

The effects of ocean acidification on organisms: an ecophysiological perspective

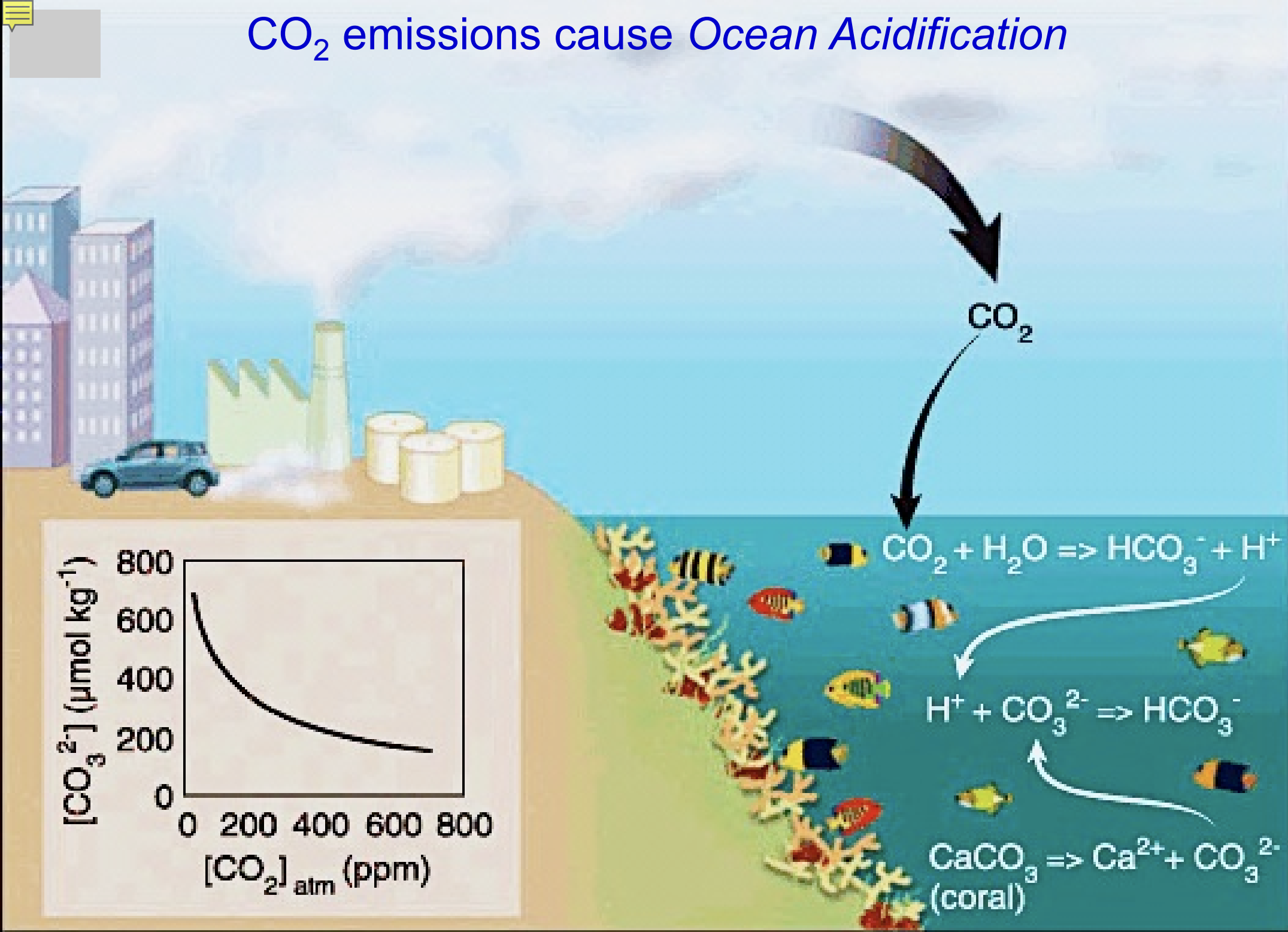
Jim Barry, MBARI, UCSC, 2011



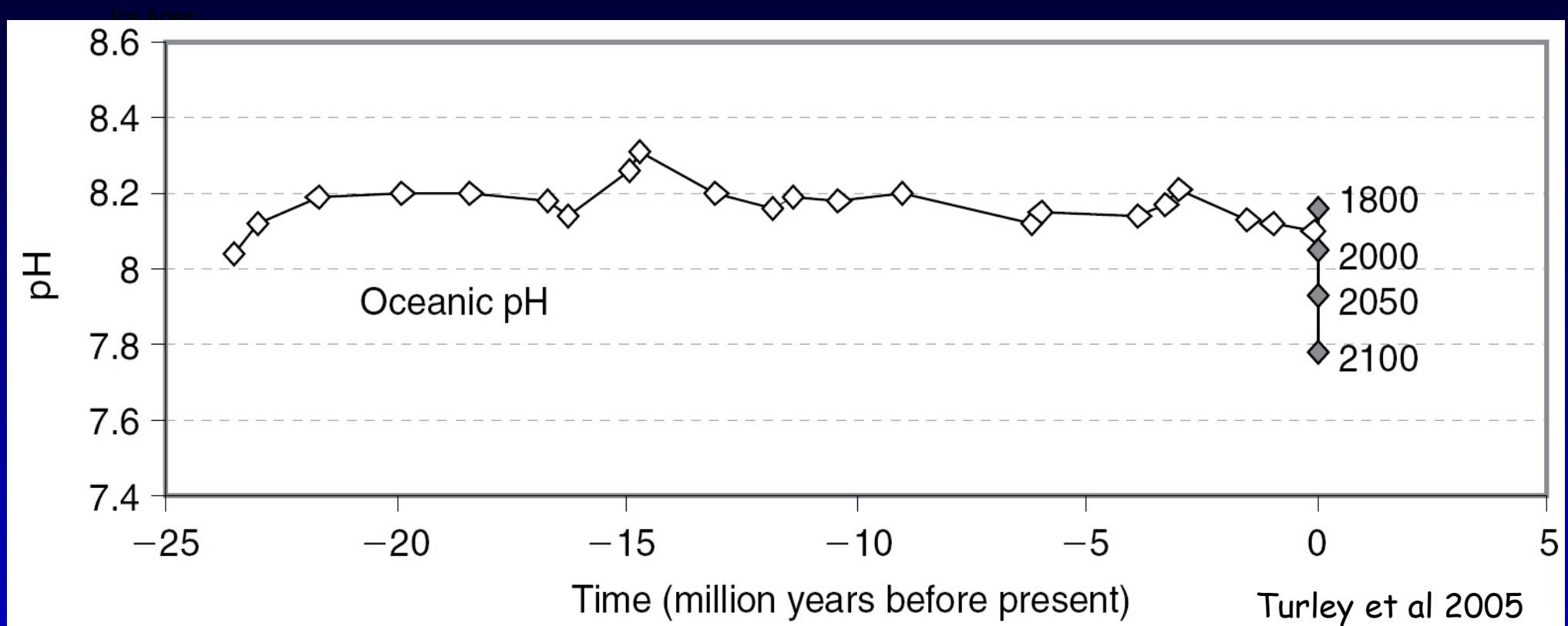
- Ocean acidification, warming, hypoxia related to CO₂ emissions
- Environmental changes can affect the physiological performance of many marine organisms
- Potential for large effects on ocean ecosystems and society



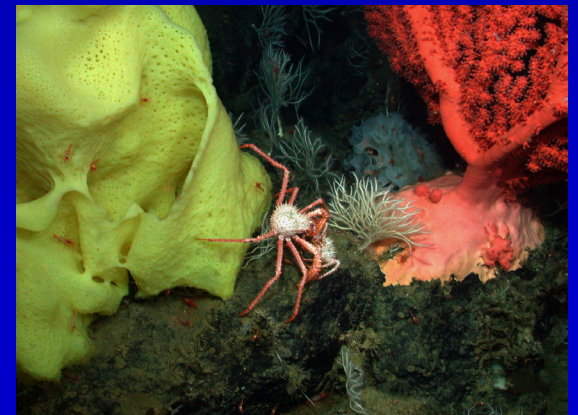
CO₂ emissions cause *Ocean Acidification*



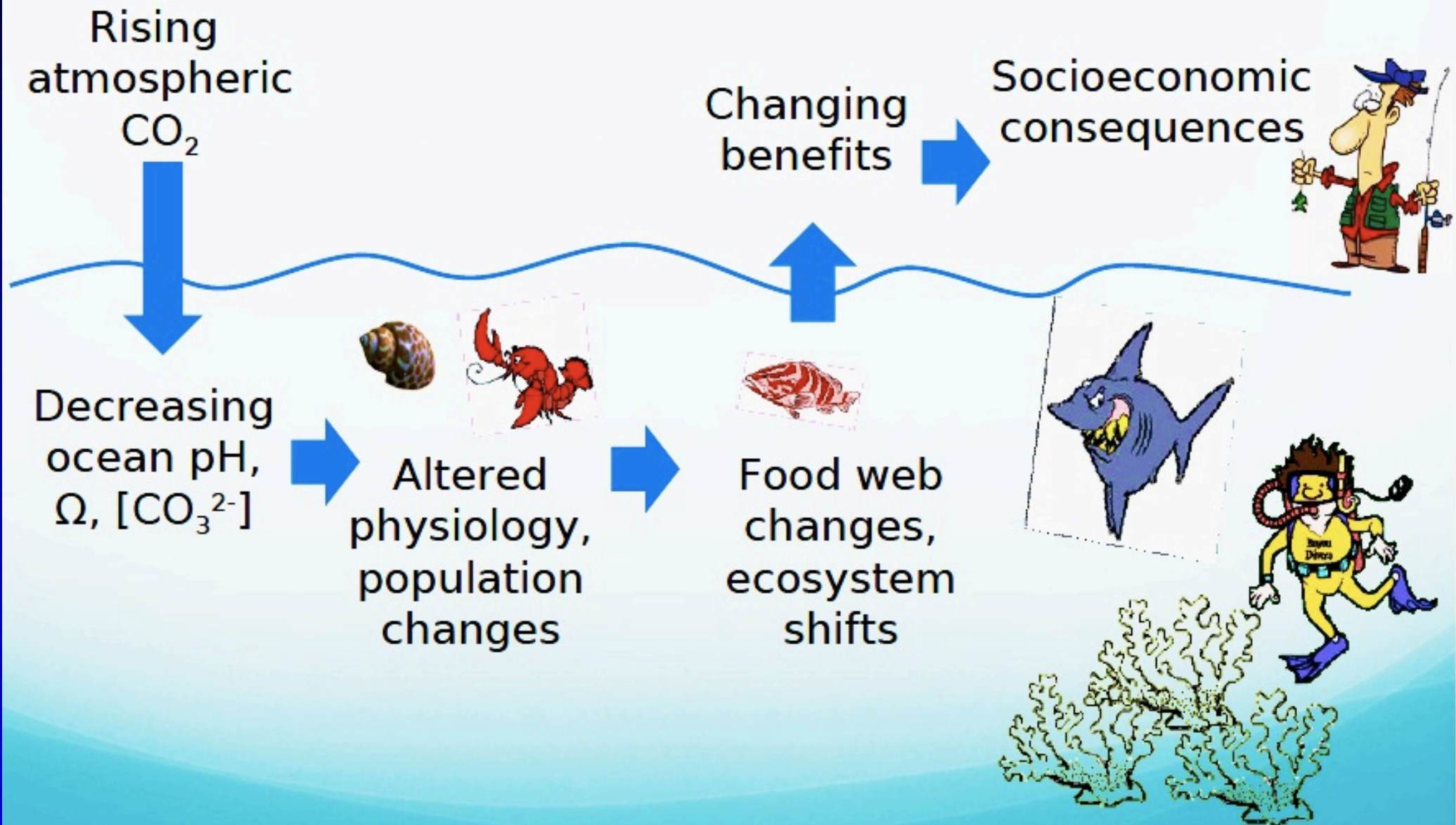
Change in ocean pH over 25 million years



- Estimated from boron isotopes in seabed foraminifera
- Note speed and size of current pH change

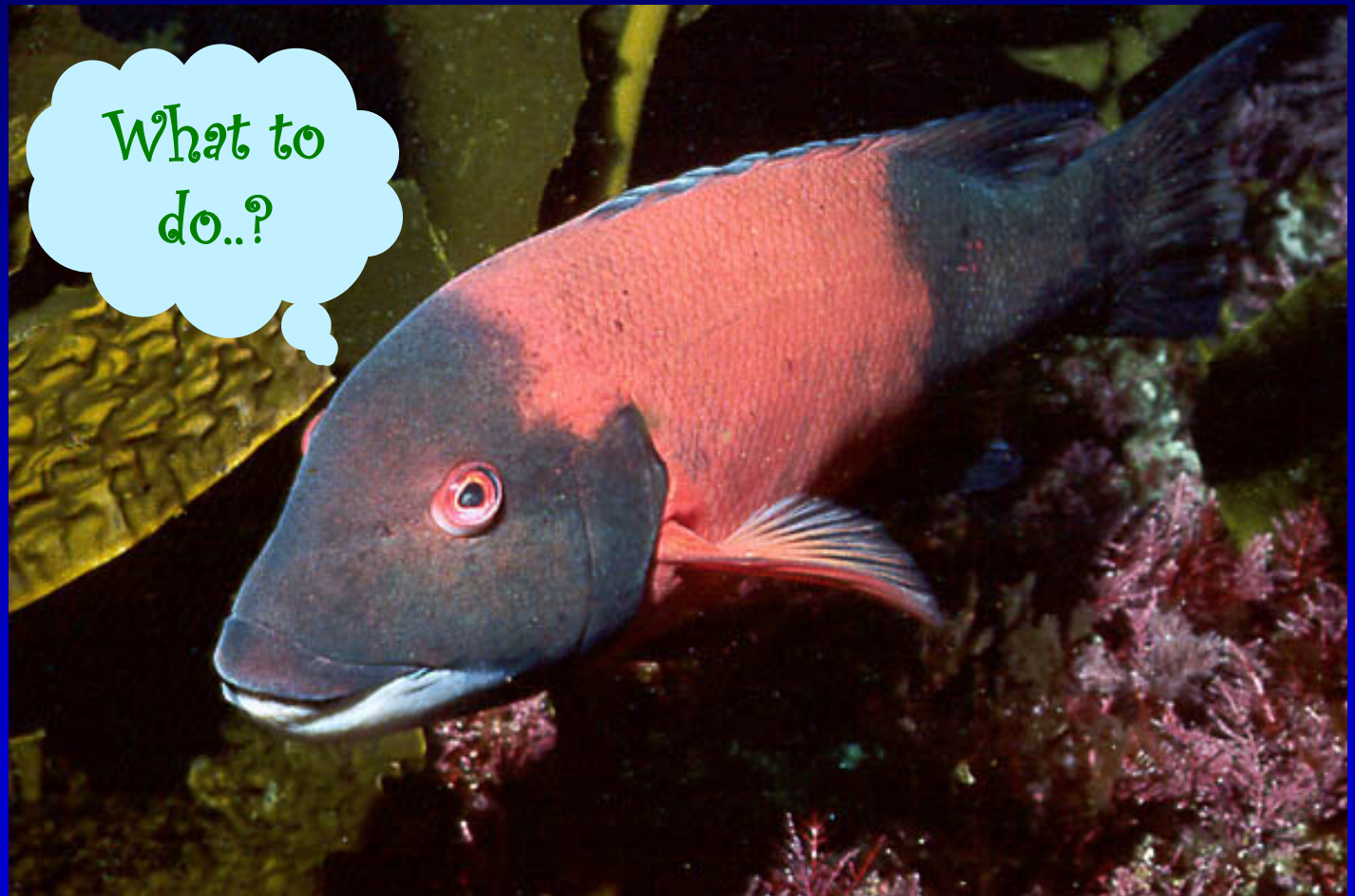


A worrisome storyline

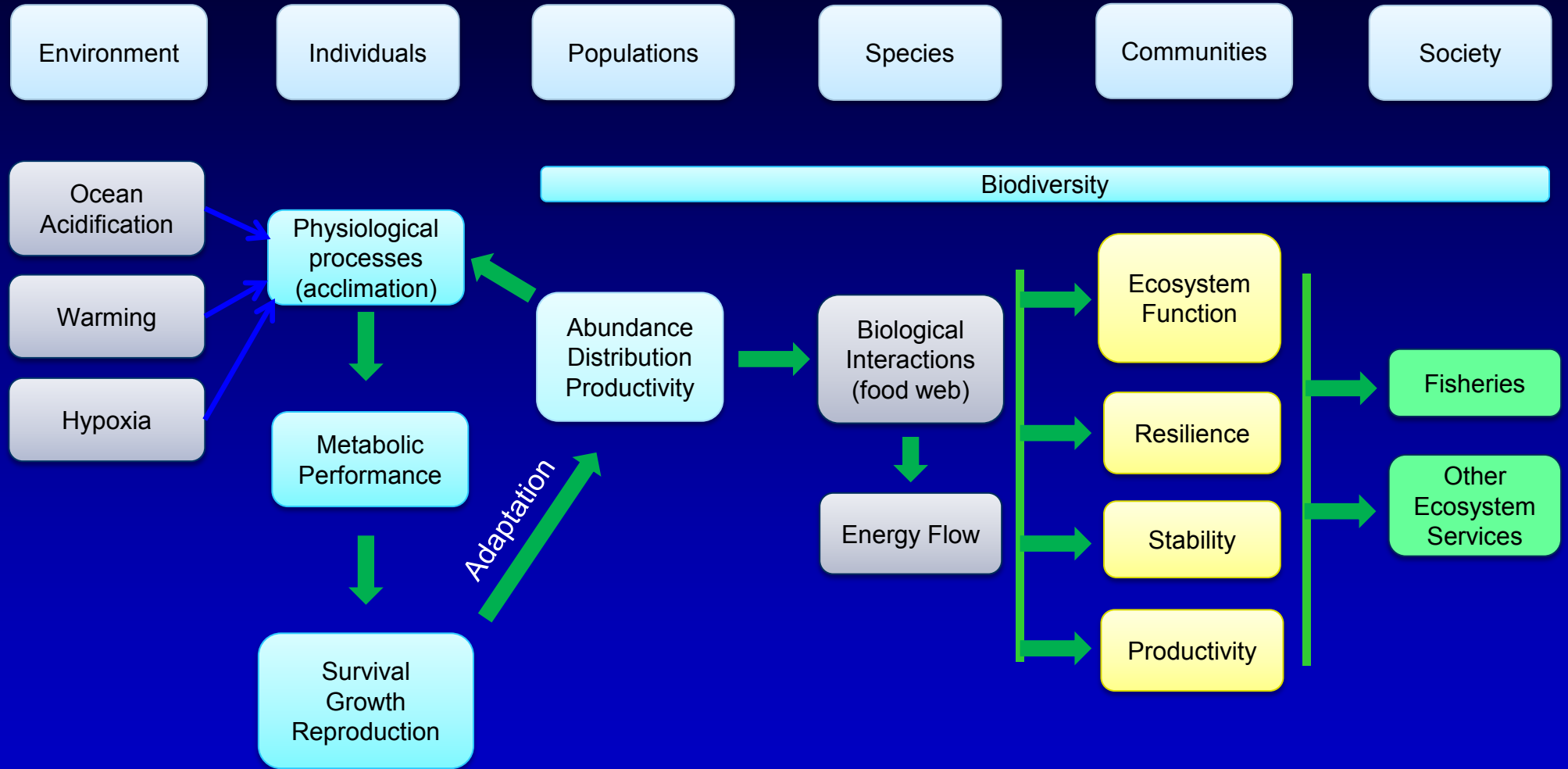


How do animals cope with changing ocean conditions?

- Migration
- Acclimation
- Adaptation
- Extinction

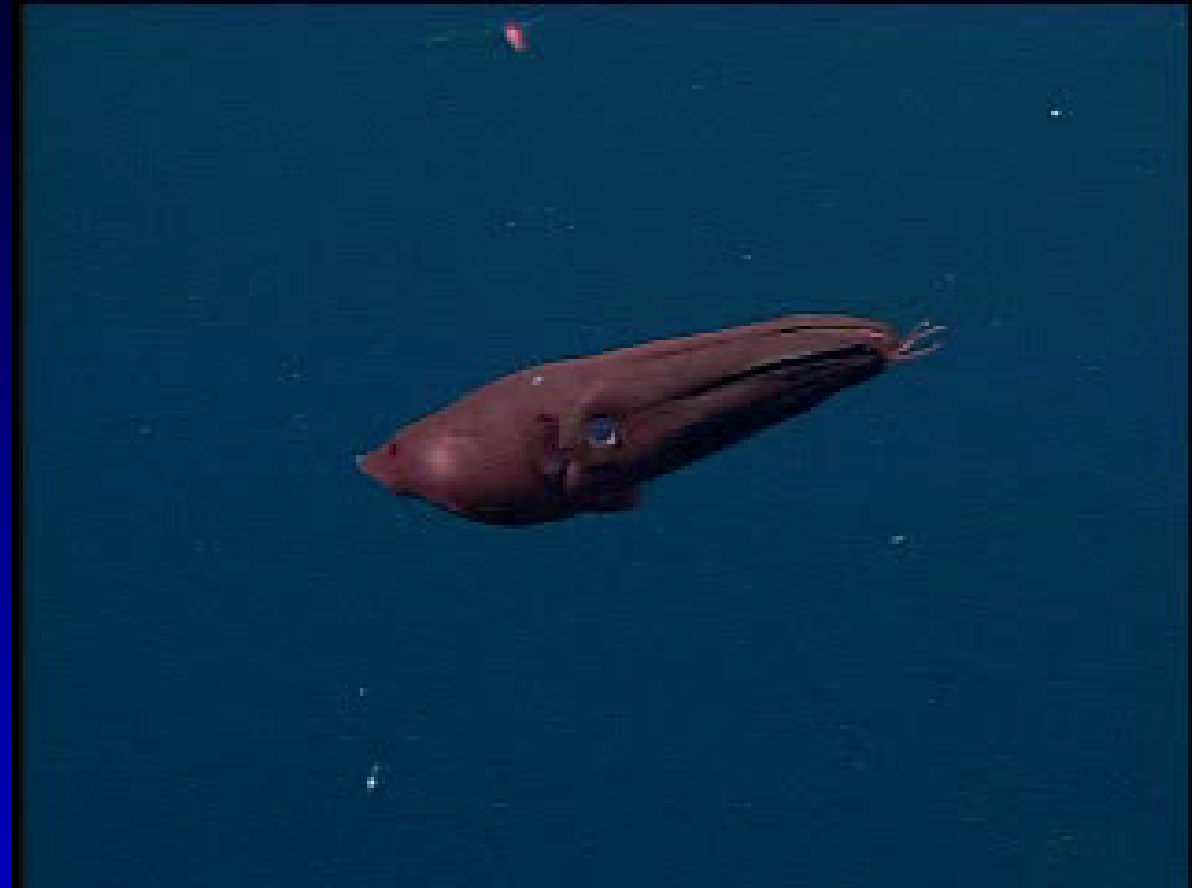


Environmental Stress, Ecosystems, and Society

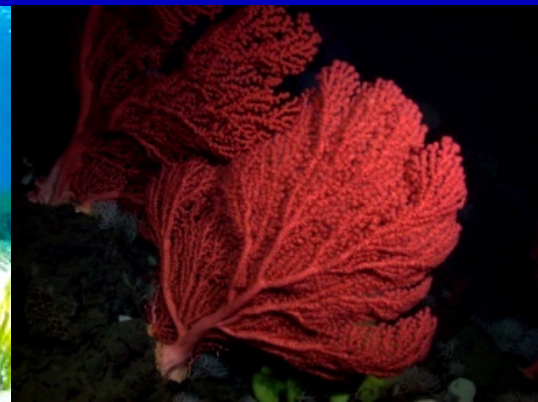
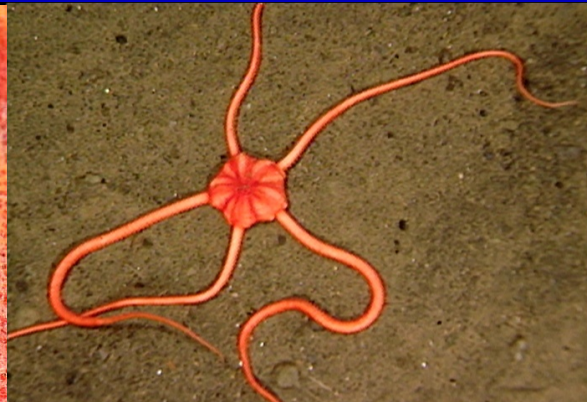


