Assessing ocean acidification's effects on humans through ecosystem services

Sarah Cooley

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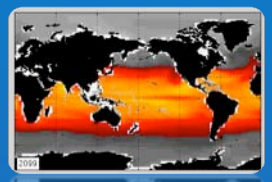
With thanks to: S. Doney, N. Lucey, H. Kite-Powell, R. Feely, I. Lima, A. Cohen, D. McCorkle

Photo: SpecialKRB via Flickr

Overview



- OA background and forecast

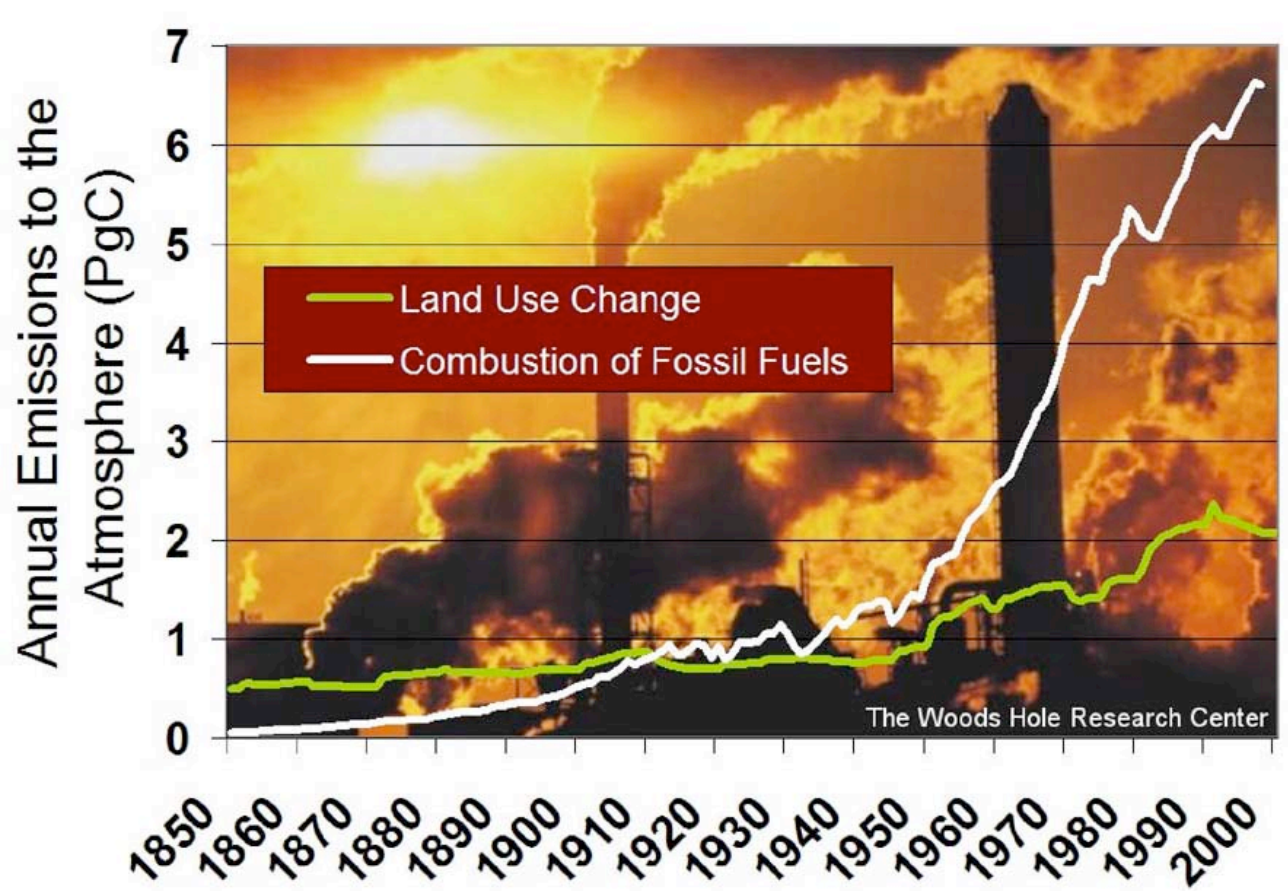
- Biological groups at risk

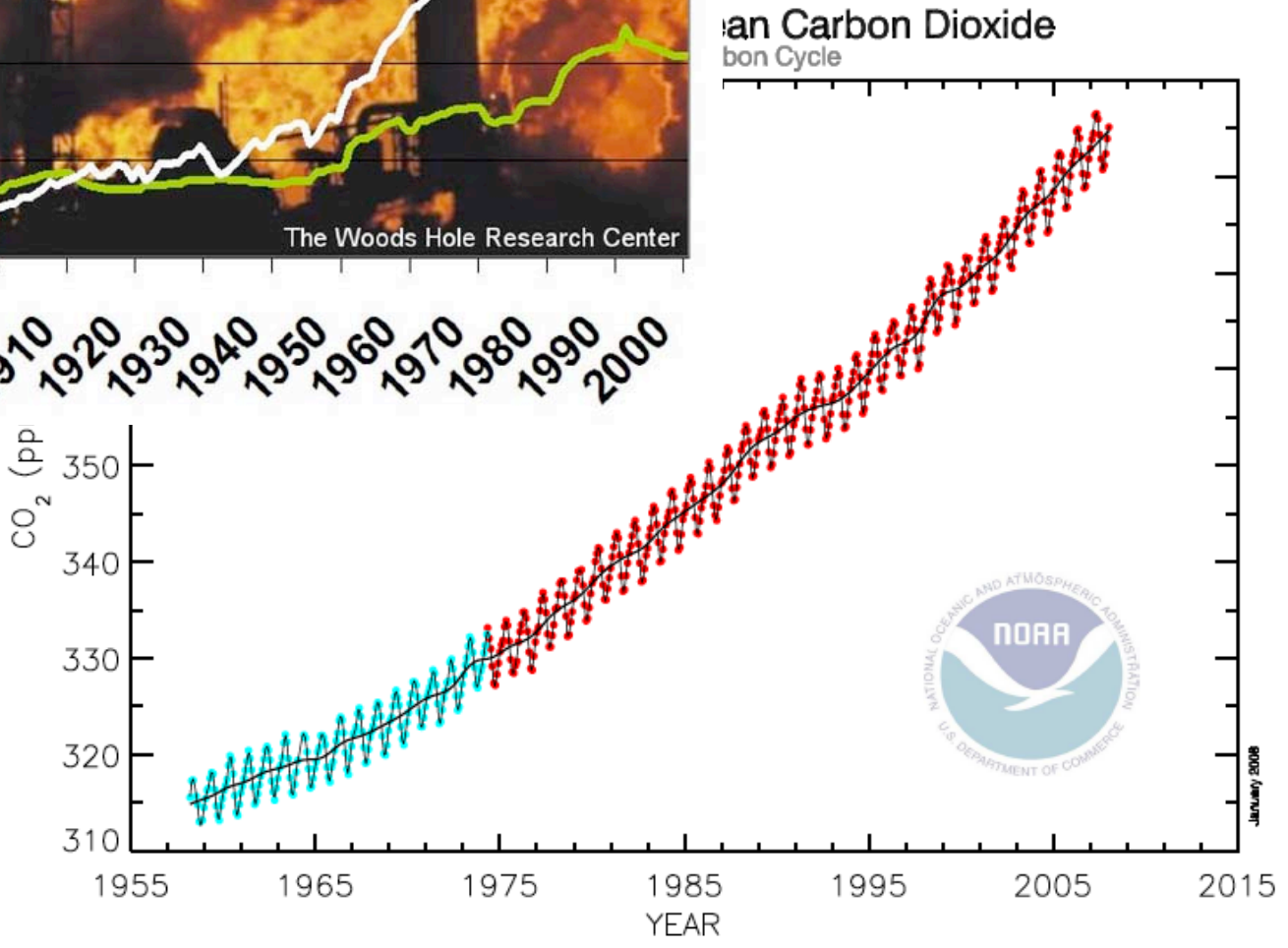
- Trickle-up socioeconomic effects

- Case studies

- Where next?

Rising Atmospheric Carbon Dioxide





Fate of Anthropogenic CO_2 (2000-2007)

