heptyl prodigiosin	commensal bacterium found on tunicate Phillipines	antimalarial; <i>P. falciparum</i> & <i>P. berghei</i> inhibition	 heptyl prodigiosin (128)	128
icadamides	sponge (<i>Leiosella</i> sp.) Phillipines	anticancer, antiviral, & immunostimulant	 Icadamide B (106)	59,106
iyengaroside A	algæ (<i>Codium iyengarii</i>) Arabian Sea	antibacterial; gram negative & gram positive inhibition	 Iyengaroside A (128)	128


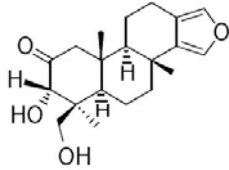

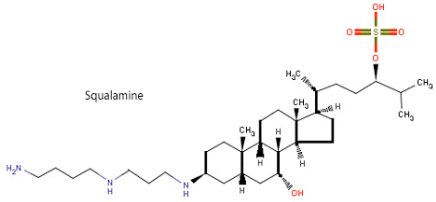
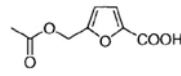

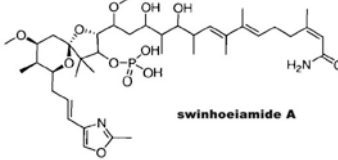

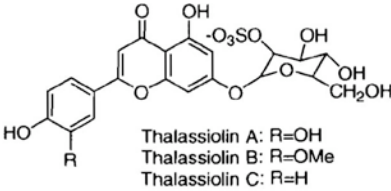
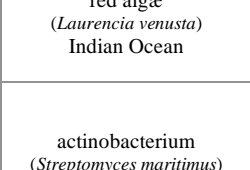
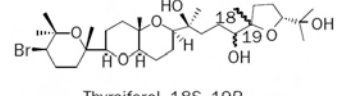
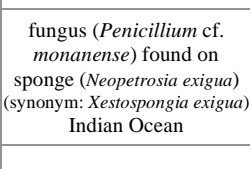
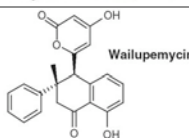
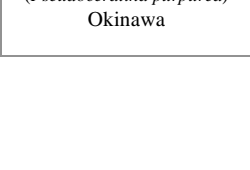
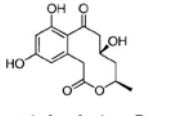

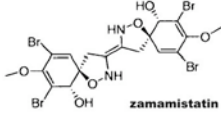
Anti-infective drugs				
Chemical	Source	Uses & Status	Structure	Citations
jasplakinolide (jaspamide)	sponge (<i>Jaspis</i> sp.) Fiji 	antifungal & antiparasitic; <i>P. falciparum</i> inhibition	 Jasplakinolide (103)	103,128 photo: 23
jorumycin	nudibranch (<i>Jorunna funebris</i>) Pacific 	antibiotic	 Jorumycin (103)	103 photo: 96
kalihinol A	sponge (<i>Acanthella</i> sp.) (photo: <i>A. cavernosa</i>) Okinawa 	antimalarial	 Kalihinol A (103)	103 photo: 118
lajollamycin	sediment actinobacterium (<i>Streptomyces nodosus</i>) California	antibiotic & anticancer; active against both drug-sensitive & drug-resistant Gram positive microbes; inhibited growth in murine melanoma cell line	 (32)	32
lamellarins (lamellarin α 20-sulfate)	tunicate (<i>Didemnum obscurum</i>) Indo-West Pacific	antiviral; HIV-1 integrase inhibitor; inhibits early steps of HIV replication	 (119)	114
lasonolides	deep-water sponge (<i>Forcepia</i> sp.) Gulf of Mexico 	anticancer & antifungal; kills cancer cells in a different way than most other cancer drugs; the exact mode of action is not yet fully understood, and is an area of active research; preclinical studies	 Lasonolide A (63)	63 photo: 64
lembyne A	red algæ (<i>Laurencia</i> sp.) Malaysia	antibacterial	 lembyne A (128)	128

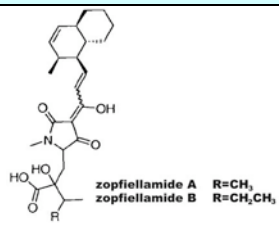
Anti-infective drugs				
Chemical	Source	Uses & Status	Structure	Citations
lepadin E & lepadin F	tunicates (<i>Clavelina lepadiformis</i> [photo], <i>Aplidium tabascum</i> , <i>Didemnum</i> sp.) Mediterranean, Indo-West Pacific 	antimalarial; <i>P. falciparum</i> inhibition	 lepadin E (128)	128 photo: 120
litosterol	alcyonarian (soft coral) (<i>Litophyton viridis</i>) Okinawa	antituberculosis	 Litosterol (103)	103
manzamine A & ircinol A (its likely biogenic precursor that lacks the β -carboline moiety)	sponge (<i>Haliclona</i> sp., <i>Pachypellina</i> sp.) Indo-Pacific (photo: <i>Haliclona sarai</i>) 	antitumor, antimalarial, anti- infective, antituberculosis, antitoxoplasmosis, & antineurogenic inflammation; has shown activity against malaria, tuberculosis, HIV, and other inflammatory diseases; preclinical studies	 (117)  Ircinol A (103)	103,117 photo: 71
manzamine F	sponge Indo-Pacific	antimalarial; <i>P. berghei</i> inhibition	 ent-manzamine F (128)	128
marinomycins A–D	actinobacterium (<i>Marinispora</i> sp.)	antibiotic; potent activity against drug-resistant bacterial pathogens & some melanomas	 Marinomycin A (44)	44
marinone	bacterium	antibiotic		25
meridine	sponge (<i>Corticium</i> sp.) Bahamas	antifungal	 Meridine (103)	103
microspinosamide	sponge (<i>Sidonops microspinosa</i>) Philippines	antiviral; HIV-growth inhibition	 Microspinosamide (103)	103,121,128
mimosamycin	commensal actinobacterium (<i>Streptomyces lavendulae</i>) found on sponge (<i>Petrosia</i> sp.) Western Pacific	antibiotic; a neutral antibiotic mainly active against mycobacteria	 Mimosamycin (106)	106
muquibilin	sponge (<i>Prianos</i> sp.) Red Sea	antimalarial	 (102)	102

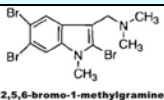
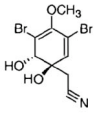
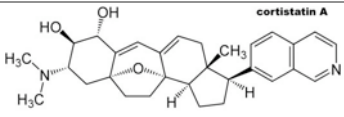

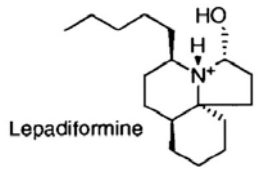

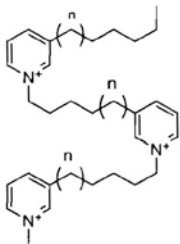

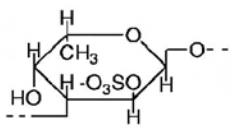
Anti-infective drugs				
Chemical	Source	Uses & Status	Structure	Citations
mycalamide A & mycalamide B	sponge (<i>Mycale</i> sp.) New Zealand	antiviral; protein synthesis inhibitors; mycalamide B has shown greater antiviral activity	 <p>Mycalamide A Mycalamide B (103)</p>	103
nafuredin	fungus (<i>Aspergillus niger</i>)	anthelmintic; inhibition of helminth NADH-fumarate reductase; competes for the quinone-binding site	 <p>nafuredin (128)</p>	128
namenamicin	commensal bacterium found on tunicate (<i>Polysyncraton lithostrotum</i>) Australia, New Zealand	antitumor & antibiotic; the enediyne moiety is very reactive with DNA, making these chemicals extremely cytotoxic for all cells & among the most potent antitumor agents known	 <p>Namenamicin (72)</p>	72
neo-kauluamine	sponge Indo-Pacific	antimalarial; <i>P. berghei</i> inhibition	 <p>neo-Kauluamine (103)</p>	103,128
onnamide A & onnamide F	sponges (<i>Theonella</i> sp. & <i>Trachycladus laevispirulifer</i>) Okinawa, Australia (photo: <i>Theonella cylindrica</i>) 	anticancer, antifungal, & anthelmintic	 <p>onnamide A (75) onnamide F (76)</p>	75,76, 114,128 photo: 77
pannosanol & pannosane	red algæ (<i>Laurencia pannosa</i>) Malaysia	antibacterial	 <p>pannosanol pannosane (128)</p>	128
papuamide A	sponges (<i>Theonella mirabilis</i> & <i>T. swinhoei</i> [photo]) Indo-West Pacific	antiviral	 <p>Papuamide A (103)</p>	103
patagonicoside A	echinoderm (sea cucumber) (<i>Psolus patagonicus</i>) Southern Ocean	antifungal; <i>Cladosporium cucumerinum</i> inhibition	 <p>patagonicoside A (128)</p>	128
pestalone	marine fungus (<i>Pestalotia</i> sp.) found on brown algæ (<i>Rosenvingea</i> sp.) Bahamas	antibacterial	 <p>Pestalone (103)</p>	103,128


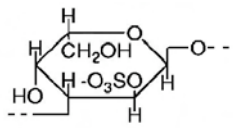
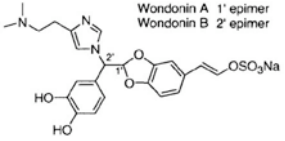
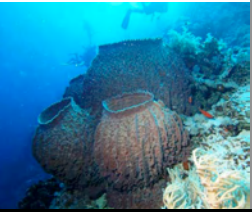
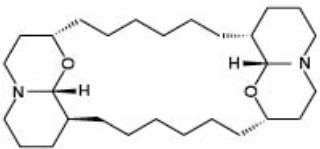
Anti-infective drugs				
Chemical	Source	Uses & Status	Structure	Citations
phorboxazole A	sponge (<i>Phorbas</i> sp.) Australia (photo: <i>P. tenacior</i>) 	antifungal	 Phorboxazole A (103)	103 photo: 122
plakortide F	sponge (<i>Plakinastrella onkodes</i>) Jamaica	antimalarial; <i>P. falciparum</i> inhibition	 Plakortide F (128)	103,128
plakortolide & plakortolide G (a 2 nd cyclic peroxide)	sponges (<i>Plakortis</i> sp. [photo] & <i>Plakinastrella onkodes</i>) Pacific (<i>Plakortis</i> sp.) Jamaica (<i>P. onkodes</i>) 	antiparasitic & antiprotozoal; active against <i>Leishmania</i> spp. parasites	 Plakortolide 2 nd cyclic peroxide (103)	103,128 photo: 123
polyacetylenetriol	sponge (<i>Petrosia</i> sp.) Mediterranean	antiviral; RNA- & DNA- directed DNA polymerase inhibition	 polyacetylenetriol (128)	128
polyester 15G256β	fungus (<i>Halorosellinia oceanica</i>) (synonym: <i>Hypoxylen oceanicum</i>) Indian Ocean	antifungal; cell wall biosynthesis inhibition	 polyester 15G236δ (128)	128
pseudopter- oxazole	gorgonian (sea whip) (<i>Pseudopterogorgia elisabethæ</i>) Caribbean 	antituberculosis	 Pseudopteroxazole (103)	12,103 photo: 11
ptilomycalin A	sponge (<i>Ptilocaulis spiculifer</i>) Australia 	antifungal	 Ptilomycalin A (103)	103 photo: 124

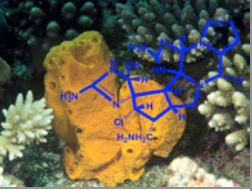
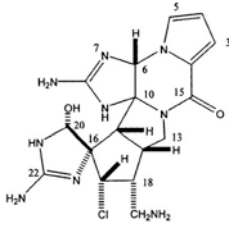
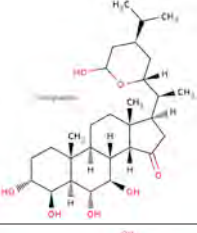
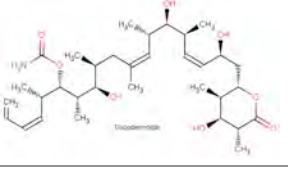
Anti-infective drugs				
Chemical	Source	Uses & Status	Structure	Citations
puupehenone	sponges (from Order Verongida & Order Dictyoceratida) Hawaii	antituberculosis	 <p>Puupehenone (103)</p>	103
renieramycins	sponge (<i>Reniera</i> sp.) Pacific	antibiotic;	 <p>(102)</p>	102
safracins	bacterium (<i>Pseudomonas fluorescens</i>)	antibiotic & antitumor	 <p>Safracin: R = OH Cyanosafracin: R = CN</p> <p>(106)</p>	106
saframycins	actinobacterium (<i>Streptomyces lavendulae</i>)	antibiotic & anticancer	 <p>(102)</p>	102
salinosporamide A	actinobacterium (<i>Salinispora tropica</i>) tropics	antibiotic & cytotoxin; very potent proteasome inhibitor; A & B inhibited colon cancer cells in vitro; A was extremely potent against NSCLC, CNS, & breast cancer lines; in Phase I trials	 <p>Salinosporamide A (44)</p> <p>B</p> <p>C (32)</p>	32,44
sigmosceptrellin & sigmosceptrellin B	sponges (<i>Sigmosceptrella</i> sp. & <i>Diacarnus erythraeanus</i>) Red Sea	antimalarial & antiparasitic	 <p>Sigmosceptrellin B (103)</p>	102,103
solenolide A	gorgonian (<i>Briareum asbestinum</i>) Gulf of Mexico 	antiviral	 <p>Solenolide A</p> <p>(103)</p>	103 photo: 125

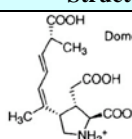

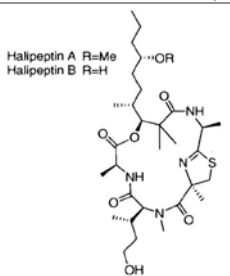
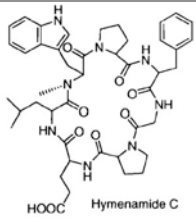
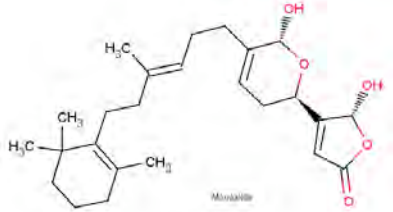
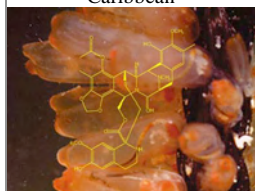
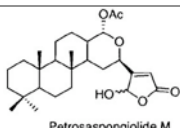

