American Museum of Natural History
Center for Biodiversity and Conservation
Network of Conservation Educators & Practitioners

Marine Reserves and Local Fisheries:An Interactive Simulation

Author(s): Eugenia Naro-Maciel and Daniel R. Brumbaugh

Source: *Lessons in Conservation*, Vol. 2, pp. 50-83

Published by: Network of Conservation Educators and Practitioners, Center for Biodiversity and Conservation, American Museum of Natural History

Stable URL: ncep.amnh.org/linc/

Marine Reserves and Local Fisheries: An Interactive Simulation

Eugenia Naro[*]-Maciel and Daniel R. Brumbaugh[†]

[*]The American Museum of Natural History, New York, NY, U.S.A., email enmaciel@amnh.org

[†]The American Museum of Natural History, New York, NY, U.S.A., email dbrumbaugh@amnh.org

Source: C. Roberts and J. Hawkins

Table of Contents

Marine Reserves and Local Fisheries: An Interactive Simulation

Eugenia Naro-Maciel and Daniel R. Brumbaugh

Introduction

In many tropical marine areas such as the Caribbean, one finds productive ecosystems harboring a large diversity of organisms. People also live in these places, and harvest marine organisms for their livelihoods. The complex question arises: How to balance marine biodiversity conservation and local fishery activities? Marine protected areas, including marine reserves that completely ban fishing and other extractive activities, are a promising approach for addressing both of these factors.

This simulation-based exercise is an educational tool that allows users to:

1. Explore various factors that influence fish population viability and fishery sustainability; and
2. Experiment with the use of marine reserves as tools in fisheries management.

Fishers and conservationists using simulation software at workshop in Ecuador (Source: A. Walton / S. Lozano. © NOAA NMSP)

Highlights

The exercise allows:

- Interactive experimentation by users with marine reserve configurations and species and fishing parameters;
- Visualization of habitat suitability for three Caribbean fisheries species;
- Visualization of species abundances and fishing profits over time;
- Visualization of average harvest catch, effort, profits, and the source of these profits across space; and
- Saving of all input parameters and simulation results.

Why is this Important?

Although the total amount of fisheries catches appears to have a reached a global maximum over the last decade (Watson and Pauly 2001), many local fisheries are known to be declining worldwide. Whereas industrial scale commercial fisheries often switch to new stocks and species after depleting a resource (sometimes leading to a pattern of serial depletions), people in smaller scale, coastal fisheries are much more vulnerable to fisheries collapses. Coral-reef fisheries, due to their relatively small areas, the slow growth and maturation rates of many reef fishes, and the complex community interactions in reef ecosystems, are especially susceptible to overfishing and habitat degradation (Birkeland 2001). Moreover, overexploitation of key reef species has contributed to the instability and decline of coral reefs, leading to threats to the biological diversity of these rich, biodiverse ecosystems (Hughes et al. 2003, Mumby et al. 2006).

Marine protected areas (MPAs), including marine reserves that restrict all take (or harvest), provide tools for addressing threats from overfishing to both the sustainability of local fisheries and the conservation of biodiversity (NRC 2001). A protected area has been defined as an "area of land and/or sea especially dedicated to the protection and maintenance of biological diversity, and of natural and associated cultural resources, and managed through legal or other effective means" (IUCN 1994). Protected areas, also known as parks, reserves, and a suite of other names, have been established at international, regional, national, state, and local scales, and many are linked as networks or other systems. Marine resource managers may opt for different combinations of MPA size, number, location, and other factors, depending on the specific objectives of a marine reserve or other MPA. This may include whether, for example, it is primarily designed for conservation or fisheries, for which target species, and in the context of what kind of fishery (e.g., gear type).

This exercise allows users to explore issues related to marine reserves and local fisheries via interactive simulations. Users are able to control (1) some attributes of a local fishery, including population dynamics and mobility of the target species as well as aspects of fisher behavior and economic factors, and (2) the extent and placement of marine reserves. By exploring the contributions of these issues to fisheries productivity over time, users should gain some understanding of the factors contributing to how reserves can interact with local fisheries. Of course, although many of the factors and dynamics in this exercise are based on actual interdisciplinary research conducted in The Bahamas (see http://bbp.amnh.org), the simulation represents a simplification of the real complexities of population dynamics, fisheries economics, and marine resource management. Adding these additional complexities, such as more variable population dynamics, more dynamic pricing of catches, and additional fishing regulations outside of marine reserves, would likely lead to different quantitative outcomes. Nevertheless, qualitative results deriving from controlled comparisons across different scenarios (e.g., species life-history, fleet, and reserve characteristics) are likely to be more general.

Literature Cited

Birkeland, C. 2001. Can ecosystem management of coral reefs be achieved? Pages 21-25 In B.A. Best and A.H. Bornbusch, editors. Global trade and consumer choices: coral reefs in crisis. AAAS Publications, Washington, D.C. 39 p.

Hughes, T.P., A.H. Baird, D.R. Bellwood, M. Card, S.R. Connolly, C. Folke, R. Grosberg, O. Hoegh-Guldberg, J.B.C. Jackson, J. Kleypas, J.M. Lough, P. Marshall, M. Nyström, S.R. Palumbi, J.M. Pandolfi, B. Rosen, and J. Roughgarden. 2003. Climate Change, Human Impacts, and the Resilience of Coral Reefs. Science 301: 929-933.

IUCN 1994. Guidelines for Protected Area Management Categories. IUCN, Gland, Switzerland and Cambridge, UK.

National Research Council (NRC). 2001. Marine protected areas: Tools for sustaining ocean ecosystems. Committee on the evaluation, design and monitoring of marine reserves and protected areas in the United States. Ocean Studies Board, National Research Council, Washington, D.C.

Watson, R. and D. Pauly. 2001. Systematic distortions in world fisheries catch trends. Nature 414, 534-536.

Local Fisheries

In the Caribbean, three important fisheries species, for economic, cultural, and ecological reasons, are the queen conch (*Strombus gigas*), the Nassau grouper (*Epinephelus striatus*), and the spiny lobster (*Panulirus argus*).

Queen Conch

The queen conch, a large snail (gastropod mollusk) in the *Strombidae* family, is found throughout and beyond the greater Caribbean, including as far north as Bermuda and as far south as Venezuela and Brazil (FAO 1977). The conch fishery is one of the most important in the region, though the species' biology makes it rather susceptible to overfishing, and it has declined throughout its range in recent decades. Trade in queen conch is now restricted following regulations of the Convention on International Trade of Endangered Species of Wild Fauna and Flora (CITES), where S. gigas is listed on

Appendix II (CITES undated, Acosta 2006). The species is also listed in Annex III of the Protocol Concerning Specially Protected Areas and Wildlife to the Convention for the Protection and Development of the Marine Environment of the Wider Caribbean Region (SPAW, UNEP undated).

Economically, the conch fishery in the Caribbean is worth millions of U.S. dollars each year. Although harvest dates to prehistoric times, high levels of commercial take are relatively recent. The meat can be prepared in a variety of ways (e.g., raw ceviche-type salad, stews and chowder, or cooked in innumerable customary ways), while shells are used to make jewelry, and as a local construction material. Fishing methods include capture by hand, use of simple gear such as forked poles, or SCUBA, which is generally illegal (Catarci 2004). These methods do not greatly negatively affect habitats or ecosystems, or other species through incidental by-catch (Cascorbi 2004). In some areas, like The Bahamas, conch is harvested during the lobster fishery closed season, or as part of a multiple species effort (Catarci 2004). Management is coordinated regionally by the International Queen Conch Initiative. The fishery is regulated through temporal or spatial closures, as well as by level of maturity, size limits, gear restrictions, and catch quotas. Conch fishing in Florida – both commercial and recreational – has been prohibited since 1985, though stocks have not recovered subsequently. In 1991, the state recognized *S. gigas* as a "protected species" (Schlesinger 2006). In many nations, fisheries management measures are not effective due to factors such as illegal fishing and inadequate enforcement (Cascorbi 2004, Acosta 2006).

Aspects of this species' biology contribute to its vulnerability to overharvest (Gascoigne 2002, Gascoigne and Lipcius 2004, Cascorbi 2004). Queen conchs are relatively long-lived, slow growing, and have delayed sexual reproduction, with a reproductive output that increases with age (CHC CIC 2003). *S. gigas* live up to about 25 years, mature at around 3-4 years, and are highly fecund. Reproduction occurs through internal fertilization, when large numbers of conch migrate to shallow waters for breeding. Females lay individual masses containing ~300,000 fertilized eggs. After about 5 days, larvae called veligers hatch from these egg masses and start a 3-4 week period in the plankton before settling onto shallow sand and algae, where they metamorphose into tiny snails. The conch's life history is characterized by high mortality at younger ages; however, older individuals are naturally protected from predators by their strong shells. This species is, however, relatively easy for humans to capture. It lives in accessible shallow waters, is clearly visible, and moves slowly. *S. gigas* occur mainly in shallow sea grass beds linked to coral reefs, with the youngest being found closest to shore. Queen conch forage on plankton as larvae, and algae, sea grass, and other plants as adults (Ray and Stoner 1995, CHN CIC 2003). Vulnerability increases when conch aggregate in large numbers to spawn. This anthropogenic mortality of the later life stages, combined with habitat loss and pollution, are likely to be driving population declines. Further, reproduction in *S. gigas* may fail below certain density thresholds, inhibiting recovery (Stoner and Ray-Culp 2000, Gascoigne and Lipcius 2004).

