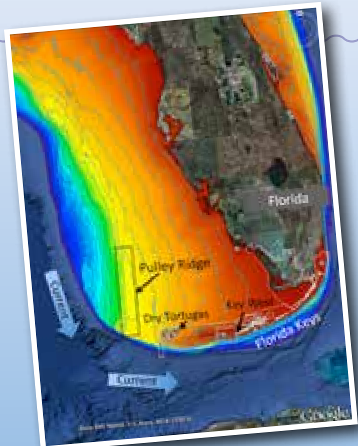
Coral Ecosystem Connectivity 2013:
From Pulley Ridge to the Florida Keys Expedition

Everyone Wins!



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lesson plan

Focus
Marine protected areas (Life Science)

Grade Level
9-12

Focus Question
What qualitative and quantitative criteria may be applied to marine protected areas to account for conservation and fishery goals?

Learning Objectives
- Students will analyze threats to coral ecosystems, and specify qualitative and quantitative criteria and constraints for marine protected areas that account for perceived tradeoffs between conservation and fishery goals.

- Students will discuss evidence that demonstrates how marine protected areas can enhance use as well as protection of marine resources.

Materials
- ❑ Copies *Some Criteria for Designing Marine Reserve Networks*, one copy for each student or student group

Audio-Visual Materials
- ❑ (Optional) Interactive white board which may be used by teacher/ students to list ideas, responses to questions, or share information they create on iPads ,or other devices, with the entire class

Teaching Time
Two 45-minute class periods, plus time for student reading and research

Seating Arrangement
Groups of two or three students

Maximum Number of Students
30

Key Words
Pulley Ridge
Marine protected area

Coral ecosystem
Fishery management
Conservation

Background Information

NOTE: Explanations and procedures in this lesson are written at a level appropriate to professional educators. In presenting and discussing this material with students, educators may need to adapt the language and instructional approach to styles that are best suited to specific student groups.

Coral reefs provide habitats for some of the most diverse biological communities on Earth. Most people have seen photographs and video images of shallow-water coral reefs, and many have visited these reefs in person. Around the world, shallow coral ecosystems are threatened by climate change, fishing, pollution, invasive species, and other human activities such as dredging and anchoring. These threats not only jeopardize coral reefs, but also endanger many benefits provided by these reefs such as supporting recreation and tourism industries, protecting shorelines from erosion and storm damage, supplying foods that are important to many coastal communities, and providing promising sources of powerful new antibiotic, anti-cancer and anti-inflammatory drugs.

In addition to shallow-water coral ecosystems, scientists have discovered two other types of coral reefs. In depths between 400 m and 700 m, ocean explorers have discovered extensive mounds of living coral. An important difference between deepwater coral species and those living in shallow waters is that shallow-water corals often have microscopic algae called zooxanthellae (pronounced "zoh-zan-THEL-ee") living inside their soft tissues. Because they are capable of photosynthesis, these algae provide an important source of nutrition for many coral species and may also be involved with the corals' growth. Deepwater corals do not contain zooxanthellae, and do not build the same type of reef that are produced by shallow-water corals; but the diversity of species in deep-water coral ecosystems may be comparable to that of coral reefs in shallow waters (for more information, activities, and lessons about coral reefs, visit the National Ocean Service Coral Reef Discovery Kit at http://oceanservice.noaa.gov/education/kits/corals/welcome.html).

Recently, ocean explorers have discovered a third type of coral ecosystem: light-dependent deep reefs living in what coral ecologists call the mesophotic zone (or "twilight zone") in depths of 30 m to over 150 m, depending upon water clarity. Mesophotic coral ecosystems have not been studied as much as shallow- and deepwater coral reefs because of technological limitations. Shallow-water coral reefs have been intensively studied by scientists using self-contained underwater

Images from Page 1 top to bottom:
Map of project area showing Pulley Ridge, off the west coast of Florida at depths of 200-330 feet in relation to the downstream reefs of the Dry Tortugas and Florida Keys. Colors represent water depth, which ranges from 33 feet (red) to depths of 820 feet or greater (dark blue). Current arrows depict prevalent current direction. Background image is from Google Earth and the depth information is from the U.S. Geological Survey and NOAA. Image courtesy: Robert Cowen.

Example of corals and algae found on Pulley Ridge: The plate corals *Leptoseris cucullata* (foreground) and *Agaricia fragilis*; the finger coral *Madracis* sp.; the leafy green algae *Anadyomene menziesii*; and the branching algae *Dictyota* sp. Image courtesy: Mike Echevarria, Florida Aquarium.

The University of Miami's technical dive team installed sensors on a mooring buoy to collect information on ocean currents. Image courtesy: Michael J. Echevarria, Florida Aquarium.

Understanding the value of the commercial fish species present at Pulley Ridge, such as the red grouper, *Ephinephelus morio*, is a key research objective for this project. Image courtesy: University of North Carolina at Wilmington.

The dominant communities providing structural habitat at Pulley Ridge are coralline algae (thin pink plates) and hard coral (brown plates are *Agaricia* sp.). Image courtesy: John Reed using the University of Connecticut's Kraken remotely operated vehicle.