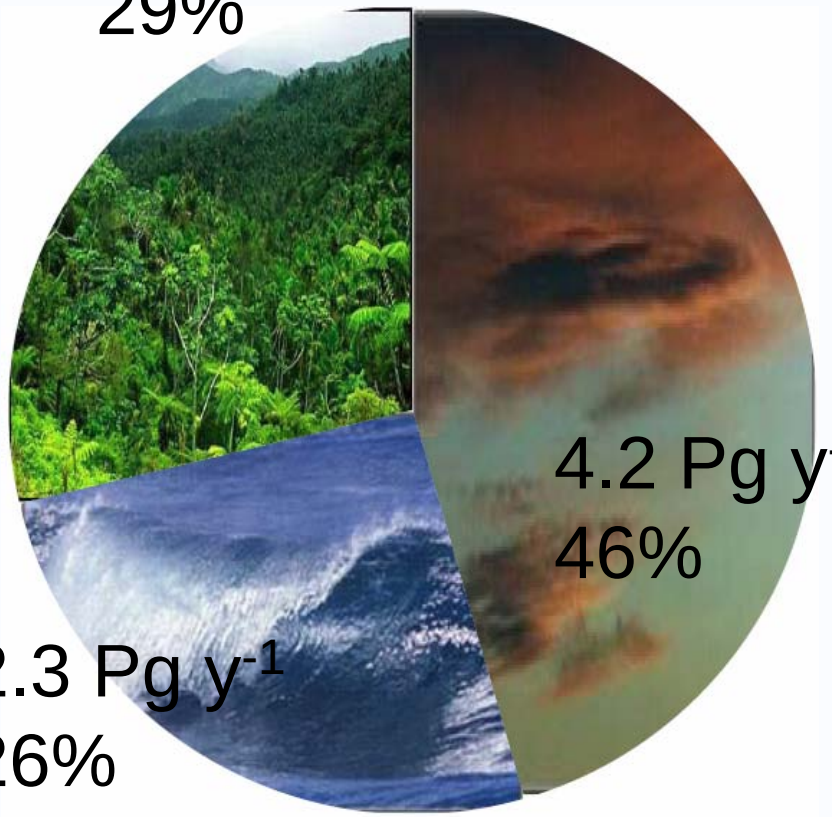
Sources

1.5 Pg C y^{-1}
17%

7.5 Pg C y^{-1}
83%

Sinks

2.6 Pg y^{-1}
29%

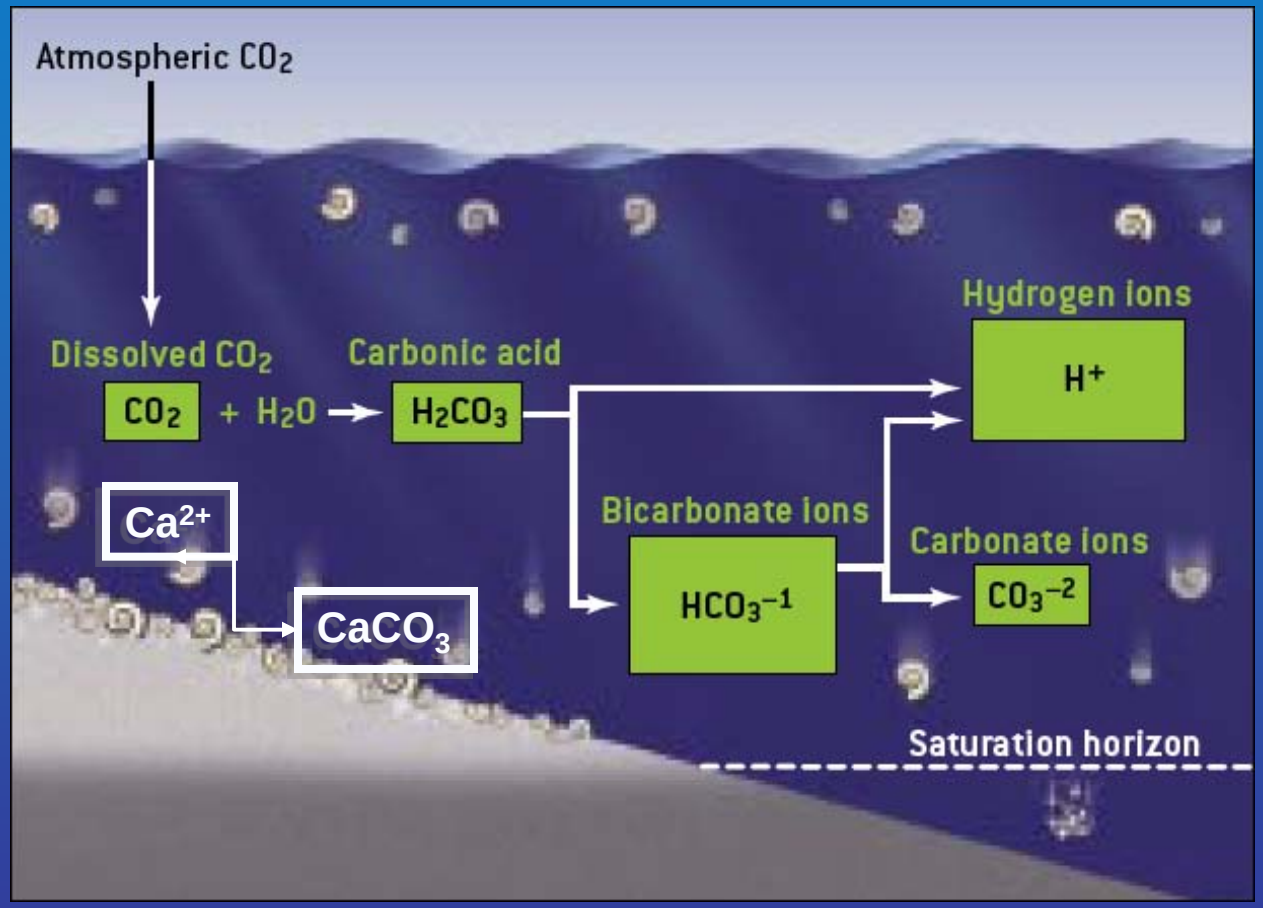


4.2 Pg y^{-1}
46%

2.3 Pg y^{-1}
26%

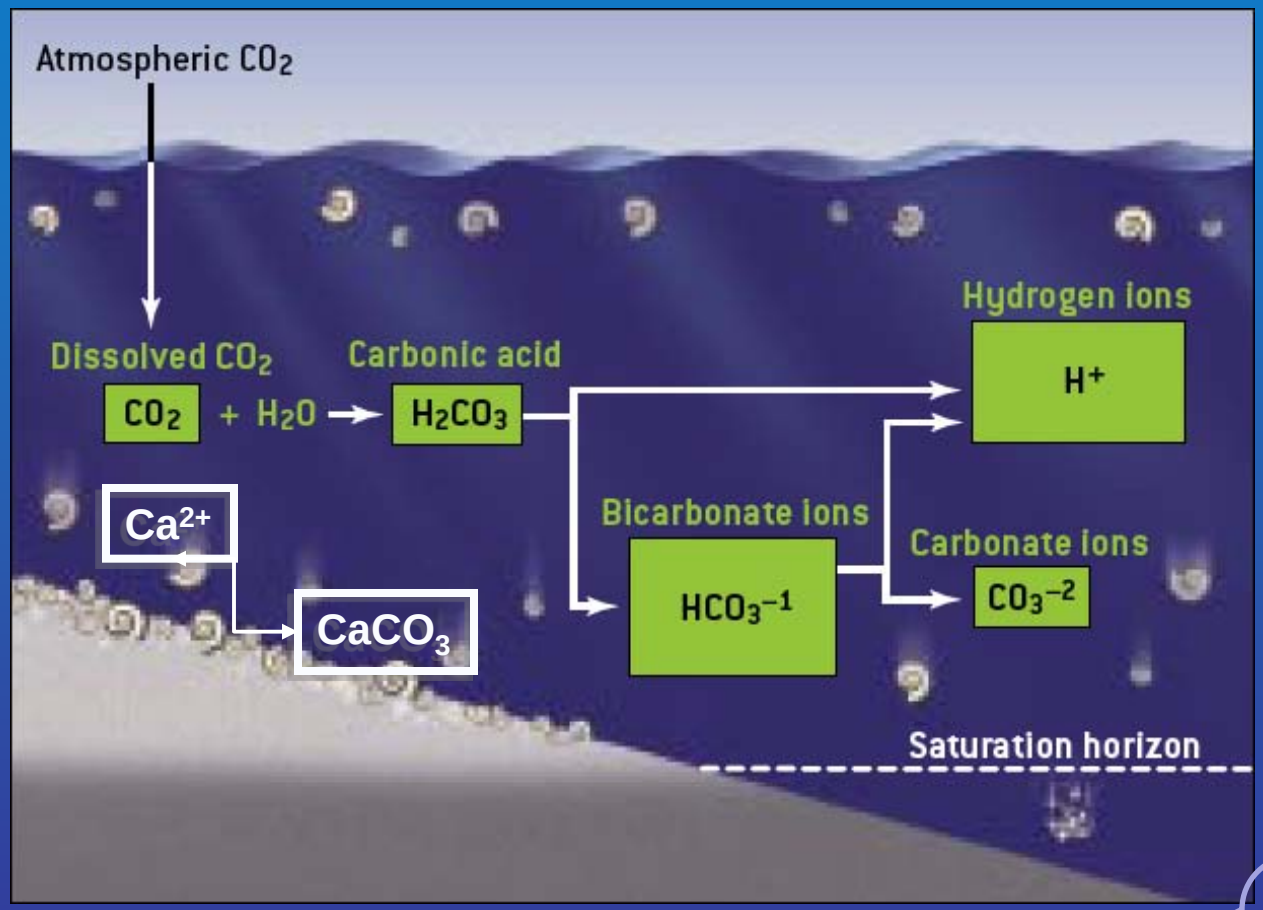
Canadell et al. 2007, PNAS (updated); http://www.globalcarbonproject.org/

Rising CO_2: ocean acidification



Increasing CO_2
- Lowers pH
- Lowers $[CO_3^{2-}]$ saturation state "^"

Rising CO_2: ocean acidification

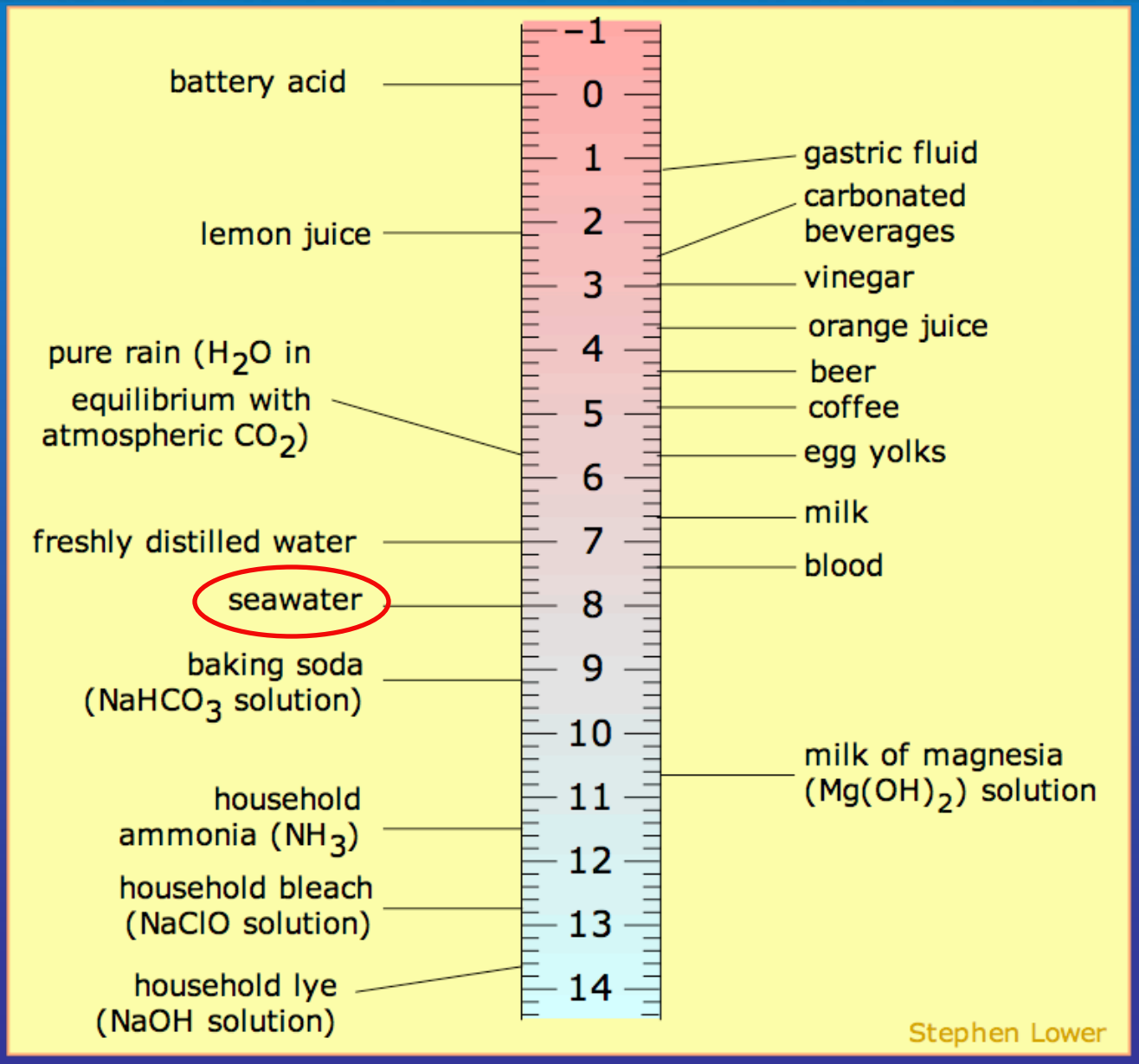


Increasing CO_2
- Lowers pH
- Lowers $[CO_3^{2-}]$ saturation state "^"

$$\Omega = \frac{[Ca^{2+}][CO_3^{2-}]}{K_{sp}}$$

$CaCO_3$'s mineral forms, including aragonite, calcite, & Mg-calcite, all have different solubilities