Literature Cited

Acosta, C.A. 2006. Impending trade suspensions of Caribbean queen conch under CITES: a case study on fishery impacts and potential for stock recovery. Fisheries 31(12): 601-606.

Cascorbi, A. 2004. Seafood Watch Seafood Report: Queen Conch *Strombus gigas*. Available from http://www.mbayaq.org/cr/cr_seafoodwatch/content/media/MBA_SeafoodWatch_QueenConchReport.pdf

Catarci, C. 2004. World markets and industry of selected commercially-exploited aquatic species with an international conservation profile. FAO Fisheries Circulars. Available from www.fao.org

CHN CIC. 2003. The geography, habitat and biology of the queen conch. Conch Heritage Network "Conch in the Classroom", curriculum resources for teachers. Available from www.savetheconch.org/classroom.html

CITES. Undated. Convention on International Trade in Endangered Species of Wild Fauna and Flora. Available from http://www.cites.org/eng/disc/species.shtml

FAO. 1977. *Strombus gigas,* Linnaeus 1758 in Species Identification Sheets for Fishery Purposes. Western Central Atlantic (fishing area 31). Gastropods. Vol. 6, Rome, FAO. Available from http://www.strombusgigas.com/strombus-percent20speciespercent20idpercent20pg1.pdf

Gascoigne, J. 2002. Grouper and conch in The Bahamas: extinction or management? The choice is now. MacAlister Elliot & Partners, Limited; B.R.E.E.F. The Bahamas Reef Environment Educational Foundation. Available from www.macalister-elliott.com/reports/1651R03A.pdf

Gascoigne, J. and R.N. Lipcius. 2004. Conserving populations at low abundance: delayed functional maturity and Allee effects in reproductive behaviour of the queen conch *Strombus gigas.* Marine Ecology Progress Series 284: 185-194.

Ray, M. and A.W. Stoner. 1995. Growth, survivorship and habitat choice in a newly settled gastropod, *Strombus gigas.* Marine Ecology Progress Series 123: 83-94.

Schlesinger, L. 2006 (last update). Marine Fisheries Approved Rules Summary, Florida Fish and Wildlife Conservation Commission. http://myfwc.com/marine/history/index.html.

Stoner, A.W. and M. Ray-Culp. 2000. Evidence for Allee effects in an over-harvested marine gastropod: density-dependent mating and egg production. Marine Ecology Progress Series 202: 297-302.

UNEP. Undated. The SPAW Programme: Specially Protected Areas and Wildlife in the Wider Caribbean Region. Available from http://www.cep.unep.org/programmes/spaw/spaw.html

Nassau Grouper

The Nassau grouper, *Epinephelus striatus,* a member of the sea bass family (Serranidae), was historically found throughout the tropical western Atlantic Ocean, including the Caribbean Sea, the Gulf of Mexico, the southeastern U.S., Bermuda, and northern South America (Sadovy and Eklund 1999). Currently, this species occupies only a fraction of its previous range, and is classified as Endangered according to the World Conservation Union (IUCN 2006). Under this definition, endangered taxa are those that have suffered a high rate of population decline and are at risk of extinction; *E. striatus* has declined by about 60% over the last three decades (IUCN 2006). Historically, the grouper fishery has been one of the most important and valuable throughout its range (Sadovy and Eklund 1999, Gascoigne 2002). Grouper is used in traditional dishes, such as boiled fish and grouper fingers, where it is valued for having relatively few bones and being easy to eat. In The Bahamas, one of the few countries where stocks remain commercially viable (though much less abundant than in previous decades) and whose capital is the namesake of the fish, Nassau grouper has been the most valuable finfish in recent years. Commercial landings there were valued at over BSD$ 2.7 million in 2003 (Department of Fisheries [now, Marine Resources], The Bahamas undated).

Nassau grouper grow slowly and have delayed reproduction, reaching sexual maturity from 4-8 years of age when they reach 40-50 cm in length (Ray and McCormick-Ray 2004). These characteristics hinder population recovery from low densities, enhancing vulnerability to overfishing. These groupers are long-lived, capable of surviving over 20 years in the wild, and have naturally low adult mortality (Sadovy and Eklund 1999). Reproductive rates and number of eggs per reproductive event increase with age in this species, with large fish producing 5-6 million eggs per season. Most groupers change sexes with age, although this may not be the case for *E. striatus.* Fishing often targets larger individuals, eliminating those with highest reproductive capacity and skewing the age class distribution to juveniles with lower survivorship (Gascoigne 2002). During the winter months (e.g., November to February in The Bahamas, and December to March in Belize), adults undergo breeding migrations to specific offshore areas, either locally or up to hundreds of kilometers away from their resident habitats, where they form ephemeral spawning aggregations during the week around the full moon (Starr et al. 2007). These groups, historically numbering in the tens of thousands, form for reproductive and courtship purposes (Sadovy and Eklund 1999). Because there aggregations are predictable and often known to local fishermen, large numbers of fish can be readily caught during spawning. Uncontrolled exploitation has completely extirpated or reduced many spawning aggregations to a few dozens to thousands of fish, rendering many stocks commercially extinct, and disrupting spawning behavior (Sala et al. 2001, Gascoigne 2002, Sadovy 2002, Ray and McCormick-Ray 2004, Sadovy and Domeier 2005). Once eliminated, spawning aggregations have not been observed to form again, suggesting that knowledge of spawning sites depends on cultural transmission (Bolden 1980). Young groupers, in the absence of enough older, reproductively experienced individuals, seem unable to locate their spawning site. As a consequence, small aggregations with too few experienced individuals to facilitate enough new recruits to the aggregation may be doomed to extinction (Sadovy and Eklund 1999, Starr et al. 2007).

Measures have been instituted to limit fisheries in response to the observed decline in grouper numbers. These include seasonal closures (e.g., during the winter spawning months) and spatial closures around known spawning sites. In place also are gear restrictions and harvest limits for fish size and number. Commonly employed fishing methods include handline, traps, and spear guns. Marine protected areas have been hailed as one of the most promising methods for protecting Nassau Grouper (Sadovy and Eklund 1999, Gascoigne 2002). Taxation based on vessel or harvesting characteristics is another possible measure.

Habitat use, diet, and ecological role vary throughout the grouper life cycle (Sadovy and Eklund 1999, Perry Institute undated). Larvae hatch from pelagic eggs within a day after fertilization. After about 30–50 days, small juveniles leave the water column, shifting to inshore benthic nursery areas such as algal beds, seagrass, or reefs, where they will start life as relatively sedentary, demersal organisms. As they grow, they gradually shift their residences, to deeper reef habitats containing adequately sized holes, cracks, and other concavities (Ray and McCormick-Ray 2004). As adults, with the exception of the annual breeding migrations, Nassau grouper rarely disperse from their territories. They also shift their diets as they age, with juveniles feeding mainly on crustaceans, and adults feeding on a mix of invertebrates and fishes. Nassau grouper are among the larger reef fish, reaching up to 120 cm (3.9 feet) in length and approximately 25 kg (55 lbs.) in weight (Ray and McCormick-Ray 2004). A predator whose diet includes crustaceans, reef fishes, and octopuses, *E. striatus* plays a key role in reef communities (Mumby et al. 2006). Throughout its life cycle, this species also serves as prey for reef sharks, barracuda, dolphins, and humans. In addition, as with other reef fishes, *E. striatus* acts in a suite of symbiotic relationships, visiting cleaning stations, for example, where various species of small fishes (especially certain wrasses and gobies) or shrimps remove parasites from their exterior and inside their mouths. Thus, Nassau groupers are functionally linked to reef communities in numerous ways, and decreases in their populations will have community-wide impacts.

Literature Cited

Bolden, S.K. 1980. Long-distance movement of a Nassau grouper (*Epinephelus striatus*) to a spawning aggregation in the central Bahamas. Fisheries Bulletin 98(3): 642-645.

Coleman, F.C., C.C. Koenig, A.M. Eklund, and C.B. Grimes. 1999. Management and conservation of temperate reef fishes in the grouper-snapper complex of the southeastern United States. In J.A. Musick (ed.) Life in the Slow Lane: Ecology and Conservation of Long-Lived Marine Animals. American Fisheries Society, Bethesda, Maryland, USA.

Coleman, F.C., C.C. Koenig, G.R. Huntsman, J.A. Musick, A.M. Eklund, J.C. McGovern, R.W. Chapman, G.R. Sedberry, and C.B. Grimes. 2000. Long-lived reef fishes: the grouper-snapper complex. American Fisheries Society Policy Statement. Fisheries 25(3): 14-21.

Fisheries Department, The Bahamas. Undated. The Nassau Grouper Fishery of the Bahamas.

Gascoigne, J. 2002. Grouper and Conch in The Bahamas: Extinction or management? The choice is now. MacAlister Elliot & Partners, Limited; B.R.E.E.F. The Bahamas Reef Environment Educational Foundation. Available from www.macalister-elliott.com/reports/1651R03A.pdf

IUCN 2006. 2006 IUCN Red List of Threatened Species. www.iucnredlist.org. (Last accessed on 06 January 2007).