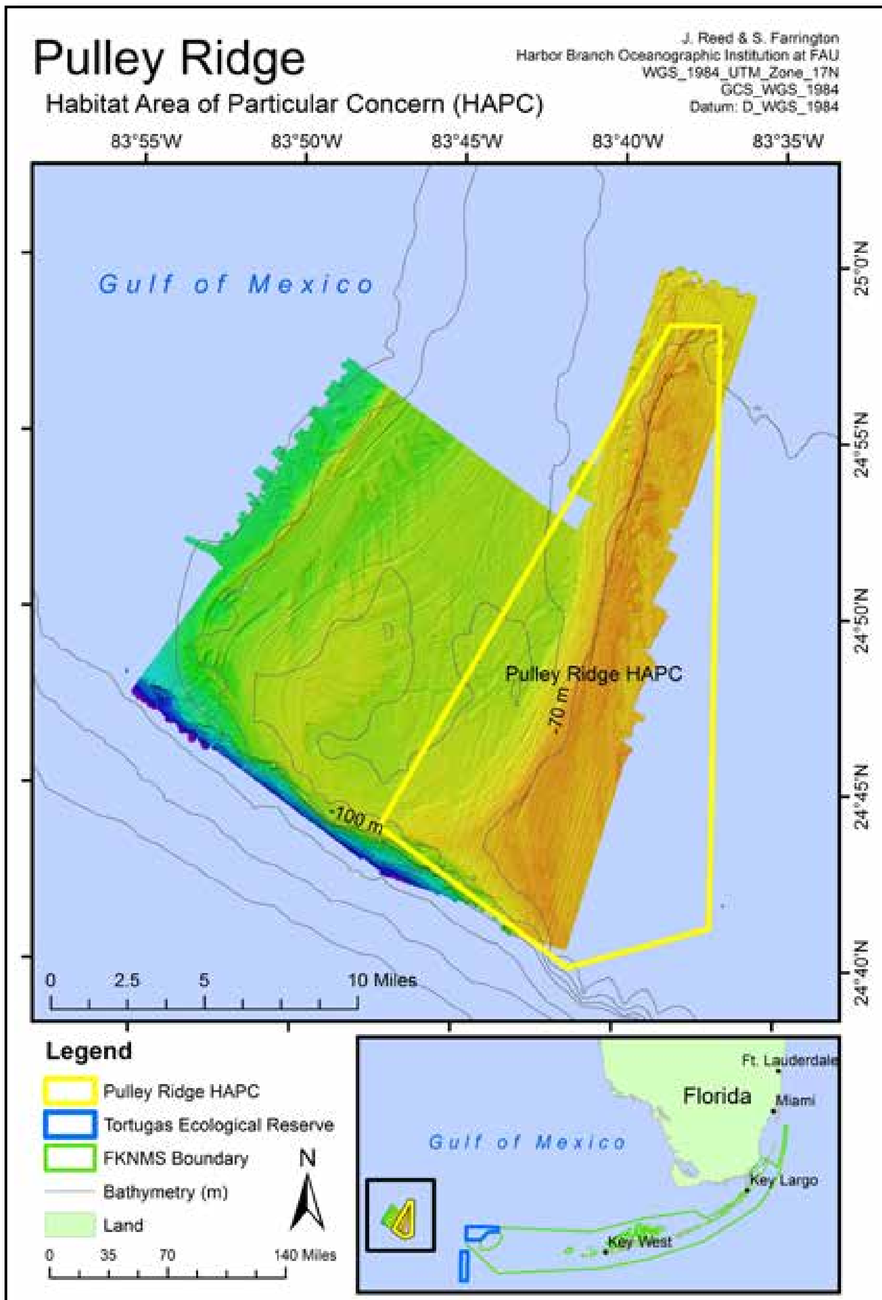
breathing (SCUBA) equipment, while deep coral systems are being investigated with human-occupied submersibles and remotely operated underwater vehicles (ROVs). Mesophotic coral ecosystems, however, are beyond the safe range of conventional SCUBA equipment, yet are too shallow and close to shore to justify the use of expensive submersibles and ROVs. Over the past decade, advances in undersea technologies have begun to make it possible to study mesophotic coral ecosystems.

While only a few studies of mesophotic zone reefs have been done using these new capabilities, data from these studies suggest these ecosystems include coral, sponge, and algal species that provide important refuges and nursery habitats for corals and fishes found on shallower reefs. Because of the threats faced by shallow-water coral reefs, scientists believe it is urgent to understand the connections between mesophotic and shallow-water ecosystems. This sense of urgency also stems from the fact that mesophotic coral ecosystems are subject to many of the same threats faced by shallower coral ecosystems, but the extent of threats

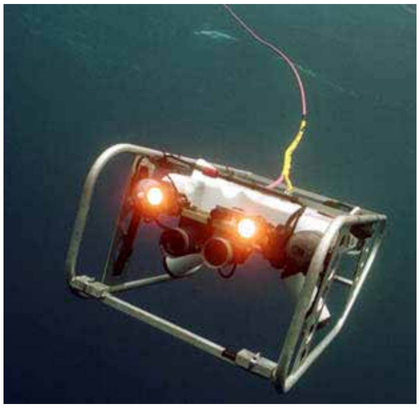
A larval squirrelfish of the Family Holocentridae. Larval fishes are sampled using plankton nets or light traps. Image courtesy: Cedric Guigand.

to mesophotic ecosystems is unknown and needs to be evaluated. Since mesophotic corals are adapted to live in low-light conditions and require sunlight for survival, anything that limits light penetration (such as dredging or sediment runoff from the land) can be very harmful. Mesophotic coral ecosystems may also include species that are only found within this depth range or geographical location. These species are known as endemic species, and are especially vulnerable to disturbances from human activities and may face extinction if they are overexploited.

Pulley Ridge is a mesophotic coral ecosystem off the southwest coast of Florida in 60-80 meters depth, and is the deepest light-



Map of Pulley Ridge Habitat Area of Particular Concern (HAPC) showing multibeam sonar. Image courtesy: Harbor Branch Oceanographic Institute.



The University of North Carolina at Wilmington's *Phantom S2* remotely operated vehicle has the capability of maneuvering in shallow water to depths of 300 m, making it possible for scientists to study mesophotic reefs. Image courtesy: University of North Carolina at Wilmington.

dependent coral reef that has been discovered off the United States. Pulley Ridge was originally discovered in 1950, and was found again in 1999 by scientists from the U.S. Geological Survey (USGS) and graduate students from the University of South Florida. Since then, a series of expeditions have revealed that coral ecosystems at Pulley Ridge are considerably healthier compared to many in the Florida Keys, and are unusual because of the variety of life they support. Scientists hypothesize that Pulley Ridge may play an important role in replenishing key fish species, such as grouper and snapper, and other organisms in downstream reefs of the Florida Keys and Dry Tortugas. Since most of Florida's reefs have severely declined over the past 30 years, this potential role means it is important to protect, and manage, Pulley Ridge as a possible source of larvae that can help sustain Florida's reef ecosystems and the tourism economy that depends on them.