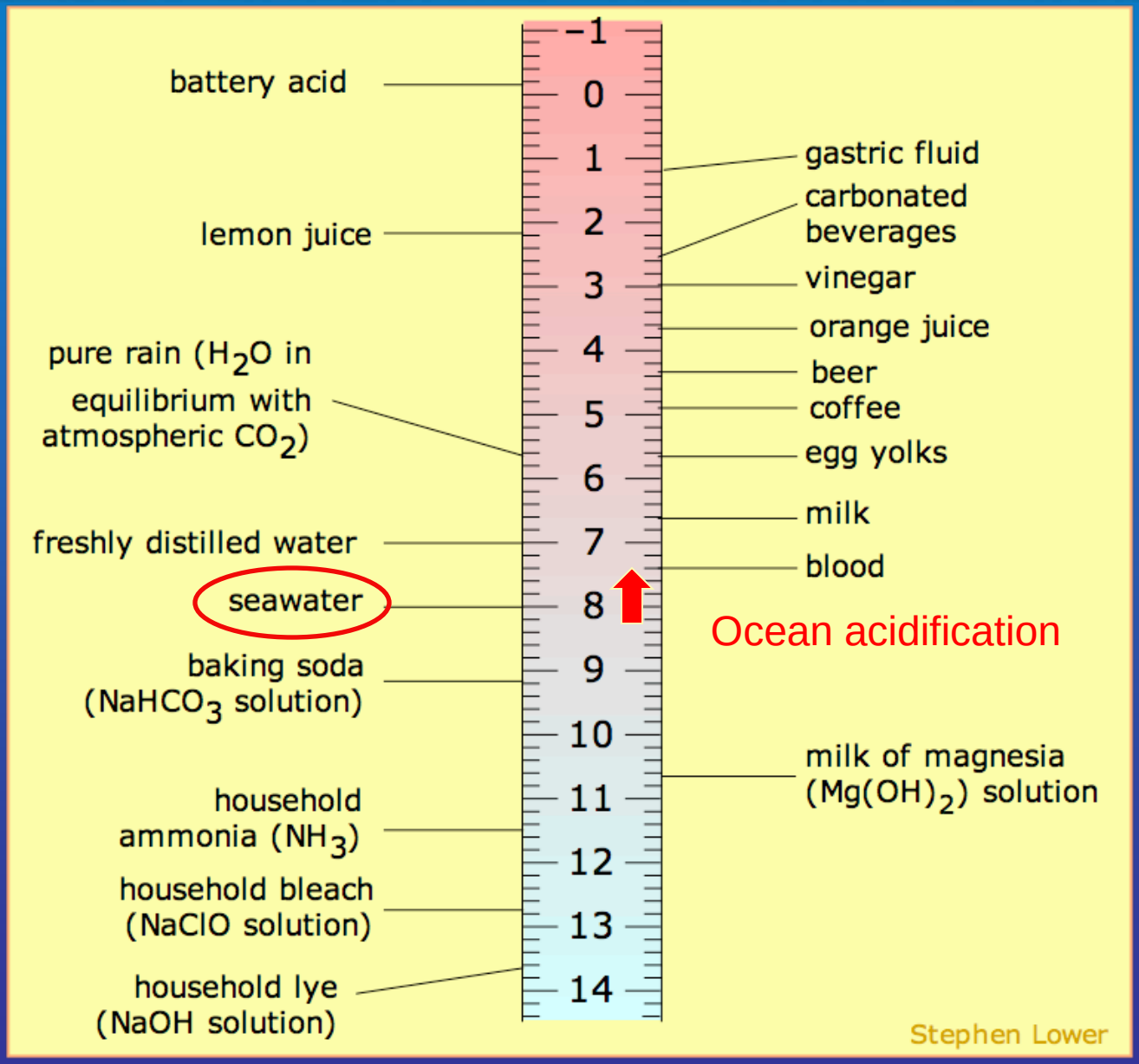
Acidification = any pH decrease



Low pH = acidic, many H+

High pH = basic, few H+

Acidification = any pH decrease



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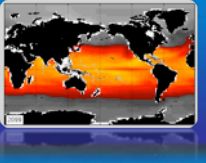
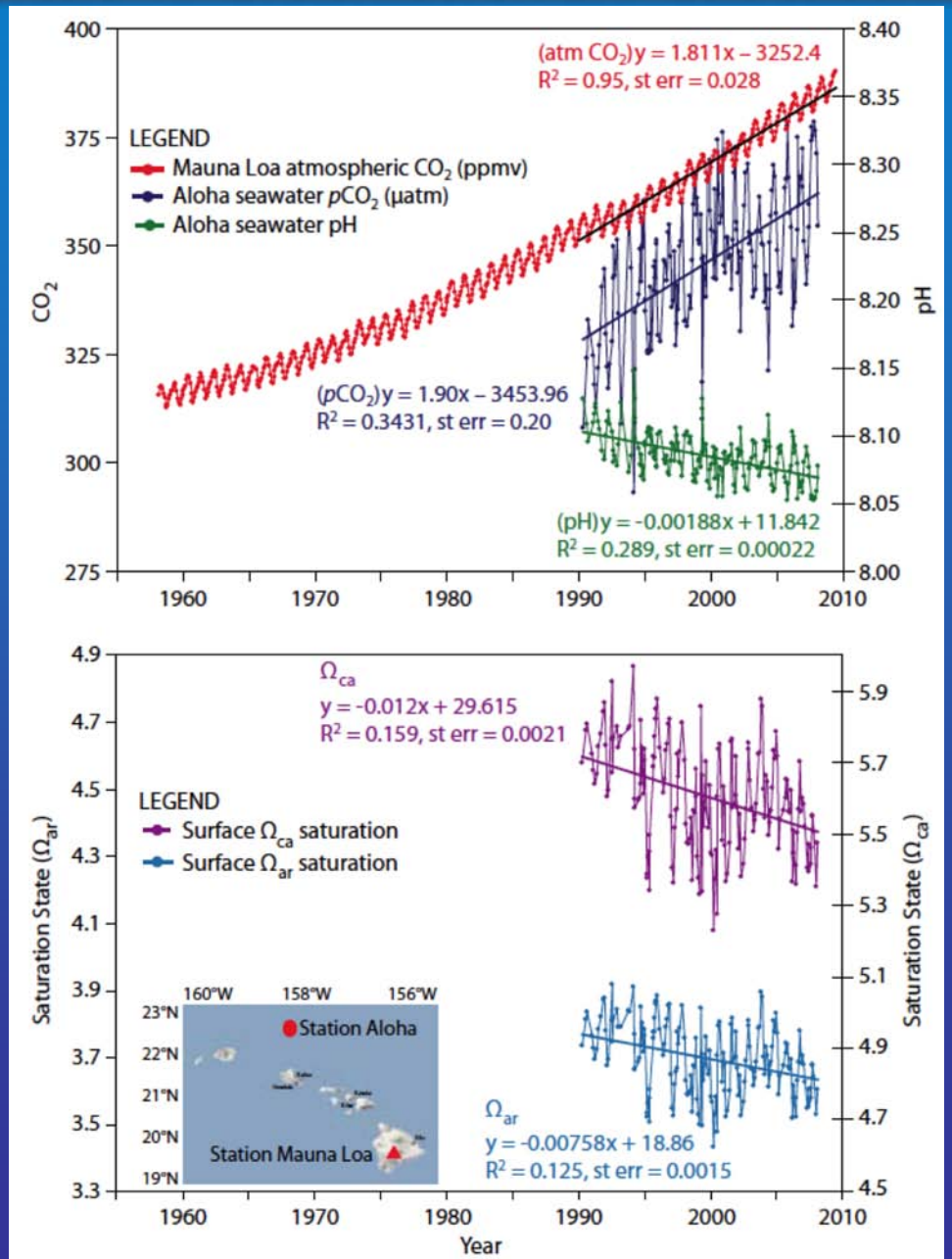
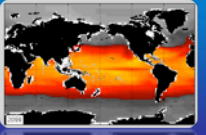


Surface Water Time Series show OA

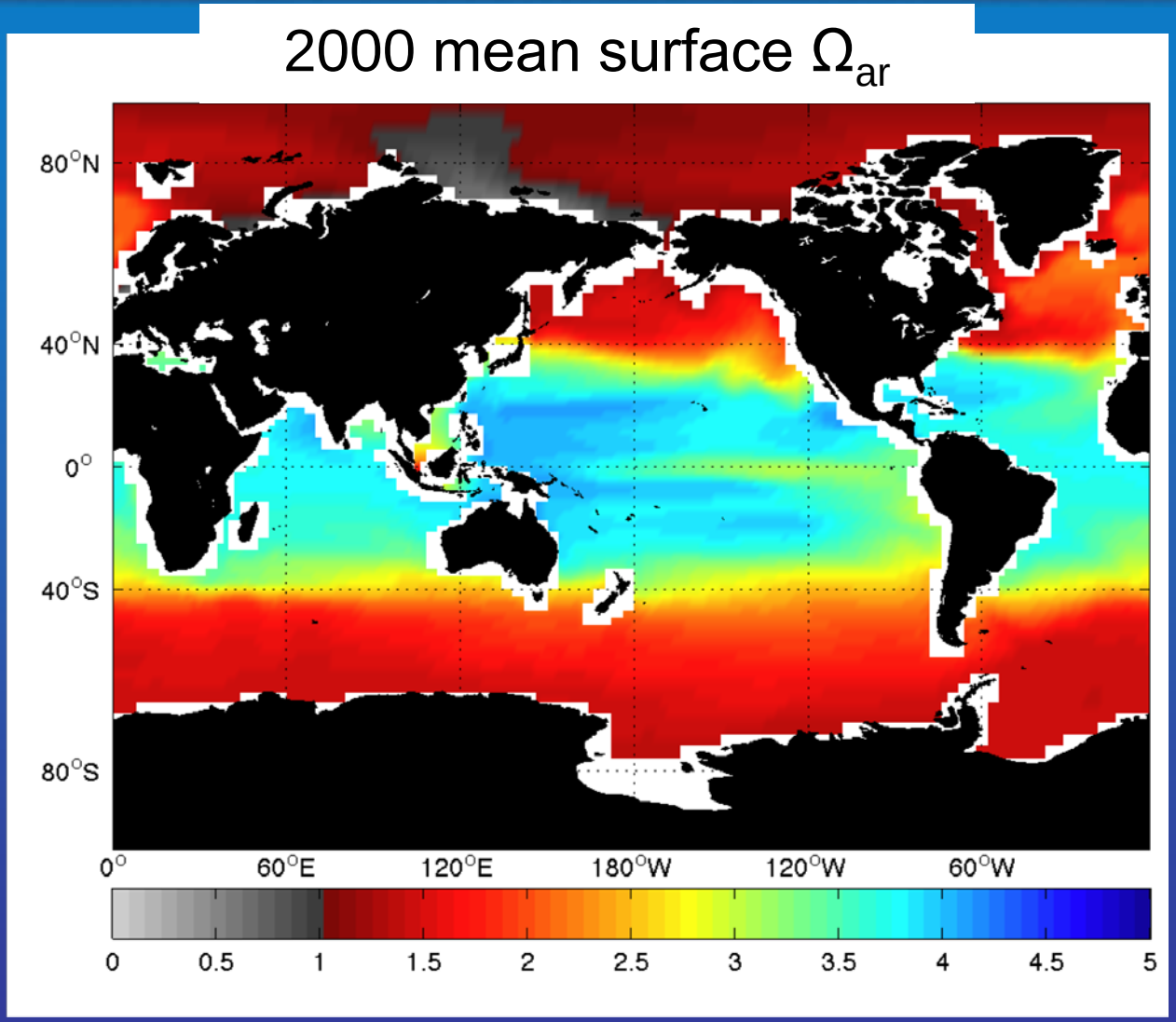
↑ Atmos. pCO_2
↑ Ocean pCO_2
↓ Ocean pH
↓ Ω_{ca}
↓ Ω_{ar}



