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A Paradigm Shift for Fisheries Management to Enhance Recovery, Resilience, and Sustainability of Coral Reef Ecosystems in the Red Sea

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Introduction

Shallow water coral reefs are found in tropical areas, between the Tropics of Cancer and Capricorn to a maximum of about 50–75 m depth, in environments with suitable temperatures, salinity, light, nutrients, sediment, hydrodynamics, and seawater carbonate chemistry. Coral reefs are estimated to cover from 284,300 km^2 (Spalding et al. 2001) to about 920,000 km^2 when associated habitats are included in calculations (Costanza et al. 1997), with 91% of this area in the Indo-Pacific. The Red Sea, which is considered part of the Indo-Pacific region, contains the most biologically diverse reef communities outside of the Southeast Asia coral triangle; it shares many of the species found in other Indo-Pacific locations and also contains approximately 10% species level endemism (DeVantier et al. 2000). The Kingdom of Saudi Arabia has the largest area of coral reefs (6,660-km^2 reef area) in the Red Sea, extending more than 1,840 km from the Gulf of Aqaba in the north to the Farasan Islands, north of Yemen, in the south.

Coral reefs are the most complex ecosystem in the marine environment. This complexity is expressed in both the variety of interconnected benthic habitats and a vast array of associated biota, with representatives from 32 of the 34 described animal phyla. At least one-third of all known marine fishes spend at least some portion of their lives in coral reef habitats (Sale 2002); at least 4,000 Indo-Pacific species, 1,400 western Atlantic species, and about 1,100 eastern Atlantic and eastern Pacific species of reef fish have been described (Sale 1991; Spalding et al. 2001; Harmelin-Vivien 2002). The high

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diversity is largely due to the heterogeneous nature of coral reef habitat, which can accommodate large size-ranges of reef fishes and numerous functional niches in relatively small areas.

Coral reefs are also one of the few ecosystems that are built upon biogenic substrates created by the dominant organisms found on reefs. The reef substrate consists of limestone originating primarily from the skeletons of stony corals and crustose coralline algae, which has undergone significant modifications in form and area on relatively short time scales. Through grazing activities, bioerosion, and physical breakage during storms, coral skeletons are progressively eroded to produce rubble and sand. Other organisms and a host of chemical, biological, and physical processes cement this material together to form a durable reef substrate, resulting in intricate structures that have enormous surface heterogeneity at a wide variety of spatial scales (Choat and Bellwood 1991).

While the diversity of reef fishes is influenced by the complexity of the reef habitat created by corals, fishes are also an important, dynamic component of this unique ecosystem. Through interactions at virtually all trophic levels, coral reef fishes modify the reef community structure and help maintain the health of the associated habitat forming corals, and they are major conduits for the movements of energy and nutrients into, within, and out of the reef ecosystem (Hobson 1991; Bellwood and Wainwright 2002). The ecological importance of coral reef fishes also extends beyond the boundaries of the coral habitat. Many reef fishes that are pelagic piscivores and planktivores often feed, and become prey, far away from the coral reef, and the pelagic egg, larval, and juvenile stages form a vast prey resource for predators in oceanic waters.

Importance of Coral Reefs

Coral reefs are a rare but critically important resource. Although they occupy less than 1.2% of the world's continental shelf area and only 0.09% of the total area of the world's ocean, at least 109 countries, territories, and states are directly dependent on the resources and services they provide (Birkeland 1997; Spalding et al. 2001). Many economies are dependent on their products, including sources of protein, biomedical compounds and traditional medicines, and raw materials for construction, as well as their value in terms of employment, recreation, coastal tourism, and coastal protection from storm damage and erosion. Coral reefs are a significant part of many countries natural heritage and are also of great value to the world overall, as they are hotspots of marine biodiversity. Costanza et al. (1997) estimated reef ecosystems globally provide US$375 billion each year from living resources and ecosystem services. Nevertheless, the value of reefs is dependent on their continued functioning as ecosystems.

Human and Natural Threats

Corals reefs in the Red Sea, like much of the rest of the world's reefs, are being rapidly degraded by a host of human and natural factors. These reefs exhibit striking contrasts in their biology and environmental attributes and in the degree of human influence. They include some of the most northerly reef communities, which are subjected to harsh climatic conditions such as unusual temperature extremes, some of the highest salinities known to occur in tropical seas, and high levels of solar radiation. Much of the Red Sea is characterized by narrow coastal fringing reefs that extend tens of meters from shore before dropping into deep water, yet several locations in north and central Red Sea contain extensive sea grass beds, offshore reef habitats, and mangroves, all of which are integrally linked. The Red Sea contains a wide range of reef morphologies, such as barrier reefs, patch reefs, ridge reefs, atolls, pinnacles, pillars, and spur and groove structures, as well as algal-derived limestone structures. These habitats often support unique species assemblages, with at least 300 species of scleractinian corals and 1,400 species of reef fish identified throughout the region thus far (DeVantier et al. 2000; Kotb et al. 2004).

Red Sea coral reefs have supported artisanal fishery harvests for thousands of years (NCWCD 1995), and most of these fisheries were considered sustainable, at least partially due to the low density of populations living along the coasts (Behairy et al. 1992). In the past few decades, increased human settlement in coastal areas and the resultant increase in artisanal and commercial fishing activities to support local consumption, and to supply a growing international trade in coral reef species and products, have led to depletion of many commercially valuable species. Threats from overfishing and destructive fishing practices have direct and indirect impacts to trophic structure and ecological function. Although large parts of the Red Sea coastline are still undeveloped, other areas face increasing levels of threat from industrial and urban development, untreated sewage, sedimentation associated with land reclamation, dredging, mining, and other industrial activities. Desalinization plants are particularly problematic as they are critical for the survival of humans in this region but they release warm, highly saline water and toxins such as chlorine. The region encompasses the world's largest oil and natural gas production area and exporter, and one of the largest global shipping routes, with substantial risks from oil pollution, ship groundings, and ballast water discharges (Dicks 1987; Sheppard et al. 1992).

Over the past decade, reefs worldwide have also witnessed an increased frequency of large-scale disturbances associated with climate change, including episodes of mass bleaching, disease outbreaks, plagues of coral-eating predators, and more severe hurricanes (Harvell et al. 2007; Baker et al. 2008; Rotjan and Lewis 2008). When compounded by anthropogenic stresses, dramatic, long-lasting changes in community composition and structure have occurred (Hughes 1989, 1994; Knowlton 1992; Aronson et al. 2004; McClanahan et al. 2007). Persistence of reefs as coral-dominated systems and continued functioning after large, stochastic perturbations depends on four primary factors: the extent of damage, synergistic impacts of anthropogenic and natural stressors, the health and resilience of reef building corals, and the communities' capacity for recovery (Smith et al. 2008). Ecological recovery and rapid restoration of normal reef processes has been documented in systems with intact functional groups and a high degree of spatial heterogeneity and connectivity (Nystrom et al. 2008), while degraded, overfished reefs fail to recover even after several decades of protection.

Conservation Initiatives

Given the recent expansion of dive tourism in the Red Sea and a greater recognition of the importance of coral reef ecosystems for socioeconomic development, new approaches to enhance management and conservation are being considered (Kotb et al. 2008). The recent Regional Action Plan for the Conservation of Coral Reefs in the Red Sea and Gulf of Aden (encompasses all countries except Eritrea; PERGSA 2003) defines priority actions for the conservation and sustainable development of coral reefs pertaining to six major objectives: (1) integrated coastal zone management; (2) education and awareness; (3) marine-protected areas (MPAs); (4) ecologically sustainable reef fisheries; (5) impacts of shipping and marine pollution; and (6) research, monitoring, and economic valuation. The overall objective of this plan is to maintain the intrinsic biodiversity, ecological integrity, and esthetic beauty of coral reefs while ensuring their continued use and ecosystem services (Gladstone 2000, 2002; Rouphael and Al-Yami 2000a; Kotb et al. 2008). A principle embedded in Islam, the recognition that there are limits to resource exploitation (Child and Grainger 1990), may help guide this and other national and regional development plans and various environmental agreements (Price et al. 1998). These commitments are particularly important in the Red Sea where transboundary resources are shared by eight countries and utilized by many others.

Information Needed to Address Management Needs

The main purpose of this chapter is to summarize the knowledge and tools needed to (1) promote sustainable use of coral reef resources, and (2) provide insurance against catastrophic declines of coral reefs and losses of ecosystem services that may be induced by large-scale global disturbances. Recommendations are presented on place-based ecosystem management approaches and the science needed to identify and implement these measures. Coral reefs off the Saudi Arabian Red Sea coast are used as a case study, with information presented on the types of fisheries, existing management approaches, and the status, recent changes, and threats to associated coral reefs. Fish are examined in terms of their functional role and as indicators of fishing pressure. The importance of corals and other benthic organisms as habitat and ecosystem engineers is discussed, along with the types of survey data needed to characterize their population dynamics and develop predictive capabilities of potential climate-related impacts. Other key factors and processes that can help ensure the viability of fisheries resources are also discussed in the context of maximizing the carrying capacity and resilience of coral reefs.