In 2011, NOAA's National Centers for Coastal Ocean Science's Center for Sponsored Coastal Ocean Research began a five-year project to investigate the role that reefs of Pulley Ridge and the northern Gulf of Mexico may play in replenishing key fish species and other organisms in the downstream reefs of the Florida Keys and Dry Tortugas. The Pulley Ridge Project is a collaboration of more than 30 scientists from ten different universities pooling their expertise through NOAA's Cooperative Institute for Marine and Atmospheric Studies (CIMAS) (http://cimas.rsmas.miami.edu/) in coordination with the Cooperative Institute for Ocean Exploration Research and Technology (CIOERT) (http://cioert.org/).

During the project's first year (2012), fieldwork began that included:

- Installing moored instruments at Pulley Ridge and the Dry Tortugas to measure temperature, salinity, and currents;
- Field-testing moored larval light traps to resolve any design issues and work out specific sampling procedures (for more about larval light traps, please see http://www.marine.usf.edu/user/djones/pubs/Jones_2006b.pdf);
- Conducting transect surveys with an ROV to quantify benthic habitats and organisms, and to identify suitable sites for technical divers to collect specimens;
- Collecting specimens with technical diving (for more about technical diving, please see Expedition Purpose for the Cayman Islands Twilight Zone 2007 Expedition, http://oceanexplorer.noaa.gov/explorations/07twilightzone/background/edu/purpose.html);
- Sampling plankton using the Multiple Opening/Closing Nets and Environmental Sampling System (MOCNESS), which is a system of nets that can be opened and closed at different depths, and also carries a number of sensors for measuring environmental parameters as it is towed (such as conductivity, temperature,

pressure, fluorescence, optical transmission, dissolved oxygen, and light levels). For more about MOCNESS, please see http://www.gulfofmaine-census.org/education/research-technology/sampling-tools-for-physical-capture/;
- Using a CTD to measure temperature, dissolved oxygen, salinity, fluorescence, turbidity, and depth (for more about CTDs, please see the "Where's the Oxygen" lesson, http://oceanexplorer.noaa.gov/explorations/10lophelia/background/edu/media/loph10_oxygen912.pdf);
- Deploying a drifter to measure surface currents (for more about drifters, please see http://oceanexplorer.noaa.gov/technology/tools/drifters/drifters.html); and
- Beginning to archive information about Pulley Ridge in a database at Harbor Branch Oceanographic Institute.

The Coral Ecosystem Connectivity 2013: From Pulley Ridge to the Florida Keys Expedition will continue this work. The overall goal of the Pulley Ridge project is to create a comprehensive understanding that can support robust resource planning and management in the eastern Gulf of Mexico. In this lesson, students investigate ways that marine protected areas (MPAs) can contribute to management and conservation of living ocean resources, and examine criteria that can be used to establish effective marine protected areas.

Learning Procedure

1. To prepare for this lesson:
   a) Review the background essays for the Coral Ecosystem Connectivity 2013: From Pulley Ridge to the Florida Keys Expedition (http://oceanexplorer.noaa.gov/explorations/13pulleyridge/welcome.html).
   b) Review information on *Some Criteria for Designing Marine Reserve Networks*, and discussion points provided in the *Educator Version* of this document. Depending upon available time and learning objectives, this document may be used in a variety of ways. For example, each student may be assigned to read the entire document individually, and prepare written responses to the discussion points. Alternatively, students may work on this assignment in groups and collaborate on the discussion points. Another approach could be to reduce the time required by assigning one or two paragraphs to different students or groups of students. Potentially unfamiliar vocabulary may be discussed with the entire class, or included with assignments to groups or individual students. Similarly, threats to corals may be discussed with the entire class as specified in Step 2, or may be part of individual or group assignments. You may also want to review the original paper (www.pnas.org/cgi/doi/10.1073/pnas.0906473107) and consider having this available for students as well.

c) Review descriptions of MPA success stories at http://www.californiampas.org/pages/about/success.html, and decide how to use these in Step 5.

d) If you want to provide students with specific MPA design scenarios (Step 6) prepare these prior to beginning the lesson.

2. Briefly introduce the Coral Ecosystem Connectivity 2013: From Pulley Ridge to the Florida Keys Expedition, including the distinction between shallow-water coral reefs, mesophotic coral reefs, and deepwater coral reefs. Discuss the threats faced by coral reefs worldwide, and the extent to which human activities contribute to these threats. Whenever possible, it is desirable to engage students in conversations, either in small groups or as an entire class, to elicit their ideas and perspectives; rather than rely primarily on a lecture-based approach.

3. Briefly introduce the concept of marine protected areas (MPAs), and ask students to identify which of the threats discussed in Step 2 might be addressed with MPAs. If students are not familiar with the engineering design process, briefly review the description provided in Appendix B. Highlight the fact that most design problems include specific criteria for successful designs, and often involve various types of tradeoffs. Ask students what criteria and tradeoffs might be applied to MPA designs. These should include criteria that reflect conservation as well as various objectives for using marine resources (tourism, sport fishing, commercial fishing, etc.).

   Provide each student or student group with a copy of *Some Criteria for Designing Marine Reserve Networks*. You may also want to discuss potentially unfamiliar vocabulary (see Appendix A) and/or provide a list of discussion topics (see Step 4). Tell students that this document is based on a technical paper about designing marine protected areas, and that they are to use this information to design a hypothetical MPA to protect shallow-water coral reef resources. Provide any additional instructions needed pertaining to vocabulary and/or discussion points (Step 1b).

4. Have students present their responses to Discussion Points provided in the Educator Version of *Some Criteria for Designing Marine Reserve Networks*, or discuss these Points with the class as a whole if they were not assigned in Step 3. In addition to the comments provided in the *Educator Version*, this discussion should include:
   - Threats that cannot be mitigated by MPAs include climate change, pollution, and invasive species.

   - Students' perceptions of constraints and tradeoffs involved with establishing marine reserves will probably include a perspective that conservation objectives are inherently conflicted with use objectives. Be sure to highlight this perspective for later discussion after students examine case studies from actual MPAs (Step 5).

- "Fishery Prosperity" may have a variety if meanings, including profits from commercial fishing, reliable success for recreational fishing, presence of certain species (such as game fish that are released after being caught), and support for non-extractive uses such as tourist diving or snorkeling. The common feature for all of these meanings is that they depend upon healthy and persistent fish populations.

