Managing for Resilience in Benthic Marine Environments

The Challenge of a Sustainable Future: Contributions of LTER Science

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- **Many ecological systems can shift suddenly from one state to another that has a reduced capacity to provide ecosystem services**

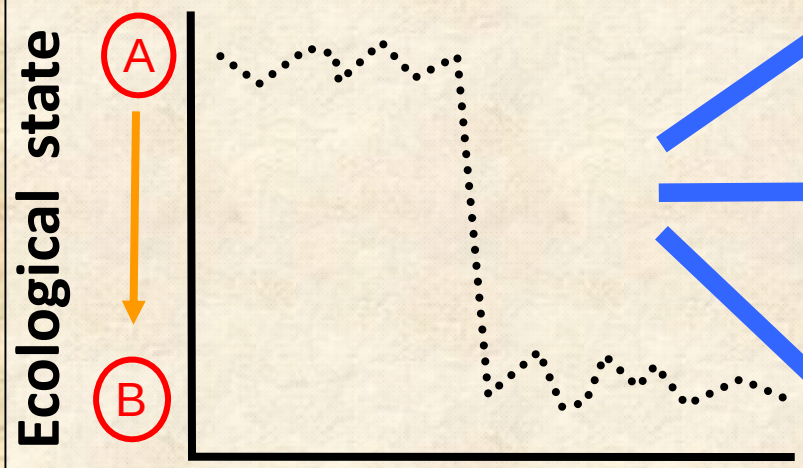
- **Growing concern that some abrupt shifts to alternate states may be difficult to reverse (‘regime shifts’, ‘phase shifts’, ‘ecological catastrophes’)**

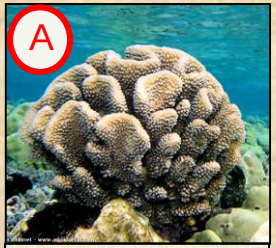
- **Major challenges to sustainability science & action:**
  - **forecast abrupt state changes**
  - **understand reversibility of a state change**
  - **identify means to prevent undesired shifts**

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

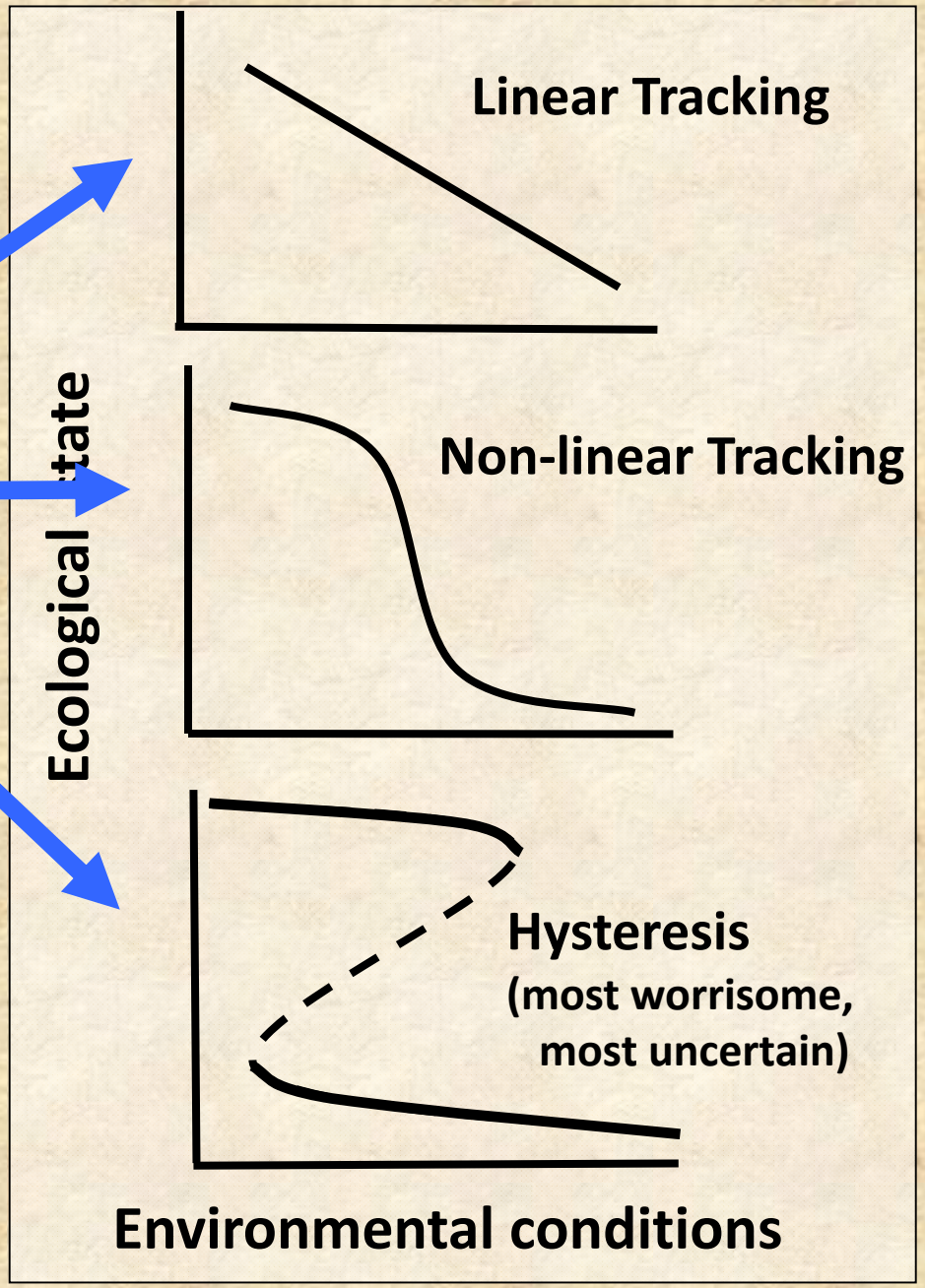
Modes of Abrupt State Shifts



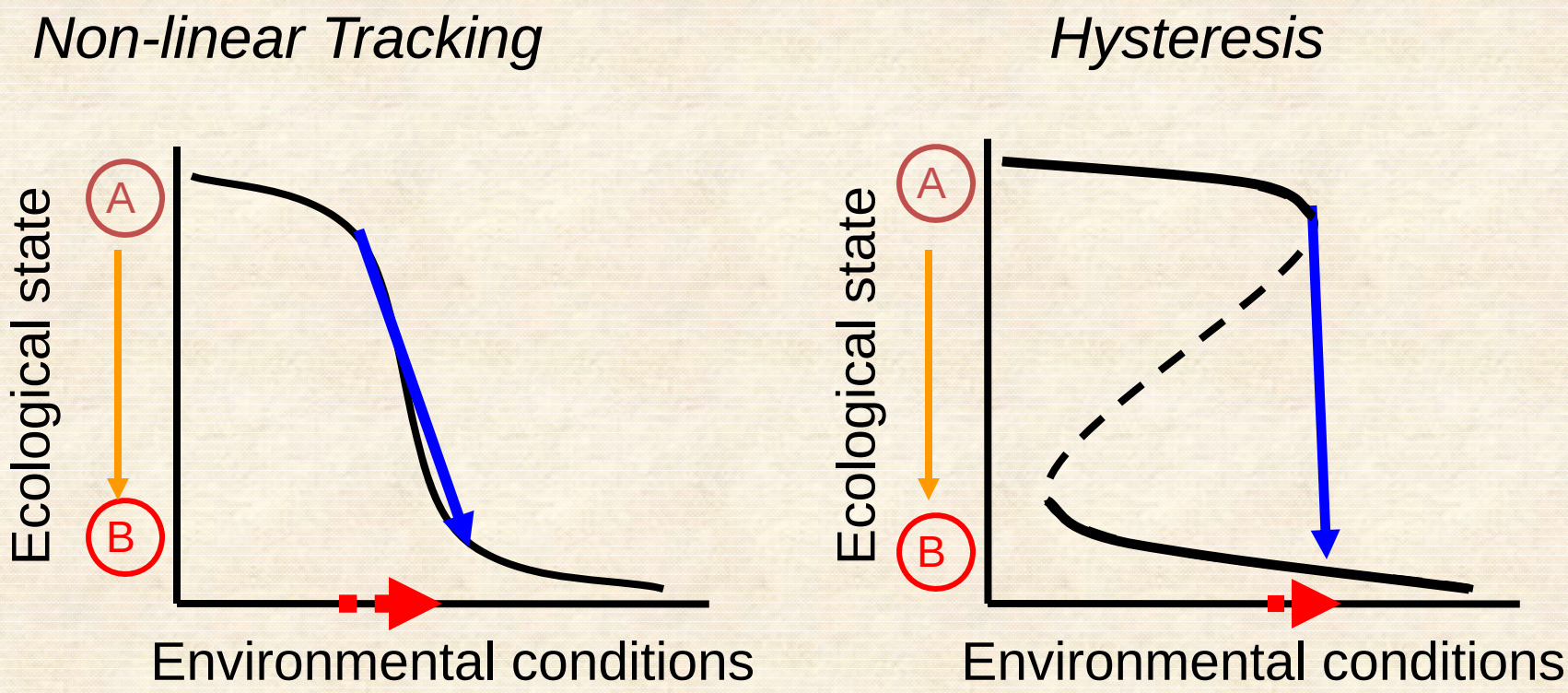


Coral dominates

Macroalgae dominates



Non-linear responses to gradual change in environmental conditions

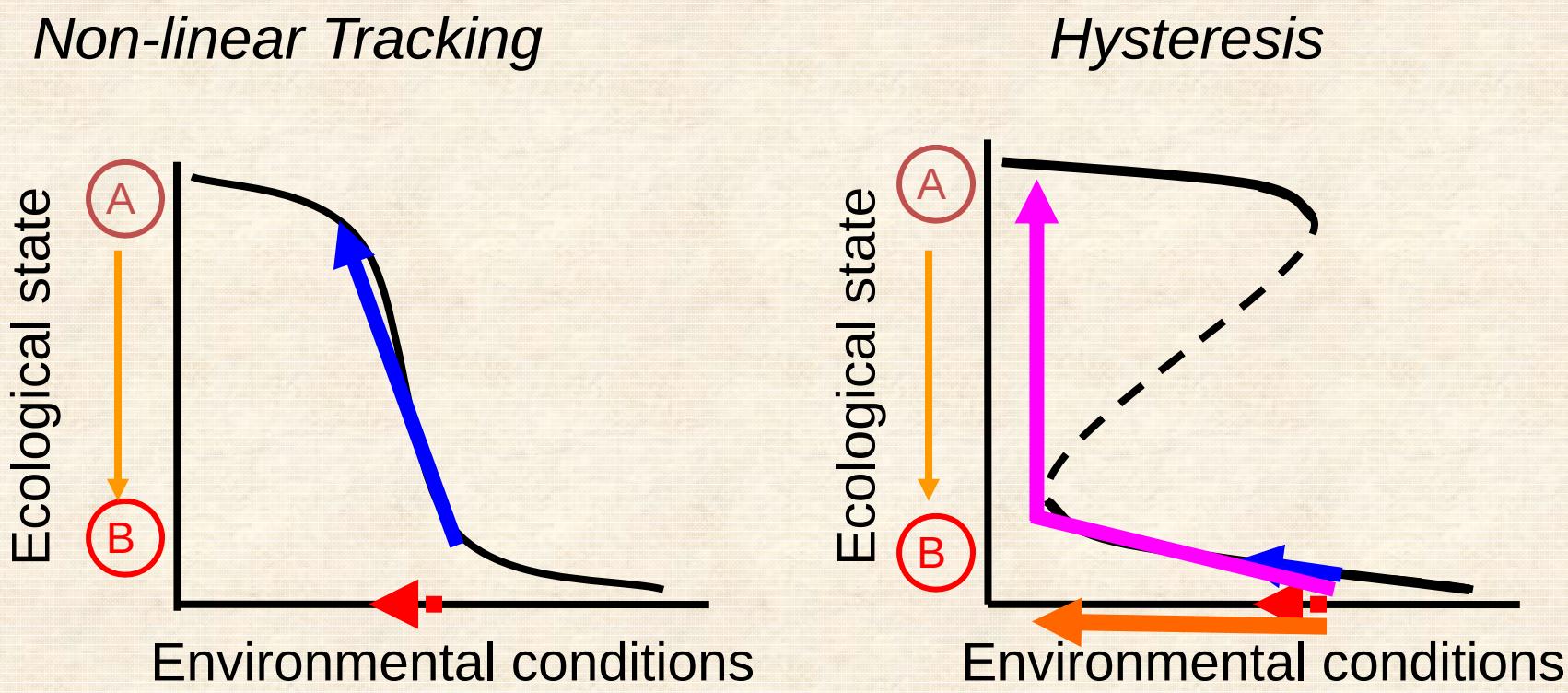


Both cases: small change in environmental conditions can result in a large, abrupt shift in ecological state

adapted from Scheffer et al. 2001 Nature
(North Temperate Lakes LTER)