Mumby, P.J., C.P. Dahlgren, A.R. Harborne, F. Micheli, D.R.

Brumbaugh, K.E. Holmes, J.M. Mendes, K. Broad, J.N. Sanchirico, K. Buch, S. Box, R.W. Stoffle, and A.B. Gill. 2006. Fishing, trophic cascades, and the process of grazing on coral reefs. Science 311: 98-101.

Perry Institute. Undated. Nassau Grouper *Epinephelus striatus*. CMRC Poster Series No. 3. Lee Stocking Island, Bahamas and Jupiter, Florida.

Ray, G.C. and J. McCormick-Ray. 2004. Coastal-Marine Conservation: Science and Policy. Blackwell Science, Malden, Massachusetts, USA.

Sadovy, Y. 2002. The Nassau Grouper: A Cautionary Tale of Discovery, Science and Management. Available in part from www.scrfa.org/server/spawning/doc/Grouper.pdf

Sadovy, Y. and M. Domeier. 2005. Are aggregation-fisheries sustainable? Reef fish fisheries as a case study. Coral Reefs 24:254-262.

Sadovy, Y. and Eklund, A.-M. 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. Available from http://www.flmnh.ufl.edu/fish/Gallery/Descript/NassauGrouper/tr146.pdf

Sala, E., E. Ballesteros, and R.M. Starr. 2001. Rapid decline of Nassau grouper spawning aggregations in Belize: Fishery management and conservation needs. Fisheries, 26:23-31.

Starr, R.M., E. Sala, E. Ballesteros, and M. Zabala. 2007. Spatial dynamics of the Nassau grouper (*Epinephelus striatus*) in a Caribbean atoll. Marine Ecology Progress Series. In press.

Spiny Lobster

The Caribbean spiny lobster (*Panulirus argus*), found in the Gulf of Mexico, the Caribbean Sea, and the Western Atlantic Ocean from North Carolina, U.S.A., to Rio de Janeiro, Brazil (FAO 2004), is a member of the ecologically and economically important rock or spiny lobster family, Panuliridae. Apart from supporting lucrative commercial and recreational fisheries, these gregarious crustaceans are known for their migratory behavior, which can involve single-file group movements of juveniles and adults from shallow to deeper waters, related to seasonal, severe weather, or other factors (Herrnkind et al. undated). Larvae often disperse across national territories, so that management in one country may affect populations in others. This arthropod is omnivorous, scavenging mainly nocturnally on diverse kinds of plant and animal matter, including crustaceans and mollusks (Bliss 1982, Briones-Fourzan et al. 2003). Lobsters, in turn, are prey for various organisms, including sharks, groupers, snappers, sea turtles, octopuses, and humans.

(Source: T. McClanahan)

Spiny lobsters, commonly known as crawfish, are harvested throughout their range. This multi-million dollar fishery is one of the most valuable in the Caribbean (Cascorbi 2004, Bene and Tewfik 2001). Capture methods include free diving, use of traps, spears, and trawls (Bene and Tewfik 2001, FAO 2004). Spiny lobster fisheries in Florida and The Bahamas are intense, but do not result in notable harm to habitats and ecosystems, and levels of by-catch are low (Davis 1977, Davis and Dodrill 1989, Eggleston et al. 2003, Cascorbi 2004). In some areas, such as the Turks and Caicos, *Panulirus argus* may be harvested jointly with the Queen Conch (Bene and Tewfik 2001). Caribbean spiny lobsters are not classified as endangered or threatened, although they are listed on the SPAW protocol (UNEP undated). Aspects of their biology, such as rapid growth, a relatively early age of sexual maturity, high reproductive potential, and the potential for long-distance dispersal, may contribute to a relatively low susceptibility to extirpation from overfishing (Cascorbi 2004). Fisheries are regulated, including measures such as closures during spawning season, trap-reduction programs, and legal size and bag limits. Also illegal in some countries is harvesting of egg-bearing females, and fishing with firearms or explosives. Effectiveness of enforcement varies regionally (Cascorbi 2004). Marine reserves protect lobsters and their habitats, although very small protected areas may be inadequate (Eggleston and Dahlgren 2001).

Spiny lobsters occupy a variety of environments throughout their life cycle, which spans up to 30 years. Reproduction and fertilization occur in offshore reef areas, generally during late spring or early summer. During the mating process, males deposit a sticky fluid containing sperm onto the female's abdomen; this fertilizes the eggs upon release (Herrnkind et al. undated, Bliss 1982). Fertilized eggs remain under the female's tail until they hatch, and clutch size varies with location and fishing pressure. In the Dry Tortugas, for example, lobsters became reproductively active at larger sizes, and the average number of eggs is higher than in a south Florida fishery (Bertelsen and Matthews 2001). Eggs hatch into transparent phyllosome larvae that drift offshore with the surface currents. This pelagic stage generally lasts 6-12 months, resulting in long distance dispersal spanning hundreds of kilometers (Herrnkind et al. undated). They next molt into free-swimming puerulus postlarvae, which leave the open ocean to settle in nearshore vegetated benthic areas such as sea grasses, algal beds, or mangroves (Acosta et al. 1997, Acosta 1999, Butler et al. 1997). This process is thought to vary with characteristics of the nursery habitat, postlarval supply, environmental factors, fishing pressure, and oceanographic circulation (Lipcius et al. 1997, Butler et al. 2001, 1997, Cruz et al. 2001, Lipcius et al. 2001, Yeung et al. 2001). Postlarvae metamorphose into juveniles, whose movements are asocial and initially restricted to sheltered areas such as algal beds (Butler et al. 1997, Herrnkind et al. undated). As time goes on they become increasingly vagile and social, living in small aggregations inside crevices, under rocks, seaweeds, sponges and corals (Eggleston and Dahlgren 2001). As lobsters approach maturity, which may occur around 2-3 years of age, they move to deeper waters in coral reef systems where reproduction occurs (Herrnkind et al. undated).

Literature Cited

Acosta, C.A. 1999. Benthic dispersal of Caribbean spiny lobsters among insular habitats: implications for the conservation of exploited marine species. Conservation Biology 13(3): 603-612.

Acosta, C.A. and M.J. Butler, IV. 1997. Role of mangrove habitat as a nursery for juvenile spiny lobster, *Panulirus argus*, in Belize. Marine and Freshwater Research 48: 721-727.

Bene, C. and A. Tewfik. 2001. Fishing Effort Allocation and Fishermen's Decision Making Process in a Multi-Species Small-Scale Fishery: Analysis of the Conch and Lobster Fishery in Turks and Caicos Islands. Human Ecology 29 (2): 157-186.

Bertelsen, R.D. and T.R. Matthews. 2001. Fecundity dynamics of female spiny lobster (*Panulirus argus*) in a south Florida fishery and Dry Tortugas National Park lobster sanctuary. Marine Freshwater Research 52: 1559-1565.

Bliss, D. 1982. Shrimps, Lobsters and Crabs. New Century Publishers, Piscataway NJ: 242 pp.

Briones-Fourzan P, V.C.F. de Lara, E. Lozano-Alvarez, and J.

Estrada-Olivo. 2003. Feeding ecology of the three juvenile phases of the spiny lobster *Panulirus argus* in a tropical reef lagoon. Marine Biology 142 (5): 855-865.

Butler, M.J., IV, W.F. Herrnkind, and J.H. Hunt. 1997. Factors affecting the recruitment of juvenile Caribbean spiny lobsters dwelling in macroalgae. Bulletin of Marine Science 61: 3-19.

Butler, M.J., IV, T. Dolan, W. Herrnkind, and J. Hunt. 2001, Modeling the effect of spatial variation in postlarval supply and habitat structure on recruitment of Caribbean spiny lobster. Marine Freshwater Research 52: 1243-52.

Cascorbi, A. 2004. Seafood Watch Seafood Report: Caribbean Spiny Lobster *Panulirus argus*. Available from http://www.mbayaq.org/cr/cr_seafoodwatch/content/media/MBA_SeafoodWatch_CarribbeanSpinyLobsterReport.pdf

Cruz, R., E. Diaz, M. Baez, and R. Adriano. 2001. Variability in recruitment of multiple life stages of the Caribbean spiny lobster, *Panulirus argus,* in the Gulf of Batabano, Cuba. Marine Freshwater Research 52: 1263-70.

Davis, G.E. 1977. Effects of recreational harvest on a spiny lobster, *Panulirus argus*, population. Bulletin of Marine Science 27(2) 223-236.

Davis, G.E. and J.W. Dodrill. 1989. Recreational fishery and population dynamics of spiny lobsters, *Panulirus argus*, in Florida Bay, Everglades National Park. Bulletin of Marine Science 44: 78-88.

Eggleston, D.B. and C.P. Dahlgren. 2001. Distribution and abundance of Caribbean spiny lobsters in the Key West National Wildlife Refuge: relationship to habitat features and impact of an intensive recreational fishery. Marine Freshwater Research 52: 1567-76.

Eggleston, D.B., E.G. Johnson, G.T. Kellison, and D.A. Nadeau. 2003. Intense removal and non-saturating functional responses by recreational divers on spiny lobster *Panulirus argus.* Marine Ecology Progress Series 257: 197-207.