- A larva that drifts for two weeks in current of 2 knots will be transported

  (2 nautical miles/hour) x (24 hours/day) x (14 days) = 672 nautical miles

  from the area in which it was spawned.

- "Demographic bailout" is an example of making technical writing more interesting by using unusual phrasing. The authors could have said "larvae" instead, but "demographic bailout" is a more dynamic phrase that links to the larger point about how to rescue reserves with declining populations.

5. Direct students to descriptions of MPA success stories at http://www.californiampas.org/pages/about/success.html, and discuss examples that involved tradeoffs as well as examples in which both conservation and fishery objectives were served. The Tortugas Ecological Reserve in the Florida Keys National Marine Sanctuary is particularly relevant to the Pulley Ridge Project, since the mesophotic coral reefs at Pulley Ridge may provide similar conservation and fishery benefits to the Florida Keys.

6. Challenge each student or student group to design a hypothetical MPA that will achieve both conservation and use benefits. These may be based on design criteria (location and size of reef areas, species to be protected, conservation and fishery objectives, etc.) provided by the educator or criteria that the students specify themselves. The completed design should include a clear definition of the MPA objectives, known constraints, assumptions about currents, species involved, length of relevant larval stages, habitats needed, and other criteria discussed in the *Some Criteria for Designing Marine Reserve Networks* handout. Specific responses to this assignment will vary, and evaluation should be based primarily upon the extent to

which design decisions are based on the criteria presented in *Some Criteria for Designing Marine Reserve Networks*, and those discussed in class.

The BRIDGE Connection

www.vims.edu/bridge/ – Scroll over "Ocean Science Topics" in the navigation menu to the left, then "Habitats," then "Coastal," then "Coral" for resources on corals and coral reefs.

The "Me" Connection

Have students write a short essay about how mesophotic coral ecosystems might affect their own lives.

Connections to Other Subjects

English Language Arts

Assessment

Student presentations and class discussions provide opportunities for assessment.

Extensions

Have students visit http://oceanexplorer.noaa.gov/explorations/13pulleyridge/welcome.html to find out more about the Coral Ecosystem Connectivity 2013: From Pulley Ridge to the Florida Keys Expedition.

Multimedia Discovery Missions

http://oceanexplorer.noaa.gov/edu/learning/welcome.html Click on the links to Lessons 3 and 12 for interactive multimedia presentations and Learning Activities on deep-sea corals and biotechnology.

Other Relevant Lesson Plans from NOAA's Ocean Exploration Program

What's Down There?

(from the 2007 Cayman Island Twilight Zone Expedition)
http://oceanexplorer.noaa.gov/explorations/07twilightzone/background/edu/media/whatsdown.pdf

Focus: Mapping coral reef habitats (Life Science/Earth Science)

Students access data on selected coral reefs, manipulate these data to characterize these reefs, and explain the need for baseline data in coral reef monitoring programs; and identify and explain five ways that coral reefs benefit human beings, and explain three major threats to coral reefs.

The Benthic Drugstore

(from the 2007 Cayman Island Twilight Zone Expedition)
http://oceanexplorer.noaa.gov/explorations/07twilightzone/background/edu/media/drugstore.pdf
Focus: Pharmacologically-active chemicals derived from marine invertebrates (Life Science/Chemistry)
Students identify at least three pharmacologically-active chemicals derived from marine invertebrates, describe the disease-fighting action of at least three pharmacologically-active chemicals derived from marine invertebrates, and infer why sessile marine invertebrates appear to be promising sources of new drugs.

Watch the Screen!

(from the 2007 Cayman Island Twilight Zone Expedition)
http://oceanexplorer.noaa.gov/explorations/07twilightzone/background/edu/media/watchscreen.pdf
Focus: Screening natural products for biological activity (Life Science/Chemistry)
Students explain and carry out a simple process for screening natural products for biological activity, and infer why organisms such as sessile marine invertebrates appear to be promising sources of new drugs.

Now Take a Deep Breath

(from the 2007 Cayman Island Twilight Zone Expedition)
http://oceanexplorer.noaa.gov/explorations/07twilightzone/background/edu/media/breath.pdf
Focus: Physics and physiology of SCUBA diving (Physical Science/Life Science)
Students define Henry's Law, Boyle's Law, and Dalton's Law of Partial Pressures, and explain their relevance to SCUBA diving; discuss the causes of air embolism, decompression sickness, nitrogen narcosis, and oxygen toxicity in SCUBA divers; and explain the advantages of gas mixtures such as Nitrox and Trimix and closed-circuit rebreather systems.

Keep It Complex!

(from The Charleston Bump 2003 Expedition)
http://oceanexplorer.noaa.gov/explorations/03bump/background/education/media/03cb_complex.pdf
Focus: Effects of habitat complexity on biological diversity (Life Science)
Students describe the significance of complexity in benthic habitats to organisms that live in these habitats, describe at least three attributes of benthic habitats that can increase the physical complexity of these habitats, give examples of organisms that increase the structural complexity of their communities, and infer

and explain relationships between species diversity and habitat complexity in benthic communities.

How Diverse is That?
(from the 2003 Windows to the Deep Expedition)
http://oceanexplorer.noaa.gov/explorations/03windows/background/education/media/03win_hdiverse.pdf
Focus: Quantifying biological diversity (Life Science)
Students discuss the meaning of biological diversity; compare and contrast the concepts of variety and relative abundance as they relate to biological diversity; and given abundance and distribution data of species in two communities, calculate an appropriate numeric indicator that describes the biological diversity of these communities.

Other Resources

The Web links below are provided for informational purposes only. Links outside of Ocean Explorer have been checked at the time of this page's publication, but the linking sites may become outdated or non-operational over time.

http://oceanexplorer.noaa.gov/explorations/13pulleyridge/welcome.html – Web site for the Coral Ecosystem Connectivity 2013: From Pulley Ridge to the Florida Keys Expedition

http://mcbi.marine-conservation.org/publications/pub_pdfs/Deep-Sea%20Coral%20issue%20of%20Current.pdf – A special issue of Current: the Journal of Marine Education on deep-sea corals.(You may need to copy and paste this URL into your browser.)