Two reasons to distinguish between these 2 non-linear modes

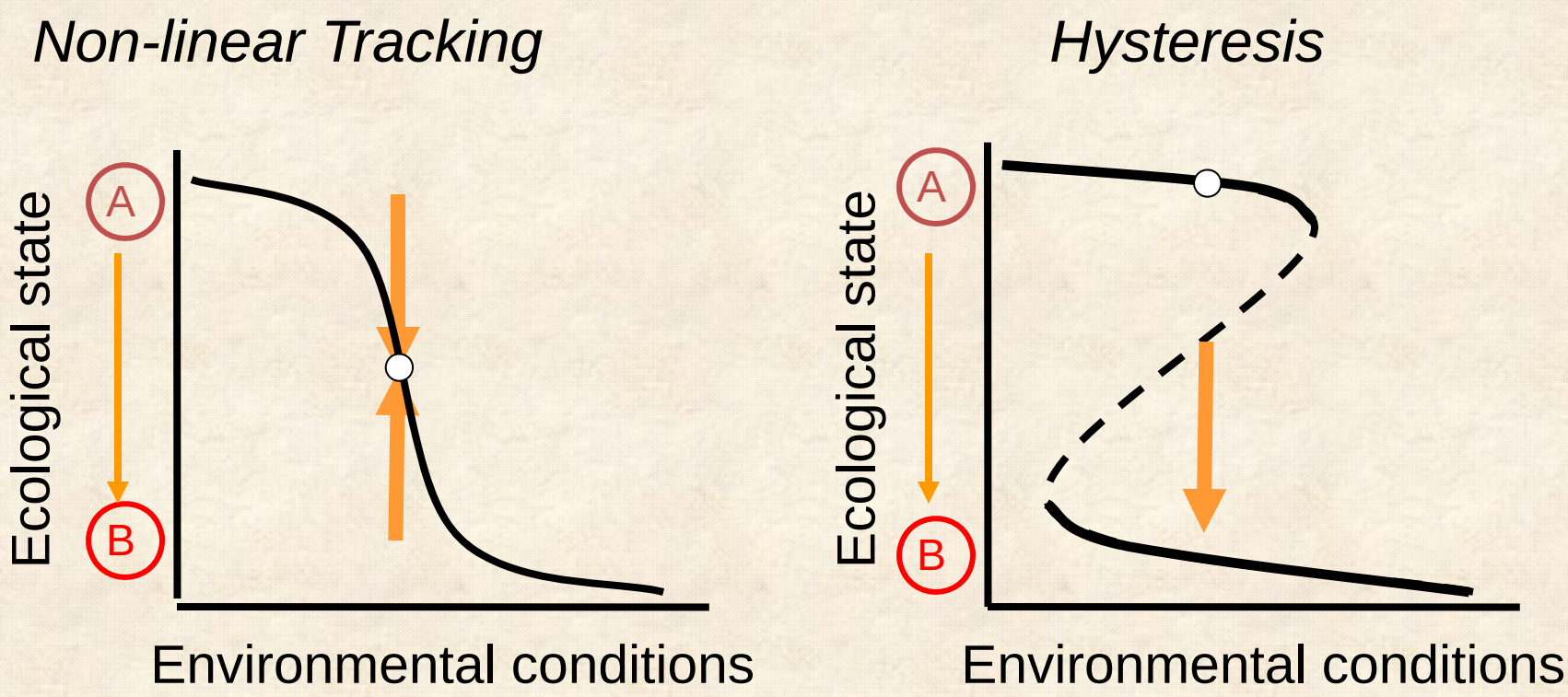
1) Reversibility of the state change



- **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

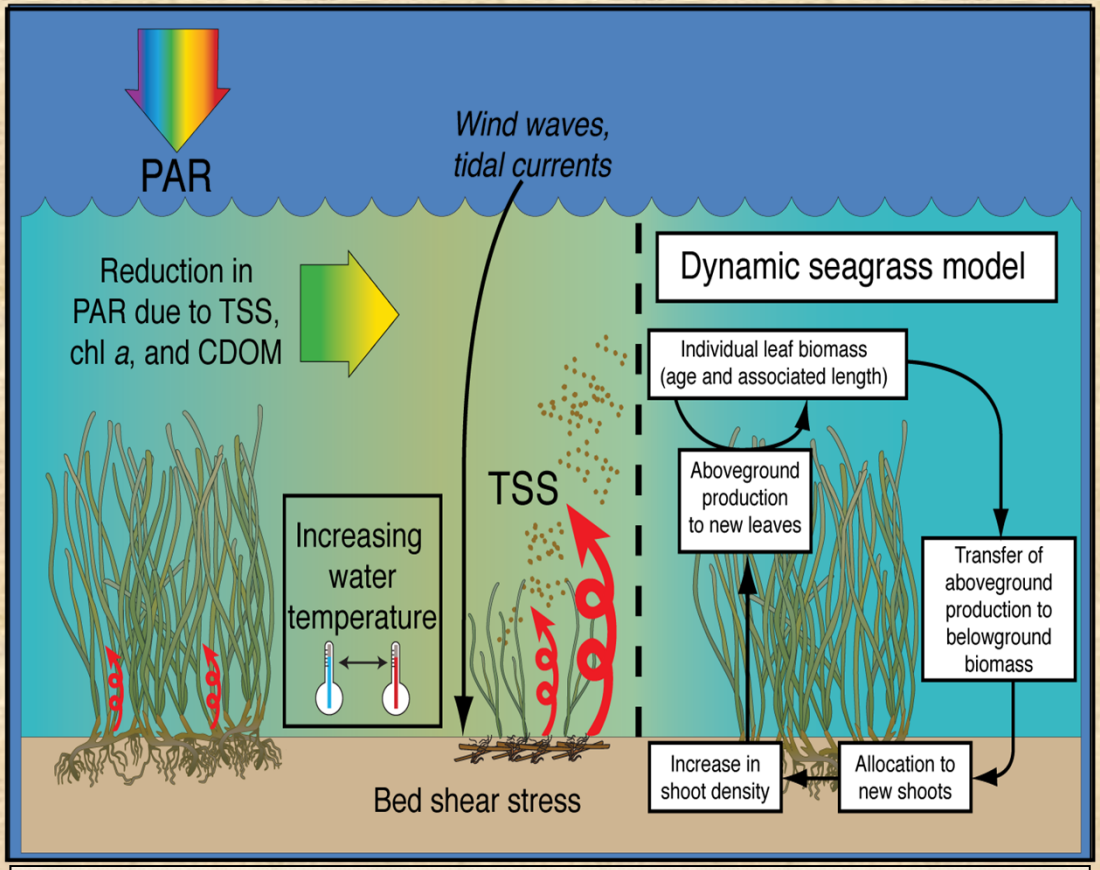
North Temperate Lakes LTER: Persistent 'clear-water' (macrophyte) and 'cloudy-water' (phytoplankton) states in lakes

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.

NORTH TEMPERATE LAKES
Long Term Ecological Research

Carpenter et al. 1999 Ecol. App.
Scheffer & Carpenter 2003. TREE
Folke et al. 2004. Annual Rev. Ecol. Evol.

VCR LTER: Subtidal seagrass & mudflats - alternate persistent states



Model of how positive feedback of seagrass on sediment suspension & light can create alternate persistent states (Carr 2011, 2012)

LTER Long Term Data also have advanced general understanding of state shifts

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

esa 2011. Ecosphere 2(12):129. doi:10.1890/ES11-00216.1 ECOSPHERE

SYNTHESIS & INTEGRATION

Analysis of abrupt transitions in ecological systems

Brandon T. Bestelmeyer,[1,†] Aaron M. Ellison,[2] William R. Fraser,[3] Kristen B. Gorman,[3,4] Sally J. Holbrook,[5,8] Christine M. Laney,[6] Mark D. Ohman,[7] Debra P. C. Peters,[1] Finn C. Pillsbury,[1] Andrew Rassweiler,[8] Russell J. Schmitt,[5,8] and Sapna Sharma[9]