FAO. 2004. FIGIS Species Fact Sheets Panulirus argus (Latreille, 1804). A world overview of species of interest to fisheries. Chapter: *Panulirus argus*. Available from http://www.fao.org/figis/servlet/species?fid=3445

Herrnkind, W.F. et al. Undated. Life History and Ecology of the Caribbean spiny lobster. Available from http://bio.fsu.edu/~herrnlab/lifehistory.html

Lipcius, R.N., W.T. Stockhausen, D.B. Eggleston, L.S. Marshall, Jr., and B. Hickey. 1997. Hydrodynamic decoupling of recruitment, habitat quality and adult abundance in the Caribbean spiny lobster: Source-sink dynamics? Marine and Freshwater Research 48(8): 807-815.

Lipcius, R.N., W.T. Stockhausen, and D.B. Eggleston. 2001. Marine reserves for Caribbean spiny lobster: Empirical evaluation and theoretical metapopulation recruitment dynamics. Marine and Freshwater Research 52(8): 1589-1598.

UNEP. Undated. The SPAW Programme: Specially Protected Areas and Wildlife in the Wider Caribbean Region. Available from http://www.cep.unep.org/programmes/spaw/spaw.html

Yueng, C., D.L. Jones, M.M. Criales, T.L. Jackson, and W.J. Richards. 2001. Influence of coastal eddies and countercurrents on the influx of spiny lobster, *Panulirus argus*, postlarvae into Florida Bay. Marine Freshwater Research 52: 1217-32.

Fishery Management and Biodiversity Conservation

Despite its extraordinary value, the marine environment faces myriad threats from local to global sources. The world's oceans encompass about three quarters of the earth's surface. In addition to supporting critical natural processes, oceanic resources are important for maintaining human economies, amenities, and cultures along the world's coastlines. For example, oceans play a key role in climate regulation, harbor a substantial amount of the planet's biodiversity (especially in coral reefs), and host fisheries, tourism, and shipping industrial sectors.

Marine organisms and habitats are under intense stress, which has resulted in worldwide biodiversity loss (Agardy 2000a). Systems are strained principally by unsustainable fishing practices, as well as other factors such as habitat degradation, coastal development, and climate change (Jackson et al. 2001, Pauly et al. 2002). These factors impact not only the marine environment, but humans as well. Many of the world's commercial fisheries are currently overexploited. World fisheries landings have been slowly declining since the late 1980s, by about 0.7 million tons per year (Pauly et al. 2002). Importantly, fishery operations typically have targeted large, long-lived predatory fishes. With the depletion of these top predators, fisheries have shifted their focus to organisms lower on the food web. This phenomenon, known as "fishing down food webs", may lead to fishery collapses and negative cascading effects that alter the entire system (Pauly et al. 2002). Overexploitation degrades fish stocks and ultimately threatens food security in coastal populations.

There are different ways to address these issues, ranging from single-species to ecosystems-based fishery or biodiversity management. Traditional fishery management has focused on Maximum Sustainable Yield (MSY), calculated for target stocks using population dynamic models (Agardy 2006). This can be employed to determine harvest restrictions, such as size/age limits, quotas, restrictions on numbers of boats, maximum harvest and gear limits, and closures. By setting a size limit above which organisms can be harvested, younger members of the population are protected. Quotas set a maximum limit to capture, which may be essential in curbing efficient fishery operations capable of harvesting above sustainable levels. Closed seasons may ban fishing during times key to organismal life cycles. In parts of the Nassau Grouper range, for example, fishing is prohibited during spawning season to prevent the detrimental effects discussed previously (Sadovy 2002). Traditional measures alone, however, are insufficient to counter the hazards mentioned above (Pauly et al. 2002, Botsford et al. 1997). Management based on MSY, for example, may suffer from uncertainty, imperfect models, insufficient data, and inadequate consideration of ecosystem effects (Stergiou 2002, Pauly et al. 2002). Improved technology and the open-access nature of the sea further contribute to resource depletion.

Marine protected areas (MPAs) are a promising tool for sustaining ocean ecosystems through biodiversity conservation and fishery enhancement (Agardy and Staub 2006, and references therein). MPAs embody a precautionary and ecosystems-based approach to marine management. They protect biodiversity from genes to ecosystems by safeguarding vital processes. An increase in diversity, density, biomass, and size of organisms within marine reserves has been demonstrated in areas protected from resource extraction and habitat damage. This may lead to increased reproduction, as older individuals often make greater reproductive contributions. Closed areas may enhance fisheries by increasing the size and abundance of important target species, replenishing fished areas. The term "spillover" refers to increased production outside reserve boundaries attributed to emigration from within the MPA (Agardy and Staub 2006, and references therein). MPAs also present a solution for management difficulties in working with species of vastly different life histories (Roberts 1997a). Further, they provide a safety valve against inherent uncertainty (Roberts 1997a).

Use of MPAs or reserves alone, however, may be insufficient to protect target stocks from overexploitation (Agardy and Staub 2006). These areas, for example, are often not as large as the focal species' home range. In addition, the ecology and life history of many organisms remain insufficiently understood. Chances of success for marine reserves to protect target groups may be greater if managed adaptively, in combination with other conventional methods. Of note, reserves designed to protect focal taxa may not result in ecosystem conservation. Ecosystem-based fisheries management is a promising means of addressing this limitation. This approach focuses on interactions among multiple species and habitats used throughout their life cycles. This strategy recognizes that marine elements are not isolated, and that changes may affect the whole system. The greatest benefits to fishers and biodiversity may accrue from participatory approaches involving multiple stake-holders (Villa et al. 2002).

Written with Camila Sibata, Columbia University.

Literature Cited

Agardy, T. 2000a. Effects of fisheries on marine ecosystems: a conservationist's perspective. ICES J. of Marine Science 57:

761-765.

Agardy, T. 2006. Marine Conservation Biology. NCEP module synthesis document. Available from http://ncep.amnh.org/

Agardy, T. and F. Staub. 2006. Marine Protected Areas and MPA Networks. NCEP module synthesis document. Available from http://ncep.amnh.org/

Botsford, L.W., J.C. Castilla, and C.H. Peterson. 1997. The Management of Fisheries and Marine Ecosystems. Science 277: 509-515.

Jackson, J.B.C., M.X. Kirby, W.H. Berger, K.A. Bjorndal, L.W. Botsford, B.J. Bourque, R.H. Bradbury, R. Cooke, J. Erlandson, J.A. Estes, T.P. Hughes, S. Kidwell, C.B. Lange, H.S. Lenihan, J.M. Pandolfi, C.H. Peterson, R.S. Steneck, M.J. Tegner, and R.R. Warner. 2001. Historical overfishing and the recent collapse of ocean ecosystems. Science 293: 629-638.

Pauly, D., V. Christensen, S. Guénette, T.J. Pitcher, U.R. Sumaila, C.J. Walters, R. Watson, and D. Zeller. 2002. Towards sustainability in world fisheries. Nature 418: 689-695.

Sadovy, Y. 2002. The Nassau Grouper: A Cautionary Tale of Discovery, Science and Management. Available in part from www.scrfa.org/server/spawning/doc/Grouper.pdf

Stergiou, K.I. 2002. Overfishing, tropicalization of fish stocks,

Table 1. Summary of default values employed in the simulation exercise

	Grouper	Conch	Lobster
Initial population	50,000	150,000	110,000
Lifespan (days)	3285	3102	2920
Intrinsic growth rate	0.2	0.4	0.5
Carrying capacity	10000	15000	12500
Average catch rate (kg)	5	0.4	1
Dispersal rate	8	1	6
Fishing efficiency	0.02	0.09	0.04
Speed (km/hr)	20	20	20
Travel cost ($/km)	1	1	1
Boat cost ($/day)	12	12	12
Maximum boats/port	35	35	35
Maximum harvest (kg)	200	40	100
Price ($/kg)	5	6	8

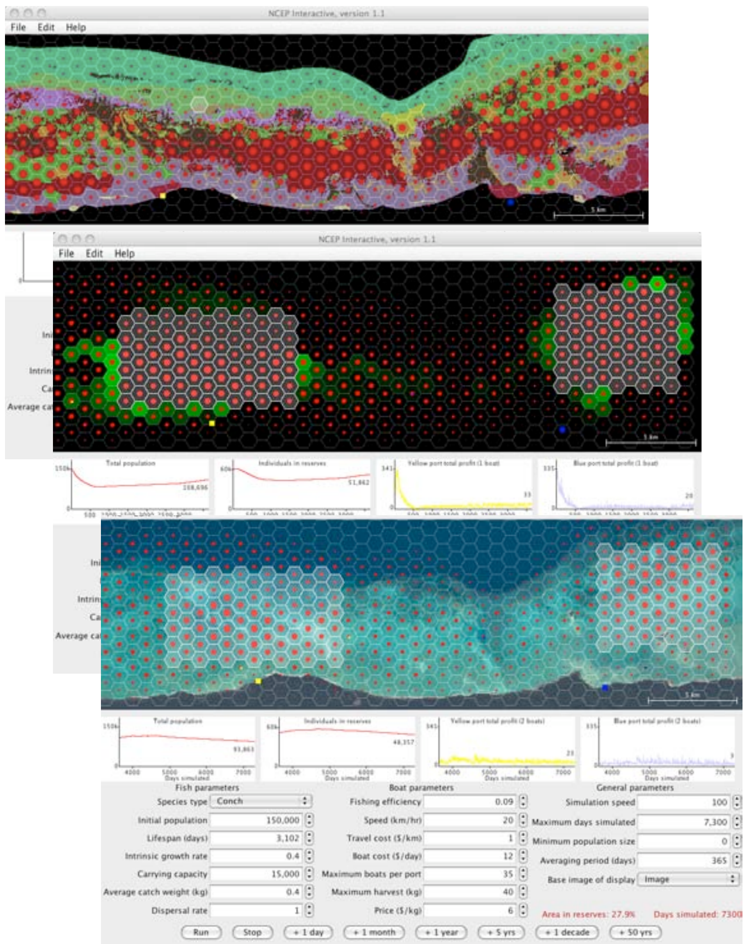
uncertainty and ecosystem management: resharpening Ockham's razor. Fisheries Research 55: 1-9.