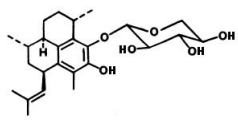
Anti-infective drugs				
Chemical	Source	Uses & Status	Structure	Citations
spongiadiol	deep-water sponge (<i>Spongia</i> sp.) (photo: <i>S. officinalis</i>) Caribbean 	antiviral	 Spongiadiol (103)	103 photo: 126
squalamine	spiny dogfish (<i>Squalus acanthias</i>) worldwide 	anticancer, antiangiogenic, & antibiotic; broad spectrum antibiotic; also shows anti-angiogenic activity and may be useful to treat age-related macular degeneration; Phase II trials for nonresponding solid tumors as part of combination therapy and for advanced ovarian cancer as primary treatment; Phase III trials for wet macular degeneration show significant activity	 Squalamine (92)	18,44, 92,103 photo: 93
Sumiki's acid (acetyl derivative)	fungus	antibacterial; <i>B. subtilis</i> & <i>S. aureus</i> inhibition	 Sumiki's acid (128)	128
swinhoeiamide A	sponge (<i>Theonella swinhoei</i>) Indo-West Pacific 	antifungal; <i>C. albicans</i> & <i>A. fumigatus</i> inhibition	 swinhoeiamide A (128)	128
thalassiolins A–C	sea grass (<i>Thalassia testudinum</i>) Gulf of Mexico 	antiviral; HIV-1 integrase inhibition	 Thalassiolin A: R=OH Thalassiolin B: R=OMe Thalassiolin C: R=H (128)	128 photo: 127
thyrseferol	red algæ (<i>Laurencia venusta</i>) Indian Ocean 	antiviral	 Thyrseferol 18S, 19R (103)	103
wailupemycins	actinobacterium (<i>Streptomyces maritimus</i>) 	antibiotic & antiviral	 Wailupemycin D (106)	106
xestodecalactone B	fungus (<i>Penicillium</i> cf. <i>monanense</i>) found on sponge (<i>Neopetrosia exigua</i>) (synonym: <i>Xestospongia exigua</i>) Indian Ocean 	antifungal; <i>C. albicans</i> inhibition	 xestodecalactone B (128)	128
zamamistatin	sponge (<i>Pseudoceratina purpurea</i>) Okinawa 	antibacterial; <i>Rhodospirillum salexigens</i> inhibition	 zamamistatin (128)	128

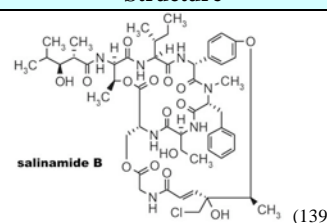
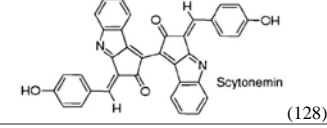
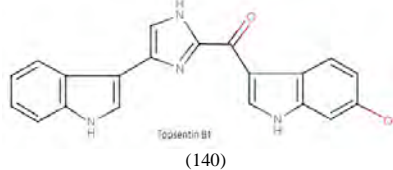
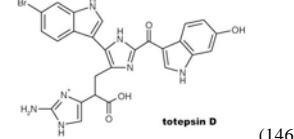
Anti-infective drugs				
Chemical	Source	Uses & Status	Structure	Citations
zopfiellamide A & zopfiellamide B	fungus (<i>Zopfiella latipes</i>)	antibacterial; gram negative & gram positive inhibition	 <p>zopfiellamide A R=CH₃ zopfiellamide B R=CH₂CH₃</p> <p>(128)</p>	128

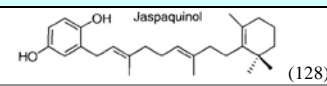
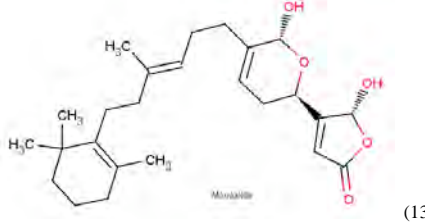
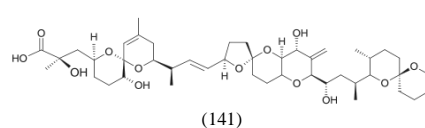
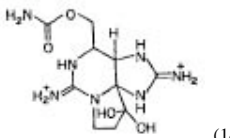
Cardiac & circulatory system drugs; Anti-angiogenesis drugs				
Chemical	Photo of Source	Uses & Status	Structure	Citations
2,5,6-tribromo-1-methylgramine (TBG)	bryozoan (<i>Zoobotryon verticillatum</i>) (synonym: <i>Z. pellucidum</i>) worldwide	cardiovascular; vasorelaxation; Ca ²⁺ inhibition & increase cyclic AMP	 <p>2,5,6-bromo-1-methylgramine (128)</p>	128
aeropylsinin-1	sponge	antiangiogenic	 <p>Aeropylsinin-1 (128)</p>	128
bryoanthra-thiophene	bryozoan	inhibits angiogenesis		128
cortistatins	sponge (<i>Corticium simplex</i>) Australia	possesses a highly selective & perhaps mechanistically unique antiangiogenic activity	 <p>cortistatin A (129)</p>	129
lepadiformine	tunicates (<i>Clavelina moluccensis</i> & <i>C. lepadiformis</i> [photo]) Mediterranean, Indo-West Pacific 	cardiovascular; inhibition of cardiocirculatory system; reduction in inward K ⁺ current	 <p>Lepadiformine (128)</p>	128 photo: 130
polymeric 1,3-alkylpyridinium salts	sponge (<i>Haliclona (Rhizoniera) sarai</i>) (synonym: <i>Reniera sarai</i>) Mediterranean 	blood coagulation & platelet aggregation; induces blood coagulation, platelet aggregation, & cytotoxicity in rats; previously found to be cholinesterase inhibitors	 <p>polymeric 1,3-alkylpyridinium salts (128)</p>	128 photo: 71
sulfated α-L-fucan	sea urchins (<i>Echinometra lucunter</i> [photo] & <i>Strongylocentrotus franciscanus</i>) Brazil & Gulf of Mexico 	anticoagulant	 <p>sulfated α-L-fucan <i>S. franciscanus</i> (128)</p>	128 photo: 131


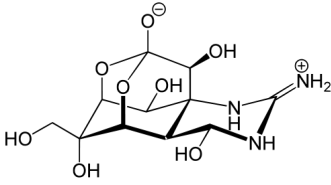
Cardiac & circulatory system drugs; Anti-angiogenesis drugs				
Chemical	Photo of Source	Uses & Status	Structure	Citations
sulfated α -L-galactan	sea urchins (<i>Echinometra lucunter</i> & <i>Strongylocentrotus franciscanus</i> [photo]) Brazil & Gulf of Mexico 	anticoagulant	 sulfated α-L-galactan <i>E. lucunter</i> (128)	128 photo: 132
wondonin A & wondonin B	sponge	modulation of angiogenesis	 Wondonin A 1' epimer Wondonin B 2' epimer (128)	128
xestospongins C	sponge (<i>Xestospongia</i> sp.) (photo: <i>Xestospongia</i> <i>testudinaria</i>) Okinawa 	vasodilation; a potent, cell-permeable inhibitor of Ca; inhibits voltage-dependent Ca & K currents	 (133)	133 photo: 134


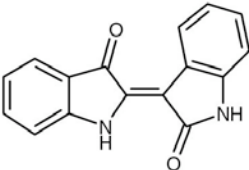
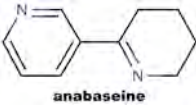
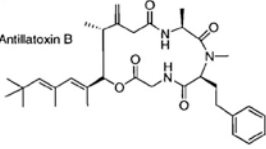
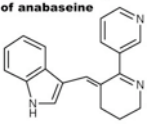
Immunological drugs				
Chemical	Source	Uses & Status	Structure	Citations
(-)-palau'amine	sponge (<i>Stylissa massa</i>) (synonym: <i>Stylotella aurantium</i>) Indo-West Pacific 	immunosuppressant; strongly cytotoxic; antibiotic	 (-)-palau'amine (135)	135 photo: 136
contignasterol	sponge (<i>Neopetrosia contignata</i>) (synonym: <i>Petrosia contignata</i>) Indonesia 	antihistamine & antiasthmatic	(16)	16,18
discodermolide	deep-water sponge (<i>Discodermia dissoluta</i>) Caribbean 	anticancer & immunosuppressive; tubulin polymer stabilizer (like taxol); essentially arresting cells at a specific stage in the cell cycle and halting cell division; Phase I trials; licensed to Novartis by Woods Hole; may be used in combination with Taxol	(43)	24,25,42,43



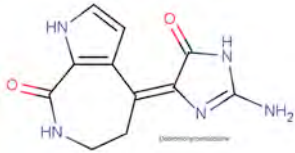
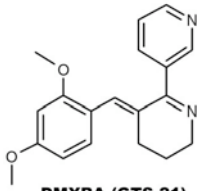
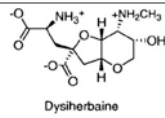
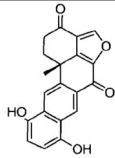

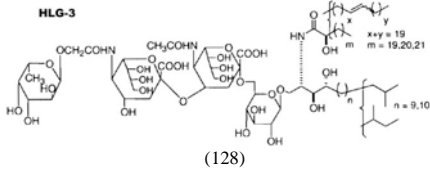
Immunological drugs				
Chemical	Source	Uses & Status	Structure	Citations
Domoic acid (causes amnesic shellfish poisoning in humans)	diatom (<i>Pseudo-nitzschia</i> sp.) worldwide	immune system; limits TNF- α & matrix metalloproteinase-9 release from brain microglia	 <p>Domoic acid</p> <p>(128)</p>	128
halipeptin A & halipeptin B	sponge (<i>Haliclona</i> sp.) Indo-Pacific (photo: <i>Haliclona sarai</i>) 	anti-inflammatory; inhibition of carrageenan-induced edema	 <p>Halipeptin A R=Me Halipeptin B R=H</p> <p>(103)</p>	103,117 photo: 71
hymenamide C	sponge (<i>Stylissa carteri</i>) (synonym: <i>Axinella carteri</i>) Indo-West Pacific	anti-inflammatory; neutrophil & macrophage mediator modulation	 <p>Hymenamide C</p> <p>(128)</p>	128
manoalide (AGN-190093) (related to the cacospongiolides from the same sponge)	sponge (<i>Luffariella variabilis</i>) Indo-Pacific	anti-inflammation; antipsoriatic; nervous system; first substance ever observed to selectively inhibit phospholipase A ₂ (PLA ₂); inhibits seizures & epileptogenic properties of crotoxin; pharmacological probe; commercially available; licensed to Allergan; Phase II trials stopped due to formulation problems (insufficient dermal absorption); research continuing	 <p>Manoalide</p> <p>(138)</p>	18,24,25,128 137,138
oxepinamide	fungus (<i>Acremonium</i> sp.) found on tunicate (<i>Ecteinascidia turbinata</i>) Caribbean 	anti-inflammatory		114 photo: 50
petrosaspongiolide	sponge (<i>Petrosaspongia nigra</i>) New Caledonia	anti-inflammatory; phospholipase A ₂ inhibition	 <p>Petrosaspongiolide M</p> <p>(128)</p>	128
pseudopterosins (including methopterosin, a derivative)	gorgonian (sea whip) (<i>Pseudoptero-gorgia elisabethae</i>) Caribbean 	arthritis, anti-inflammation, & analgesic; modify the arachidonic acid cascade; inhibit synthesis of eicosanoids, (hormone-like substances) in specific white blood cells (polymorphonuclear leukocytes); extremely selective; they appear to be pharmacologically distinct from other NSAIDs; novel MOA; Phase II trials; sold as a cosmetic "anti-wrinkle" cream by Estee Lauder under the name <i>Resilience</i>	 <p>pseudopterosin A</p> <p>(9)</p>	9,10,12, 24,25 photo: 11


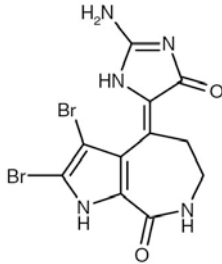
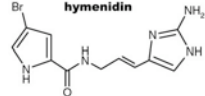
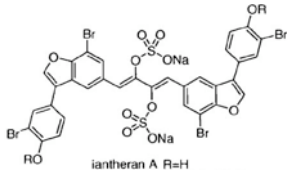
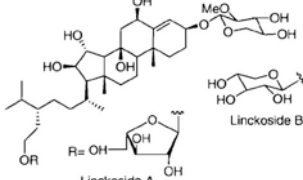
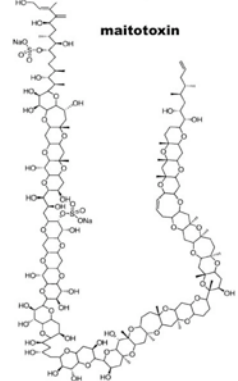
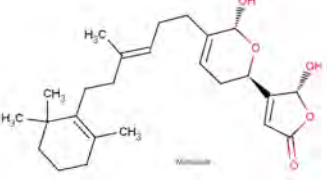
Immunological drugs				
Chemical	Source	Uses & Status	Structure	Citations
salinamide A & salinamide B	bacterium	anti-inflammatory	 <p>salinamide B (139)</p>	25,139
scytonemin	cyanobacterium	anti-inflammatory & anticancer; inhibition of PMA-induced mouse ear edema; inhibits active cell proliferation	 <p>Scytonemin (128)</p>	128
thalassospiramide A & thalassospiramide B	bacterium (<i>Thalassospira</i> sp.)	immunosuppressant		44
topsentin B1	deep-water sponges (<i>Halichondria genitrix</i> [synonym: <i>Topsentia genitrix</i>], <i>Hexadella</i> sp., <i>Spongosorites ruetzleri</i>) Mediterranean, North Atlantic, Caribbean	anti-inflammatory; suppresses immunogenic & neurogenic inflammation; early research suggests potential use for colon cancer, Alzheimer's disease, & inflammatory bowel disease; preclinical studies	 <p>Topsentin B1 (140)</p>	140
toteptin D	sponge (<i>Spongosorites</i> sp.)	anti-inflammatory	 <p>toteptin D (146)</p>	146


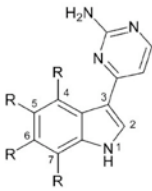
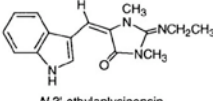
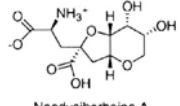

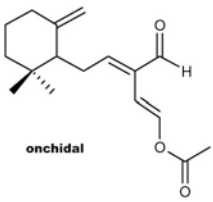
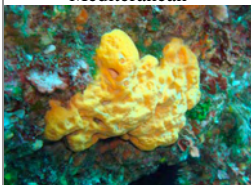
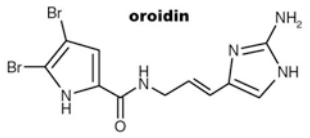

