Ecological impacts of ocean acidification: A prospective synopsis

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Scope of discussion

- Studies of OA growing exponentially
  - Ecological and “systems” connections play out differently in different ecosystems
  - Many ways to partition recent and ongoing work
- Fundamental advances in marine ecological theory have mostly occurred via shoreline studies
  - Keystone and foundation species (Paine, Dayton)
  - Intermediate disturbance and diversity (Connell)
  - Stress gradient (Menge & Sutherland)
  - Succession (Sousa), facilitation (Bertness & Calloway), etc.
- Also important insights from open-ocean studies
  - Often tied more tightly to microbial, biogeochemical processes (subject for tomorrow)

Focus mostly on benthic shoreline systems

Not an exhaustive overview

OA influences ecology at multiple levels

- Individual ecology
  - Organism interactions with the environment

- Population ecology
  - Demographic rates
  - Changes in abundance/distribution

- Community/ecosystem
  - Species interactions
  - Trophic relationships

Scaffold for considering population responses

Population dynamics at their simplest

$$N_{t+1} = N_t + B - D + I - E$$

- Physiological studies have provided insights into impacts on demographic rates
  - Increases or declines in reproduction, mortality
- But have been connected less well to population consequences
  - Some formal population models starting to be developed

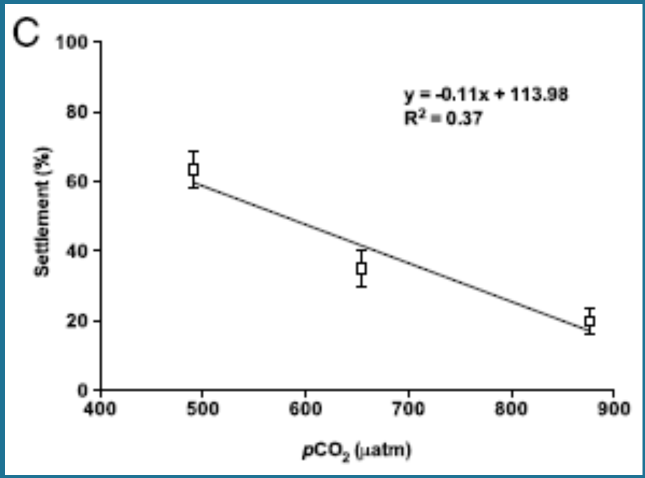
Ecology, 91(10), 2010, pp. 2931–2940

Can ocean acidification affect population dynamics of the barnacle *Semibalanus balanoides* at its southern range edge?

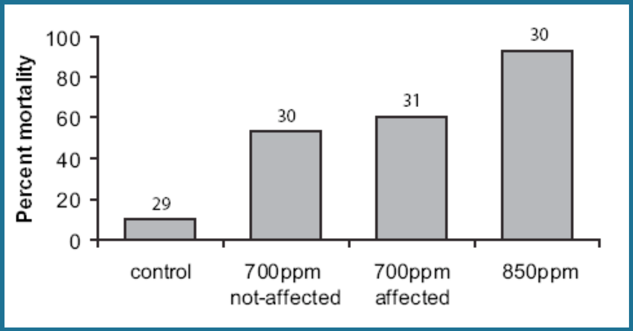
Helen S. Findlay,[1,4] Michael T. Burrows,[2] Michael A. Kendall,[1] John I. Spicer,[3] and Stephen Widdicombe[1]

Biggest challenge for population models may be accounting for effects on immigration and emigration

- Majority of marine species have complex life cycles
- Dispersal is usually accomplished via larval stage
- Starting to understand impacts on larvae in some groups
  - Altered recruitment success
  - Increased vulnerability to predation



Albright et al. 2010



Munday et al. 2010

Quantifying all demographic parameters requires completing the life cycle

- Susceptibility to OA can differ across stages
  - Larval, juvenile, adult
  - Different habitats
  - Different response to stressors

- Complete studies are emerging; more required

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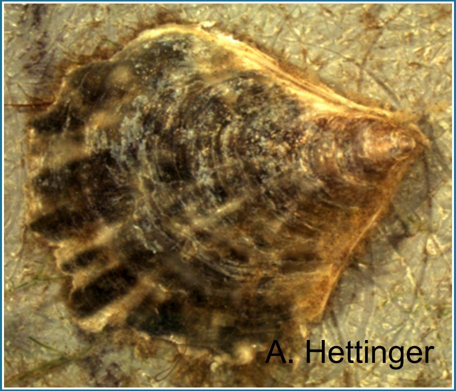
Effects of ocean acidification over the life history of the barnacle *Amphibalanus amphitrite*