Villa, F., L. Tunesi, and T. Agardy. 2002. Zoning Marine Protected Areas through Spatial Multiple-Criteria Analysis: the Case of the Asinara Island National Marine Reserve of Italy. Conservation Biology 16 (2), 515-526.

Download the Simulation

If you do not already have the simulation installed on your computer:

1. To run the simulation, you will need to have Java version 1.4 or later on your computer. This is available for download free of charge at http://java.sun.com/j2se/1.5.0/download.jsp. Please note that if you are working on a Macintosh computer, the version of Java used should be 1.4.2.
2. Download the exercise onto your computer by clicking on the file or simulation icon. **Note**: To run the simulation, you will need to have a recent version of the Java Runtime Environment on your computer, available for free download at http://java.sun.com/j2se/1.5.0/download.jsp. If your operating system is MacOSX, click on the Apple icon on the upper left part of your screen. Then click on "Software Update". If no Java Runtime Environment update is required, quit Software Update and proceed.
3. Save the program to your directory of choice.



Images of MPA interactive simulation software

Interactive Simulation

1. Double-click on the simulation icon to start the exercise.
2. After a few seconds, a window will appear. This includes a satellite image, as well as several variables describing fishery biology and economics, and simulation general parameters (see Glossary).
3. There are three species-types to choose from. These are Grouper, Conch, and Lobster. Their characteristics are based on those of real organisms.
4. Each variable (for example: lifespan) is set to default values that are within ranges published in the literature for the focal species, when these are known (Table 1). It is important to note that the exercise simulates "species types" and their fisheries. As such, the simulated organisms and their fisheries, although generally similar to grouper, conch, and spiny lobsters, are not intended to represent real world situations. Consider that this is a single-life stage model, which inflates this simplified composite number. To simulate other organisms of your choice, you can alter these numbers by selecting them and typing in your own values.
5. Pointing at each parameter with your cursor causes tool tips to appear. These explain each parameter, and provide minimum and maximum values. Parameters are also described in the Glossary. Please note: these tool tips will

only appear if your mouse is rolled over the value legend (such as "Initial population" or "Lifespan (days)". The tool tips will not appear if the mouse is rolled over the value field, or boxes where the variables are set.

6. You will see that the base image is overlaid by a hexagonal grid. In conservation planning, landscapes or seascapes are often subdivided into such units for planning purposes.
7. The red dots in each hexagon reflect the relative abundance of adult organisms within each planning unit. Pointing at a planning unit with your cursor will cause the number of organisms present in the hexagon, as well as the habitat type (see below), to appear.
8. Later on in the exercise, you will be able to construct a reserve system by clicking on hexagonal planning units of your choice. This will cause the hexagon to become outlined in white. No fishing will occur in protected hexagons, although boats may transit through without fishing.
9. You will also be able to follow boat movements along the seascape. Boats belong to one of two ports (Yellow or Blue), and are represented by small dots of the corresponding colors.
10. Pressing the Run button will start the simulation.
11. You may interrupt the run by pressing the Stop button. The speed of the simulation can also be changed in the appropriate field. Please note that 100 is the maximum available speed (as noted in the tool tips). There are additional buttons to speed up the simulation by the chosen time period (for example, "+1 decade").
12. While the simulation is running, the base image will depict changes in numbers of adults through corresponding alterations in size of the red dots.
13. Changes in population numbers (total and within reserves), as well as economic aspects of the fishery are shown in 4 graphs. Please note that the scale of the graphs changes as the data warrant. Clicking on a graph will cause a larger version to appear in a separate window. The graphs can also be saved using the "Save" option in the "File" menu.
14. Boats exit the simulation if their profits are negative, so that boat numbers may vary throughout the run. **This simulation assumes there will be at least one boat from each port participating in the fishery, even at negative profits.** The model for the behavior of fishermen is that if all boats from a given port have negative profit one day, then one boat drops out of service. One or more boats can be making a profit, even while the average profit (shown in the graphs) is negative. Thus, the average profit can go negative for a while, before boats start dropping out of service, and more than one boat may be present even at negative profits.
15. The percentage of total area in reserves at any given time is shown on the bottom right of the panel, as are the number of days simulated. Both are highlighted in red.
16. The simulation will end automatically when either the maximum days simulated or the minimum population size are reached. The default value for maximum days simulated is 20 years (7300 days). These variables can be specified in the column headed "General Parameters" on the right hand side of the panel.
17. You may alter the base image of the simulation using the "Base image of display" button on the bottom right. Toggle between a satellite image, an image showing habitat classifications, and an image reflecting habitat suitability for each species type. Species occurrence in each kind of habitat is based on its biology. Sea grass is appropriate habitat for conch, for example, while coral reefs are more suitable for spiny lobsters and groupers. Pointing your cursor at any hexagon will cause these classifications to appear. In the suitability screen, the most suitable habitats are lighter in color. The habitats, classified as follows, are defined in the Glossary:
    - Unclassified (land or deep water)
    - Sparse seagrass
    - Medium density seagrass
    - Dense seagrass
    - Sand
    - Silt / mud
    - *Batophora* dominated
    - Sargassum on hardbottom

- Dead coral and *Microdictyon*
- Sparse gorgonians and algae
- Uncolonized pavement and sparse gorgonians
- *Montastraea* reef
- *Acropora palmata* reef
- *Porites* reef
- Patch reef
- Mangrove

18. The "Base image of display" menu also contains options that summarize the following simulation outputs: Average effort, Average harvest, Potential yellow or blue boat profits, and Yellow or Blue boat profit sources. Values corresponding to each cell are provided in the tool tips. The Average effort and Average harvest options output the average effort and catch over the last year of the simulation. The Potential profit displays reveal the projected profits for each color boat at the time. The profit source feature tracks the cells of origin (i.e., birth) for individuals that are caught by blue or yellow boats in fishable areas. The lighter colors indicate larger amounts, and the values corresponding to each cell are provided in the tool tips.
19. You can save your results by opening the File menu under the Save option, on the upper right hand side of the screen.
20. You will be able to Reset to Time 0, Clear reserves, or Reset default values by selecting these options under the Edit menu, on the upper left side of the screen.

Glossary

Acropora palmata reef: habitat classification. Reefs with the coral Acropora palmata, also called Elkhorn Coral, typically have high vertical relief. This habitat is found at the crest of the reef. Although *A. palmata* is generally the most common coral in this habitat, the bottom community also includes other stony corals, gorgonians, and algae. This habitat is found between approximately 1 and 5 meters depth.

Average catch weight (kg): simulation fish parameter. Average weight of fish caught (kg; 0.1 -1000.0).

Base image of display: simulation general parameter. Image that is used for the background of the simulation.

Batophora dominated: habitat classification. This habitat contains abundant patches of the club-like algae *Batophora* and is typically on a hard bottom with a small amount of sediment. This kind of algae is also often seen growing on conch shells. Other algae and some patches of seagrass are often present in this habitat, which is founding low energy lagoonal environments.

Boat cost ($/day): simulation boat parameter. Cost per day to operate a boat, excluding travel (0 - 1000).

Carrying capacity: simulation fish parameter: maximum population per hexagon, in optimal conditions (0 – 100,000).

Dead coral and *Microdictyon*: habitat classification. In some areas, the majority of corals have died, possibly during bleaching events. These habitats are in shallow waters and appear to have been similar to *Montastraea* reef communities. They still have the rough structure of a coral rich area. The mesh-like algae *Microdictyon* is seasonally common and covers the substrate, presumably flourishing after the loss of live coral colonies. This habitat is found in a limited number of areas just landward of the reef crest.

Dense seagrass: habitat classification. This habitat is dominated by the seagrass *Thalassia*, also called Turtle Grass, but may contain the tube-like seagrass *Syringodium*. Dense Seagrass habitats have high biomass (tall plants, high density) and a low amount of visible sand and silt. This habitat is found in lagoonal environments where sediment is deep enough for the seagrasses to take root.

Dispersal rate: simulation fish parameter: percent of fish that move to another cell per day (0.0 – 75.0).

Fishing efficiency: simulation boat parameter: fraction of a cell's fish that a boat can catch per day (0.0 – 1.0).

Initial population: simulation fish parameter: initial total fish population (0 - 10,000,000). For purposes of the simulation, some of the default values may be more representative of well-established and protected areas than initially unprotected systems. These can be changed at will.