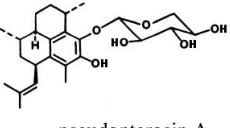

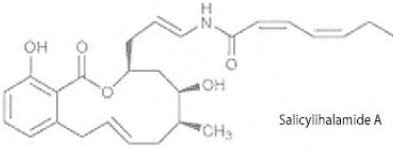
Molecular probes				
Chemical	Source	Uses & Status	Structure	Citations
jaspaginol	sponge	molecular probe; human 15-lipoxygenase inhibition	 <p>Jaspaginol (128)</p>	128
manoalide (AGN-190093) (related to the cacospongiolides from the same sponge)	sponge (<i>Luffariella variabilis</i>) Indo-Pacific	anti-inflammation; antipsoriatic; first substance observed to selectively inhibit phospholipase A ₂ (PLA ₂); inhibits seizures & epileptogenic properties of crotoxin; pharmacological probe; commercially available; licensed to Allergan; Phase II trials stopped due to formulation problems (insufficient dermal absorption); research continuing	 <p>Manoalide (138)</p>	18,24,25, 128,137,138
okadaic acid	red tide dinoflagellate (<i>Prorocentrum lima</i>) Northeast Atlantic, Gulf of Mexico	molecular probe; cellular phosphorylation processes; causes Diahrrctic Shellfish Poisoning (DSP); selective inhibitor of the enzyme protein phosphatase; pharmacological probe, commercially available	 <p>(141)</p>	12,24,25, 141
saxitoxin		molecular probe; neurotoxin; ion channel nerve transmission; pharmacological probe	 <p>(142)</p>	12,142

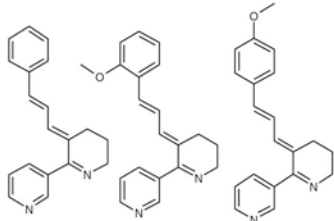
Molecular probes				
Chemical	Source	Uses & Status	Structure	Citations
tetrodotoxin	<p>horseshoe crab (<i>Limulus polyphemus</i> [NW Atlantic & Gulf of Mexico], <i>Carcinoscorpius rotundicauda</i> [Asia], <i>Tachypleus</i> sp. [Asia]), blue-ringed octopus (<i>Hapalochlaena lunulata</i> [Western Pacific] [photo], <i>Hapalochlaena maculosa</i> [Australia])</p> 	molecular probe; neurotoxin; ion channel nerve transmission; pharmacological probe	 <p>(143)</p>	12,142,143 photo: 144

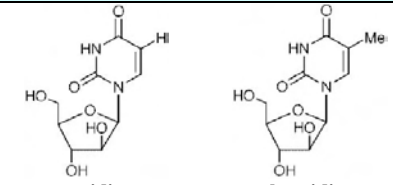
Neurological drugs				
Chemical	Source	Uses & Status	Structure	Citations
6-bromoindirubin	<p>mollusk (sea snail) (<i>Hexaplex trunculus</i>) Mediterranean</p> 	anti-Alzheimer's; selective inhibitor of GSK-3 β	 <p>6-bromoindirubin (146)</p>	146 photo: 145
anabaseine (hoplonemertine toxin)	<p>nemertine worm (<i>Paranemertes peregrina</i>) North Pacific</p>	anti-Alzheimer's & memory enhancement; stimulates vertebrate neuromuscular nicotinic receptors & increasing cholinergic transmission; has potential as a treatment of cognitive function loss	 <p>anabaseine (147)</p>	18,146,147
antillatoxin & antillatoxin B	<p>cyanobacterium (<i>Lyngbya majuscula</i>) Indian Ocean, Gulf of Mexico, Southeast Atlantic</p>	nervous system; activates voltage sensitive Na channel	 <p>Antillatoxin B (128)</p>	128
aplysallene	<p>sea hare</p>	nervous system; Na ⁺ , K ⁺ -ATPase inhibition		128
bipyridinyl analog of anabaseine (synthetic analog of anabaseine)	<p>nemertine worm (<i>Paranemertes peregrina</i>) North Pacific</p>	nervous system; treatment of neurodegenerative diseases; patented by Memory Pharmaceuticals Corp.	 <p>bipyridinyl analog of anabaseine (146)</p>	146,147
chlorogentisyl-quinone	<p>fungus</p>	nervous system; neutral sphingomyelinase inhibition		128

Neurological drugs				
Chemical	Source	Uses & Status	Structure	Citations
conantokin G	mollusk (cone snail) (<i>Conus geographus</i>) Indo-Pacific 	analgesic & anti-seizure; 17-amino-acid competitive antagonist of N-methyl-D-aspartate (NMDA) receptors; Phase I trials discontinued	precursor amino acid sequence shown at (128, Figure 2, p. 275)	1,2,18 photo: 3
conantokin L	mollusk (cone snail) (<i>Conus lynceus</i>) Indo-Pacific 	anti-seizure & neuroprotective; N-methyl-D-aspartate (NMDA) receptor antagonist	precursor amino acid sequence shown at (128, Figure 2, p. 275)	128 photo: 148
Debromo hymenialdisine (DBH)	sponge (<i>Stylotella aurantium</i>) Palau	anti-Alzheimer's & osteoarthritis; acts as a highly selective inhibitor of a specific target cell DNA damage checkpoint enzyme during the G2 phase of the cell cycle; Phase I trials	 (149)	149 photo: 149
DMXB (DMXB-A, GTS-21) (synthetic analog of anabaseine)	nemertine worm (<i>Paranemertes peregrina</i>) North Pacific	anti-Alzheimer's & memory enhancement; stimulates vertebrate neuromuscular nicotinic receptors & increasing cholinergic transmission; has potential as a treatment of cognitive function loss; Phase II trial for treatment of Alzheimer's and schizophrenia; licensed to Taiho by U. Florida; only marine drug in trials for palliative treatment of Alzheimer's (2005)	 DMXB (GTS-21) (146)	146,147
dysiherbaine	sponge (<i>Lamellodysidea herbacea</i>) (synonym: <i>Dysidea herbacea</i>) Indian Ocean	nervous system; induces convulsant action in mice; inhibits kainic acid & mGluR5 glutamate receptors	 Dysiherbaine (128)	128
halenaquinol	sponge	nervous system; Na ⁺ , K ⁺ -ATPase inhibition	 Halenaquinol (128)	128
HLG-1, HLG-2, & HLG-3	echinoderm (sea cucumber) (<i>Holothuria leucospilota</i>) Indian Ocean 	nervous system	 (128)	128 photo: 150

Neurological drugs				
Chemical	Source	Uses & Status	Structure	Citations
hymenialdisine	sponges <i>(Axinella damicornis</i> [photo], <i>Axinella verrucosa</i> , <i>Stylissa carteri</i> [synonym: <i>Acantella aurantiaca</i>]) Mediteranean, Atlantic Ocean, Indian Ocean 	anti-Alzheimer's & anti-Parkinson's; ATP-competitive kinase inhibitor; inhibits cyclin-dependent kinases & blocks <i>in vivo</i> phosphorylation; Potent inhibitor of mitogen-activated protein kinase kinase-1 (MEK-1)	 hymenialdisine (146)	146,151,152 photo: 153
hymenidine	sponge <i>(Hymeniacidon</i> sp.) Okinawa	anti-Alzheimer's & anti-Parkinson's; a potent antagonist of serotonergic receptors	 hymenidin (146)	146,154
iantheran A & iantheran B	sponge	nervous system; Na ⁺ , K ⁺ -ATPase and plasmin inhibition	 iantheran A R=H iantheran A diacetate R=Ac (128)	128
linckoside A & linckoside B	starfish	nervous system; induces neuritogenesis	 Linckoside A Linckoside B (128)	128
maitotoxin	algae	nervous system; modulates calcium & sodium influx	 maitotoxin (128)	128
manoalide (AGN-190093) (related to the cacospongiolides from the same sponge)	sponge <i>(Luffariella variabilis)</i> Indo-Pacific	anti-inflammation; antipsoriatic; nervous system; first substance ever observed to selectively inhibit phospholipase A ₂ (PLA ₂); inhibits seizures & epileptogenic properties of crotoxin; pharmacological probe; commercially available; licensed to Allergan; Phase II trials stopped due to formulation problems (with dermal application, insufficient amount absorbed through skin); research continuing	 Manoalide (138)	18,24,25, 128,137,138

Neurological drugs				
Chemical	Source	Uses & Status	Structure	Citations
meridianins	tunicate (<i>Aplidium meridianum</i>) Southern Ocean 	anti-Alzheimer's; protein kinase inhibitors	 <p>Meridianin A Meridianin B Meridianin C Meridianin D Meridianin E Meridianin F Meridianin G</p> <p>(155)</p>	155 photo: 156
<i>N</i> -3'-ethylaplysinopsin	sponge (<i>Smenospongia aurea</i>) Jamaica	nervous system; binds to human serotonin 5-HT _{2C} receptor	 <p><i>N</i>-3'-ethylaplysinopsin (128)</p>	128
neodysiherbaine A	sponge (<i>Lamellosysidea herbacea</i>) (synonym: <i>Dysidea herbacea</i>) Indian Ocean	nervous system; induces convulsant action in mice; inhibits kainic acid glutamate receptors	 <p>Neodysiherbaine A (128)</p>	128
onchidal	mollusk (sea slug) (<i>Onchidella binneyi</i>) Gulf of California (photo: <i>Onchidella</i> sp.) 	anti-Alzheimer's; an active site-directed irreversible inhibitor of AChE	 <p>onchidal (146)</p>	146 photo: 157
oroidin (related to hymenialdisine)	sponge (<i>Agelas oroides</i>) Mediterranean 	anti-Alzheimer's & anti-Parkinson's; a potent antagonist of serotonergic receptors	 <p>oroidin (146)</p>	146 photo: 158
pseudopterosins (including methopterosin, a derivative)	gorgonian (sea whip) (<i>Pseudopterozorgia elisabethae</i>) Caribbean 	arthritis, anti-inflammation, & analgesic; appear to modify the arachidonic acid cascade; inhibit synthesis of eicosanoids, (locally functioning hormone-like substances) in specific white blood cells called polymorphonuclear leukocytes; their extreme selectivity intrigues to researchers; they appear to be pharmacologically distinct from other NSAIDs & their MOA seems novel; preclinical studies; sold as a cosmetic anti-wrinkle cream by Estee Lauder under the name <i>Resilience</i>	 <p>pseudopterosin A (9)</p>	9,10,12, 24,25 photo: 11
salicylhalimides	sponge (<i>Haliclona</i> sp.) Indo-Pacific (photo: <i>Haliclona sarai</i>) 	anticancer & anti-osteoporosis; first marine Vo-ATPase inhibitor (Vo-ATPases are eukaryotic enzymes whose principal role is to pump hydrogen ions across cell vacuolar membranes); may mediate bone resorption; preclinical studies	 <p>Salicylhalamide A (86)</p>	18,86 photo: 71

Neurological drugs				
Chemical	Source	Uses & Status	Structure	Citations
<i>trans</i> -3-cinnamylidene analogs of anabaseine	nemertine worm (<i>Paranemertes peregrina</i>) North Pacific	nervous system; developed by Univ. of Florida; potentially useful for treating brain nicotinic subtype receptors	 <i>trans</i> -3-cinnamylidene analogs of anabaseine (146)	146,147
tridentatol	hydroid (<i>Tridentata marginata</i>) Gulf of Mexico	antioxidant & UV protection		114

Templates				
Chemical	Source	Uses & Status	Structure	Citations
spongouridine & spongothymidine	sponge (<i>Tectitethya crypta</i>) (synonym: <i>Cryptotethya crypta</i>) Caribbean	template for antiviral & antitumor agents; template for nucleosides with sugars other than ribose or deoxyribose; led to synthesis of zidovudine (AZT)	 spongouridine spongothymidine (102)	19,102

1. http://www.nlm.nih.gov/cgi/mesh/2009/MB_cgi?mode=&term=Conotoxins
2. <http://www.anaspec.com/products/product.asp?id=30979>
3. <http://en.wikipedia.org/wiki/File:Conus-geographicus.jpg>
4. Wang C-Z & Chi C-W. 2004. Conus Peptides - A Rich Pharmaceutical Treasure. *Acta Biochimica et Biophysica Sinica*, **36**(11):713-723.
5. http://en.wikipedia.org/wiki/File:Conus_catus_001.jpg
6. Craig AG, Norbert T, Griffin d, Hoeger C, Akhtar M, Schmidt K, Low W, Dykert J, Richelson E, Navarro V, Mazella J, Watkins M, Hillyard D, Imperial J, Cruz LJ & Olivera BM. 1999. Conatulakin-G, an *O*-Glycosylated Invertebrate Neurotensin. *Journal of Biological Chemistry*, **274**:13752-13759.
7. <http://www.patentstorm.us/patents/6369193/description.html>
8. For an explanation of des- prefix, see <http://www.chem.qmul.ac.uk/iupac/sectionF/RF45n6.htm>
9. Look SA, Fenical W, Jacobs RS & Clardy J. 1986. The pseudopterosins: anti-inflammatory and analgesic natural products from the sea whip *Pseudopteroorgia elisabethae*. *Proceedings of the National Academy of Sciences*, **83**(17):6238-6240.
10. <http://www.marinebiotech.org/pseudopterosins.html>
11. <http://web.ncifcrf.gov/events/springfest/2011/highlight.aspx>
12. Hay ME & Fenical W. 1996. Chemical Ecology and Marine Biodiversity: Insights and Products from the Sea. *Oceanography*, **9**(1):10-20.
13. <http://www.marinebiotech.org/ziconotide.html>
14. http://en.wikipedia.org/wiki/File:Ziconotide_1DW5.png
15. http://en.wikipedia.org/wiki/File:Conus_magus_001.jpg
16. <http://www.marinebiotech.org/contignasterol.html>
17. <http://www.marinebiotech.org/aplidine.html>
18. Newman DJ & Cragg GM. 2004. Marine natural products and related compounds in clinical and advanced preclinical trials. *Journal of natural products*, **67**:1216-1238.
19. Bruckner AW. 2002. Life-Saving Products from Coral Reefs. *Issues in Science and Technology Online*, Spring 2002. http://www.issues.org/18.3/p_bruckner.html
20. <http://www.marinebiotech.org/cryptophycins.html>
21. Davidson BS. 1993. Ascidians: producers of amino acid-derived metabolites. *Chemical Reviews*, **93**(5):1771-1791.