Michelle R. McDonald[1], James B. McClintock[1,*], Charles D. Amsler[1], Dan Rittschof[2], Robert A. Angus[1], Beatriz Orihuela[2], Kay Lutostanski[2]

Further complexity: Multiple life stages can be connected

- Larval carryover effects
  - Effects of larval exposure persist to influence later life stages
  - E.g., west coast native oysters
    - Larvae exhibit modest (order 10%) declines in growth under OA
    - Effect gets magnified in juveniles. Individuals exposed only as larvae show 40% reductions in growth after settlement (Hettinger et al. in review)
  - Note that if conducted only larval and juvenile exposures independently, would have missed such effects

Ostrea lurida veliger

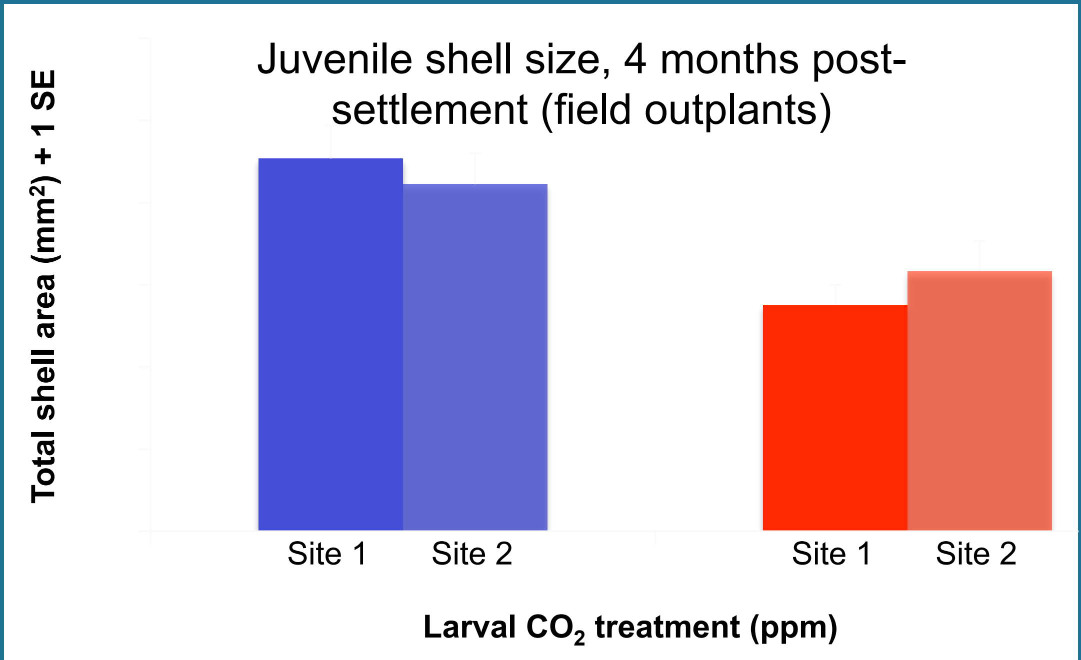


Ostrea lurida juvenile

Effects can persist long after exposure ends

- Oysters exposed to OA only as larvae still smaller, 4 months after settlement
  - Half-way to reproductive age
  - Size often influences fecundity
  - Impacts on production rates of subsequent generation?

Ostrea lurida juvenile



Hettinger et al. unpubl.

Population impacts – good progress, more to do

$$N_{t+1} = N_t + B - D + I - E$$

- We have a start at defining effects on demographic parameters
  - Reproduction and survivorship → fitness
  - Less known about implications for organism dispersal → population connectivity
  - Links among life stages can be important
- Greater effort required to make explicit ties to population-level issues
  - Lots of physiological experiments
  - Infrequently considered within population framework

OA influences ecology at multiple levels

- Individual ecology

- Population ecology

- <u>Community/ecosystem</u>

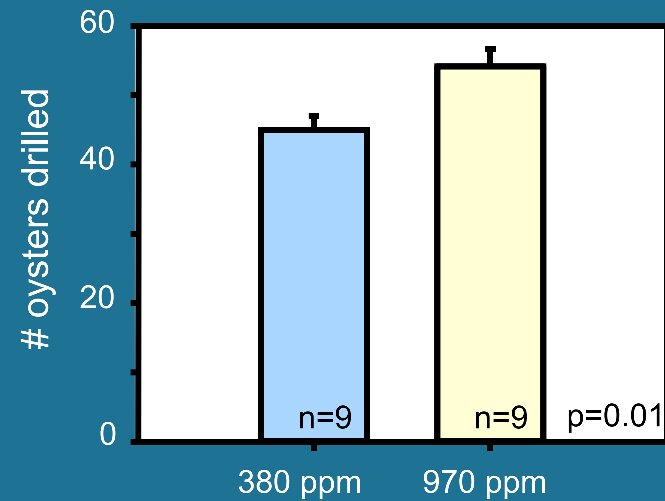
Focal areas for assessing community responses to OA

