# Mapping coral reef resilience

Structure:

1. Definitions of resilience, specifically in the coral reef context.
2. Overview of what RS can map directly on coral reefs, depth limits of passive optical data, some mention of the effects of spatial and spectral characteristics on accuracy.
3. Spatial predictive modeling basics – to go beyond what can be mapped directly.
4. Case studies
   1. Knudby Fiji
   2. Rowlands Saudi
   3. Pittman UVI
   4. Wooldridge water quality
   5. Maina Global exposure
5. Pulling everything together to map resilience (rather than indices): Suggest integration through simple mechanical models (Mumby) or more elaborate models that include dynamic human disturbances (Melbourne-Thomas).
6. Management applications – what would a manger do with a resilience map?

## Introduction

Global climate change is now recognized as one of the most important threats to coral reefs, primarily due to the increased frequency of mass coral bleaching events and severe storms expected as a result of our warming climate (Hoegh-Guldberg 1999, Hughes et al. 2003). A new paradigm has therefore emerged for coral reef management: Restoring and maintaining the natural ability of coral reef ecosystems to rebound to a desired state after exposure to climate-driven disturbances (Bellwood et al. 2004). That ability is most commonly termed “resilience” (Holling 1973). This chapter presents a review of how remote sensing and distribution modeling can be used to map coral reef resilience and thus help inform coral reef management in the 21st century.

## Coral reef ecosystem resilience

There are two broad notions of resilience, both focused on a system in dynamic equilibrium with deviations from a stable (climax) state caused by periodic disturbances (Holling 1996, Gunderson 2000). “Engineering resilience” assumes the system in question has a single stable state that it will return to in the absence of disturbance, and resilience is typically quantified as the magnitude of deviation from, and speed of return to, the stable state following a disturbance. “Ecological resilience”, on the other hand, assumes that multiple stable states exist, each bounded by a domain of attraction, and resilience is considered the amount of disturbance the system can be exposed to without moving beyond its current domain of attraction and transitioning to another stable state (Holling 1996). Although these represent separate views of resilience, it is clear that in the context of frequent disturbances the magnitude of deviation from, and speed of return to, the stable state following an individual disturbance (i.e. engineering resilience) will determine the system state at the time of the following disturbance, and thus have bearing on the amount of disturbance the system can be exposed to without moving beyond its current domain of attraction (i.e. ecological resilience) (Gunderson 2000).

The determination of both the state and internal dynamics of a system depends on the specific definition of the system as opposed to the external environment that influences its dynamics. For example, a recent disagreement in the literature has centered on whether grazing by herbivores should be considered an internal component of a coupled benthic-pelagic system (Dudgeon et al. 2010), or whether grazing is so dominantly controlled by fishing of herbivores, and its dependence on coral-algal dynamics so limited, that is should be considered an external environmental factor influencing a benthic system (Mumby et al. 2013). In addition, the spatial and temporal scales at which the system is considered influence notions of stability and resilience. The local functional extinction of a dominant species may result in dramatic state change that is irreversible in the short term, but with resettlement from nearby reefs and subsequent recovery the long term fluctuations in state may be considered a dynamic equilibrium. For example, coral reef ecosystems considered stable within the last ~50 years of monitoring may already have been pushed into non-climax unstable states by pre-historic and historic fishing pressure (Jackson 2001), from which recovery is not possible on human time scales. It is thus not always clear what the stable state that we want coral reef ecosystem to be able to rebound to after exposure to climate-driven disturbances looks like (Pauly).

Although spatial and temporal scales are rarely specifically defined, it is broadly accepted that multiple stable states exist for coral reef ecosystems (Knowlton 1992, Mumby et al. 2013 in Oikos, but see Dudgeon et al. 2010). Classically these include a desired coral-dominated state that, given a combination of press and pulse disturbances, can be replaced by an undesired macroalgae-dominated state. Stable states dominated by other organisms have also been documented (Davis 1982, Aronson et al. 2002, Loya 2004). Ecological resilience has thus been broadly adopted as the relevant resilience concept by the coral reef community, but it is difficult or impossible to measure in the absence of observed transitions between stable states, and thus not practical as a basis for resilience assessment or management. Engineering resilience, on the other hand, can be assessed by focusing on its two aspects, often termed “resistance” (to disturbance) and “recovery” (from disturbance), which can be quantified through natural experiments by monitoring relevant system state variables before, during and after a disturbance. In order to manage for resilience, factors that influence resistance and recovery can thus be identified and protected.

## Factors that influence the resilience a coral-dominated reef ecosystem

## What remote sensing can map on coral reefs

In theory remote sensing could map past variability, which would be a very direct way to map resilience, but the relevant changes (e.g. bleaching and recovery by either corals or algae) basically require airborne hyperspectral data, so in reality we don’t have that capability. Perhaps (though I’m not a believer) EnMAP will help with this. It will certainly be the best bet.

## Spatial distribution modeling

## Case studies

This section needs a good introduction that explains why we are presenting all these different case studies and how they form a coherent whole. The basic idea is to provide a broad picture of the work that has been done so far on mapping all things relevant to coral reef resilience, including both resistance and recovery indicators and exposure.

## Integration through mechanistic modeling

Again, my basic idea here is that if we can populate a model like Mumby’s or the CORSET model, and introduce spatial dynamics, we get a way to map not just indicators, but an actual quantification of resilience (e.g. Mumby’s model can produce “probability to end in coral-dominated state after XX years).

## Management applications

The great problem for current coral reef conservation is to operationalize our understanding of ecosystem resilience, and apply it for management. This section should basically answer the question of “so you have a map of reef resilience, now what do you do?”

## Conclusion