Halpern B., S. Walbridge, K. Selkoe, C. Kappel1, F. Micheli, C. D'Agrosa, J. Bruno, K. Casey, C. Ebert, H. Fox, R. Fujita, D. Heinemann, H. Lenihan, E. Madin, M. Perry, E. Selig, M. Spalding, R. Steneck, and R. Watson. 2008. A global map of human impact on marine ecosystems. Science 319:948–952.

Jeffrey, C.F.G., V.R. Leeworthy, M.E. Monaco, G. Piniak, M. Fonseca (eds.). 2012. An Integrated Biogeo¬graphic Assessment of Reef Fish Populations and Fisheries in Dry Tortugas: Effects of No-take Reserves. NOAA Technical Memorandum NOS NCCOS 111. Prepared by the NCCOS Center for Coastal Monitoring and Assessment Biogeography Branch. Silver Spring, MD. 147 pp.

Gaines, S., C. White, M. Carr, and S. Palumbi. 2010. Designing marine reserve networks for both conservation and fisheries management. Proceedings of the National Academy of Sciences, 107(43):18286–18293; available online at www.pnas.org/cgi/doi/10.1073/pnas.0906473107

Alignment to the Next Generation Science Standards Performance Expectations

HS-ETS1 Engineering Design

Performance Expectation:

HS-ETS1-1. Analyze a major global challenge to specify qualitative and quantitative criteria and constraints for solutions that account for societal needs and wants.

Science and Engineering Practices:

Asking Questions and Defining Problems

- Analyze complex real-world problems by specifying criteria and constraints for successful solutions.

Disciplinary Core Idea:

ETS1.A: Defining and Delimiting Engineering Problems

- Criteria and constraints also include satisfying any requirements set by society, such as taking issues of risk mitigation into account, and they should be quantified to the extent possible and stated in such a way that one can tell if a given design meets them.
- Humanity faces major global challenges today, such as the need for supplies of clean water and food or for energy sources that minimize pollution, which can be addressed through engineering. These global challenges also may have manifestations in local communities.

Crosscutting Concepts:

- None

Connections to Engineering, Technology, and Applications of Science

Influence of Engineering, Technology, and Science on Society and the Natural World

- New technologies can have deep impacts on society and the environment, including some that were not anticipated. Analysis of costs and benefits is a critical aspect of decisions about technology.

Common Core State Standards Connections

ELA/Literacy –

- RST.11-12.7 Integrate and evaluate multiple sources of information presented in diverse formats and media (e.g., quantitative data, video, multimedia) in order to address a question or solve a problem.
- RST.11-12.9 Synthesize information from a range of sources (e.g., texts, experiments, simulations) into a coherent understanding of a process, phenomenon, or concept, resolving conflicting information when possible.

Additional Science and Engineering Practices:

Asking Questions and Defining Problems

- Ask questions that arise from examining models or a theory, to clarify and/or seek additional information and relationships.
- Ask questions that can be investigated within the scope of the school laboratory, research facilities, or field (e.g., outdoor environment) with available resources and, when appropriate, frame a hypothesis based on a model or theory.

Developing and Using Models

- Develop, revise, and/or use a model based on evidence to illustrate and/or predict the relationships between systems or between components of a system.

Constructing Explanations and Designing Solutions

- Design, evaluate, and/or refine a solution to a complex real-world problem, based on scientific knowledge, student-generated sources of evidence, prioritized criteria, and tradeoff considerations.

Additional Crosscutting Concepts:

Cause and Effect: Mechanism and Prediction

- Cause and effect relationships can be suggested and predicted for complex natural and human designed systems by examining what is known about smaller scale mechanisms within the system.

Systems and System Models

- Models (e.g., physical, mathematical, computer models) can be used to simulate systems and interactions—including energy, matter, and information flows— within and between systems at different scales.
- Models can be used to predict the behavior of a system, but these predictions have limited precision and reliability due to the assumptions and approximations inherent in models.

Stability and Change

- Much of science deals with constructing explanations of how things change and how they remain stable.

Ocean Literacy Essential Principles and Fundamental Concepts

Essential Principle 1.

The Earth has one big ocean with many features.

Fundamental Concept h. Although the ocean is large, it is finite and resources are limited.

Essential Principle 5.
The ocean supports a great diversity of life and ecosystems.

Fundamental Concept c. Most of the major groups that exist on Earth are found exclusively in the ocean and the diversity of major groups of organisms is much greater in the ocean than on land.

Fundamental Concept e. The ocean provides a vast living space with diverse and unique ecosystems from the surface through the water column and down to, and below, the seafloor. Most of the living space on Earth is in the ocean.

Essential Principle 6.
The ocean and humans are inextricably interconnected.

Fundamental Concept b. The ocean provides food, medicines, and mineral and energy resources. It supports jobs and national economies, serves as a highway for transportation of goods and people, and plays a role in national security.

Fundamental Concept e. Changes in ocean temperature and pH due to human activities can affect the survival of some organisms and impact biological diversity (coral bleaching due to increased temperature and inhibition of shell formation due to ocean acidification).

Fundamental Concept g. Everyone is responsible for caring for the ocean. The ocean sustains life on Earth and humans must live in ways that sustain the ocean. Individual and collective actions are needed to effectively manage ocean resources for all.

Essential Principle 7.
The ocean is largely unexplored.

Fundamental Concept a. The ocean is the last and largest unexplored place on Earth—less than 5% of it has been explored. This is the great frontier for the next generation's explorers and researchers, where they will find great opportunities for inquiry and investigation.

Fundamental Concept b. Understanding the ocean is more than a matter of curiosity. Exploration, inquiry and study are required to better understand ocean systems and processes.

Fundamental Concept c. Over the last 50 years, use of ocean resources has increased significantly; the future sustainability of ocean resources depends on our understanding of those resources and their potential.

Fundamental Concept d. New technologies, sensors and tools are expanding our ability to explore the ocean. Ocean scientists are relying more and more on satellites, drifters, buoys, subsea observatories and unmanned submersibles.

Send Us Your Feedback

In addition to consultation with expedition scientists, the development of lesson plans and other education products is guided by comments and suggestions from educators and others who use these materials. Please send questions and comments about these materials to: oceanexeducation@noaa.gov.