Doney et al. Oceanography 2009

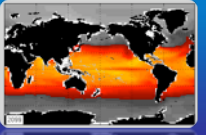


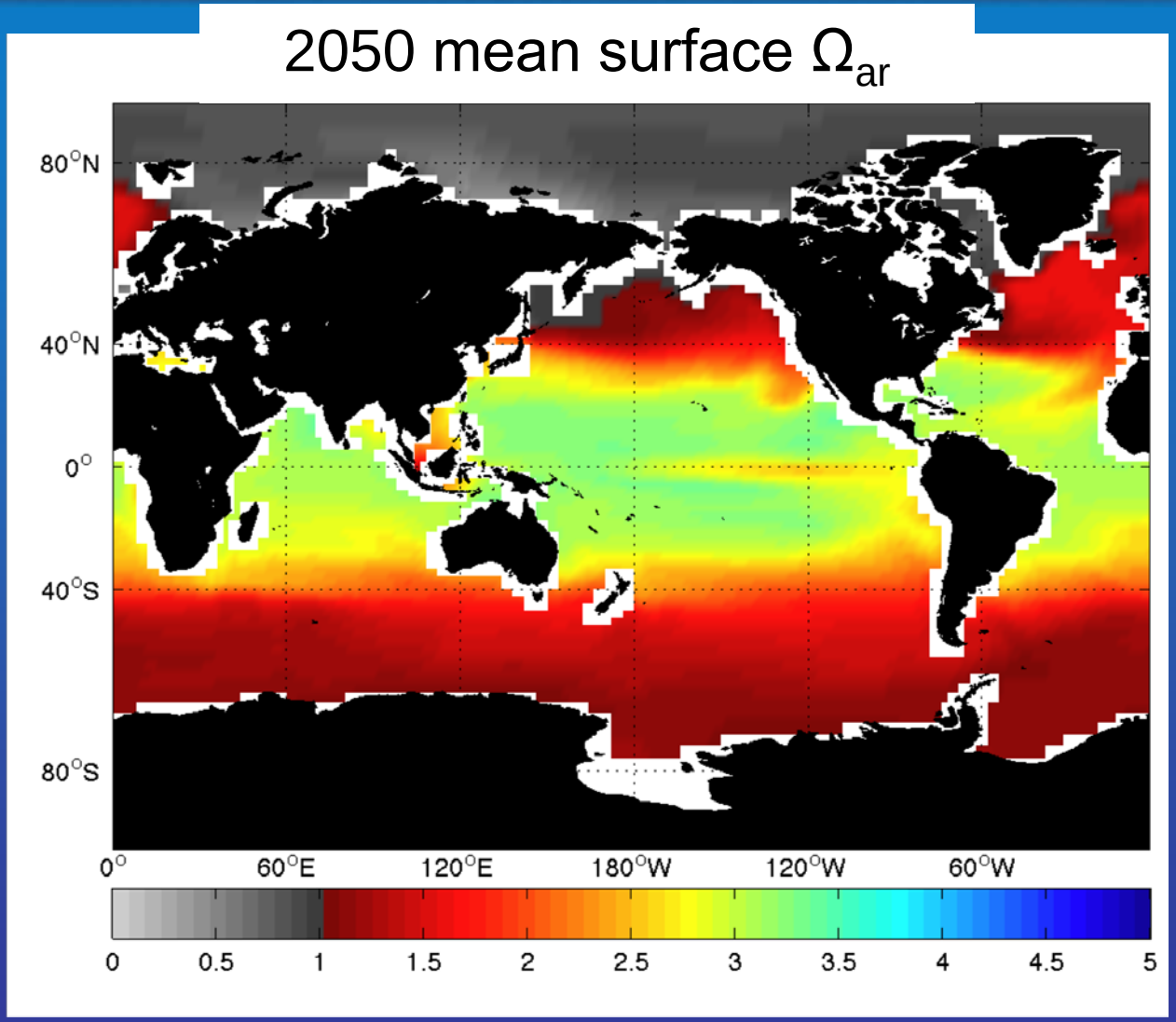
$CaCO_3$ saturation decreasing worldwide



Where $\Omega < 1$, unprotected aragonite structures will dissolve.

$CaCO_3$ saturation decreasing worldwide





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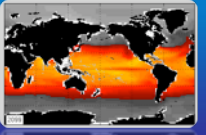
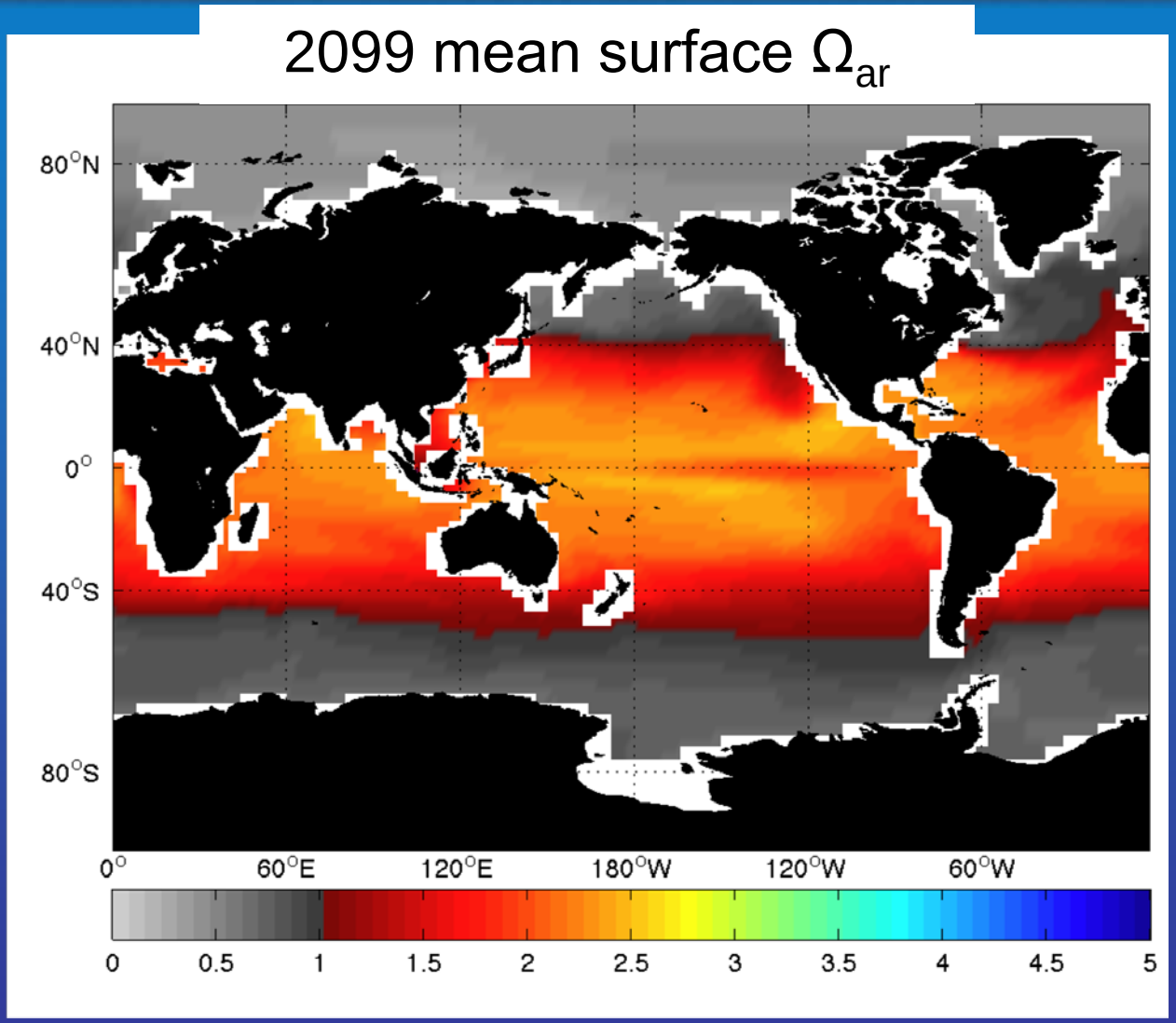