Physiological processes affected by high CO₂

- *Photosynthesis*
- *Calcification*
- *Respiration*
- *Acid - Base Balance*
- *Metabolic Rate*

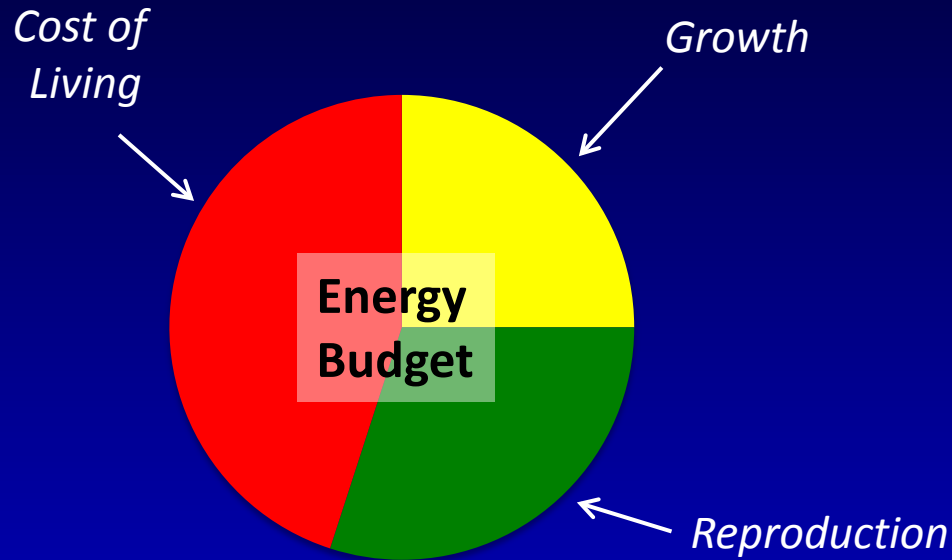


Vampire Squid

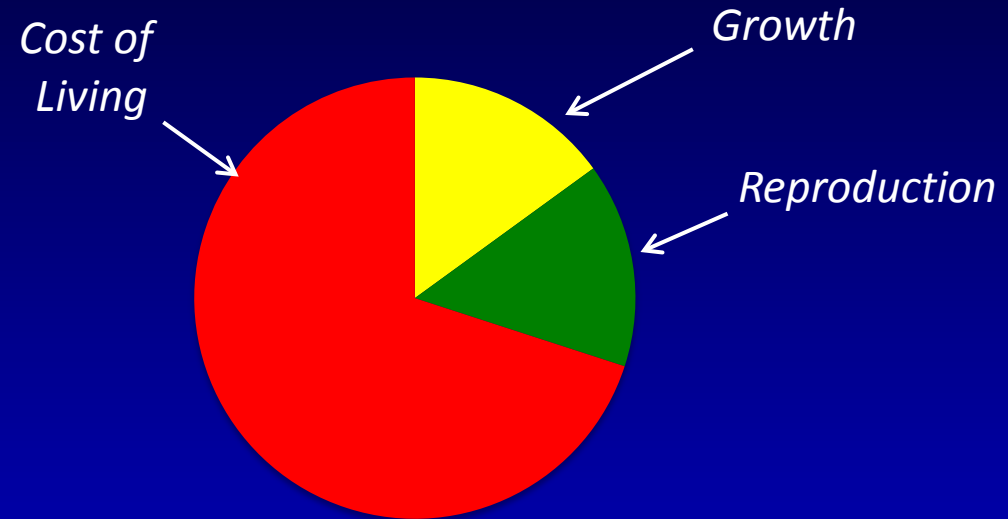


Stress increases the 'cost of living'

Normal



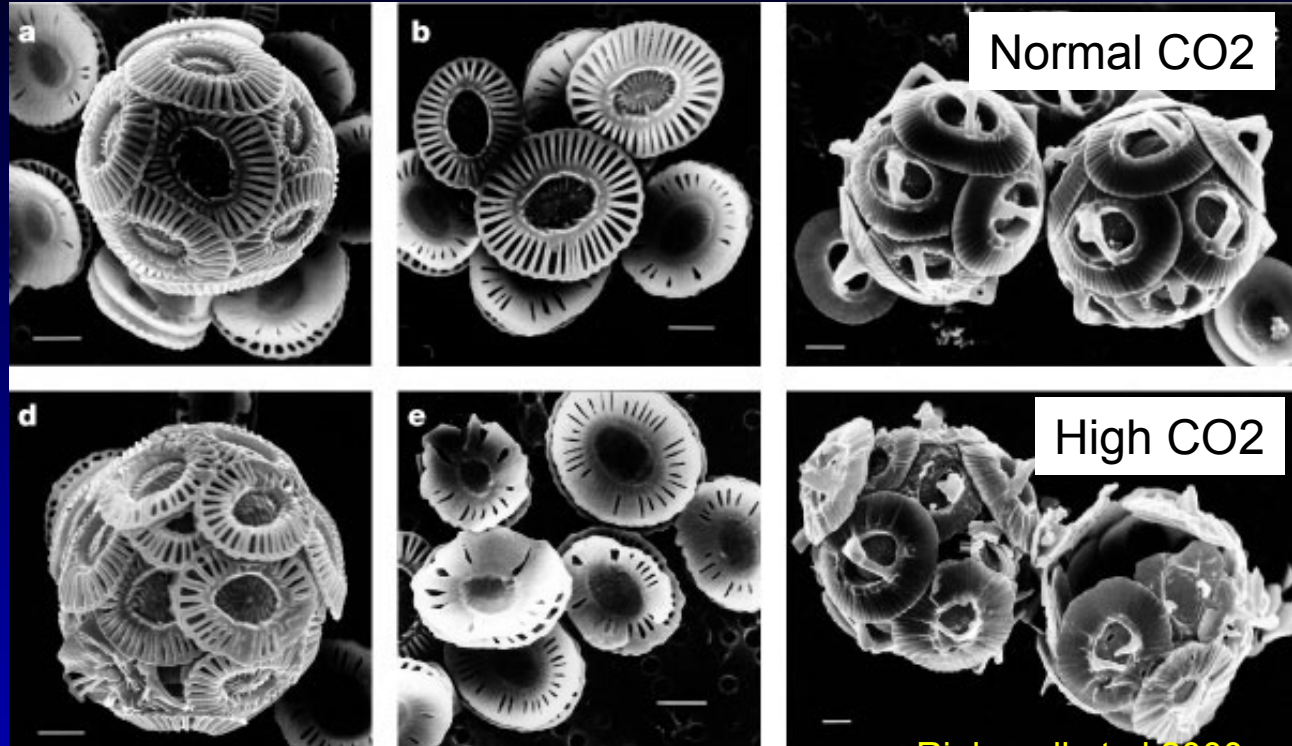
Stressed



Energy budgets - If the cost of living (e.g. shells) increases, less is available for growth and reproduction.

Reduced Calcification

Pteropod Mollusc



Normal CO2

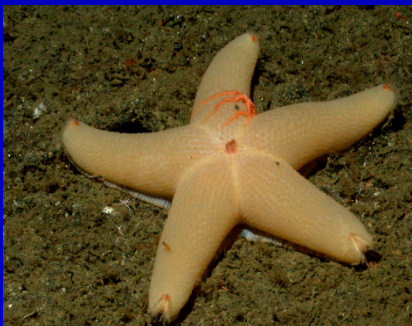
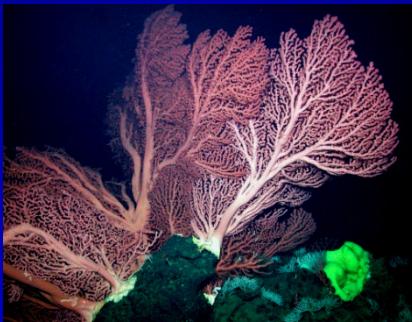
High CO2

Riebesell et al 2000

Environmental hypercapnia may affect calcification for many species

- Clams, snails, sea stars, urchins, crabs, shrimps, corals, ...
- Calcareous echinoderms largely absent from vent sites

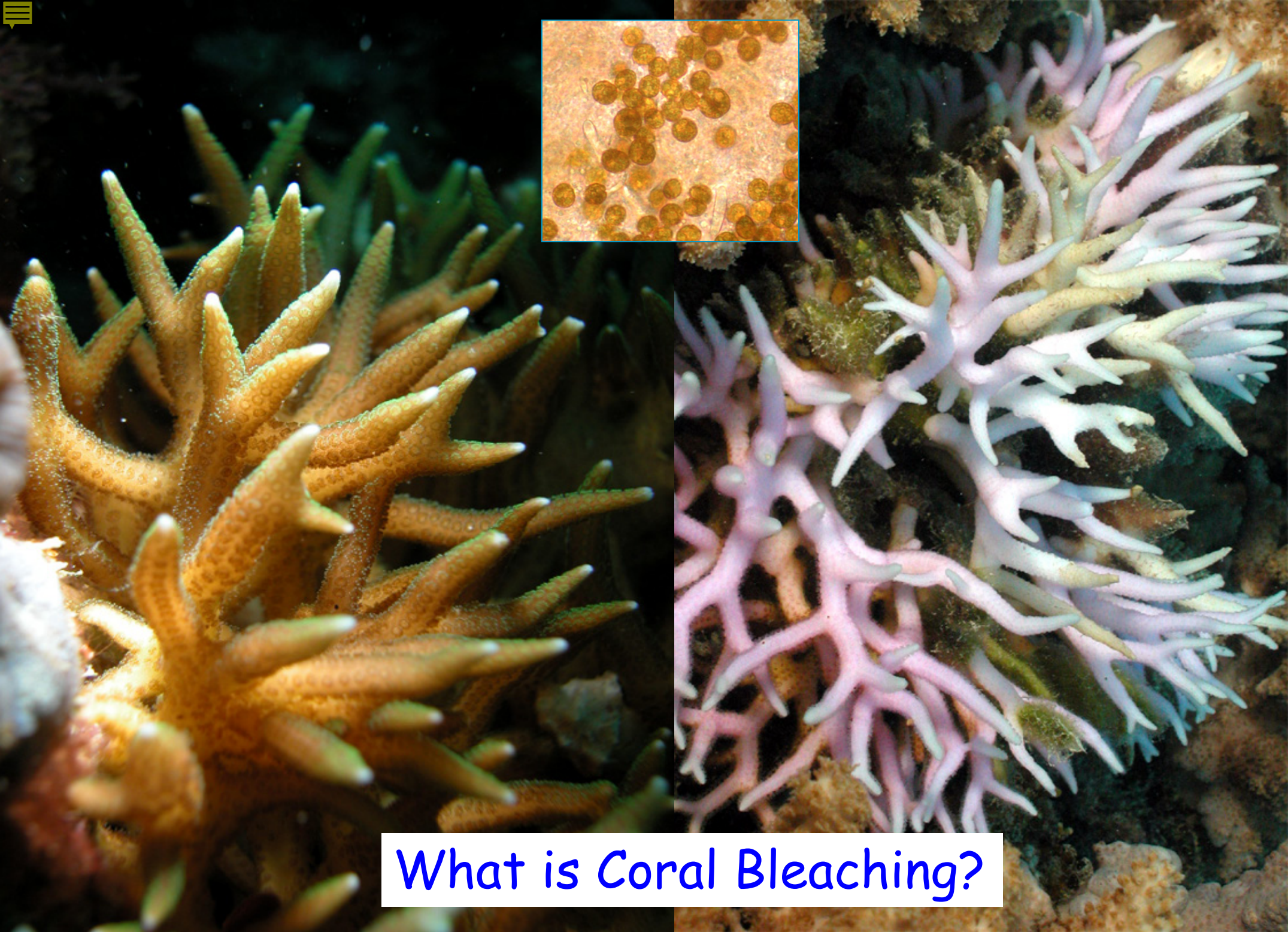
Corals,
Echinoderms



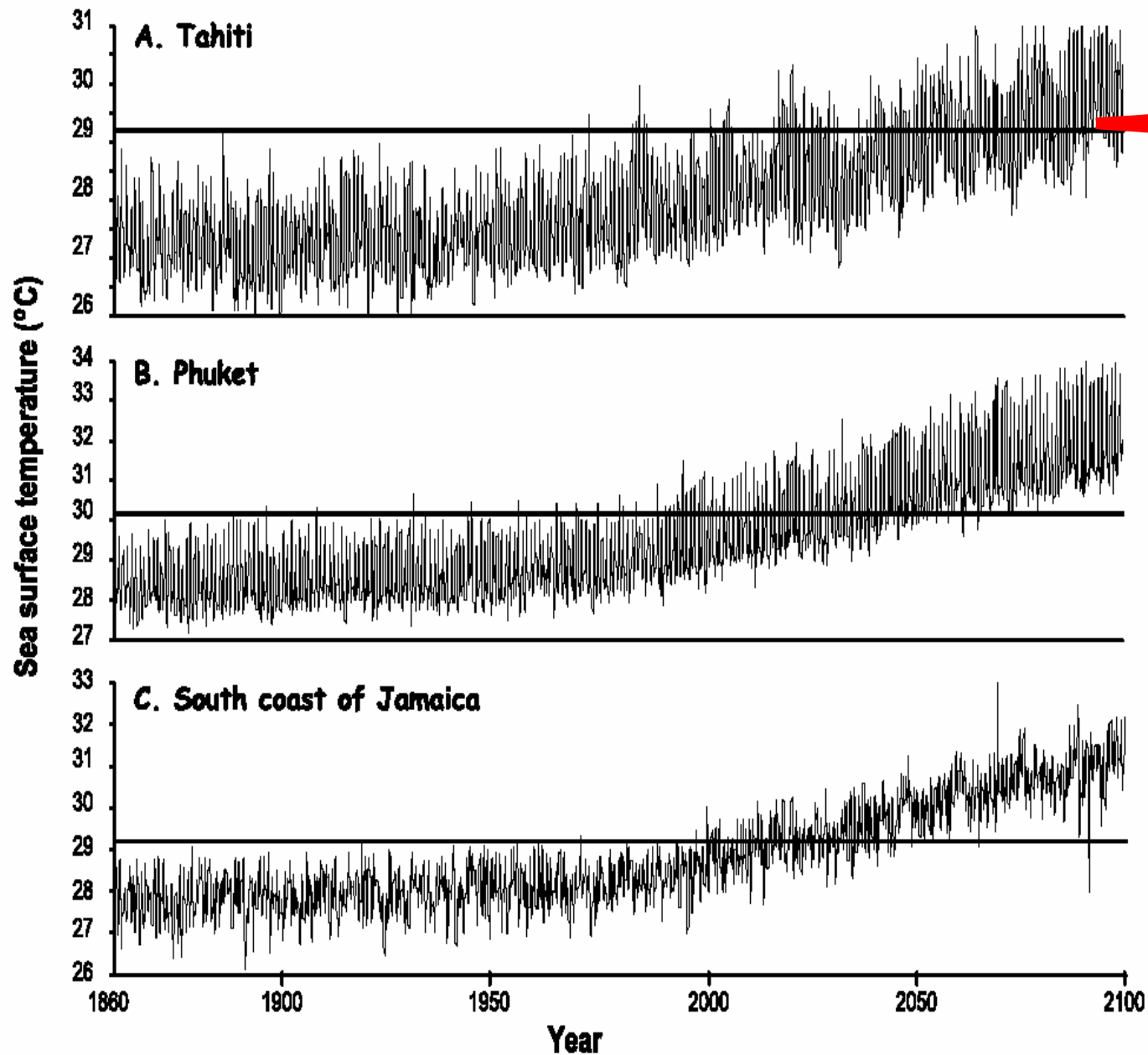
Model of Coral Calcification



Ambient pH



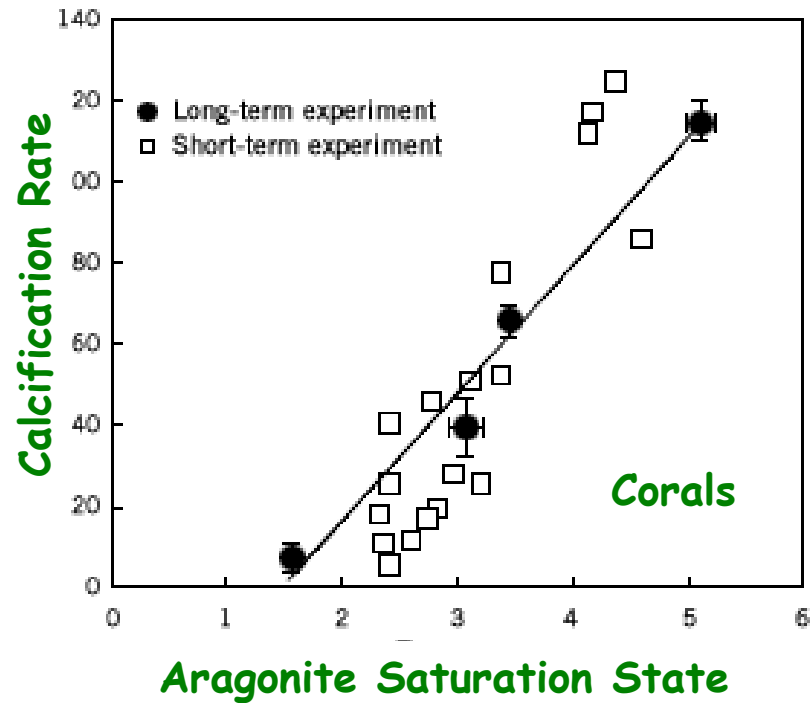
What is Coral Bleaching?



Threshold temperature - above which bleaching manifests itself (1-2°C above the long-term summer maximum temperatures)

WHAT DOES THE FUTURE HOLD?

Coral calcification is reduced in high-CO₂ ocean



Hoegh-Guldberg et al. 2007

Low aragonite saturation associated with low calcification rate

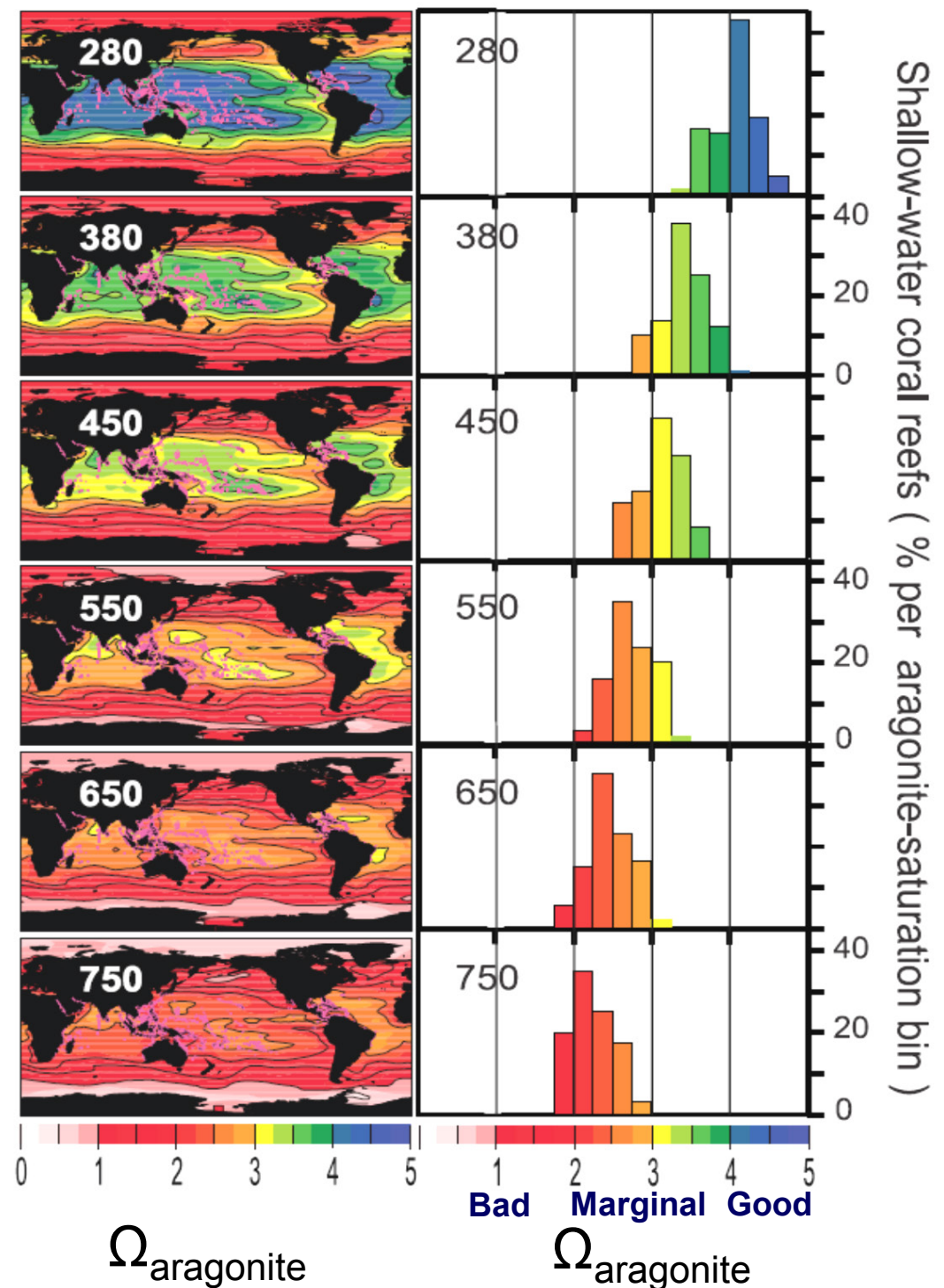
Ocean chemistry and the future of coral reefs?

Predicted **aragonite saturation (Ω)** [a measure of the amount of minerals available to make coral skeletons] is shown over a global map of existing coral reef locations (pink dots) for various atmospheric CO₂ levels. Note that Ω decreases drastically with higher CO₂ levels.

280 ppm is the preindustrial level of CO₂ in the atmosphere. During 2011 CO₂ is ~390 ppm. Most climate models indicate that we will reach ~800 ppm CO₂ by 2100.

Corals grow best when carbonate minerals are abundant ($\Omega > 3$), and cease to grow at low mineral levels ($\Omega \sim 2$) and can dissolve at very low levels ($\Omega < 1$).

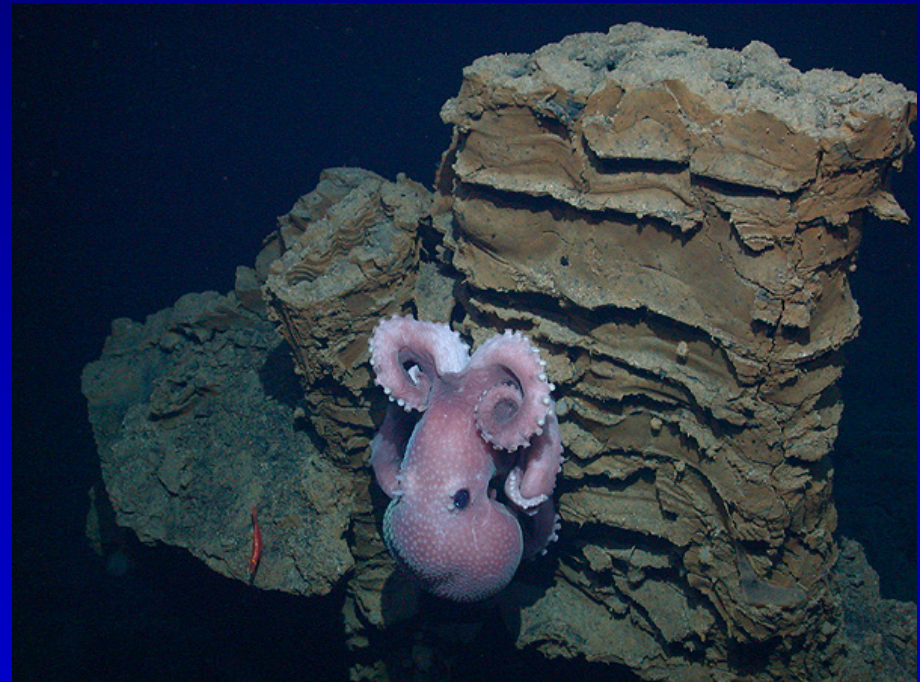
On the right, there is a count of the mineral conditions for the locations of all global coral reefs. Note that the preindustrial climate (280 ppm CO₂) all reef locations had mineral conditions favorable to growth (high Ω). **As CO₂ levels rise through this century, ALL existing reef are expected to have marginal or poor conditions for coral growth.**



Are CO₂-related stresses severe for deep-sea animals?