Status of Reef-Associated Fisheries of the Red Sea

Red Sea fisheries are diverse due to the broad variety of species available for exploitation (Sheppard et al. 1992). The productivity of fisheries varies widely throughout the region but is generally highest wherever there are high levels of nutrient input. Areas with seasonal upwelling of nutrients—rich cool water, such as that found in the southern Red Sea—result in high water column productivity, high yields of pelagic fishes, and productive demersal crustacean and mollusk fisheries. Broad, shallow shelf areas also support most of the reef fish fisheries. Although coral reefs are highly productive ecosystems, commercial exploitation was historically limited due to their topography, which prevents access of large boats and the use of trawls, seines, and large nets. Most reef fisheries are artisanal, yet there has been a move towards greater commercialization, especially in Saudi Arabia, and the introduction of new, destructive gear types.

The main methods used to catch reef-associated fishes are hook and line, traps, trammel nets, gill nets, and spears; throw nets are also used to collect baitfish, and bottom-set longlines may be employed. Catch composition varies by fishing method and season, with considerable effort directed at large predators that migrate to mass spawning sites. Despite the large variety of species landed, a small number make up the bulk of the catch. For instance, 3 of the 13 species of parrotfish (family Labridae) in the Red Sea dominate landings because they feed over sandy bottoms adjacent to coral reefs and are easily caught in trammel nets and small gill nets. Reef-associated predators from Egypt are dominated by four species of grouper (Serranidae) and two species of emperor (Lethrinidae) (Sheppard et al. 1992). Reef fisheries throughout the Red Sea historically targeted predatory piscivores, although total productivity of these stocks is relatively low (e.g., 0.4 metric tons [mt]/km^2 per year; Kedidi 1984). More than 25 years ago, the fishery was already thought to be fully exploited and production could not be increased above these levels. Nevertheless, as piscivores have been depleted, increased effort has been directed towards species lower down the food chain, such as herbivores and planktivores (Sheppard et al. 1992).

Types of Fisheries

In Saudi Arabia, the Ministry of Agriculture completes an annual assessment of fisheries based on voluntary reporting by the industrial, investment, and artisanal sectors. Investor and artisanal fisheries are pooled in fishery reports as "traditional fisheries." Data are compiled on numbers of foreign and national fishermen, size of the fleet, and gear type; landings are reported for four regions (industrial fisheries) or five regions (traditional fisheries) for up to 70 species or species complexes of fishes and six invertebrates, with data pooled into 35 groups for regional summaries.

There was a substantial increase in the size of both industrial and traditional fishery sectors since the 1980s; landings dropped significantly in 1995 from that reported during the previous decade, but have been relatively stable since 2003 (Figure 1A; Sheppard et al. 1992). Between 1988–2006, industrial vessels increased from 30 to more than 160 while smaller boats used for traditional and investor fisheries increased from about 3,100 to 10,000 (Figure 1B; MFD 2008). The investment fishery is controlled by a small number of Saudi investors (<45), with about 10% (1,764) of the registered fishermen being Saudi Arabia nationals and 90% (>16,000) consisting of foreign fishery workers. Foreign fishermen are primarily from Bangladesh (49%), India (18%), Egypt (15%), Philippines (11%), and Yemen (3%), with 3% total from Sri Lanka, Turkey, and Burma. Most fishermen are 20–40 years in age; 8% are 60 years or older.

As of 2006, artisanal and investor fisheries accounted for 68% of the landings reported from the Saudi Arabian Red Sea, with 32% by the industrial fishery sector. The industrial fisheries include line fishing, gill netting, fish trapping, and demersal fish and shrimp trawling, while investor fisheries use similar gear types except for trawling gear. The investor fishing sector consisted of Saudi nationals and foreigners employed by local businesses ("investors") that provide boats and equipment to the crew, typically two to four men that lived on the boat fishing in the same areas as artisanal fishermen. These fishermen sell fish to the markets in large cities such as Jeddah, Yanbu, and Madinah, where fish prices are considerably higher. Industrial fishing is undertaken by a single company, the Saudi Fisheries Company; this company primarily operates out of Jizan, south of the Farasan Banks (143 vessels), with only six vessels targeting reefs and associated habitats in the central and northern sectors. Traditional fishing in the Red Sea is mostly undertaken by self-employed independent fishermen who use handlines and gill nets (89% of total landings for 2006), with pot traps accounting for 10% of the landings.

Fisheries Landings

Fishing pressure is greatest in central and southern waters from Jeddah to the Farasan Islands, and in remote locations, which are not patrolled as frequently. The coastline bordering the Red Sea represents about 79% of the total Saudi Arabian coast, yet fish production is about 35% of the total production, compared to 65% from the Arabian Gulf. Marine fisheries catch in 2006 was 65,472 mt, with 23,435 mt landed in the Red Sea and 42,037 mt from the Arabian Gulf. While total catches of marine fish have substantially increased over the past 15 years in the Arabian Gulf (from about

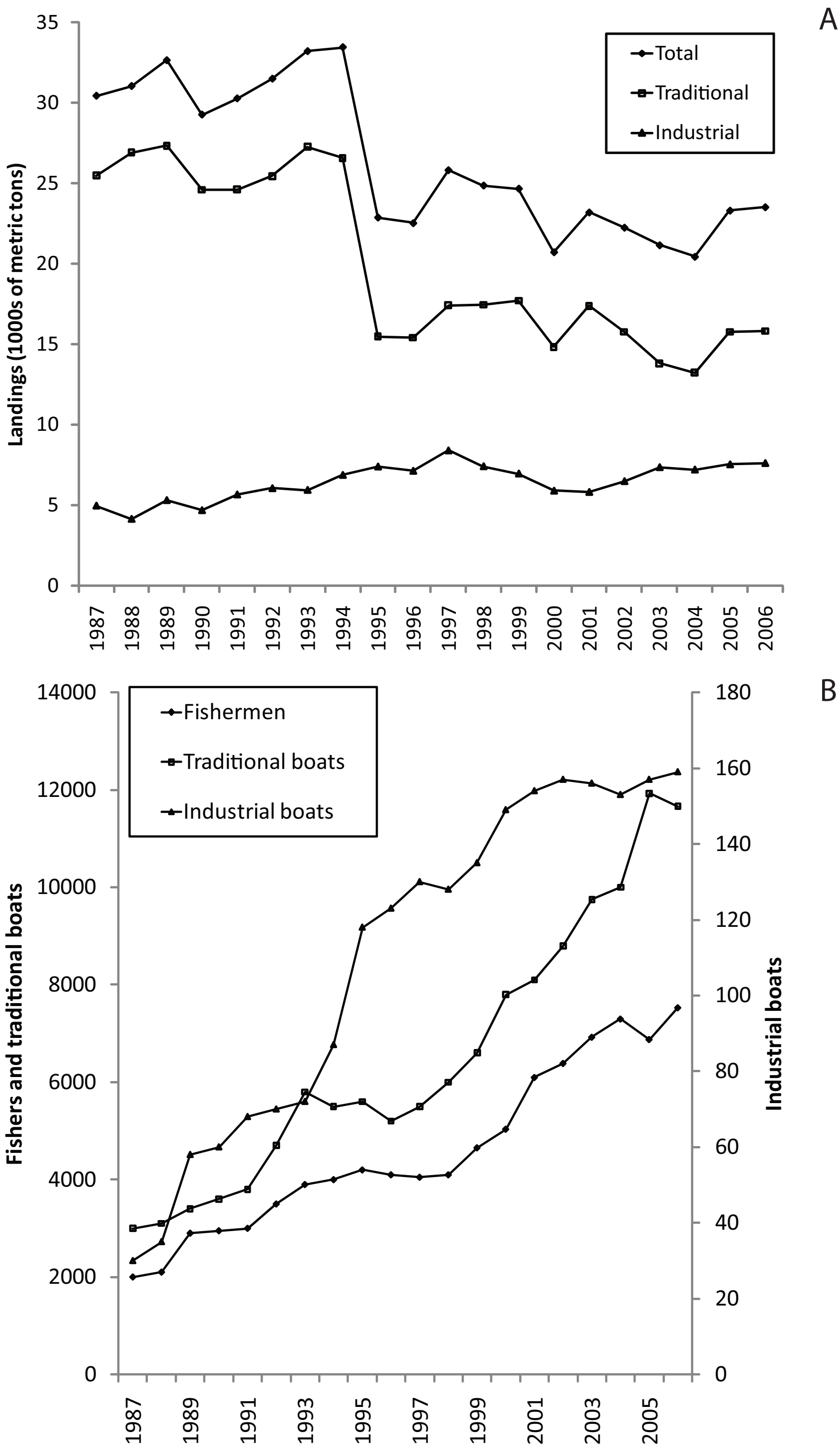

Figure 1. (A) Change in landings in the Saudi Arabian Red Sea over the past 20 years; (B) changes in fishing effort in the Saudi Arabian Red Sea over the past 20 years.

