Current Biology
Magazine

Similar understanding will also allow us to better characterize the impacts of rising levels of anthropogenic noise. Particle motion sensors based on the model of a fish ear and dolphin-inspired sonar will provide opportunities for improved sensing technology for instrumentation, autonomous underwater vehicles, and perhaps even augmented reality options for human divers to enhance our direct experience of the underwater acoustic world.

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Primer

Marine ecosystem services

Edward B. Barbier

Coastal and marine environments can begin up to 100 kilometers inland, extend to the continental shelf, and include ocean systems with waters up to 50 meters in depth. The distinct marine ecosystems found in these environments include estuarine and coastal wetlands, such as marshes and mangroves, sand beaches and dunes, seagrass beds, and coral and oyster reefs.

Marine ecosystems represent some of the most heavily exploited ecosystems throughout the world. For example, coastal zones make up just 4% of the earth's total land area and 11% of the world's oceans, yet they contain more than a third of the world's population and account for 90% of the catch from marine fisheries. However, human activities are now threatening many of the world's remaining marine ecosystems and the benefits they provide. Due to coastal development, population growth, pollution and other human activities, 50% of salt marshes, 35% of mangroves, 30% of coral reefs, and 29% of seagrasses have already been lost or degraded worldwide over several decades. As much as 89% of oyster reefs may also have been lost globally. Overfishing has been a persistent and growing problem in marine environments, and loss of fisheries is also linked to declining water quality through the increasing occurrence of harmful algal blooms, offshore pollution and oxygen depletion (hypoxia). Given the current rapid loss of coastal and marine environments, it is important to understand what is at stake in terms of the foregone economic benefits and values as marine ecosystems disappear.

In this Primer, I provide an overview of some of the key benefits, or 'services', provided by marine ecosystems before going on to discuss some of the key challenges in quantifying and valuing marine ecosystem services. One important feature of these critical habitats is that they are interconnected from the land to the ocean. Thus, the challenge for future research is to assess the benefits that arise from such an interconnected seascape.

Marine ecosystem services

Collectively, the benefits provided to humans by ecosystems are referred to as *ecosystem services*. Table 1 provides some examples of marine ecosystem services, which comprise various goods, services and cultural or other benefits. The goods produced by marine ecosystem services are the products obtained from these habitats, such as fish

Table 1. Examples of marine ecosystem services.

Goods	Services	Cultural benefits
• Fish harvests	• Recreation and tourism	• Carbon sequestration
• Wild plant and animal resources	• Transportation	• Bequest for future generations
• Raw materials	• Scientific and educational opportunities	• Religious significance
• Genetic material	• Flood control	
• Water	• Storm protection	
	• Pollution control	
	• Breeding and nursery habitats	
	• Shoreline stabilization and erosion control	
	• Carbon sequestration	

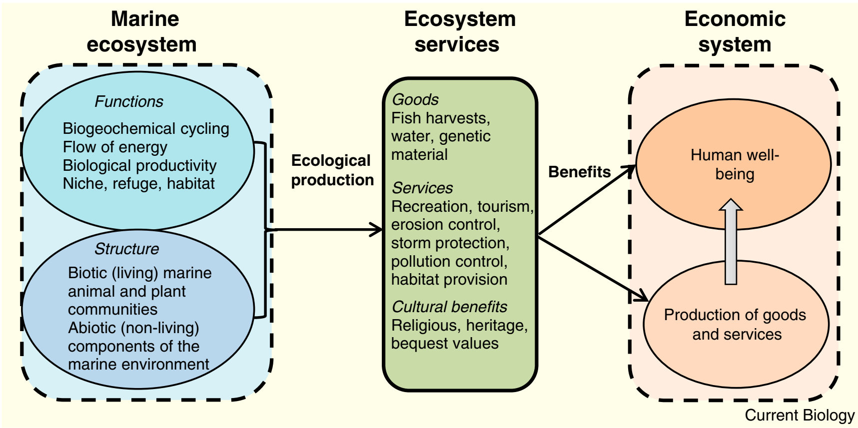

Figure 1. How marine ecosystems generate economic benefits.
The structure and functioning of marine ecosystems lead to the ecological production of ecosystem services. Some of these goods, services and cultural benefits directly impact human well-being, whereas others indirectly impact the welfare of humans through supporting or protecting valuable economic assets and production activities.

harvests, wild plant and animal resources, and abstracted water. In developing countries, some of the more important uses of marine ecosystems tend to involve both small-scale commercial and 'informal' economic activity to support the livelihoods of local populations, for example, through fishing, hunting, fuelwood extraction, and so forth.

Recreation, tourism and water transport are familiar services provided by many marine ecosystems. Some unique estuarine, coastal, and marine habitats are also important stores of genetic material and have educational and scientific research value as well. Coral reefs are particularly important in this regard, as they are the most structurally complex and taxonomically diverse marine ecosystems, providing habitat for tens of thousands of associated fishes and invertebrates.