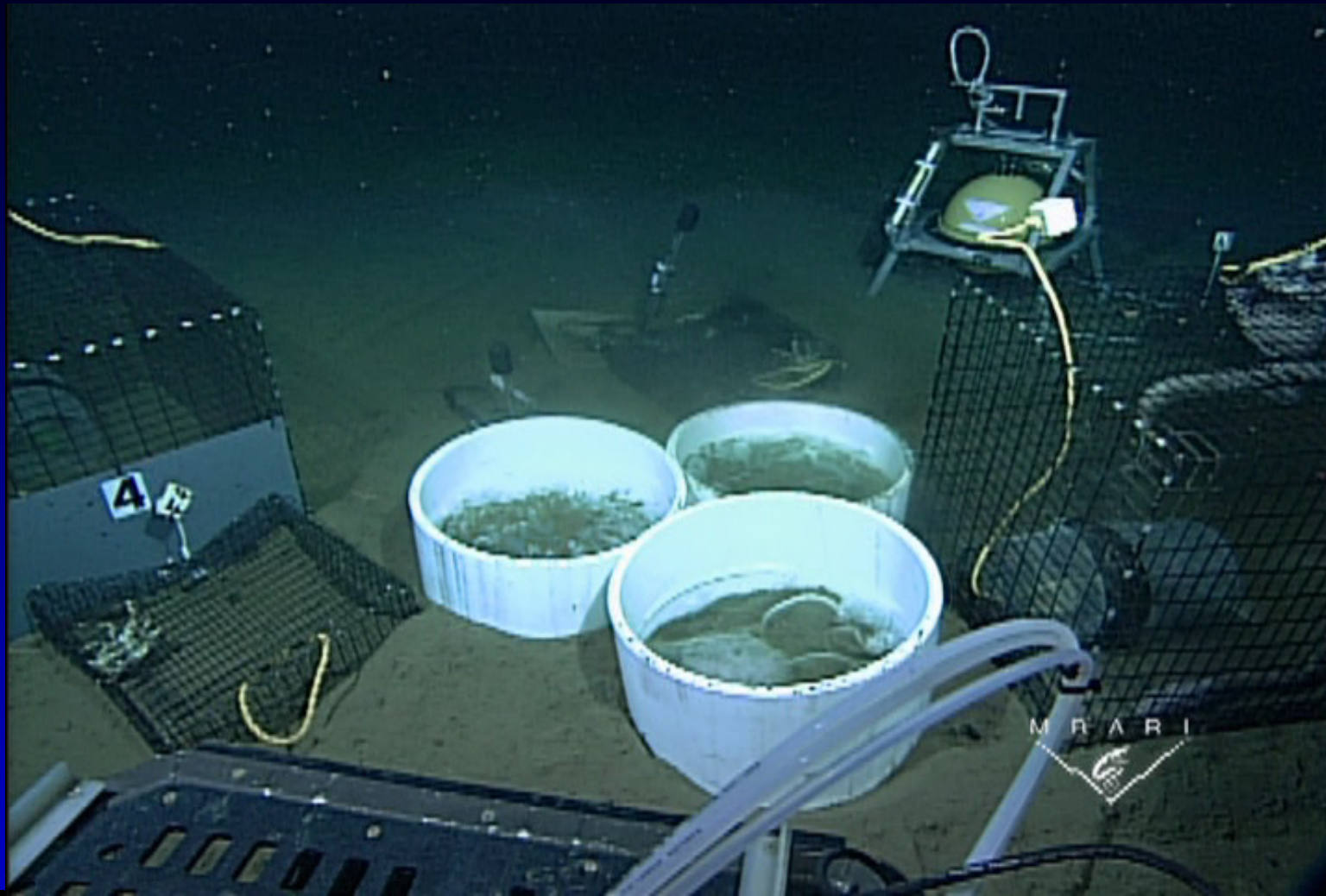
Deep-Sea Animals

1. Reduced metabolic rates
2. Reduced enzyme function
3. Evolved in highly stable deep-sea environment
4. Food-limited -
 "Living on the edge"

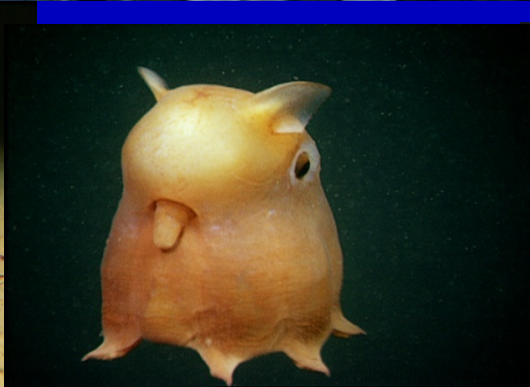


Deep-sea Octopus

Deep-Sea CO₂ - Release Experiments

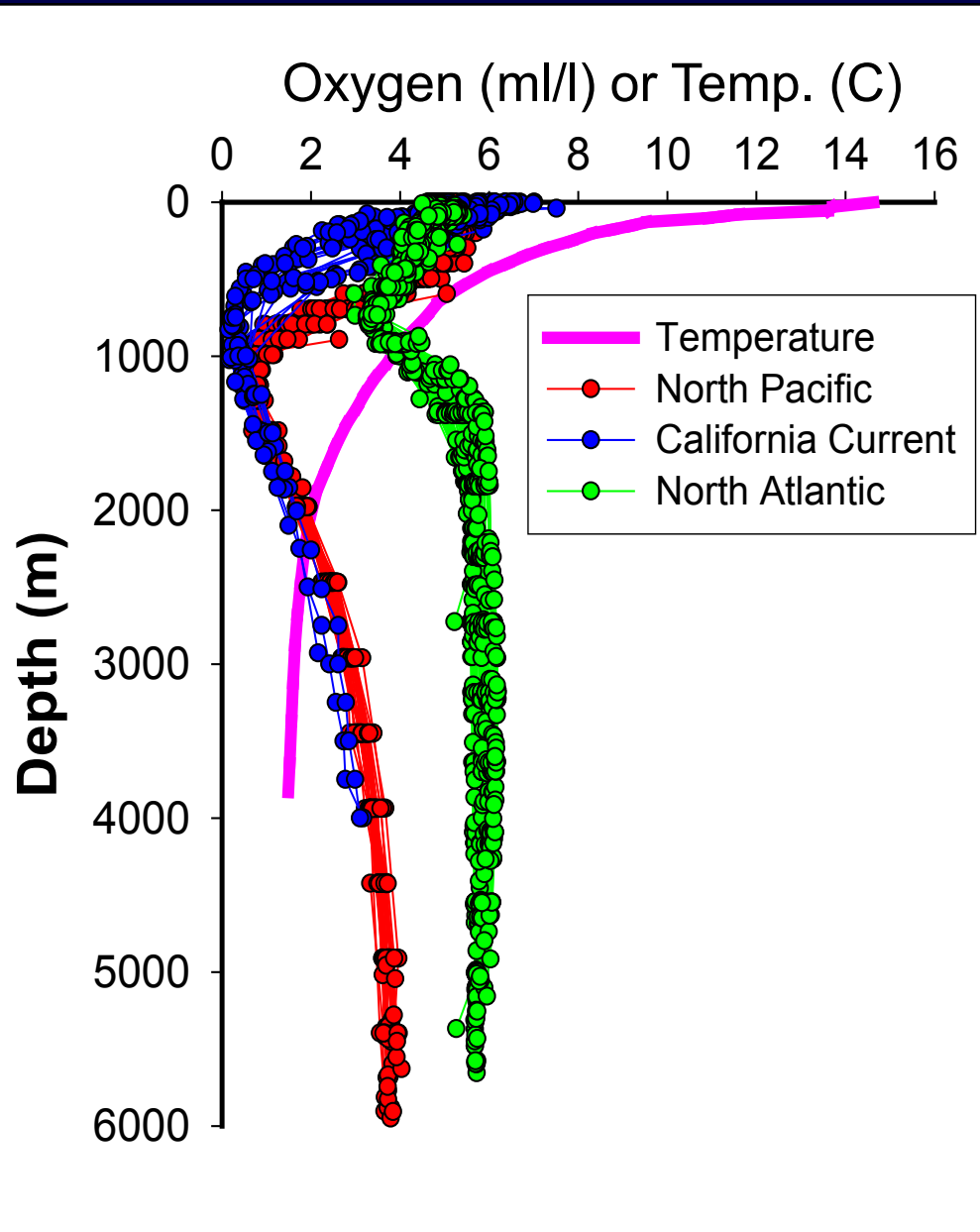


- 3600 m (~12,000 ft.)
- Effects of CO₂-rich seawater on animals
- Initial studies of effect of deep-sea CO₂ storage

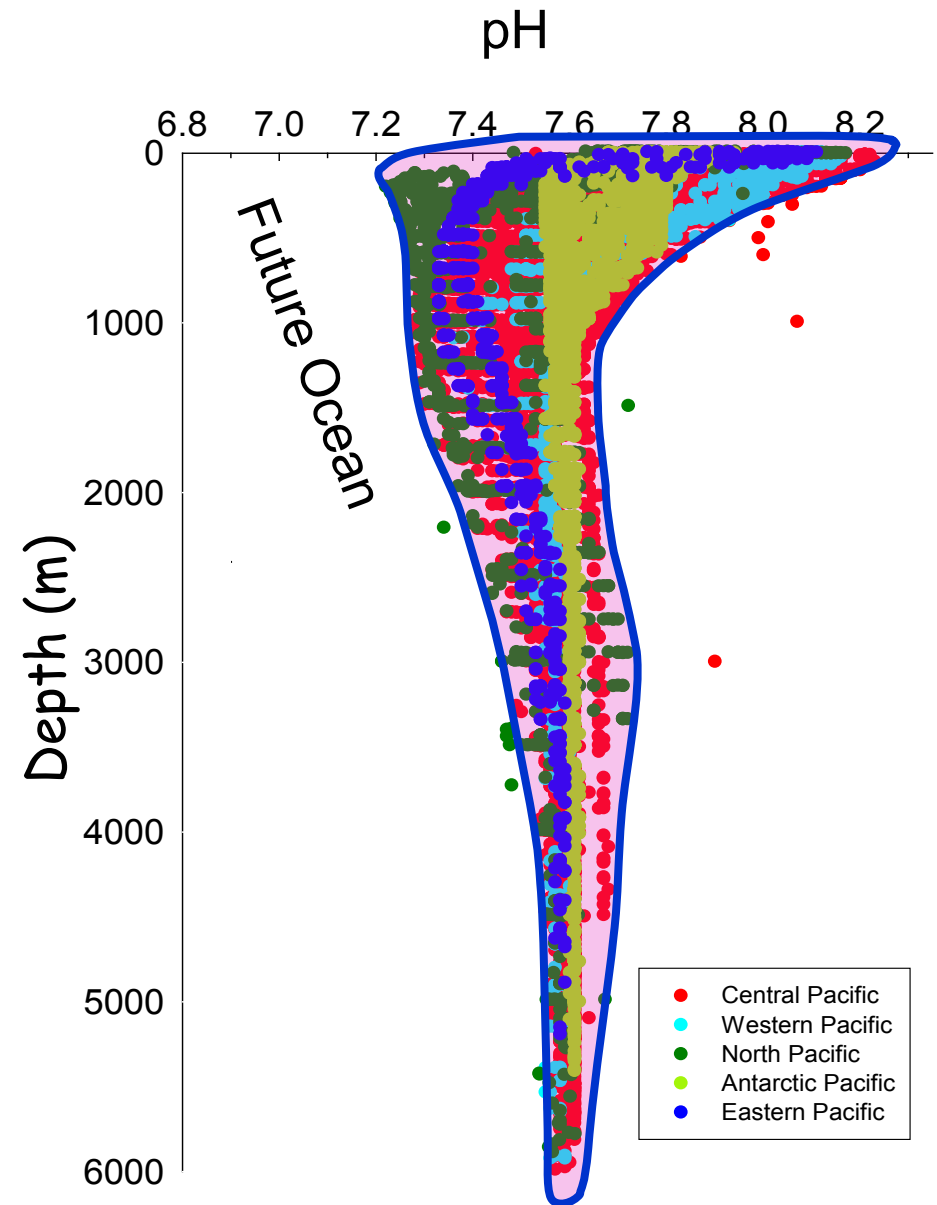


Depth-related trends in O₂, T, pH

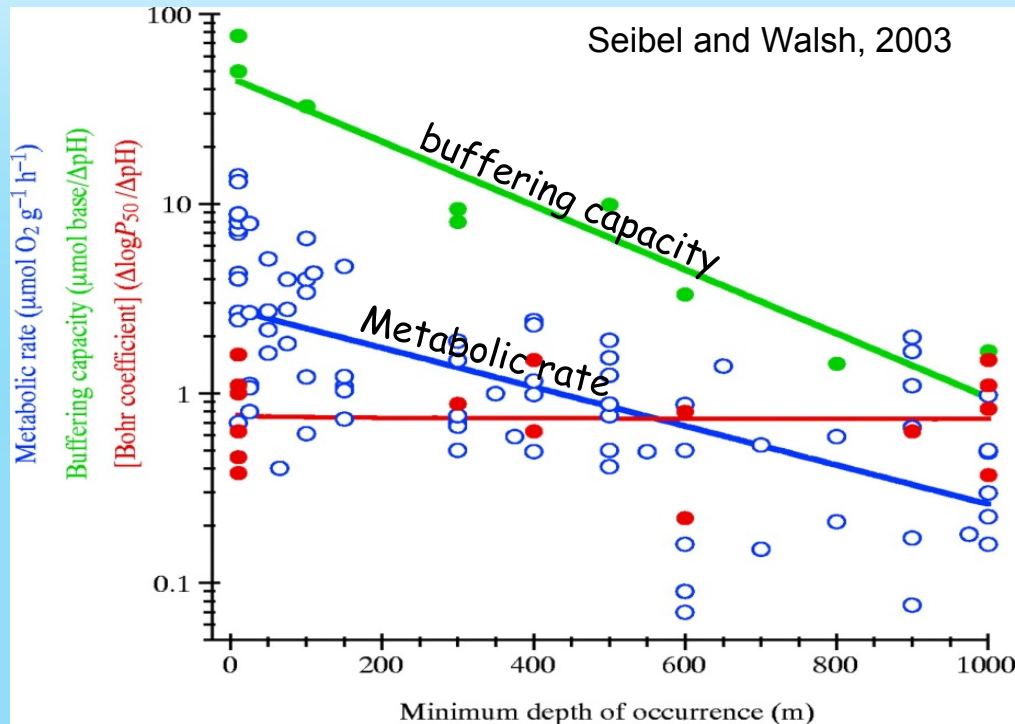
Oxygen & Temp. vs. Depth



pH variation in the Pacific Ocean

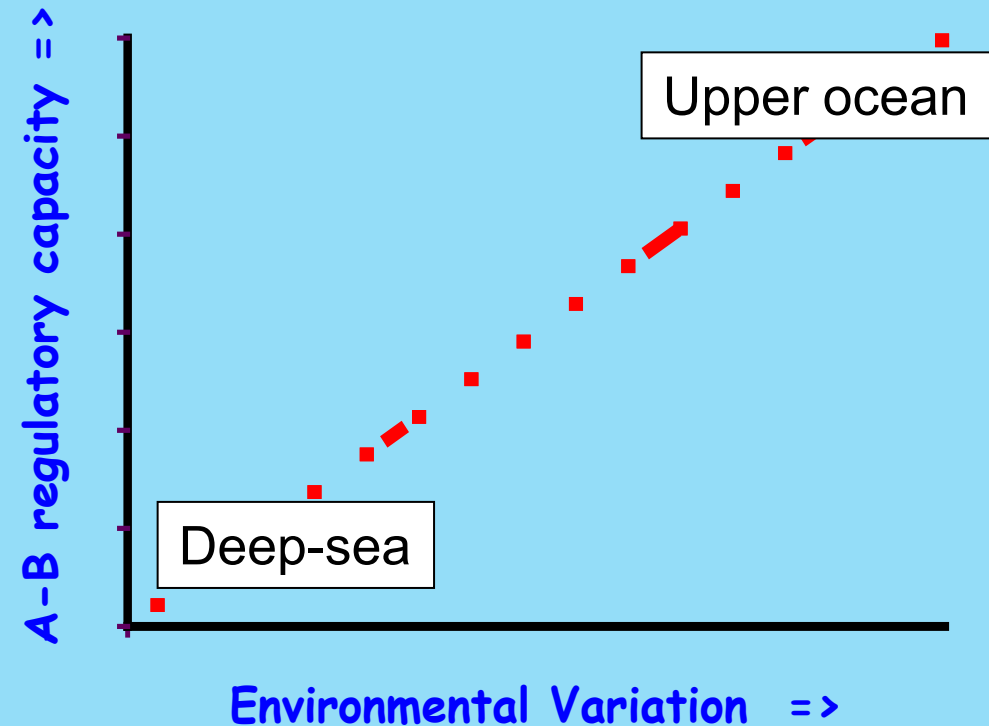


Are CO_2 -related stresses severe for deep-sea animals?

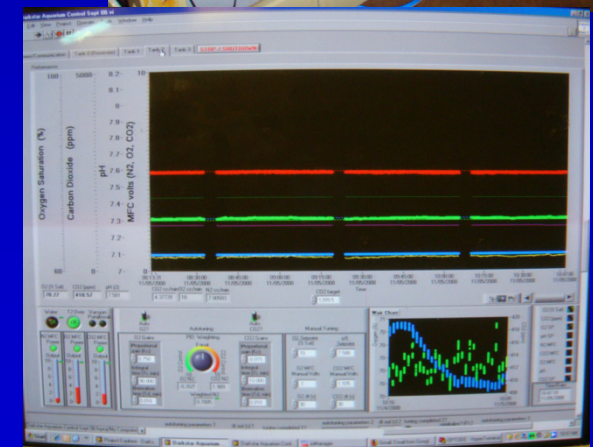
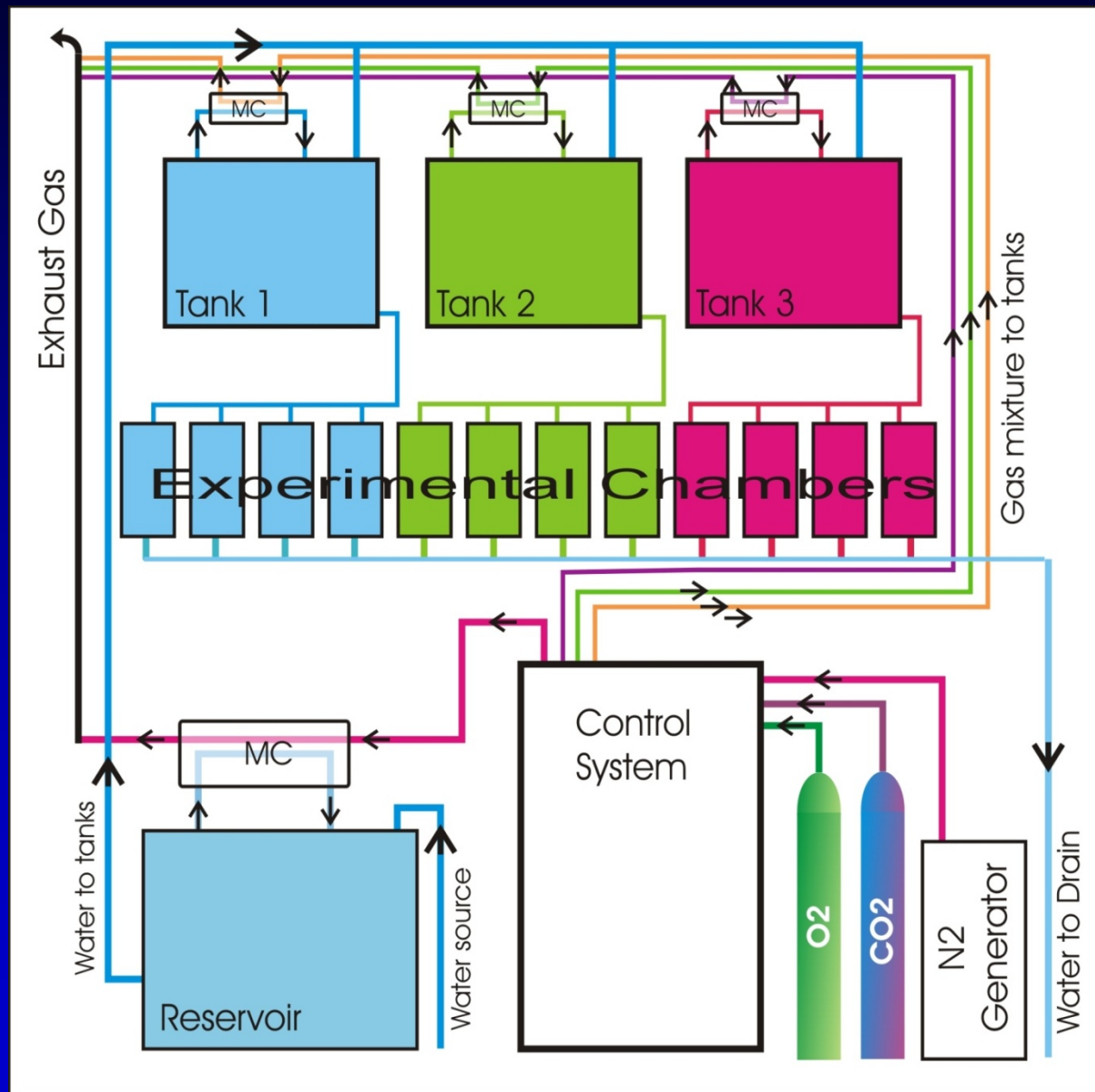


General hypothesis: Hypometabolic deep-sea animals will be particularly sensitive to respiratory acidosis associated with hypercapnia

- Strong A-B regulation evolves in aquatic animals from naturally variable environments
- The deep sea is one of the most invariant environments on Earth



Controlled-gas Aquarium System for lab-based studies of CO_2 tolerance



Acid-Base Regulation in Crabs

- Deep-sea vs. shallow-living crab
- Normoxic vs. hypoxic conditions

- Metabolic Rates
- Acid-base regulatory capacity
- Ion exchange
- Role of oxygen

Chionoecetes tanneri

The grooved Tanner crab

(~ 500 to 1500 m)h



Cancer magister

The Dungeness crab

(~ 10 to 200 m)

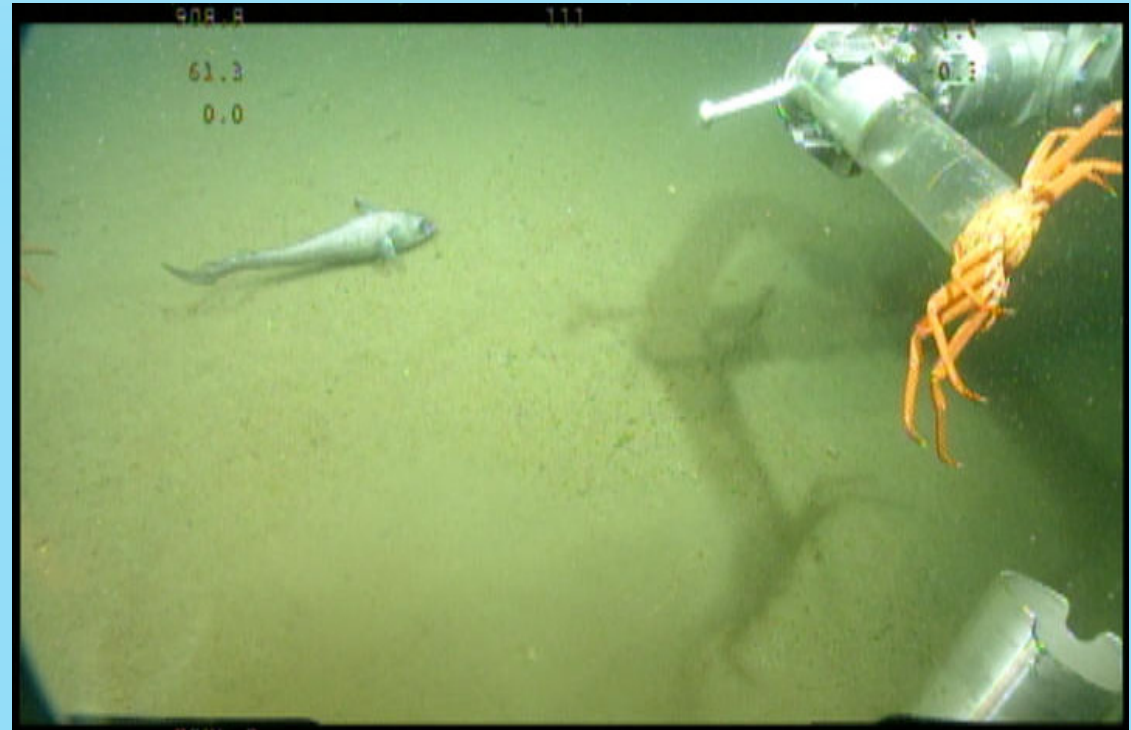
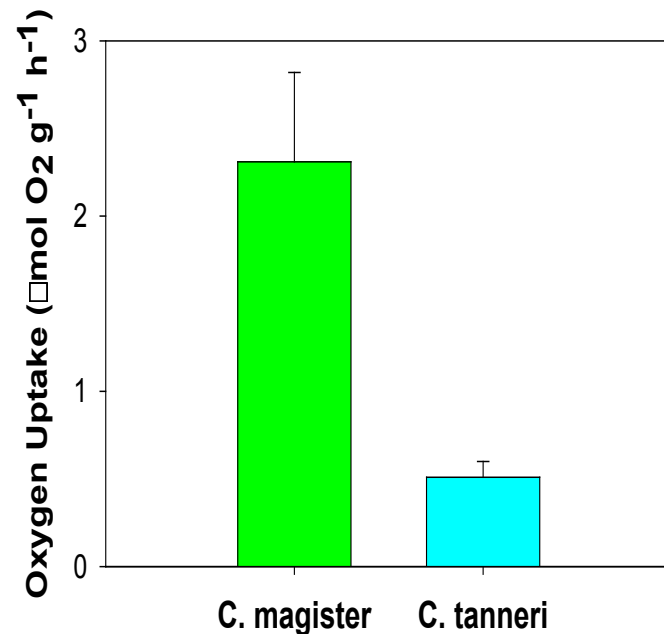