12,000 mt in 1990), landings from the Red Sea have remained fairly constant since 1995, fluctuating between about 20,000 and 24,000 mt. In contrast, landings in the Red Sea between 1987 and 1994 ranged from 30,000 to 33,000 mt per year (Figure 1A). Fishing effort (numbers of boats and fishermen and amount of effort) has also increased significantly over the past two decades while landings of individual stocks continue to vary by region and species. For example, landings over the past 4 years increased annually in the northern (from 2,580 to 4,018 mt) and central sectors (from 2,800 to 4,635 mt), while they declined in the southern sectors (from 7,419 to 6,419 mt).

The major fisheries species caught, in order of importance for 2006 by all fisheries sectors, were mackerels (Scombridae, 13.8%); groupers (Serranidae, 13.4%); emperors (Lethrinidae, 13.4%); scads, jacks, and trevallies (Carangidae, 11.6%); kingfishes (8%); barracudas (Sphyraenidae, 6%); shrimps (4%); snappers (Lutjanidae, 3.5%); tunas (Scombridae, 3.4%); and squids and cuttlefishes (2.5%). The industrial fishery primarily targets Indian mackerel *Rastrelliger kanagurta*, shrimps, squids and cuttlefishes, jacks and trevallies, emperors, threadfin breams, barracudas, crabs, mojarras, and sea catfishes, respectively, with most effort directed at open-water fishes (Table 1). In contrast, traditional fisheries operate in shallow coastal lagoons and reefal habitats, with landings in 2006 dominated by groupers (3,117 mt; 20%), emperors (2,650 mt), jacks and trevallies (2,200 mt), kingfishes (1,745 mt), barracudas (1,095 mt), snappers (773 mt), and 28 other functional groups, including herbivores (unicornfishes, parrotfishes, surgeonfishes, rabbitfishes; 775 mt) and top predators (sharks, 434 mt) (Table 2). The numbers of species landed over the past decade has increased while certain major species have varied in abundance between years (Figure 2). In particular, comparisons between mean landings in the 1990s (1996–1999) versus the 2000s (2000–2006) illustrate large declines in kingfishes (35%), parrotfishes (52%), rabbitfishes (121%), mackerels (51%), sea breams (64%), mojarras (84%), milkfishes (39%), and wrasses (28%). Increases were also observed in barracudas (16%), tunas (24%), grunts (19%), squirrelfishes (68%), and queenfishes (11%). In addition to food fishes, ornamental reef fish for the aquarium trade (Box 1) were also collected in southern regions, with seven aquarium fish exporters operating out of Jeddah; this industry was banned in 2004. Shark fisheries were also banned in 2008.

Table 1. Total landings and targets of the industrial fisheries and size of the fleet in 2006 within four regions of the Saudi Arabian Red Sea.

Region	Catch (metric tons)	Dominant species	Number of vessels and dominant gear type
Northern (Tabouk, Madeenah)	18	Lizardfishes, shrimp	1 boat; trawl nets
Middle (Makkah)	190	Sea breams (20%), shrimp (17%), mojarras (17%), lizardfishes, ponyfishes, rubber lips	5 boats; shrimp and fish trawl nets
South-central (Aseer)	86	Tunas (38%), kingfishes (30%), Indian mackerel (17%)	Purse-seine nets
Southern (Jizan)	7,342	Indian mackerel (37%), shrimp (12%), squids and cuttlefishes (8%), jacks (7%), emperors (7%), barracudas (4%), crabs (3%),	143 boats; trawl nets, purse-seine nets
Total catch	7,616		

Table 2. Total landings for traditional fisheries in the Red Sea off Saudi Arabia for 2006 in metric tons reported for major groups of species in order of importance. Tab = Tabouk, Mad = Madeenah, and Mak = Makkah.

	Total	Tab	Mad	Mak	Aseer	Jizan
Groupers	3,117	711	228	1,135	112	931
Emperors	2,650	886	284	515	91	874
Scads, jacks, trevallies	2,217	373	119	652	324	749
Kingfishes	1,745	59	19	205	135	1,327
Barracudas	1,095	41	13	291	16	734
Snappers, jobfishes	773	154	49	350	14	206
Tunas	744	52	17	353	17	305
Indian mackerel *Rastrelliger kanagurta*	475	34	11	47	0	383
Sharks, rays	434	22	7	112	4	289
Parrotfishes	354	119	38	156	0	41
Rabbitfishes	223	78	25	100	0	20
Surgeonfishes, unicornfishes	202	79	25	96	2	0
Sea breams	155	110	35	9	1	0
Grunts, sweetlips	150	10	3	58	5	74
Mullets	150	36	12	57	0	45
Squirrelfishes	146	19	6	121	0	0
Mojarras	121	27	9	67	0	18
Needlefishes	98	30	10	57	1	0
Milkfishes	89	7	2	78	0	2
Queenfishes	70	0	0	18	0	52
Wrasses	69	26	8	34	1	0
Sea catfishes	53	0	0	0	0	53
Cobias	50	0	0	4	0	46
Angle fishes	28	0	0	0	28	0
Sardines	20	12	4	4	0	0
Snubnose chub	19	14	5	0	0	0
Goatfishes	14	10	3	1	0	0
Triggerfishes	9	6	2	0	1	0
Rainbow runner *Elagatis bipinnulata*	5	4	1	0	0	0
Flatfishes	4	0	0	4	0	0
Crabs	3	0	0	0	0	3
Batfishes	1	0	0	1	0	0
Squids and cuttlefishes	1	0	0	1	0	0
TOTAL	15,819	3,044	974	4,635	751	6,415

Catch composition is highly dependent on fishing method. The two major types of gears used by traditional fishers are hand lines and gill nets, which account for about 89% of all landings in 2006. Predatory species, such as groupers (Serranidae), snappers (Lutjanidae), emperors (Lethrinidae), and breams (Sparidae) are targeted mainly by hook-and-line fishing. Traps were not used historically by artisanal fishermen, but their use is increasing. Approximately 10% of all landings were from traps in 2006 compared with only 6% in 2005 and 3.8% in 1996. In areas north of Jed-

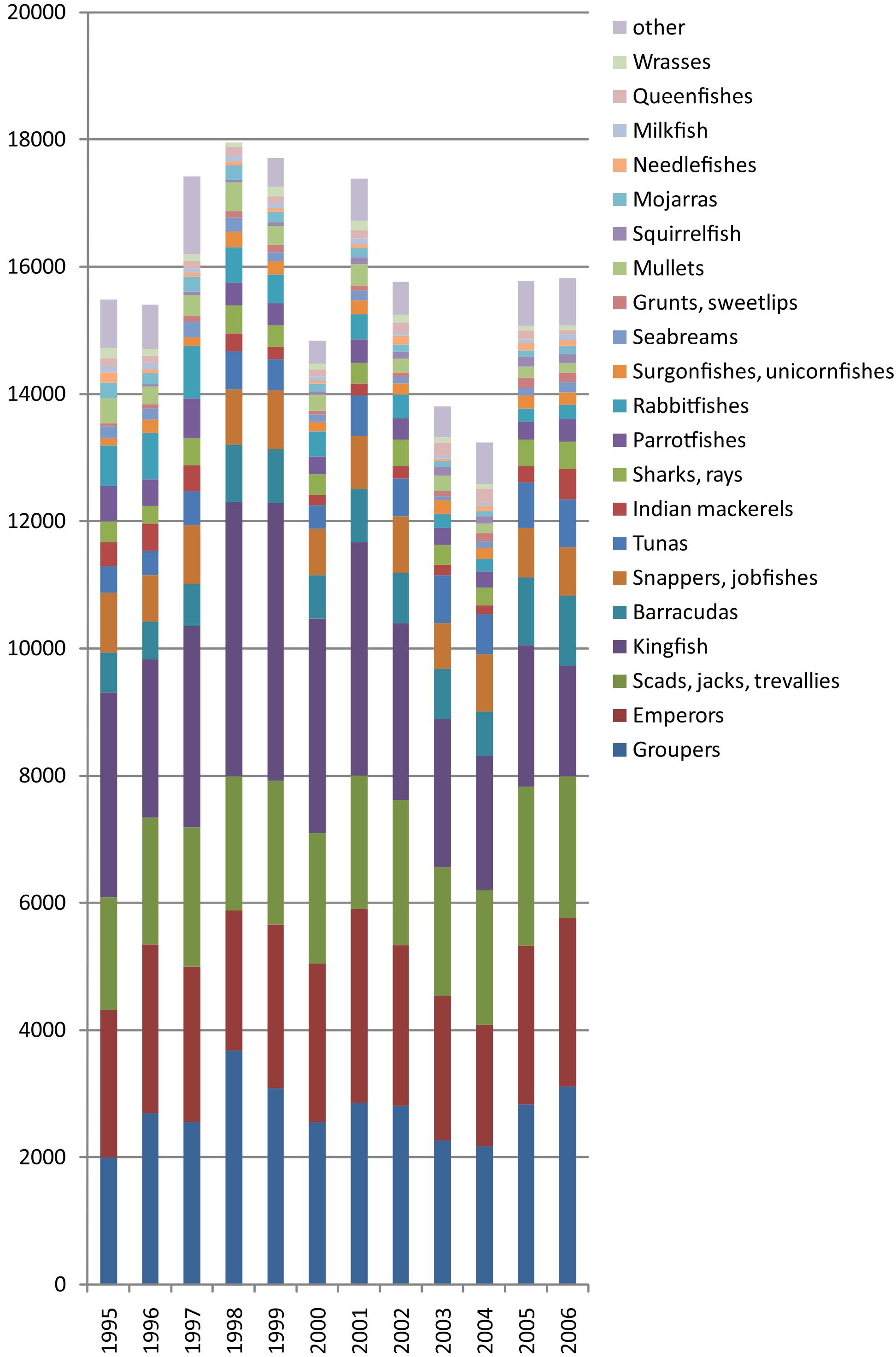

Figure 2. Changes in landings between 1995 and 2006 for the 21 dominant groups of fish and all other species (pooled as other) by traditional fisheries off the Red Sea coast of Saudi Arabia.