Marine ecosystems also provide other important services, associated with their regulatory and habitat functions, such as pollution control, storm protection, flood control, habitat for species, and shoreline stabilization. For example, in the case of mangrove ecosystems, the mangrove swamps may serve as a nursery and breeding habitat for many important fish species, some of which may migrate as adults to offshore fisheries. In addition, mangroves can reduce the economic damages inflicted by tropical storms on coastal property and communities. Finally, mangrove systems are thought to prevent coastal erosion, thus preserving valuable agricultural land and coastal properties.

Many unique marine habitats are considered to have important cultural and other benefits. That is, people may benefit from the knowledge that an ecosystem simply exists or that it will be around for future generations to enjoy. These values may be particularly important among indigenous communities in rural areas, as they see their culture, heritage and traditional knowledge closely intertwined with the surrounding environment. Even some of the poorest rural communities have expressed interest in seeing their 'way of life' passed on to their heirs and future generations.

Quantifying and valuing marine ecosystem services

Quantifying the contributions, or 'benefits', provided by ecosystems in terms of human welfare is often referred to as *valuing ecosystem services.* The biggest challenge to quantifying and valuing marine ecosystem services is the inadequate knowledge available to link changes in ecosystem structure and function to the production of valuable goods and services (Figure 1).

This connection is more straightforward for well-known goods and services, such as fish harvests and recreation. Landed fish catch can be easily observed and, in many cases, the fish are often marketed; reliable prices therefore exist to indicate the value of the catch. Recreation and tourism values can also be determined by estimating the willingness-to-pay of visitors to unique marine habitats for specific activities, such as coral reefs for recreational fishing or scuba diving, bird watching in salt marshes, and tourist visits to marine parks.

However, valuing the services associated with regulatory and habitat functions of marine ecosystems is often more challenging. For one, these services, such as storm protection, habitat support for offshore fisheries, and erosion or pollution control, are generally not marketed. Instead, the value of these services needs to be determined indirectly through their support for valuable production activities or through the protection of property and other important economic assets from damages. This requires knowledge of how the specific marine ecosystem functions and structure influence the 'ecological production' of a particular service, such as storm protection or habitat–fishery linkages, as well as the market conditions of the final marketed commodity that is impacted by the marine ecosystem service.

For example, one important service of mangroves, marshes, reefs and seagrass beds is that they provide a coastal breeding and nursery habitat for offshore fisheries. As many fisheries are exploited commercially, the inability to control fishing access and the presence of production subsidies and other market distortions can impact harvests, the price of fish sold and, ultimately, the estimated value of coastal habitats in supporting these fisheries. In addition, it is important to determine how variations in the breeding and nursery habitat affect the biological production and growth of the offshore fisheries and, in turn, both current and future harvests. More than one marine habitat may also contribute to the 'life cycle' of the fishery, including larval dispersal and fish migration among the various habitats, which is important when determining the contribution of each habitat to the value of the fishery. Finally, there is evidence that the nursery and breeding habitat function of mangroves and marshes is greater at the seaward edge or fringe of the coastal habitat than further inland. This means that the seaward edge may have more value in supporting offshore fisheries than habitats located away from the sea.

Marine ecosystems also have an important role in protecting coastal populations and property from flood and wind damage resulting from periodic storms. For example, marshes, mangroves, beaches and dunes, seagrass beds, and reefs are able to buffer shorelines from severe weather, thus protecting coastal human populations, property, and economic activities. In the case of flood damage, the critical role of such ecosystems is attenuating and dissipating the wave surges caused by storms. Both the hydrodynamic properties of storm surges offshore and the presence and friction of ecosystems and their vegetation may be important in determining how well coastal properties and lives are protected from the surge once it lands onshore. In addition, the protection against wind and wave damage from coastal storm and surge events may vary significantly across marine habitats. For salt marshes and mangroves, wave attenuation diminishes as the habitat moves further inland (i.e. as its distance from the shoreline increases). In the case of near-shore coral or oyster reefs and seagrasses, wave attenuation is a function of the water depth above the reef or grass bed, which also varies spatially. Wave attenuation by sand beaches and dunes displays exponentially increasing protection at higher elevations or where dune vegetation cover is greatest.

As progress is made in quantifying and valuing marine ecosystem services, we are improving our understanding of the structure and function of the marine ecosystems that provide such benefits. Further progress in valuing critical marine ecosystem services is dependent on understanding how the ecological production of these services arises