-
22. <http://www.marinebiotech.org/bengamides.html>
 23. [http://docs.lib.noaa.gov/OEDV/FLoSEE_2010/image/Digital Stills/Deck Photos/20100805/5-VIII-10-1/201008051006 Jaspis sp Deck.jpg](http://docs.lib.noaa.gov/OEDV/FLoSEE_2010/image/Digital%20Stills/Deck%20Photos/20100805/5-VIII-10-1/201008051006%20Jaspis%20sp%20Deck.jpg)
 24. Fenical W. 1996. Marine Biodiversity and the Medicine Cabinet. The Status of New Drugs from Marine Organisms. *Oceanography*, **9**(1):23-27.
 25. Fenical W. 1997. New pharmaceuticals from marine organisms. *Trends in Biotechnology*. **15**(9):339-341.
 26. Pettit GR, Herald CL, Doubek DL, Herald, DL, Arnold E & Clardy J. 1982. Isolation and Structure of Bryostatin I. *Journal of the American Chemical Society*. **104**:6846-6848.
 27. <http://www.marinebiotech.org/bryostatin.html>
 28. <http://www.marinespecies.org/photogallery.php?album=709&pic=25675>
 29. <http://en.wikipedia.org/wiki/File:Calyculin.png>
 30. <http://en.wikipedia.org/wiki/Calyculin>
 31. http://en.wikipedia.org/wiki/File:Swa_hare_DSC01663.JPG
 32. Blunt JW, Copp BR, Hu WP, Munro MHG, Northcote PT & Prinsep MR. 2007. Marine natural products. *Natural Product Reports*, **24**(1):31-86
 33. Gerwick WH, Proteau PJ, Nagle DGG, Hamel E, Blokhin A & Slates DL. 1994. Structure of Curacin A, a Novel Antimitotic, Antiproliferative, and Brine Shrimp Toxic Natural Product from the Marine Cyanobacterium *Lyngbya majuscula*. *Journal of Organic Chemistry*, **59**:1243-1245.
 34. <http://www.marinebiotech.org/curacina.html>
 35. McAlpine JB, Banskota AH, Charan RD, Schlingmann G, Zazopoulos E, Pirae M, Janso J, Bernan VS, Aoudate M, Farnet CM, Feng X, Zhao Z & Carter GT. 2008. Biosynthesis of Diazepinomicin/ECO-4601, a *Micromonospora* Secondary Metabolite with a Novel Ring System. *Journal of Natural Products*, **71**(9):1585-1590.
 36. Charan RD Schlingmann G, Janso J, Bernan V, Feng X & Carter GT. 2004. *Journal of Natural Products*, **67**(8):1431-1433.
 37. <http://www.marinebiotech.org/diazonamidea.html>
 38. <http://www.marinebiotech.org/dictyostatin.html>
 39. Rinehart KL Jr, Shaw PD, Shield LS, Gloer JB, Harbout GC, Koker MES, Samain D, Schwartz RE, Tymiak AA, Weller DL, Carter GT, Munro MHG, Hughes RG Jr, Renis HE, Swynenberg EB, Stringfellow DA, Vavra JJ, Coats JH, Zurenko GE, Kuentzel SL, Li LH, Bakus GJ, Brusca RC, Craft LL, Young DN & Connor JL. 1981a. Marine natural products as sources of antiviral, antimicrobial, and antineoplastic agents. *Pure and Applied Chemistry*, **53**(4):795-817.
 40. Rinehart KL Jr, Gloer JB, Cook JC Jr, Mizzsak SA, Scahill TA. 1981b. Structures of the Didemnins, Antiviral and Cytotoxic Depsipeptides from a Caribbean Tunicate. *Journal of the American Chemical Society*, **103**:1857-1859.
 41. <http://www.marinebiotech.org/didemninb.html>
 42. ter Haar E, Kowalski RJ, Hamel E, Lin CM, Longley RE, Gunasekera SP, Rosenkranz HS & Day BW. 1996. Discodermolide, A Cytotoxic Marine Agent That Stabilizes Microtubules More Potently Than Taxol. *Biochemistry*, **35**:243-250.
 43. <http://www.marinebiotech.org/discodermolide.html>
 44. Cragg GM & Newman DJ. 2009. Nature: a vital source of leads for anticancer drug development. *Phytochemistry Reviews*. **8**(2):313-331.
 45. Pettit GR, Kamano Y, Herald CL, Tuinman AA, Boettner FE, Kizu H, Schmidt JM, Baczynskyj L, Tomer KB & Bontems RJ. 1987. The Isolation and Structure of a Remarkable Marine Animal Antineoplastic Constituent: Dolastatin 10. *Journal of the American Chemical Society*, **109**:6883-6885.
 46. <http://www.marinebiotech.org/dolastatins.html>
 47. Rinehart KL, Holt TG, Fregeau NL, Stroh JG, Keifer PA, Sun F, Li LH & Martin DG. 1990. Ecteinascidins 729,743, 745, 759A, 759B, and 770: Potent Antitumor Agents from the Caribbean Tunicate *Ecteinascidia turbinata*. *Journal of Organic Chemistry*, **55**:4512-4515.
 48. Wright AE, Forleo DA, Gunawardana GP, Gunasekera SP, Koehn FE & McConnell OJ. 1990. Antitumor Tetrahydroisoquinoline Alkaloids from the Colonial Ascidian *Ecteinascidia turbinata*. *Journal of Organic Chemistry*, **55**:4508-4512.
 49. <http://www.marinebiotech.org/ecteinascidin743.html>
 50. <http://oceanexplorer.noaa.gov/explorations/07twilightzone/logs/may28/media/ecteinascidin.html>
 51. <http://www.marinebiotech.org/eleutherobin.html>
 52. http://commons.wikimedia.org/wiki/File:Erythropodium_caribaeorum_01_by_Line1.JPG
 53. Mayer AMS, Glaser KB, Cuevas C, Jacobs RS, Kem W, Little RD, McIntosh JM, Newman DJ, Potts BC & Shuster DE. 2010. The odyssey of marine pharmaceuticals: a current pipeline perspective. *Trends in Pharmacological Science*, **31**(6):255-265.
 54. Alday PH & Correia JJ. 2009. Macromolecular Interaction of Halichondrin B Analogues Eribulin (E7389) and ER-076349 with Tubulin by Analytical Ultracentrifugation. *Biochemistry*, **48**(33):7927-7938.
 55. <http://www.marinebiotech.org/girolline.html>
 56. Hirata Y & Uemura D. 1986. Halichondrins—antitumor polyether macrolides from a marine sponge. *Pure and Applied Chemistry*, **58**(50):701-710.
 57. <http://www.marinebiotech.org/halichondrins.html>
 58. <http://www.marinebiotech.org/hemiasterlins.html>
 59. <http://www.patentstorm.us/patents/5476953/description.html>

60. <http://www.marinebiotech.org/kahalalidef.html>
61. <http://pubchem.ncbi.nlm.nih.gov/summary/summary.cgi?cid=72941>
62. <http://www.marinebiotech.org/km7000.html>
63. <http://www.marinebiotech.org/lasonolides.html>
64. http://de.wikipedia.org/wiki/Datei:Forcepia_sourceoflasonolides.jpg
65. <http://www.marinebiotech.org/latrunculins.html>
66. <http://www.marinebiotech.org/laulimalide.html>
67. Wipf P. 1998. Synthesis and Structure-Activity Studies of Lissoclinum Peptide Alkaloids. In: Pelletier SW (ed), *Alkaloids: chemical and biological perspectives*. New York: Elsevier.
68. http://pl.wikipedia.org/wiki/Plik:Lissoclinum_patellum.jpg
69. National Academy of Science. 2002. *Marine Biotechnology in the Twenty-First Century: Problems, Promise, and Products*. National Research Council, Ocean Studies Board. Washington, DC. p. 50.
70. Venables DA, Concepción GP, Matsumoto SS, Barrows LR & Ireland CM. 1997. Makaluvamine N: A New Pyrroloiminoquinone from *Zyzzya fuliginosa*. *Journal of Natural Products*, **60**(4):408-410.
71. http://en.wikipedia.org/wiki/File:Reniera_sarai.png
72. National Academy of Science. 2002. *Marine Biotechnology in the Twenty-First Century: Problems, Promise, and Products*. National Research Council, Ocean Studies Board. Washington, DC. p. 49.
73. <http://en.wikipedia.org/wiki/File:Tiburón.jpg>
74. Kim D, Lee IS, Jung JH & Yang S-I. 1999. Psammaphin A, a natural bromotyrosine derivative from a sponge, possesses the antibacterial activity against methicillin-resistant *Staphylococcus aureus* and the DNA gyrase-inhibitory activity. *Archives of Pharmacal Research*, **22**:25-29.
75. <http://pubchem.ncbi.nlm.nih.gov/summary/summary.cgi?sid=47205088&viewopt=Deposited>
76. http://pubchem.ncbi.nlm.nih.gov/summary/summary.cgi?sid=87305570&loc=es_rss
77. [http://fr.wikipedia.org/wiki/Fichier:Theonella_cylindrica_\(Tube_sponge\).jpg](http://fr.wikipedia.org/wiki/Fichier:Theonella_cylindrica_(Tube_sponge).jpg)
78. Flipo M, Charton J, Hocine A, Dassonneville S, Deprez B & Deprez-Poulain R. 2009. Hydroxamates: Relationships between Structure and Plasma Stability. *Journal of Medicinal Chemistry*, **52**(21):6790-6802.
79. Ishida T, In Y, Shinozaki F, Doi M, Yamamoto D, Hamada Y, Shioiri T, Kamigauchi M & Sugiura M. 1995. Solution Conformations of Patellamides B and C, Cytotoxic Cyclic Hexapeptides from Marine Tunicate, Determined by NMR Spectroscopy and Molecular Dynamics. *Journal of Organic Chemistry*, **60**(13):3944-3952.
80. Schmidt TM, Hay ME, & Lindquist N. 2005. Constraints on Chemically Mediated Coevolution: Multiple Functions for Seaweed Secondary Metabolites. *Ecology*, **76**(1):107-123.
81. <http://www.marinebiotech.org/pelorusidea.html>
82. Goldring WPD and Pattenden G. 2006. The Phomactins. A Novel Group of Terpenoid Platelet Activating Factor Antagonists Related Biogenetically to the Taxanes. *Accounts of Chemical Research*, **39**(5):354-361.
83. Sugano M, Sato A, Iijima Y, Furuya K, Kuwano H & Hata T. 1994. Phomactin E, F, and G: New Phomactin-group PAF Antagonists from a Marine Fungus *Phoma* sp. *Journal of Antibiotics*, **48**(10):1188-1190.
84. http://en.wikipedia.org/wiki/File:Blue_Chionoecetes_opilio.JPG
85. Jiang X, Williams N & De Brabander JK. 2007. Synthesis of Psymberin Analogues: Probing a Functional Correlation with the Pederin/Mycalamide Family of Natural Products. *Organic Letters*, **9**(2):227-230.
86. <http://www.marinebiotech.org/salicylihalamides.html>
87. http://carsten-thoms.net/sponges/biotec/2_zentr.html
88. http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6THS-3WJ7NNJ-G&_user=10&_coverDate=04%2F09%2F1999&_rdoc=1&_fmt=high&_orig=search&_sort=d&_docanchor=&view=c&_searchStrId=1244782038&_rerunOrigin=google&_acct=C000050221&_version=1&_urlVersion=0&_userid=10&md5=18b697ce6b50830e4cb771a4fda f2119
89. http://en.wikipedia.org/wiki/File:Halodule_wrightii.jpg
90. [http://commons.wikimedia.org/wiki/File:Sarcodictyon_roseum_\(=Rolandia_rosea\)_\(Phillipi,_1842\)_-_expulsant_sa_ponte_.jpg](http://commons.wikimedia.org/wiki/File:Sarcodictyon_roseum_(=Rolandia_rosea)_(Phillipi,_1842)_-_expulsant_sa_ponte_.jpg)
91. <http://www.marinebiotech.org/spisulosine.html>
92. <http://www.marinebiotech.org/squalamine.html>
93. http://en.wikipedia.org/wiki/File:Squalus_acanthias_stellwagen.jpg
94. <http://www.marinebiotech.org/thiocoraline.html>
95. <http://www.marinebiotech.org/vitilevuamide.html>
96. http://en.wikipedia.org/wiki/File:Jorunna_funebris.jpg
97. http://en.wikipedia.org/wiki/File:Scalloped_hammerhead_cocos.jpg
98. Butler MS. 2008. Natural products to drugs: natural product-derived compounds in clinical trials. *Natural Product Reports*, **25**(3):475-516.