Box 1. Ornamental Fish

More than 2,200 species of coral reef fishes, 200 stony corals, thousands of tons of live rock, and more than 1,000 species of other invertebrates are collected from coral reefs and associated habitats to supply the marine ornamental industry with animals for home and public aquaria and for use as curios, jewelry, art objects, and other uses (Bruckner 2005). Coral reef fishes traditionally made up about 85% of the value of the trade (Wood 2001), with more than 45 countries supplying global markets and an estimated 30 million specimens in trade per year. These fisheries emerged in the 1930s in Sri Lanka, spread to Hawaii and the Philippines in the 1950s, and expanded to a multi-million dollar global industry by the 1970s. Marine ornamental fisheries occur throughout the tropical Pacific, Indian, and Atlantic oceans and Red Sea today; the largest suppliers are Indonesia and the Philippines (>60%), followed by Brazil, Maldives, Vietnam, Sri Lanka, and Hawaii. The United States is the world's largest consumer, followed by the European Union and Japan. Damselfish, anemonefish, and angelfish constitute more than 50% of the global volume of reef fishes; butterflyfish, wrasses, blennies, gobies, triggerfishes, filefishes, hawkfishes, groupers, and basselets account for 31% of the trade, and the remaining 16% is represented by 33 families (Table 1), with less than 1% produced through captive breeding (Wabnitz et al. 2003). Each country with an ornamental fishery tends to export a fairly small number of species in high volumes and a larger number of species at a low volume, including a few unique species that are very highly valued. These may be endemics, like the Banggai cardinalfish *Pterapogon kauderni*, which only occurs in a limited area in Indonesia, or deepwater species like Tinker's butterflyfish *Chaetodon tinkeri* from Hawaii. Marine fishes are primarily collected on coral reefs, but associated grassbeds, mangroves, lagoons, algal flats, rubble fields, and other habitats are also important sources. Juveniles are preferred as they are less costly to transport, they generally survive better due to their small size, and they are typically

Table 1. The dominant fishes targeted for the global marine aquarium trade. The overall percent of the trade and the percent of the value of the trade are presented for the 10 most important families of coral reef fishes.

Fish type	Family	Volume (%)	Value (%)
Damsel/anemonefishes	Pomacentridae	29	13.0
Angelfishes	Pomacanthidae	24	46.0
Butterflyfishes	Chaetodontidae	11	10.0
Wrasses	Labridae	7	12.0
Blennies/gobies	Blennidae/Gobidae	5	3.0
Triggerfishes/filefishes	Balistidae/Monacanthidae	4	2.5
Hawksfishes	Cirrhitidae	2	3.0
Groupers/basselets	Serranidae	2	1.5
Other	33 families	15	8.0

(Box continues)

Box 1. Continued.

much more colorful than the adult fish. Males are also preferentially caught over females due to their coloration. Herbivores are the dominant trophic group in the trade, but planktivores (e.g., *Chromis* spp.), corallivores (*Chaetodon* spp.), piscivores (*Epinephelus* spp.), cleaner fishes (*Gobiosoma* spp.), and other trophic groups are also collected. While the volume of coral reef fishes in trade has remained fairly stable, exports of live coral and other invertebrates for use in reef displays has increased by 20–50% each year, with more than 1.5 million live corals and 1.5 million kg live rock in trade during 2007, most from Southeast Asia and the South Pacific.

Environmental and biological impacts of the fishery include the overharvesting and extirpation of key species, coral reef degradation associated with the use of cyanide, changes in reef health and resilience due to unsustainable collection of herbivores and other key functional groups, and loss of biodiversity due to removal of rare species. A lack of comprehensive fisheries and trade data and biological information hinders effective management. Other issues include the potential introduction of nonnative species, conflicts with other uses of the resources, low income in exporting countries, lack of training in environmentally friendly collection practices, human health issues associated with diving practices such as hookah, and harvest of species that are rare or play a key role in ecosystem health. Further, reef fishes often experience high postharvesting and transport mortalities that may exceed 80% as a result of the use of cyanide to stun fishes, poor capture and handling techniques, inadequate husbandry and transportation practices, and sale of species that are difficult to maintain in captivity (Johannes and Riepen 1995; Wood 2001; Sadovy and Vincent 2002). Measures to ensure sustainability fall into four main categories: fishery management, improved handling and transport standards, mariculture alternatives to wild harvest, and international trade restrictions (Table 2).

Table 2. Primary concerns associated with ornamental coral reef fisheries.

Issue	Impact	Possible management strategy
Overexploitation	Population declines Loss of diversity	Species-specific quotas
Destructive fishing techniques (use of cyanide and other poisons)	Habitat damage Coral breakage Mortality of nontarget fishes	Net training; cyanide testing and penalties for violations
Decline of trophic groups • Herbivores • Invertebrate feeders • Piscivorees	Ecological changes • Phase shifts (e.g, algal overgrowth) • Increased corallivores • Increased bioerosion	Species-specific quotas Spatial and temporal closures

(Box continues)

Box 1. Continued.

Table 2. Continued.

Issue	Impact	Possible management strategy
Postharvesting mortality	Additional take to supply demand	Improved handling and water quality standards
Poor survivorship in captivity	Increased harvest pressure	Prohibitions on take of certain species
Lack of fishery dependent and independent data	Inability to make rational management decisions	Reporting requirements Monitoring programs Research into life history
Release of aquarium pets into the wild	Introduction of exotics, pest species, parasites, and diseases	Education; penalties
Socioeconomic problems	Resource use conflicts Human health risks Low income for fishers Dive training and standards	Zoning Diving Better pay

dah, such as the Wajh Bank area, fish traps now dominate the artisanal fisheries, and there is also an expansion in southern areas around the Farasan Banks. Traps, trammel nets, and gill nets are less selective, catching a wide variety of species and functional groups. Several species, such as most parrotfishes, rabbitfishes, surgeonfishes, unicornfishes, and other herbivores are rarely caught using handlines (Figure 3). Overall, more than 240 species of fish are reported to be landed using traps and nets (about 25% of all species reported from the region), although a smaller number of species make up the bulk of the catch. For instance, three species of the family Labridae (longnose parrotfish *Hipposcarus harid*, bluechin parrotfish *Scarus ghobban*, and common parrotfish *S. psittacus*) that comprise the bulk of the landings caught in trammel and gill nets when the fish feed over sand bottoms adjacent to reefs. Other gear types of minor importance include small trawl nets, cast nets for bait, and wall nets (with relatively large openings) used to catch large herbivorous fish that cannot be caught with handlines. These nets were also used to catch transient reef predators, such as trevallys (*Caranx* spp.) and dogfin tunas (*Gymnosarda* spp.) by chumming or baiting an area close to the reef, then enclosing it with the net so the fish are caught between the reef and the net with nowhere to escape. Spearfishing is illegal, although it is reported to be used occasionally with scuba to target large parrotfishes (Labridae), surgeonfishes (Acanthuridae), and groupers (Serranidae).