- Species interactions
  - Direct and indirect
- Consequences for critical players
  - Foundation and keystone species
- Community-wide and ecosystem-level effects
  - Natural experiments (CO_2 seeps)
  - Broad “bottom-up” impacts

All operating under multiple scales of environmental variation

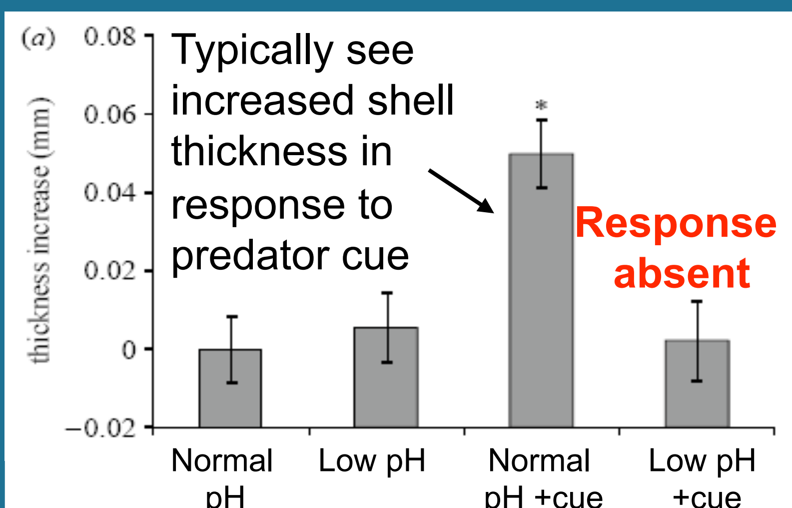
Species interactions – sparse but emerging examples

- Direct effects of predation – Consumption of oysters by drilling snails



Sanford et al. unpubl.

- Indirect effects – Inducible defenses via olfactory cues



Bibby et al. 2007

Littorina littorea

Carcinus maenas

- Less work on competitive relationships
- Some attention to facilitative interactions (OA amelioration by primary producers)

Impacts on foundation species

- Corals

- Mussels

- Seagrasses

- Oysters

…and keystone species

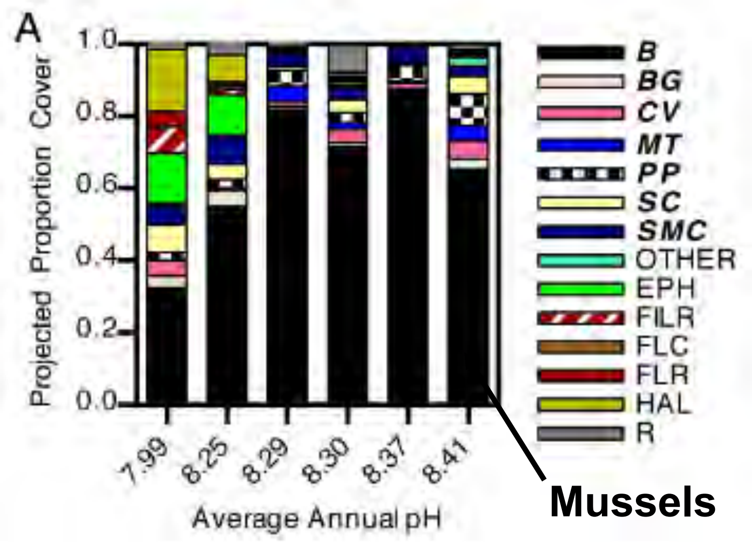
- Seastars

Understanding ecological impacts can require moving beyond simple assays

- California mussels are major space occupiers; also provide food and refuge for many species