99. Fiedler H-P, Bruntner C, Bull AT, Ward AC, Goodfellow M, Potterat O, Puder C & Mihm G. 2005. Marine actinomycetes as a source of novel secondary metabolites. *Antonie van Leeuwenhoek*, **87**(1):37-42.
100. Bister B, Bischoff D, Ströbele M, Riedlinger J, Reicke A, Wolter F, Bull AT, Zähner H, Fiedler H-P & Süssmuth RD. 2004. Abyssomicin C - A Polycyclic Antibiotic from a Marine Verrucosipora Strain as an Inhibitor of the p-Aminobenzoic Acid/Tetrahydrofolate Biosynthesis Pathway. *Angewandte Chemie International Edition*, **43**(19):2574-2576.
101. Nicolaou KC & Harrison ST. 2006. Total Synthesis of Abyssomicin C and atrop-Abyssomicin. *Angewandte Chemie International Edition*, **45**(20):3256-3260.
102. Newman DJ, Cragg GM & Snader KM. 2000. The influence of natural products upon drug discovery. *Natural Product Reports*, **17**:215-234.
103. Donia M & Hamann MT. 2003. Marine natural products and their potential applications as anti-infective agents. *The Lancet Infectious Diseases*, **3**(6):338-348.
104. http://en.wikipedia.org/wiki/File:Amphimedon_queenslandica_adult.png
105. <http://en.wikipedia.org/wiki/File:Eunicella.jpg>
106. Bowling JJ, Kochanowska AJ, Kasanah N & Hamann MT. 2007. Nature's bounty – drug discovery from the sea. *Expert Opinion on Drug Discovery*, **2**(11):1505-1522.
107. <http://www.enzolifesciences.com/alx-350-319/avarol/>
108. <http://www.marinespecies.org/photogallery.php?album=714&pic=40121>
109. <http://en.wikipedia.org/wiki/Zidovudine>
110. [http://fr.wikipedia.org/wiki/Fichier:Clathria_tuberosa_\(Sponge\).jpg](http://fr.wikipedia.org/wiki/Fichier:Clathria_tuberosa_(Sponge).jpg)
111. <http://www.wipo.int/pctdb/en/wo.jsp?wo=1988000946&IA=US1987001926&DISPLAY=STATUS>
112. Xiang L, Kalaitzis JA & Moore BS. 2004. EncM, a versatile enterocin biosynthetic enzyme involved in Favorskii oxidative rearrangement, aldol condensation, and heterocycle-forming reactions. *Proceedings of the National Academy of Sciences*, **101**(44), 15609-15614.
113. <http://www.noaanews.noaa.gov/stories2004/s2334.htm>
114. National Academy of Science. 2002. *Marine Biotechnology in the Twenty-First Century: Problems, Promise, and Products*. National Research Council, Ocean Studies Board. Washington, DC. p. 54.
115. <http://www.photolib.noaa.gov/htmls/exp10565.htm>
116. <http://en.wikipedia.org/wiki/File:Featherx.JPG>
117. <http://www.marinebiotech.org/manzaminea.html>
118. <http://www.marinespecies.org/photogallery.php?album=714&pic=40115>
119. <http://www.niot.res.in/m5/mbic/pg/mcdb/view.php?cmdid=109>
120. http://en.wikipedia.org/wiki/File:Clavelina_lepadiformis_02.jpg
121. <http://www.spongeguide.org/imageinfo.php?img=901>
122. http://en.wikipedia.org/wiki/File:Phorbas_tenacior_Capo_Gallo02.JPG
123. [http://en.wikipedia.org/wiki/File:Synaptula_lamperi_\(Sea_cucumber\)_on_Plakortis_sp._\(Chicken_liver_sponge\).jpg](http://en.wikipedia.org/wiki/File:Synaptula_lamperi_(Sea_cucumber)_on_Plakortis_sp._(Chicken_liver_sponge).jpg)
124. [http://docs.lib.noaa.gov/OEDV/FLoSEE_2010/image/Digital Stills/Deck Photos/20100711/11-VII-10-2/201007112003 Ptilocaulis.JPG](http://docs.lib.noaa.gov/OEDV/FLoSEE_2010/image/Digital%20Stills/Deck%20Photos/20100711/11-VII-10-2/201007112003%20Ptilocaulis.JPG)
125. http://commons.wikimedia.org/wiki/File:Briareum_asbestinum_1.jpg
126. http://en.wikipedia.org/wiki/File:Spongia_officinalis.jpg
127. http://en.wikipedia.org/wiki/File:Seagrass_Grahams_Harbour.jpg
128. Mayer MS & Hamann MT. 2005. Marine pharmacology in 2001-2002: Marine compounds with anthelmintic, antibacterial, anticoagulant, antidiabetic, antifungal, anti-inflammatory, antimalarial, antiplatelet, antiprotozoal, antituberculosis, and antiviral activities; affecting the cardiovascular, immune and nervous systems and other miscellaneous mechanisms of action. *Comparative Biochemistry and Physiology Part C: Toxicology & Pharmacology*. **140**(3-4):265-286.
129. http://upload.wikimedia.org/wikipedia/commons/thumb/e/ee/Cortistatin_A.svg/1000px-Cortistatin_A.svg.png
130. http://en.wikipedia.org/wiki/File:Bluebell_tunicates_Nick_Hobgood.jpg
131. http://commons.wikimedia.org/wiki/File:Echinometra_lucunter.jpg
132. http://en.wikipedia.org/wiki/File:Strongylocentrotus_franciscanus.jpg
133. <http://www.enzolifesciences.com/BML-CA409/xestospongina-c/>
134. <http://en.wikipedia.org/wiki/File:Barrel6.jpg>
135. Gautschi JT, Whitman S, Holman TR & Crews P. 2004. An Analysis of Phakellin and Oroidin Structures Stimulated by Further Study of an Agelas Sponge. *Journal of Natural Products*, **67**:1256-1261.
136. <http://oceanexplorer.noaa.gov/explorations/07twilightzone/background/biotechnology/media/styllissa.html>
137. Potts BCM, Faulkner DJ, de Carvalho MS & Jacobs RS. 1992. Chemical Mechanism of Inactivation of Bee Venom Phospholipase A2 by the Marine Natural Products Manoalide, Luffariellolide, and Scalardial. *Journal of the American Chemical Society*, **114**:5093-5100.
138. <http://www.marinebiotech.org/manoalide.html>
139. Kerr RG & Kerr SS. 1999. Marine natural products as therapeutic agents. *Expert Opinion on Therapeutic Patents*, **9**(9):1207-1222.
140. <http://www.marinebiotech.org/topsentins.html>

-
141. http://en.wikipedia.org/wiki/File:Okadaic_acid.svg
 142. Narahashi T. 2008. Tetrodotoxin: a brief history. *Proceedings of the Japan Academy. Series B, Physical and biological sciences*, **84**(5):147-154.
 143. <http://en.wikipedia.org/wiki/Tetrodotoxin>
 144. http://en.wikipedia.org/wiki/File:Hapalochlaena_lunulata2.JPG
 145. [http://en.wikipedia.org/wiki/File:Mušle_\(2\).jpg](http://en.wikipedia.org/wiki/File:Mušle_(2).jpg)
 146. Alonso D, Castro A & Martinez A. 2005. Marine compounds for the therapeutic treatment of neurological disorders. *Expert Opinion on Therapeutic Patents*, **15**(10):1377-1386.
 147. <http://www.marinebiotech.org/anabaseine.html>
 148. http://en.wikipedia.org/wiki/File:Conus_lynceus_003.jpg
 149. <http://www.marinebiotech.org/debromohymenialdisine.htm>
 150. http://en.wikipedia.org/wiki/File:Holothuria_leucospilota_nisekuronamako01.jpg
 151. <http://www.enzolifesciences.com/bml-ei333/hymenialdisine/>
 152. <http://www.enzolifesciences.com/ALX-350-289/10z-hymenialdisine/>
 153. http://en.wikipedia.org/wiki/File:Axinella_damicornis.jpg
 154. Kobayashi J, Ohizumi Y, Nakamura H & Hirata Y. 1986. A novel antagonist of serotonergic receptors, hymenidin, isolated from the Okinawan marine sponge *Hymeniacidon* sp. *Cellular and Molecular Life Sciences*, **42**(10):1176-1177.
 155. Gompel M, Leost M, Bal De Kier Joffe E, Puricelli L, Franco LH, Palermoc J & Meijer L. 2004. Meridianins, a new family of protein kinase inhibitors isolated from the Ascidian *Aplidium meridianum*. *Bioorganic & Medicinal Chemistry Letters*, **14**:1703-1707.
 156. <http://www.boldsystems.org/views/taxbrowser.php?taxid=299527>
 157. <http://en.wikipedia.org/wiki/File:Onchidella.jpg>
 158. http://en.wikipedia.org/wiki/File:Agelas_orooides_Capo_Gallo_025.JPG

Chapter 6

Coral Reefs: Summary

The ESRP coral reefs project is intended to advance the understanding of coral reef ecosystem services, how they are affected by human activities, and how management and policy decisions influence their delivery. Clear definitions of the ecosystem services provided, including the reef attributes that support these services are needed.

In the previous chapters, we have provided a review of past studies focused on four primary ecosystem services provided by coral reefs (shoreline protection, fishing, tourism and recreation, and natural pharmaceutical and biochemical products). The chapters have summarized the economic benefits provided by each of the services, the methods used to quantify the services, and how those ecosystem services were linked to characteristics (attributes) of coral reefs. Table 6-1 shows the combined final ecosystem services table.

6.1 Lessons learned

The management of ecosystem services and the establishment of policies that will result in the preservation of coral reefs will require extensive collaboration between natural and social scientists. We need to better understand:

- The physical and biological processes that provide the ecosystem services;
- The nature of the ecosystem services and how they can be quantified;
- Sustainable exploitation of reef services; that is,
 - ▶ How do we define sustainable levels of exploitation?
 - ▶ How do we estimate a reef's carrying capacity or potential to supply a service? and,
- The social benefits derived from ecosystem services and how they can be measured.

Our decision framework needs to change. Decisions must move towards sustainability (that is, consideration of the “triple bottom line”, where economic, social, and ecological aspects receive equal consideration in decision-making). We are currently hindered by our incomplete understanding of all the benefits provided by coral reefs. We need to look at this from two directions:

- On one hand, what does society gain by having the reef.
- On the other hand, what do we lose if the reef goes away. (e.g., “How much of the protein consumption in the USVI or Samoa comes directly or indirectly from their coral reefs?” “How would that be replaced and at what cost.”)

Measuring an ecosystem service is often confused with valuing that service. For the past twenty years, economists have been conducting studies to estimate the economic value of coral reefs. These studies have often focused on a single ecosystem service, and data limitations have often precluded comprehensive measurements and valuations. In addition, some services provided by coral reefs have been ignored in these studies. For example:

- Conotoxins provide significant improvement in quality of life as compared to opiate painkillers in some therapeutic situations, because conotoxins reduce pain more effectively than opiates without inducing sleep or impairing cognitive functions. How do we most appropriately capture the value of this improved quality-of-life.
- There are over 10 million surfers. Many of the best surfing locations are provided by reef breaks. This service has not yet been quantified.
- Coral reefs provide protection from flooding during storms. Better quantification of this service could potentially support reduced flood insurance rates for those areas protected by reefs.

Valuation tends to be more accurate at the micro level, where economists are able to apply methods for eliciting individuals' values (both market and nonmarket). However, aggregation and estimation of nonmarket benefits at the macro scale remain a challenge. As a result, coral reef ecosystem services have been undervalued, perhaps significantly. Most studies have not directly measured the ecosystem services.

There is a need to consider all aspects of the ecosystem service that can be provided in the valuation process. The present value of the actual use of the ecosystem service, the service that could potentially be available, and the service that would be available under management for sustainable use should all be determined. For example, current practice does not include services being provided but not exploited because supporting services (e.g., access) are not available. However, the development of supporting infrastructure brings environmental impacts to the reef that must be considered in the light of sustainable use. We recommend that all three aspects of the ecosystem service be quantified, when possible.

6.2 Next steps

The ultimate goal of the ESRP coral reefs project is to identify coral reef indicators that can be used to estimate the quantity of ecosystem services being delivered by coral reef ecosystems and to predict the extent to which the current quantities are likely to change in the future. In 2011, we will fully document the linkages between coral reef condition, function, and ecosystem services and the coral reef attributes that support those services. We will also create the coral reef system model that links the coral reef ecological production functions with policy/management-relevant final ecosystem services. We will identify a manageable suite of candidate indicators of final ecosystem services and directly tie the valuation activities to particular management decision(s).

Our literature review has shown that many of the ecosystem indicators are already being collected. However, the aggregation of the indicators and of the underlying data and relating them to ecosystem services is not being done. Missing items include landscape attributes (both onshore and offshore), many of which have been collected but not analyzed for the purpose of relating them to ecosystem services. We plan to begin research in this area using existing and new ORD expertise and resources.

We intend to design the next generation of survey questionnaires, which will address the value that stakeholders assign to coral reef attributes. In addition, modern technology would support web-based surveys, which could greatly facilitate the ease of collecting and analyzing the survey data. One of our collaborators, NOAA's Bob Leeworthy, successfully used a web-based survey questionnaire in a recent valuation of Hawaii's coral reefs. We are collaborating with Bob to design a web-based study for the Guánica Bay Watershed. This is a longer-term research activity (2012-2013).

Table 6-1. Combined final ecosystem services and supporting features for coral reefs

Ecosystem Service(s)		Natural Features	Social Values	Complementary Goods & Services	Ecosystem-Derived Benefits	Potential Indicators of Final Ecosystem Service(s)
Final (FES)	Intermediate					
Tourism & recreation						
Recreational Fishing Opportunity	Production of benthic and aquatic prey for consumption by recreational fish	Fish diversity and abundance	Desirability of fish species and size for rod-and-reel catches	Adequate infrastructure (boats, marinas, etc.)	Revenues from tourism and recreation activities	Abundance of catchable snappers and groupers
Recreational Diving/Snorkeling Opportunity	Coral reef formation & maintenance; maintenance of water clarity; Production of benthic and aquatic prey for consumption by recreational fish	Coral diversity, abundance and health; fish diversity and abundance; water clarity	Desirability of coral reef for recreation based on physical appearance (color, visibility, etc.)	Access to reef, safe swimming conditions, adequate infrastructure (hotels, dive boat operators, etc.)	Revenues from tourism and recreation activities	Taxa richness, size and density of reef organisms
Recreational Underwater Photography Opportunity	Coral reef formation & maintenance; maintenance of water clarity; Production of benthic and aquatic prey for consumption by recreational fish	Coral diversity, abundance and health; fish diversity and abundance; water clarity	Desirability of coral reef for recreation based on physical appearance (color, visibility, etc.)	Access to reef, safe swimming conditions, adequate infrastructure (hotels, dive boat operators, etc.)	Revenues from tourism and recreation activities	Taxa richness, size and density of reef organisms
Recreational Surfing Opportunity	Reef breaks	3-D reef structure	Desirability based on wave size and speed	Access to reef, adequate infrastructure (hotels, board shops, etc.)	Revenues from tourism and recreation activities	3-D structure and proximity to deep ocean
Opportunity to View Nature and Wildlife	Biological integrity	Biodiversity (birds, marine mammals, turtles)	Desirability of species (rarity, size)	Access to reef and adequate infrastructure (boats, tour guides)	Revenues from tourism and recreation activities	Taxa richness, presence of specific species
Opportunity to Sunbath and Swim at the Beach	Water quality, shoreline protection, sand production	White coralline sands; calm waters	Desirability of coralline sand beach for sunbathing (size, cleanliness, appearance)	Access to beach	Revenues from tourism and recreation activities	Areal extent of beach, color of beach, water temperature, days of sunshine, beach trash
Opportunity to Collect Objects (beachcombing)	Water quality	Wide sandy beaches, biodiversity, occasional storms	Desirability of walking on beach and of finding beautiful & unusual objects	Access to beach	Revenues from tourism and recreation activities	Areal extent of beach, frequency of storms, proximity of reef, taxa richness of invertebrates

Table 6-1 (continued)