Threats to Fisheries and Fishery Resources

An increase in fishery production from the Red Sea over the past 30 years and an expansion in the use of destructive fishing are key threats affecting the sustainability of reef resources. These threats are increasing in severity, mainly due to increased commercial fishing pressure; more frequent trawl-

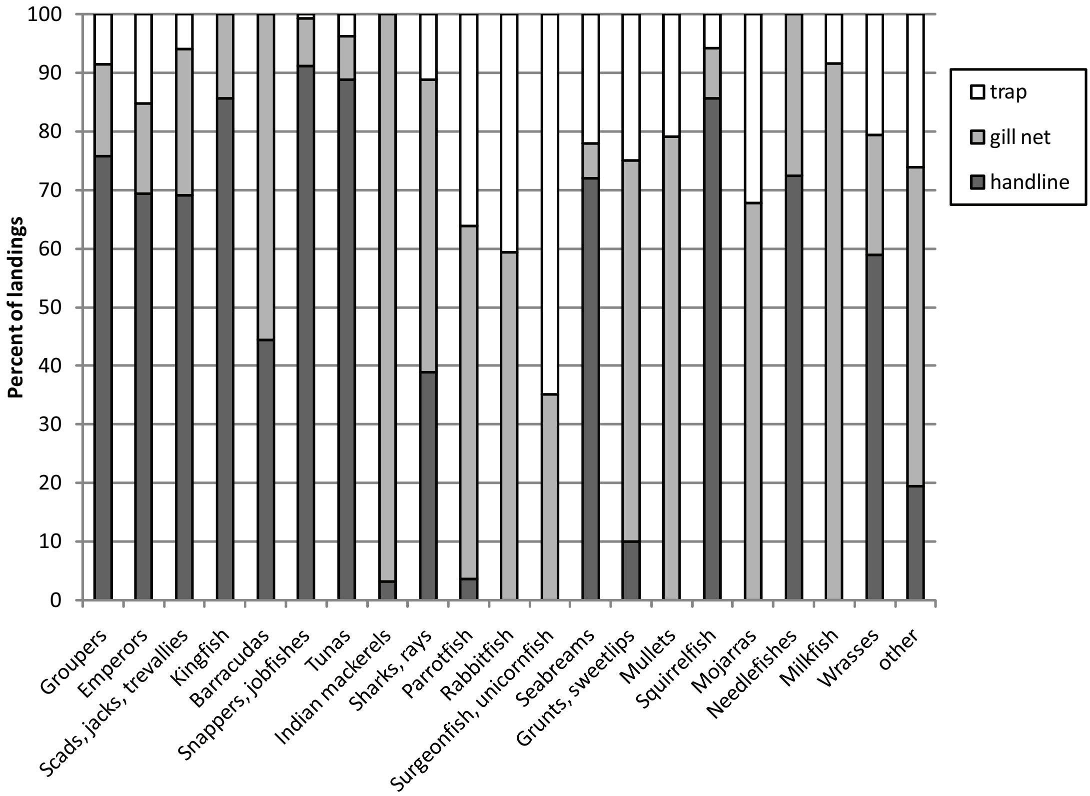

Figure 3. Differences in the relative proportion of the major groups of fish caught in coral reef environments off the Red Sea coast of Saudi Arabia by traditional fisheries using three different gear types.

ing, fish traps, and other destructive methods; poaching in no-take zones; increased fishing pressure at spawning and nursery sites; and growing pressure on sharks, sea cucumbers, and other species in high international demand (Kotb et al. 2008). In several countries, traditional fishermen are abandoning fishing for more lucrative opportunities such as tourism, and local knowledge of the ecology of reefs is being irreversibly lost. Local nationals are being replaced by migratory fishermen and visiting fishers from other countries who lack knowledge about the resource. These nonnationals have also introduced unsustainable and destructive gear types, including purse-seine nets, traps, and dynamite fishing, which is contributing to habitat damage and bycatch, including harvest of a high diversity of undersized (juvenile) fishes due to a small mesh size. These traps are being used by investor fisheries in the same areas fished by artisanal fishers; they catch the same species as those targeted by artisanal fishers as well as nontarget species important to the health and ecology of reefs, such as angelfishes, butterflyfishes, and surgeonfishes.

Nearly a decade ago, artisanal fishers interviewed by Gladstone (2002) reported declines in catches, sizes of fish, and income from fishing, and both more time and larger areas were required to catch the same number of fish as in the past. Rapid urban, industrial, and commercial development of Saudi Arabia has led to population growth, development of coastal areas, and increased exploitation of marine resources through commercial fishing (Gladstone et al. 1999). The government has also provided interest-free loans, engines, and new materials for boat making for the fishery sector in an attempt to expand and further develop the traditional fishing sector, yet management of the resources has not kept pace with fisheries growth. In many of the locations throughout the Red Sea, signs of depleted fishery resources have been reported, especially on reefs with declining coral cover. Inadequate data on the status of stocks and the biology of the fished species limits the ability to design and implement sustainable management approaches, and many countries lack adequate regulatory structures. Loss and degradation of habitat, especially the removal of mangroves and grass beds, are reducing the amount of coastal areas available as nursery areas, with further deleterious effects on fisheries production. Unless new management interventions are adopted, these factors are a potential threat to the resource sustainability, conservation status, and cultural values.

Management of Fisheries

Saudi Arabia has introduced a number of management measures to control exploitation of its fishery resources in the Red Sea. These include (1) closed seasons for the shrimp fishery, (2) closed seasons for grouper, (3) mesh-size restrictions for gill nets, and (4) proposals for additional no-take MPAs. In other countries, bans have been implemented on sea cucumber fisheries and shark fishing, yet most other reef fisheries have few top-down controls. In 2000, the National Commission for Wildlife Conservation and Development released a "system plan of protected areas" that identified 46 environmentally sensitive areas along the Red Sea coast and offshore islands. To date, two MPAs have been developed in the southern-central region, at the Farasan Islands and Jazirat Umm al-Gumari, and there are proposals for addition MPAs near Ras Quisbah and Al Wajh Bank area.

Addressing Gaps in Science

Over the past two decades, our understanding of coral reefs has greatly improved and basic monitoring programs are being implemented around the globe, including developing countries. Nevertheless, existing information often lacks the details and there are large gaps in spatial and temporal coverage; the capacity for management and enforcement is also often lacking. Typical monitoring programs provide data on cover of various organisms and the diversity and abundance of fishes, but these may have limited taxonomic specificity (e.g., growth forms of corals are recorded instead of genera- or species-based data). Monitoring programs only rarely include an examination of the population dynamics of reef-building corals (e.g., size structure and amount of partial mortality); relationships among coral, algae, and other functional groups; impacts of various threats; or patterns of recovery from acute and chronic perturbations.

A simple, rapid assessment of representative coral reef habitats for a proposed management unit can provide the baseline data needed to identify targets for management. These assessments will also provide data that can be used to develop predictive tools to recognize and address the vulnerability of these reefs to large-scale disturbances before they destroy critical habitat, and to evaluate the effectiveness of management (Table 3). A rapid assessment protocol combining methods from the Atlantic and Gulf Rapid Reef Assessment (Lang 2003) and the IUCN (International Union for Conservation of Nature) Resilience Assessment of Coral reefs protocol (Obura and Grimsditch 2009) was applied to coral reefs in the Saudi Arabian Red Sea coastline in four major regions (Farasan Islands, 2006; Ras Quisbah, 2007; Yanbu and Al Wajh Bank, 2008; and Farasan Banks, 2009). The protocol includes four major components: (1) an assessment of the primary biotic compartments that make up the reef

Table 3. Types of scientific information that can contribute to spatially based ecosystem management of coral reef ecosystems.

Category	Recommendation
Habitat mapping	Identify habitat types, sizes, and boundaries through development of high-resolution habitat maps using multispectral satellite imagery and field validation of bathymetry, structural features, substrate types, environmental attributes, and dominant species assemblages.
Characterize species assemblages	Assess the composition, distribution, and population structure of ecologically relevant organisms (corals, fish, and algae) within representative habitats across biophysical and anthropogenic gradients.
Assess ecosystem health	Identify major threats and synergistic impacts to ecologically relevant organisms, how stressors vary spatially (latitudinal, with distance from the mainland, and over depth gradients), and how they degrade coral reef resilience.
Characterize resilience indicators	Conduct rapid assessments of key biological, ecological, physical, and environmental attributes that enhance coral reef health and resilience.
Evaluate the human dimension	Compile existing scientific knowledge, management scenarios, and socioeconomic attributes of the management unit.
Categorize and rank reef condition	Develop a report card for individual sites within the larger management unit, considering the importance for biodiversity conservation, connectivity, presence of unique or rare organisms, intact trophic assemblages, human impacts, and presence of environmental factors that enhance or degrade resilience.
Identify critical areas	Use maps and information to identify possible marine protected areas, with consideration of optimal size, shape, representative habitat types, replication of representative sites, connectivity, and ecosystem attributes.
Recommend spatially based management options	Characterize the vulnerability of sites and develop predictions on the stability and changes to sites within the management unit under different Characterize the vulnerability of sites and develop predictions on the stability management scenarios and disturbance regimes.

community; (2) ecological interactions that drive dynamics within and among these groups; (3) habitat and environmental influences that directly affect the reefs; and (4) external drivers of change, including anthropogenic and climate factors (Table 4) . Representative sites were selected using high resolution multispectral satellite images and habitat maps, with sampling undertaken across gradients of human pressure and environmental regimes. The types of data collected include (1) the abundance and size structure of more than 100 species of reef fishes, emphasizing species of major importance in the ecological functions of the reef ecosystem and fisheries targets, including key herbivores, piscivores, scavengers, coral feeders, sessile invertebrate feeders, planktivores, and detritivores; (2) cover, size structure, and condition of reef-building corals by genera, including levels of recruitment; and (3) more than 30 physical, environmental, and anthropogenic resilience indicators were also evaluated (Table 4). These data were compiled into a geographic information system (GIS) database containing high resolution habitat maps developed concurrently for the region to allow a spatial examination of the status and trends of the coral reefs and to recommend options for management.

