

Chapter 18

Regime Shifts and Spatial Resilience in a Coral Reef Seascape

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OBJECTIVES

Ecosystems are shaped by natural processes such as predator–prey interactions and climate, as well as by human activities such as harvesting and pollution. Resilient ecosystems are able to absorb disturbances, but chronic stressors may reduce the capacity of an ecosystem to cope with change (Nyström et al. 2000). The ability of ecosystems to absorb disturbance and at the same time maintain their structure, processes, and function is known as **resilience** (sensu Holling 1973). Accumulated evidence from many systems (e.g., coral reefs, forests, rangelands, and shallow lakes) suggests that when pushed past a threshold (i.e., beyond their resilience), ecosystems can undergo a regime shift to an alternative state (Walker and Salt 2006; Knowlton 1992; Dublin et al. 1990; Scheffer et al. 1993; Peterson 2011). From an anthropocentric perspective these alternative states may be less desirable than the initial state depending on the ecosystem goods and services they produce (Moberg and Folke 1999). Strong feedbacks in the alternate state may also make recovery to the original state difficult, even after the original stressors are removed (Scheffer et al. 2001; Nyström et al. 2012). Human dimensions such as opportunity and

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governance also comprise an important aspect of resilience because they influence how sustainably resources are used (Ostrom 2009; Cinner 2009), thereby shifting the resilience threshold. The objectives of this lab are to:

1. Investigate how the ecological dynamics of a system can promote resilience or lead to regime shifts;
2. Explore how interactions between social and ecological processes can influence the state of a system; and
3. Use simple spatial modeling to investigate spatial aspects of resilience and to examine how resilience is influenced by social–ecological processes operating at different scales.

In this lab, you will investigate how social and ecological factors influence resilience across scales using simple nested models and maps within a spreadsheet (**reef.xlsx**) which can be found on the book web site. First, you will explore a model of a patch coral reef. This model will allow you to understand the ecological feedbacks that maintain reefs in a healthy coral-dominated state, in contrast to a degraded, algae-dominated state (Nyström et al. 2012). You will also learn how fishing practices affect reef resilience. Secondly, you will work with a spatial model that expands the patch reef dynamics to a series of linked reefs. This helps us understand how the spatial adjacency of multiple reefs influences resilience and spatial resilience (Nyström and Folke 2001). Third, you will explore how social and ecological factors across multiple scales interact to influence the resilience of the seascape. The lab concludes with a series of synthesis questions which allow for opportunity to think about conservation implications of the lab and spatial resilience in other systems.

NOTE: Before you begin, we recommend two things:

- View the fantastic color images of coral reef systems and small-scale fisheries in the Appendix. These images explain the organisms and fishing practices and will help you visualize the heterogeneity of this seascape;
- Print the map associated with this lab which will be used in Part 3. It can be found on the web site for this book (file called **reef_map.pdf**) and within your **reefs.xlsx** spreadsheet under the tab entitled: **seascape map PRINT THIS**.

INTRODUCTION

Biotic and abiotic factors influence how an ecosystem functions. New elements can be added (invasive species), old pieces can be lost (local extinction), and the most common components can change over time. Such changes can cause an ecosystem to shift to an alternative state. In a coral reef system, a shift from a coral-dominated to a macroalgae-dominated system provides one classic example of a regime shift (see Appendix Image Series 1). Such shifts are generally driven by human impacts, and the alternate state is characterized by changes in ecological structures and species interactions. Regime shifts can have a significant influence on societal and

economic development through changes in ecosystem services provided by the system. For example, coral-dominated reefs provide protein and livelihoods to millions of people in tropical coastal zones (Burke et al. 2011). In contrast, once reefs are dominated by macro-algae, reefs are likely to provide less food and fewer types of fish to dependent communities. Consequently, social and ecological systems are intimately linked (Graham et al. 2013).

An Introduction to the Dynamics of Coral Reefs

Corals—the main architects of coral reef ecosystems—are small colonial invertebrates (3–56 mm) that form colonies and build the reefs as shelters (Appendix Image Series 2). The evolutionary success of reef-building (hermatypic) corals in forming reefs is to a large extent due to the symbiosis between the coral host (polyp) and its unicellular symbiotic microalgae (zooxanthellae). The creation of this three-dimensional framework has supported many dependent species and, over time, has made coral reefs to one of the most diverse ecosystems on Earth. Coral reefs have suffered mass extinctions throughout geologic history and the present reef ecosystems are therefore a product of only the past 45–50 Ma of evolution. The current distribution of corals is much the result of the last ice age (i.e., approximately 10,000 years ago (Kauffman and Al Fagerstrom 1993).

Herbivory and the Balance Between Corals and Macroalgae

Reef ecosystems are shaped by important ecological feedbacks (Figure 18.1; Nyström et al. 2012). Competition between corals and algae for resources such as light and space is paramount (Burkpile and Hay 2008). When in a healthy state, corals are the primary space-holders (Appendix Image Series 1a) and algae are kept under control by the constant grazing of herbivorous fish (Hughes et al. 2007). This process depends on the abundance of herbivores and the area of algae that needs to be grazed (Mumby et al. 2007). Reefs face many perturbations, such as typhoons or destructive fishing, which open up space by removing or killing corals. The loss of corals promotes algal growth and can overwhelm the grazing capacity of herbivores. This is when the regime shift occurs (Appendix Image Series 1b; Williams et al. 2001). Once macroalgae are established there is a range of feedback mechanisms that can reinforce their presence and the macroalgae-dominated state.

Coral Reefs in the Anthropocene

Despite their long history, coral reefs have suffered significant impacts from human activities (Pandolfi et al. 2003), which have resulted in worldwide loss of coral reefs (Gardner et al. 2003; Bruno and Selig 2007). The drivers causing these impacts are in many cases related to human activities, such as overfishing, pollution, and

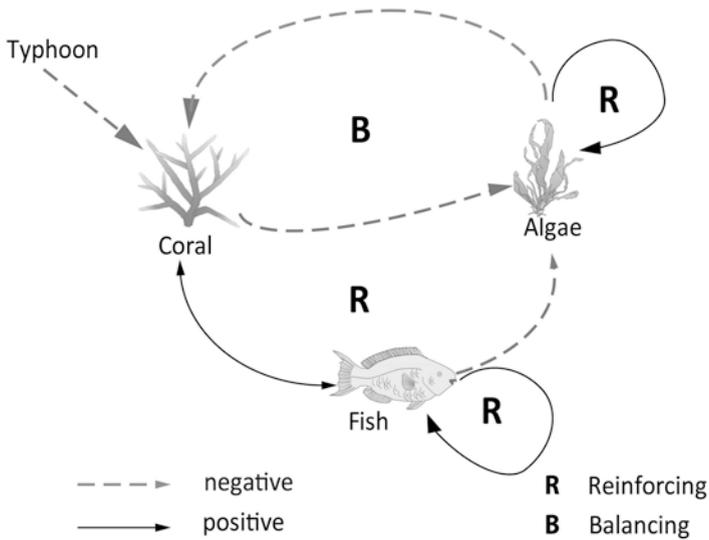


Figure 18.1 A conceptual model of the dynamics influencing whether coral or algae dominates a reef ecosystem. Note both negative (balancing) feedbacks as well as the positive (self-reinforcing) feedbacks. Images: Dieter Tracy, Tracy Saxby. IAN image library (ian.umces.edu/imagelibrary)

climate change, but they operate in tandem with natural disturbance regimes such as hurricanes and diseases (Hughes and Connell 1999; Nyström et al. 2000). Loss of resilience is making coral reefs increasingly vulnerable to these perturbations (Nyström et al. 2000). Since an algae-dominated ecosystem may no longer provide the goods and services desired by society (Moberg and Folke 1999; Burke et al. 2011), avoiding shifts to degraded states is important for societal and economic development (Nyström et al. 2012).