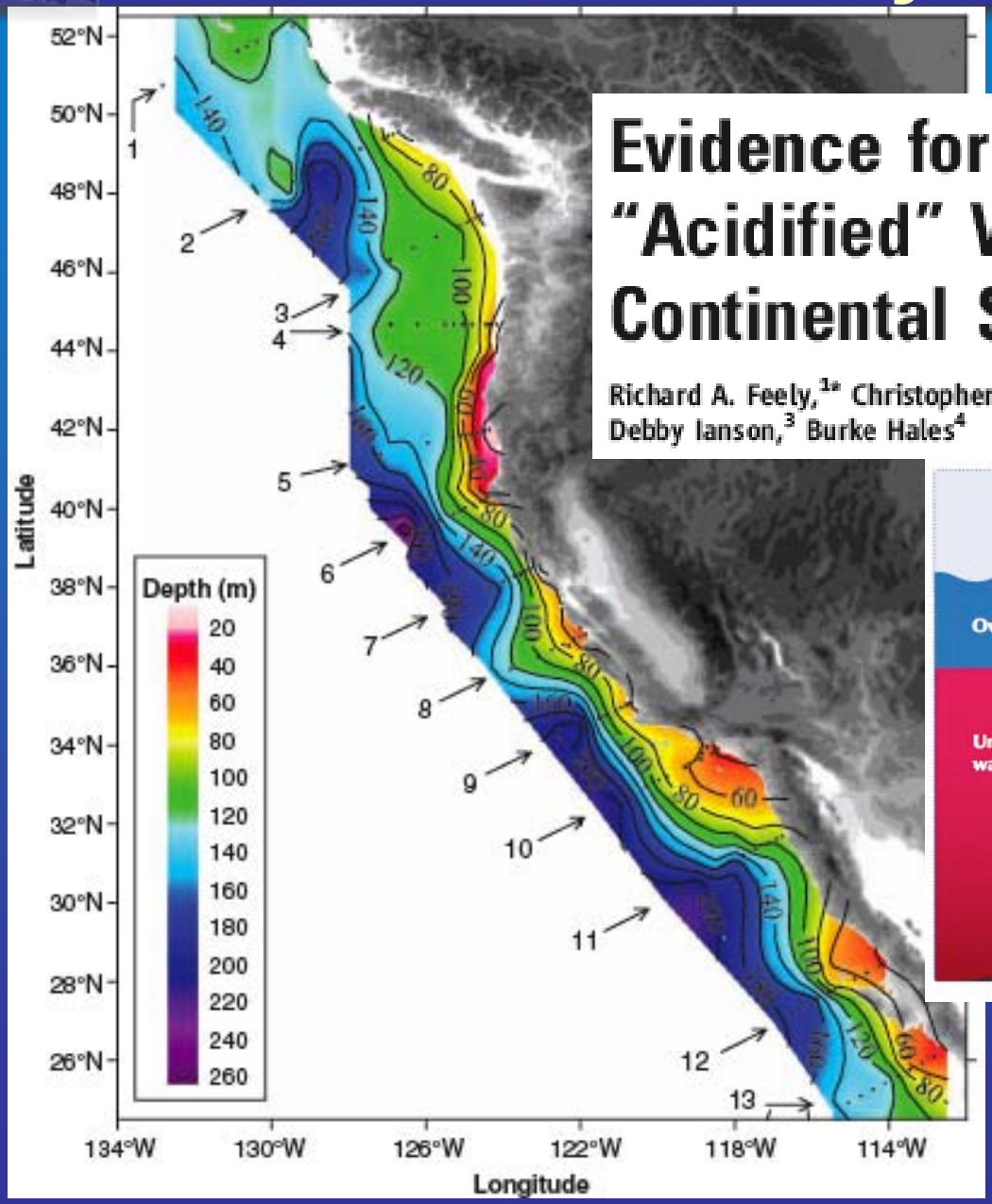


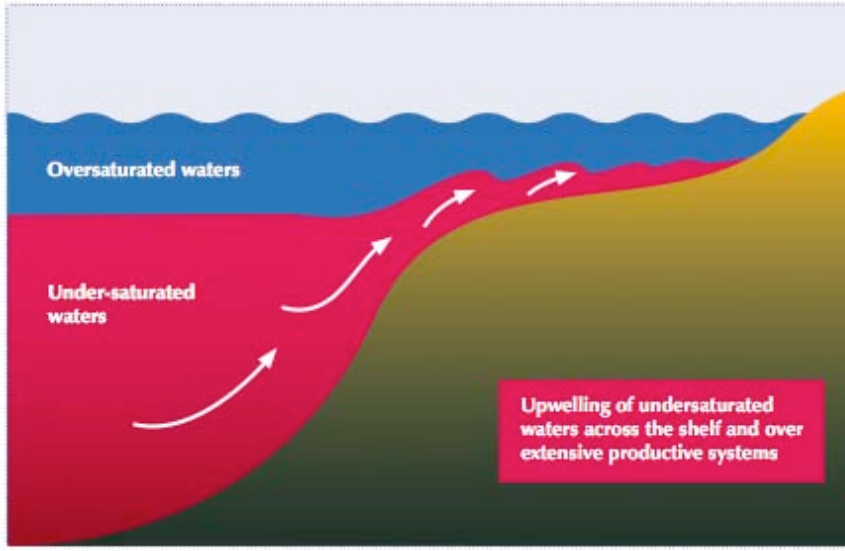
Where Ω < 1, unprotected aragonite structures will dissolve.

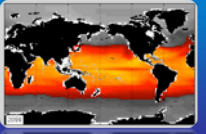
Coastal variability increasing?

Evidence for Upwelling of Corrosive "Acidified" Water onto the Continental Shelf

Richard A. Feely,[1*] Christopher L. Sabine,[1] J. Martin Hernandez-Ayon,[2] Debby Ianson,[3] Burke Hales[4]

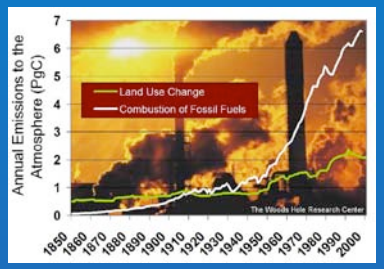


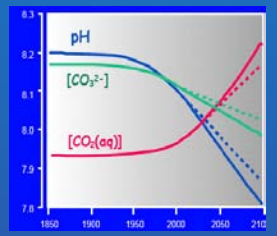


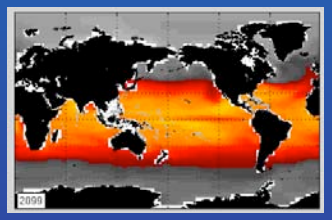


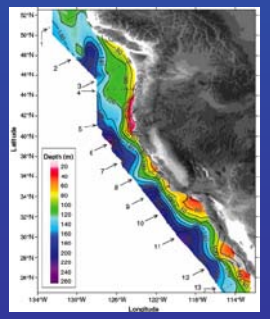
OA background & forecast

- OA ≠ climate change, but caused by anthropogenic CO_2.
- Decreasing pH, CO_3, and Ω globally
- Poles, deep waters undersaturated w/ $CaCO_3$ in future
- Potential for large coastal variability





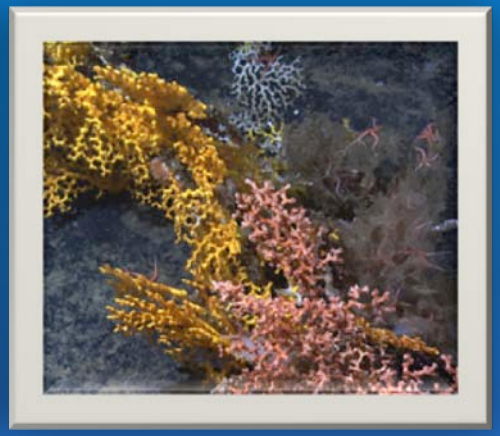




Biological Groups at Risk

Known

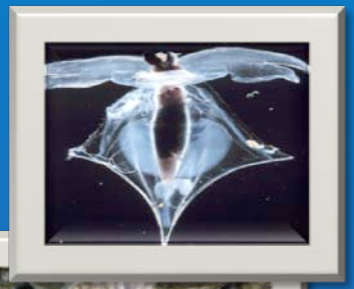
Warm-water corals



Cold-water corals

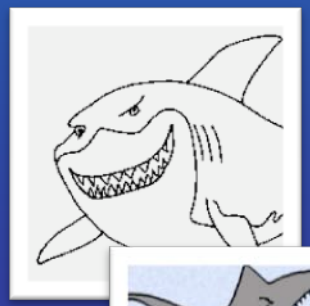
Some plankton

Pteropods

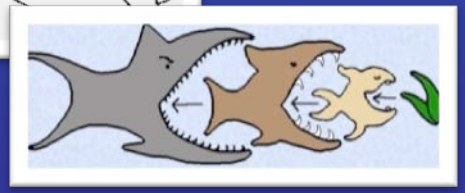


Many mollusks

Anticipated



Reef communities



Marine predators

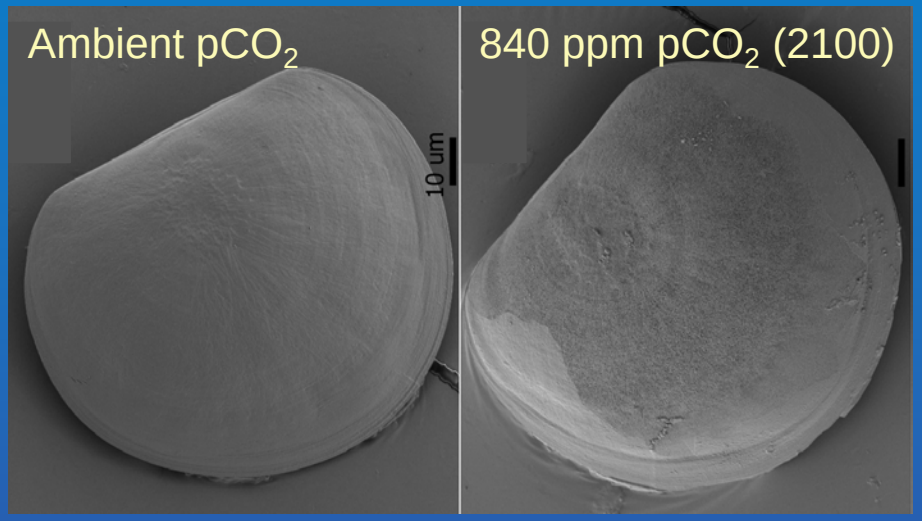
Coastal environments

Businesses

Fishermen

OA as a geohazard

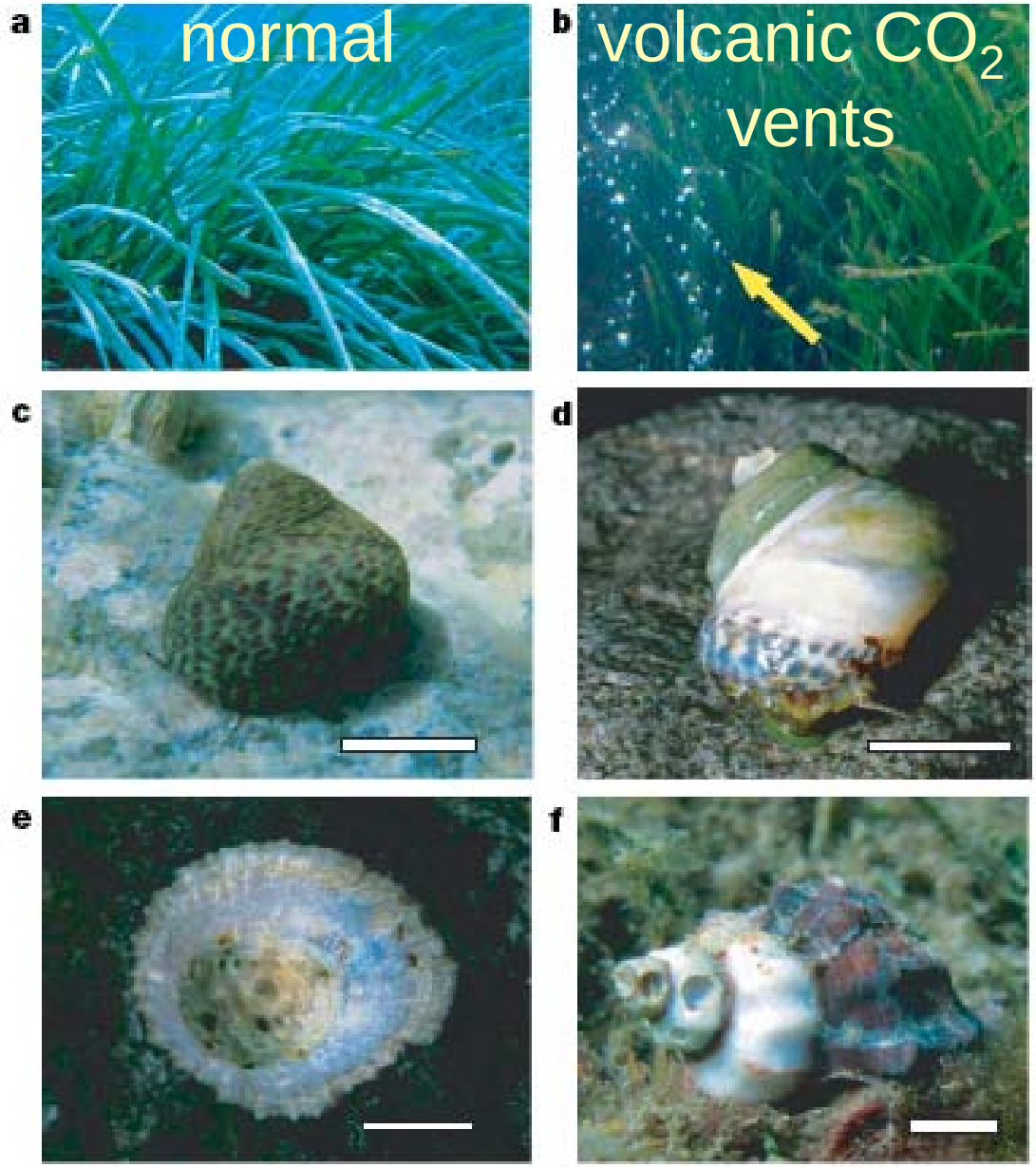
- OA may decrease calcifier populations via
  - -calcification decreases
  - -declining larval survival
  - -life history changes