California Current Ecosystem LTER

Palmer Station Antarctica LTER

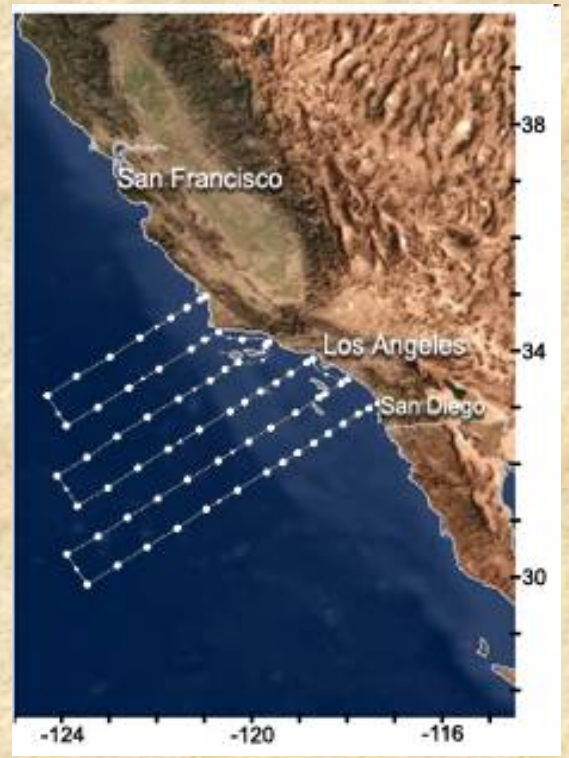
Santa Barbara Coastal LTER

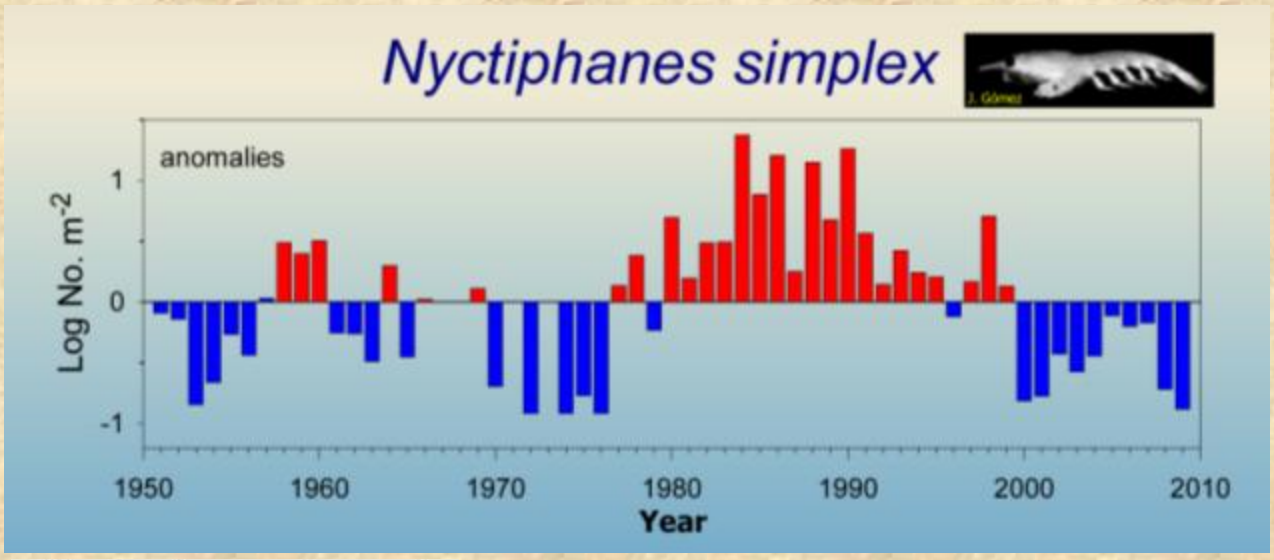
Jornada Basin LTER

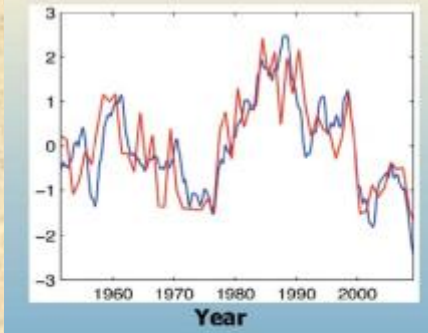
California Current Ecosystem
LTER

Response: Abundance of krill (*Nyctiphanes simplex)* - 48 year time series

Driver: Decadal climate variability in the Pacific (Pacific Decadal Oscillation - PDO)







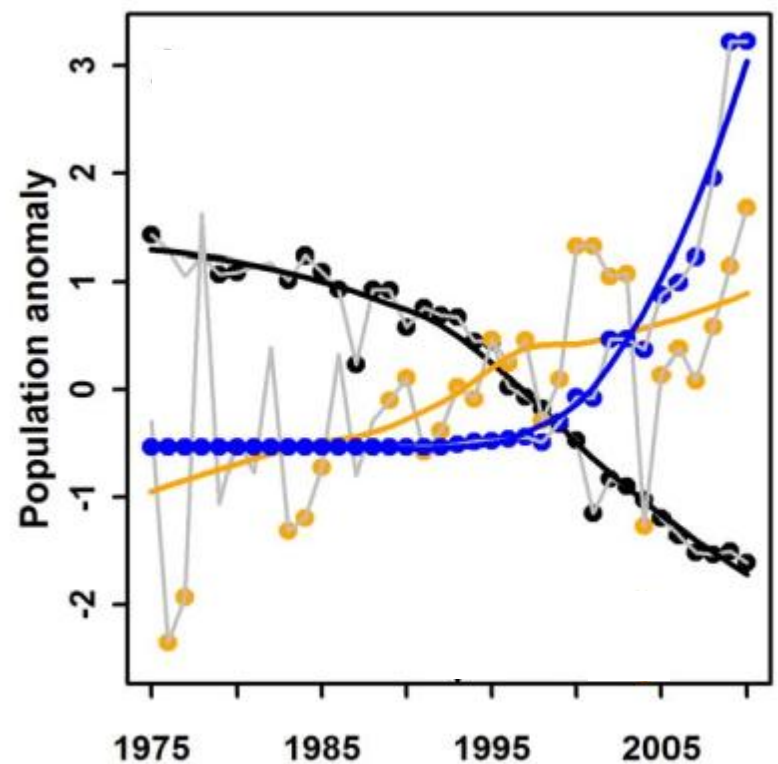
PDO
AR1 model

Palmer Station Antarctica
Long Term Ecological Research

Response: Abundance of 3 species of penguins (*Pygoscelis* spp.) – 40 years

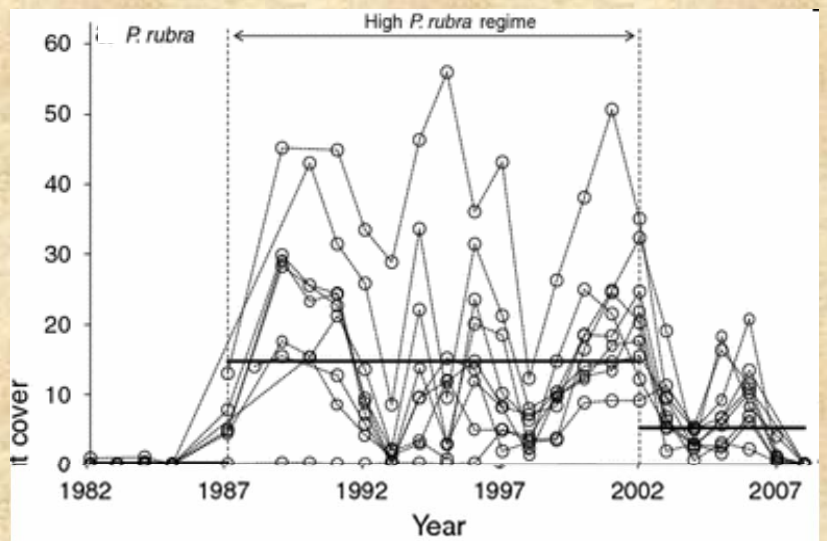
Driver: Annual duration of sea ice

Chinstrap **Gentoo** **Adélie**



Response: Abundance of a sea cucumber (*Pachythyone rubra*) – 28 years

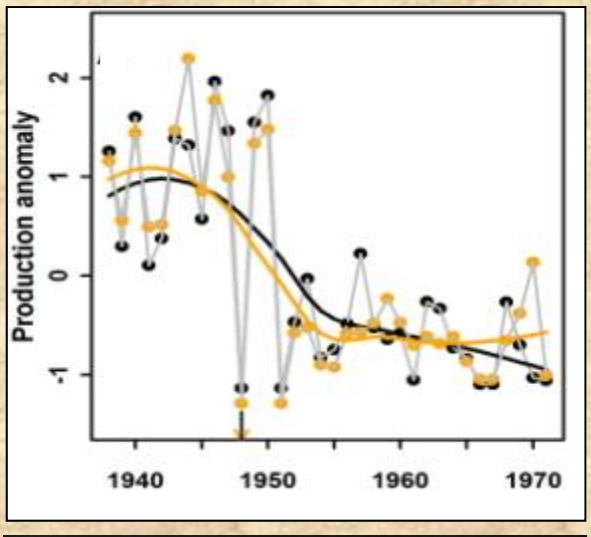
Driver: Annual storm wave regime

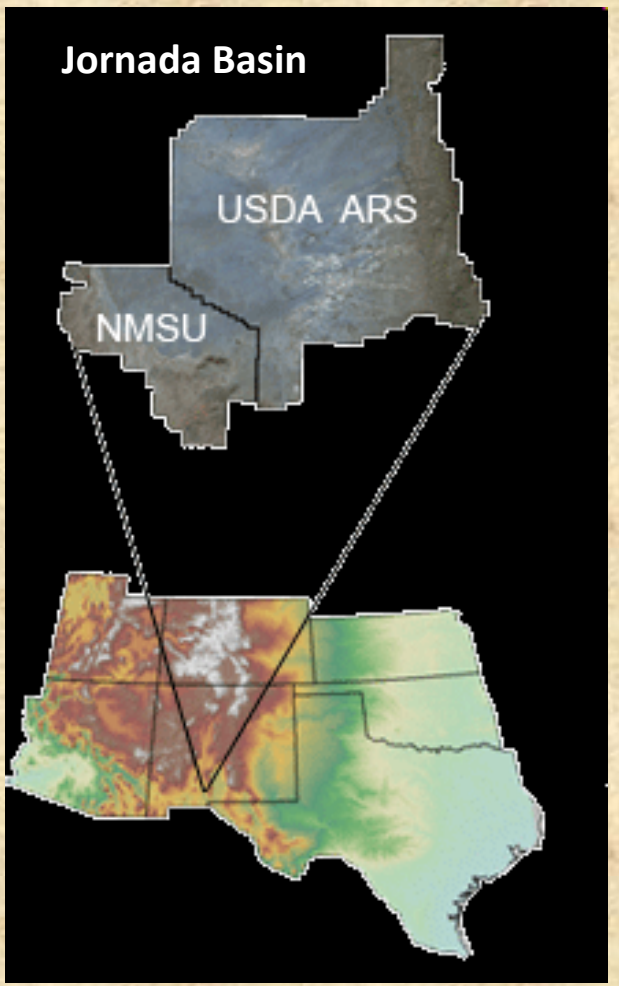


Jornada Basin Long Term Ecological Research

Response: Production of black grama grass (*Bouteloua eriopoda*) – 34 years

Driver: Growing season rainfall regime

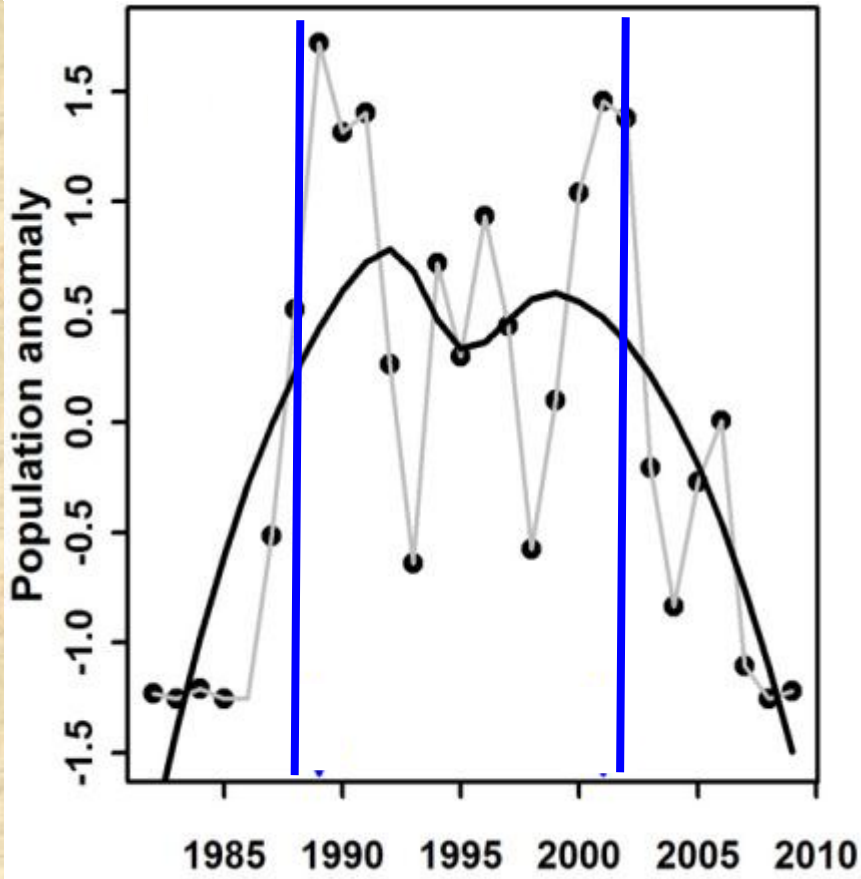




Issue 1: Analytical evidence for abrupt transitions in biological state

Statistical breakpoints in detrended data

Santa Barbara Coastal LTER:
2 abrupt transitions detected



Abrupt transition(s) identified with correct timing?