This lab is set in a hypothetical landscape based on the central Philippines (Figure 18.2), an area with breathtaking marine biodiversity, located in the Coral Triangle which is considered the global center of marine biodiversity. Despite their rich diversity, coral reefs in the Philippines are increasingly vulnerable to disturbance with a large human population that depends heavily on the reefs for livelihoods.

Part 1. Patch-Level Dynamics of a Reef

Model Description

We have developed a model of coral reef dynamics that explores the shift from a coral to an algae dominated state in one patch reef. The model is based on basic population dynamics where the birth rate of a population is steady, the death rate

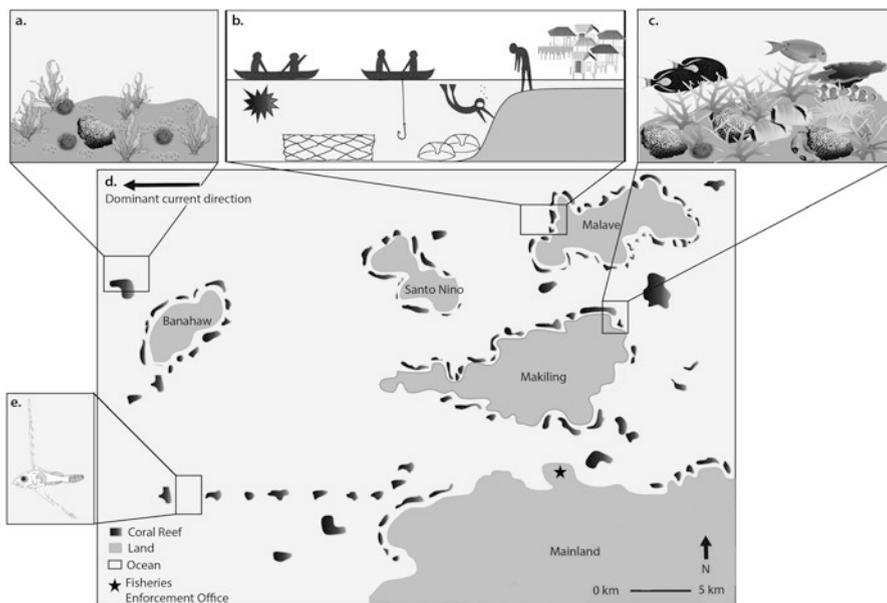


Figure 18.2 Hypothetical landscape in central Philippines with a westward ocean current. Zoom panels show different aspects of this social–ecological landscape. Panel (a) Degraded reef with low spatial complexity and low fish biomass. Panel (b) Small-scale fishers using different gears on the fringing reefs near their village. From *right to left*: blast fishing; nets; hand lines; traps; skin diving; gleaning. Panel (c) A healthy reef with high spatial complexity and high fish biomass. Panel (d) The marine landscape. Panel (e) Reef fish larvae dispersing between reefs. Fisher drawings: Danika Kleiber. Images: Dieter Tracy, Tracy Saxby. IAN image library (ian.umces.edu/imagelibrary)

increases with increasing population size, and the population size is stable, where the birth rate and the death rate intersect (Figure 18.3). The model incorporates stochastic dynamics, which are the random events that naturally occur in ecosystems such as storms and disease outbreaks. You can find this model in the **1.reef fishery** tab of the **reef.xlsx** file.

The model reef is composed of coral, algae, and a population of fish. In the model, coral growth depends upon the cover of coral, space available to colonize, and the biomass of herbivorous fish. The herbivorous fish keep algae in control and hence help to maintain high coral cover. Herbivorous fish biomass is influenced by feedbacks because fish biomass affects competition and reproduction. The maximum fish biomass is set by the amount of coral available as shelter. In a reef with low coral cover, algae will outgrow coral and dominate the reef (Figure 18.4). When fish biomass is low algae become more competitive and a high coral cover is required for corals to be self-sustaining. These dynamics mean that a reef can be dominated by either coral or algae, and that the size of the herbivorous fish population increases the resilience of a coral reef. In the model, fishing lowers the resilience of a coral reef by removing fish and coral. For the model's *Initial Conditions*, 1 represents the proportion of the potential coral cover or fish biomass for the site (i.e., a proportion of 1 = 100%).

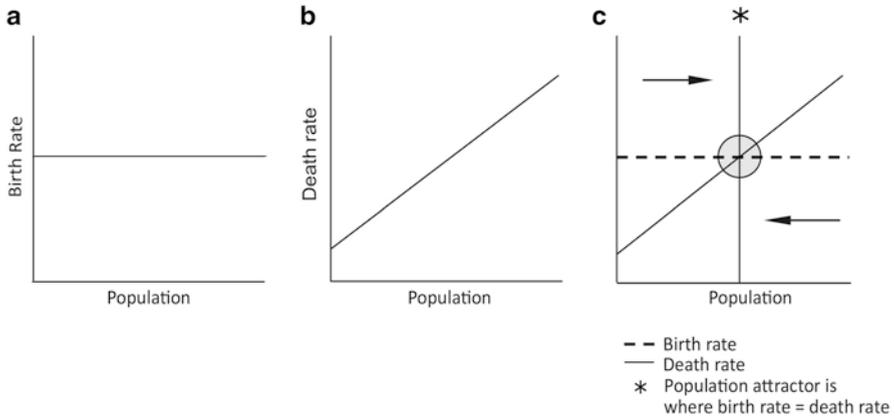


Figure 18.3 Dynamics of a population. (a) The birth rate is steady, (b) the death rate increases with population size, and (c) the population is stable when the birth rate equals the death rate