- Field/modeling data suggest vulnerability to low pH

Mytilus californianus



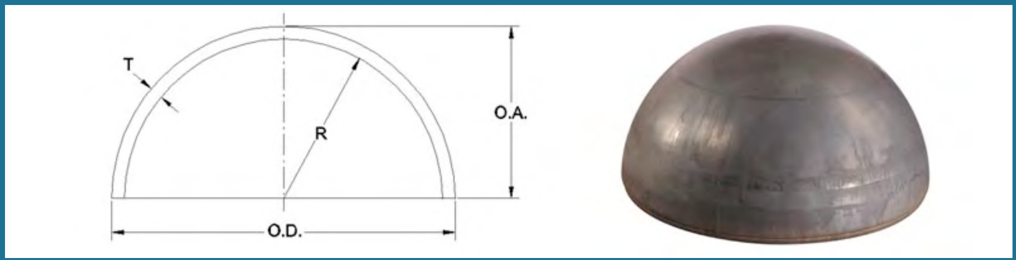
Wootton et al. 2008

- Knowledge of mechanisms can provide further insights
  - Multiple possible origins for pattern
  - What approach to use?

Where are the declines in ecological function?

- Many organisms grow slower, die at faster rate, or reproduce less
  - Fairly general responses
  - Could contribute to declines in mussel cover
- Reduced calcification is also common in molluscs
  - Shells often smaller and/or thinner
  - Thinner shells could be weaker → functional costs

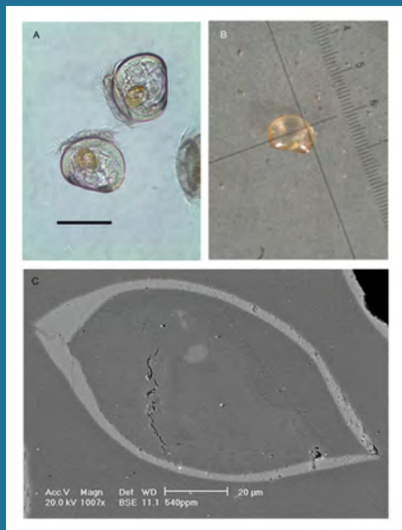
- But are they weaker? (data gap in calcification work)
  - Morphological plasticity could obscure outcome



Important to test assumed consequences

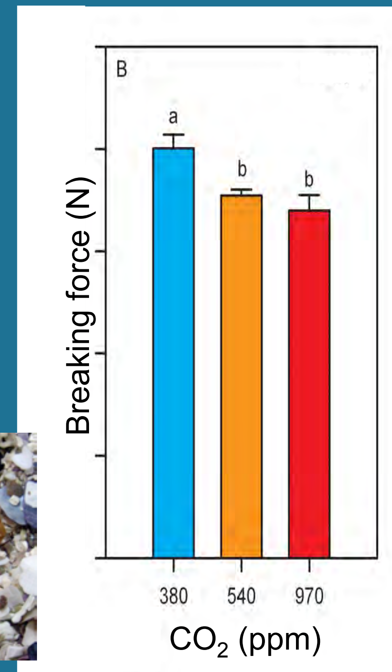
Loss of function – with ecological repercussions

Mytilus californianus larvae



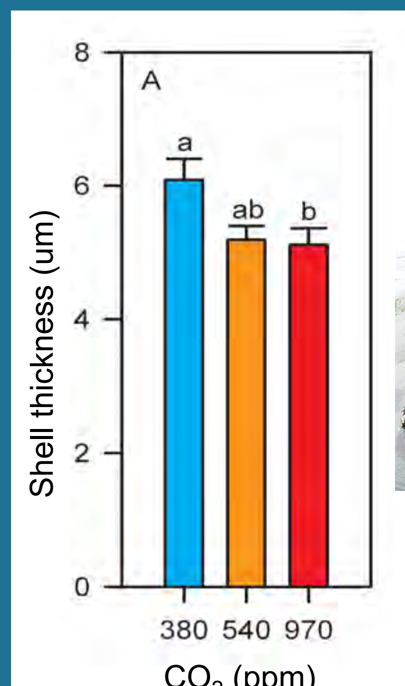
Larval shells weakened by OA

- Mussel larvae retain shells upon settlement
- More vulnerable to crushing predators like crabs