Intrinsic growth rate: simulation fish parameter. Population growth rate per year, in optimal conditions (0.0 - 2.0).
Lifespan: Simulation fish parameter. Typical lifespan (days; 0 - 100,000).

Mangrove: habitat classification. Mangrove trees grow in shallow, brackish waters along coasts and up creeks of some islands. Their roots provide nursery habitat for many important fish species. Mangroves in and around estuaries also trap sediments that might otherwise flow onto reefs and smother corals to death.

Maximum boats per port: simulation boat parameter. Maximum number of boats per port (0 – 1000).

Maximum days simulated: simulation general parameter. Stop simulation after this number of days (1 – 1,000,000).

Maximum harvest (kg): simulation boat parameter. Maximum catch per day (kg; 0 – 10,000).

Medium density seagrass: habitat classification. This habitat is dominated by the seagrass *Thalassia*, also called Turtle Grass, but may contain the tube-like seagrass *Syringodium* and the thin-bladed seagrass *Halodule*. Occasionally one also finds small coral colonies within the seagrass. Medium Density Seagrass habitats have medium biomass (medium plant height, medium density) and a medium amount of substratum is visible, when compared to Dense and Sparse Seagrass. This habitat is found in lagoonal environments.

Minimum population size: simulation general parameter. Stop simulation if fish population drops below this number (0 – 10,000,000).

Montastraea reef: habitat classification. The coral species *Montastraea annularis*, also called Boulder Star Coral, is the dominant coral species in this habitat. This benthic community is diverse, including corals, sponges, gorgonians, and algae. *Montastraea* Reef also supports a diverse and abundant fish community. This habitat is found in some reef environments between approximately 5 and 15 meters deep.

Patch reef: habitat classification. Patch reefs are reef formations often found in lagoons and surrounded by seagrass beds. They commonly have a small 'halo' around them of relatively clear sand cleaned by grazing fish and invertebrates. They support much more diverse invertebrate and fish communities than surrounding habitats.

Porites reef: habitat classification. At some sites, there are unusual areas of extensive growth of the Finger Coral *Porites porites*. These areas typically support an abundant number of juvenile fish, particularly grunts, parrotfish, wrasse, and damselfish. These reefs are found in shallow water less than 2 meters deep.

Price ($/kg): simulation boat parameter. Price per kilogram received by fishermen (0.0 – 100.0).

Sand: habitat classification. This habitat includes both clean sand and sand with a sparse algal community. It is found in lagoonal areas and near reefs.

Sargassum on hardbottom: habitat classification. This habitat contains numerous *Sargassum* plants, typically on a hardbottom with a limited covering of sediment. In some areas, the *Sargassum* plants reach greater than 1 meter tall. Other algae often occur between the *Sargassum* plants. This habitat occurs in medium energy lagoonal environments.

Silt / mud: habitat classification. Silt, which is finer than sand, is often present near shore areas and creeks. Seagrass and algae are often present in this shallow water habitat.

Simulation speed: simulation general parameter. Number of days simulated per second of animation (1 - 100).

Sparse gorgonians and algae: habitat classification. Gorgonians include sea fans, sea feather plumes, sea whips, and sea rods. This habitat is composed of sparse gorgonians on a hardbottom with some algae. In some areas, this benthic community is found in shallow reef environments and on hardbottom in the lagoon area.

Sparse seagrass: habitat classification. This habitat is dominated by the seagrass *Thalassia,* also called Turtle Grass, but may contain the tube-like seagrass *Syringodium* and the thin-bladed seagrass *Halodule*. Occasionally one also finds small coral colonies within the seagrass. Sparse Seagrass habitats have relatively low biomass (short plants, low density) and a high amount of substratum is visible. This habitat is found in lagoonal environments where sediment is deep enough for the seagrasses to take root.

Speed (km/hr): simulation boat parameter. Speed of travel to fishing grounds (km/hr; 0 – 100).

Travel cost ($/day): cost per day to operate a boat to and from fishing grounds (0 - 1000).

Uncolonized pavement and sparse gorgonians: habitat classification. Uncolonized Pavement is found in one of the high energy 'cuts' through the *Acropora* reef crest. This habitat is similar to the Sparse Gorgonians and Algae habitat but it has very few gorgonians and algae.

Marine Reserves and Local Fisheries An Interactive Simulation

The Exercise

Eugenia Naro-Maciel and Daniel R. Brumbaugh

OBJECTIVES

In this simulation exercise, you will be able to explore various factors that influence fish population viability and fishery sustainability. You will also experiment with the use of marine reserves as tools in fisheries management.

Discussion Questions for All Seven Levels

As you complete each level, think about the major lessons you have learned, regarding marine populations, fishery management, and marine reserves. The simulations provide a useful heuristic tool for exploring many issues in
marine reserve design, and are highly illustrative and useful for comparative and educational purposes. Even so, it is important to consider the limitations of the exercise. The simulation is based on a mathematical model describing organismal population dynamics and fishery economics. The main parameters of this model are the variables on the simulation panel. This model was written by Steven Phillips. The author himself, however, is the first to note that there are limitations to any model, which must be kept in mind when interpreting results. If you would like to learn more about the model, it can be found in Appendix I (see below). This model focuses mainly on the adult life stage.

Can you think of some important caveats, and reasons why, although theoretically useful, the results of this exercise cannot be applied directly to any specific area or species? It might be helpful to read over the introductory pages, as they contain relevant information on complexities in life cycles and fisheries of Nassau Grouper, Spiny Lobster, and Queen Conch.

Notes for All Seven Levels

In working through this exercise, you will notice there are many details. For example, rolling your mouse over each hexagon will cause the exact number of organisms within to be revealed. Keep in mind the overall amount of time your teacher has given you for each assignment, and before focusing on details, try to get an idea of the larger picture.

Although efforts have been made to provide a realistic scenario, due to necessary simplifications and model assumptions, simulation results are not intended to reflect reality.

LEVEL I STARTING UP

Take a few minutes to familiarize yourself with the exercise, and to become comfortable with the simulation. This part of the exercise focuses on an unprotected system, where there are no reserves in place.

- Make sure that no part of the total area is protected in reserves, by selecting "Clear Reserves" under the "Edit" menu before you begin.
- Select any species-type.
- Press Run. The simulation will automatically run for 20 years.

When the simulation has ended, indicate the option/s that best describe/s overall trends observed. Click on the relevant graph to visualize trajectories over the course of the simulation.

Species: ___________________________________

Population size:	increase	decrease	remain stable
Yellow port total profits:	increase	decrease	remain stable
Blue port total profits:	increase	decrease	remain stable

LEVEL II OPEN-ACCESS FISHERIES

Divide into groups of 3-6 students. Within each group, one or two students will focus on each species-type, so that all species-types are represented in one group. Make sure you are working on a different organism than you did for Level I. For your new species-type, explore the effects of fisheries on fish population size and fishery economics, when no areas are closed to fishing.

Ongoing fishery crisis. More than two thirds of the world's fisheries are considered fished beyond capacity, or in danger of this (FAO 1995). Increasingly efficient boats and fishery technology, combined with reduced fish population sizes, contribute to this phenomenon.

- To explore this, run the simulation for 20 years and fill out the table below. Use the default values, or the numbers that appear automatically for each species-type at the start of the simulation. The "+ year", "+ 5 years" and "+ decade" buttons may be useful in this regard.

Species: ___________________________________

Number	After 1 Year	After 5 Years	After 10 Years	After 15 Years	After 20 Years
Organisms					
Yellow Boats					
Yellow Total Profits					
Blue Boats					
Blue Total Profits					

Indicate the option/s that best describe/s overall trends:

Population size:	increase	decrease	remain stable
Yellow port total profits:	increase	decrease	remain stable
Blue port total profits:	increase	decrease	remain stable

Discussion points

After running your individual simulations, get together as a group. Discuss your results for the three species-types.

Do you have any thoughts about why patterns might be similar or different?

There are also many interesting points do discuss regarding historical over-fishing, shifting baselines, and trophic cascades (Jackson et al. 2001, Pauly et al. 1998). Overturning prior assumptions, Jackson et al. (2001) showed that many marine populations were overfished even in historical times, and occur today at fractions of their past levels. You may wish to explore this by running the simulations for longer than 20 years, starting at different initial population levels, or reducing fishery effectiveness and maximum harvest.

In related work, Pauly and colleagues coined the term "shifting baseline syndrome" to describe the arbitrary nature of some recovery targets. These authors noted that, in some cases, recovery targets are set at the size the fish population was at the start of the manager's career. On the other hand, if historical levels were considered, recovery targets would be set higher. In the simulation, shifting baselines can be modeled by using different initial population sizes and keeping other parameters constant.

One commonly used definition of an overfished stock is one that occurs at 20% of initial levels. Can you think of a limitation of such definitions, especially when considering history? Can you think of other ways to define overfishing? Of note, when one species becomes overfished, fishers tend to shift their attention to other species, resulting in trophic cascades (Pauly et al. 1998). How might the trends detectable in your simulations be affecting other organisms in the ecological community? Also, consider how different fishing methods might vary in the degree of harm caused to the environment, for example through by-catch, or accidental harvest of non-target species.

LEVEL III MARINE RESERVES AND SINGLE-SPECIES MANAGEMENT

You will now be able to design your own reserve networks for each species-type. Break up again into small groups, or work individually. One or two people will be assigned to work on each species-type within a 2 - 6 person group. You may also wish to have one student or group focus on biological issues, while the other concentrates on economic aspects.