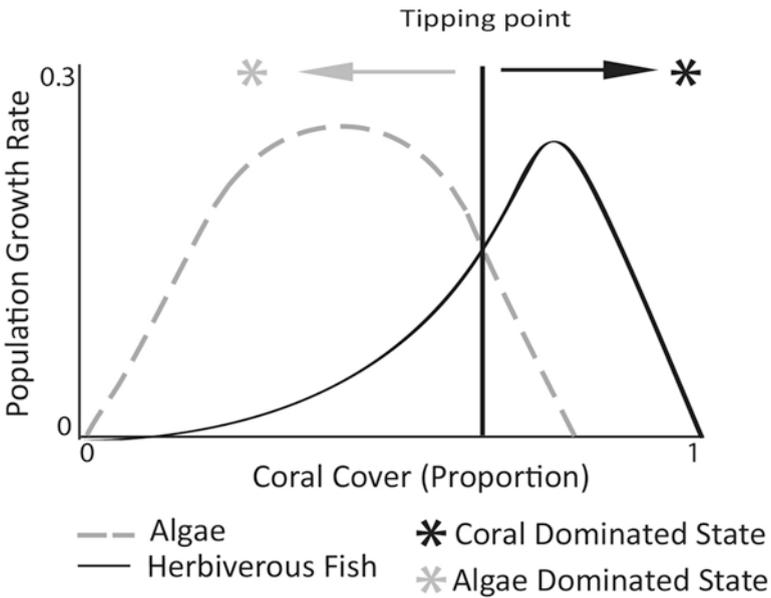


Figure 18.4 The dynamics of coral reef systems are influenced by the relationships between the growth of algae, the growth of the herbivorous fish population, and coral cover. The tipping point of a coral ecosystem exists at the balance between herbivore biomass and algal density. The system tends towards a coral-dominated state above the tipping point and towards an algal-dominated state below the tipping point

SPREADSHEET HINTS

- Download the file **reefs.xlsx** from the book web site
- Figures and Tables embedded in the reefs.xlsx file are labeled with Excel before their name (e.g., **Excel.Figure 1.1** will be in reefs.xlsx in the 1.reef fishery tab).
- Answers for all questions can be entered into reefs.xlsx. The answers you type will be added automatically to the **5.answers** tab. Hitting the update key (explained below) will update your answers.
- Update or rerun the model by pressing “F9” on a PC.
- For Macs, rerun the model by pressing “command” and “=” at the same time.
- You can also rerun the model by changing the text in an unused cell and pressing Enter. On old versions of Excel for Macs “+/-” also works.

EXERCISE 1: Dynamics in a Small Coral Reef

1. Begin by using the **1.reef fishery** tab in the **reef.xlsx** file.
2. Set the initial model parameters in the **1.reef fishery** tab in the **Excel.Table 1.1 Model Parameters** table to match below (Figure 18.5).
3. To generate stochastic dynamics in the model, you can rerun the model by hitting an **update** key or set of keys. [“F9” on a PC; for a Mac use “command” and “=” simultaneously]. Each time you rerun the model, the graph in **Excel.Figure 1.1** will update. This happens because every time you rerun the model you create a new random trajectory for the reef. The trajectory is based on two things: the starting conditions and the years when typhoons occur. Typhoons are a shock to the ecosystem, which reduce resilience by suddenly removing large amounts of coral. In the graph in **Excel.Figure 1.1**, typhoons are indicated by black squares. In the same figure, the different color lines represent characteristics of corals (orange), fish (purple), algae (green), and the fishers’ catch (blue).
4. Try three different **Initial Conditions** values for **Coral Cover**: 0.99; 0.65; and 0.50. Changing the initial condition value for coral initializes the system within different regimes (i.e., different dynamics of fish, algae, and coral and different responses to typhoons). Run the model **10+ times** for each initial condition and track the dynamics of the reef over time in **Excel.Figure 1.1**. Pay attention to the system’s response (a) to one typhoon, and (b) to multiple typhoons that occur over short time periods.

| Excel.Table 1.1 Model Parameters | | Initial Conditions (Proportion) | |
|----------------------------------|------|---------------------------------|------|
| FISHING | | | |
| Yes(1)/No(0) | 0 | Coral Cover | 0.99 |
| Catchability (q) | 0.15 | Herbivorous Fish | |
| Effort | 0.99 | Biomass | 0.98 |

Figure 18.5 Start with these Model Parameter values in the **1.reef fishery** tab in your spreadsheet

Q1 Compare the trajectories of reefs with initial coral cover values of 0.99 and 0.65.

- (a) What is the meaning of the two initial values for coral cover?
- (b) When you change the initial coral cover, does the reef remain coral dominated or shift to algae?
- (c) How many years does it take these changes to occur for fish and coral?

EXERCISE 2: Reef Fisheries

Human activities such as fishing can alter the ecological dynamics of coral reef systems. Overfishing of herbivorous fish can change the competitive balance between corals and algal (Figures 18.1 and 18.4). Different fishing gears vary in their effectiveness in capturing fish and also in the damage they cause to coral (see Appendix Image Series 3). The use of destructive gears such as **blast fishing** (using explosives) is an extremely effective way to catch many fish in a short time. However blast fishing is bad for the ecosystem and the fishery. Blast fishing kills all nearby fish and invertebrates, including species not targeted by the fishers, juveniles, and corals (Alcala and Gomez 1987). By damaging corals, blast fishing destroys the shelters and reproduction grounds of herbivorous fish (Appendix Image Series 3a; Graham et al. 2006). **Traps** are more selective in what they catch. They can cause some localized damage if they get caught in the corals, but the damage is minimal when compared to blast fishing (Appendix Image Series 3b). **Hook and Line** fishing is another commonly used gear in the region (Appendix Image Series 3c, d). However, this gear catches fewer herbivorous fish and does virtually no damage to corals. In this sense, hook and line fishing has less of an effect on the resilience of coral reefs than destructive gears such as blast fishing.

Next, you will explore the relative impact of fishing on the resilience of a small reef patch. The **Catchability (q)** parameter characterizes the efficiency of a fishing gear that is catching herbivorous fish so switching this parameter is similar to switching gear. Catchability is influenced by several factors including the efficiency of fishing gear, fish behavior, and fish biomass. In the model, catchability can range from 0 (no fish are caught) to 1 (all fish are caught). The **Effort** parameter describes the amount of time that fishers spend fishing. In this model, the effort parameter describes relative effort: 0 means no effort and 1 means fishing as much as possible.

Effects of Fishing and Catchability

- Remain on the **1.reef fishery** tab. Turn on fishing in **Excel.Table 1.1** by typing in the new **Model Parameters** shown in Figure 18.6.
- Run the model **10+ times** and track the outcomes.

Q2 What happens to the resilience of the system when fishing is added? Explore the impact of different levels of **catchability** (0.05, 0.1, 0.2) and track the outcomes.

| FISHING | | Initial Conditions (Proportion) | |
|------------------|------|---------------------------------|------|
| Yes(1)/No(0) | 1 | Coral Cover | 0.99 |
| Catchability (q) | 0.1 | Herbivorous Fish | |
| Effort | 0.99 | Biomass | 0.98 |

Figure 18.6 Use these Model Parameter values to turn on fishing in the **1.reef fishery** tab

Q3 How does the catchability of the fishing gear influence the fish population's resilience to typhoons? How could you manage fishing gear catchability to improve system resilience?

Q4 How could you manage fishing gear catchability and/or fishing effort to improve system resilience?