Table 4. (A) Biological resilience indicators for coral reef ecosystems; (B) physical and environmental resilience indicators for coral reef ecosystems.

A

Measure	Description
Stony coral	Genus-level identification of the composition, abundance, cover, size structure, condition, and level of recruitment within representative habitats.
Species composition	The diversity and structural complexity of a site. Communities with higher numbers of functional groups (e.g., branching, plating, and massive corals) and redundancy of these groups may support more associated species and be more resilient.
Cover	Measure of amount of living coral, but provides limited information on population dynamics. Small changes in cover are difficult to document, but abrupt changes may reflect a major disturbance. Useful metric for comparison among reef habitats with a managed area.
Size structure	Maturity and ecological state of the taxa. Large numbers of large corals may be a sign of stable environmental conditions and long-term persistence of the community; a dominance by small corals suggests frequent disturbance or recovery from a recent disturbance.
Recruitment	Abundance of recruits reflects the reef's potential for growth and recovery after major disturbances and the influx of genetic diversity.
Fragmentation	Level of physical disturbance and potential for asexual propagation. Locations of fragments (accumulations in sand channels or on reef) and fragment condition (no tissue loss; fusion to the substrate; presence of new growth) reflects the potential survival and contribution of fragments to recovery.
Dead standing coral	Amount of dead standing coral can be used to hindcast past disturbance events up to a decade or more.
Old mortality	Presence of dead areas on corals that are colonized by other biotic agents (e.g., skeleton is not white) provides evidence of past disturbances. Species-specific differences reflect the life history strategies, population dynamics, and susceptibility to stressors. Old mortality may increase with colony size.
Recent mortality	Overall extent of recent mortality (white skeleton) reflects the severity and duration of a stressor; percent partial mortality within colonies is indicative of the severity of the stressors (e.g., rates of tissue loss). The rate of transformation from recent mortality (white, uncolonized skeleton) to old mortality is influenced by sedimentation, bioerosion, and competition. Rates of mortality may allow prediction of rates of turnover of corals.
Bleaching	Reef-wide bleaching may be associated with recent or ongoing temperature anomalies; extent of recent mortality in bleached corals may indicate the duration and severity of the temperature stress.
Disease	Spatial patterns of disease occurrence reflect potential for spread and level of contagion. Distinction can be made between background mortality (chronic stressors) and acute mortality caused by disease outbreaks. Presence of isolated small lesions reflects low-intensity stressors within the ability of the coral to regenerate new tissue; larger lesions are more likely to be colonized by other competitive organisms and may affect the normal functioning of the coral (e.g. reproductive potential).

Table 4. Continued.

A

Measure	Description
Corallivores	Abundance of coral predators (*Drupella* and *Coralliophila* snails, *Acanthaster* sea stars) indicative of the amount of recent mortality and possible changes to coral community structure and species diversity due to chronic high level infestations or outbreaks.
Competition and overgrowth	Negative factors inhibiting the growth and recovery of corals and causes of chronic mortality (e.g. algal competition) and bioerosion (e.g. sponges) of skeletons. Extent and composition of competitive organisms may reflect status of fish communities (herbivores), nutrient loading, and sedimentation.
Coral associates	Obligate corallivores (butterflyfish) provide an indication of the health of the coral community or a particular taxa.
	Abundance and diversity of fishes and invertebrates within coral branches are indicative of the topographic complexity and health of the site.
	An abundance of territorial damselfish within branches and large algal lawns indicate possible overfishing of piscivores.
Algae	Species rich, productive and functionally important components of benthic coral reef environments that may be involved in construction of the reef, components of the food chain, or space occupiers that are not eaten.
Fleshy macroalgae	Indicators of grazing pressure, nutrients, and levels of disturbance. Macroalgae should be low; macroalgal dominance reflects a loss of herbivores (urchins fish), nutrient input, and loss of corals.
Turf algae	Low to moderate cover of turfs reflect moderate levels of herbivory; increasing biomass of turfs and trapping of sediments within turfs degrades substrate quality and reduces recruitment potential of reef-builders.
Crustose coralline	Cover of certain species of crustose coralline algae is linked to coral recruitment; CCAs bind sediments and consolidate the reef.
Erect coralline	Taxa (Halimeda) produce sand that forms beaches and contribute to the infilling of reefs.
Motile invertebrates	
Urchins	Abundance of key taxa of urchins (*Diadema* and *Echinometra*) are indicators of levels of herbivory and bioerosion, potential survival of coral recruits, and interactions among other herbivores. High densities of sea urchins associated with extensive bioerosion of reef substrates and low recruitment and survival of newly settled corals; macroalgae may increase in absence of sea urchins, especially sites with few herbivorous fishes.
Mollusks and crustaceans	Abundance of commercially important species such as large crabs, lobsters, and giant clams are indicators of fishing pressure and habitat quality.
Fish	Fish community structure within sites can be attributed to environmental conditions, habitat complexity and quality, connectivity with other sites and intactness of adjacent habitats, fishing pressure, and management regimes.
Herbivores	Suppress the growth of algae. Herbivore biomass is negatively correlated with macroalgal biomass and amount of cropped habitat. Different functional

Table 4. Continued.

A

Measure	Description
	groups prefer different taxa and growth forms of algae; grazing pressure varies based on the size of bites and frequency of feeding.
Browsers	Feed on fleshy and filamentous macroalgae, controlling overgrowth and shading of corals by algae. Examples: *Calotomus*, *Leptoscarus*, *Naso*.
Grazers	Remove epilithic algae from reef surfaces without removal of underlying reef substrate. Examples: *Acanthurus*, *Zebrasoma*, *Siganus*.
Scrapers	Remove algae and small pieces of underlying reef substrate. Examples: *Scarus*, *Hipposcarus*.
Excavators	Consume coral and large pieces of reef substrate and play a key role in bioerosion and sand production. Examples: *Bolbometapon*, *Chlorurus*.
Omnivores	Consume small invertebrates and fish, including larvae; some consume phytoplankton, benthic algae, and sea grass.
Detritivores	Feed on organic material in the sediment and on reef substrates. High numbers may reflect conditions of eutrophication. Examples: goatfishes, *Ctenochaetus*.
Planktivores	Indicative of the level of plankton in the water column, including larvae important for reseeding the reef, and water column nutrient levels. Examples: fusiliers, some triggerfishes.
Carnivores	Carnivore density, size, and biomass is a sensitive indicator of the type of fishing pressure; control abundances of lower trophic level fishes.
Invertebrate feeders	Control populations of corallivores and bioeroders, including snails, sea stars, and urchins. Some feed on sessile invertebrates like soft corals and sponges, which compete with stony coral for space. Examples: triggerfishes, snappers, sweetlips, wrasses, angelfishes.
Obligate coral feeders	Provide indication of the health of the coral. Example: certain butterflyfishes.
Piscivores	Important control of lower trophic level fish; first indicators of overfishing.

B

Physical and environmental parameters	
Tides	Large tides may reduce thermal stress and increase nutrients in subtidal areas; frequent exposure at low tide may increase resistance to thermal, salinity, and light stress.
Currents	Likelihood of connectivity with other sites; helps maintain cooler water temperatures.
Wave action	Affects distribution of species and growth form; enhance exchange of water and may maintain cooler temperatures.
Deep water	Deep water adjacent to reefs associated with upwelling of cool, nutrient rich waters; pelagic fish that migrate and feed on reefs.
Inter-reef distances	Potential for connectivity with adjacent sites.
Distance from mainland	Gradient of anthropogenic stressors and exposure to open ocean conditions.

Table 4. Continued.

B

Habitat attributes	
Substrate type and quality	Extent of sedimentation, turbidity, presence of rubble, smooth versus rugose hardground all reflect the potential for recruitment and survival of juvenile corals.
Reef slope	Proximity of deep water and potential for refuge populations; extensive shallow reef flats heat up during calm periods and hot, hypersaline water may flow down the reef slope.
Shading	Above water features and canopy corals may shade understory corals, enhancing resistance to temperature-related stressors.
Turbidity	Reduces penetration of UV, potentially reducing stress from thermal anomalies; may restrict vertical distribution of corals.
Depth	Affects abiotic parameters (light, temperature, wave exposure), coral composition and growth form, and habitats available for reef-associated fishes.
Compass direction	Angle of incidence of the sun and diurnal changes affect amount of solar radiation on the reef; easterly facing reefs exhibit more light stress than westerly facing reefs.
Associated habitats	Proximity, connectivity, and size of associated sea grass beds, mangroves, and algal flats. Importance: stabilize sediments, reduce run-off to reef habitats, and translocate nutrients; feeding grounds, shelter, and nursery areas for reef-associated species during different life stages.