Metabolic rates

- Crabs collected from field (tanner crab) or purchased (dungeness)
- Acclimated to 95% O₂ saturation, in situ temperature (3.5, 10 C) for 3 weeks
- Metabolic rates measured in closed cell respirometers

Metabolic Rates

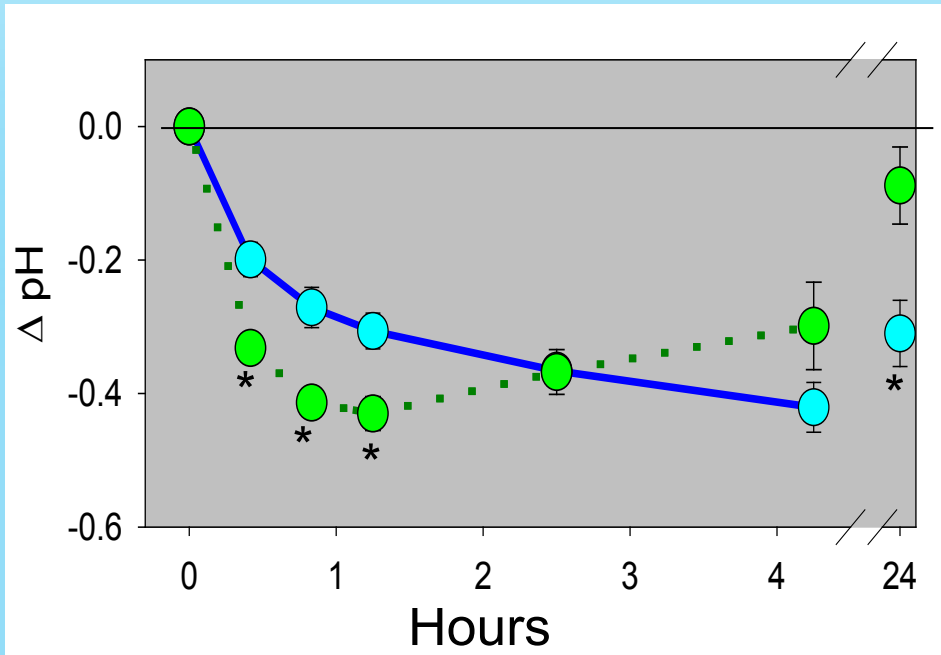
Dungeness = 4.5 X Tanner



Tanner crab collection by ROV

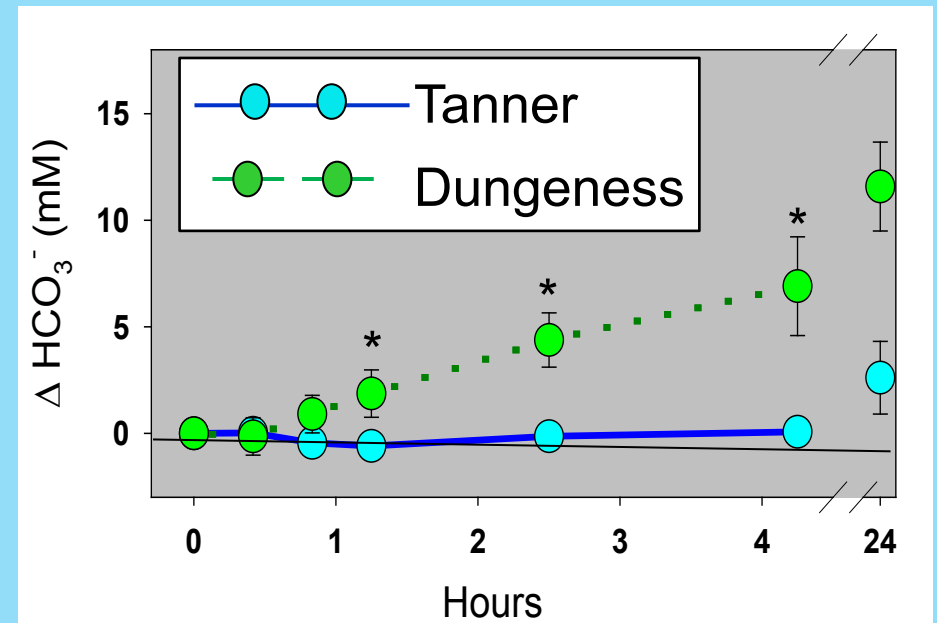
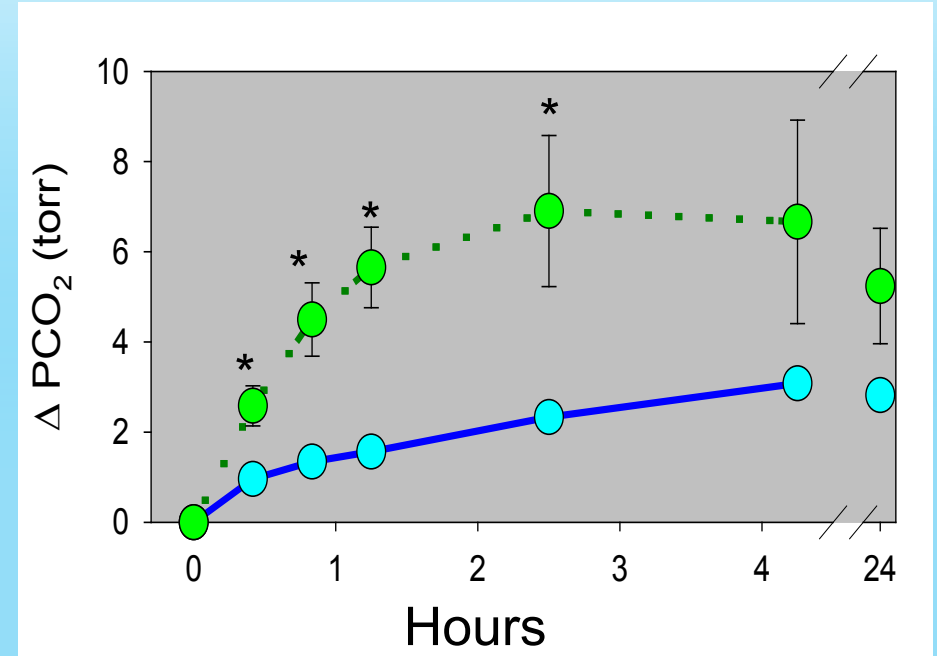
Acute (24 h) High-Level (~ 1% CO₂) Hypercapnic Exposure

Post-branchial blood parameters



Experimental Conditions

- Atmospheric pressure
- 3.5°C Tanner
- 10°C Dungeness
- 95% O₂ saturation
- 3 weeks acclimation
- Hemolymph sampled through carapace above heart



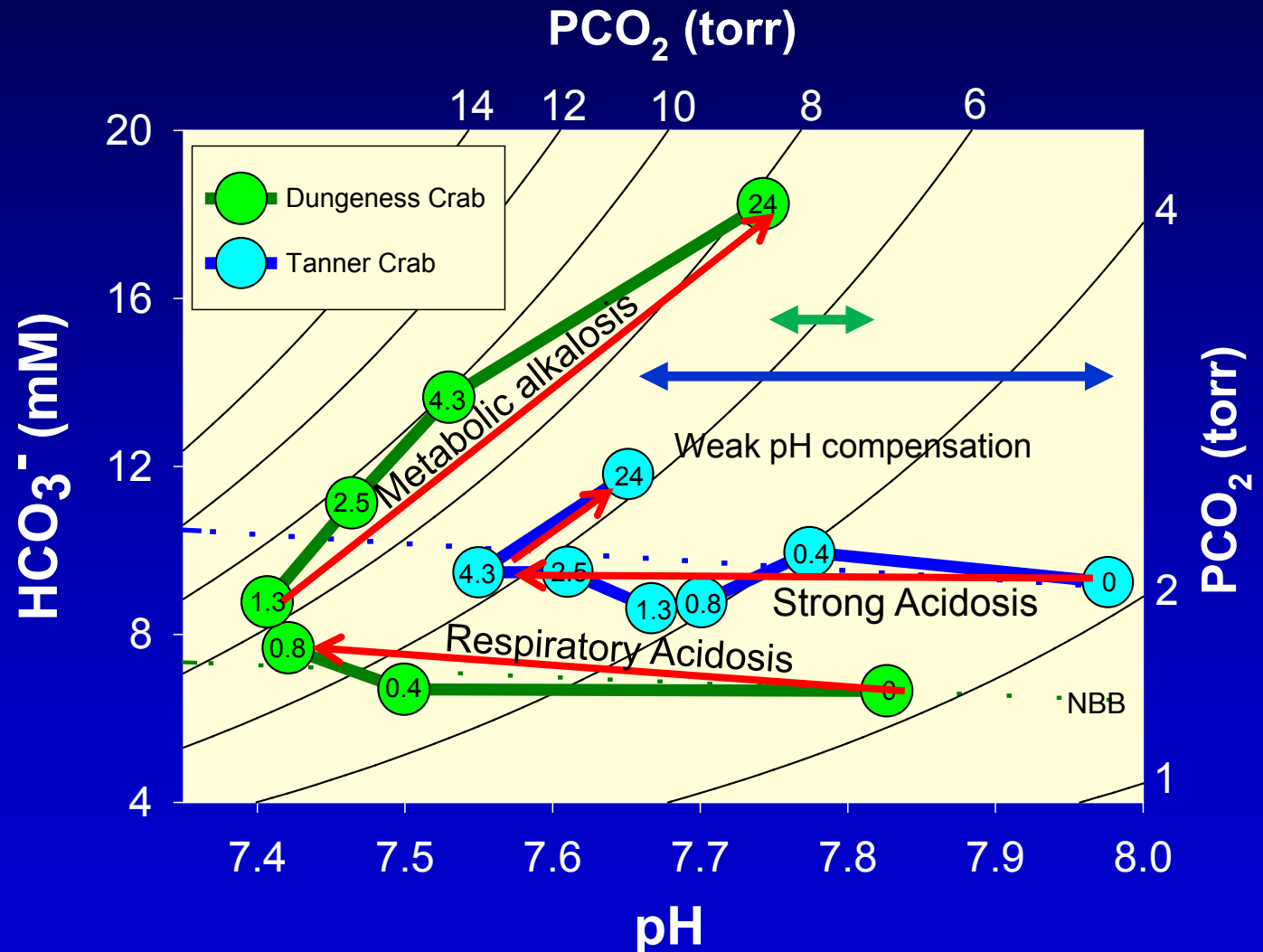
pH compensation in deep-water crab is weak

- Dungeness crab is tolerant of CO_2 stress
- Effects of ambient oxygen levels?

Dungeness Crab (shallow water)



Tanner Crab (deep-sea)



Hypercapnic compensation after 24 h

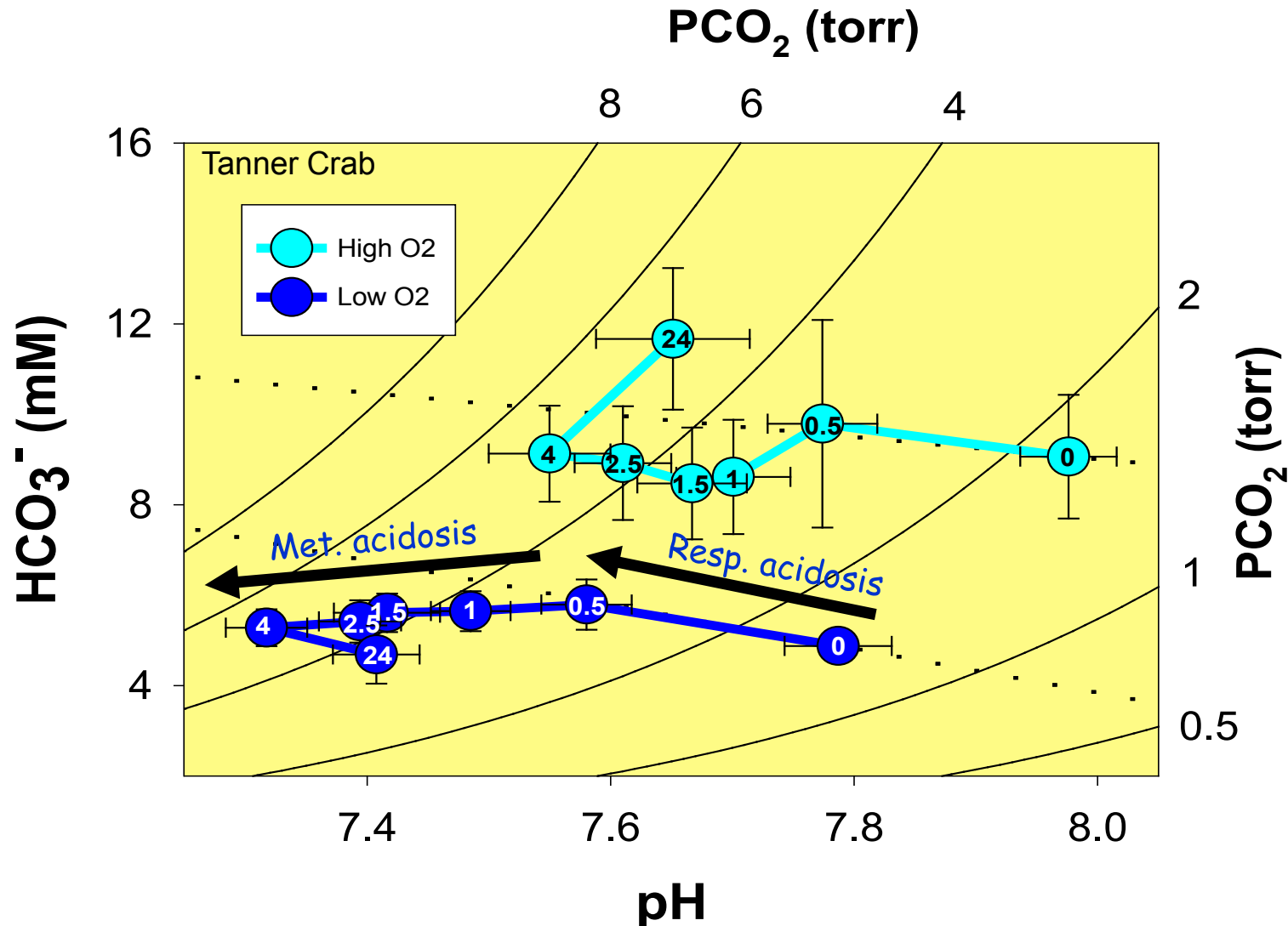
		Tanner, High O ₂	Dungeness
pH Drop		0.32 units	0.08 units
Increase in [H ⁺]		111%	21%
Increase in [HCO ₃ ⁻]		28%	174%
			

Hypoxia reduces hypercapnic compensation

"High" O₂ (95% saturation) (*Hyperoxia*)

vs.

"Low" O₂ (10-15% saturation) (*In situ*)

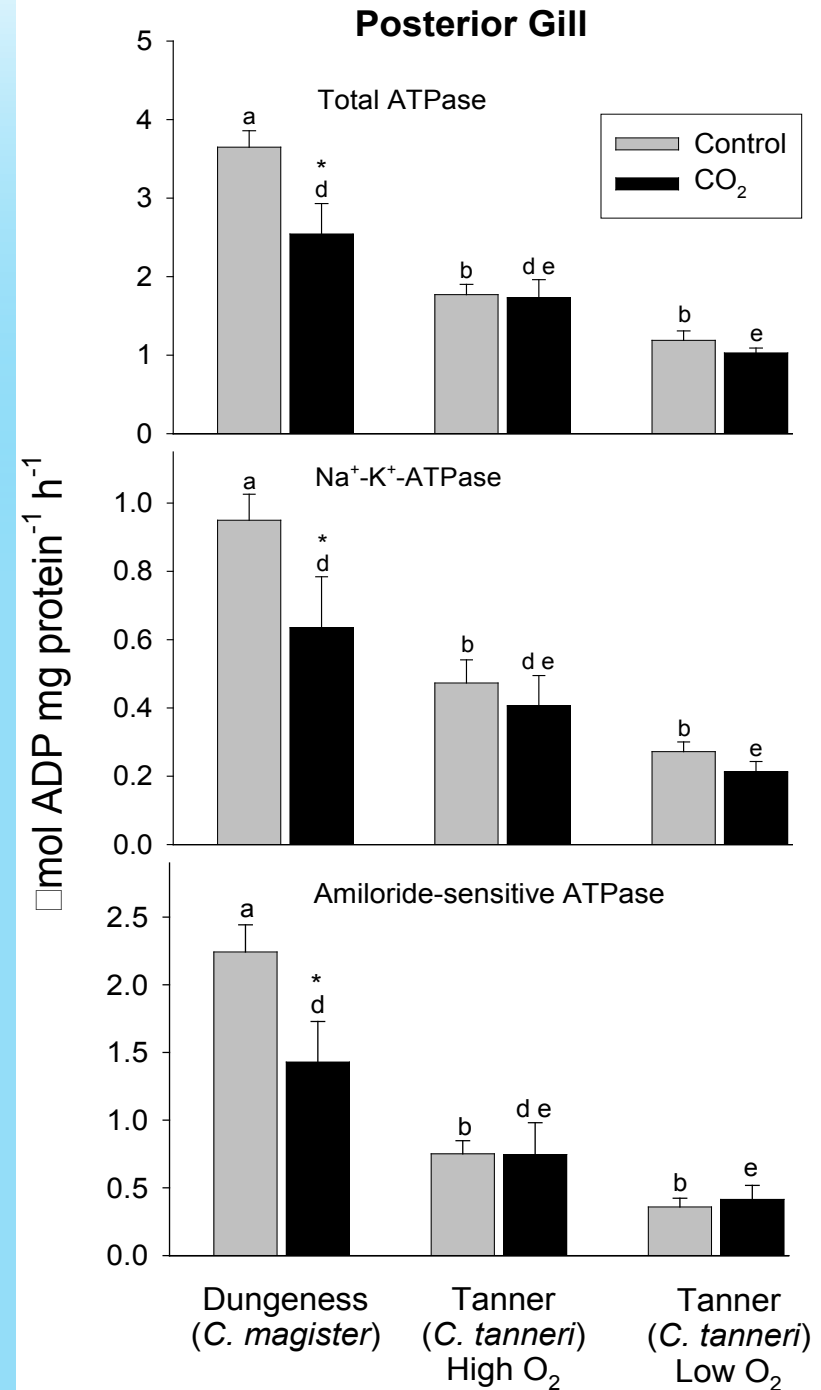
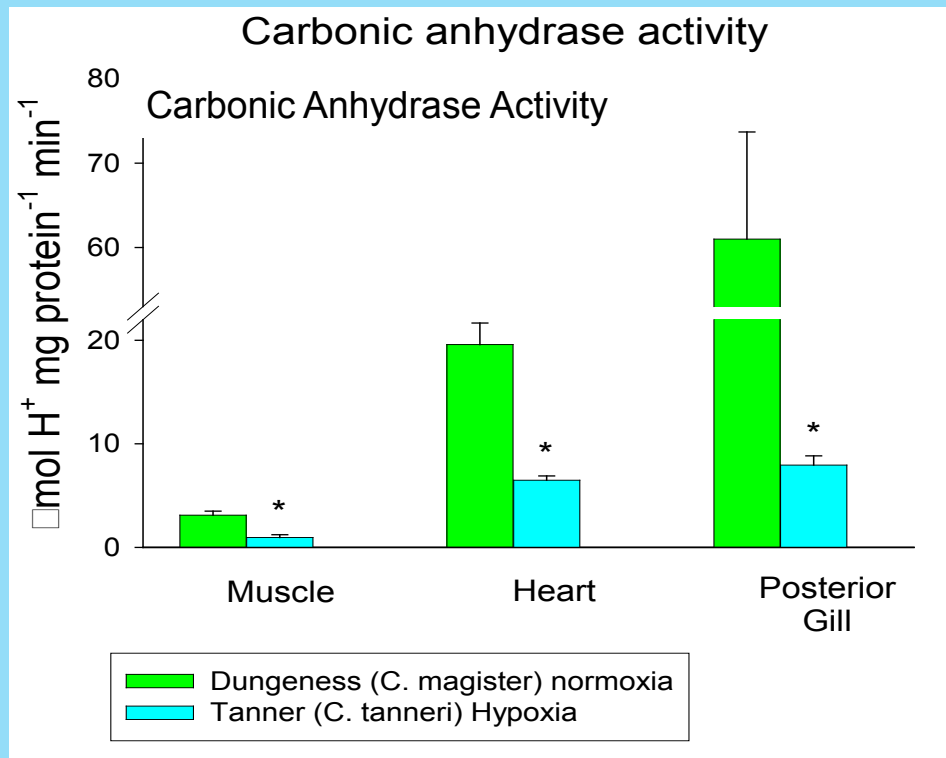


Hypercapnic compensation after 24 h

	Tanner, Low O ₂	Tanner, High O ₂	Dungeness
pH Drop	0.38 units	0.32 units	0.08 units
Increase in [H ⁺]	140%	111%	21%
Increase in [HCO ₃ ⁻]	-3.9%	28%	174%
			