Ecosystem Service(s)		Natural Features	Social Values	Complementary Goods & Services	Ecosystem-Derived Benefits	Potential Indicators of Final Ecosystem Service(s)
Final (FES)	Intermediate					
Fishing						
Seafood Products: Fish, shellfish, algae harvested	Biological integrity	Fish diversity and abundance; coral health; seascape connectivity; and structural complexity	Desirability of species based on taste	Adequate infrastructure (boats, marinas, etc.)	Revenue from commercial seafood fisheries	Abundance of commercially desirable fish species
Aquarium Products (live fish & coral taken)	Biological integrity	Coral diversity, abundance and health; fish diversity and abundance; seascape connectivity; and structural complexity	Desirability of species for aquaria based on physical appearance (color, size, etc.), rarity		Revenue from sales of aquarium fish and coral	Species abundance and diversity of target populations
Material for Curios and Jewelry removed	Biological integrity	Coral diversity, abundance and health; water clarity	Aesthetic values and artistic inspiration	Diving and boating infrastructure	Revenue from sales of curios and jewelry	Species abundance and diversity of target populations
Shoreline protection						
Protection from shoreline erosion; Decreased erosion in kg/ha/y	Reduction in wave energy, velocity, or height	Presence of reef; reef height, width, slope, & roughness; reef continuity. <i>Physical variables:</i> Offshore wave energy, wave height, tidal depth; beach elevation, sediment grain size	Attractiveness of sandy beaches; desirability of housing near water	Absence of constructed breakwaters	Higher property values; opportunity to use beaches (see Ch. 2)	% reduction in rates of shoreline erosion due to presence of reef
Protection from coastal inundation during extreme events area in hectares protected	Reduction in wave set-up, or storm surge	Presence of reef; reef height, width, slope, roughness; reef continuity. <i>Physical variables:</i> Wave energy; distance from hazard event; slope of coastline; frequency & intensity of extreme events	Past history of extreme events	Absence of constructed breakwaters; location, intensity, and value of coastal development	Lower insurance rates; higher property values; lower property damage and loss of life	% reduction in coastal inundation due to presence of reef
Pharmaceuticals from natural products						
Marketable natural product or a template that results in a marketable product	Unique biologically active secondary metabolite	Shallow, marine biodiverse, species-dense ecosystem	Desirability of good health and well-being	Pharmaceutical research programs for both field collection and laboratory analysis	Increased revenues from pharmaceuticals; increased health and well-being	Species density, biological integrity, sponge diversity, rare species

Definitions (proposed by the Ecosystem Services Research Program and currently under discussion by the Program)

- **Final Ecosystem Service** – Output of ecological functions or processes that directly contributes to social welfare or has the potential to do so in the future (broadly based on Boyd & Banzhaff [2007]).
- **Intermediate Ecosystem Service** - Output of ecological functions or processes that indirectly contributes to social welfare or has the potential to do so in the future.
- **Natural Features** – The biological, chemical, and physical attributes of an ecosystem or environment.
- **Social Values** – The social attributes that influence economic demand for an ecosystem service.
- **Complementary Goods & Services** - Inputs (usually built infrastructure or location characteristics) that allow a good or service to be used by complementing the ecological condition. For example, complementary goods and services that allow the presence of fishable fish to become an opportunity for recreational fishing will include aspects of site accessibility, such as road access, available parking and the presence of a fishing pier, all of which make fishing at the site possible and enhance enjoyment of the activity.
- **Ecosystem-Derived Benefits** - The contribution to social welfare of ecosystem goods and services. In the ESRP, the term applies specifically to net improvements in social welfare that result from changes in the quantity or quality of ecosystem goods and services attributable to policy or environmental decisions.
- **Indicator of Final Ecosystem Service** – Biophysical feature, quantity, or quality that requires little further translation to make clear its relevance to human well-being (*i.e.*, “public-friendly” measurement)

Coral Reefs: Glossary

Words in **bold** are defined in this glossary.

A

Acropora	A genus of stony corals that contain the elkhorn and staghorn corals (NOAA 2010).
actinomycetes	Gram-positive bacteria of the order Actinomycetales in the phylum Actinobacteria that are mostly aerobic but can be anaerobic. Some resemble fungi, because they produce a characteristic, branched mycelium. Actinobacteria are well-known sources of secondary metabolites having pharmaceutical uses. Often found in symbiont relationships with megafauna, notably sponges.
alcyonarian	An octocoral .
algæ	A large and diverse group of simple unicellular or multicellular organisms that use chloroplasts for photosynthesis, although they are not plants. Algæ, which are chiefly aquatic, form the basis of the marine food chain. Common algæ include dinoflagellates, diatoms, seaweeds, and kelp.
antifouling agents	Agent that inhibits the growth of barnacles and other marine organisms on a ship's bottom (an antifouling paint or other coating). Organotin compounds have been the most often used agents in this application since they are effective against both soft and hard fouling organisms. However, in spite of their performance, they have a negative impact on the marine environment, and their long half-life in the environment has prompted marine paint manufacturers to look for a nonpersistent alternative.
artificial breakwater	A bank or levee of stones or a timber structure, used to break the force of the sea in its entrance into a harbor or roadstead.
ascidian	Sac-like filter feeders that belong to the class Ascidiacea within the subphylum Tunicata. Often called sea squirts.
atoll reef	A type of coral reef that encircles a lagoon partially or completely.
attribute	Any measurable component of a biological system (Karr & Chu 1999).
Ayurveda	An ancient medical treatise of the Hindu art of healing and prolonging life; sometimes regarded as a 5th Veda.

B

back reef	The landward side of a reef between the reef crest and the land.
barrier reef	A type of coral reef near the shoreline , but separated from it by a deep lagoon.
Bayesian belief network (BBN)	A graphical network for modeling probabilistic interrelationships between events. Events are represented by nodes in the network and causative relationships are represented by directed arrows between the nodes. A BBN is especially useful when individual nodes of the network will be updated with evidence. For example, a BBN could represent the probabilistic relationships between diseases and symptoms. Given symptoms, the network can be used to compute the probabilities of the presence of various diseases. Decision and utility nodes can be added to a BBN to represent and solve a decision problem following maximum expected value criterion (this is called an influence diagram).
beachcombing	The recreational activity of searching the beach and the intertidal zone for items that have washed in with the tide (e.g., corals, seashells, sponges, sea fans, fossils, pottery shards, artifacts, sea beans, sea glass, and driftwood).
benefit transfer	Techniques to estimate values of ecosystem goods and services based on previously conducted valuation studies. Benefit transfer is conducted by either taking average values of existing studies or by using a transfer function to transfer values from primary studies (study sites) to new locations (policy sites). A transfer function is often developed through meta-analysis, which is a statistical (usually regression) technique to model differences in values among primary valuation studies. A transfer function allows values to be transferred from study sites to policy sites based on a set of independent variables that capture the degree of similarity between the study sites and policy sites (Wainger & Mazzotta 2009).
biochemicals	Chemicals that result from biological and chemical processes in living organisms.
biogeography	The study of ecosystem geography to understand why flora and fauna are found in certain places.
biological diversity (biodiversity)	The variability among living organisms from all sources including terrestrial, marine, and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within and among species and diversity within and among ecosystems (MEA 2009).

biophysical	Pertaining to the biological, chemical, and physical attributes of an ecosystem or environment.
bombora	A shallow area some distance from the shoreline that causes sea waves to break.
bryozoans	Aquatic animals comprising the phylum Bryozoa that form mossy colonies of small polyps each having a curved or circular ridge bearing tentacles; they attach to stones or seaweed and reproduce by budding.
C	
carbon dioxide (CO₂)	An odorless colorless gas formed during respiration and by the decomposition of organic substances; absorbed from the air by plants in photosynthesis. It is also a byproduct of burning fossil fuels and biomass, as well as land use changes and other industrial processes. It is the principal anthropogenic greenhouse gas that affects the earth's radiative balance.
charismatic megafauna	Large animal species with widespread popular appeal that environmental activists use to achieve conservation goals well beyond just those species.
clinical trials	A scientifically designed and executed investigation of the effects of a drug (or vaccine) administered to human volunteers. The goal is to define the safety, clinical efficacy, and pharmacological effects (including toxicity, side effects, incompatibilities, or interactions) of the drug.
cnidarian (the <i>c</i> is silent)	Multicellular animals comprising the phylum Cnidaria (silent <i>c</i>), including the stony corals (scleractinians) , soft corals (octocorals), anemones, sea fans, sea pens, hydroids, and jellyfish.
commercial fishing	Fishing for profit.
complementary goods and services	Inputs (usually built infrastructure or location characteristics) that allow a good or service to be used by complementing the ecological condition. For example, complementary goods and services that allow the presence of fishable fish to become an opportunity for recreational fishing will include aspects of site accessibility, such as road access, available parking and the presence of a fishing pier, all of which make fishing at the site possible and enhance enjoyment of the activity.
connectivity	A topological property relating to how geographical features are attached to one another functionally, spatially, or logically.
contingent valuation method (CVM)	A valuation method that estimates consumers' preferences by asking them how much they are willing to pay for a benefit (willingness-to-pay or WTP), or what they are willing to accept by way of compensation to tolerate a loss (willingness-to-accept or WTA).
coral	The regulatory definition is: species of the phylum Cnidaria, including: (a) all species of the orders Antipatharia (black corals), Scleractinia (stony corals), Gorgonacea (horny corals), Stolonifera (organpipe corals and others), Alcyonacea (soft corals), and Coenothecalia (blue coral), of the class Anthozoa; and (b) all species of the order Hydrocorallina (fire corals and hydrocorals) of the class Hydrozoa (16 U.S.C. 6401 et seq 2000). Current taxonomy has corals and sea anemones grouped into the class Anthozoa within the phylum Cnidaria. Anthozoa is divided into two subclasses, Octocorallia and Hexacorallia. Soft corals (including gorgonians) (order Alcyonacea) and blue corals (order Helioporacea) are under Octocorallia, and stony corals (order Scleractinia), black corals (order Antipatharia), and zoanthids (order Zoantharia) are under Hexacorallia. Neither fire corals nor hydrocorals are technically corals: they are classified as phylum Cnidaria, class Hydrozoa, order Capitata.
coral bleaching	The process in which a coral polyp, under environmental stress, expels its symbiotic zooxanthellæ from its body. The affected coral colony appears whitened (NOAA 2010).
coral cover	The covering of the sea floor by coral. It can be measured in square miles, square kilometers, or as a percentage of area with cover.
coral reef	Any reefs or shoals composed primarily of corals .
coral reef ecosystem	Coral and other species of reef organisms (including reef plants) associated with coral reefs, and the nonliving environmental factors that directly affect coral reefs, that together function as an ecological unit in nature.

cultural services	Cultural services are the nonmaterial benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experiences, including: cultural diversity, spiritual and religious values, knowledge systems (traditional and formal), educational values, aesthetic values, social relations, sense of place, cultural heritage values, and, recreation and ecotourism. In the lexicon of the ESRP, many of the elements in the MEA category (<i>e.g.</i> , spiritual and religious values) could be considered ecosystem services that are best defined specifically in terms of beneficiaries' ethical or cultural value systems, while the benefits derived from others (<i>e.g.</i> , certain aspects of recreation and ecotourism) might be valued in more generic terms. See also, provisioning services , regulating services , and supporting services (MEA 2005).
cyanobacteria	Photosynthetic aquatic bacteria that compose the phylum Cyanobacteria. They are often called blue-green algæ, but have no relationship to algæ . Cyanobacteria get their name from the bluish pigment phycocyanin, which they use to capture light for photosynthesis. They also contain chlorophyll <i>a</i> , the same photosynthetic pigment found in the chloroplasts of plants. Not all "blue-green" bacteria are blue; some common forms are red or pink, resulting from the pigment phycoerythrin (NOAA 2010).
D	
decision maker	Individual(s) or groups of people responsible for making choices or determining policy that impacts the functions, processes, and condition of ecological systems. Decisions may be local, regional, or national in scale.
demand	Generally, the amount of a particular good or service that a consumer or group of consumers will want to purchase at a given price. Demand for a good or service is determined by many different factors other than price, such as the price of substitutability and complementary goods and services. Along with supply, demand is one of the two key determinants of the market price.
direct use values	Economic values derived from direct use or interaction with a biological resource or resource system.
E	
ecological endpoint	A biophysical feature, quantity or quality that requires little further translation to make clear its relevance to human well-being (<i>i.e.</i> , "public-friendly" measurements). Ecological endpoints are the ecological inputs that, along with complementary goods and services inputs and demands by people, produce ecosystem services . For example, the abundance of watchable birds at a site is an ecological endpoint that, when combined with complementary inputs such as transportation infrastructure and demand by birders, produces the ecosystem service of recreational bird watching. Specified changes in ecological endpoints can be used in economic surveys to gauge people's willingness-to-pay for (or willingness-to-accept) increases or decreases in potentially valued ecosystem services, thereby providing quantitative information with which to evaluate decision/management mandates (adapted from Boyd [2007], Boyd & Banzhaf [2007], Wainger & Boyd [2009] and Wainger & Mazzotta [2009]).
ecological integrity	The capability of supporting and maintaining a balanced, integrated, adaptive community of organisms having a species composition, diversity, and functional organization comparable to that of natural habitat of the region (Frey 1975; Karr and Dudley 1981; Angermeier and Karr 1994; Karr et al. 1986).
ecological production function (EPF)	A description of the type, quantity and interactions of natural features required to generate outputs of natural products and services. For a simple example, the biophysical characteristics of a coastal wetland (flooding regimes, salinity, nutrient concentrations, plant species abundance, prey and predator abundances, etc.) can influence the abundance of a population of watchable wading shorebirds (the ecological endpoint). The outputs of ecological production functions, when combined with complementary goods and services and demand by humans, produce ecosystem goods and services (adapted from Wainger & Boyd [2009] and Wainger & Mazzotta [2009]).
ecological resilience	The capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks (Walker <i>et al.</i> 2004; Folke 2006).
ecosystem	A dynamic complex of plant, animal, and microorganism communities and their nonliving environment interacting as a functional unit (MEA 2009).
ecosystem functions	Physical, chemical, and biological processes that occur in ecosystems.
ecosystem goods and services	Outputs of ecological functions or processes that directly (final ecosystem service broadly based on Boyd & Banzhaf [2007]) or indirectly (intermediate ecosystem service) contribute to social welfare or have the potential to do so in the future. Some outputs may be bought and sold, but most are not marketed. Often abbreviated as ecosystem services (modified from EPA [2006]).
ecosystem service	Shorthand notation for an ecosystem good or service.