They also become thinner

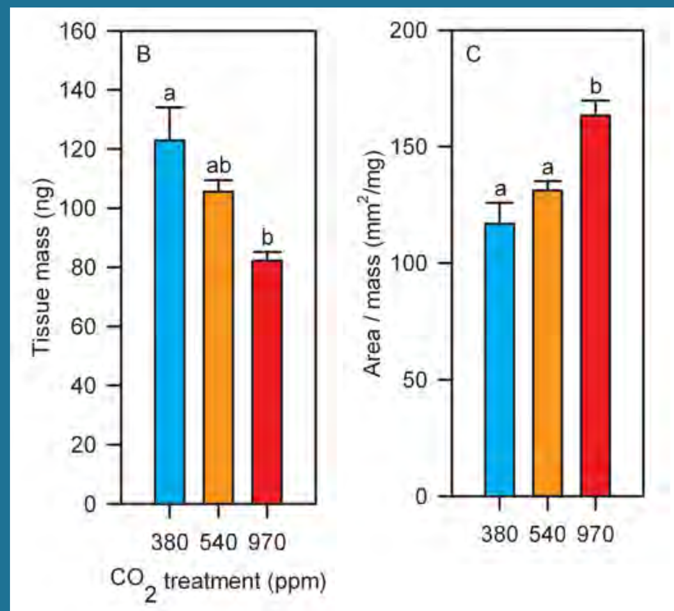
- More susceptible to drilling attacks by carnivorous snails



Gaylord et al. 2011

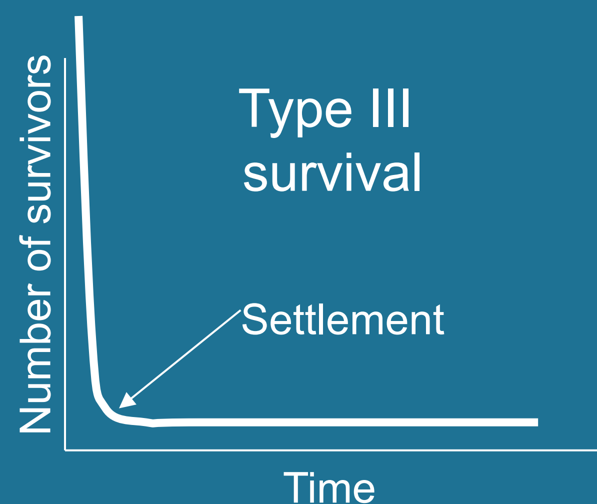
Also increases vulnerability to energetic and desiccation stresses

- Less tissue mass
  - Fewer energy stores for metamorphosis



- Greater ratio of surface area to mass
  - Dry out faster

Example of OA-imposed costs at a major constriction in the life cycle



Not all foundation or keystone species will be negatively impacted

- Seagrasses – there will be winners too
  (Palacios and Zimmerman 2007)

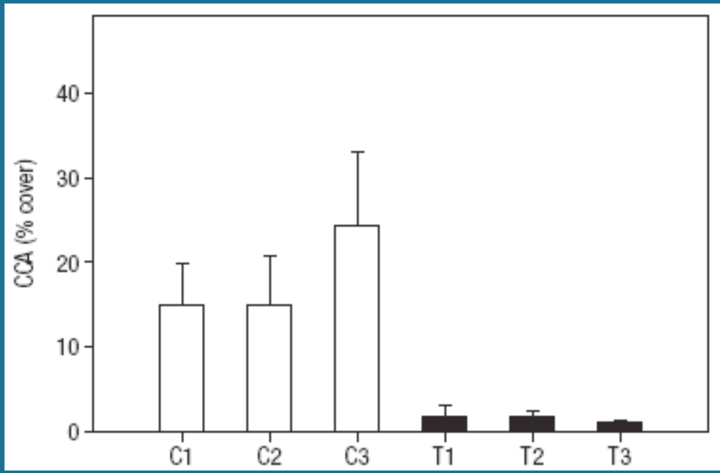
- Could reduced vulnerability of foundation species improve overall community resilience?

- Important to maintain recognition that even positive impacts on one species can still induce community change

Implicit motivation is to resolve weak links that might cause cascading community effects

- Demonstrated OA impacts on corals themselves – variety of studies

- Also are effects on crustose coralline algae
  - Framework and cementing organisms for coral reefs
  - Facilitate recruitment in other systems