For More Information

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Credit

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Appendix A

Vocabulary for *Some Criteria for Designing Marine Reserve Networks*

marine protected area (MPA) – A geographic area of ocean and seafloor in which various human activities are restricted

marine reserve – A marine protected area in which all forms of fishing are banned

self-persistent – A population of organisms that produces enough offspring to ensure that the size of the population remains the same over time

overfished – a population of aquatic organisms that has been depleted by excessive harvest

carrying capacity – the maximum number of organisms of a particular species that can be supported indefinitely in a given ecosystem

productivity – in ecology, the rate of production of new biomass by an individual, population, or community

recruitment – the addition of juvenile organisms to a population

recruitment overfishing – overfishing of organisms capable of reproducing that results in recruitment that is inadequate to maintain a stable population

habitat – the natural home of an organism

The *R/V F.G. Walton Smith*, owned and operated by the University of Miami, Rosenstiel School of Marine and Atmospheric Sciences (RSMAS), is one of two vessels to be used during the expedition. Image courtesy: University of Miami/RSMAS.

Appendix B

About the Engineering Design Process

The Engineering Design Process is a series of steps that engineers use to create solutions to problems. There are many versions of the Process, but the basic steps include:

- Define the problem
- Gather relevant information
- Brainstorm possible solutions
- Analyze possible solutions and select the most promising
- Test the solution by building a prototype
- Revise and improve the solution
- Repeat previous steps until results are acceptable
- Report the design process and results

Most problems will include certain constraints that may relate to cost, size, environmental conditions, or other specific requirements. Some constraints may be identified in the statement of the problem, but most problems need additional analysis to be certain that all constraints are understood. Often, constraints will force designers to make trade-offs in their solutions. For example the strongest material may be too expensive, or too heavy to meet cost and size constraints. Identifying the solution that meets all of the constraints with the best combination of trade-offs is called optimization. Models are frequently used to help designers visualize possible solutions, and may be two-dimensional illustrations, three-dimensional physical shapes, or mathematical calculations that predict how well a potential solution will do what is necessary to solve the problem. Each step of the Engineering Design Process involves systematically examining information that is needed to move to the next step. This kind of examination is called analysis.

Some Criteria for Designing Marine Reserve Networks

(adapted from Gaines, *et al.*, 2010)

Global concern for ocean ecosystems has driven growing calls for marine protected areas (MPAs). There are many threats to ocean ecosystems, but only a few of these threats can be mitigated by MPAs. Fishing is the human impact that has been the focus of most MPAs. A few MPAs, known as "marine reserves," ban all forms of fishing. Only a tiny fraction of the ocean has been set aside as marine reserves, but the global number of reserves now exceeds 200. Analyses of reserve impacts commonly show large benefits. Biomass typically triples relative to control areas outside the reserves, but the range of responses is enormous.

Single reserves consistently have a common failing: For nearly all species in the sea, individual marine reserves provide only minor conservation benefits, because the typical reserve size is very small compared to the geographic extent of the species it is designed to protect. In this paper, we discuss an emerging solution to this problem—networks.

Even if the number of individuals or total biomass of a species increases dramatically within a single small reserve, the benefits to the species as a whole are relatively limited. If marine reserves and other MPAs are to provide significant conservation benefits to species, they must be scaled up. One way to do this is to increase their size greatly (*e.g.*, the Papahänaumokuäkea National Monument, which covers nearly 360,000 km^2). Such large individual reserves are unlikely to be practical in heavily populated coastal areas because of the high economic and social costs. Several nations (*e.g.*, Australia and the United States) are using an alternative approach to scale up marine reserve benefits: networks of multiple MPAs. By aggregating the benefits of multiple MPAs, the network can have larger impacts. More importantly, a number of theoretical models suggest that networks can have emergent benefits that make the network more than the sum of its individual parts.

Locating Single Reserves

Worldwide, the majority of marine reserves are solitary and isolated. The most basic requirement for enhancing biological conservation and fishery prosperity is that an isolated reserve must be self-persistent and therefore must have a positive population growth. Although this concept is fundamental, it is rarely followed.

For example, in terrestrial landscapes it may be convenient to locate reserves in areas where there are few competing uses because the areas represent extreme environmental conditions (such as high elevation); but these areas often fail the persistence requirement because they depend upon immigration of organisms produced in less extreme, unprotected areas nearby.

Establishing a similarly convenient marine refuge (such as a remote reef that is inaccessible to fishing) can present similar problems of persistence if the refuge exhibits a net loss of biomass over time because more fishes and larvae leave the protected area than arrive from neighboring fished areas. Further, placing reserves in convenient locations may add little new protection, and therefore have little effect on fishery prosperity. Even if there is a high density of fishes in such locations, protecting these populations may not meet conservation goals, because these refuges can fail to persist if there is intensive fishing outside the reserve boundaries.

Large conservation gains can come from protecting populations that are inherently persistent and have a high local carrying capacity but have been historically overfished. If persistent populations in a reserve area are a source of biomass to neighboring fished areas, then economic benefits to fisheries are also expected. This can result from migration of adult fishes from the reserve into fished areas and/or from export of larvae. Whether the objectives are conservation or fisheries prosperity, the best location for a reserve may not be where there is high productivity. Highly productive areas may be more important as areas where fishing is allowed, if there is a nearby reserve that can protect a persistent population that provides a source of larvae and/or adult fishes.

The location of a reserve in relation to coastal habitats also can strongly influence the effectiveness of the reserve, but "success" may depend upon whether the objectives of the reserve are conservation or economic benefits. Matching a reserve's edge with a habitat boundary (*e.g.*, reef edge) can enhance conservation benefits for mobile species by limiting spillover into unprotected waters. On the other hand, placing a reserve edge in the midst of continuous habitat may enhance adult spillover and thus benefit fisheries.

From a fishery perspective, the optimal geographic placement of a reserve also depends on whether the goal is to maximize benefits or minimize costs. Placing a reserve edge near an access point (*e.g.*, port) can maximize benefits by minimizing transportation costs to the reserve edge. Fishing areas near ports are often the first to be overexploited and thus also may be good candidate locations for conservation. Conversely, when reserves are not expected to be a source of fish for harvest, fisheries are better served by placing reserves further from port to minimize the costs of travelling to fishing grounds on the far side of the reserve.