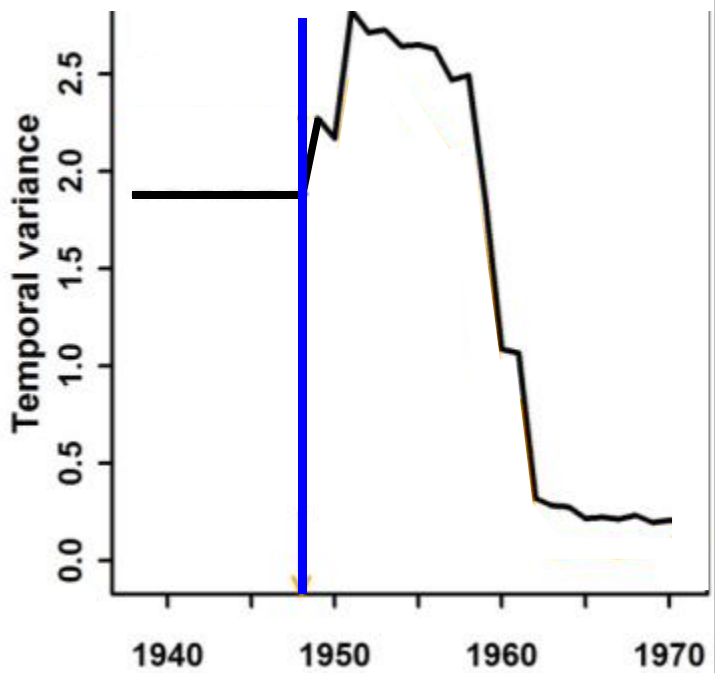
SBC LTER	Sea Cucumber	YES
	Krill	YES
	Penguins	YES
JRN LTER	Black Grama Grass	YES

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)

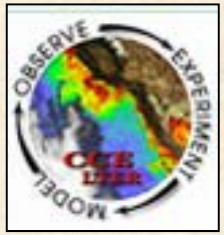
Jornada Basin LTER: Variance increased



Variance increase detected?

Black Grama Grass — **YES ?**

Sea Cucumber — **NO**

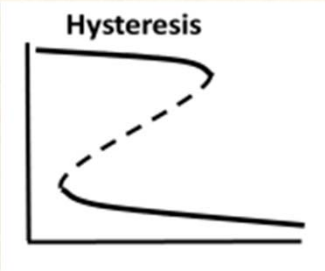
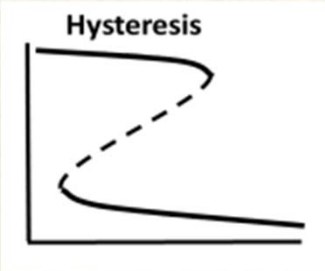
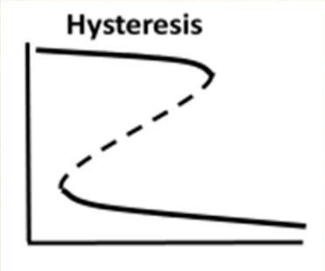


Krill — **NO**

Penguins — **NO**

Issue 3: Evidence for mode of the abrupt transition (e.g., Hysteresis)

Examined relationships between response & driver variables

Likely mode			Hysteresis mechanism? (identified by LTER studies)
Krill			—
Sea Cucumber			Positive predation-mediated feedback
Penguins			Positive predator- & breeding-mediated feedbacks
Black Grama Grass			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

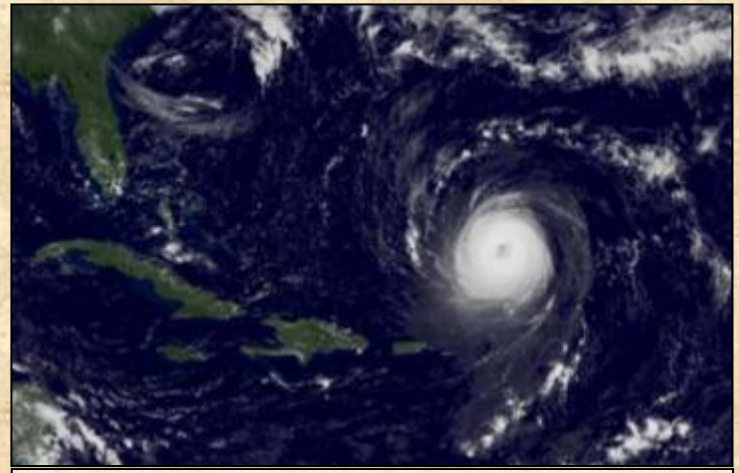
- Direct control not feasible for many conditions that drive state change

- 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

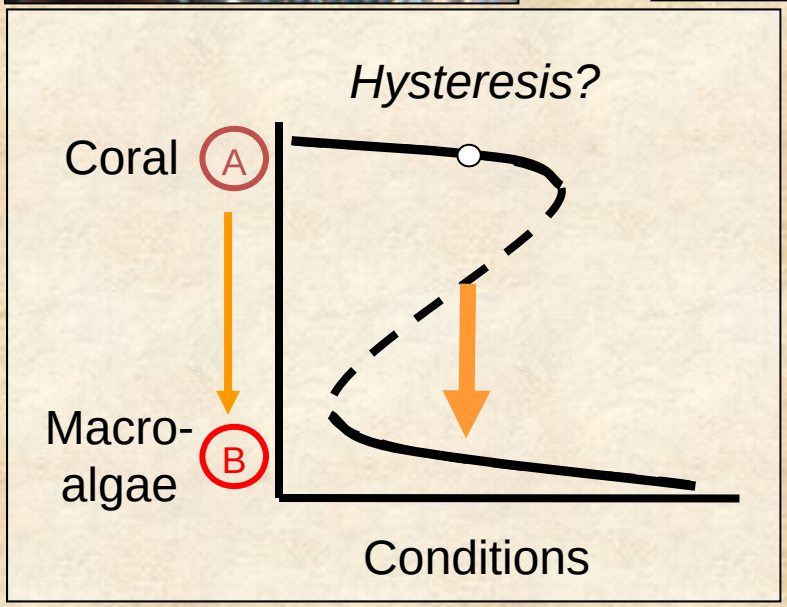
Bleaching events

Outbreaks of coral predators
Crown-of-Thorns Seastars (COTS)

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, macro-algae can kill adult coral & prevent coral recruitment