Notes: Before you plan your reserve system, think about feasibility, enforceability, and effectiveness in a real-world scenario. Simpler reserve configurations, with easily understood boundaries and a degree of contiguity, are going to be more realistic. A system of various disconnected single-hexagon reserves, for example, could be ineffective or unenforceable. In most MPAs, in light of practical issues and constraints, boundaries are marked by buoys, signs, or aligned through landmarks offshore, and designed to be readily comprehended, complied with, and enforced.

When evaluating reserve placement, it may be helpful to look at the Average effort, Average harvest and Potential profits options under the "Base Image of Display" pull down menu. Also of interest in this pulldown menu are the habitat Suitability and Classes options.

a. Proportion of area in reserves

At the Fourth World Congress on National Parks and Protected Areas (Caracas, Venezuela, 1972), it was recommended that PAs protect at least 10 percent of each biome; however, this target has not been achieved for marine sites, among others. Over 90% of the world's existing parks are terrestrial, covering about 12% of the land surface. MPAs, however, protect only 0.5% of the global oceans. The Great Barrier Reef MPA in Australia is the largest in the world. In other places, however, reserves may be very small.

- Experiment with the amount of area set aside for protection in a reserve nework of your choice, for your species-type.
- Run the simulation for 20 years.

Species: ___________________________________

Reserves

	100%	50%	25%	10%	No reserves
Total organisms					
Fish in reserves					
Yellow boats					
Yellow profits					
Blue boats					
Bliue profits					

b. Reserve placement

A complex issue in conservation planning is placement of reserves. It has been noted that much of the terrestrial reserve system includes habitats unsuitable for many species (such as the large terrestrial reserve in Greenland, composed mainly of snow).

- Go to Edit, Reset defaults.
- Switch to the Suitability option for "Base Image of Display". The lighter habitats are the most suitable for your species-type. The tool tips will indicate how many organisms are in each hexagon.
- Place 10% of the total area in marine reserves situated in the most suitable habitat (the lightest colored habitat). You may distribute the MPAs as you wish, as long as they are within the specified kind of habitat (suitable or unsuitable). When designing your reserve system, however, think about enforcement and feasibility, as discussed above.
- Run the simulation for 20 years, the default value.
- After filling in the Suitable Habitat column in the table below, go to the Edit Menu and Clear Reserves.
- Next, taking feasibility into account, place 10% of the total area in marine reserves located in unsuitable habitat (hexagons that are black or contain small red dots), and write your answers in the chart below.

- To fill out the "no reserves" column, you may draw directly from your work on previous levels.

Species: ___________________________________

Number	Suitable habitat	Unsuitable habitat	No reserves
Total organisms			
Organisms in reserveves			
Yellow boats			
Yellow profits			
Blue boats			
Blue profits			

Indicate the option that best describes overall trends when reserves are in suitable habitat:

Population size:	increase	decrease	remain stable
Yellow port total profits:	increase	decrease	remain stable
Blue port total profits:	increase	decrease	remain stable

Indicate the option that best describes overall trends when reserves are in unsuitable habitat:

Population size:	increase	decrease	remain stable
Yellow port total profits:	increase	decrease	remain stable
Blue port total profits:	increase	decrease	remain stable

c. Reserve size and connectivity

The so-called SLOSS (Single large versus several small) debate centers around the benefits and costs of choosing a single large versus several small reserves. An important issue is connectivity among groups, which varies in nature. For populations that are naturally connected, for example, instituting a system of isolated reserves may not preserve natural linkages necessary for population processes. These are key factors to consider in reserve design.

- Explore these issues by selecting 6 small, isolated reserves encompassing 10% of the area in total. Each reserve should protect between 5 and 10 hexagons (1- 2% of the total; each hexagon represents about 0.2% of the total). Every reserve should be at least 8 hexagons away from the other reserves.
- Then design one large reserve protecting 10% of the area. Each hexagon in this reserve must be connected to at least one other, except where impossible, such as along the edges.
- In each case, run the simulation for 20 years and enter your results in the table below.

Species: ______________________________

Reserves

Number	Several small isolated	1 large	No reserve
Total organisms			
Organisms in reserve			
Yellow boats			
Yellow total profits			
Blue boats			
Blue total profits			

Indicate the option that best describes overall trends with…

Several Small Reserves:

Population size:	increase	decrease	remain stable
Yellow port total profits:	increase	decrease	remain stable
Blue port total profits:	increase	decrease	remain stable

Single Large Reserve:

Population size:	increase	decrease	remain stable
Yellow port total profits:	increase	decrease	remain stable

Blue port total profits: increase decrease remain stable

d. Reserves in combination with other methods

As noted by Dr. Tundi Agardy in the "Marine Protected Areas and Networks" module, reserves may work best in combination with other measures, such as harvest, gear, and boat limits.

- Enter the 10% reserve system of your choice from your results so far.
- Set the fishing efficiency, maximum boats per port, and maximum harvest levels to ½ their default values.
- Run the simulation for 20 years, then record your results.

Species: ___________________________________

Number	Reserves only (from above)	Reserves and limits
Organisms		
In reserves		
Yellow boats		
Yellow total profits		
Blue boats		
Blue total profits		

Discussion Points

After running your individual simulations, get together as a group, to consider how results from different kinds of fisheries compare to each other, and why.

- Were you able to identify reserve networks that eventually increased or maintained stable both fishery rents and fish population sizes?
- Are the networks similar across species?

Although various elements of reserve design were explored separately in each section, in addressing the following questions consider also interactions among different factors, such as habitat suitability and proportion of area protected.

- What percentage of habitat would you recommend be set aside in reserves for each species type, and why? Can you think of limitations of using numerical percentage targets? Are there other criteria that might be important in designating sites for protection?

- How do results when there are no reserves, reserves in unsuitable habitat, and PAs in suitable habitat compare? Is habitat suitability important for effectiveness?
- How would you resolve the SLOSS debate as regards your marine organism? Can you think of a way to reconcile these two approaches? Can you think of specific cases where it would be essential to link sites into a network, and others where this might not be important? Are there local examples you view as models or that need improvement?
- Does your design account for environmental variation or catastrophes?
- What impacts do limiting gear, boats and harvest have on organismal population and fishery economics? What other measures might you employ, either singly or in combination with marine reserves, towards achieving sustainable resource use?
- Do you think your recommendation would be feasible in the real world, in particular as regards enforcement and funding? Is there a role for consumer choice?

Consider also that, in the real world and despite reserve placement, many populations, such as Conch, remain at low levels. Discuss the idea of possible thresholds below which reserve placement has little impact on population numbers, at least in the short-term.

LEVEL IV MARINE RESERVES AND MULTIPLE SPECIES

Working as a group, can you build a reserve network that keeps population numbers of all 3 species-types, as well as fishery profits, steady or increasing, after 20 years? Do you have a compromise solution to offer? Would use of other measures, perhaps in combination with marine reserves, be a useful option?

Discussion Points

Think about these results as regards ecosystem conservation, and the challenge of conserving multiple taxa or systems. Are there local examples of reserves to protect groups of interest? What are your opinions about single-species versus ecosystem level conservation? What are some ways to address controversial issues?

Other key concepts in reserve design are representation and duplication. In general, the former entails ensuring that most major habitat types are included in a reserve system. Switch to the "Classes" option under "Base image of display". Running the mouse over any hexagon will cause tip tools to appear, which will allow you to match habitat type to the color on your habitat map. How many of the 15 habitat types are included in your suggested reserve or network? Are all species and groups equally or fairly represented in your network?

LEVEL V MARINE RESERVES AND SOCIAL EQUITY

Reserve placement may affect the communities near the reserve. Fishers' costs, for example, might increase if they are obliged to fish further away because of the reserve. Place a large reserve (10% of the area) near one of the ports, for each species-type. Run the simulation for 20 years and save the results. Now clear this reserve and place a new one near the other port.

Discussion points

How does the reserve affect the economics of boats from each port? Which port community is likely to benefit from the effect of the reserve, and which is likely to experience the immediate economic costs? Think about implications of an open access fishery where people enter and exit depending on net earning relative to outside opportunities.

When you experimented in the exercises above with other conservation methods, such as fishery limits, you were in effect simulating reserves or zones where take is allowed within prescribed limits. What is your concept of a protected area? Do you think protected areas should be primarily strict, no-take reserves, or can they be sustainably used? Consider examples you may be familiar with. In either case, can you think of reserve planning strategies that could minimize conflict and allow users to voice their concerns? Do you know of any examples where this was successfully accomplished, or where important lessons were learned?

LEVEL VI PROFIT SOURCE

The "Profit Source" feature of this exercise was designed to track the cells of origin for the fish caught by boats from each port. This information can have significant impacts on reserve selection and design. It can also demonstrate the "spillover effect", whereby profits outside reserves are increased when fish protected within the reserve disperse and are harvested in unprotected waters. However, this feature significantly slows down the simulation, and was therefore not included in the exercises above. To use this feature,

- Turn on the profit source feature by going to "Edit", then "Track fish sources".
- Select a species-type. Each of the three species-types should be analyzed by a student group.
- Switch to the Yellow profit source option in "Base Image of Display". The lighter habitats are the greater profit sources for your species-type. The tool tips will indicate the profit source per hexagon.
- Run the simulation for five years, and save the results.
- Fill out the first column of the table below, then go to Edit, Reset to time 0.
- Place 10% of the total area in marine reserves. You may distribute the MPAs as you wish; however, when designing your reserve system, think about enforcement and feasibility, as discussed above. You may wish to look at the potential profit sources under the "Base Image of Display".