Why a Network?

A single reserve may play an important role in enhancing or stabilizing adult marine populations close to the reserve, but if the reserve is too small, persistence may require input of adults and/or larvae from the surrounding area. Modeling studies estimate that if a single reserve is to be persistent without contributions from other areas, it must be at least as large as the average dispersal distance for the species the reserve is intended to protect. Larval and adult movements typically are long enough to require that reserves be at least tens, and perhaps hundreds, of kilometers wide to ensure to meet the persistent requirement. Few reserves are this large, and so by these criteria few single reserves are self-sustaining.

Single reserves facing recruitment deficits can receive demographic bailouts from two sources: fished areas and other reserves. With high fishing pressure, the input of larvae from surrounding fished areas drops as the adult fished population declines, so the fate of populations within the reserve are linked directly to the health and population trends of the outside fishery. For reserves to help stabilize a fishery or reverse its declines (a fishing goal), or for the populations within reserves to be stable or increasing (a conservation goal), reserves must be individually large enough to mitigate the recruitment overfishing problem or must be able to receive sufficient larvae from nonfished sources (other reserves). As a result, adding more reserves to a system may benefit the overall system and help meet both fishery and conservation goals.

Another advantage of having more than one reserve is suggested by Hastings and Bostford, who model a hypothetical situation in which a new reserve is established to rescue a fish population that is declining within an existing reserve. Assuming that there is no input of larvae from nearby fished areas, the new reserve must supply enough larvae to reverse the population decline. Under these conditions, a more stable result would be obtained by having two new reserves that are each large enough and close enough, than by depending upon a single reserve to rescue the declining population. In this situation, a second reserve would help achieve both fishery and conservation goals. This model suggests that one simplified rule of thumb for reserve spacing is that reserves should contribute sufficient larvae to and receive sufficient larvae from other reserves to maintain populations that are being managed. Without this requirement, the fate of populations in non–self-sustaining reserves is tied primarily to the fate of the fished populations outside the reserves.

Two other rules of thumb that are generally applicable to establishing reserves in a network concern habitat representation and replication. Marine species tend to inhabit specific habitats that are defined by a variety of factors (such as depth, substrate, and salinity), and often use different habitats during different life stages. This means that all major marine habitats must be represented in a network of reserves to meet conservation and fishery goals.

Replication means that each habitat is represented in multiple locations throughout a reserve network. This allows the production of larvae in one area to reinforce (and be reinforced by) production of larvae in other areas. Replication is also important because it provides some insurance against catastrophes. Human-caused and natural disasters are a common feature of most marine environments, so replicating habitats in multiple reserves provides backups for areas that may be damaged by various disturbances.

NOTE: This reading is adapted from a portion of "Designing marine reserve networks for both conservation and fisheries management" by S. D. Gaines, C. White, M. H. Carr, and S. R. Palumbi, 2010, Proceedings of the National Academy of Sciences, vol 107(43):18286–18293; available online at www.pnas.org/cgi/doi/10.1073/pnas.0906473107*. The language of the original paper has been paraphrased and shortened for purposes of this lesson. For further explanation of the ideas presented, please refer to the original paper which also includes additional details and numerous references for the ideas presented, as well as additional discussion about size and spacing of reserves in a network, larval export considerations, and outstanding issues in reserve network design.*

Educator's Version

Some Criteria for Designing Marine Reserve Networks

(adapted from Gaines, *et al.*, 2010)

Global concern for ocean ecosystems has driven growing calls for marine protected areas (MPAs). There are many threats to ocean ecosystems, but only a few of these threats can be mitigated by MPAs. **Discussion Point:** What are some threats that cannot be mitigated by MPAs? Fishing is the human impact that has been the focus of most MPAs. A few MPAs, known as "marine reserves," ban all forms of fishing. Only a tiny fraction of the ocean has been set aside as marine reserves, but the global number of reserves now exceeds 200. Analyses of reserve impacts commonly show large benefits. Biomass typically triples relative to control areas outside the reserves, but the range of responses is enormous. **Discussion Point:** What are students' perceptions of constraints and tradeoffs involved with establishing marine reserves?

Single reserves consistently have a common failing: For nearly all species in the sea, individual marine reserves provide only minor conservation benefits, because the typical reserve size is very small compared to the geographic extent of the species it is designed to protect. **Discussion Point:** Be sure to highlight this inherent constraint: Even though there are large benefits within reserves, the overall benefit to fish populations is typically minor. In this paper, we discuss an emerging solution to this problem—networks.

Even if the number of individuals or total biomass of a species increases dramatically within a single small reserve, the benefits to the species as a whole are relatively limited. **Discussion Point:** Be sure students understand the distinction between number of individuals and total biomass. If marine reserves and other MPAs are to provide significant conservation benefits to species, they must be scaled up. One way to do this is to increase their size greatly (*e.g.*, the Papahänaumokuäkea National Monument, which covers nearly 360,000 km^2). Such large individual reserves are unlikely to be practical in heavily populated coastal areas because of the high economic and social costs. **Discussion Point:** This is another opportunity to discuss tradeoffs. Several nations (*e.g.*, Australia and the United States) are using an alternative approach to scale up marine reserve benefits: networks of multiple MPAs. By aggregating the benefits of multiple MPAs, the network can have larger impacts. More importantly, a number of theoretical models suggest that networks can have benefits that make the network more than the sum of its individual parts.

Locating Single Reserves

Worldwide, the majority of marine reserves are solitary and isolated. The most basic requirement for enhancing biological conservation and fishery prosperity is that an isolated reserve must be self-persistent and therefore must have a positive population growth. **Discussion Points:** 1. What does "fishery prosperity" mean? 2. Note that the same condition must be met for both conservation and fishery prosperity objectives. Although this concept is fundamental, it is rarely followed.

For example, in terrestrial landscapes it may be convenient to locate reserves in areas where there are few competing uses because the areas represent extreme environmental conditions (such as high elevation); but these areas often fail the persistence requirement because they depend upon immigration of organisms produced in less extreme, unprotected areas nearby. **Discussion Point:** This is a good example of the need to keep basic design requirements in mind throughout the design process; locating reserves in areas of convenience may reduce tradeoffs, but fails to meet a basic requirement for designing effective reserves.