New Directions for Management

Sound decisions to ensure the sustainability of reef fish populations require a thorough understanding of the health of corals and threats affecting them, as well as options to mitigate those threats and enhance coral reef resilience. Hard corals form the framework of the reefs, creating habitat used as nursery, feeding, resting, and schooling areas for reef fishes. Corals also form the basis of many vital ecosystem services such as coastal protection. Coral abundance and cover on reefs worldwide began to decline during the 1970s–1980s, although Red Sea reefs only began to witness major region-wide changes in the late 1990s, following large-scale bleaching events. Localized losses of coral and associated species have been attributed to land-based pollution, overfishing and destructive fishing techniques, and a variety of other human factors (Glynn 1993; McManus 1997; Aronson and Precht 2001; Hughes et al. 2003), although these impacts can have more far-reaching consequences when overlain onto large-scale disease outbreaks, bleaching events, and other manifestations of climate change. Without direct interventions to address localized stressors, corals are less likely to recover, and their continued decline may trigger cascades of decreasing fish abundance and diversity. Declining coral reef health is also negatively affecting communities dependent on reefs for food, jobs and income, and revenue from tourism. According to the "Status of Coral Reefs of the World: 2008," 55% of the world's coral reefs are in trouble, including 19% that are damaged beyond repair and 35% at a critical or threatened stage (Wilkinson 2008).

Alternate Ecosystem States

Coral reef ecosystems are known to occur in multiple ecological states based on the dominant organisms or functional groups. Different states may occur along gradients of temperature, salinity, light, nutrients, organic matter, such as that associated with offshore-nearshore systems, and also along latitudinal gradients (e.g., that observed in the Red Sea). Coral reefs may also shift to a less desirable state in response to chronic stressors associated with human impacts. One of the best recent examples of massive changes to reef structure is from the Caribbean during the 1980s and 1990s; a mass mortality of the herbivorous long-spined sea urchin *Diadema antillarum* and outbreaks of white band disease precipitated the loss of two of the most important reef-building corals (*Acropora* spp.) and resulted in a semipermanent regime shift from coral- to algal-dominated systems over a relatively short time frame (Hughes 1994; Aronson and Precht 2001). These ecosystem-level changes can affect flows of energy and materials, abundance and diversity of community inhabitants, and valuable services for human societies (Sousa 1984; Pickett and White 1985). The scale and duration of these phase shifts are related to severity of the disturbance, as well as the predisturbance conditions and resilience of the community. Changes in the interaction between hard corals, soft corals, algae, and levels of fish grazing can trigger dramatic ecosystem changes, but it often requires several factors to occur simultaneously, such as increased eutrophication and removal of important herbivorous fishes, along with ongoing degradation of corals.

Reefs that are largely intact with low levels of anthropogenic stressors and little fishing pressure are more likely to adapt to environmental fluctuations and climate change and also will show more rapid recovery following acute, large-scale disturbances. In particular, the presence of certain keystone species (e.g., parrotfishes and other herbivores) may prevent the shift from coral to algae during mass bleaching events, and related functional groups may facilitate return to a previous state following a mass die-off of corals. In sites where these keystone species have been overfished, alternate stable states may persist indefinitely, leading to reefs that are functionally dead. This may have deleterious outcomes from a human perspective, in terms of the ability of the reef to continue to provide ecosystems services and support sustainable fisheries. Thus, it is critical that considerations be made to restore and maintain intact ecological communities to allow reefs to sustain maximum productivity for all user groups.

Considerations to Ensure Sustainability of Reef Fisheries

1. Apply Place-Based Management Tools

A GIS database and associated habitat maps developed for Saudi Arabia (Figure 4) provides a spatially based platforms with baseline data on the locations, spatial extent, and condition of coral reef resources. These maps identify at least seven different geomorphologic reef structures in the Red Sea, including barrier reef systems, lagoonal patch reefs, reticulate reefs, submerged limestone platforms, coral pinnacles, atoll-like structures, and island and mainland fringing reefs. Coastal areas are further subdivided into 8–12 distinct shallow marine habitats, including specific reef environments, grass beds, mangroves, algal flats, and sand-bottom communities. Dominant benthic organisms (e.g., corals) vary in species and growth form depending on the habitat and support a variety of often nonoverlapping species and life history stages. For instance, the central-northern Red Sea coast, extending from Yanbu beyond the Al Wajh Bank area, supports an extensive, near-continuous

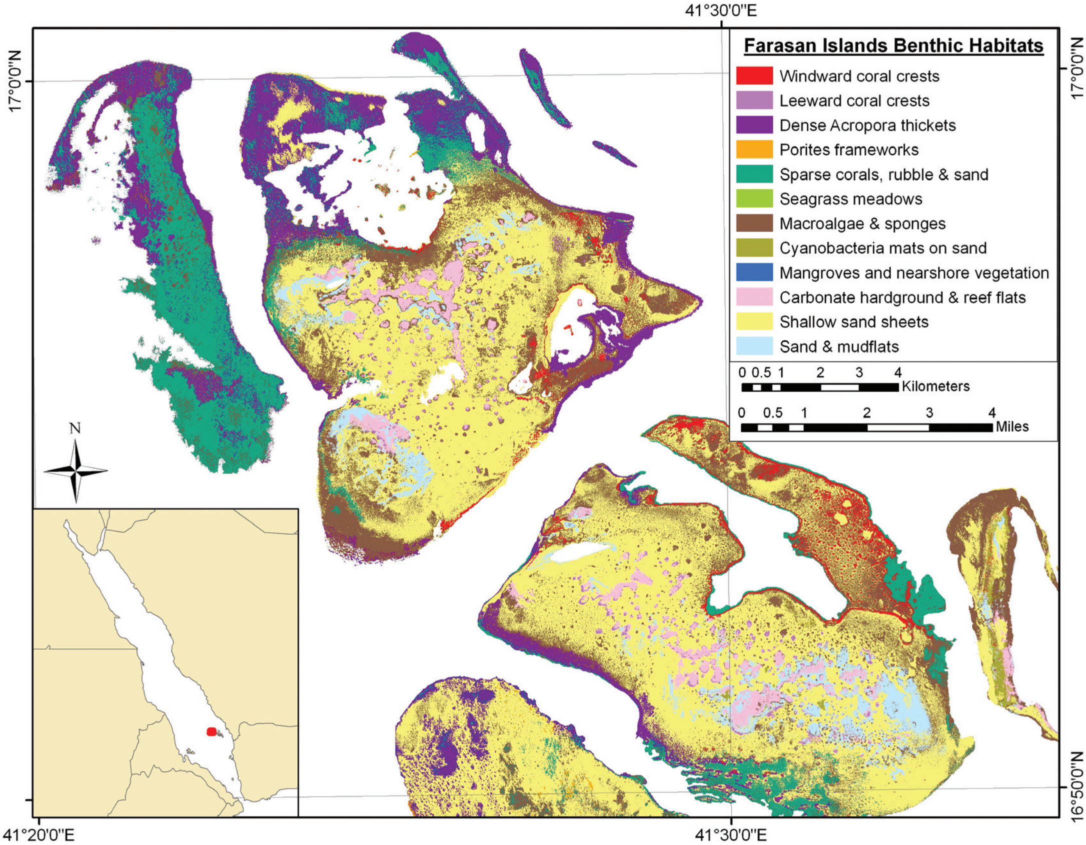

Figure 4. Example of a habitat map for a portion of the Farasan Islands, Saudi Arabia.

coral reef tract in relatively good condition, with low levels of human impact; this area contains a highly diverse assemblage of reef-building corals and large populations of herbivorous and predatory fishes, including large numbers of threatened humphead wrasse *Cheilinus undulatus*, large groupers, sharks, giant clams, and other vulnerable species. Superimposed on the complex reef systems are a number of critically linked habitats, including grass beds, deeper algal flats, and mangroves that serve as nursery and breeding areas, as well as extremely rich inshore turbid reefs with unusually high cover of the topographically complex branching coral, Acropora. To ensure sustainability, spatially placed zoning with certain high-diversity sites established as no-take MPAs need to be considered, in addition to measures to reduce effort and eliminate the use of destructive techniques in these fragile habitats.