Part 2. Spatial Dynamics of Reefs

The resilience of an ecosystem is influenced by anthropogenic impacts. However, impacts from threats such as fishing can be camouflaged by sharing of resilience among spatially separated areas, such as neighboring reefs (Nyström and Folke 2001; McCook et al. 2009). One of the reasons that reefs share resilience is because of the movement of individual fish and invertebrates among reefs during their larval dispersal phase (Kinlan and Gaines 2003). During this phase most marine organisms, including corals, fish, and algae, travel from their birth site to recruit (i.e., settle) at a new location. This process is made possible by ocean currents. In this sense, spatial exchange of biodiversity provides some insurance against disturbances (Loreau et al. 2003).

EXERCISE 3: Linked Reefs

You will now work with a spatially explicit model that is found on the **2.spatial reefs** tab of **reefs.xlsx**. The spatial reefs model represents the dynamics for 10 reefs that are spatially linked. In this model, larval fish (Figure 18.2e) and algae disperse among reefs, but reefs at the edges receive fewer recruits than central reefs because they only have one neighbor.

1. Open the **2.spatial reefs** tab in **reefs.xlsx**.
2. Examine **Excel.Figure 2.1**. This figure shows the average value of coral, fish, algae, and catch for the 10 linked reefs.
3. Examine **Excel.Figure 2.2**. The reefs are numbered based on their distance to the village (1=close, 10=far). The arrows indicate that larvae from the reefs travel in both directions. There is connectivity between adjacent reefs.
4. Examine **Excel.Figures 2.3–2.5**. These figures show the spatial dynamics of coral cover, fish biomass, and catches, respectively. From top to bottom each figure shows the value at reefs 1–10. Thus, the top of the graphs are the reefs

| Excel.Table 2.1 Model Parameters | | | | | | |
|-----------------------------------|------|---------------------|------|--------------------|--------|-------|
| Fishing | | Catchability | | Initial Conditions | | |
| Fishing: Yes(1)/No(0) | 0 | q (Hook & line) | 0.15 | Site | Coral0 | Fish0 |
| Mobile Fishing:Yes (1)/No (0) | 0 | q (Blast fishing) | 0.6 | 1 | 0.99 | 0.59 |
| Location (if not mobile) | 1 | | | 2 | 0.99 | 0.85 |
| Gear | | Coral Damage | | 3 | 0.99 | 0.94 |
| Hook & Line(0); Blast fishing (1) | 0 | Hook & Line | 0.01 | 4 | 0.99 | 0.98 |
| Effort | 0.99 | Blast | 0.1 | 5 | 0.99 | 0.98 |
| | | | | 6 | 0.99 | 0.98 |
| Max Catch | 0 | | | 7 | 0.99 | 0.98 |
| | | | | 8 | 0.99 | 0.94 |
| | | | | 9 | 0.99 | 0.85 |
| | | | | 10 | 0.99 | 0.59 |

Figure 18.7 In Excel.Table 2.1, set these Model Parameters in the **2.spatial reefs** tab

closest to the fishing village while the bottom of the graph indicates the reefs furthest from the fishing village. From left to right, the figure shows the progression of time from Year 1 to Year 100.

- In the **Excel.Table 2.1**, the **Initial Conditions** indicate the relative value of coral and fish at each reef (reefs 1–10) and in the first year (time=0). The values for Coral0 and Fish0 equal the proportional cover or abundance of corals and fishes in the first year at each reef. In the first year, coral cover is high at all reefs (Coral0=0.99) while fish are highest in the middle reefs (Fish0=0.98). We will change the fishing dynamics and see how this affects the coral, fish, and catch.
- Confirm that the **Excel.Table 2.1 Model Parameters** match those in Figure 18.7. When fishing=0, *no other fishing parameters are turned on because fishing is not running in the model.*
- Run the model **10+ times** with the initial conditions described in Table 18.3. Look at the spatial and temporal dynamics in **Excel.Table 2.1** and **Excel.Figures 2.3–2.5**. Notice how coral and fish respond to typhoons.
- In **Excel.Table 2.1**, change **Site 1** and **Site 5** to algae dominated by setting **Coral0=0.2**.
- Run the model **10+ times** with these new parameter values. Track the spatial and temporal dynamics.

Q5 How do algae-dominated reefs affect the resilience of their neighboring reefs to typhoons?

EXERCISE 4: Heterogeneous Fishing and Fisher Mobility

Continuing to use the model in the **2.spatial reefs** tab, we will now examine the influence of humans on resilience by exploring how heterogeneous fishing across a reef interacts with the spatial dynamics we explored above. In the model, when:

- Mobile Fishing: Yes(1)/No(0)=0, fishing is not mobile and is restricted to shore (Location 1).

- When Mobile Fishing: Yes(1)/No(0) = 1, fishing is mobile and fishers can fish anywhere, targeting sites with the most fish.

In the model, we represent two types of fishing gear. **Hook & line** has moderate catchability and is not destructive. **Blast fishing** has high catchability and is very destructive.

1. Set the **Excel.Table 2.1 Model Parameters** to match Figure 18.8. Return **Initial Conditions** to **Coral0=0.99** for all sites.
2. Run the model with fishers only fishing near land (Location 1 is the reef that is adjacent to the fishing community). Run the model **10+ times** for:
 - Hook and line fishing (set **Gear=0** and Mobile Fishing = 0)
 - Blast fishing (set **Gear=1** and Mobile Fishing = 0)

Q6 How does the location of stationary fishing (i.e., only targeting the closest reef) influence the dynamics of the fish and coral at that reef and at the neighboring reefs?

3. In **Excel.Table 2.1** turn on mobile fishing by changing the cell **Mobile Fishing: Yes(1)/No(0)=1**. This allows fishers to target any reef. Run the model **10+ times** for:
 - Hook and line fishing (**Gear=0** and Mobile Fishing = 1)
 - Blast fishing (**Gear=1** and Mobile Fishing = 1)

Q7 How does the resilience of the ecosystem change when the fishers are able to target all of the reefs?

Q8 How would you manage fishing on a network of reefs differently from an isolated reef to make the fishery more sustainable? Is it possible to make the fishery sustainable while reducing the possibility of a regime shift?

| Excel.Table 2.1 Model Parameters | | | | | | |
|-----------------------------------|------|---------------------|------|--------------------|--------|-------|
| Fishing | | Catchability | | Initial Conditions | | |
| Fishing: Yes(1)/ No(0) | 1 | q (Hook & line) | 0.15 | Site | Coral0 | Fish0 |
| Mobile Fishing:Yes (1)/ No (0) | 0 | q (Blast fishing) | 0.6 | 1 | 0.99 | 0.59 |
| Location (if not mobile) | 1 | | | 2 | 0.99 | 0.85 |
| Gear | | Coral Damage | | 3 | 0.99 | 0.94 |
| Hook & Line(0); Blast fishing (1) | 0 | Hook & Line | 0.01 | 4 | 0.99 | 0.98 |
| Effort | 0.99 | Blast | 0.1 | 5 | 0.99 | 0.98 |
| | | | | 6 | 0.99 | 0.98 |
| Max Catch | 0 | | | 7 | 0.99 | 0.98 |
| | | | | 8 | 0.99 | 0.94 |
| | | | | 9 | 0.99 | 0.85 |
| | | | | 10 | 0.99 | 0.59 |

Figure 18.8 In Excel.Table 2.1, set these Model Parameters in the **2.spatial reefs** tab

Part 3. Linking Social–Ecological Landscapes Across Scales

In the previous section, we considered how coral cover, fish biomass, disturbance, and fishing gears interact to influence the probability of a regime shift. We looked at an individual reef and at the interaction of connected reefs across the landscape.