Post-branchial Ion Exchange

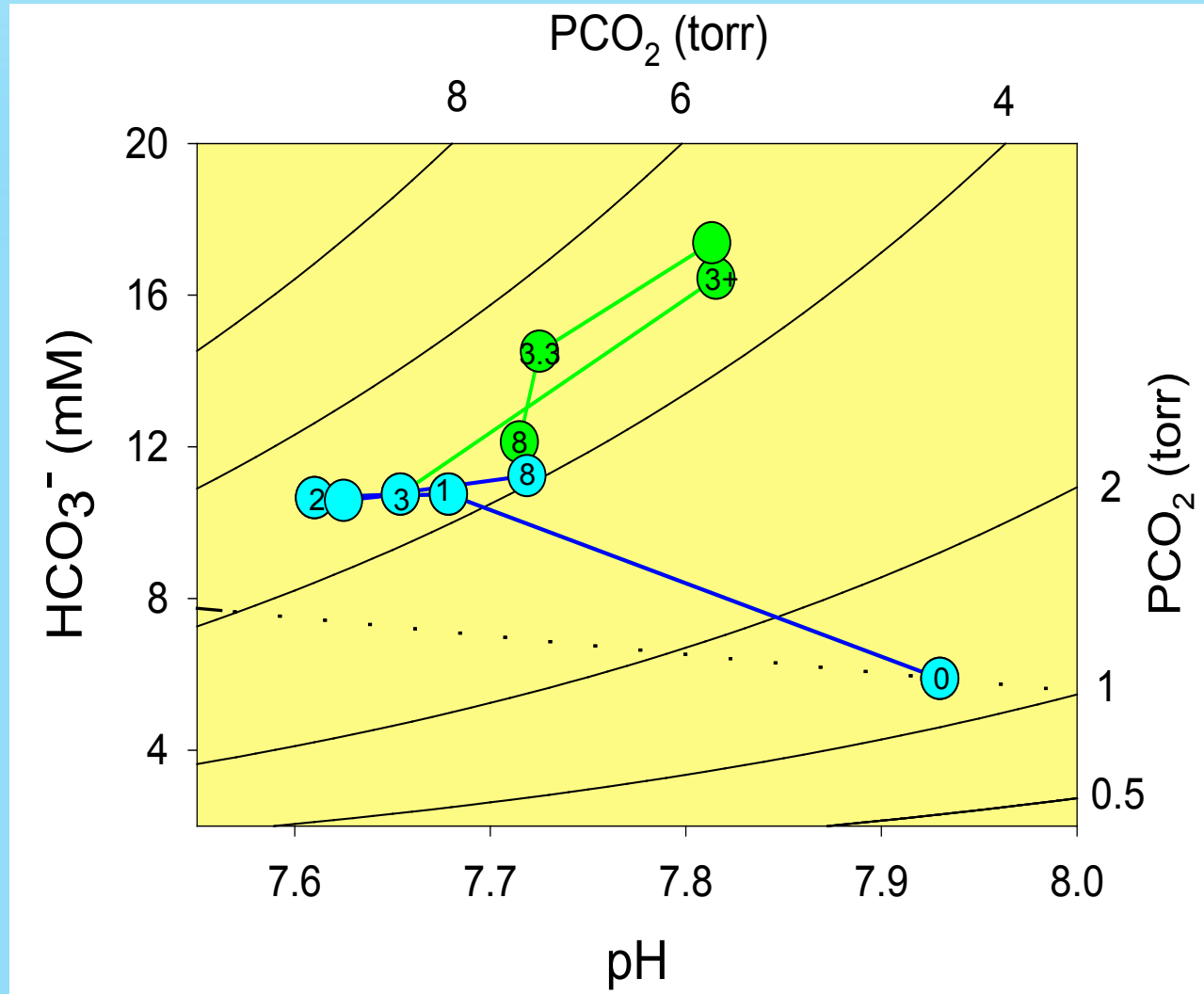
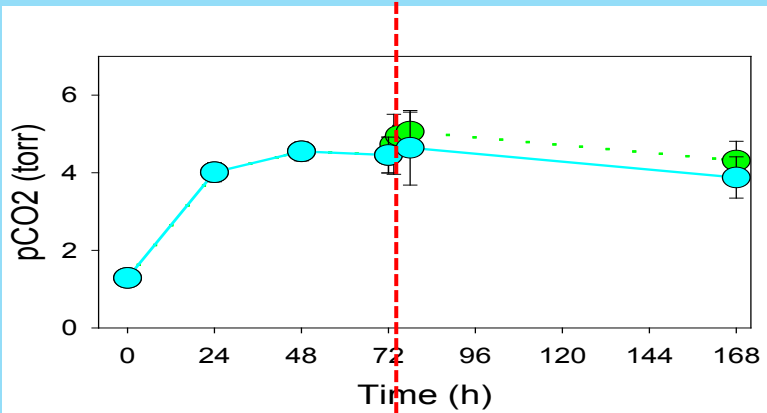
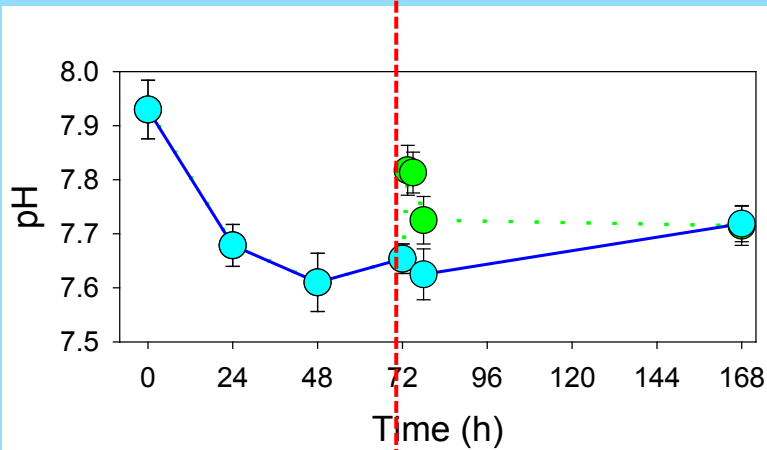
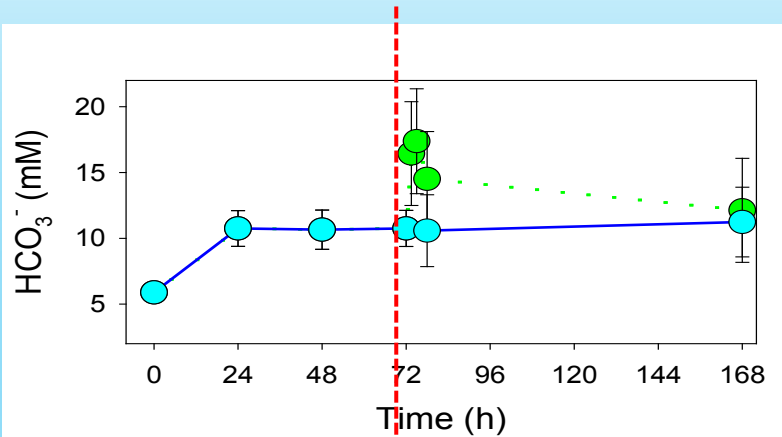
- Hypercapnia inhibits ATPase activity
Dungeness only
- Dungeness > High O₂ Tanner
Ion transport more effective in dungeness
- High O₂ Tanner ~ > Low O₂ Tanner
Ion transport in tanner too energetically costly?



Tanner Crab: HCO_3^- infusion helps pH compensation

8 days of recovery after postbrachial infusion (low O_2)

- HCO_3^- elevation not sustainable
- weak pH compensation after 8d



Conclusions - Crab physiology

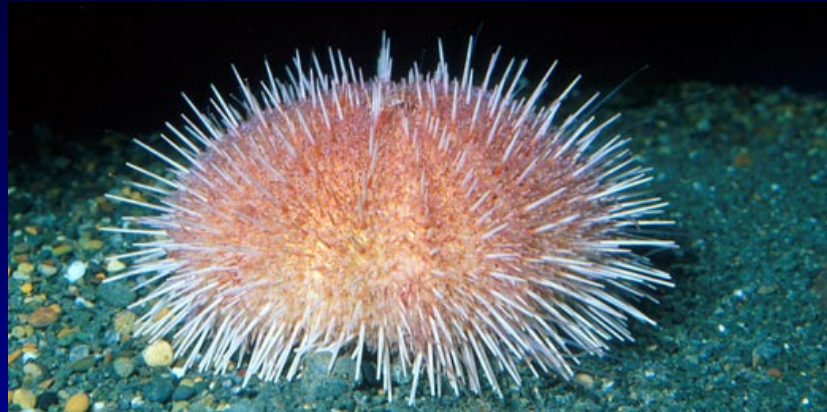
Deep vs. Shallow Habitats

- Acid-base regulation in hypometabolic deep-sea crabs is weak
 - Shallow water crab compensated in 24 h, but little recovery in deep crab
- Supports hypothesis of slow ion exchange at gill in deep-sea animals
 - Reduced rates of key enzymes in deep-sea animals
 - Ion-regulation is energetically costly, difficult for hypometabolic taxa

Effects of Oxygen

- Hyperoxia led to improved extracellular pH compensation, bicarbonate accumulation.
 - Oxygen limitation on metabolic rate may be responsible.
- Synergistic effects of hypercapnia and hypoxia for A-B regulation indicates potential for greater OA related stress in future

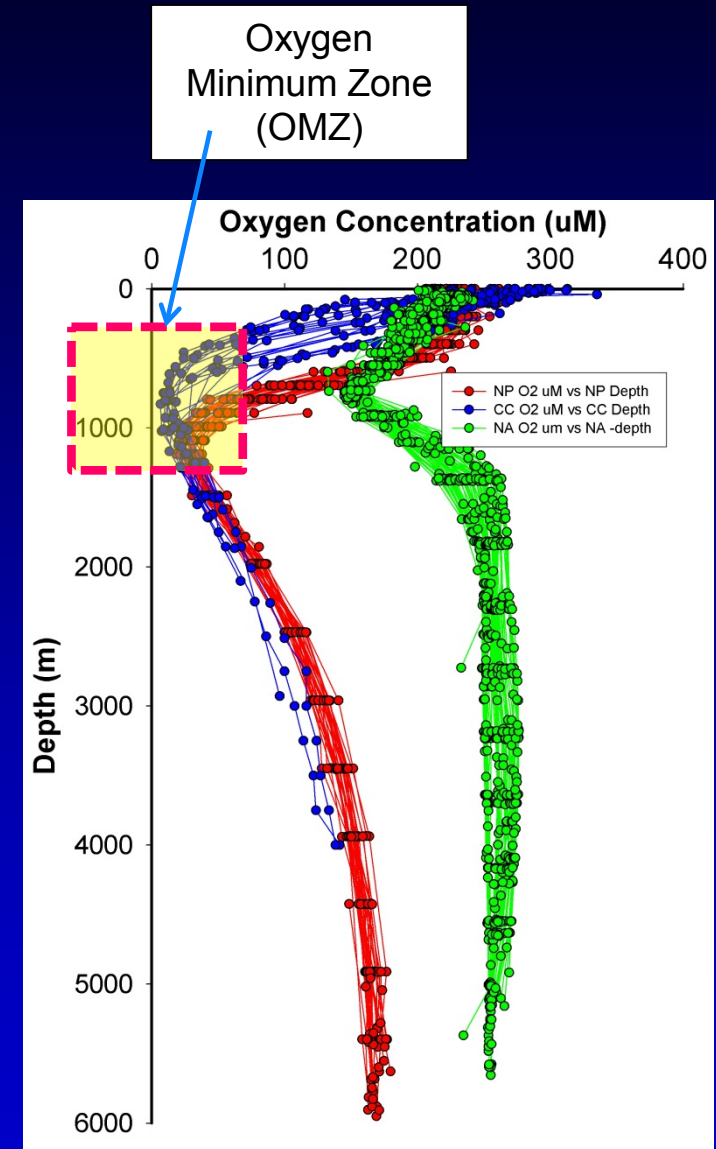
Deep-Sea Urchins to are vulnerable to ocean acidification



Allocentrotus fragilis

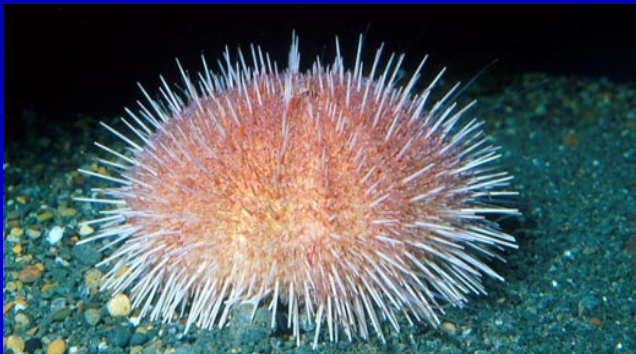
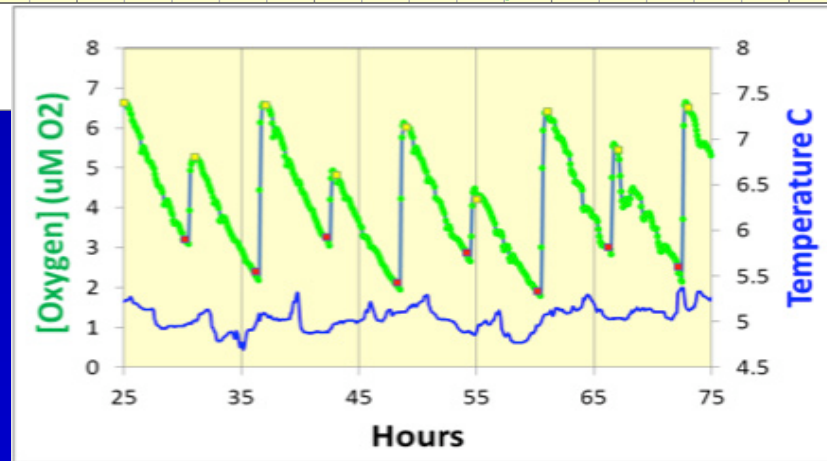
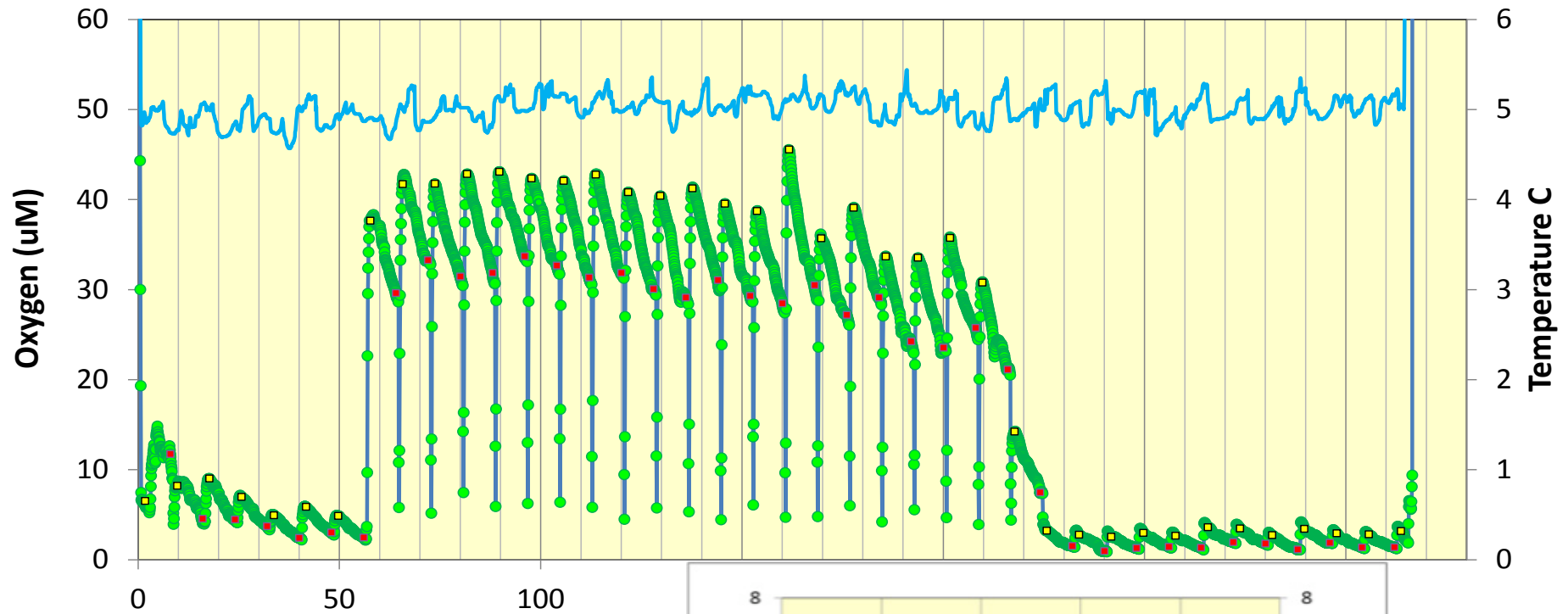


Measuring sea urchin respiration rates in the deep-sea



Urchins are oxygen-stressed in the OMZ

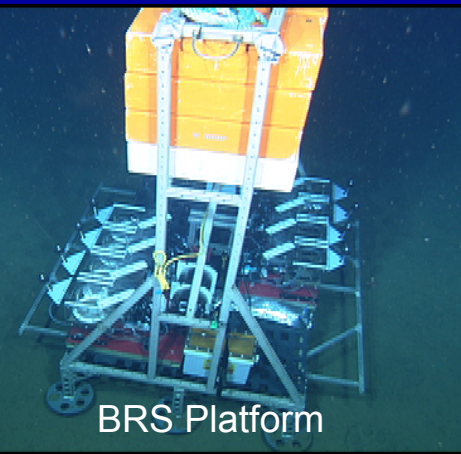
Given more oxygen, respiration increases



Fragile Urchin – *Allocentrotus californiensis*

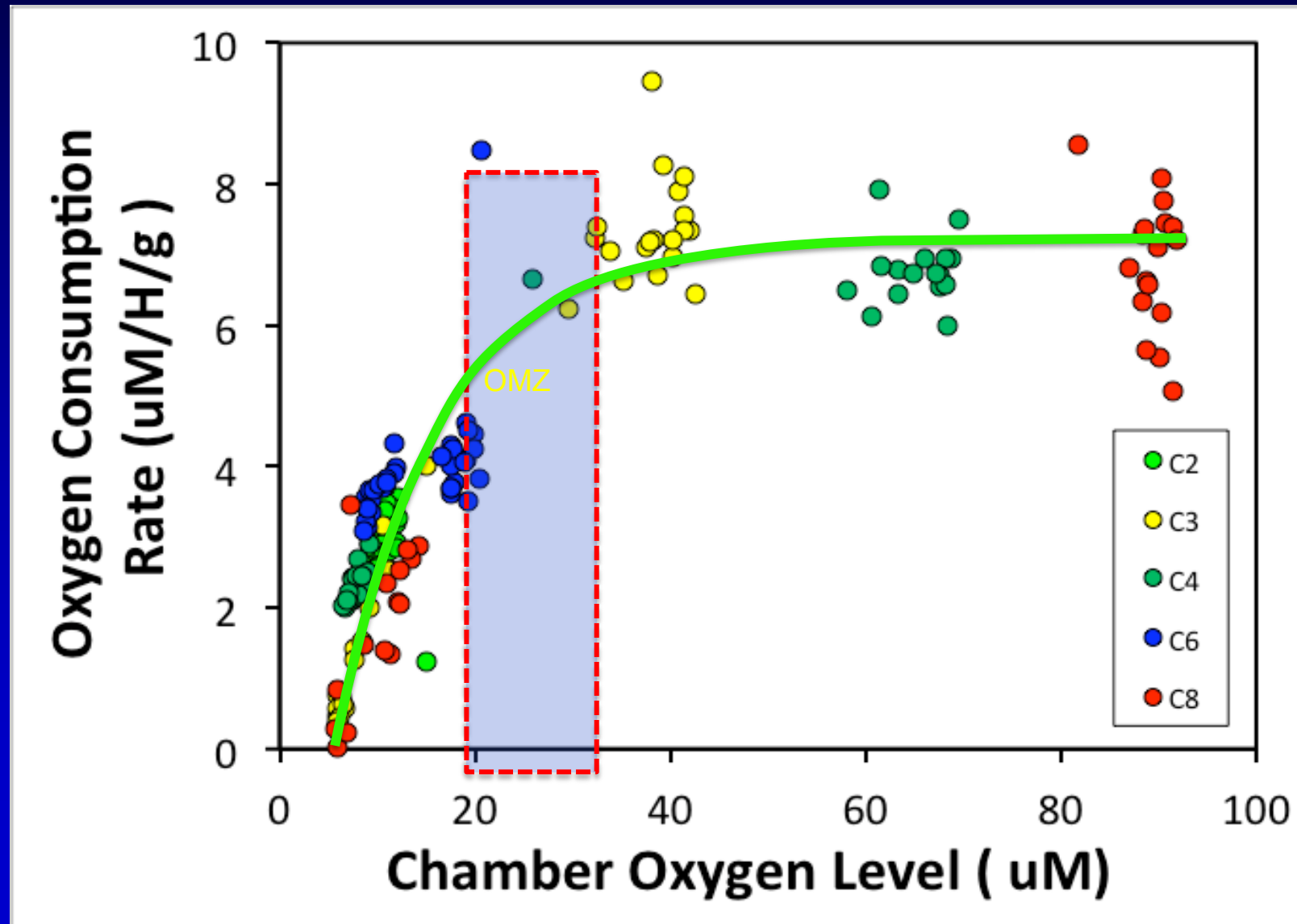
Expansion of hypoxia likely to affect deep-sea urchins and other animal populations

Urchin O₂ Consumption vs. Available O₂



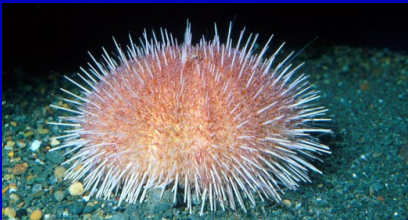
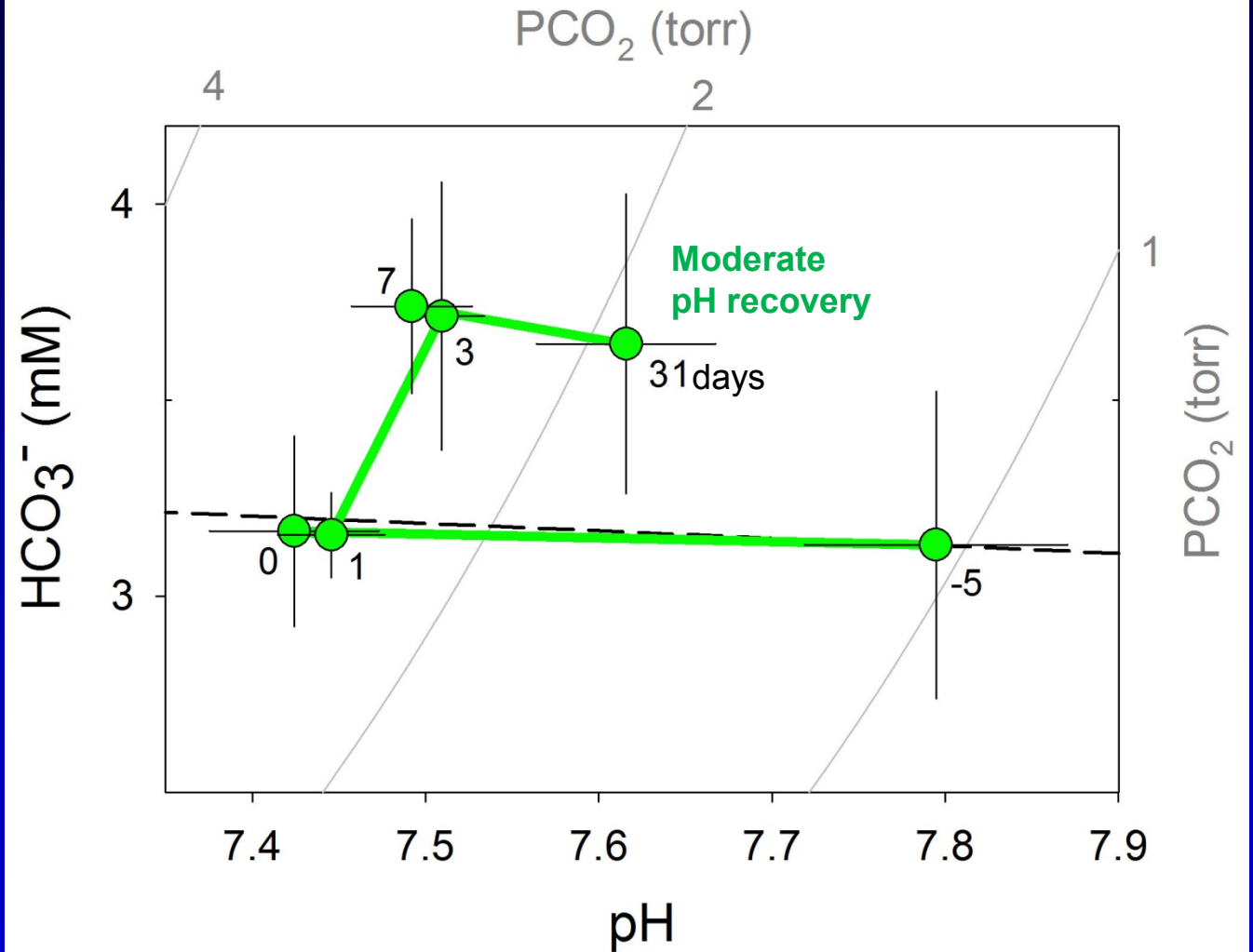
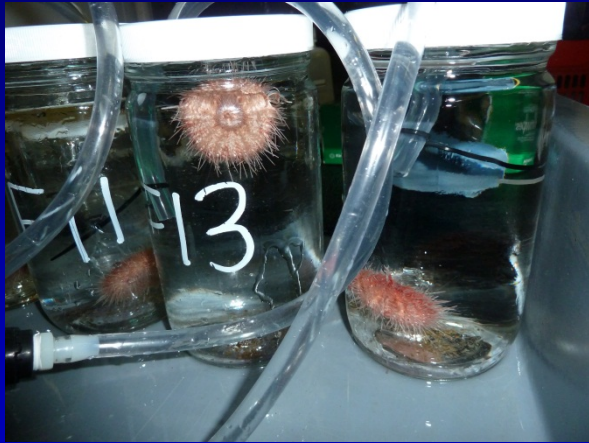
BRS Platform