2. Incorporate Ecosystem Roles of Fishes in Fishery Measures

An evaluation of the population structure of reef fishes and specific management measures should be targeted at those species that maintain healthy reef systems, due to the complexity and diversity of reef fish (Table 4A). In the Red Sea, approximately 100 species are ecologically valuable to the health of the reef ecosystem and also directly important as a food resource (Rouphael and Al-Yami 2000a, 2000b; Obura and Grimsditch 2009). The harvests of coral reef fishes typically have disproportionate impacts on the abundance of larger piscivorous or predatory species, which are targeted as the favored food fish with the highest economic value. These top-level predators (sharks, groupers, and jacks) control abundances of lower trophic level fish and provide a good indication of fishing pressure, while second-level predators such as snappers and sweetlips may prevent population explosions of invertebrates, including *Acanthaster* (crown of thorns sea stars) and *Drupella* (coral eating snails) corallivores. Herbivores (e.g., parrotfishes, surgeonfishes, rabbitfishes, and unicornfishes) can be allocated into four functional groups: excavators, scrapers, grazers, and browsers, based on their feeding strategy and importance in controlling phase shifts from coral to algae and in reversing this shift following a disturbance. Obligate and facultative coral feeders (butterflyfishes and filefishes) provide an indication of the health of the coral, and sessile invertebrate feeders (especially angelfishes) are important indicators of the abundance of soft corals and sponges, which may monopolize bottom substrates and outcompete hard coral. Certain planktivores (triggerfishes) provide an indication of the condition of the water column and abundance of larvae critical to reseeding degraded reefs. Detritivores (goatfishes) are also included in our surveys as they are indicators of eutrophication and conditions that may be unsuitable for corals. Because these species exert top down control on reef dynamics, knowledge of the numbers of fish species, abundance, density, and composition by these functional and/or trophic groups can provide critical information on the ability of the coral reef to resist change and recover rapidly following large-scale climatic perturbations.

Throughout the Red Sea, reef fish communities are reported to be overfished or at their limit of exploitation, with few large predatory fishes observed and most herbivores of a small size. Exceptions occur, especially in MPAs and in certain offshore sites, such as the Yanbu Barrier Reef north of Jeddah, Saudi Arabia, where fishing is prohibited. Many deeper and more remote locations, especially those sites with high structural relief and adjacent deep water (e.g., Farasan Banks) often have larger populations of predatory fishes due to reduced access by small coastal fishing vessels. For instance, a large number of juvenile and subadult humphead wrasse are found in shallow habitats surrounding Al Wajh and the Farasan Banks. This is a species is listed as endangered on the IUCN Red List and is now protected through CITES (Convention on International Trade in Endangered Species) due to heavy fishing pressure in support of the live reef food fish trade. Giant clams also appeared to be very abundant, although the largest individuals were generally less than 20 cm, possibly because these were formerly important targets of artisanal fisheries. Populations of small groupers and snappers still occur in most locations, except degraded reefs, and are generally found at higher numbers than that reported from other IndoPacific locations. However the size structure of these may be unnatural as most are now less than 30 cm in length. Sharks were rare throughout the Saudi Arabian Red Sea, with low numbers observed in offshore sites at the edge of the reef, adjacent to deep water. The shark fishery poses fairly recent threats to reefs of Egypt and Saudi Arabia, mainly due to increased international demand for shark fins.

Once the major predators become overfished, fishery targets often shift to lower trophic level species; this may increase biomass landed, with cascading impacts on reef health. As coral reefs that are relatively close to the mainland are degraded, artisanal and investor fishers are targeting more remote locations. Expanded use of fish traps and nets with small mesh sizes is of concern due to the sensitivity of corals to physical impacts and the associated removal of a high diversity of lower trophic level species, especially juveniles that help maintain proper functioning of these sites.

3. Evaluate and Incorporate Information on Nontarget Species, Ecosystem Threats, Resilience Indicators, and Linkages with Manageable Human Stressors into Decision-Making Processes

In addition to quantitative data on the cover, size frequency, and abundance of major coral functional groups, the rapid assessment protocol described here allows characterization of reefs on the basis of their health and resilience, incorporating key ecological and physical attributes related to the reef structure (rugosity, slope, and habitat condition), oceanographic and environmental parameters (upwelling, circulation, wave exposure, and water clarity), and biological attributes, including the composition and abundance of reef fishes, corals, and algae. Coral cover within reef habitats in the Red Sea range from less than 5% to about 70%, with the highest cover in the reef crest and shallow fore reef from 3 to 5 m depth, and in certain turbid inner patch reefs (<5 m depth). Many reefs have been damaged near urban and industrial centers by human impacts; in other locations, outbreaks of crown of thorns sea stars, episodes of coral bleaching, and other natural disturbances have caused widespread mortalities. While patterns of recovery are highly variable, sites with low levels of human influence are showing positive signs of recovery, including levels of recruitment that exceed reports from adjacent sites in the Indian Ocean impacted by the 1998 mass bleaching event. Fleshy macroalgal cover remains low (<5%) in most locations, with exception of some inshore reef flat communities and urbanized areas, suggestive of low nutrient conditions and/or high herbivory. Soft corals, turfs, and crustose coralline algal cover typically account for 5–20% of the bottom cover, although cover of *Xenia* soft coral may exceed 50% in reef environments that had been damaged by previous disturbances, and this may prevent recolonization by important reef builders. The presence of small coral colonies throughout the Red Sea (most are 1–30 cm diameter) suggests a high turnover and frequent disturbance. Maintenance of these populations, and the habitat they create, depends on local sources of recruitment, which may diminish following regional perturbations. Physical and environmental parameters, such as the distance from shore, reef slope, facing direction, wave exposure, proximity to deep water, and disturbance regime, are important factors affecting coral population dynamics. These factors cannot be easily manipulated but can be to identify sites worthy of protection due to their role as refuge and sources of seed stock. By maintaining high diversity and biomass of certain keystone species, such as herbivores that control macroalgae, reef resilience can be enhanced. Reduction of anthropogenic stressors, such as unsustainable fisheries, coastal and industrial development, and runoff and sewage may also enhance coral survival, prevent recruitment failure, and promote adaptation to climate change (Table 4).

Conclusions

There are multiple problems associated with coral reef fisheries related to gear types, fishing effort, and fisheries targets. Predatory fish are vulnerable to most fishing gears and they usually disappear first under conditions of unsustainable fishing pressure. Fishermen often remove fish before they reach their most productive size, resulting in growth overfishing, partially due to the use of gear types that have mesh sizes that are too small, such as fish pots and gill nets. Intense exploitation of a particular reef, especially where there are few external sources of larvae to replenish the reef, may drive numbers to levels that are inadequate to maintain viable population (e.g., recruitment overfishing). As the top predators are depleted, fishing shifts to lower trophic levels to maintain high production. While this may arise because a greater proportion of the primary production is incorporated into fish biomass at these levels (Sheppard et al. 1992), unsustainable removal can cause a progressive shift in the balance of species on the reef, resulting in ecosystem overfishing. This is likely to distort the natural balance of energy flow from the bottom to the top of the food chain. Some fishing techniques, such as dynamite and cyanide fishing and the placement of fish traps on live coral, damage the complex environment fish need to survive.

During the past decade, Saudi Arabia and most other countries bordering the Red Sea have taken important steps towards developing a coordinated multinational network of MPAs, encompassing a wide variety of reef types and other marine and coastal habitats (DeVantier et al. 2000). In many cases, these MPAs were identified without a thorough baseline understanding of the reefs or the needs and desires of the user groups, and management plans are largely absent. Furthermore, fishing activities by nonnative fishermen have continued unabated in MPAs (due to lack of enforcement and other factors), lessening the benefits of MPAs to marine conservation (Gladstone 2002). Natural resource management and conservation organizations in the Red Sea typically site the lack of data or the inability to use available data as the reason for the lack of marine management.

Marine ecosystem management in situations of uncertainty or constrained resources and capacity can still be achieved through the use of decision support tools such as the high resolution habitat maps created for the Saudi Arabian Red Sea coastline. The habitat maps, in concert with a GIS database, compile recent information on reef health and resilience, providing a framework for spatially based, ecosystem-based approaches to management. Presence of certain resilience indicators in key ecological areas in the Red Sea that were undamaged by past disturbances. Because the Red Sea may contain coral reefs that exhibit unusually high resilience due to their tolerance to extreme temperatures, these sites may be of global ecological importance as sites resistant to future climatic events and priority areas for conservation and MPA designation. Effective management through rigorously enforced no-take zones and concurrent efforts to mitigate pollution and other coastal threats is a critical tool for managing fisheries associated with coral reefs and other habitats. This effort must be inclusive since reef fish use multiple habitat types during their lives, such as offshore spawning aggregation sites and inshore nursery habitats.

Science and research play major roles in coral reef management by providing the information required to plan and implement actions (Ablan et al. 2004). Management of Red Sea coral reef fisheries will also benefit from the direct involvement of chief fishermen with local knowledge of the marine environment and local customs and politics, their respected position among other fishermen and their ability to communicate between government agencies and their community (Gladstone 2002). Furthermore, management depends on transparent communication of scientific results to the broader public. These approaches allow managers to consider the status of the reefs, recent changes to reefs, associated habitats and resources contained therein, and drivers of changes in decision-making processes. When combined with a socioeconomic evaluation of various user groups, along with strengthened institutional capacity for management and enforcement and involvement by key stakeholders and community groups, management decisions provide greater confidence that future levels of exploitation do not compromise the sustainability of reef resources or the associated food security for humans dependent on these resources.

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