Here, we increase the complexity of the system and examine the potential for regime shifts to occur under social–ecological conditions operating at different scales. We will take a more in-depth look at how the biological processes that operate inside individual reefs interact with the biophysical and social processes that occur across a seascape. While the calculations in the lab are simplified from the dynamics found on reefs, they provide a conceptual outline of many processes that influence reef resilience. We will consider three social factors: human population size, livelihood availability, and enforcement of fishing regulations (as a proxy for community support of sustainable fishing).

- Look at the map shown in Figure 18.2. This seascape is based on a region of the Philippines.
- Look at the printed **seascape map** or the **4.seascape map** tab in **reefs.xlsx**. The **seascape map** (Excel.Figure 4.1) is a raster (grid) version of the map on Figure 18.2, which you will use to do further calculations in the lab. *NOTE:* We recommend that you print the larger version of this map found in the **6.seascape map PRINT THIS** tab in the spreadsheet or **reef_map.pdf**.

Livelihoods on Islands

The four islands in this ecosystem (Figure 18.2; seascape map) are surrounded by fringing coral reefs (reefs adjacent to the island). Islanders focus their fishing on the fringing reef adjacent to their home island. Since the human population has been increasing, there are more fishers than the reefs can support. On a large island, other livelihoods such as farming or construction work are available. However, on small islands most livelihoods depend on extracting resources from the ocean and from the nearby fringe reefs, even though catches have been declining. Some fishers have responded to declining catches by turning towards destructive gears.

Q9 Based on what you learned in Part 1 and Part 2, how might each of the social factors listed below influence the resilience of a coral reef system?

- Human population size
 - Availability of alternative livelihoods
 - Community support for sustainable fishing and enforcement
- Open the **3.seascape** tab in **reefs.xlsx**. (*NOTE:* You will scroll down through the 3.seascape tab as you go along, but do not need to see the entire worksheet at one time).
 - Type your answers in the boxes provided in the **3.seascape** tab. Your answers in the blue columns will be automatically added to the **4.seascape map** tab and to the **5.answers** tab.

EXERCISE 5: Patch-Scale Influence of Structural Complexity, Reef Size, and Island Size

The total number of fish on the island are influenced by the structural complexity of the coral and the total reef area (Lingo and Szedlmayer 2006; Graham and Nash 2013). In the social realm, the area of an island can correspond to the percentage of adult men on an island who work as fishers (Selgrath, unpub data).

- In **Excel.Table 3.1**, look at the relationship between reef structural complexity and herbivore density. Notice how the density of herbivorous fish changes as structural complexity goes up or down.

Calculation 1: Reef Area

Using the **seascape map**, calculate the total area for the fringing reef (i.e., patch size) associated with each island. **Each cell on the map is 1 km × 1 km. (Excel.Table 3.1).** (*NOTE:* Some of the calculations have been done for you to save time, but be sure to look at all of the answers. The columns where you will enter answers are indicated in green).

Calculation 2: Herbivores on Entire Reef

Based on the herbivore densities of each island (**Excel.Table 3.1**), calculate the total number of herbivores found on each island's fringing reef, using the following equation. Enter your results in **Excel.Table 3.1**.

$$\text{Number of Herbivores} = \text{Herbivore Density} \times \text{Reef Area}$$

Q10 Based on relative herbivore abundance, you'll make a hypothesis about which islands have higher resilience, which we will compare with the outcomes at the end of the lab:

- (a) Which island's coral reefs seem to have coral states that are resilient and which seem to not be resilient?
 - (b) List two reasons why you made this selection.
- In **Excel.Table 3.2**, the area of each island and the number of fishers has been calculated for you. Notice how the number of fishers is similar on some islands with different population sizes.

$$\text{Number of Fishers} = \% \text{ fishers on island} \times \text{adult male population}$$
 - In **Excel.Table 3.3**, look at the relationship between island size and the % of men who are involved in fishing.
 - Fill in the number of fishers on each island (from **Excel.Table 3.2**) into **Excel.Table 3.4** to answer Question 11. (*NOTE:* Islands in Excel.Table 3.4 are ordered by size, so are not in the same order as Excel.Table 3.2)
 - Refresh **Excel.Question 11 Graph**, which shows the relationship between island size and number of fishers. The Excel.Question 11 graph will also be copied into the **5.answers** tab.

Q11 Based on **Excel.Table 3.2** and the **Excel.Question 11 Graph**, how does the number of fishers vary with island size? Why do you see this pattern? Is this the relationship you expected?

Q12 How might the percentage of people dependent on fisheries influence the ability of the island communities to adapt to a changing environment?

EXERCISE 6: Landscape-Scale Factors Influencing System Dynamics

Larval recruitment and the social conditions that influence fishers' decisions about what fishing gears to use are examples of ecological and social processes occurring over broad spatial scales. Importantly, both processes may affect resilience and may vary widely across the seascape.

Ocean Currents and Connectivity

As you learned in Part 2, herbivore recruitment is influenced by self-recruitment (larvae that stay at their home reef) and external recruitment from neighboring reefs. **Nearest-neighbor distance** (here, the distance between two patches of coral) is one factor that can influence recruitment.

- Look at **Excel.Table 3.5** where the distance between each island's fringing reef and its nearest neighboring reef is calculated for you. This distance is from the fringing reef to the nearest reef in any direction.

Calculation 3: Distance to Nearest Reef

Due to a current pattern which travels from east to west, larval recruitment of herbivores from external reefs can only come from neighboring reefs that are directly eastward. Larvae born at such **source reefs** disperse with the ocean current, and recruit to **sink reefs** where they will live as adults. Calculate the distance between each island's fringing reef and the nearest reef that is also directly east. This can include the fringing reefs of other islands. Answers go in **Excel.Table 3.5**.

Calculation 4: Recruitment via Dispersal

Assume that herbivore larvae can travel up to 4 km, and only along the prevailing East → West current. Assess whether herbivore recruitment from external reefs that are larval sources occurs at each island's fringing reef. Answers go in **Excel.Table 3.5**.

- External recruitment (via dispersal)=YES if:
 A source reef is ≤ 4 km from an island's fringing reef; **and**
 The source reef is directly up-current from the fringing reef (i.e., it is eastward)

- External recruitment (via dispersal)=NO if:
The fringing reef >4 km from the nearest neighboring reef that is directly up-current (i.e., it is not eastward)

Q13 How does the distance between reefs interact with current patterns to influence recruitment (via dispersal)? For Banahaw Island, explain how you might predict such external recruitment patterns differently if you did or did not have knowledge about currents.