Bay Scallop (*Argopecten irradians*)
Anne Cohen, WHOI, 2009

- Calcifiers provide <u>income</u> and high-quality <u>nutrition</u> worldwide

Ecosystem changes



Natural habitat with high CO_2:

-no corals, coralline algae, or juvenile mollusks

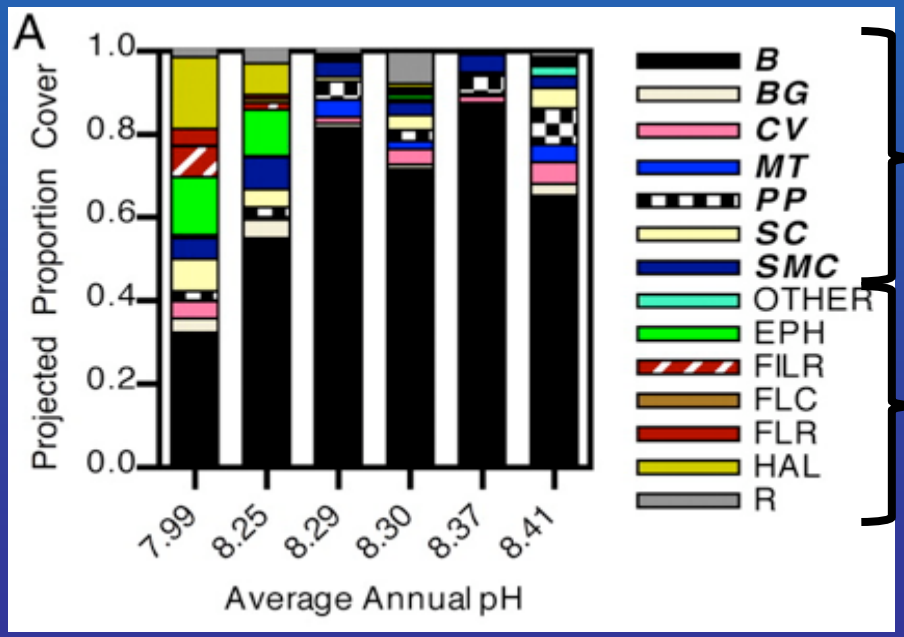
-damaged adults

Hall-Spencer et al. Nature 2008

Ecosystem changes

In a coastal lagoon, noncalcifiers replaced calcifiers over multiple years with declining pH

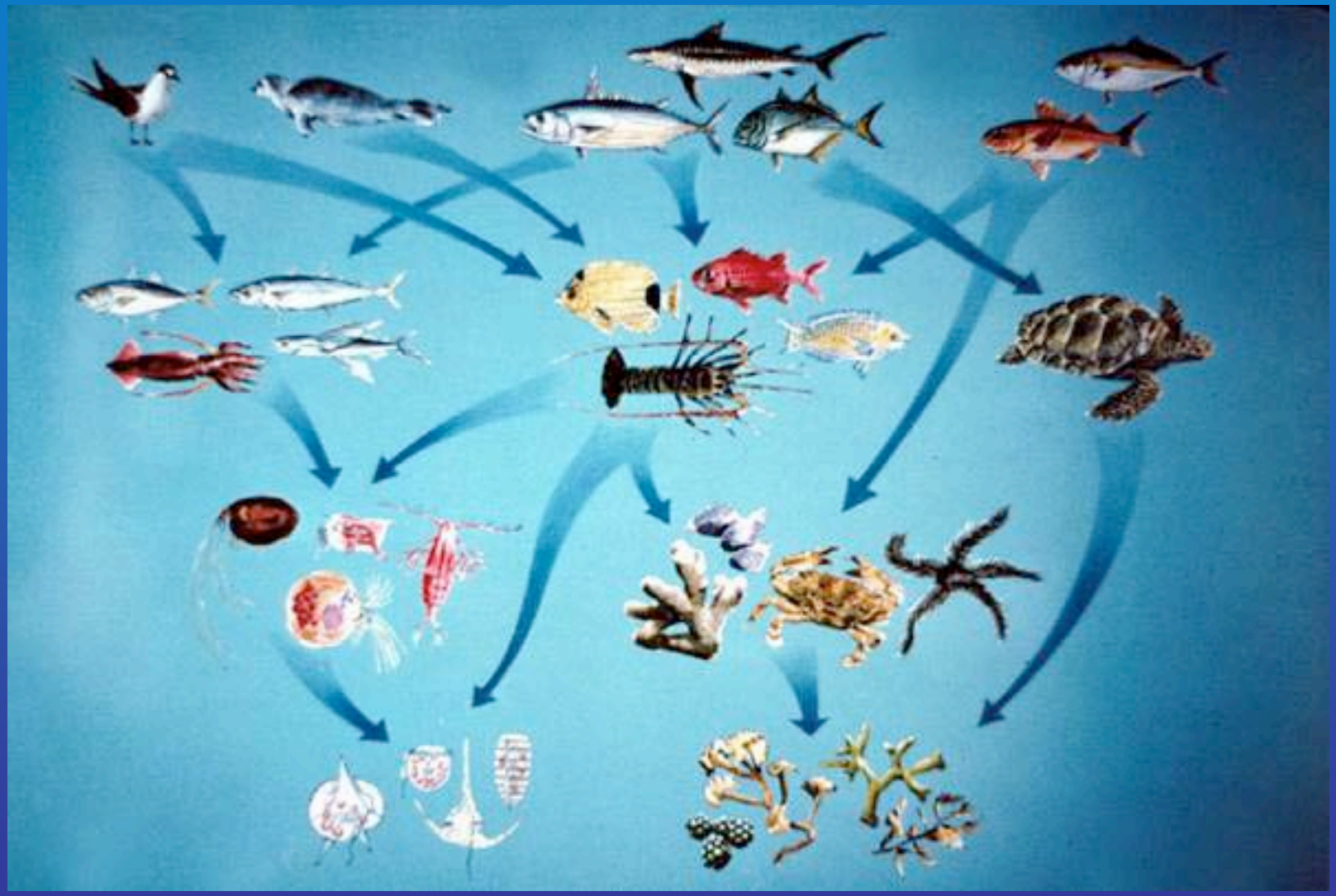
Photo, U. Washington



← Time

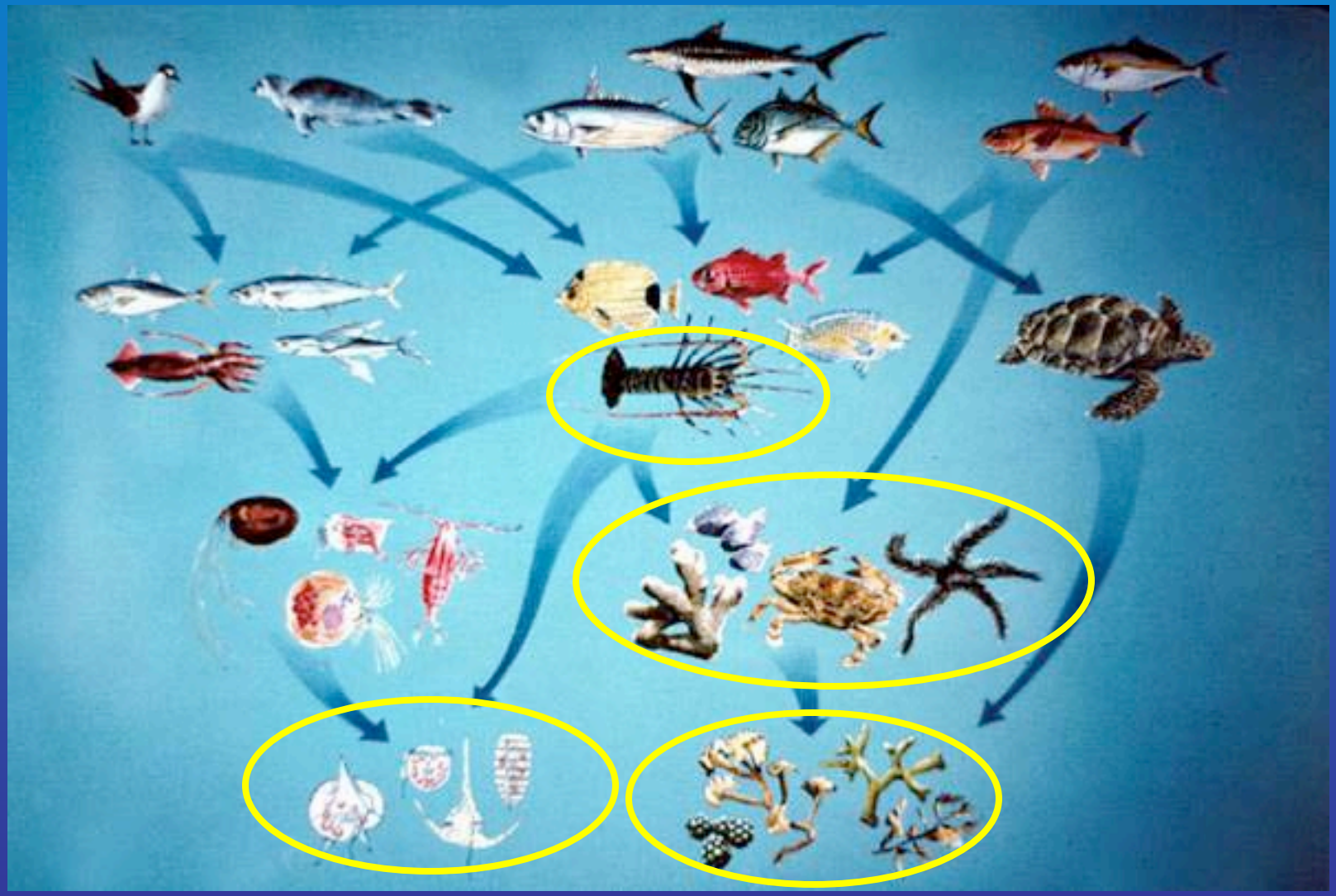
Wootton et al. PNAS 2008.

Ecological implications



Food web effects of OA are unknown

Ecological implications



Food web effects of OA are unknown, could be extensive

Environmental benefits at stake

OA-vulnerable marine life
Calcifiers
Coral dwellers
Calcifiers' predators
Top predators
pH-sensitive species

Ecosystem services
Fishing
Aquaculture
Culture & Tourism
Coastline protection
Environmental support

Communities
Wholesale
Retail
Service Industries
Business-to-business
Municipalities
Demographics

Images: NOAA Photo Library; www.holidayrentals.co.uk; C. Pesch, courtesy EPA

Supporting ecosystem services

- Habitat
- Nutrient recycling
- C sequestration in mangrove-coral ecosystem wetlands
- Poorly understood, hard to value

Cooley, Kite-Powell, and Doney, Oceanography 2009

Coastal protection

Photo: NOAA Coral Reef Watch

- Coral reefs and calcified structures protect shorelines from wave and storm damage
- US$9.0B/yr
- Protection + fisheries = US$30B/yr value.