ecosystem structure	The individuals and communities of plants and animals of which an ecosystem is composed, their age and spatial distribution, and the nonliving natural resources present. The elements of ecosystem structure interact to create ecosystem functions.
effect on production (EoP)	An estimate of the difference in value of productive output before and after the impact of a threat or a management intervention.
emergy	The available energy of one kind previously used-up directly and indirectly to make a product or service. Emergy is expressed in its own unit, the emjoule, which connotes the energy of equivalent quality (<i>e.g.</i> , solar emjoules) used in the past to make a product or service (<i>e.g.</i> , a wetland), as compared with the energy (J) content of the product or service (Odum 1996).
enzymes	Proteins that catalyze (<i>i.e.</i> , increase the rates of) chemical reactions.
erosion	Wearing away of rock or soil by the gradual detachment of soil or rock fragments by water, wind, ice, and other mechanical, chemical, or biological forces.
ex-vessel price	The price received by a commercial fishing captain for the catch (Thayer <i>et al.</i> 2005).
F	
fauna	Animal life, especially the animals characteristic of, or endemic to, a region.
final ecosystem service	Components of nature directly enjoyed, consumed, or used to yield human well-being (Boyd & Banzhaf 2007).
financial analysis	Uses the observed current financial activities, revenues, costs, and financial flows in the economy from market-based uses of the reef (such as diving and snorkeling) to analyze the economic activity generated by use of an ecosystem good or service.
flora	Plant life, especially the plants characteristic of, or endemic to, a region, period, or special environment.
fore reef	The seaward edge of a reef that is fairly steep and slopes down to deeper water.
fringing reef	A type of coral reef that borders the shoreline , separated from shore by only a shallow lagoon or none at all.
functions	The physical, chemical, and biological processes that occur in ecosystems.
fungi	A kingdom separate from animals, bacteria, and plants consisting of usually multicellular, heterotrophic eukaryotes that have multinucleated cells enclosed within cell walls. Fungi obtain nutrition by decomposing dead and dying organisms and absorbing the decomposition products (NOAA 2010).
G	
gorgonian	An octocoral having a horny or calcareous branching skeleton (<i>e.g.</i> , sea fans and sea whips).
H	
habitat	A place where the physical and biological elements of ecosystems provide a suitable environment including the food, cover, and space needed for plant and animal livelihood (EPA 2009a).
hardbottom	Shallow and deep-water habitats with solid floor that can provide an attachment surface for sessile (nonmoving) organisms such as corals.
health	Health is the general condition of a person in all aspects, including physical and mental. The term health is also sometimes used to represent the condition of other organisms as well as ecosystems and social structures. Ecosystem health is an element of overall ecosystem integrity (Campbell 2000). Organism and ecosystem health usually implies normal functioning of the system and absence of disease as a dominant factor in the system. Ecosystem health can be thought of as functional integrity. Ecosystems also have structural integrity, which is related to the presence of all the normally expected elements of the system. Overall ecological integrity is a combination of the two (<i>i.e.</i> , wholeness and normal functioning). For example, a person with only one arm might be healthy but would not be structurally whole.
herbivore	An animal that feeds on plants (EPA 2010).
I	
index	A usually dimensionless numeric combination of scores derived from biological measures called metrics (EPA 2000).

indicator	Information based on measured data used to represent a particular attribute, characteristic, or property of a system (MEA 2009).
indigenous	A species is defined as native to a given region or ecosystem if its presence in that region is the result of only natural processes, with no human intervention. Every natural organism (as opposed to a domesticated organism) has its own natural range of distribution in which it is regarded as native. Outside this native range, a species may be introduced by human activity, after which it is referred to as an “introduced species” in such locales.
integrity	The extent to which all parts or elements of a system (<i>e.g.</i> , an aquatic ecosystem) are present and functioning.
intermediate ecosystem service	Components of nature that are not directly enjoyed, consumed or used to yield human well-being, but that are important for the production of final ecosystem services .
L	
landscape	An area of land that contains a mosaic of ecosystems, including human-dominated ecosystems. The term cultural landscape is often used when referring to landscapes containing significant human populations (MEA 2009).
M	
macroalgae	Macroscopic, multicellular algae commonly referred to as seaweed.
macroinvertebrate	Animals without backbones of a size large enough to be seen by the unaided eye and that can be retained by a U.S. Standard No. 30 sieve (28 meshes per inch, 0.595 mm openings) (EPA 2009a).
macrophyte	Large aquatic plants that may be rooted or non-rooted, vascular or algal (such as kelp), including submerged aquatic vegetation, emergent aquatic vegetation, and floating aquatic vegetation (EPA 2000).
mangrove	A general name for several species of halophyte (a plant able to grow in saline conditions) belonging to different families of plants (including trees, shrubs, a palm tree, and a ground fern) occurring in intertidal zones of tropical and subtropical sheltered coastlines and exceeding one-half meter in height. The term is applied to both the individual and the ecosystem (which is termed mangal). Mangroves provide protected nursery areas for juvenile reef fishes, crustaceans, and mollusks. They also provide a feeding ground for a multitude of marine species. Many organisms find shelter either in the roots or branches of mangroves. Mangrove branches are nesting areas for several species of coastal birds. The root systems harbor organisms that trap and cycle nutrients, organic materials and other important chemicals. Mangroves also contribute to higher water quality by stabilizing bottom sediments, filtering water, and protecting shorelines from erosion. They protect reefs from land runoff and sedimentation. Conversely, coral reefs protect mangroves and seagrasses from erosion during heavy storms and strong wave action. The nations with the largest mangrove areas include Indonesia (with 21% of global mangroves), Brazil (9%), Australia (7%), Mexico (5%), and Nigeria (5%). The global area of mangroves—150,000 km ² —is equivalent to the area of the state of Illinois, or half the area of the Philippines. About one-fifth of all mangroves are thought to have been lost since 1980, and although loss rates are declining, they are still three to four times higher than average global forest loss estimates (NOAA 2010).
Marine Protected Area (MPA)	Any area of the marine environment that has been reserved by federal, state, territorial, tribal or local laws or regulations to provide lasting protection to part or all of the natural or cultural resources within them. Familiar examples of U.S. MPAs include national parks, national wildlife refuges, national monuments, national marine sanctuaries, fisheries closures, critical habitat, habitat areas of particular concern, state parks, conservation areas, estuarine reserves and preserves, and numerous others. MPAs are sometimes called Marine Managed Areas (MMA). However, “marine protected area” is a broad, inclusive term that includes both multipurpose sites with some restrictions as well as the more restrictive “no-take marine reserves” (NOAA 2010).
marine reserve	An area in the ocean that is protected from uses that remove animals, plants, and other organisms, or alter their habitats (NOAA 2010).
marine tourism	Includes those recreational activities that involve travel away from one’s place of residence and that have as their host or focus the marine environment (where the marine environment is defined as those waters that are saline and tide-affected) (Orams 1999).
metabolites	A substance that takes part in the process of metabolism, which involves the breakdown of complex organic constituents of the organism’s body with the liberation of energy for use in bodily functioning. The various compounds that take part in, or are formed by, these reactions are called metabolites (NOAA 2010).
model	A physical, mathematical, or logical representation of a system of entities, phenomena, or processes; an abstracted view of a complex reality.
molecular probe	Chemicals that are used to explore and elucidate biochemical structures and processes at the cellular and molecular levels.

Montastraea A genus of hard (stony) coral (**octocoral**) that includes the boulder coral and the great star coral (NOAA 2010).

N

National Account Systems (NAS) NAS provide a complete and consistent conceptual framework for measuring the economic activity of a nation. NAS are derived from a wide variety of source data including surveys, administrative and census data, and regulatory data. Most countries have a national statistical office or central bank that compiles, integrates, harmonizes, and publishes the data. NAS include a number of aggregate measures (*e.g.*, gross domestic product [GDP], disposable income, savings, and investment) and other information (*e.g.*, input-output tables that show how industries interact with each other in the production process).

natural feature A readily observable characteristic of natural systems such as type of vegetation and arrangement of land use (Wainger & Boyd 2009).

nature and wildlife watching The practice of observing nature and wildlife (*e.g.*, birds, dolphins, fish, manatees, turtles, whales) in their natural habitat.

nonmarket value Value recognized by people but not usually expressed in prices because the thing either is not currently, or cannot be, traded in markets.

nonuse value The value people hold for a service that they do not directly use. (Sometimes referred to as “passive use value”.) Early literature in environmental economics split nonuse value into three components: existence value, option value, and bequest value. Nonuse values are theoretically distinct from use values, although the boundary between use and nonuse values is often fuzzy.

North American Industry Classification System (NAICS) The standard used by Federal statistical agencies in classifying business establishments for the purpose of collecting, analyzing, and publishing statistical data related to the U.S. business economy. NAICS was developed under the auspices of the Office of Management and Budget (OMB), and adopted in 1997 to replace the Standard Industrial Classification (SIC) system. It was developed jointly by the U.S. Economic Classification Policy Committee (ECPC), Statistics Canada, and Mexico’s Instituto Nacional de Estadística y Geografía, to allow for a high level of comparability in business statistics among the North American countries (U.S. Census Bureau 2010).

nudibranch A marine gastropod mollusk that has no protective covering as an adult. Gills or other projections on the dorsal surface carry on respiration. They comprise the clade Nudibranchia (formerly a suborder).

nutraceuticals A term that combines the words *nutrition* and *pharmaceutical* and is a food or food product that provides health and medical benefits, including the prevention and treatment of disease (Kalra 2003).

O

octocoral Aquatic organisms formed of colonial polyps with 8-fold symmetry. They comprise the subclass Octocorallia. Examples include blue coral, soft corals, and **gorgonians** (sea fans and sea whips). See also **coral**.

opportunity cost The cost of something in terms of an opportunity forgone (and the benefits that could be received from that opportunity), or the most valuable forgone alternative (*i.e.*, the second best alternative).

overfishing Occurs when fishing activities reduce fish stocks below a level that is biologically or economically sustainable.

P

patch reef Small circular or irregular reefs that arise from the floor of lagoons, behind **barrier reefs**, or within an **atoll**.

pharmaceutical Biologically active chemicals used to treat diseases, disorders, and illnesses (NOAA 2010).

preclinical stage of testing Research (sometimes using animal models) to assess whether a candidate drug, procedure, or treatment is likely to be of therapeutic value in humans. Preclinical studies take place before any testing in humans is done.

presence of reef Quantifies whether or not an offshore reef is present near the coastal area of interest.

protein A large complex molecule made up of one or more chains of amino acids. A typical protein contains 200–300 amino acids, but some are much smaller and some much larger (*e.g.*, titin, a protein found in skeletal muscle, contains approximately 27,000 amino acids in a single chain). Proteins perform a wide variety of essential activities in cells, including: (1) they largely form the physical structure of cells and cellular matrices; (2) proteins are enzymes, which are the catalysts for all biochemical reactions; (3) the transport of materials in body fluids depends on proteins; (4) the receptors for hormones and other signaling molecules are proteins; (5) motion and locomotion of cells and organisms depends on contractile proteins; (6) the transcription factors that turn genes on and off are proteins; and, (7) proteins are an essential nutrient for heterotrophs. The activities of cells and organisms are largely dependent on the activities of their proteins (NOAA 2010).

provisioning services A category of **ecosystem services** as described by the *Millennium Ecosystem Assessment*. Provisioning services (ecosystem goods) are the products obtained from ecosystems, including: food; fiber; fuel; genetic resources; biochemicals, natural medicines, and pharmaceuticals; ornamental resources; and, fresh water. In the lexicon of the ESRP and when quantified appropriately, elements in the MEA provisioning services category could be considered ecological endpoints. Also see the other MEA categories of **cultural services**, **regulating services**, and **supporting services** (MEA 2005).

R

recreation “Refreshment of strength or spirits after work; also: a means of refreshment or diversion” (Merriam Webster 2010). Recreational activities are enjoyed by both tourists and residents of a given geographic location. However, the common practice of economists is to differentiate between tourism and recreation based upon the source of demand.

recreational (sport) fishing Fishing for pleasure or competition. It is included as a component of tourism and recreation.

reef break A wave that breaks over a coral reef or a rock seabed.

reef continuity The uninterrupted distribution the reef, namely the absence of large gaps or fragmentation due to degradation or coral mining.

reef crest The sharp break in slope, or peak in **reef height** at the seaward edge of the **reef flat**.

reef depth The distance from the ocean surface to the top of the reef; may be an assumed or fixed value in simulation models, or an average value from field observations for the reef under consideration.

reef distance The distance between the **reef crest** and the edge of the **shoreline**; essentially the width of the lagoon.

reef flat The relatively shallow, flat expanse of coral reef between the **reef crest** and the **shoreline**.

reef height The distance from the top of the reef to its base; may be an assumed or fixed value in simulation models, or an average value from field observations for the reef under consideration.

reef roughness The bottom drag coefficient that quantifies friction and may be approximated in field studies by variability in colony height, or other measures of topography, along the **reef flat**.

reef slope The angle, from gradual to steep, of the reef front where offshore waves are first encountered; may be an assumed or fixed value in simulation models, or an average value from field observations for the reef under consideration.

reef type Describes the general structure of the reef and its relationship to the **shoreline**, including **fringing reefs** that border the shoreline, **barrier reefs** that are separated from shore by a deep lagoon, **atoll reefs** that form a circular barrier around an island, and **patch reefs** that are small, isolated reef outcrops.

reef width The length of the **reef flat**, the flat expanse of reef from where offshore waves first crest over the reef to the edge closest to the **shoreline**; may be an assumed or fixed value in simulation models, or an average value from field observations for the reef under consideration.

refugia An area or refuge where biota can live and breed without suffering excess predation from other organisms.

regulating services A category of **ecosystem services** as described by the *Millennium Ecosystem Assessment*. Regulating services are the benefits obtained from the regulation of ecosystem processes, including: air quality regulation, climate regulation, water regulation, erosion regulation, water purification and waste treatment, disease regulation, pest regulation, pollination, and natural hazard regulation. In the lexicon of the ESRP, elements in the MEA regulating services category could be considered ecological processes that can produce ecological endpoints, that when combined with complementary goods and services and demand by humans, could produce ecosystem goods and services. See also the other MEA categories of **cultural services**, **provisioning services**, and **supporting services** (MEA 2005).

replacement costs The amount that an entity would have to pay to replace an asset at the present time.

residents People who live at a particular place for a prolonged period (Leeworthy 2002; Princeton WorldNet Glossary 2010a).

resilience The ability of a system to absorb or recover from disturbance and change, while maintaining its **functions** and **services** (Carpenter *et al.* 2001). For example, a reef’s ability to recover from a **coral bleaching** event.

revealed preference The use of the recovery of expenditure to “reveal” the preference of a consumer or group of consumers for the bundle of goods they purchase.