EXERCISE 7: Seascape Co-Management, Enforcement, and Fishing Gear

In 1998, the Philippine Fisheries Code prohibited the use of most destructive gears, but the use of these practices continues. To reduce destructive fishing, some fishing communities, NGOs, and municipal governments collaborated to hire boat-based fisheries enforcement officers. This co-management model of enforcement led to more successfully managed nearshore islands, but did not have a significant effect on outlying islands. Enforcement is limited by the cost of fuel because officers are not able to afford the gas to travel to distant islands. Limited enforcement and a culture that is tolerant of destructive fishing mean that destructive fishing practices persist in these outlying areas (Marcus et al. 2007; **Excel.Table 3.6**).

Calculation 5: Gear Usage

Based on their distance to the enforcement office, what fishing gears do communities use? Enter the names of the gears used by communities in **Excel.Table 3.5**. Information to answer this question can be found in **Excel.Table 3.5** and **Excel.Table 3.6**.

EXERCISE 8: Regime Shifts and Cross-Scale Interactions

As you learned in the previous section of the lab, social–ecological factors can interact across scales to influence the resilience of these linked systems. Here, we will explore the interaction of factors operating at patch and landscape spatial scales (i.e., cross-scale dynamics).

Calculation 6: Herbivores Caught per Year per Island

Based on results from **Calculation 5**, each island's annual number of fisher catch can be estimated from **Excel.Table 3.6**. Calculate the total number of herbivores caught per year for each island. Answers go in **Excel.Table 3.7** and will be automatically added to the **4.seascape map** tables.

$$\text{Herbivores Caught per Year per Island} = \text{Number of Fishers on island} \times \text{Annual catch per fisher}$$

- Examine **Excel.Table 3.7**, where the number of **Herbivores Remaining** after 1 year is the initial number of herbivores less the fish that were caught and natural mortality.

The total number of new recruits (juvenile fish) for each fringing reef is influenced by larval supplies. Recruitment is a combination of **self-recruiting** individuals (i.e., those that stay at their home reef, which is influenced by local fish populations) and individuals that recruit from up-current reefs (i.e., via dispersal; see **Excel.Table 3.7, Recruitment to Reef**). The estimated recruitment has been calculated for you and was calculated using the formula below. Only reefs with neighbors ≤ 4 km receive external recruitment.

- If Neighbors < 4 km: self-recruitment + recruitment from up-current reefs

$$\text{Recruitment} = (0.25 \times \text{remaining fish population}) + (700,000 \times (1/\text{distance to nearest eastward reef}))$$
- If Neighbors > 4 km: self-recruitment only

$$\text{Recruitment} = (0.25 \times \text{remaining fish population})$$

Calculation 7: Final Number of Herbivores on Reef

In **Excel.Table 3.7**, estimate the final number of herbivores at the end of the year after adjusting for recruitment for each island's fringing reef.

$$\text{Final Number of Herbivores} = \text{Number of Herbivores Remaining} + \text{Recruitment}$$

Calculation 8: Difference Between Final and Original Number of Herbivores

In **Excel.Table 3.7**, calculate the difference between initial and final herbivore densities on each reef after a year of fishing.

$$\text{Difference} = \text{Final Number of Herbivores} - \text{Original Number of Herbivores}$$

(from Excel.Tables 3.7 and 3.1, respectively)

Calculation 9: Number of Herbivores on Reef with High Structural Complexity

In **Excel.Table 3.7**, calculate the theoretical number of herbivores expected at each reef if the reef had high structural complexity. The number of herbivores found on reefs with high quality habitat is 148,000 per km^2 .

$$\text{Number of Herbivores on Healthy Reef} = 148,000 \text{ per km}^2 \times \text{Reef Area (from Excel.Table 3.1)}$$

Fishing decreases fish densities directly through removal and indirectly through habitat destruction. Thus, a complex reef can sustain a high density of reef fish while a fished reef that has experienced habitat destruction can support fewer fish.

Calculation 10: Percent of Herbivores Present on Reef

Determine what percent of the total possible herbivores on healthy reefs is present at each reef after a year of fishing? Place your answers in **Excel.Table 3.7**. (*NOTE: Enter as a percentage*).

$$\text{Percent of Herbivores} = \frac{\text{Final Number of Herbivores (Calculation 7)}}{\text{Number of Herbivores on Healthy Reef (Calculation 9)}}$$

The likelihood of a coral reef to shift to an algae state when hit by a disturbance (e.g., a typhoon) is affected by the abundance of herbivorous fish.

Calculation 11: Resilient Reef

Based on the percent of herbivores present on the reef from **Excel.Table 3.7**, use **Excel.Table 3.8** to predict if each island's fringing reef is resilient and hence likely to remain in a coral dominated state. Here, reefs are considered resilient if herbivore populations are more than 40% of the herbivore population size expected if the reef had high habitat structure.

Resilient Reef = Is Calculation 10 > 40%? (Yes/No)

- Open the **4.seascape map** tab in **reefs.xlsx**. On this tab, the several answers from your calculations in the **3.seascape** tab can be found, but this time they are arranged by island. Blue indicates cells containing the answers you calculated.
- Examine how characteristics of the island vary spatially. Use the information about each island to answer Questions 14–17.

DISCUSSION QUESTIONS

Open **4.Seascape map** to answer these two questions.

Q14 Which island(s) are the most vulnerable to fishing impacts? Which island(s) are ecologically resilient (i.e., which island(s) have a combination of social–ecological factors that are keeping them from undergoing a regime shift)? How does this differ from your original predictions (based on your response to **Q10**)?

Q15 Although it may seem homogenous at first glance, this seascape is quite diverse. How can accounting for spatial variability in this or other landscapes improve our understanding of an ecosystem's spatial resilience?

SYNTHESIS

These are optional and can be assigned as homework.

Q16 We've presented a simplistic model of the relationship between enforcement and gear choice. In real situations, the use of illegal fishing gears is often influenced by complex factors such as management resources, corruption, social acceptability of illegal practices, and external actors such as migrant fishers. Discuss how one of these factors might influence the effectiveness of community efforts to manage their fisheries.