- Run the simulation for five years.
- Fill out the second column of the table below.
- To view the results for the blue port, switch to “Blue profit source” under “Base Image of Display”.
- Go to File, Save, and save the results.

Species: ___________________________________

Number	No reserves	Reserves
Total organisms		
Organisms in reserves		
Yellow boats		
Yellow totap profits		
Blue boats		
Blue total profits		

Discussion points

Get together as a class to discuss these questions, referring to the profit source maps you saved. Can reserves be economically valuable as sources of individuals that “spillover” to surrounding areas? Do results vary by species-type, and if so, can you think of some biological characteristics that could explain this? How can choices about reserve placement and design affect biological and economic aspects of the fishery?

LEVEL VII SENSITIVITY TO DEMOGRAPHIC AND ECONOMIC VARIATION

In this section, you will explore how select variables contribute to population growth and fishery total profits by completing the table below, following the Initial Population Size example in the table.

- Break up into at least 4 groups.
- If you were working on Level VI, don’t forget to turn off the Profit source feature. Go to “Edit”, then “Don’t track fish sources”.
- Each group will be assigned or choose to work with the lobster species-type and a set of variables. One group will work with the first 5 values (biological) with no

reserves. The second group will work with the first 5 variables (biological) with 25% reserves. The third group will work with the last 5 (economic) variables from the table below, without reserves. The fourth group will work with the last 5 (economic) variables, with 25% reserves.

- Depending on the size of the group, one person can be assigned to one or two variables. If there are more than four groups, additional species-types can be worked with.
- Change one variable from the table below at a time to their minimum (a value of at least 10) or maximum values. The minimum and maximum values will appear in the tool tips and can also be found in the Glossary. Please remember that the tool tips will only appear when the mouse is rolled over the legend, not the value field.
- Before moving on to the next variable, remember to reset to: 1) time 0; and 2) to your previous values.
- Run the simulation for 20 years.

Discussion Points

Get together as a class for discussion. Now that you have explored the effects of fish and fishing characteristics on organismal populations and the fishery, consider the following questions.

What would the ideal species to protect using marine reserves be, in terms of demographic characteristics (lifespan: long vs. short; intrinsic growth rate: high versus low; dispersal rate)? What are the fishery characteristics most likely to produce a balanced system (fishing efficiency: high or low; costs: high or low)?

What combinations of factors produce better results in terms of larger fish populations, overall fishery statistics, and per capita earnings? What combinations tend to produce population crashes? Why might extreme values such as these not provide the full picture?

____No reserves
____Reserves

	Fish population		Economics Yellow		Economics Blue	
VARIABLES	Min.	Max.	Min.	Max.	Min.	Max..
Initial population						
Overall effect	A high initial population size results in rapid over-harvest, and therefore collapse of both population and profits. A very small population size results in negative profits.					
Lifespan						
Overall effect						
Intrinsic growth						
Overall effect						
Ave. catch weight						
Overall effect						
Dispersal rate						
Overall effect						
Fishing efficiency						
Overall effects						
Travel costs						
Overall effects						
Number of boats						
Overall effects						
Max. harvest						
Overall effects						
Price						
Overall effects						

Next Steps

Please feel free to explore the simulation further. You may wish to run the simulation using different time frames, for example to explore effects of historical overfishing. You may also choose to model other organisms by inputting new variables into the simulation panel. Make sure, however, that the habitat is appropriate to your organism. Consider visiting the following websites for more information on these and other species:

- www.fishbase.org
- www.arkive.org
- www.natureserve.org
- http://www.strombusgigas.com/
- http://marinebio.org

Additional Reading

Marine Conservation Biology: The Science of Maintaining the Sea's Biodiversity. 2005. Elliott A. Norse and Larry B. Crowder (Editors). Marine Conservation Biology Institute, Island Press.

The Science of Marine Reserves. 2003. Ecological Applications: Volume 13, Issue 1, Supplement.

Special Section: Implementation and Management of Marine Protected Areas. 2005. Conservation Biology: Volume 19 Issue 6.

Agardy, T. 2006. Marine Conservation Biology. NCEP module. Available from http://ncep.amnh.org/

Agardy, T. and F. Staub. 2006. Marine Protected Areas and MPA Networks. NCEP module. Available from http://ncep.amnh.org/

Naro-Maciel, E., E. J. Sterling, and M. Rao. 2006. Protected Areas and Biodiversity Conservation I: Reserve Planning and Design. NCEP module. Available from http://ncep.amnh.org/

TERMS OF USE

This material is based on work supported by the National Science Foundation under the Course, Curriculum and Laboratory Improvement program (NSF 0127506), the National Oceanic and Atmospheric Administration Undersea Research Program (Grant No. CMRC-03-NRDH-01-04A), and the New York Community Trust.

Appendix I: The Simulation Model (By Steven Phillips)

The map is divided into a set of (hexagonal) grid cells, and I'll use variables x and y to refer to cells. The basic population growth equation relates the population p_{i+1} on day $i+1$ to the population on day i:

$$p_{i+1} = p_i(x)(1 + g_x(p_i(x))) - \delta_x p_i(x) - h_i(x) + \sum_y \delta_{y,x} p_i(y)$$

where the terms represent population growth inside x, dispersal out of x, harvest from x, and dispersal into x, respectively. The dispersal rate out of x is just

$$\delta_x = \sum_y \delta_{x,y}.$$

Each cell x has a "habitat suitability" $H(x)$, between 0 and 1. Growth inside a cell is logistic growth, with some natural mortality. In symbols:

$$g_x(p) = -\mu + r\left(1 - \frac{p}{KH(x)}\right)$$

Here μ is the mortality, which we estimate as one over the typical lifespan of a fish, in days. The upper limit on the population size is $KH(x)$, where $H(x)$ is the habitat suitability of cell x, and K is the carrying capacity (maximum population) of a grid cell with perfect conditions for the species. The constant r is the rate of growth when the population in a cell is far from the maximum; this is called the "intrisic growth rate".

A fraction α of the fish in each cell swim to a neighbouring cell each day. The choice of which cell a fish moves to depends on the availability of resources. If we set

$$\sigma_x = \sum_{y \in \text{neighbours}(x)} H(y)/(1 + p(y))$$

then

$$\delta_{x,y} = \frac{\alpha H(y)}{(1 + p(y))\sigma_x}.$$

Now for the harvest term: it's the sum of the harvests of all boats currently in existence. I'll use the variable b to refer to a boat:

$$h_i(x) = \sum_b [\gamma_i(b) = x]\phi_b(x)$$

where $[\gamma_i(b) = x]$ is in indicator variable equal to 1 if boat b is in cell x on day i and 0 otherwise, and $\phi_b(x)$ is the number of fish b harvests if it does visit x. The latter term depends on the boat's efficiency $e(b)$, its maximum daily capacity $m(b)$, the commute time to get to x, and the population in x:

$$\phi_b(x) = \min\{m(b), e(b)p(x)t_b(x)\}$$

Here $t_b(x)$ is the fraction of a day that b can spend at x (considering commute time), which can be calculated from boat speed and distance, assuming an 8-hour working day:

$$t_b(x) = 1 - \frac{d_{x,\text{port}(b)}}{8 * \text{speed}(b)}.$$

Appendix I (Continued)

Finally, we need to specify the boat behaviour. Say that a boat b visited cell x one day and had profit ρ. If $\rho \leq 0$ or ρ is less than a third of the average profit of boats from the same port, or randomly (with probability 0.03), then the next day b visits a random cell, as described below. Otherwise, b visits either x or one of the (non-reserve) neighbours or x, with the choice made to maximize profit. Note that this assumes some prescience from the boats, as it assumes they know what the profit would be in each neighbour.

The profit of a boat depends on the harvest, the wholesale price of the fish ($\$f$ per kg), the average weight of a fish (w kg), travel costs (at a rate of $t(b)$ dollars per km) and daily boat cost, $\omega(b)$:

$$\text{profit}_b(x) = \phi_b(x) f w - 2t(b) d_{x,\text{port}(b)} - \omega(b)$$

If the boat chooses a random cell, it does so as follows. If there is any (nonreserve) cell in which it can make a profit, it chooses from all such cells with probability proportional to the profit. Otherwise, it chooses from all non-reserve cells with probability proportional to exponential profit, $e^{\text{profit}_b(x)}$. The latter rule biases the choice in favor of cells where the boat will make the smallest loss.

Lastly, this is an open fishery, so we need rules for when boats come and go. Each port has a maximum number of boats. If no boats from a port have any profit in any one day, and there are currently at least two boats operating from the port, then one boats stops fishing. If all the boats have at least $50 profit per day for at least 30 days, and the current number of boats is less than the maximum, then another boat starts fishing.

For an initial configuration, the user picks an initial total population, i.e., number of fish. The initial population is divided between the cells in proportion to their suitability. Initially there are 2 boats per port.