BRS Platform



Deep-sea urchin capable of pH compensation under mild ocean acidification

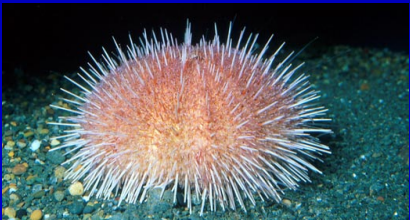
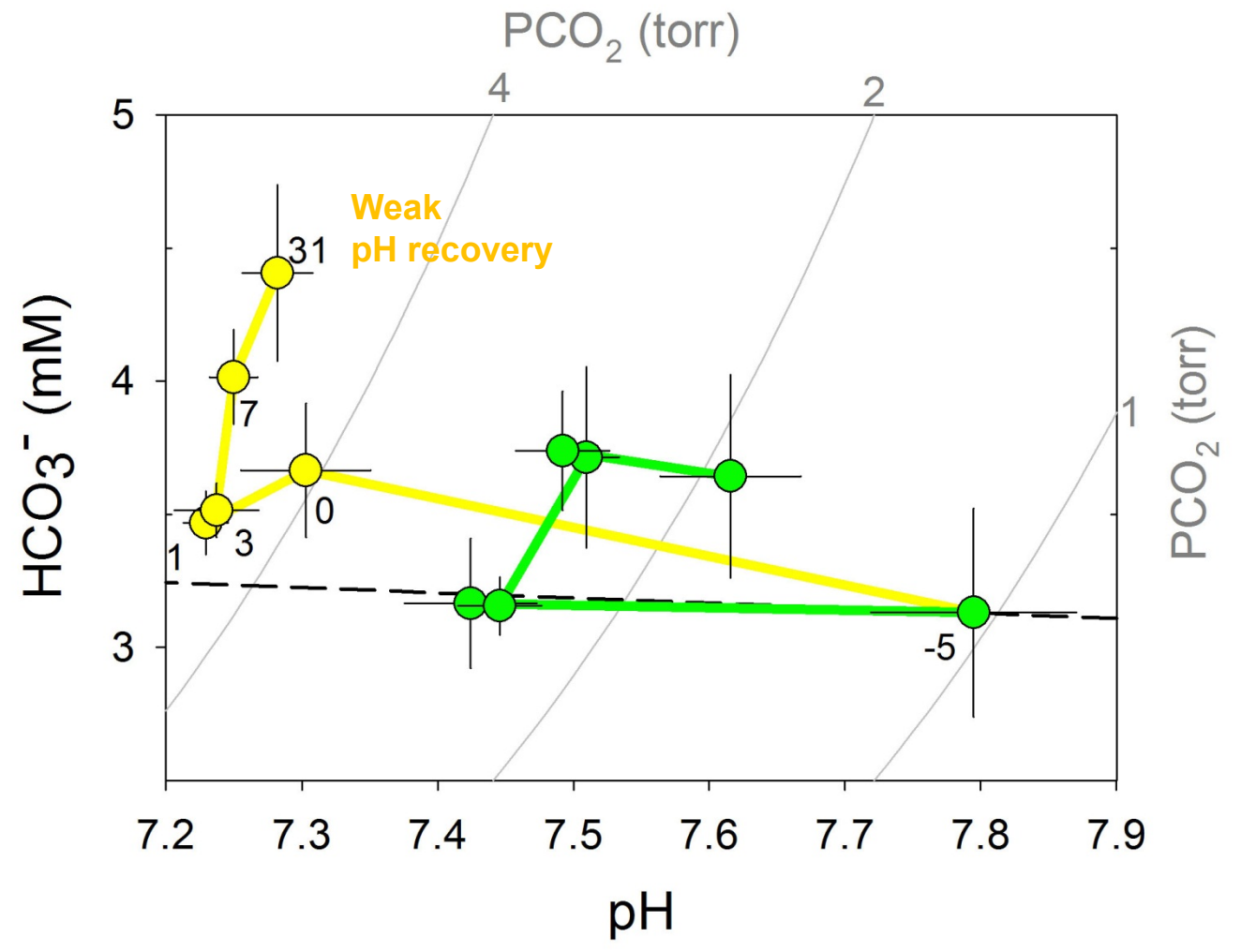
- Tank pH = 7.5
- Tank $O_2 \sim 100 \mu M$
- Moderate compensation after mild acidosis



Fragile Urchin

pH compensation weak under moderate ocean acidification

- Tank pH = 7.1
- Tank $O_2 \sim 100$



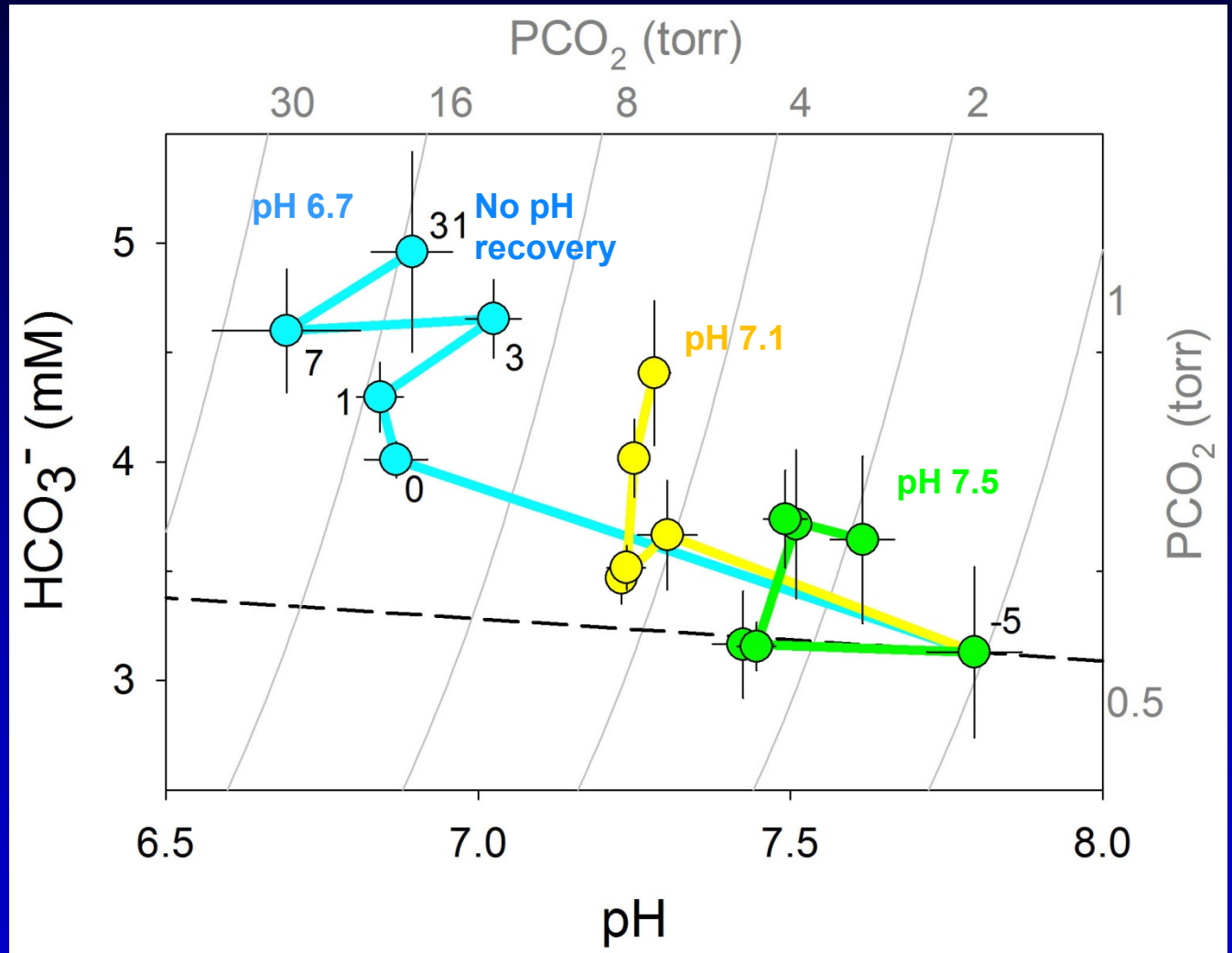
Fragile Urchin

No pH compensation under severe ocean acidification

- Tank pH = 6.7
- Tank $O_2 \sim 100 \mu M$



Fragile Urchin



Urchin physiological performance impaired by ocean acidification

- Deep-sea urchin metabolism
 - Low, limited by hypoxia
- Acid-base compensation
 - Weak
- Consequences for performance?
 - Survival
 - Growth
 - Reproduction

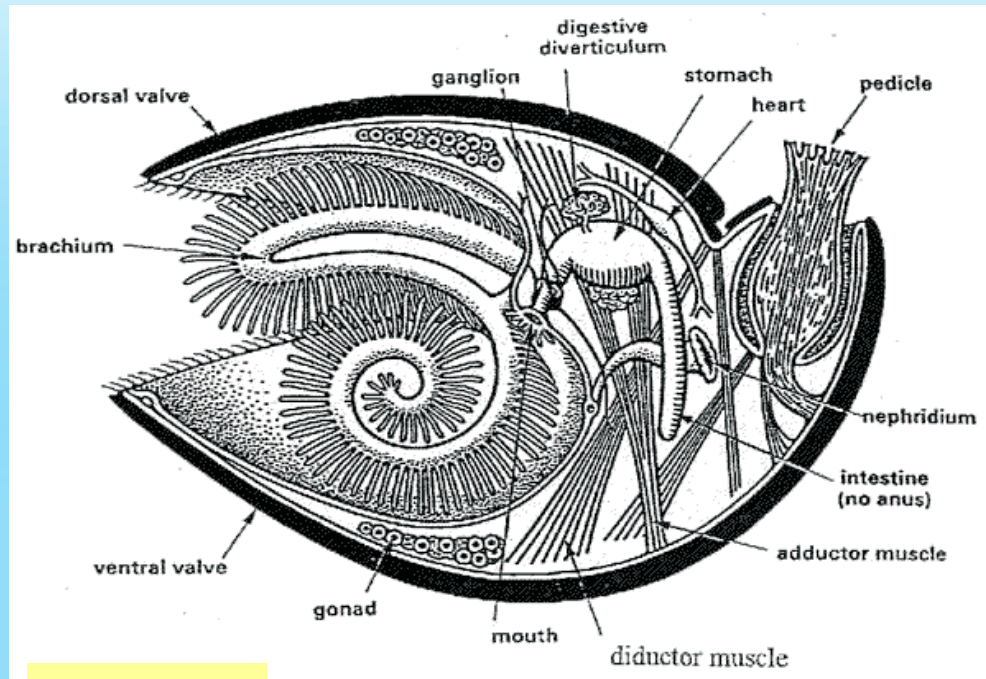


EFFECTS OF OCEAN ACIDIFICATION ON METABOLISM AND ACID-BASE BALANCE IN BRACHIOPODS (*LAQUEUS* SP.): IMPLICATIONS FOR THE FOSSIL RECORD AND THE FUTURE

J. P. Barry; K. Buck; E. F. Pane; C. Lovera; P. J. Whaling; C. Tanner
MBARI, Moss Landing, CA, United States.



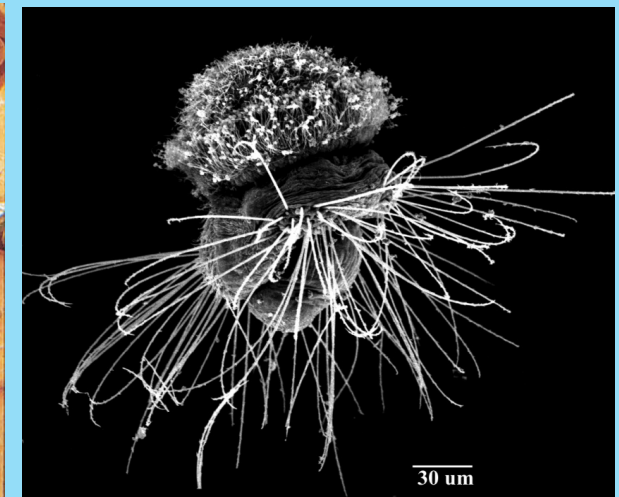
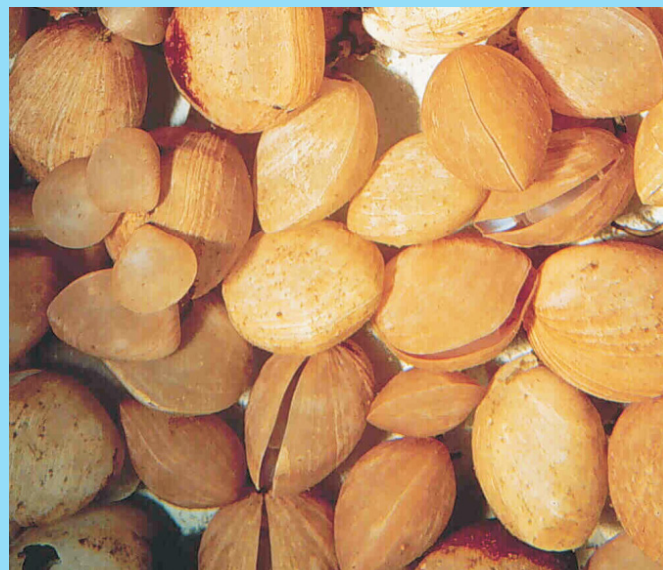
Laqueus californianus



Morphology

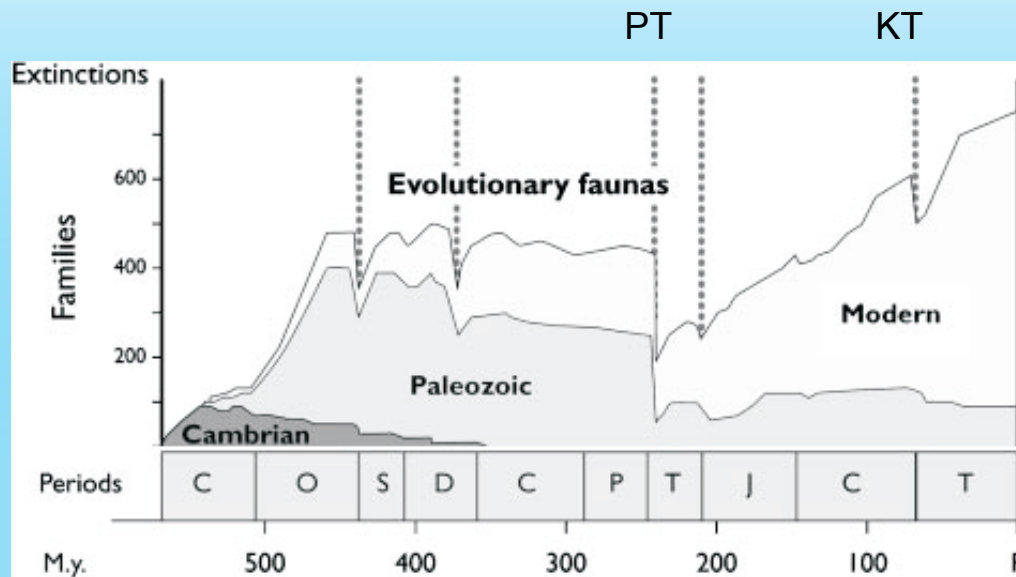


Continental Shelf aggregation



Pennington et al. 1999

Mass Extinctions and Brachiopods

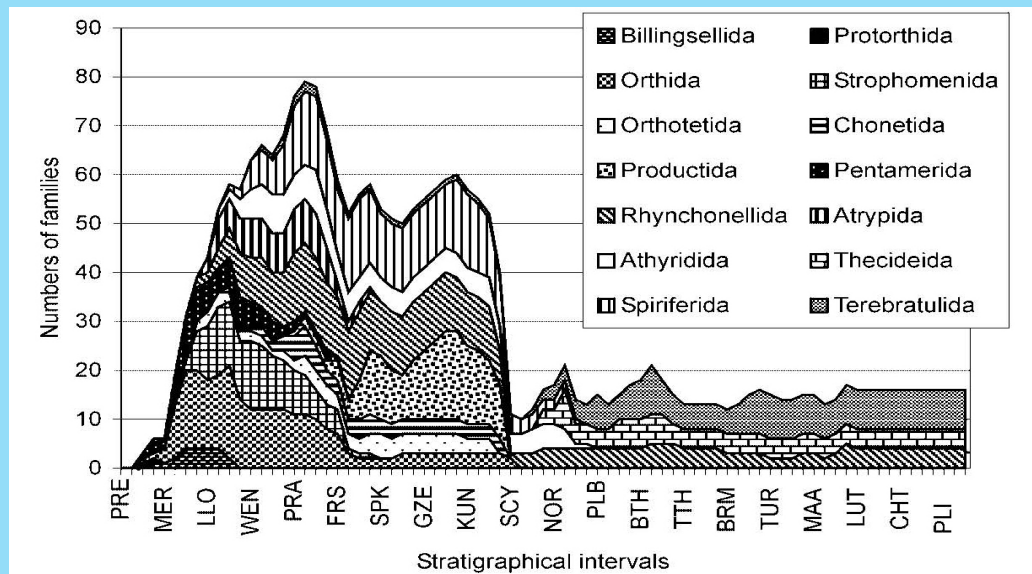


Permian – Triassic Boundary (~250 mya)

- Siberian Traps volcanism
- ~85-95% extinction of marine life
- “Kill mechanisms (Knoll et al 2007)
 - Hypoxia / Anoxia
 - Ocean acidification
 - Hydrogen sulfide
 - Global warming
 - Productivity collapse

Brachiopoda

- 12,000+ fossil species
- High rates of extinction
- Survivors smaller, generalist taxa

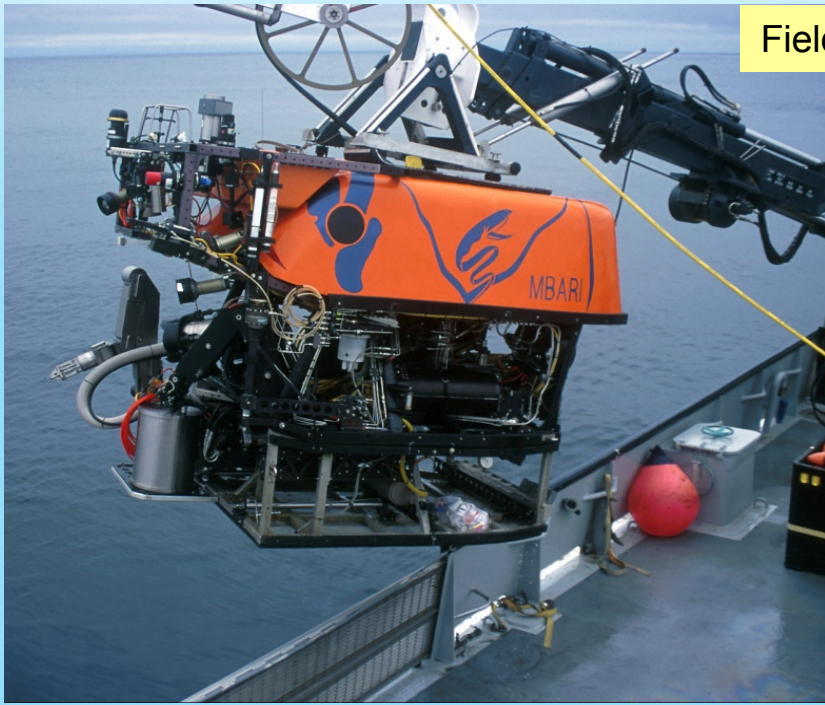


Harper & Jia-Yu (2001)

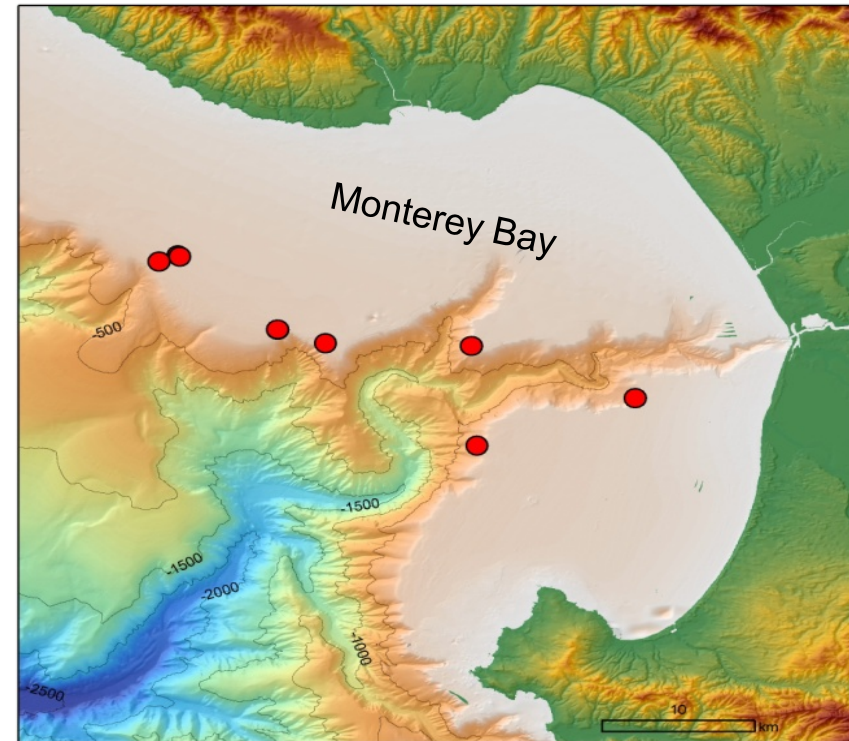
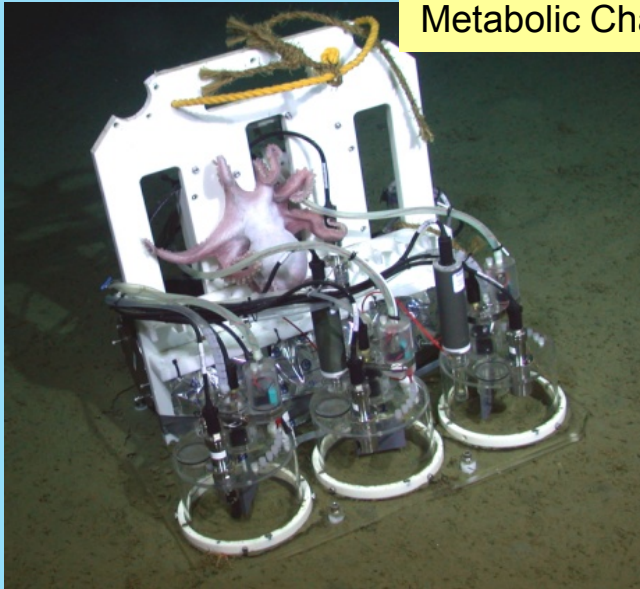
Are extant brachiopods
sensitive to OA stress?