- Q17** Marine Protected Areas (MPAs) are an important management tool in spatially managing fisheries. The placement of MPAs can vary based on different conservation priorities, including protecting vulnerable areas, protecting important source areas (i.e., where larvae come from), protecting areas that are the least vulnerable to climate change, and protecting areas that receive the greatest community support for protection.
- Considering how fishing pressure, recruitment patterns, and social situations might influence MPA placement, come up with three MPA sites for this seascape. Each MPA can include up to 5 grid cells (1 grid cell = 1 km²).
 - Explain where you would put the MPA on the map and describe how the placement of each of the MPAs would meet a conservation priority that you identify.
 - You can draw your MPAs on the printed copy of the seascape.
- Q18** When considering regime shifts in terrestrial environments, recruitment may be a factor, but will operate in different ways. In the case of urban forest patches, acorns are spread up to 18 km by Jays gathering acorns in distant patches and storing them in seed caches (Lundberg et al. 2008). In this way, Jays increase a system's resilience by creating greater connectivity among patches and improving the seed supply to isolated patches.
- Discuss similarities and differences between this terrestrial dispersal process and the coral dispersal process modeled in this lab.
 - If you were going to make an urban protected area, how would you design the park to support this seed dispersal process?
- Q19** In this lab, we have considered the resilience of a coral reef ecosystem; however, many other types of ecosystems are subject to regime shifts. Visit the regime shift database (www.regimeshifts.org) and look over other examples of regime shifts. Choose one regime shift and list:
- the alternate regimes
 - the drivers behind the regime shift, and
 - the feedbacks reinforcing the alternative states.
- Q20** For the regime shift you picked in the prior question, consider the following:
- Over what scale(s) are drivers and feedbacks operating?
 - Are the drivers and feedbacks social or ecological or perhaps inter-linked social–ecological?
- Q21** For your chosen regime shift, use pictures (cornerstones, graphs, ball and cup diagram, etc.) and write a one page description of the ways that the drivers and feedbacks at different scales might interact to lower the resilience of one system, cause a regime shift, and then maintain the new system in a new state.

APPENDIX: CORAL REEF AND SMALL-SCALE FISHING IMAGE SERIES

Image Series 1 Two potential regimes in coral reefs: (a) shows a “healthy” coral-dominated reef with abundant herbivorous fish, habitat complexity, and high productivity, whereas (b) shows a reef dominated by macro-algae. Image Credits: Jennifer Selgrath/Project Seahorse

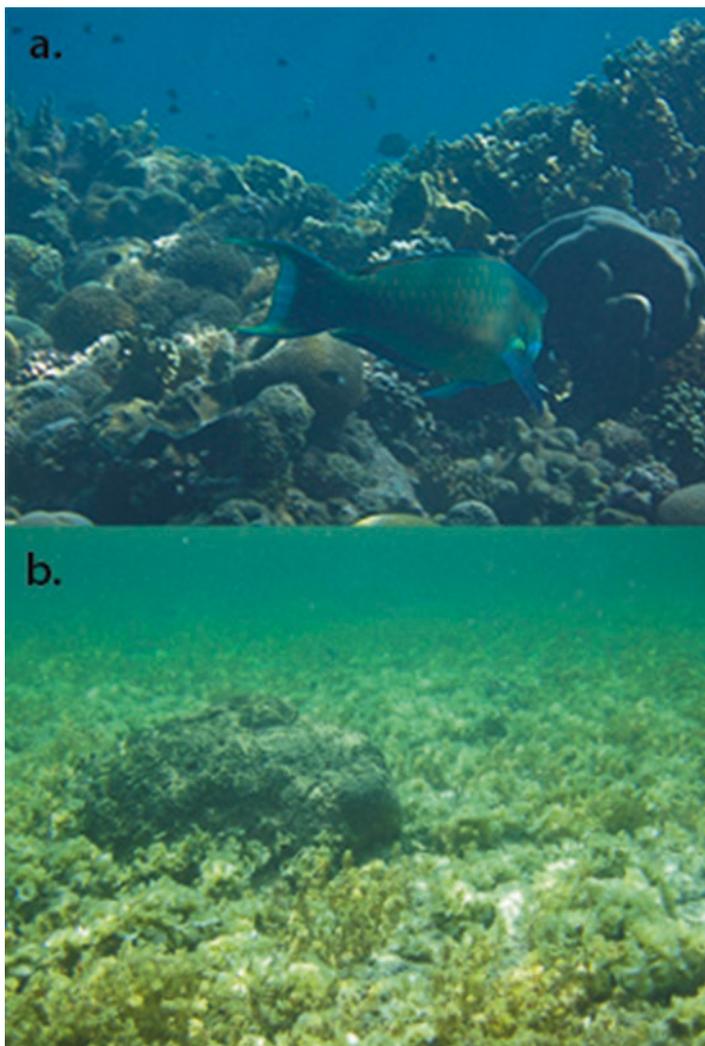
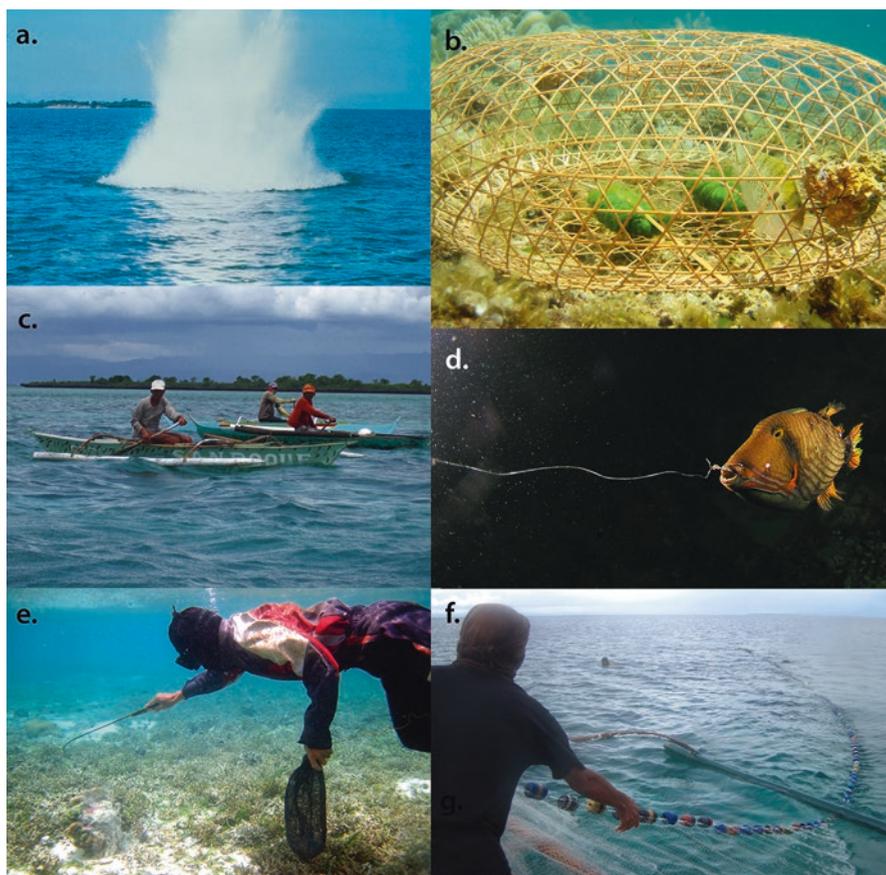


Image Series 2 Living coral polyps (a) form colonies (b) and are the building blocks of coral reefs. (c) Destruction of corals from blast fishing. Image Credits: Jennifer Selgrath/Project Seahorse