Cooley, Kite-Powell, and Doney, Oceanography 2009

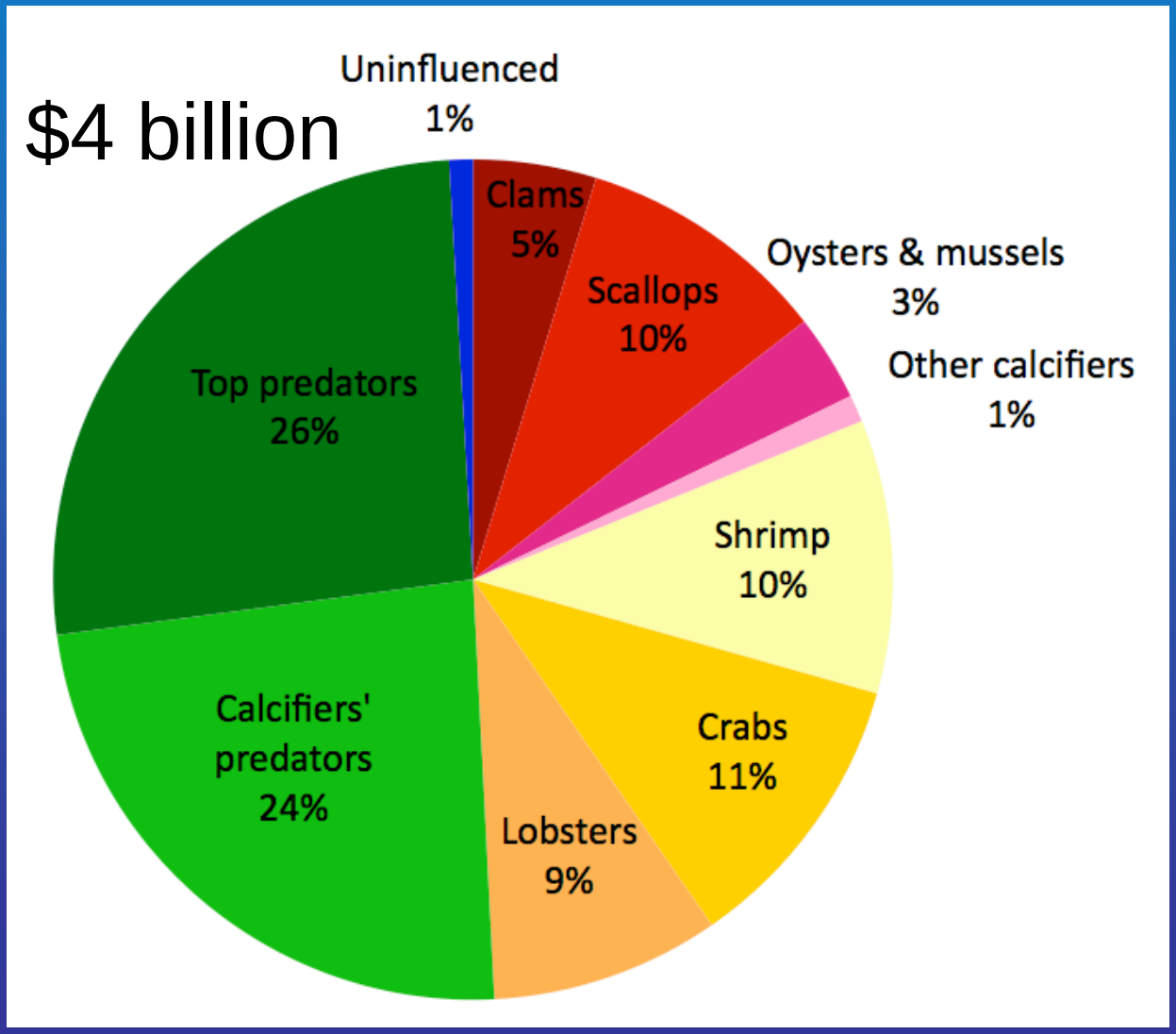
Tourism

- Generates much of marine resources' value
- Likely that recreational fishing value ≈ commercial fishing.
- Associated spending adds up–
  2006, Tobago:
  US$43.5 M (15% of GDP) from tourism of coral reefs;
  US$58-86M (~20%-30% of GDP) from indirect impacts of tourism

Cooley, Kite-Powell, and Doney, Oceanography 2009

U.S. commercial fisheries depend on calcifiers

2007 U.S. domestic ex-vessel revenue



Cooley and Doney ERL 2009

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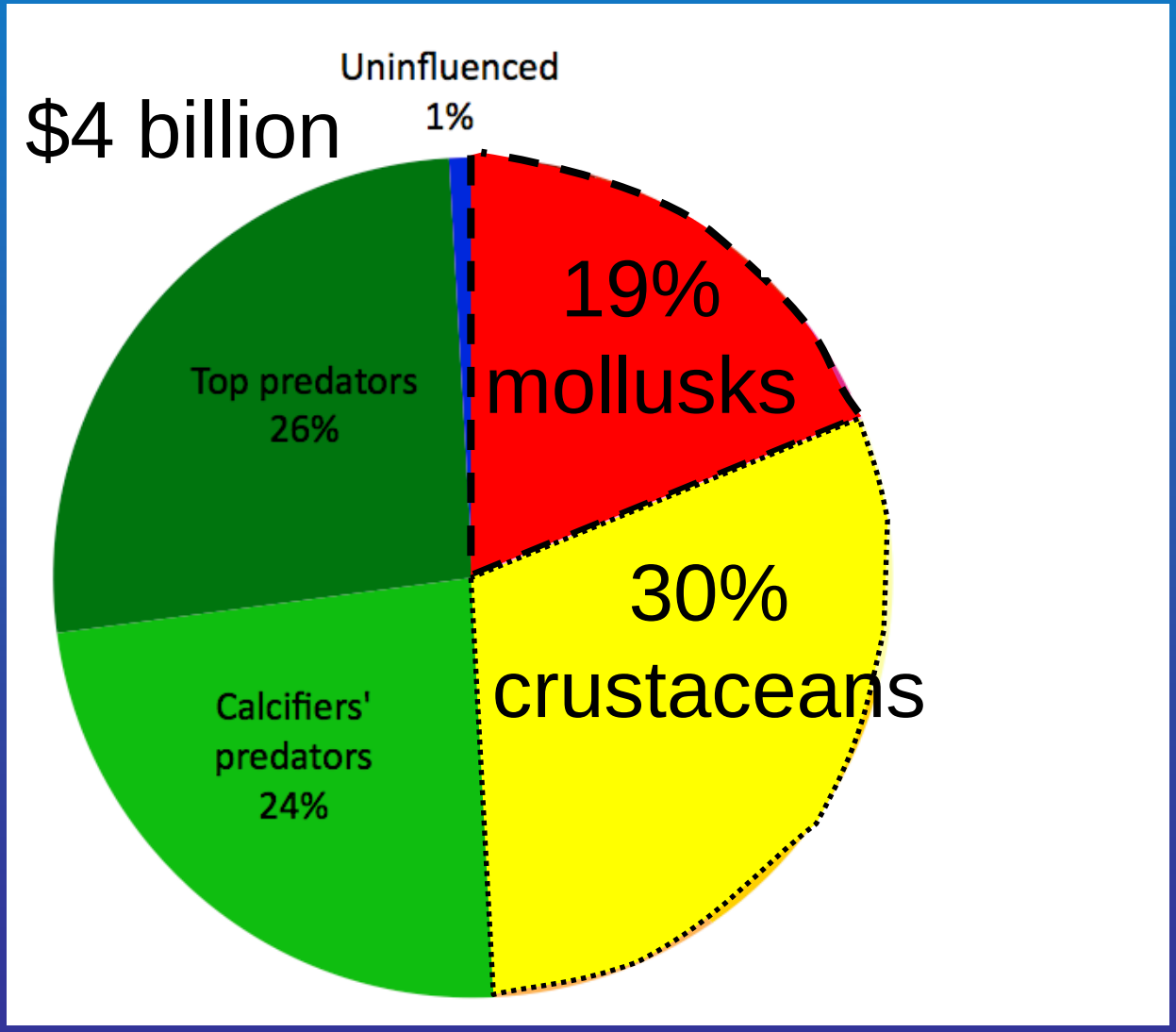
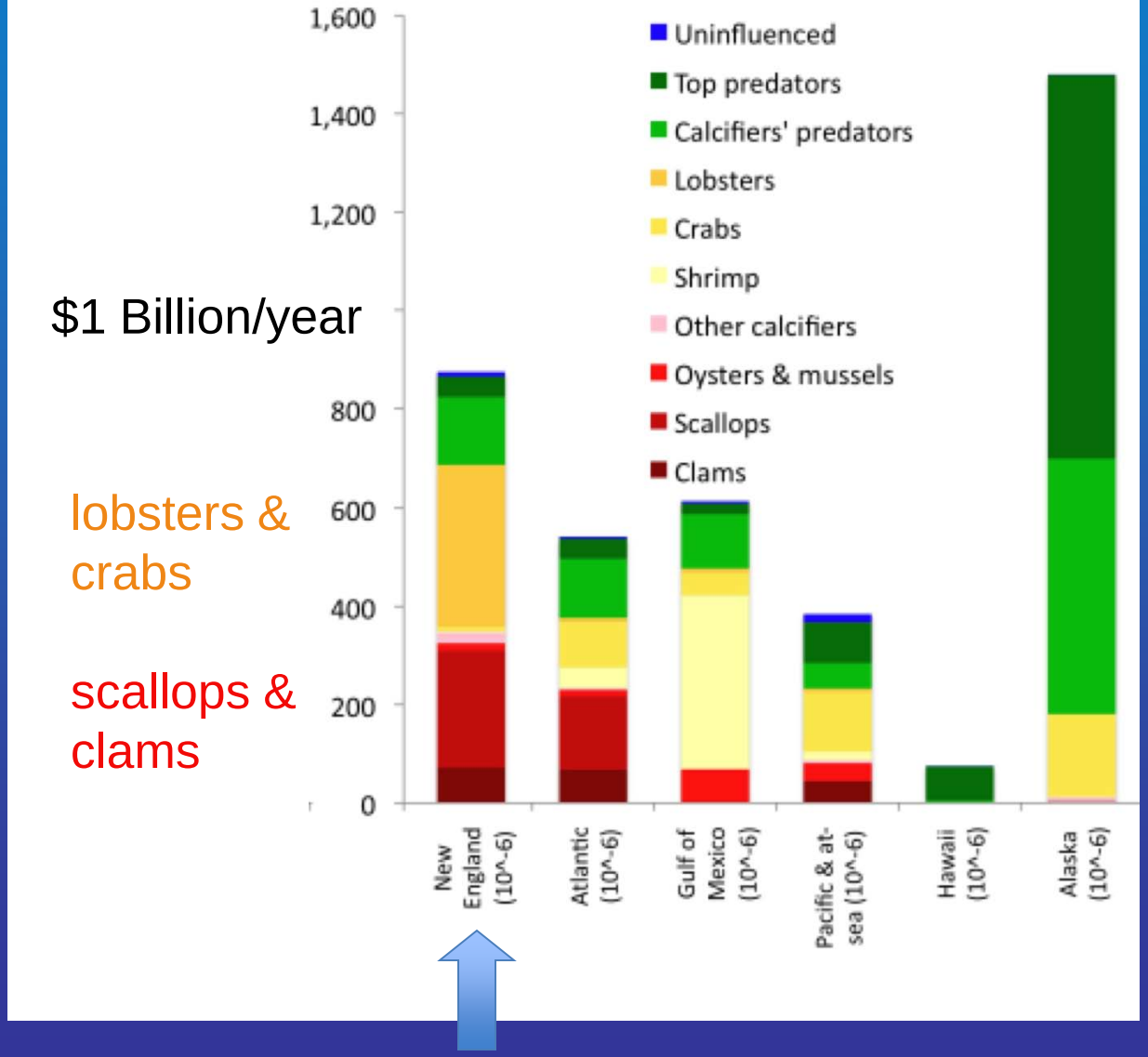