Establishing a similarly convenient marine refuge (such as a remote reef that is inaccessible to fishing) can present similar problems of persistence if the refuge exhibits a net loss of biomass over time because more fishes and larvae leave the protected area than arrive from neighboring fished areas. **Discussion Point:** Be sure students understand the problem presented by the larval stage of most fishes; during this stage, ocean currents may carry larvae many miles away from adult populations. Further, placing reserves in convenient locations may add little new protection, and therefore have little effect on fishery prosperity. **Discussion Point:** The point here is that such locations are already protected by their remoteness or inaccessibility, so making it illegal to fish these locations doesn't change the actual amount of fishing that happens. Even if there is a high density of fishes in such locations, protecting these populations may not meet conservation goals, because these refuges can fail to persist if there is intensive fishing outside the reserve boundaries.

Large conservation gains can come from protecting populations that are inherently persistent and have a high local carrying capacity but have been historically overfished. **Discussion Point:** Be sure students understand the situation that is described here: The biology and ecology of these populations would allow them to be persistent without heavy fishing pressure. If persistent populations in a reserve area are a source of biomass to neighboring fished areas, then economic benefits to fisheries are also expected. This can result from migration of adult fishes from the reserve into fished areas and/or from export of larvae. Whether the objectives are conservation or fisheries prosperity, the best location for a reserve may not be where there is high productivity. Highly productive areas may be more important as areas where fishing is allowed, if there is a nearby reserve that can protect a persistent population that provides a source of larvae and/or adult fishes. **Discussion Point:** One way to envision this situation is to imagine a reef that has habitat suitable for a certain species and that is upstream from a much larger area with similar habitat. A population of the species on the smaller, upstream reef could provide a source of larvae to the downstream reef where the larvae would mature into a larger population of adults because of greater habitat availability.

The location of a reserve in relation to coastal habitats also can strongly influence the effectiveness of the reserve, but "success" may depend upon whether the objectives of the reserve are conservation or economic benefits. Matching a reserve's edge with a habitat boundary (*e.g.*, reef edge) can enhance conservation benefits for mobile species by limiting spillover into unprotected waters. On the other hand, placing a reserve edge in the midst of continuous habitat may enhance adult spillover and thus benefit fisheries. **Discussion Point:** Be sure students understand that "spillover" means individual fishes move from the reserve area into unprotected areas where they may be harvested.

From a fishery perspective, the optimal geographic placement of a reserve also depends on whether the goal is to maximize benefits or minimize costs. Placing a reserve edge near an access point (*e.g.*, port) can maximize benefits by minimizing transportation costs to the reserve edge. Fishing areas near ports are often the first to be overexploited and thus also may be good candidate locations for conservation. Conversely, when reserves are not expected to be a source of fish for harvest, fisheries are better served by placing reserves further from port to minimize the costs of travelling to fishing grounds on the far side of the reserve. **Discussion Point:** This is a good example of how seemingly unrelated factors, such a fuel costs, may affect the suitability of a reserve design for fishery objectives.

Why a Network?

A single reserve may play an important role in enhancing or stabilizing adult marine populations close to the reserve, but if the reserve is too small, persistence may require input of adults and/or larvae from the surrounding area. Modeling studies estimate that if a single reserve is to be persistent without contributions from other areas, it must be at least as large as the average dispersal distance for the species the reserve is intended to protect. Larval and adult movements typically are long enough to require that reserves be at least tens, and perhaps hundreds, of kilometers wide to ensure to meet the persistent requirement. Few reserves are this large, and so by these criteria few single reserves are self-sustaining. **Discussion Point:** Suppose a fish species has a larval stage that lasts for two weeks, and the larvae are spawned in an area that has a steady current of 2 knots. How far will the larvae be transported from the spawning area before they become juvenile fishes?

Single reserves facing recruitment deficits can receive demographic bailouts from two sources: fished areas and other reserves. **Discussion Point:** Why did the authors use the term, "demographic bailout?" With high fishing pressure, the input of larvae from surrounding fished areas drops as the adult fished population declines, so the fate of populations within the reserve are linked directly to the health and population trends of the outside fishery. For reserves to help stabilize a fishery or reverse its declines (a fishing goal), or for the populations within reserves to be stable or increasing (a conservation goal), reserves must be individually large enough to mitigate the recruitment overfishing problem or must be able to receive sufficient larvae from nonfished sources (other reserves). As a result, adding more reserves to a system may benefit the overall system and help meet both fishery and conservation goals.

Another advantage of having more than one reserve is suggested by Hastings and Bostford, who model a hypothetical situation in which a new reserve is established to rescue a fish population that is declining within an existing reserve. Assuming that there is no input of larvae from nearby fished areas, the new reserve must supply enough larvae to reverse the population decline. Under these conditions, a more stable result would be obtained by having two new reserves that are each large enough and close enough, than by depending upon a single reserve to rescue the declining population. **Discussion Point:** This is basically "not putting all of your eggs into one basket." In this situation, a second reserve would help achieve both fishery and conservation goals. This model suggests that one simplified rule of thumb for reserve spacing is that reserves should contribute sufficient larvae to and receive sufficient larvae from other reserves to maintain populations that are being managed. Without this requirement, the fate of populations in non–self-sustaining reserves is tied primarily to the fate of the fished populations outside the reserves.

Two other rules of thumb that are generally applicable to establishing reserves in a network concern habitat representation and replication. Marine species tend to inhabit specific habitats that are defined by a variety of factors (such as depth, substrate, and salinity), and often use different habitats during different life stages. This means that all major marine habitats must be represented in a network of reserves to meet conservation and fishery goals.

Replication means that each habitat is represented in multiple locations throughout a reserve network. This allows the production of larvae in one area to reinforce (and be reinforced by) production of larvae in other areas. Replication is also important because it provides some insurance against catastrophes. Human-caused and natural disasters are a common feature of most marine environments, so replicating habitats in multiple reserves provides backups for areas that may be damaged by various disturbances.

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