Image Series 3 Images of gears used by small-scale fishers in the Philippines: (a) blast fishing explosion; (b) fish trap with three fish inside; (c) hand line fishers paddling to their fishing grounds; (d) trigger fish caught by a hook; (e) dive fisher using a crowbar (KayKay) to pry abalone out of their hiding places in the coral reef; and (f) encircling gill net being pulled in by squid fishers. Image Credits: (a) Wolcott Henry 2005/Lynn Funkhauser; (b) Rebecca Weeks/Marine Photobank; (c, e, f) Jennifer Selgrath/Project Seahorse; (d) Lawrence Alex Wu/Marine Photobank



REFERENCES AND RECOMMENDED READINGS¹

- Alcala AC, Gomez ED (1987) Dynamiting coral reefs for fish: a resource destructive fishing method. In: Salvat B (ed) *Human impacts on coral reefs: facts and recommendations*. Antenne Museum E.P.H.E, French Polynesia
- Bruno JF, Selig ER (2007) Regional decline of coral cover in the indo-pacific: timing, extent, and subregional comparisons. *PLoS One* 2:1–8
- Burke L, Reyntar K, Spalding MD et al (2011) *Reefs at risk revisited*. World Resources Institute, Washington, DC
- Burkepile DE, Hay ME (2008) Herbivore species richness and deeding complementarity affect community structure and function on a coral reef. *Proc Natl Acad Sci USA* 105:16201–16206
- Cinner JE, McClanahan TR, Daw TM et al (2009) Linking social and ecological systems to sustain coral reef fisheries. *Curr Biol* 19:206–212
- Dublin HT, Sinclair ARE, Mcglade J (1990) Elephants and fire as causes of multiple stable states in the Serengeti-Mara woodlands. *J Anim Ecol* 59:1147–1164
- Gardner TA, Côté IM, Gill JA et al (2003) Long-term region-wide declines in Caribbean corals. *Science* 301:958–960
- Graham NAJ, Nash KL (2013) The importance of structural complexity in coral reef ecosystems. *Coral Reefs* 32:315–326
- Graham NAJ, Wilson SK, Jennings S et al (2006) Dynamic fragility of oceanic coral reef ecosystems. *Proc Natl Acad Sci USA* 103:8425–8429
- Graham NAJ, Bellwood DR, Cinner JE et al (2013) Managing resilience to reverse phase shifts in coral reefs. *Front Ecol Environ* 11:541–548
- Holling CS (1973) Resilience and stability of ecological systems. *Ann Rev Ecol Evol Syst* 4:1–23
- Hughes TP, Connell JH (1999) Multiple stressors on coral reefs: a long-term perspective. *Limnol oceanogr* 44:932–940
- Hughes TP, Rodrigues MJ, Bellwood DR et al (2007) Phase shifts, herbivory, and the resilience of coral reefs to climate change. *Curr Biol* 17:360–365
- Kauffman EG, Al Fagerstrom J (1993) The Phanerozoic evolution of reef diversity. In: Schluter D, Ricklefs RE (eds) *Species diversity in ecological communities: historical and geological perspectives*. University of Chicago Press, Chicago
- Kinlan BP, Gaines SD (2003) Propagule dispersal in marine and terrestrial environments: a community perspective. *Ecology* 84:2007–2020
- Knowlton N (1992) Thresholds and multiple stable states in coral reef community dynamics. *Am Zool* 32:674–682
- Lingo ME, Szedlmayer ST (2006) The influence of habitat complexity on reef fish communities in the northeastern Gulf of Mexico. *Environ Biol Fishes* 76:71–80
- Loreau M, Mouquet N, Holt RD (2003) Meta-ecosystems: a theoretical framework for a spatial ecosystem ecology. *Ecol Lett* 6:673–679
- Lundberg J, Andersson E, Cleary G et al (2008) linkages beyond borders: targeting spatial processes in fragmented urban landscapes. *Landsc Ecol* 23:717–726
- Marcus JE, Samoilys MA, Meeuwig JJ et al (2007) Benthic status of near-shore fishing grounds in the central philippines and associated seahorse densities. *Mar pollut bull* 54:1483–1494
- *McClanahan TR, Graham NAJ, MacNeil MA et al (2011) Critical thresholds and tangible targets for ecosystem-based management of coral reef fisheries. *Proc Natl Acad Sci USA* 108:17230–33. *Quantifies resilience by comparing fish biomass to metrics characterizing the state of the ecosystem. This paper also considers the fisheries and ecosystem management strategies that correspond to the various ecosystem states.*

¹NOTE: An asterisk preceding the entry indicates that it is a suggested reading.

- McCook LJ, Almany GR, Berumen ML et al (2009) Management under uncertainty: guide-lines for incorporating connectivity into the protection of coral reefs. *Coral Reefs* 28:353–366
- Moberg F, Folke CS (1999) Ecological goods and services of coral reef ecosystems. *Ecol Econ* 29:215–233
- Mumby PJ, Harborne AR, Williams J et al (2007) Trophic cascade facilitates coral recruitment in a marine reserve. *Proc Natl Acad Sci USA* 104:8362–8367
- *Nyström M, Folke C (2001) Spatial resilience of coral reefs. *Ecosystems* 4:406–417. *In-depth discussion of various aspects of spatial resilience.*
- Nyström M, Folke CS, Moberg F (2000) Coral reef disturbance and resilience in a human-dominated environment. *Trends Ecol Evol* 15:413–417
- *Nyström M, Graham NAJ, Lokrantz J et al (2008) Capturing the cornerstones of coral reef resilience: linking theory to practice. *Coral Reefs* 27:795–809. *Discusses approaches to operationalizing (quantifying) resilience.*
- *Nyström M, Norström AV, Blenckner T et al (2012) Confronting feedbacks of degraded marine ecosystems. *Ecosystems* 15:695–710. *Explores how human actions influence ecological feedbacks in six marine ecosystems.*
- *Olds A, Pitt KA, Maxwell PS et al (2012) Synergistic effects of reserves and connectivity on ecological resilience. *J Appl Ecol* 49:1195–1203. *Quantifies the influence of spatial location and protected status on reef fish.*
- Ostrom E (2009) A general framework for analyzing sustainability of social-ecological systems. *Science* 325:419–422
- Pandolfi JM, Bradbury RH, Sala E et al (2003) Global trajectories of the long-term decline of coral reef ecosystems. *Science* 301:955–958
- Peterson GD (2011) Estimating resilience across landscapes. *Ecol Soc* 6:17–28
- Scheffer M, Hosper SH, Meijer ML et al (1993) Alternative equilibria in shallow lakes. *Trends Ecol Evol* 8:275–279
- Scheffer M, Carpenter SR, Foley JA et al (2001) Catastrophic shifts in ecosystems. *Nature* 413:591–596
- Walker BH, Salt D (2006) Resilience thinking: sustaining ecosystems and people in a changing world. Island Press, Washington, DC, Coral Reefs
- Williams ID, Polunin NVC, Hendrick VJ (2001) Limits to grazing by herbivorous fishes and the impact of low coral cover on macroalgal abundance on a coral reef in Belize. *Mar Ecol Prog Ser* 222:187–196