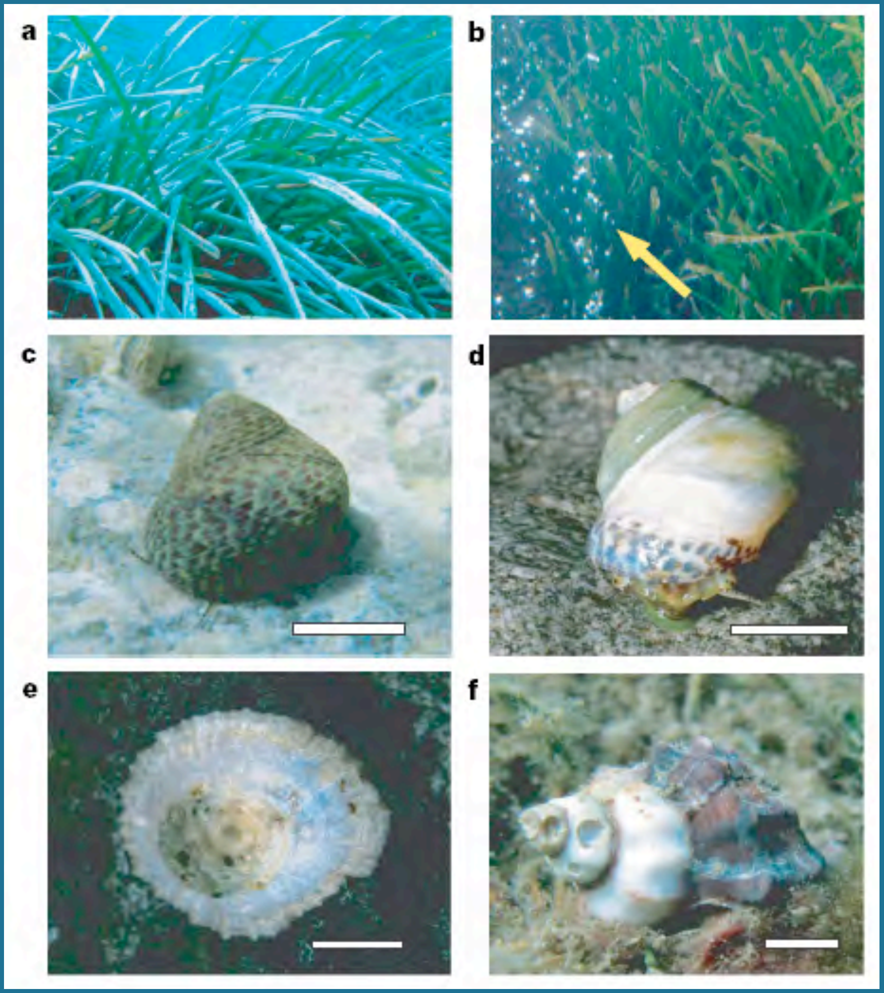


Kuffner et al. 2008

Another thrust: Whole-community responses using "natural experiments"

Ischia, Italy – geologic CO_2 vents

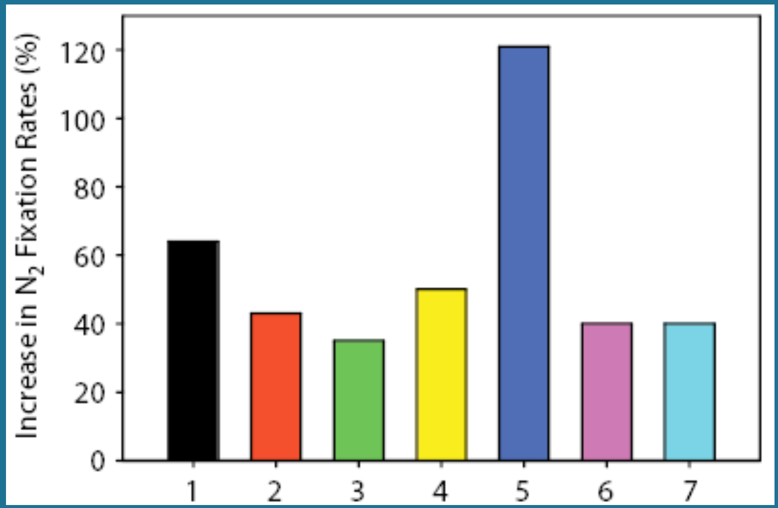
- Declines in calcifiers
  - Corals, urchins, coralline algae
- Higher seagrass production
- Some important omissions
  - E.g., larval inputs



