Managing for Resilience in Benthic Marine Environments

The Challenge of a Sustainable Future: Contributions of LTER Science

Russell J. Schmitt
UC Santa Barbara
Moorea Coral Reef LTER
Santa Barbara Coastal LTER

2012 LTER Science Council Meeting
Andrews Experimental Forest
May 16 - 17, 2012
• Many ecological systems can shift suddenly from one state to another that has a reduced capacity to provide ecosystem services

• Growing concern that some abrupt shifts to alternate states may be difficult to reverse (‘regime shifts’, ‘phase shifts’, ‘ecological catastrophes’)
• Major challenges to sustainability science & action:
  - forecast abrupt state changes
  - understand reversibility of a state change
  - identify means to prevent undesired shifts
Seminal contributions of LTER science to understanding state change in ecological systems

- Evaluating the nature of shifts
- Developing & testing methods to warn of abrupt shifts
- Evaluating reversibility
- Identifying factors that strengthen resilience
Modes of Abrupt State Shifts

- **Linear Tracking**
- **Non-linear Tracking**
- **Hysteresis** (most worrisome, most uncertain)

### Environmental conditions

#### Ecological state

- **A**: Coral dominates
- **B**: Macrolalgae dominates

#### Time

- **A**: Coral state
- **B**: Macrolalgae state

**Notes:**
- Coral state
- Macrolalgae state
Non-linear responses to gradual change in environmental conditions

Non-linear Tracking

Hysteresis

Both cases: small change in environmental conditions can result in a large, abrupt shift in ecological state

adapted from Scheffer et al. 2001 Nature (North Temperate Lakes LTER)
Two reasons to distinguish between these 2 non-linear modes

1) Reversibility of the state change

- **Non-linear Tracking**: The state shift is reversible, occurring smoothly without hysteresis.

- **Hysteresis**: A state shift is difficult to reverse, requiring much greater relaxation in environmental conditions.

**Key Points**

- **Hysteresis makes a state shift difficult to reverse** – requires much greater relaxation in environmental conditions.
Two reasons to distinguish between these 2 non-linear modes

2) Respond differently to disturbance

- **Non-linear Tracking** – system will tend to return to pre-disturbed state
- **Hysteresis** – large disturbance can trigger a persistent shift to an alternate state *with no change* in environmental conditions
LTER has advanced general understanding of state shifts through theoretical & empirical approaches
Hysteresis well described in models but challenging to find support for in nature

North Temperate Lakes LTER: Persistent ‘clear-water’ (macrophyte) and ‘cloudy-water’ (phytoplankton) states in lakes

NTL experiment showing that a disturbance can cause a persistent shift from the ‘Cloudy-water’ to the ‘Clear-water’ state in the same environmental conditions.

Scheffer & Carpenter 2003. TREE
Model of how positive feedback of seagrass on sediment suspension & light can create alternate persistent states (Carr 2011, 2012)
Cross-site analysis of LTER time series data from 4 sites to:

1) Assess analytically whether & when abrupt transitions occurred

2) Evaluate proposed methods of forecasting abrupt shifts

3) Seek evidence of hysteresis
Response: Abundance of krill (*Nyctiphanes simplex*) - 48 year time series

Driver: Decadal climate variability in the Pacific (Pacific Decadal Oscillation - PDO)
Response: Abundance of 3 species of penguins (*Pygoscelis* spp.) – 40 years

Driver: Annual duration of sea ice
Response: Abundance of a sea cucumber (*Pachythyone rubra*) – 28 years

Driver: Annual storm wave regime
Response: Production of black grama grass (*Bouteloua eriopoda*) – 34 years

Driver: Growing season rainfall regime
Issue 1: Analytical evidence for abrupt transitions in biological state
Statistical breakpoints in detrended data

Santa Barbara Coastal LTER: 2 abrupt transitions detected

<table>
<thead>
<tr>
<th>Abrupt transition(s) identified with correct timing?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sea Cucumber</td>
</tr>
<tr>
<td>Krill</td>
</tr>
<tr>
<td>Penguins</td>
</tr>
<tr>
<td>Black Grama Grass</td>
</tr>
</tbody>
</table>
Issue 2: Ability to forecast abrupt transitions

Models & lake studies (NTL LTER) - increased variance in time series of biological responses foreshadow abrupt transitions
(Scheffer et al. 2009 Nature; Carpenter & Brock 2006 Ecology Letters; Carpenter et al. 2011 Science)

Jornada Basin LTER: Variance increased

<table>
<thead>
<tr>
<th>Variance increase detected?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black Grama Grass</td>
</tr>
<tr>
<td>Sea Cucumber</td>
</tr>
<tr>
<td>Krill</td>
</tr>
<tr>
<td>Penguins</td>
</tr>
</tbody>
</table>
### Issue 3: Evidence for mode of the abrupt transition (e.g., Hysteresis)

Examined relationships between response & driver variables

<table>
<thead>
<tr>
<th>Likely mode</th>
<th>Hysteresis mechanism?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Krill</td>
<td>Linear tracking</td>
</tr>
<tr>
<td>Sea Cucumber</td>
<td>Hysteresis</td>
</tr>
<tr>
<td>Penguins</td>
<td>Hysteresis</td>
</tr>
<tr>
<td>Black Grama Grass</td>
<td>Hysteresis</td>
</tr>
</tbody>
</table>