Laqueus californianus Studies

Field Collections

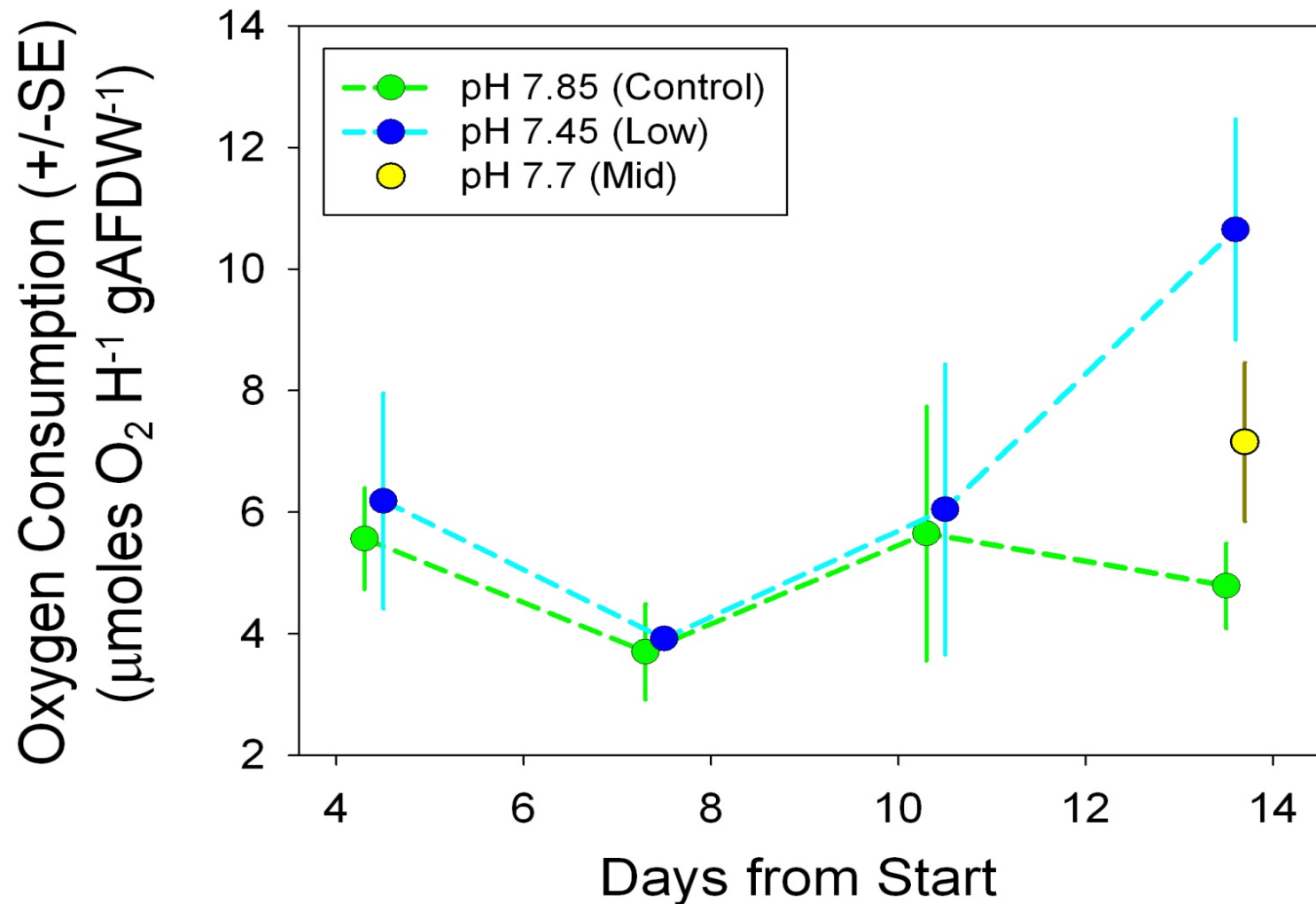


Metabolic Chambers

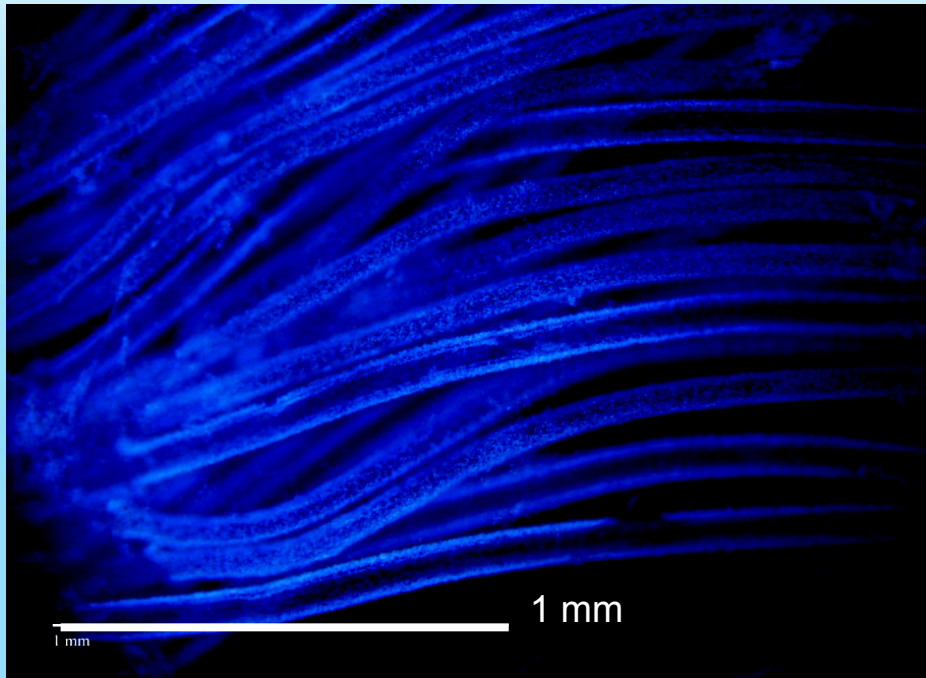


Metabolic Rate Measurements

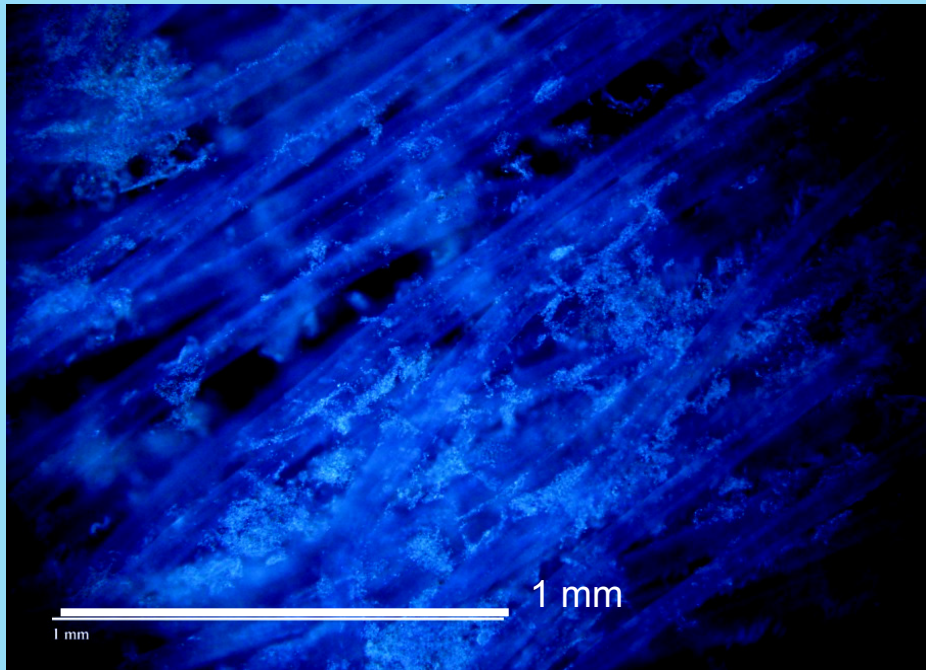
- High survival, apparently good health for most animals
- No effect of pH on metabolic rate until day 14
 - Increase in O₂ consumption with low pH
- 4 days acclimation



Microbial Fouling of Lophophore



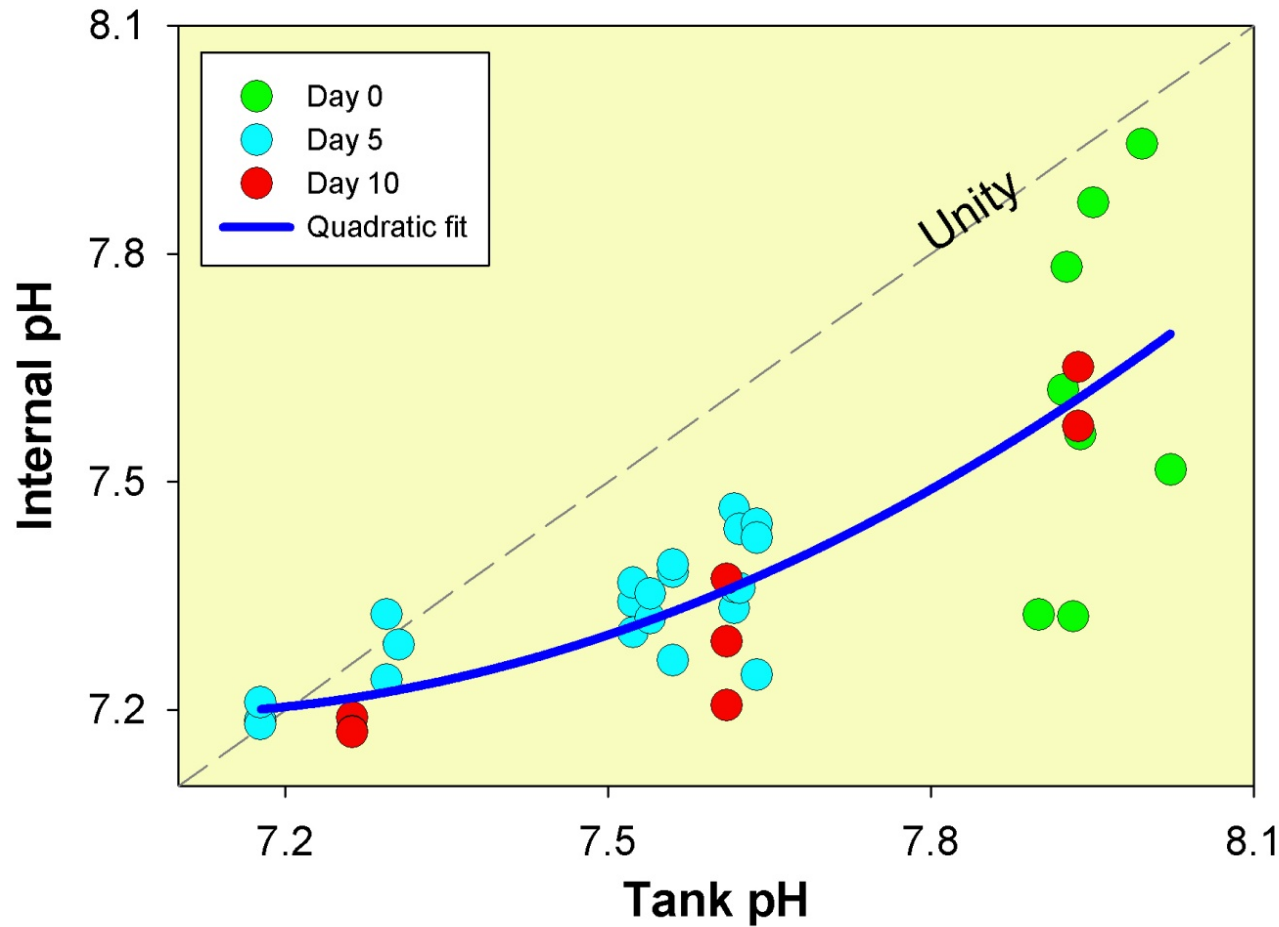
- **Healthy animal**
 - thin microbial film on tentacles
 - no shedding of tentacles



- **Unhealthy brachiopod**
 - high microbial load on tentacles
 - degraded tentacles, shedding



Acid-Base Balance



- Normal pH poise ~0.2 – 0.3 units below ambient
- Become isoprotic with SW near pH=7.2

Unhealthy animals?

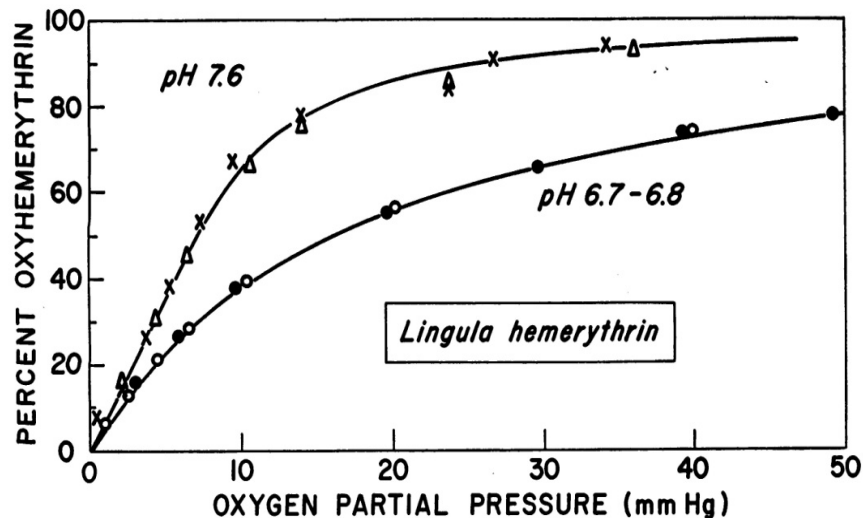
Metabolic Consequences of poor ion-regulatory control

- **Ion Regulation possible, but costly**
 - Increased metabolic cost of pH compensation +

- **Ion Regulation ineffective**
 - Metabolic depression?
 - Respiratory stress
 - Ineffective enzyme function
 - Metabolic inefficiency

- Growth
- Aerobic scope
- Reproduction
- Survival

Manwell 1960
Brachiopod hemerythrin (Bohr Effect)



- Population dynamics
- Extinction?
- Community interactions

Implications for Brachiopod Fossil Record and Future

Fossil Record – PT boundary (high pCO₂, low O₂, low productivity)

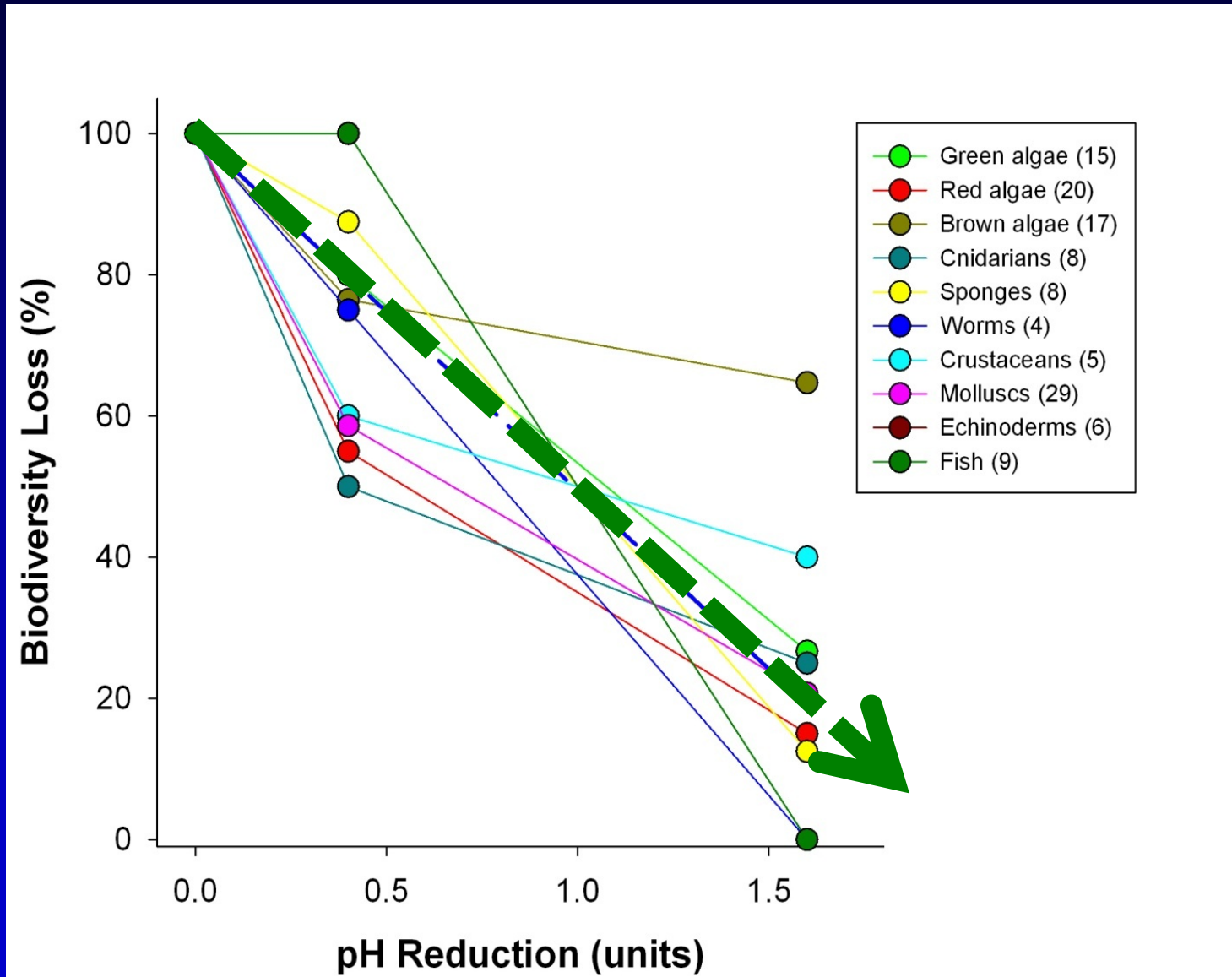
- **Lack of ion-regulatory control probably caused severe problems for many brachiopods**
 - Acid-base disruption, weaker gas exchange capacity
 - Respiratory stress
 - Reduced activity?
- **Multiple stressors (hypoxia, low food availability)**
 - Respiratory stress would cause severe problems (pO_{2(atm)} dropped from 35% to 15%)
 - Reduced food for specialists vs. generalist

Future Ocean Acidification

- pH, pCO₂ levels used correspond to likely future scenarios
- Results suggest that brachiopods may have acid-base problems in future
- **But:**
 - They already live in a highly variable environment
 - Acclimation? Adaptation?

Biodiversity is reduced in natural CO₂ vents

51 percent reduction in species richness per 1 pH unit



Data from Hall-Spencer et al. 2008

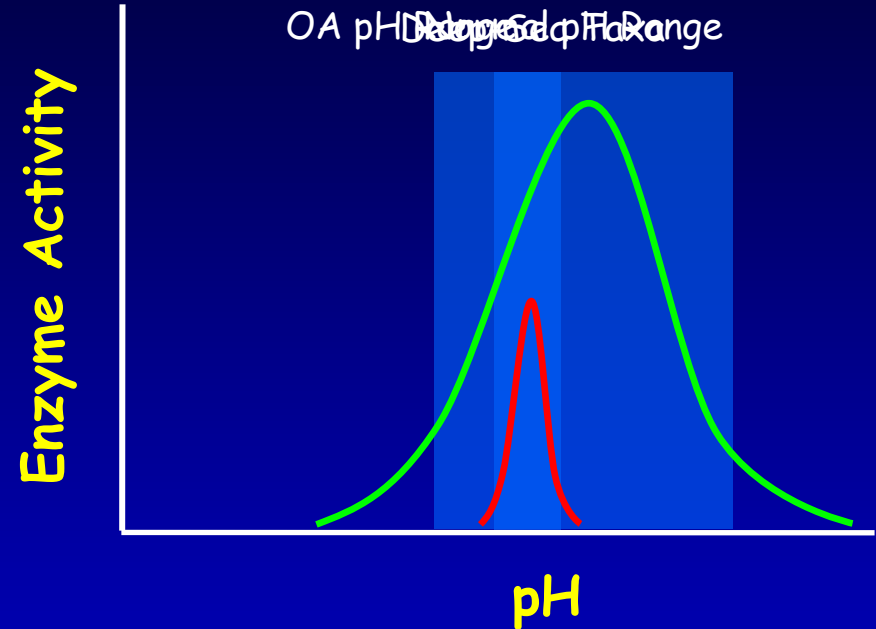
Acid-base disruption affects enzyme activity

Consequences?

- Reduced enzyme activity under OA

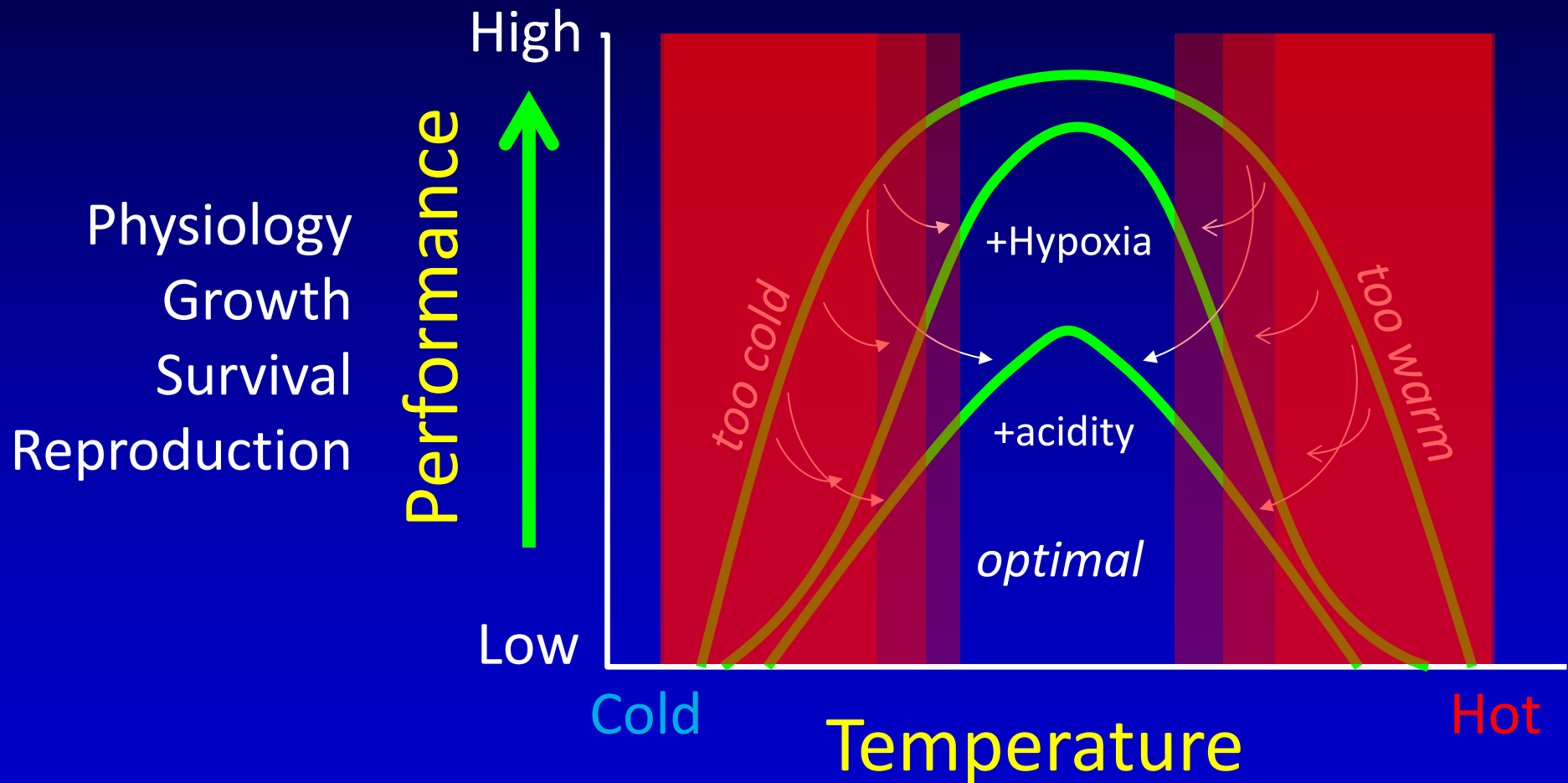
Deep-Sea Taxa

- Narrower optimal pH range?
- Lower enzyme activity in general
- More severe OA stress for deep taxa