For reefs to be resilient, herbivores must control macroalgae

Herbivorous parrotfish

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

MCR LTER

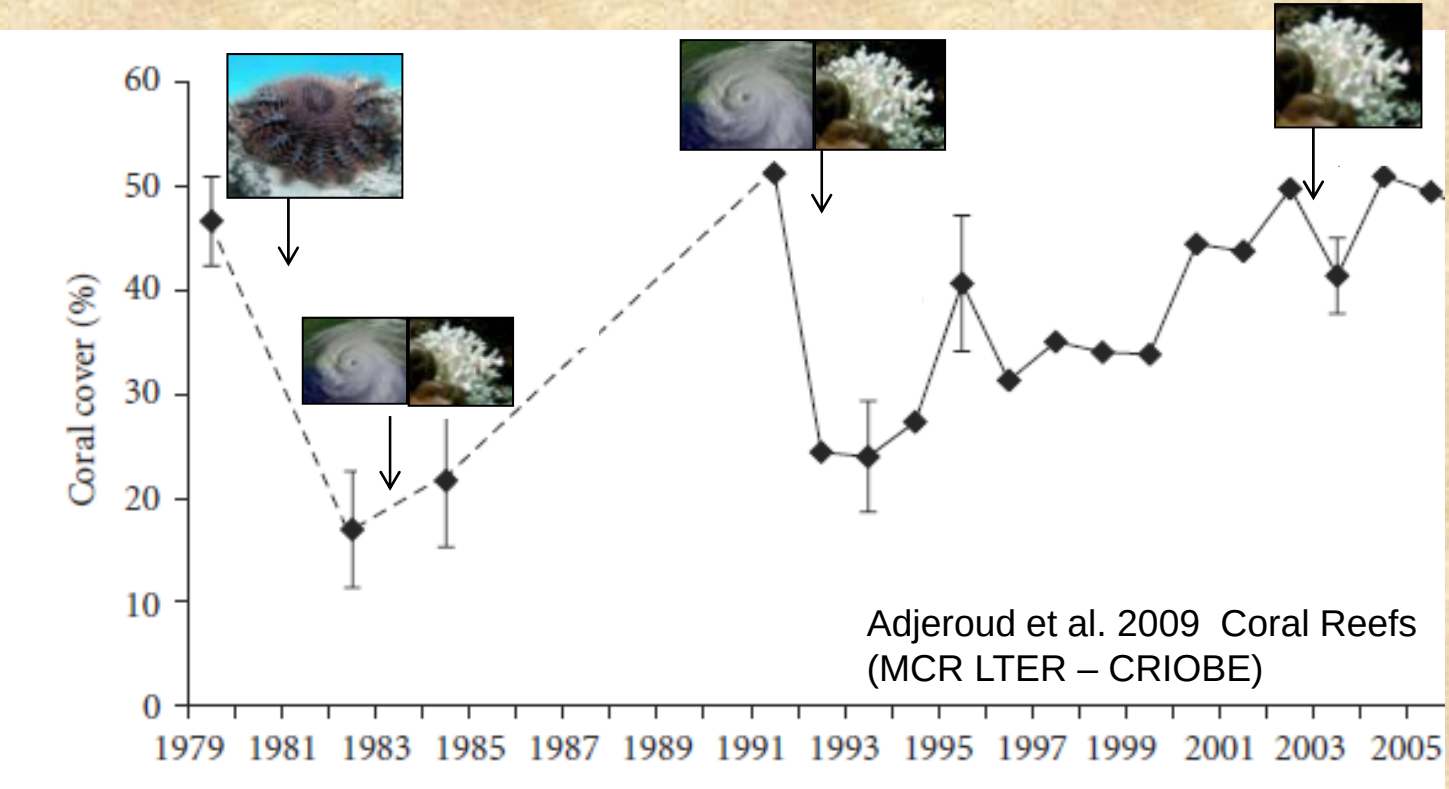
UCB Gump Research Station

Coral dynamics on the fore reef of Moorea: 1979 - 2005

Crown-of-thorns outbreak

Bleaching event

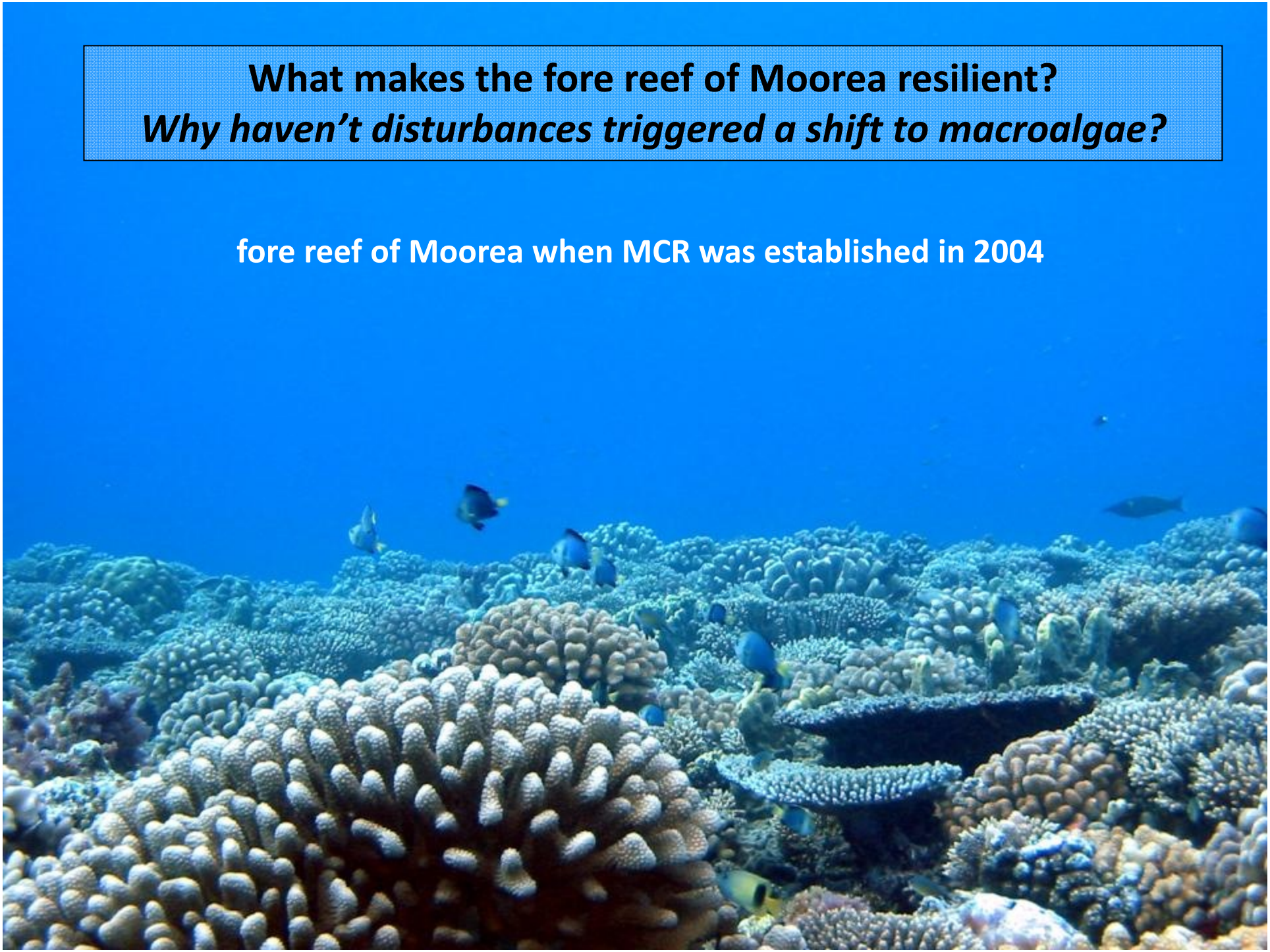
Cyclone

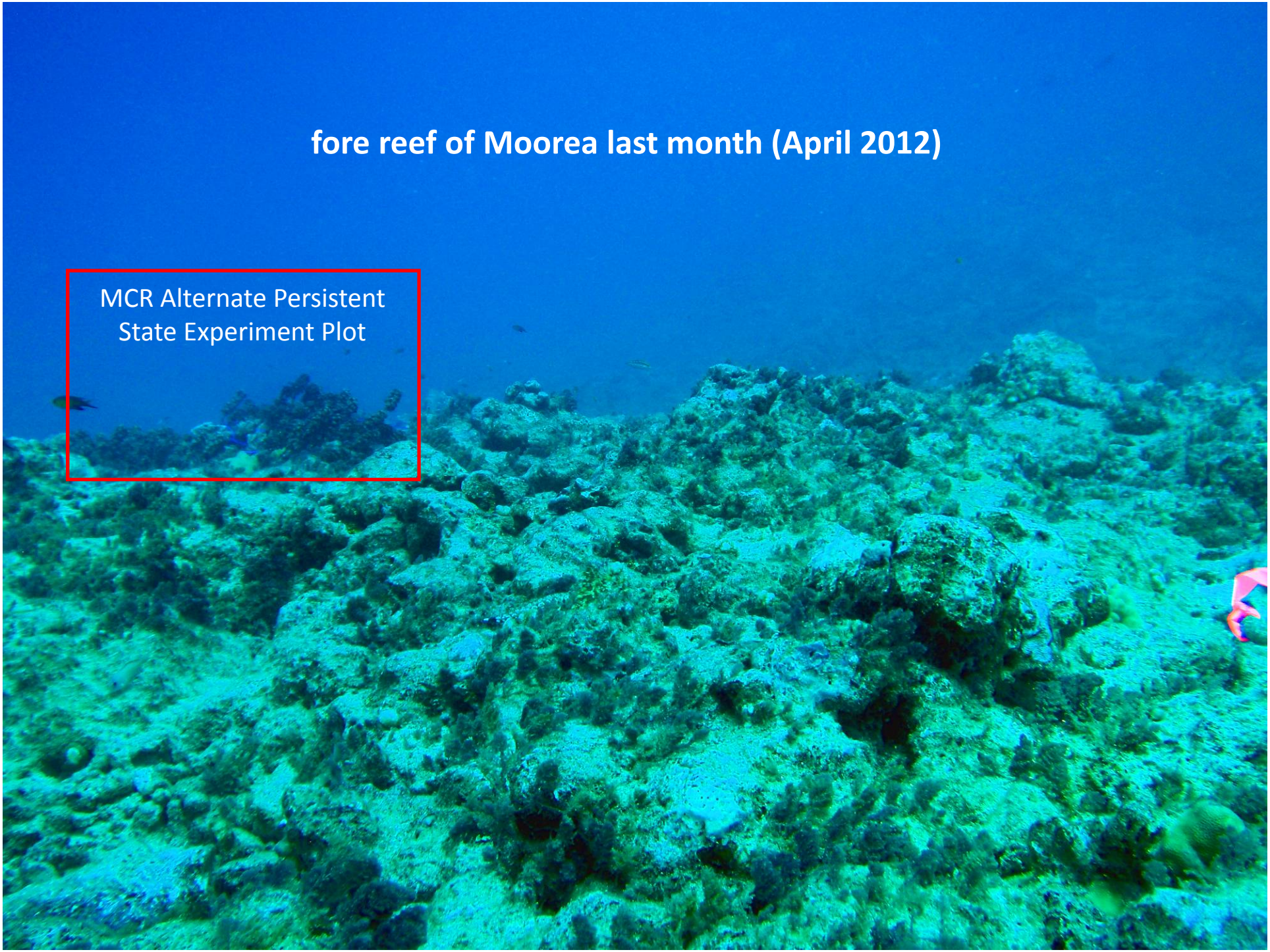


- **Multiple disturbances on the fore reef**
- **Fore reef returned to coral dominance within ~ 1 decade**
- **No transition to a macroalgal state**

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



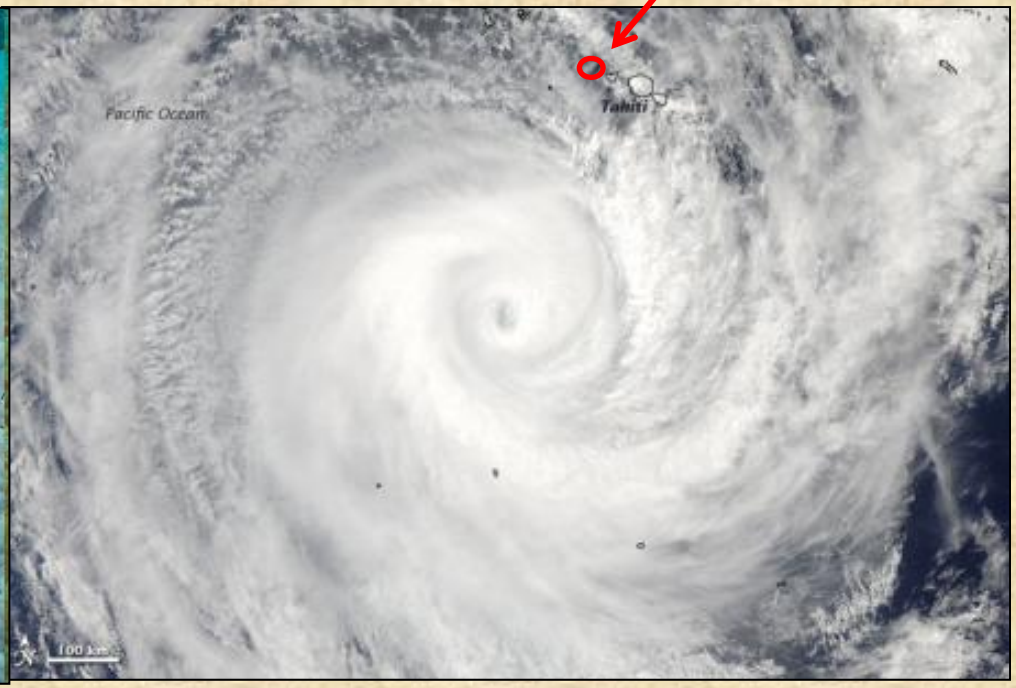

fore reef of Moorea last month (April 2012)
MCR Alternate Persistent
State Experiment Plot

Since 2005, the fore reef of Moorea experienced two more disturbances

Providing opportunity to explore features that make the fore reef resilient

Outbreak of crown-of-thorns seastars (COTS)