- **Hysteresis mechanism?** (identified by LTER studies)
  - Positive predation-mediated feedback
  - Positive predator- & breeding-mediated feedbacks
  - Positive feedback between soil erosion & low grass cover
Analysis of LTER long term data

- Applying a suite of general concepts & methods to long term data advances understanding of state changes
- Forecasting a shift from increased variance may have limited utility
  - need more frequent measures than typically made to estimate the state of an ecosystem (auto-correlation)
  - VCR & others seeking ‘leading indicators’ of an impending shift (e.g., leaves per shoot of seagrass)
- Analysis of driver – response relationships provides insight on the mode of response
- State changes with hysteresis appear to be occurring in multiple types of ecosystems
Can we manage state changes?  
What coral reefs are telling us

| • Direct control not feasible for many conditions that drive state change |
| • Human activities can make state change more likely; some activities highly amenable to control |
| • Managing for resilience: Goals: |
| - maintain capacity of ecosystem to absorb stresses without changing state |
| - speed return to the desired state if disturbed |
| • Information needs: What are the critical feedbacks & how are they affected by human activities |
Coral reefs frequent experience large disturbances that kill coral on landscape scales

- Tropical cyclones
- Outbreaks of coral predators
  Crown-of-Thorns Seastars (COTS)
- Bleaching events

Disturbances have triggered phase shifts on some coral reefs in recent decades
Disturbed reefs can return to coral dominance or switch to dominance by macroalgae.

**Disturbance**

Once established, macroalgae can kill adult coral & prevent coral recruitment.

For reefs to be resilient, herbivores must control macroalgae.

Hysteresis?
Why do some reefs return to the coral state while others shift to a macroalgal state?

Fundamentally related to herbivory

Coral reefs of Moorea ideal for determining the features of herbivory that confer resilience

Moorea, French Polynesia
Multiple disturbances on the fore reef

Fore reef returned to coral dominance within ~ 1 decade

No transition to a macroalgal state
What makes the fore reef of Moorea resilient? Why haven’t disturbances triggered a shift to macroalgae?

fore reef of Moorea when MCR was established in 2004
fore reef of Moorea last month (April 2012)
Since 2005, the fore reef of Moorea experienced two more disturbances, providing opportunity to explore features that make the fore reef resilient. 


Cyclone Oli: February 2010
MCR collects time series data from 3 coral reef habitats (Fore reef, Back reef, Fringing reef) all around the island.

Community dynamics differ between fore reef & lagoon habitats.
Changes on the reef since 2005

Lagoon

Fore reef
Back reef
Fringing reef

Crown-of-thorns

Adam et al. 2011  PLoS One
Changes on the reef since 2005

Adam et al. 2011  PLoS One
Changes on the reef since 2005

Adam et al. 2011  PLoS One
Changes on the reef since 2005

Adam et al. 2011  PLoS One
Changes on the reef since 2005

Adam et al. 2011  PLoS One
An MCR long term grazing experiment has revealed:

• Macroalgae would have dominated fore reef without control by herbivory
• Control was exerted by fishes, primarily parrotfish
Parrotfish – 6-fold increase in biomass on the fore reef in a year resulted from:

- Doubling in average biomass of an individual

- Increase in parrotfish abundance (numerical response) (~50% increase in number of parrotfish island-wide)
Nursery habitat in lagoon critical to numerical response of adult parrotfish on fore reef

- Juvenile parrotfish recruit to mounding coral that only occurs in the lagoon
- Parrotfish move to fore reef within a year as they grow – a connectivity critical to resilience
Disturbances that kill coral on the fore reef do not harm parrotfish nursery habitat.

Stable nursery habitat in lagoon enabled rapid numerical response of parrotfish.
What makes the fore reef of Moorea resilient?

The capacity of parrotfish populations to respond rapidly to increases in food following the sudden loss of coral.
Resilience models for Moorea show that if parrotfish grazing falls below a critical level, system undergoes phase shift from coral to macroalgae

- Hysteresis in response means grazing must be restored to a higher rate than the critical tipping point for system to return to coral

- Grazing in Moorea still well right of the tipping point

- Human activities reduce grazing in 2 ways: fishing adult parrotfish and destroying parrotfish nursery habitat.
Managing for resilience requires ecosystem-based strategies that protect critical functions, which may be sensitive to different stresses.

- **Fishing a key process that can trigger a phase shift**
  - Artisanal fishery for parrotfish on Moorea

- **Parrotfish nursery habitat sensitive to land use practices**
  - Pineapple plantation on Moorea
The Challenge of a Sustainable Future

- Long term research critical to
  - our understanding of abrupt state changes in ecological systems
  - science needed to develop sustainable management strategies

- LTER has been a leader in providing new answers
  - uniquely able to combine long term data with process studies of underlying mechanisms
  - focus on long term phenomena and landscape scales necessary to reveal processes critical for resilience
  - network of diverse ecosystem enables comparative studies that reveal generality

Thank you