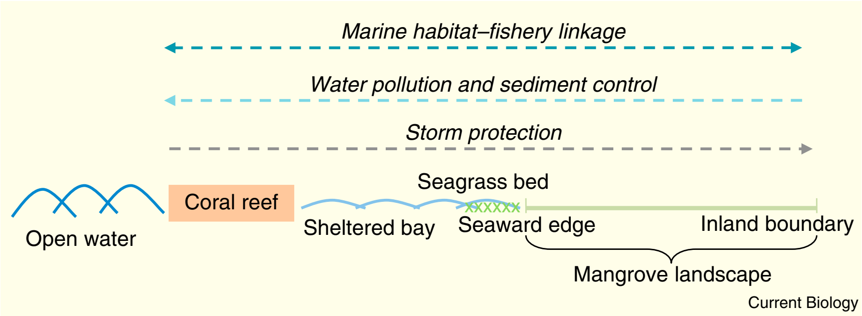

Figure 2. A mangrove–seagrass–coral reef seascape and marine ecosystem services.
In a mangrove–seagrass–coral reef seascape, all three habitats interact to provide support for marine fisheries, water pollution and sediment control, and storm protection. The connectivity among habitats mutually reinforces the support of marine fisheries because adult fish use the coastal habitats for breeding and nurseries and the resulting fry migrate to coral reef fisheries. The sheltering effect of reefs may enhance the ability of seagrass beds, marshes, mangroves and other coastal habitats to attenuate waves and buffer winds. Water pollution and sediment control by mangroves and seagrass beds may also protect coral reefs, thus enhancing their goods and services.

and, in turn, how these services directly and indirectly lead to economic benefits.

The marine seascape and ecosystem services

Marine ecosystems do not exist in isolation but are often interconnected across a continuous land–sea interface, or *seascape*. Typical marine habitats found in a seascape that extends from the coast to open water are mangroves, salt marshes, seagrass meadows, coral reefs and oyster reefs, as the *connectivity* between and among these coastal and near-shore marine habitats is the most pronounced. As a result of nutrient fluxes and material exchange, including movements of marine fauna, these habitats provide important goods and services both individually and through functional linkages across the seascape.

Figure 2 illustrates how the interconnectivity among the marine habitats comprising a mangrove–seagrass–coral reef seascape may enhance three important ecosystem services: habitat–fishery linkages; water pollution and sediment control; and storm protection. How the three habitats interact is important in determining the provision of these services across the entire seascape and the multiple economic benefits provided.

For example, mangroves and seagrass beds serve as breeding and nursery grounds for some marine fisheries, whereas the bays sheltered by coral reefs protect the coastal ecosystems and their ability to act as reproductive habitats. In addition, all three habitats interact to support the life cycle underlying the marine fisheries. Coral fisheries depend on the coastal habitats for breeding and nurseries and the resulting fry migrate back to the reefs. Thus, the presence of mangroves and seagrass beds considerably enhances the biomass of coral reef fish communities.

Mangroves and seagrass beds absorb waste water discharge into the sea and act as sinks for pollutants, sediment and other organic materials. This pollution and sediment control service not only benefits coastal communities and their production activities but also protects coral reefs, thus enhancing their goods and services as well. In the case of storm protection, the presence of coral reefs may enhance the benefits provided by coastal habitats. Coral reefs often shelter coastal habitats by buffering oceanic waves and currents and slowing down periodic storm surges, and thus support the ability of seagrass beds and mangroves to attenuate waves and buffer winds.

Taking into account the possible connectivity of habitats comprising the seascape clearly has implications for both the valuation of benefits, such as storm and flood protection, habitat–fishery linkages and pollution control, and the management of coastal and near-shore marine habitats. Because of seascape connectivity, a decision to develop, exploit or protect one part of the seascape, such as a mangrove along the coast, could have important implications for the habitat in the rest of the seascape, such as a coral reef, and thus the goods and services they provide. For example, mangroves and seagrass beds could become more important as nursery habitat when excessive fishing effort levels are applied to the reef because the mangroves can directly offset the negative impacts of fishing effort. This suggests that managing fisheries to take into account ecological and economic synergies across an entire mangrove–seagrass–coral reef seascape would require four additional considerations: the relative importance of mangrove and seagrass nursery sites to the coral reef and marine fisheries; the connectivity of individual reefs to the coastal nurseries; areas of nursery habitat that have an unusually large importance to specific reefs and marine fisheries; and identification of priority coastal sites for mangrove and seagrass bed restoration projects.

Future trends in marine ecosystem services

Marine ecosystems are disappearing at a rapid rate and on an alarming scale worldwide. Yet many of their benefits are undervalued or even ignored in coastal and marine development decisions. It is critically important to assess the benefits provided by these systems so that we can better understand what is at stake as marine habitats are lost and how to improve coastal and marine management and policy. This article has sought to contribute to the literature concerning these habitats by reviewing the current state of knowledge about marine ecosystem services, documenting the progress made as well as the challenges remaining in the economic valuation of these services, and demonstrating how valuing marine ecosystem services can influence policy decisions concerning the management of these environments.

Recent research has revealed how key functional linkages arising from the connectivity across an entire seascape of marine habitats influences the provisioning of ecosystem goods and services, and valuing these benefits across a seascape is providing new analytical, management and policy insights. Future research is likely to focus on: estimating the multiple benefits arising from seascapes with interconnected habitats, such as estuaries and mangrove–seagrass–coral reef systems; accounting for the spatial variability of ecosystem services across various marine habitats; and estimating lesser-known marine ecosystem services, such as reduction of wind damage, control of erosion, mitigation of temperature variations, and protection from sea-level rise.

As we learn more about marine ecosystem services and the ecological production underlying them, we should expect our assessment and valuation of these benefits to evolve as well. Thus, this field will likely continue to provide fertile ground for research for some years to come.

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