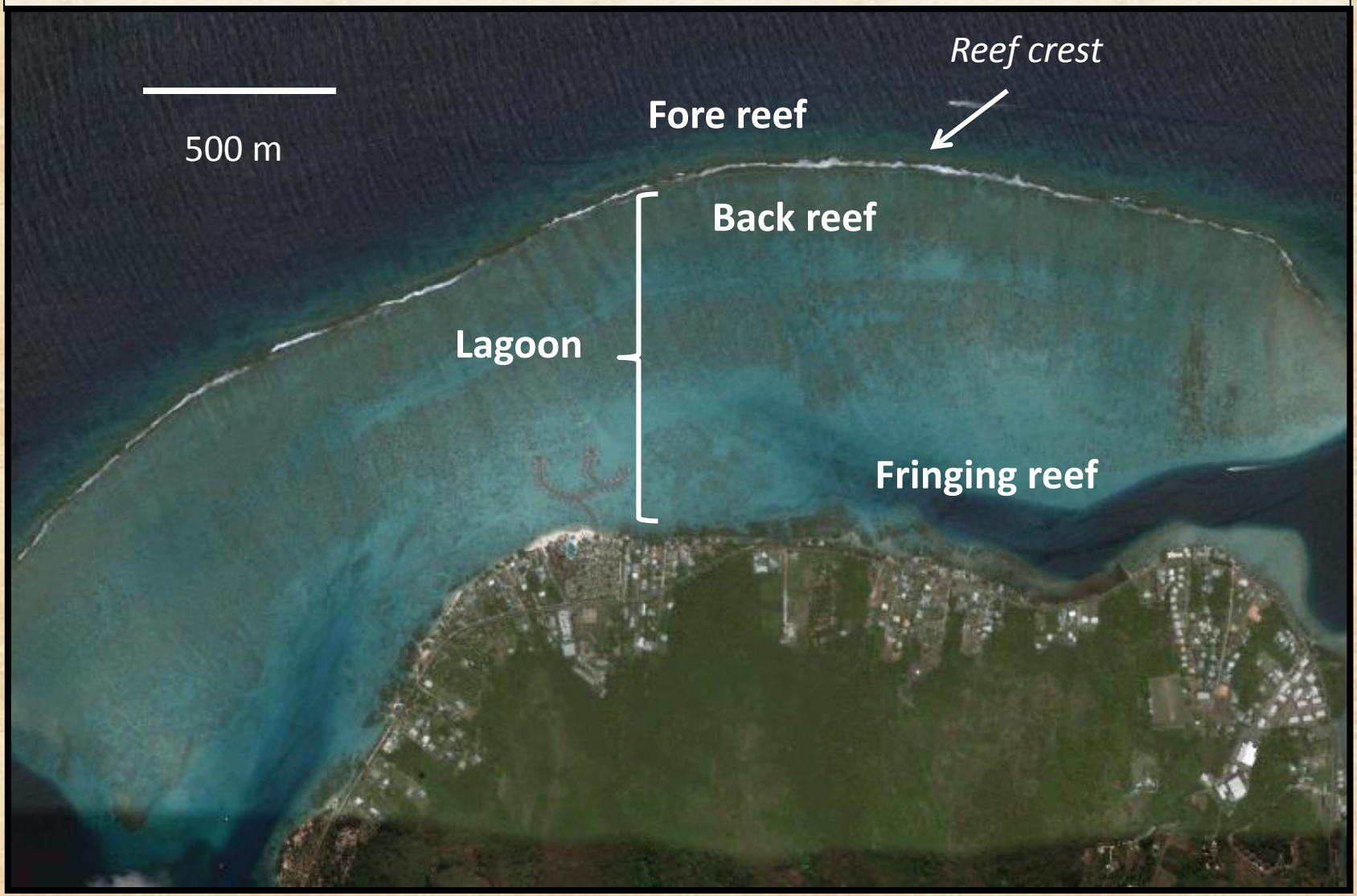
2007-2009



Cyclone Oli

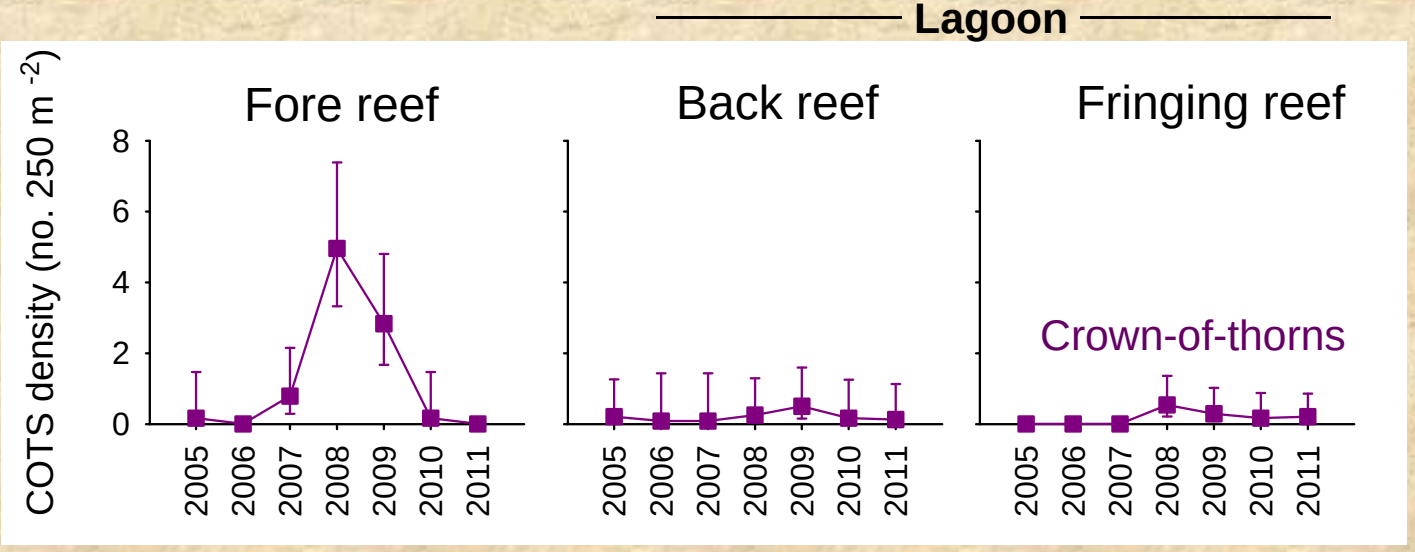
February 2010

MCR collects time series data from 3 coral reef habitats (Fore reef, Back reef, Fringing reef) all around the island



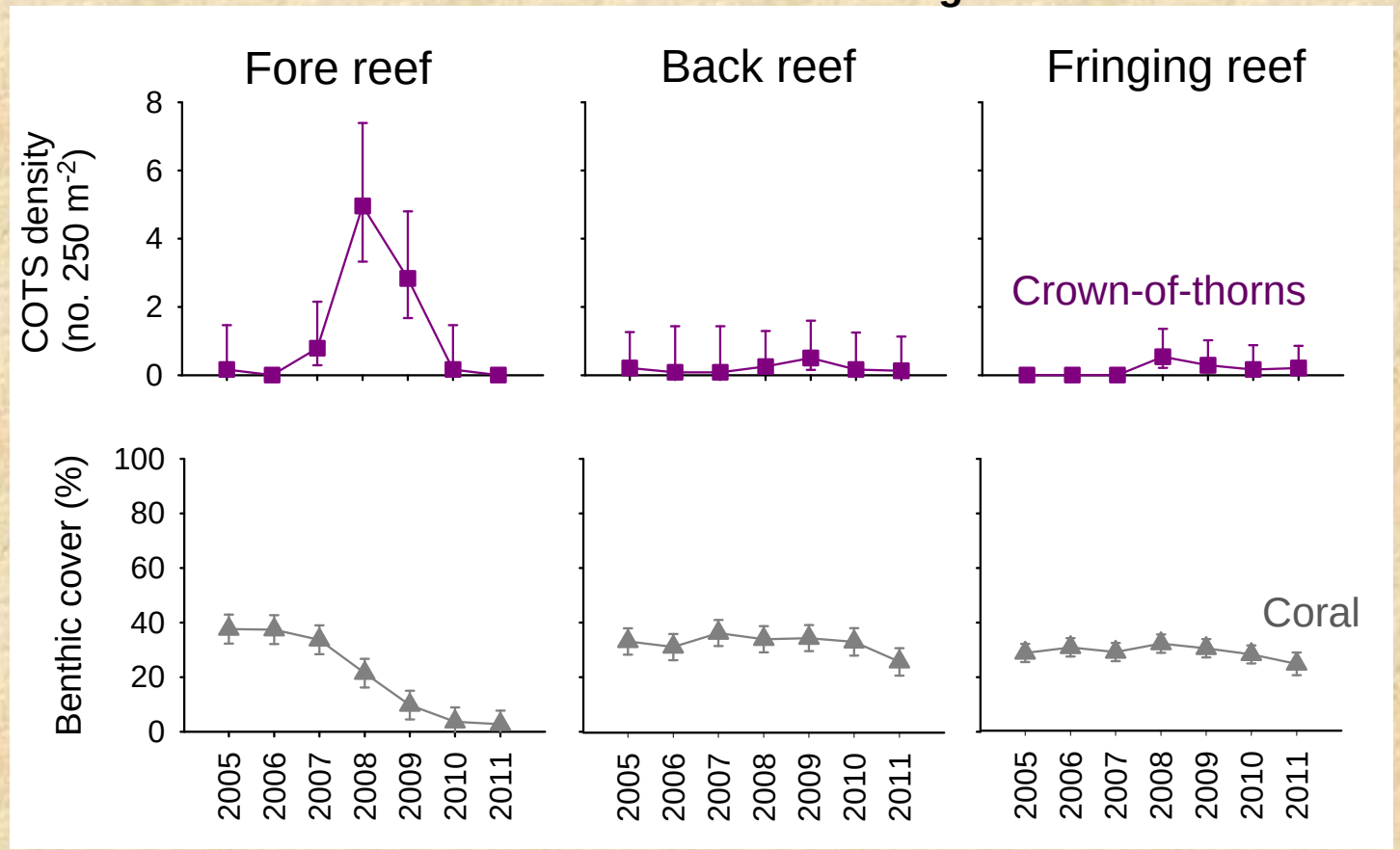
Community dynamics differ between fore reef & lagoon habitats