Stress affects animal performance

Multiple stressors can interact to affect animal performance

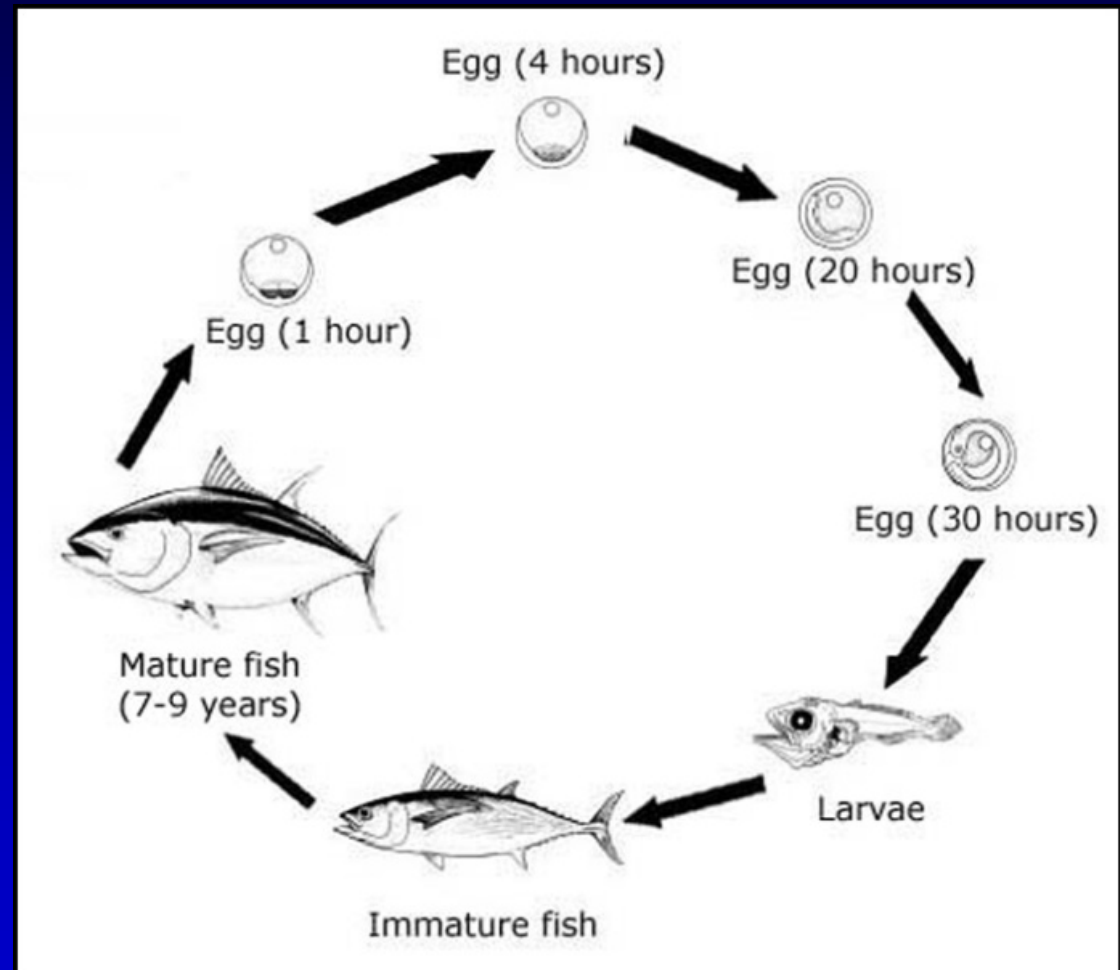


Effects on different life stages

Stage: **Duration:** **Sensitivity:**

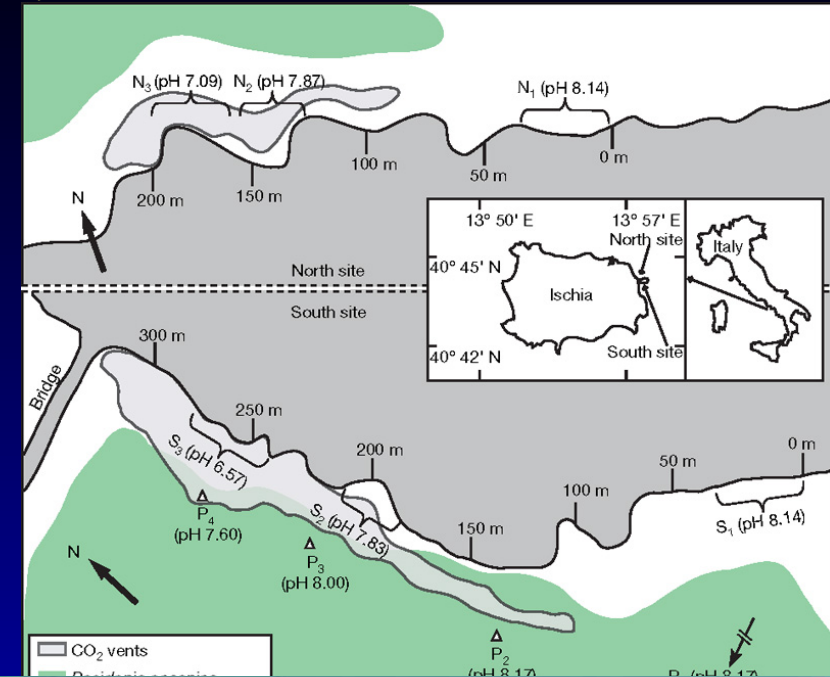
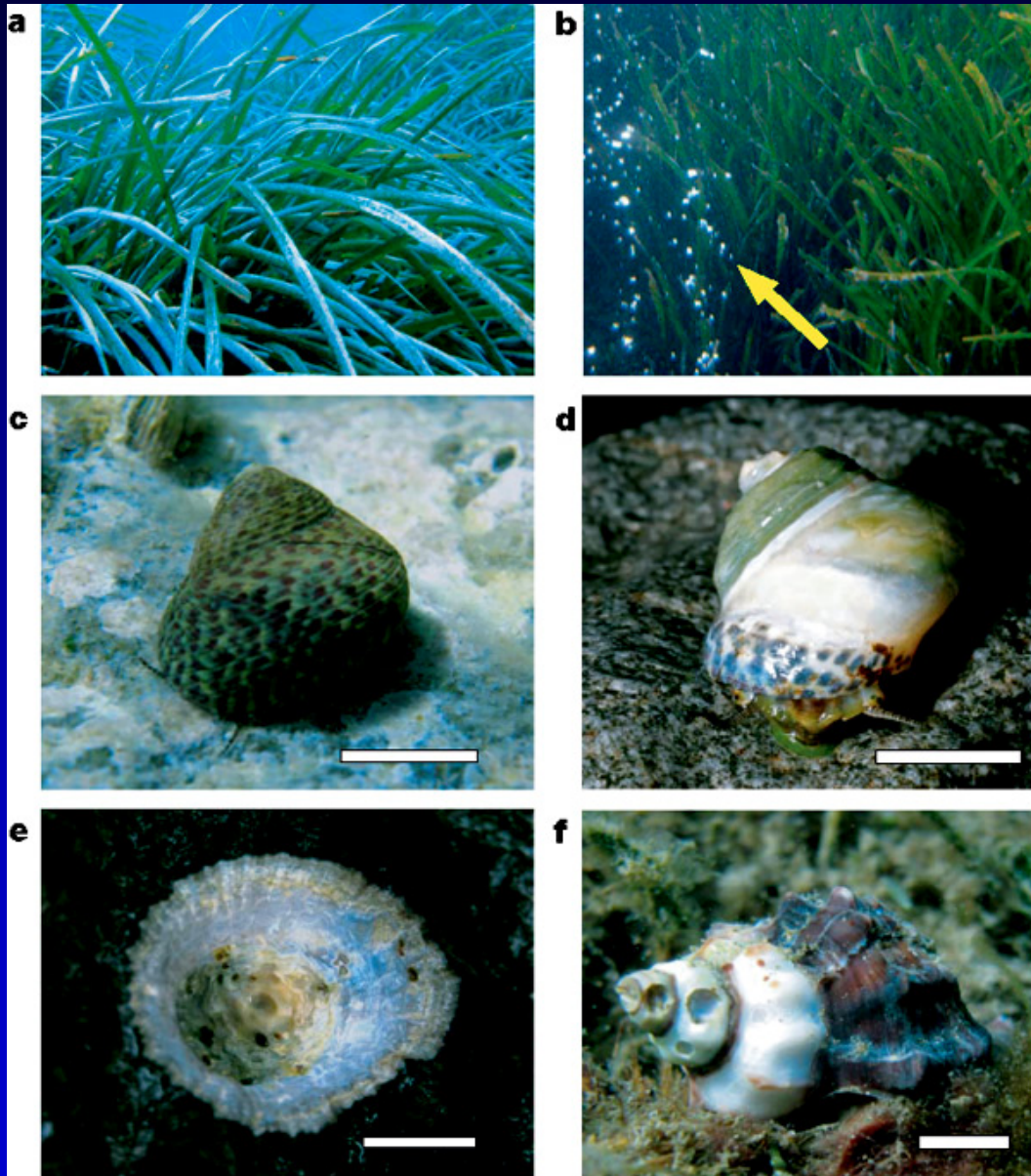
Fertilization	Seconds	High?
Embryo	Hours - Days	High?
Larva	Days - Months	Mod. - High?
Juvenile	Mo. - Yr.	Moderate?
Adult	Yr. - Cent.	Low - Mod.?

Tuna Life Cycle

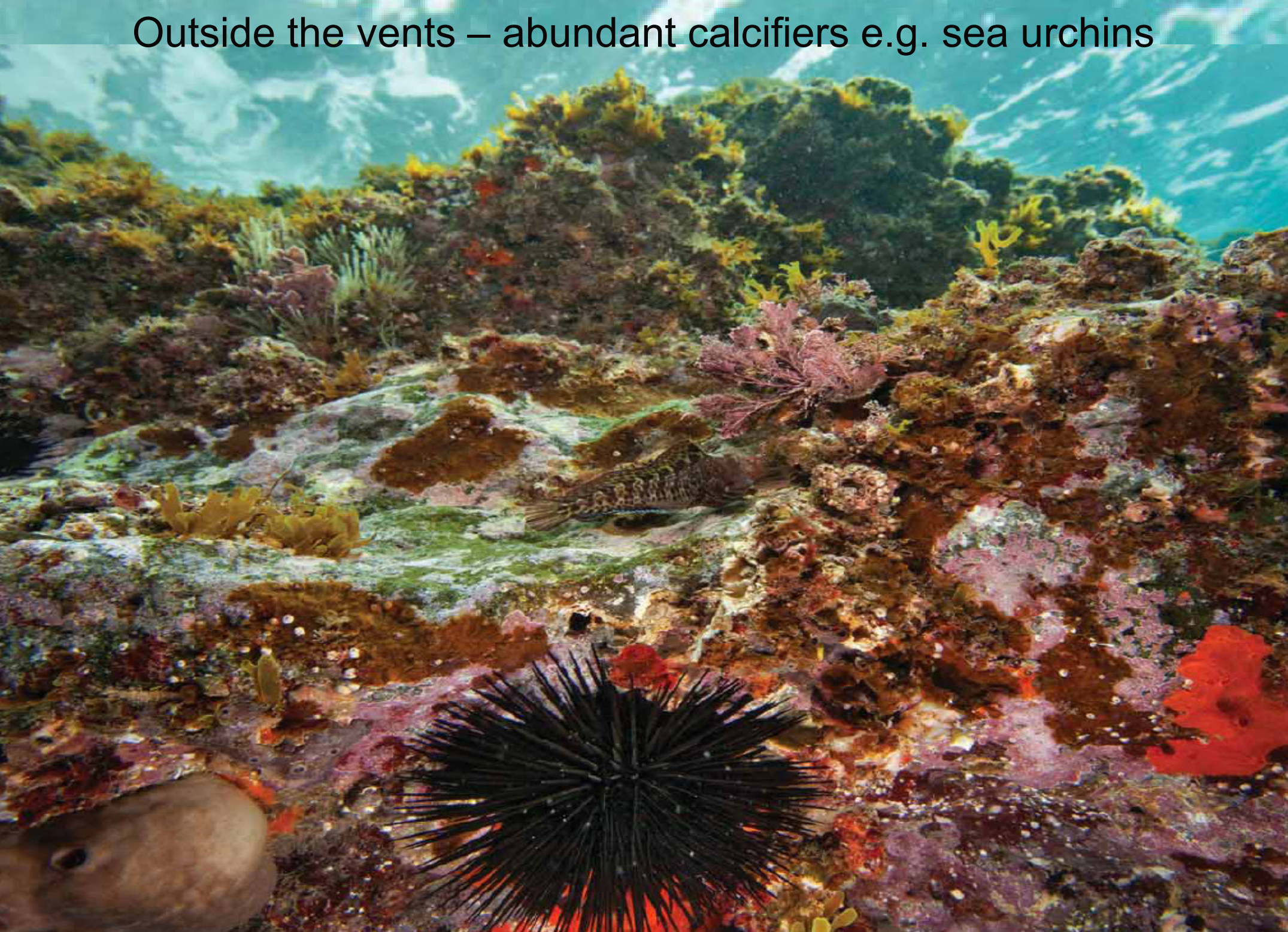


Field Survey of Natural CO₂ Venting Sites in Italy

- Echinoderms conspicuously absent, shell dissolution
- Seagrasses thrive



Outside the vents – abundant calcifiers e.g. sea urchins

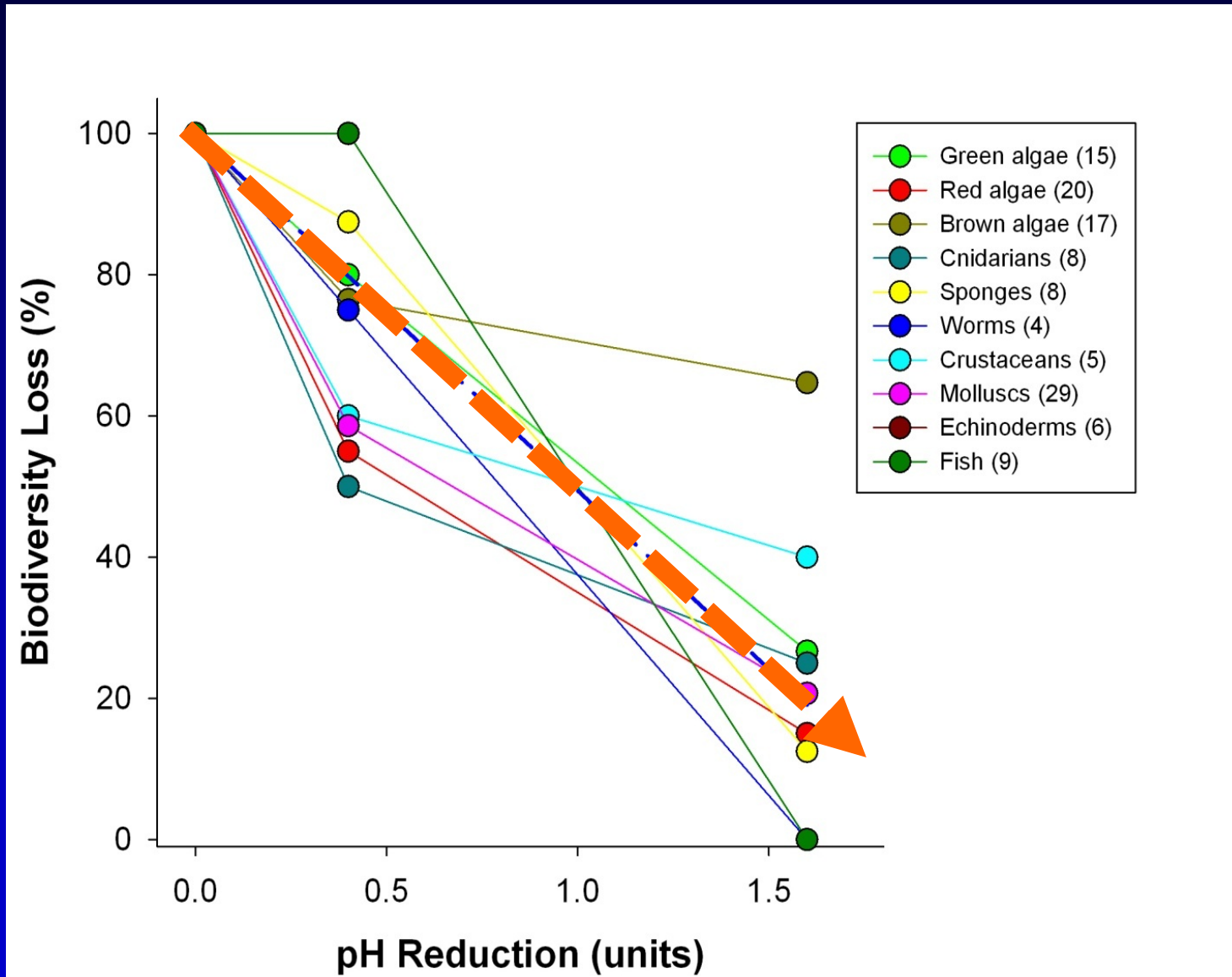


At high CO₂ there are almost no calcifiers, fleshy algae and invasive species dominate

250 taxa now examined including macroalgae (Porzio in press, JEMBE) , seagrasses, foraminifera, sponges, nematodes, polychaetes, molluscs, crustaceans, chaetognaths, bryozoans.

Biodiversity is reduced in natural CO₂ vents

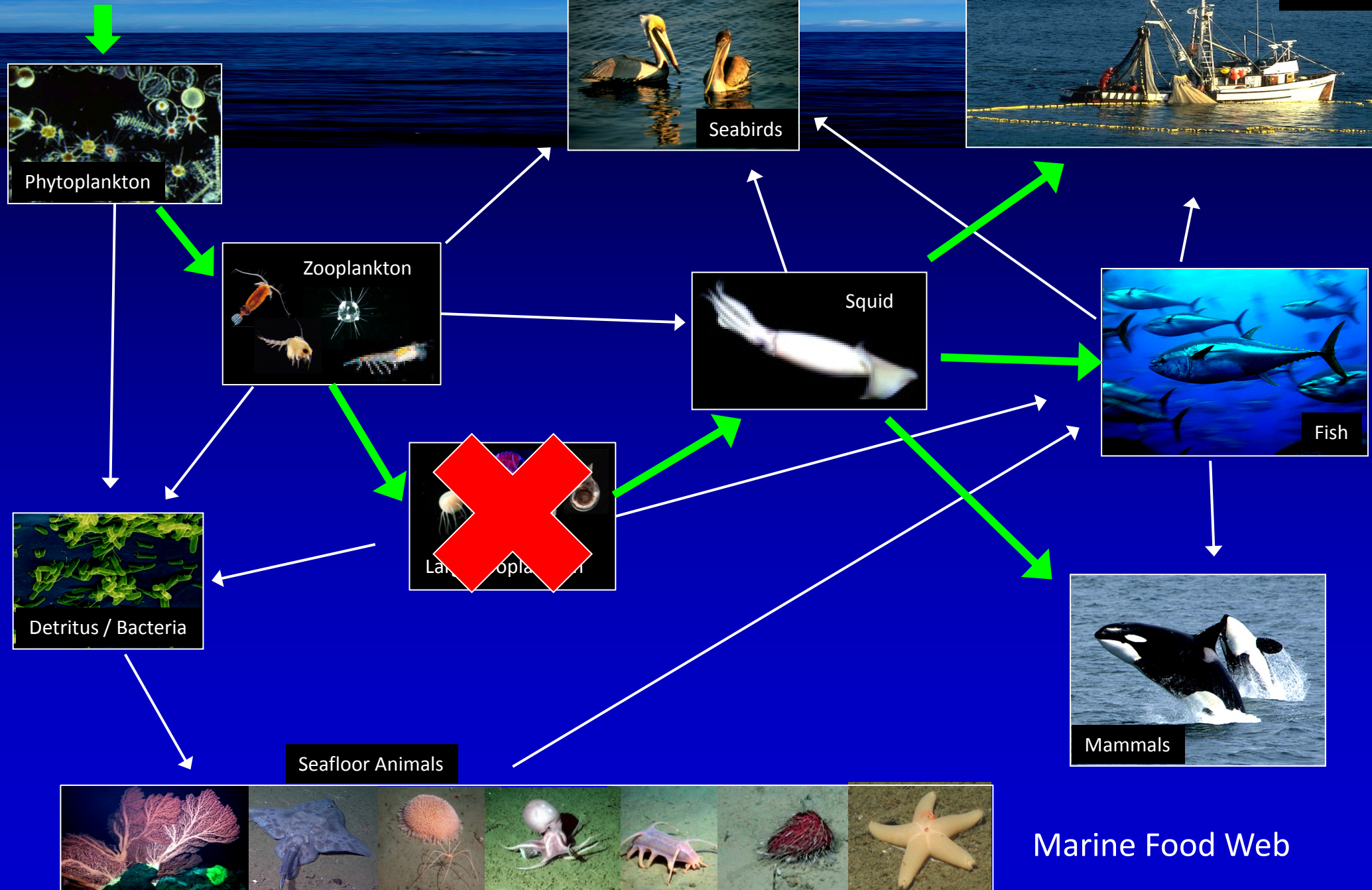
51 percent reduction in species richness per 1 pH unit



Modified from Barry et al. 2011

Marine Communities are Biological Networks

Primary Production



Effects of Ocean Acidification on Ocean Food Webs

Ocean Acidification:

- Reduced shell formation in pteropods
- Reduced growth & survival of pteropods

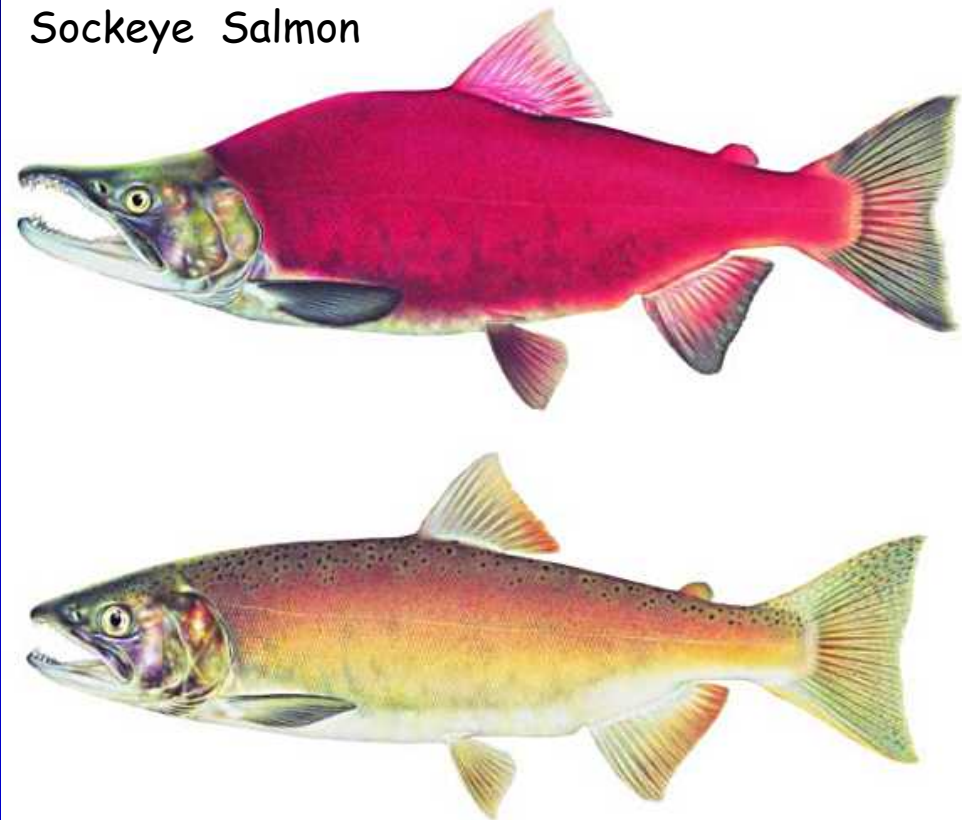
Disruption of Salmon Food Web

Cascading effects for higher predators (mammals, humans)

Pteropod = Salmon food



Sockeye Salmon



Summary

What we know:

- OA can cause physiological stress
 - More severe for taxa with;
 - low metabolic rates
 - limited respiratory capacity
 - deep-sea taxa
- Variation in sensitivity among taxa (winners and losers)
- Calcification is most consistent and widespread impact
- Acid-base disruption can affect overall cellular function
- Reduced physiological function leads to reduced performance

What we expect:

- Food webs will be affected
- Ecosystem services (e.g. fisheries) will change

What we don't know:

- Long term (i.e. lifelong) effects
- Developmental bottlenecks, cumulative impacts
- Capacity for acclimation and adaptation
- Interaction with other environmental changes (warming, pollution)
- Effects on marine communities, ecosystems - tipping points?

Society has choices for adaptation to a changing ocean

- Ocean change is a problem for society
- Food and energy needs for society linked to ocean health
- How to balance ocean health and societal demands?
- Can we avoid ocean tipping points?
- Early action reduces severity of impacts



**Ecosystem
impacts**

**Ecosystem
Services**

Past

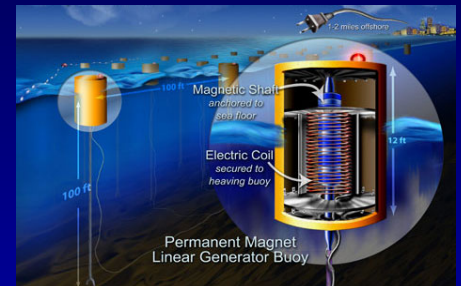
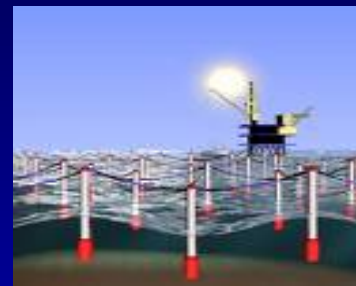
Future

Reasons for Hope?

High-efficiency cars and trucks



Wave and Tidal Energy



Photovoltaic Energy (Solar)



Wind Power





Value the Oceans