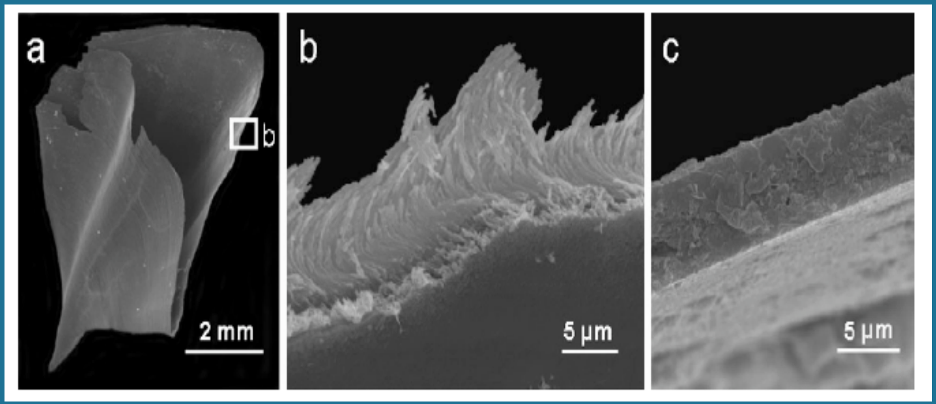
Hall-Spencer et al. 2008

Yet another target area: Broad bottom-up responses

- Impacts on key players in biogeochemical cycling
  - Cyanobacteria (*Trichodesmium*)
  - Responsible for 25-50% of nitrogen fixation in global oceans
  - Potential implications for "bottom up" processes
- Other food web examples
  - Pteropods, food resources for many fishes



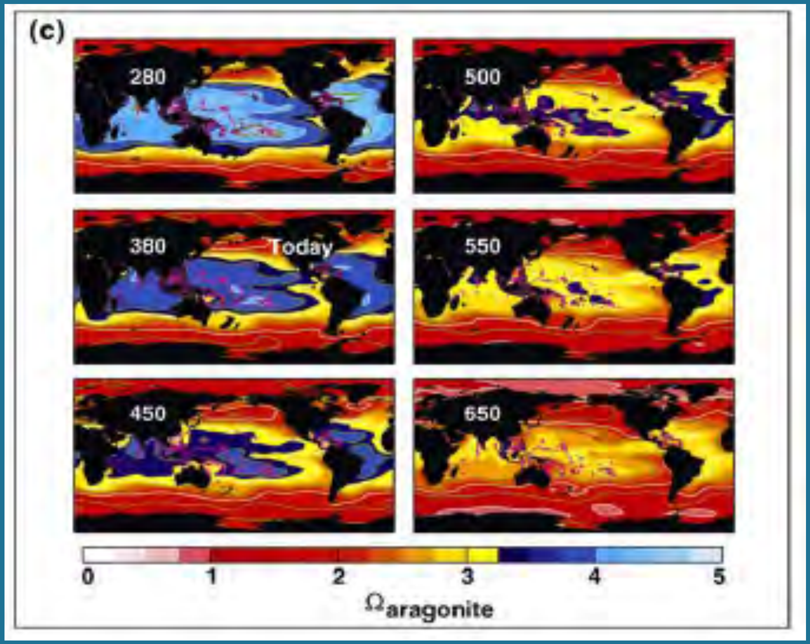
Hutchins et al. 2009



Orr et al. 2005

Environmental variation is characteristic

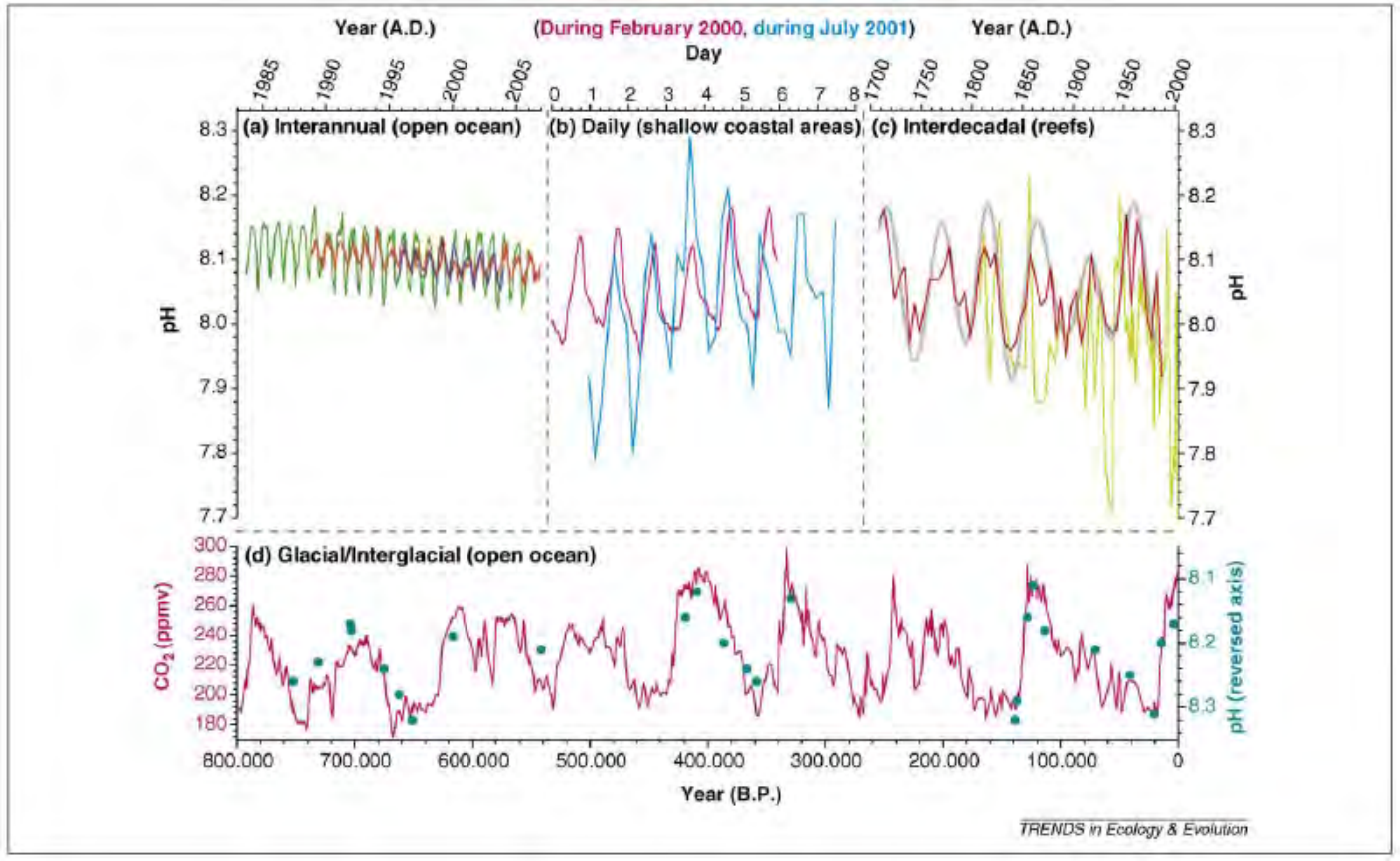
- Key element missing in most lab experiments is temporal fluctuation
  - Most studies heavily focused on IPCC projections
  - Organisms do not experience global means
  - Even if focus regionally, real world is not static