Changes on the reef since 2005



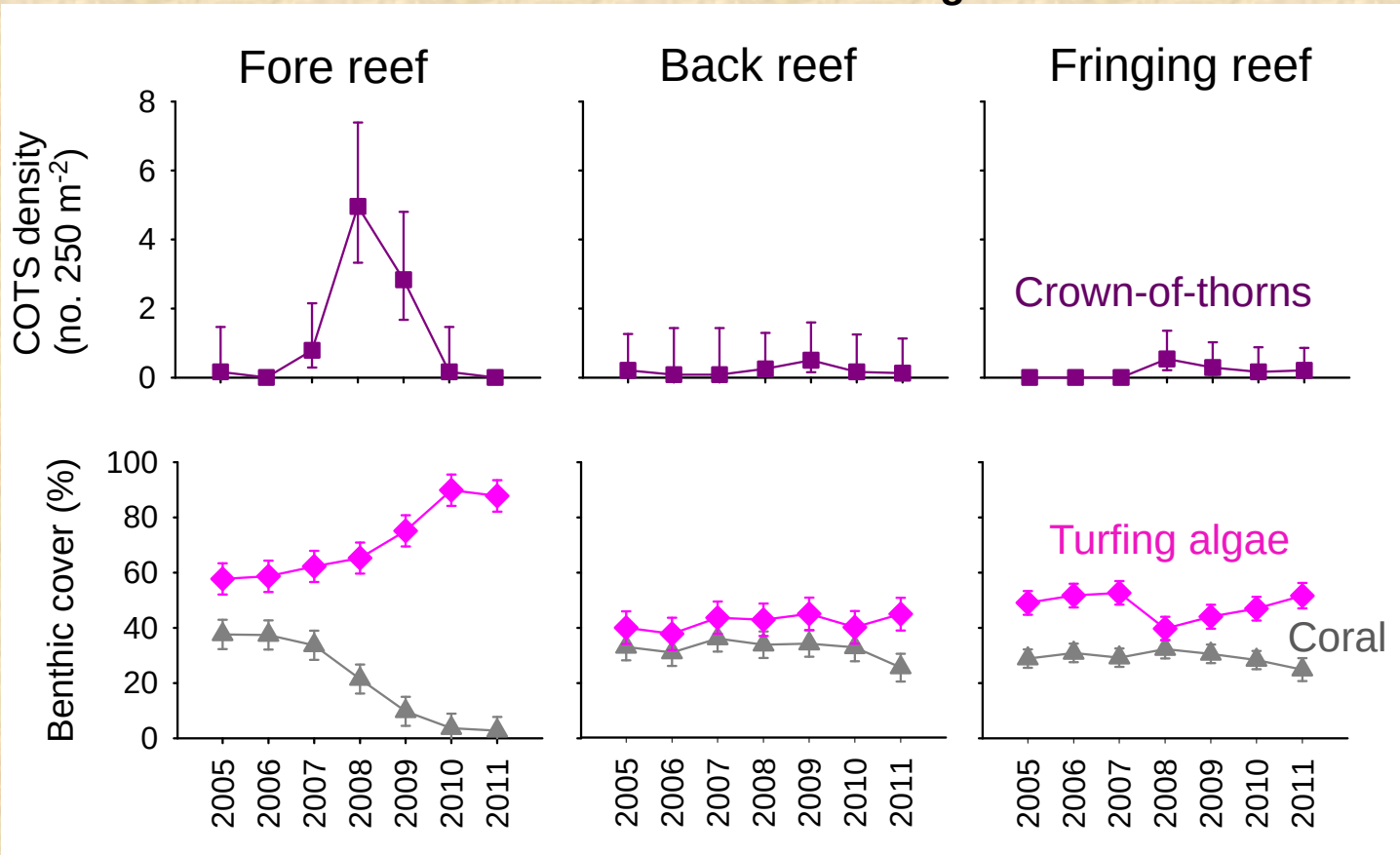
Adam et al. 2011 PLoS One

Changes on the reef since 2005



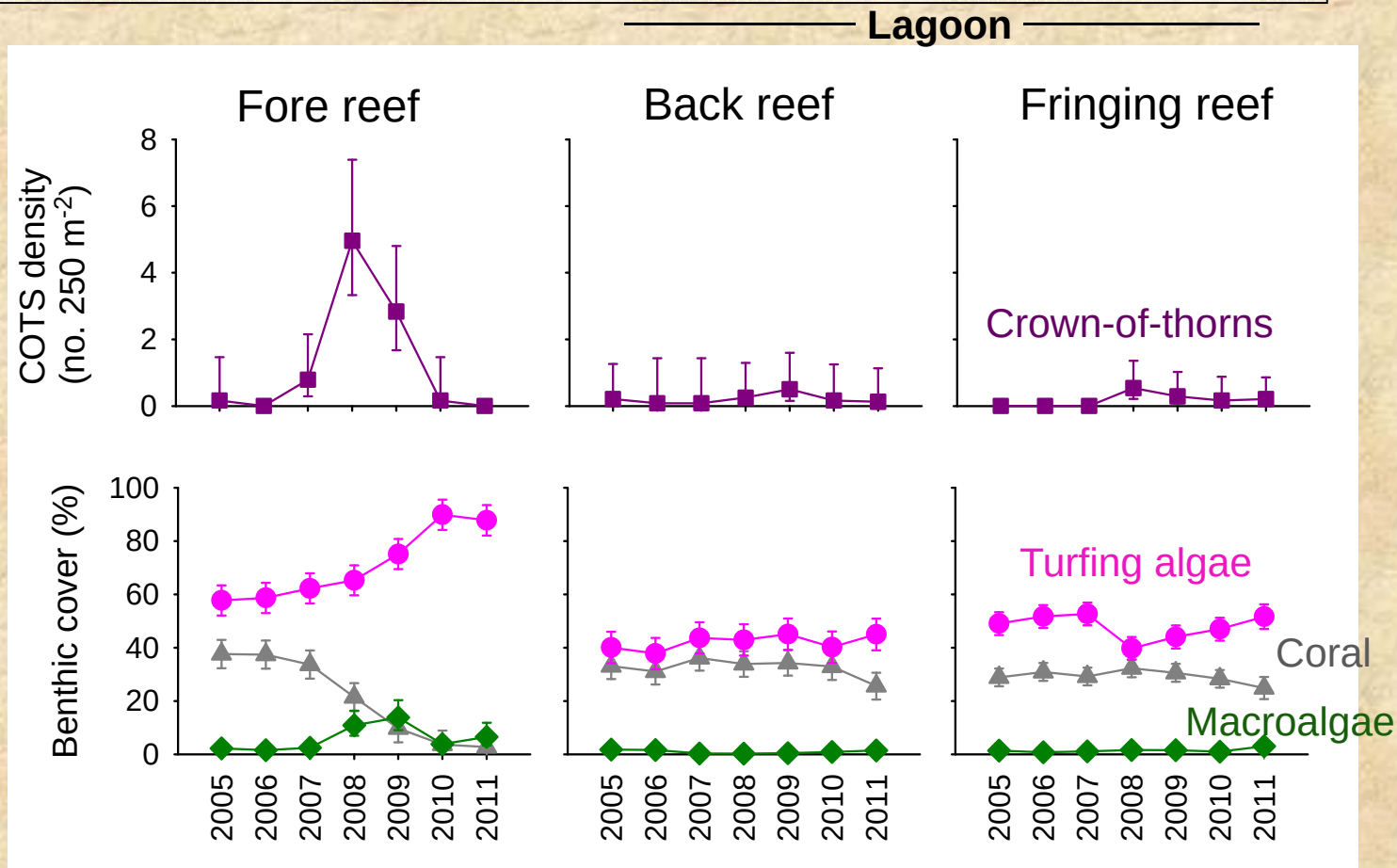
Adam et al. 2011 PLoS One

Changes on the reef since 2005



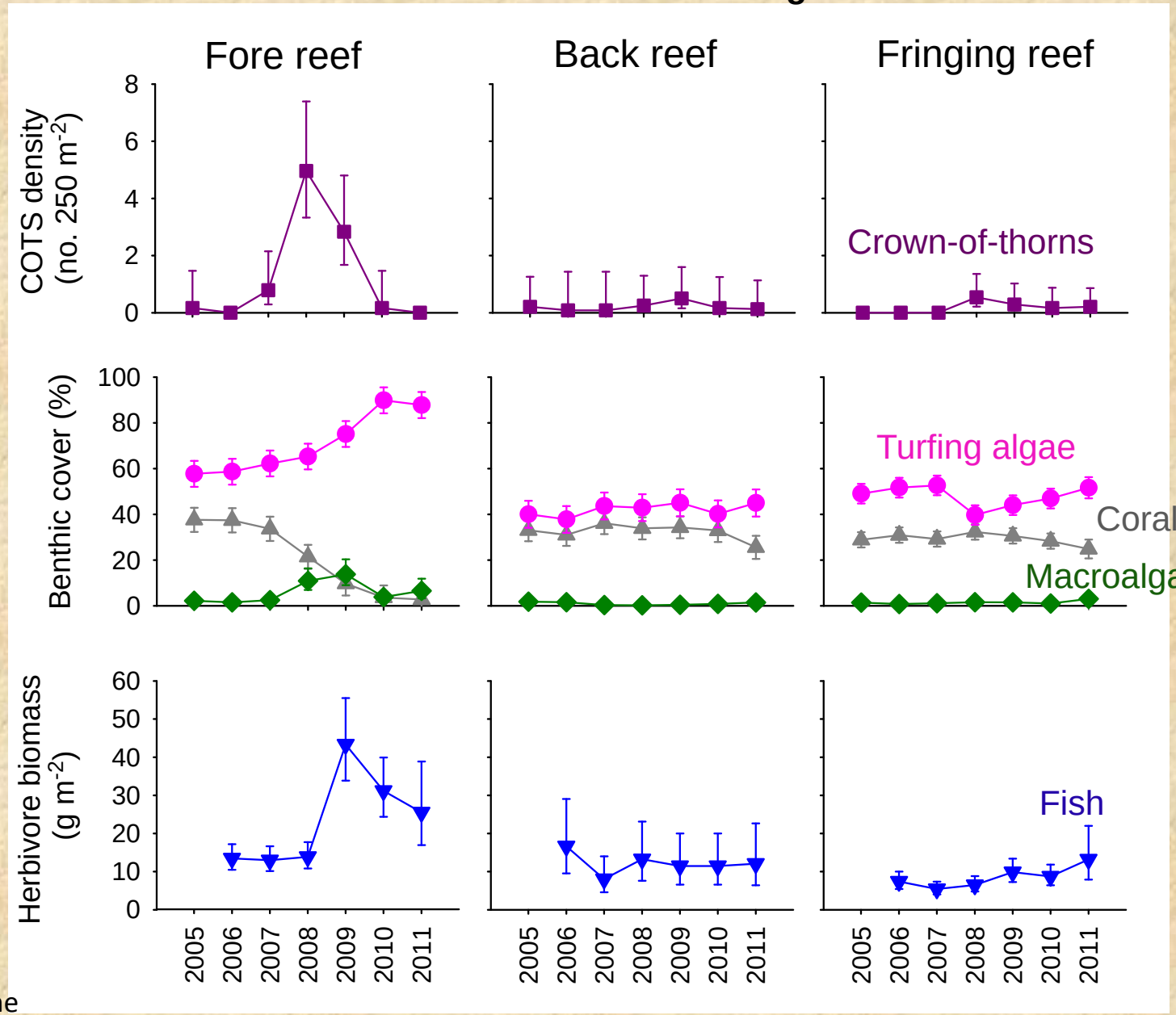
Adam et al. 2011 PLoS One

Changes on the reef since 2005



Adam et al. 2011 PLoS One

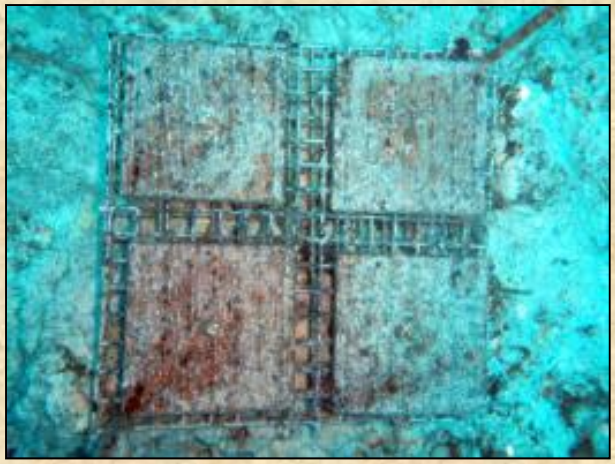
Changes on the reef since 2005



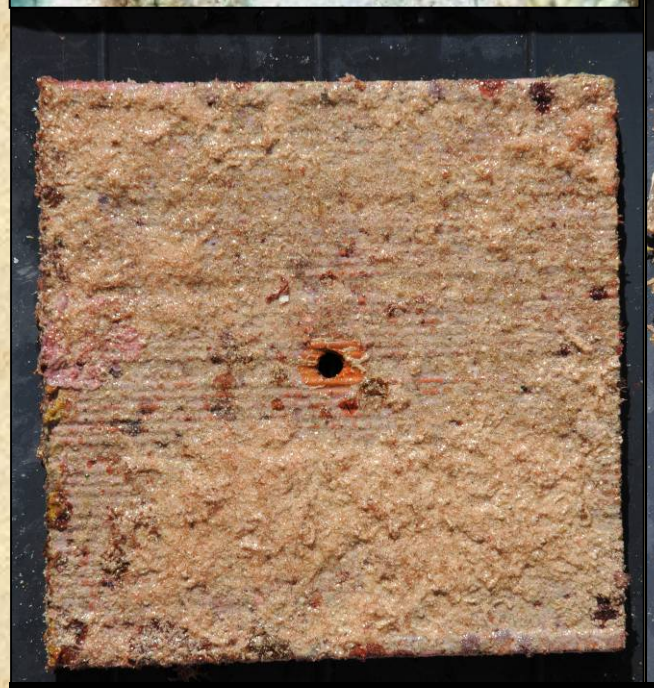
Adam et al. 2011 PLoS One

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**



Bullethead Parrotfish

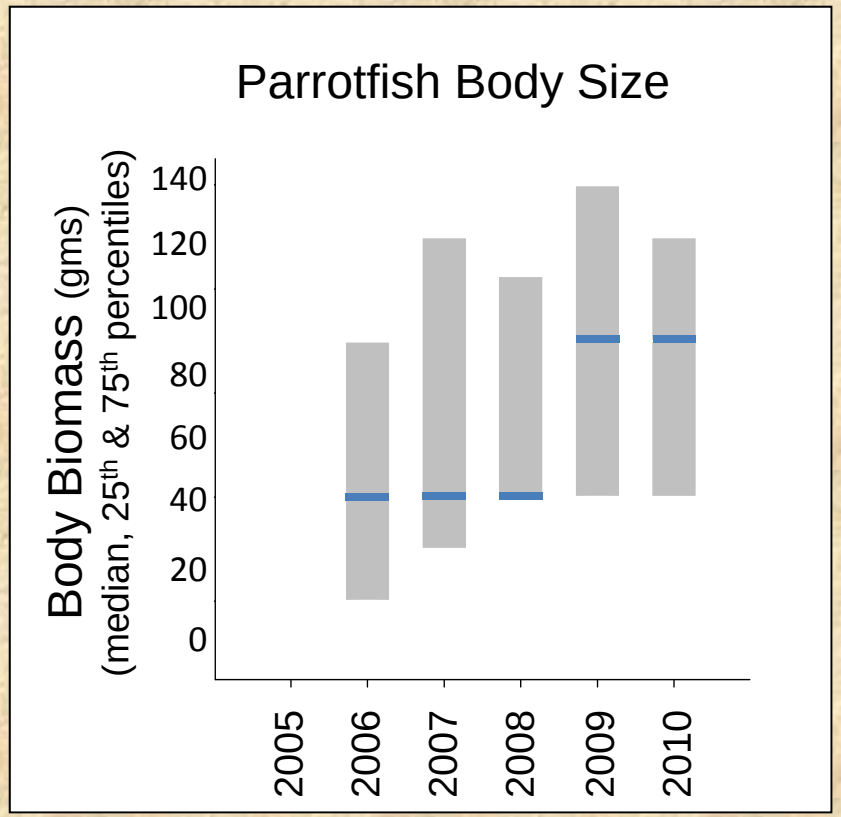


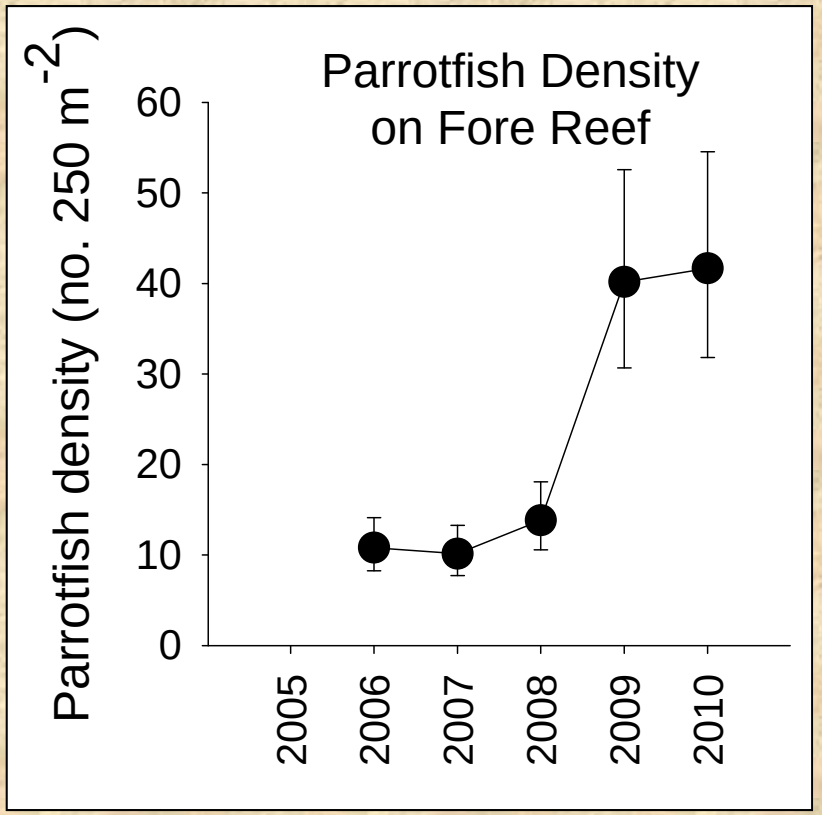
Ambient Herbivory