risk assessment	The determination of quantitative or qualitative value of risk related to a concrete situation and a recognized threat (also called hazard).
rugosity	Describes the amount of “wrinkling” or roughness of the reef profile. It is an index of substrate complexity. Areas of high complexity are likely to provide more cover for reef fishes and more places of attachment for algæ, corals, and various sessile invertebrates (2010).
S	
salient	A type of beach morphology in which sediments are deposited and accumulate in the lee of a breakwater structure, growing seaward from the shoreline to form a bell-shaped structure.
scleractinians	Corals that have a hard limestone skeleton and belong to the order Scleractinia. See stony coral .
scuba	An apparatus carried by a diver that includes a tank holding a mixture of oxygen and other gases, used for breathing underwater. Scuba is an acronym for “self-contained underwater breathing apparatus”.
seagrass	A flowering plant, complete with leaves, a rhizome (an underground, usually horizontally-oriented stem), and a root system. They are found in marine or estuarine waters. Most seagrass species are located in soft sediments. However, some species are attached directly to rocks with root hair adhesion. Seagrasses tend to develop extensive underwater meadows (NOAA 2010).
seascape	A mosaic of interconnected coastal and marine ecosystems (coral reefs, seagrass meadows, and mangrove forests).
secondary metabolite	A substance produced by an organism that seemingly has no direct role in the organism’s metabolism, though they are often produced via pathways that are derived from primary metabolic pathways. It is believed that they are created because they confer some evolutionary advantage, particularly in sessile (nonmoving) organisms. Most often, secondary metabolites are used by the organism in intraspecies or interspecies interactions usually related to defense or signaling (NRC 1999; Croteau <i>et al.</i> 2000; Seigler 2002; Wink 2003).
services	The benefits that human populations receive from functions that occur in ecosystems.
shoreline	The intersection of the land, including man-made waterfront structures, with the water surface. The shoreline depicted on NOAA National Ocean Service (NOS) maps and charts represents the line of contact between the land and a selected water elevation. In areas affected by tidal fluctuations, the shoreline is the interpreted mean high water line. In confined coastal water of diminished tidal influence, the mean water level line may be used. In nontidal waters, the line represents the land/water interface at the time of survey. In areas where the land is obscured by marsh grass, cypress or similar marine vegetation, the actual shoreline can not be accurately represented. Instead, the outer limit line of the vegetation area is delineated (where it would appear to the mariner as the shoreline), in this case, it is referred to as the apparent shoreline (NOAA 2010).
shoreline protection	The ability of reefs to attenuate offshore wave energy, to provide sheltered nearshore waters, and to protect coastlines from erosion, flooding, and storm damage.
snorkeling	The practice of swimming while equipped with a diving mask, a shaped tube called a snorkel, and fins.
species	A category of taxonomic classification, ranking below a genus or subgenus and consisting of related organisms capable of interbreeding. Also refers to an organism belonging to such a category.
species diversity	The number of different species in an area and their relative abundance (NOAA 2010).
species richness	The number of species in an area or biological collection (NOAA 2010).
sponge	A sessile (nonmoving), multi-cellular marine animal whose body consists of a jelly-like endoskeleton sandwiched between two layers of cells. Sponges comprise the phylum Porifera.
stony coral	Corals (comprising the order Scleractinia) that form hard, calcium carbonate skeletons. Examples include the brain corals, fungus or mushroom corals, staghorn corals, elkhorn corals, table corals, flower pot corals, bubble corals, and lettuce corals. These corals are largely responsible for the physical form of coral reefs.
subsistence fishing	Fishing for survival. Fishing for food (consumed by the local group of people who do the fishing), not for commercial sale.

supporting service	A category of ecosystem service as described by the <i>Millennium Ecosystem Assessment</i> . Supporting services are those that are necessary for the production of all other ecosystem services. They differ from provisioning services , regulating services , and cultural services in that their impacts on people are often indirect or occur over a very long time, whereas changes in the other categories have relatively direct and short-term impacts on people. (Some services, like erosion regulation, can be categorized as both a supporting service and a regulating service, depending on the time scale and immediacy of their impact on people.) Examples of supporting services include: soil formation, photosynthesis, primary production, nutrient cycling, and water cycling. See also the other MEA categories of cultural services, provisioning services, and regulating services (MEA 2005)
surf break	A permanent obstruction such as a reef, headland, bombora , rock, or sandbar that causes waves to break (Silimalis 2007).
surfing	The sport of riding a surfboard toward the shore on the crest of a wave.
sustainability	A characteristic or state whereby the needs of the present and local population can be met without compromising the ability of future generations or populations in other locations to meet their needs (MEA 2009).

T

tombolo	A type of beach morphology in which sediments are deposited and accumulate in the lee of a breakwater structure, growing seaward from the shoreline until they are connected to the structure.
topography	The physical features of a surface area including relative elevations and the position of natural and man-made (anthropogenic) features.
total economic value (TEV)	The sum of the change in all relevant use values and nonuse values for ecosystem goods and services produced by a given change in the ecosystem (<i>i.e.</i> , the full social benefits). This is distinct from the “total value” of an ecosystem, which is the value of the entire system (<i>e.g.</i> , the value of an entire wetland), but instead is the value of a marginal change to that ecosystem that results from some action.
Tourism Satellite Account (TSA)	A statistical accounting framework in the field of tourism that measures goods and services according to international standards for concepts, classifications, and definitions, that allow valid comparisons from country to country in a consistent manner. A complete TSA contains detailed production accounts of the tourism industry and their linkages to other industries, employment, capital formation, and additional non-monetary information on tourism.
tourists	People who “travel to and stay in places outside their usual environment for more than twenty-four (24) hours and not more than one consecutive year for leisure, business and other purposes not related to the exercise of an activity remunerated from within the place visited” (UNWTO 1995).
travel cost	A valuation method that uses the travel time or travel costs as a proxy “total entry fee”, and therefore, a person’s willingness-to-pay for visiting a particular tourist location.
tunicate	Members of the subphylum Tunicata (also called Urochordata); a group of underwater sac-like filter feeders with incurrent and excurrent siphons that is classified within the phylum Chordata. While most tunicates live on the ocean floor and are commonly known as sea squirts (ascidians) and sea pork, others—such as salps, doliolids and pyrosomes—live above in the pelagic zone as adults.

V

valuation	The process of expressing a value for a particular good or service in a certain context (<i>e.g.</i> , decision-making) usually in terms of something that can be counted, often money, but also through methods and measures from other disciplines (sociology, ecology) (MEA 2009).
value	Generally, the worth, merit, or desirability of something. It can be expressed quantitatively (for example, in monetary terms) or qualitatively. Specifically with respect to ecological benefits, a quantitative or qualitative description of those benefits. Using this definition, the value of an ecosystem might be defined in terms of its beauty, its uniqueness, its irreplaceability, its contribution to life support functions or commercial or recreational opportunities, or its role in supporting wildlife or reducing environmental or human health risks, or providing many other services that benefit humans (Ecosystem Valuation 2009).

W

wetlands A type of ecosystem, generally occurring between upland and deepwater areas, that provides many important functions including fish and wildlife habitat, flood protection, erosion control, water quality maintenance, and recreational opportunities. A wetland is an area that is covered by water or has water-saturated soil during a portion of the growing season. In general, it is often considered the transitional area between permanently wet and dry environments. The Ramsar Convention on Wetlands identifies the following marine/coastal wetlands: permanent shallow marine waters; marine subtidal aquatic beds (kelp beds, sea-grass beds, tropical marine meadows); coral reefs; rocky marine shores (including rocky offshore islands and sea cliffs); sand, shingle or pebble shores; estuarine waters; intertidal mud, sand or salt flats; intertidal marshes (includes salt marshes, salt meadows, saltings, raised salt marshes); intertidal forested wetlands (includes mangrove swamps, nipah swamps, and freshwater tidal brackish and freshwater marshes); coastal brackish/saline lagoons; coastal freshwater lagoons; and marine and coastal karst and other subterranean hydrological systems (RAMSAR 2001).

willingness-to-accept (WTA) The amount of money (or other goods) that a person must be paid to accept the loss of something else.

willingness-to-pay (WTP) The amount of money (or other goods) that a person is willing to give up to get something else.

Z

zooplankton Free-floating or drifting animals with movements determined by the motion of the water.

zooxanthellæ A group of dinoflagellates living endosymbiotically in association with one of a variety of invertebrate groups (e.g., corals). In corals, they provide carbohydrates through photosynthesis, which are used as one source of energy for the coral polyps. They also provide coloration for the corals and receive a sheltered habitat in return. (NOAA 2010).

Bibliography

- 16 USC 6401 *et seq.* 2000. The Coral Reef Conservation Act.
- Angermeier PL and Karr JR. 1994. Biological integrity versus biological diversity as policy directives: Protecting biotic resources. *BioScience*, **44**(10):690-697.
- Boyd JW and Banzhaf S. 2007. What are ecosystem services? The need for standardized environmental accounting units. *Ecological Economics*, **63**: 616-626.
- Boyd JW. 2007. The endpoint problem. *Resources*, **165**:26-28.
- Campbell DE. 2006. Using Energy Systems Theory to define, measure, and interpret ecological integrity and ecosystem health. *Ecosystem Health*, **6**(3):181-204.
- Carpenter S, Walker B, Anderies JM and Abel N. 2001. From metaphor to measurement: Resilience of what to what? *Ecosystems*, **4**:765-781.
- Croteau R, Kutchan TM and Lewis NG. 2000. Natural Products (Secondary Metabolites). In: Buchanan BB, Gruissem W and Jones R (eds). *Biochemistry & Molecular Biology of Plants*. Rockville (MD): American Society of Plant Physiologists. Chapter 24, pp. 1250-1318.
- Ecosystem Valuation. Glossary. 2009. <<http://www.ecosystemvaluation.org/glossary>>
- Folke C. 2006. Resilience: The emergence of a perspective for social-ecological system analyses. *Global Environmental Change*, **16**(3):253-267.
- Frey D. 1975. Biological integrity of water: An historical perspective. In: Ballentine RK and Guarraia LJ (eds). *The Integrity of Water*. Washington, DC: U.S. Environmental Protection Agency (EPA), pp. 127-139.
- Kalra EK. 2003. Nutraceutical - Definition and Introduction. *AAPS PharmSci.*, **5**(3):27-28. Published online 2003 September 3. doi: 10.1208/ps050325.
- Karr JR and Chu EW. 1999. *Restoring life in running waters: Better biological monitoring*. Washington, DC: Island Press, 206 pp.
- Karr JR and Dudley DR. 1981. Ecological perspective on water quality goals. *Environmental Management*, **5**:55-68.
- Karr JR, Fausch KD, Angermeier PL, Yant PR and Schlosser IJ. 1986. Assessing biological integrity in running waters, a method and its rationale. Illinois Natural History Survey, Special Publication 5.
- Leeworthy VR. 2002. Economic impact of tourist and resident uses of coastal resources in the Florida Keys: Survey methods and impact assessment methodology. In: Letson D and Milon JW (eds), *Florida Coastal Environmental Resources*. Florida Sea Grant, SGR 124.
- Merriam-Webster. 2010. Dictionary. <<http://www.merriam-webster.com/dictionary/recreation>>
- Millennium Ecosystem Assessment (MEA). 2005. *Ecosystems and Human Well-Being*. Washington, DC: Island Press. Available from <<http://www.millenniumassessment.org/documents/document.356.aspx.pdf>>
- Millennium Ecosystem Assessment (MEA). 2009. Glossary. <<http://www.millenniumassessment.org/documents/document.59.aspx.pdf>>
- National Oceanic and Atmospheric Administration (NOAA). 1999. Discounting and treatment of uncertainty in natural resource damage assessment. Silver Spring (MD): Damage Assessment and Restoration Program, Damage Assessment Center. Technical Paper 99-1.
- National Oceanic and Atmospheric Administration (NOAA). 2010. *Coral Reef Identification System: Glossary of Terminology*. <<http://coris.noaa.gov/glossary/>>

- National Research Council (NRC). 1999. *From Monsoons to Microbes. Understanding the Ocean's Role in Human Health*. Washington, D.C.: National Research Council, Commission on Geosciences, Environment, and Resources, Ocean Studies Board, Committee on the Ocean's Role in Human Health. ISBN 0-309-06569-0. 166 pp.
- Odum HT (ed). 1996. *Environmental Accounting: Energy and Environmental Decision Making*. New York: John Wiley.
- Orams M. 1999. *Marine Tourism – Development, Impacts, and Management*. New York: Routledge.
- Princeton WorldNet Glossary. 2010a. Residents. <<http://wordnetweb.princeton.edu/perl/webwn?s=resident>>
- Princeton WorldNet Glossary. 2010b. Surfing. <<http://wordnetweb.princeton.edu/perl/webwn?s=surfing>>
- Ramsar Convention Bureau (2001). *The Ramsar Convention on Wetlands* <<http://www.ramsar.org>>
- Seigler DS. 2002. *Plant Secondary Metabolism*. Norwell, MA: Kluwer Academic Publishers. 2nd printing. ISBN 0-412-01981-7.
- Silmalis L. 2007. Surf break names recognized. *The Daily Telegraph*, April 08, 2007.
- Thayer GW, McTigue TA, Salz RJ, Merkey DH, Burrows FM and Gayaldo PF (eds). 2005. Science-Based Restoration Monitoring of Coastal Habitats. Volume Two: Tools for Monitoring Coastal Habitats. NOAA Coastal Ocean Program, Decision Analysis Series No. 23, Volume 2.
- U.S. Census Bureau. 2010. *North American Industry Classification System (NAICS)*. <<http://www.census.gov/eos/www/naics/>>
- U.S. Environmental Protection Agency (EPA). 2000. Estuarine and Coastal Marine Waters: Bioassessment and Biocriteria Technical Guidance. EPA-822-B-00024. <<http://www.epa.gov/waterscience/biocriteria/States/estuaries/estuaries.pdf>>
- U.S. Environmental Protection Agency (EPA). 2000. Guidelines for Preparing Economic Analyses. EPA 240-R-00-003. Office of the Administrator, Washington, DC. <<http://yosemite.epa.gov/ee/epa/eed.nsf/webpages/Guidelines.html#download>>
- U.S. Environmental Protection Agency (EPA). 2006. Ecological Benefits Assessment Strategic Plan. EPA-240-R-06-001. Office of the Administrator, Washington, DC. <<http://yosemite.epa.gov/ee/epa/eed.nsf/webpages/EcologBenefitsPlan.html>>
- U.S. Environmental Protection Agency (EPA). 2009a. Biocriteria Glossary. <<http://www.epa.gov/waterscience/biocriteria/glossary.html>>
- U.S. Environmental Protection Agency (EPA). 2010. Terms of Environment: Glossary.
- Wainger L and Mazzotta M. 2009. Proposed framework for quantifying ecosystem services and their economic benefits – Guidance for creating ecological endpoints. ESRP Working Paper Series #2.
- Wainger LA and Boyd JW. 2009. Valuing ecosystem services. In: McLeod K and Leslie H (eds). *Ecosystem-Based Management for the Oceans*. Washington, DC: Island Press.
- Walker B, Holling CS, Carpenter SR and Kinzig A. 2004. Resilience, adaptability and transformability in social–ecological systems. *Ecology and Society*, 9(2):5. [online] <<http://www.ecologyandsociety.org/vol9/iss2/art5/>>
- Wikipedia. 2010. Underwater Photography. <http://en.wikipedia.org/wiki/Underwater_photography>
- Wink M. 2003. Evolution of secondary metabolites from an ecological and molecular phylogenetic perspective. *Phytochemistry*, **64**(1):3-19.
- World Tourism Organization (UNWTO). 1995. Collection of Tourism Expenditure Statistics. Technical Manual No. 2, 14 pp.



Printed on 100% recycled/recyclable paper
with a minimum of 50% post-consumer
fiber using vegetable-based ink.



PRESORTED STANDARD
POSTAGE & FEES PAID
EPA
PERMIT NO. G-35

Office of Research and Development (8101R)
Washington, DC 20460

Official Business
Penalty for Private Use
\$300