Pelejaro et al. 2010

Scales of variation

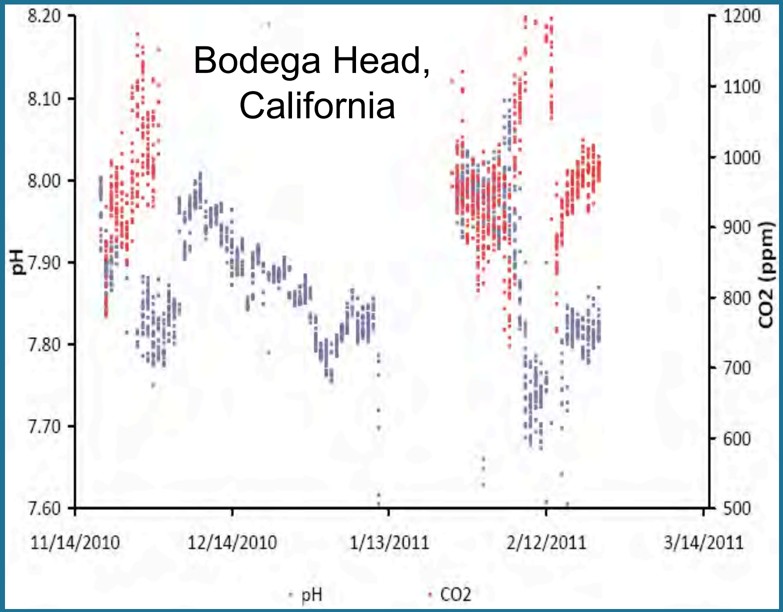
- Daily to decadal scales are relevant for ecology of populations and communities – raises issue of acclimation potential
- Often longer scales for evolution – adaptation becomes key question



Pelejaro et al. 2010

Variation differs across ecosystems

- Tropics
  - More constant seasonally, slower chemical responses to anthropogenic CO_2
- Poles
  - Faster and more dramatic chemical changes
- Temperate upwelling
  - Large fluctuations over days/weeks
  - Response to synoptic winds – themselves shifting with climate change
- Estuaries
  - Exceptional variation due to freshwater input



Hill et al. unpubl.

Moving forward

- Work to understand population consequences
  - Complete the life cycle, account for all demographic parameters

- Extend beyond single-species lab experiments
  - Mesocosms (species interactions)
  - Field outplants (natural variation)

- Begin to account for multiple factors
  - Synergistic and nonlinear effects
  - Connections between physical/chemical/biological processes
  - Recognize environmental complexity

- Account for ecological-evolutionary connections

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