Reduced Herbivory

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)**

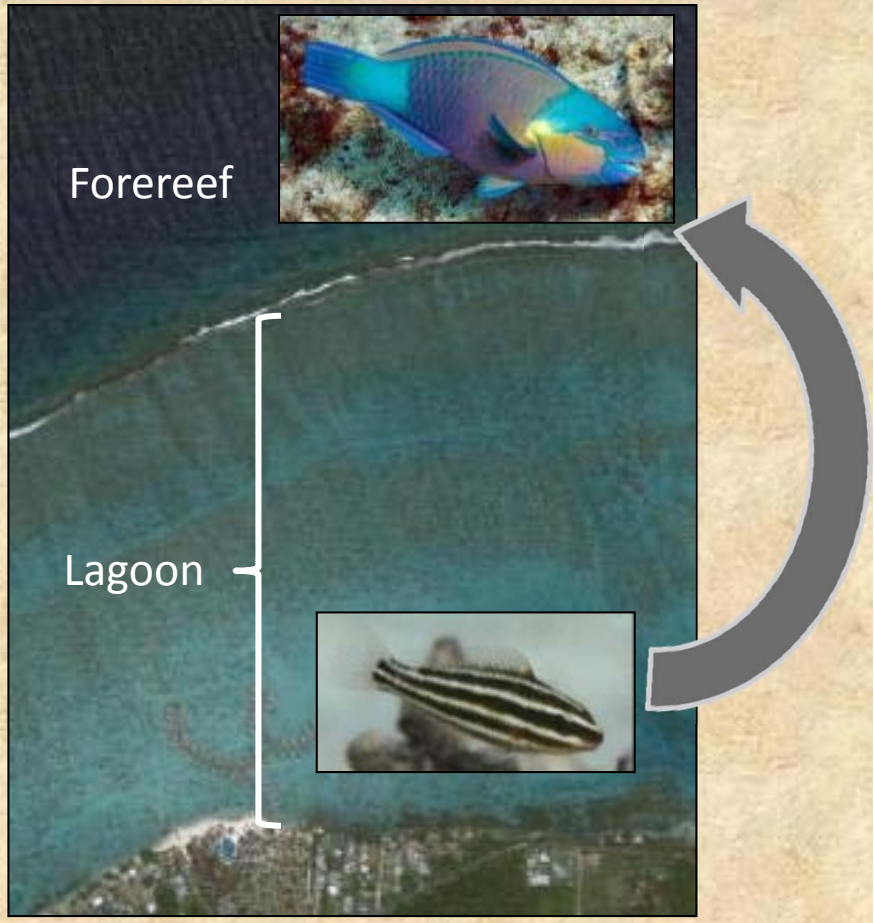




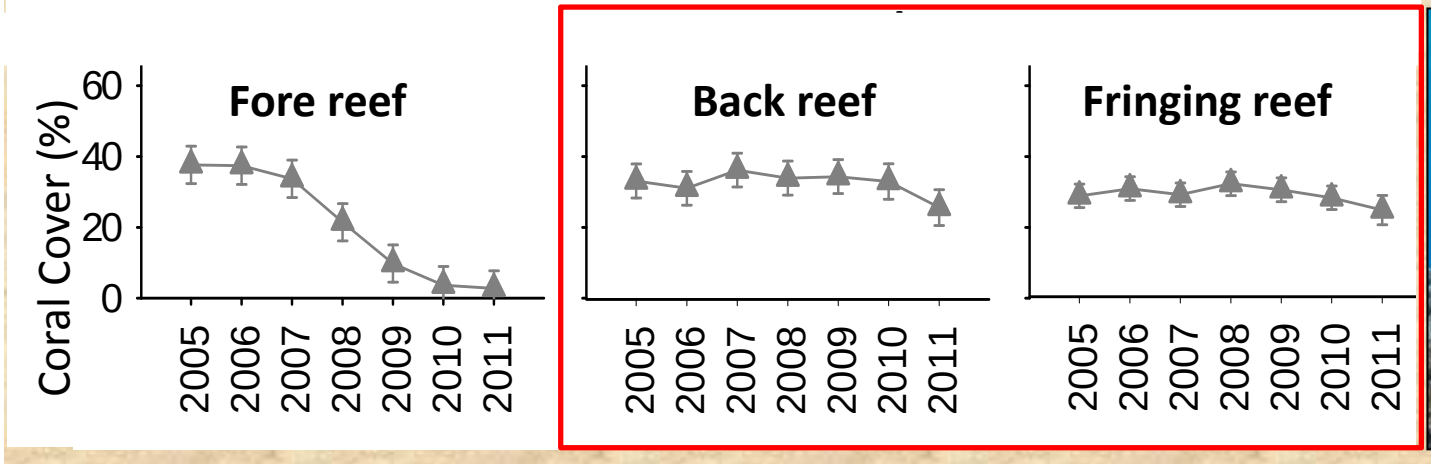
Nursery habitat in lagoon critical to numerical response of adult parrotfish on fore reef

- **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**

Juvenile parrotfish nursery habitat



Disturbances that kill coral on the fore reef do not harm parrotfish nursery habitat



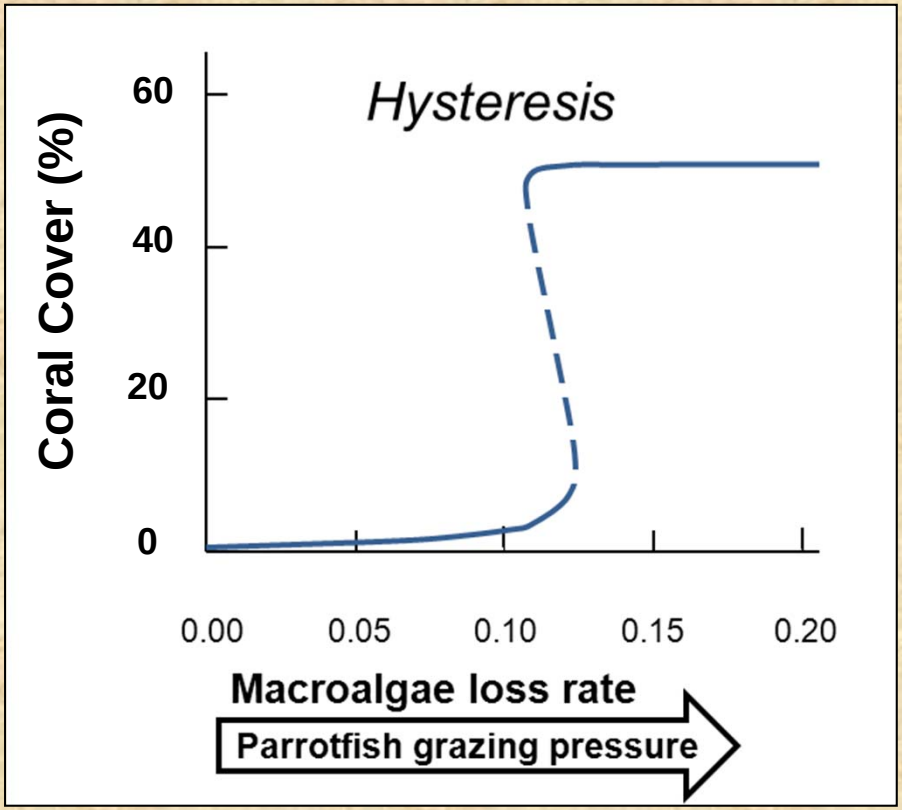
Stable nursery habitat in lagoon enabled rapid numerical response of parrotfish

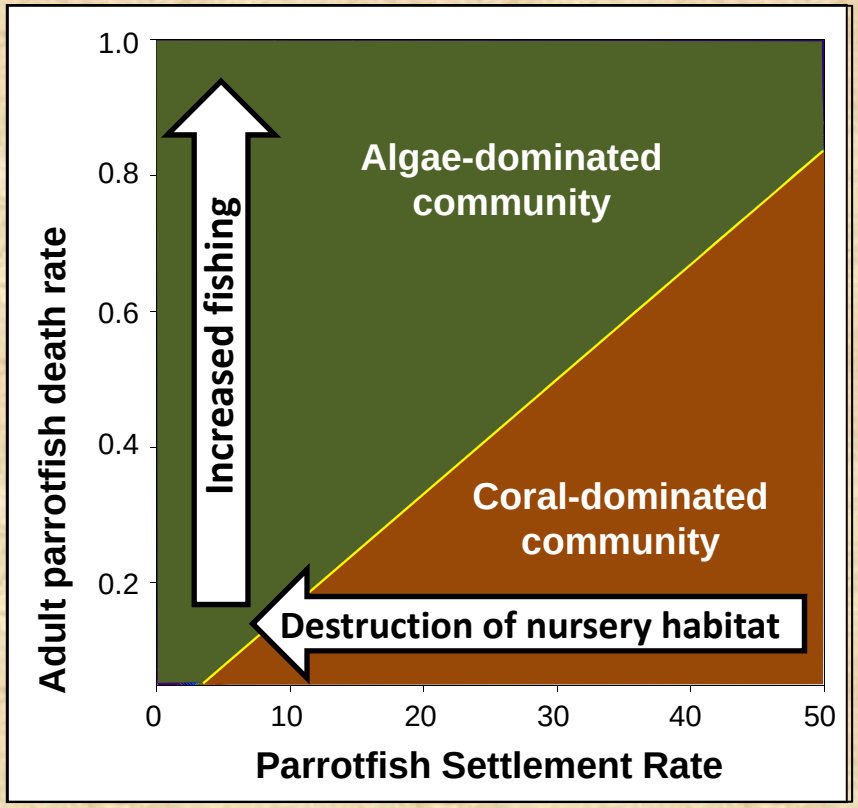
What makes the fore reef of Moorea resilient?

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