$ 4B domestic
+$ 1.1B other + aquacult.
$ 5.1B primary sales
+ import
+ processing
+ wholesale
+ retail
$ 68.3B sales
- costs
$34.2B
value added to GNP

Cooley and Doney ERL 2009

Regional dependence on calcifiers varies



$1 Billion/year

lobsters & crabs

scallops & clams

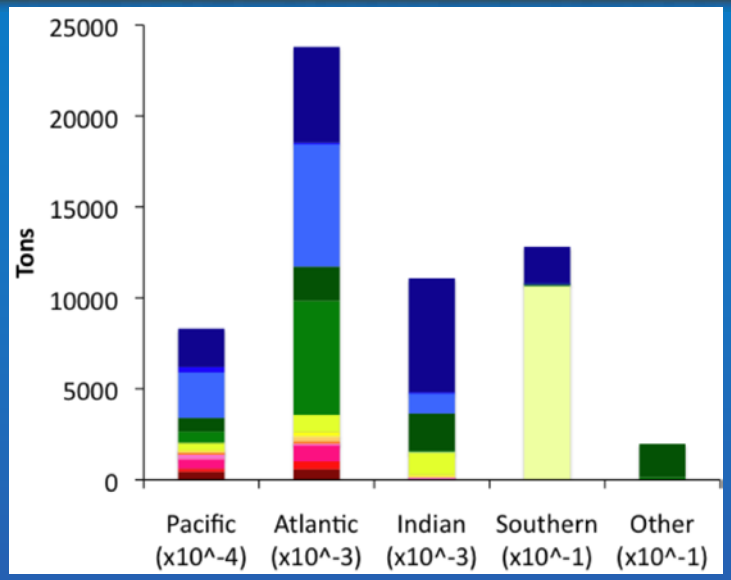
Example: New England primary fishery revenue

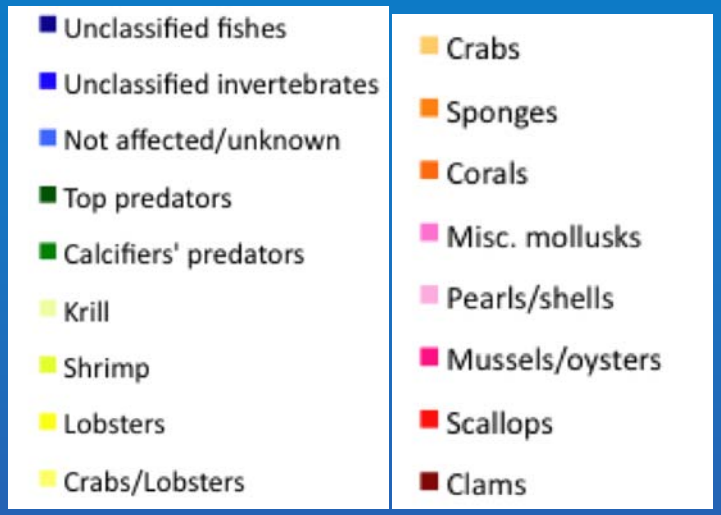
~$850 million/year

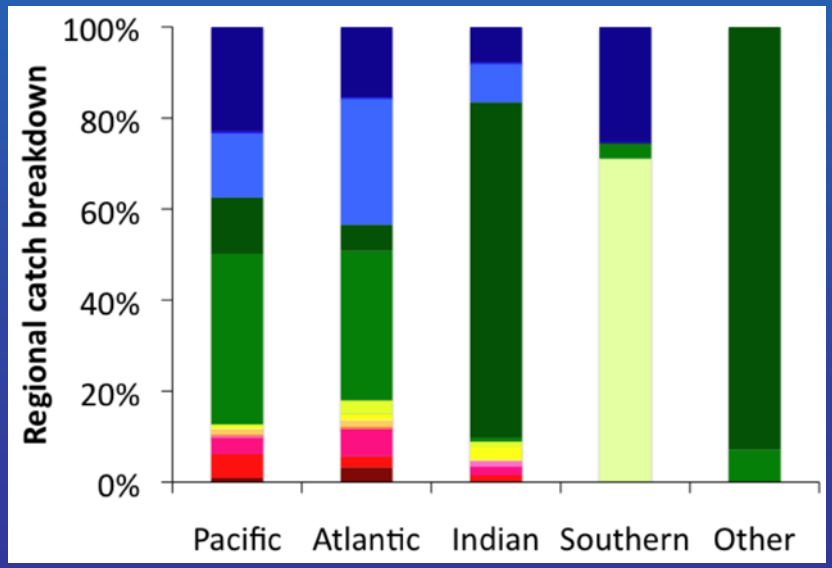
~80% are from shellfish

Cooley and Doney *ERL* 2009

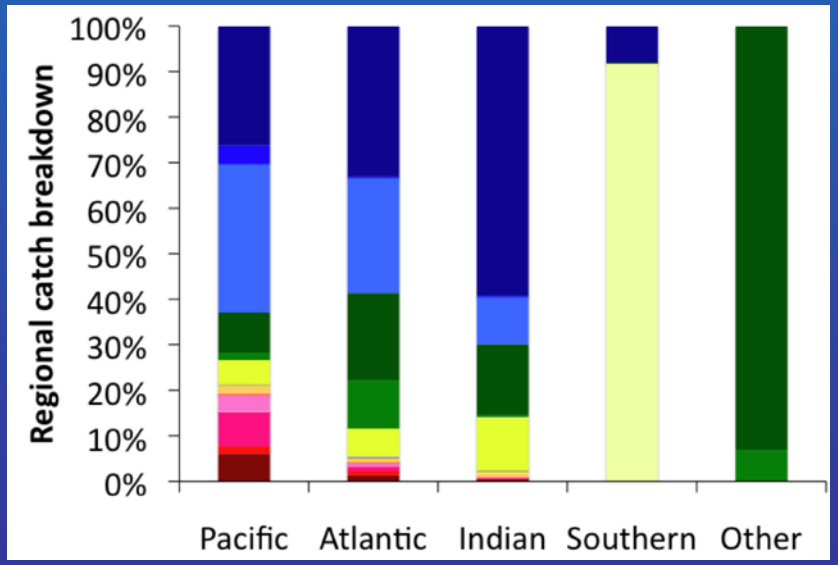
Global calcifier harvests vary







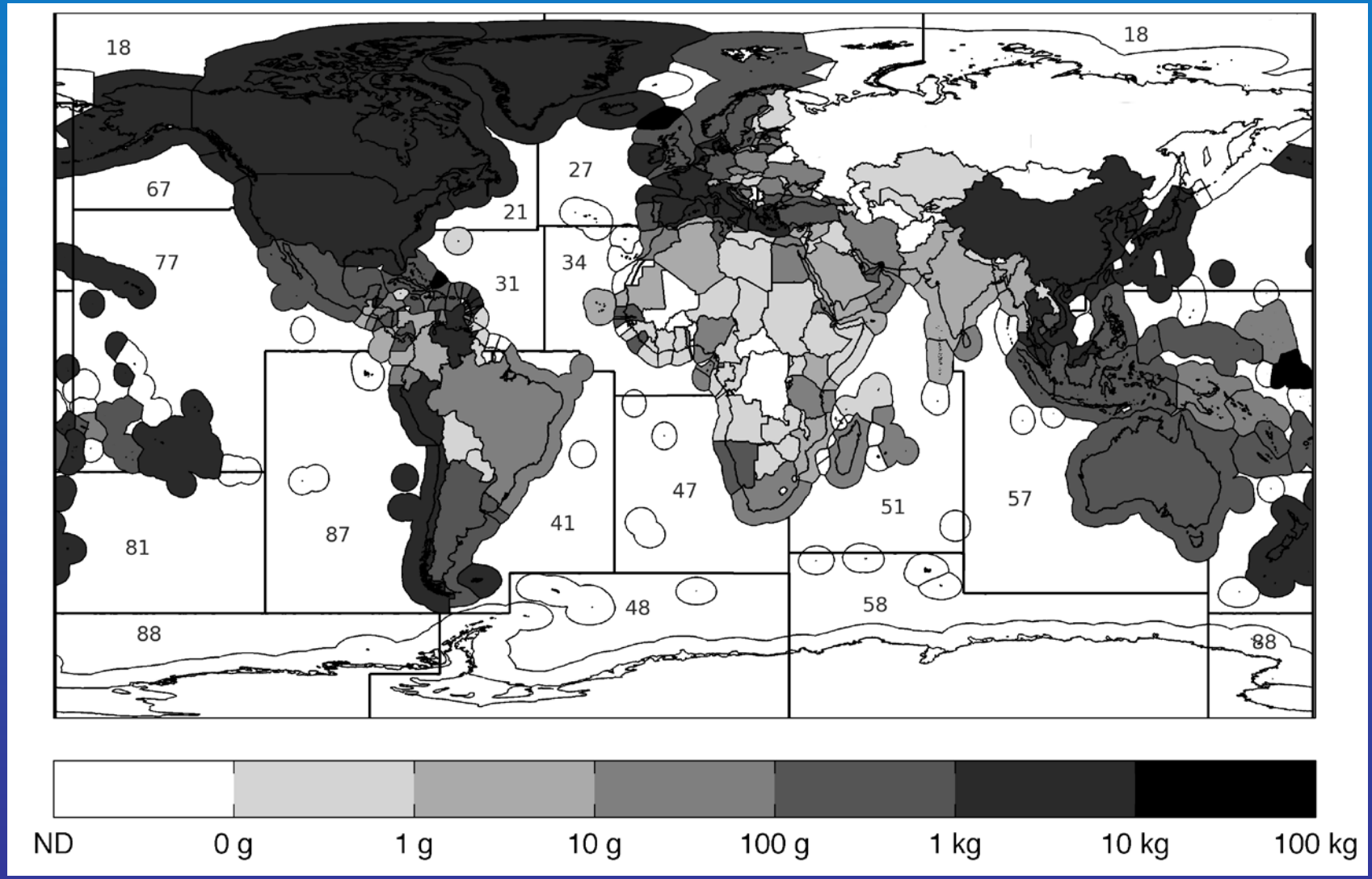
Industrial nations



Developing nations

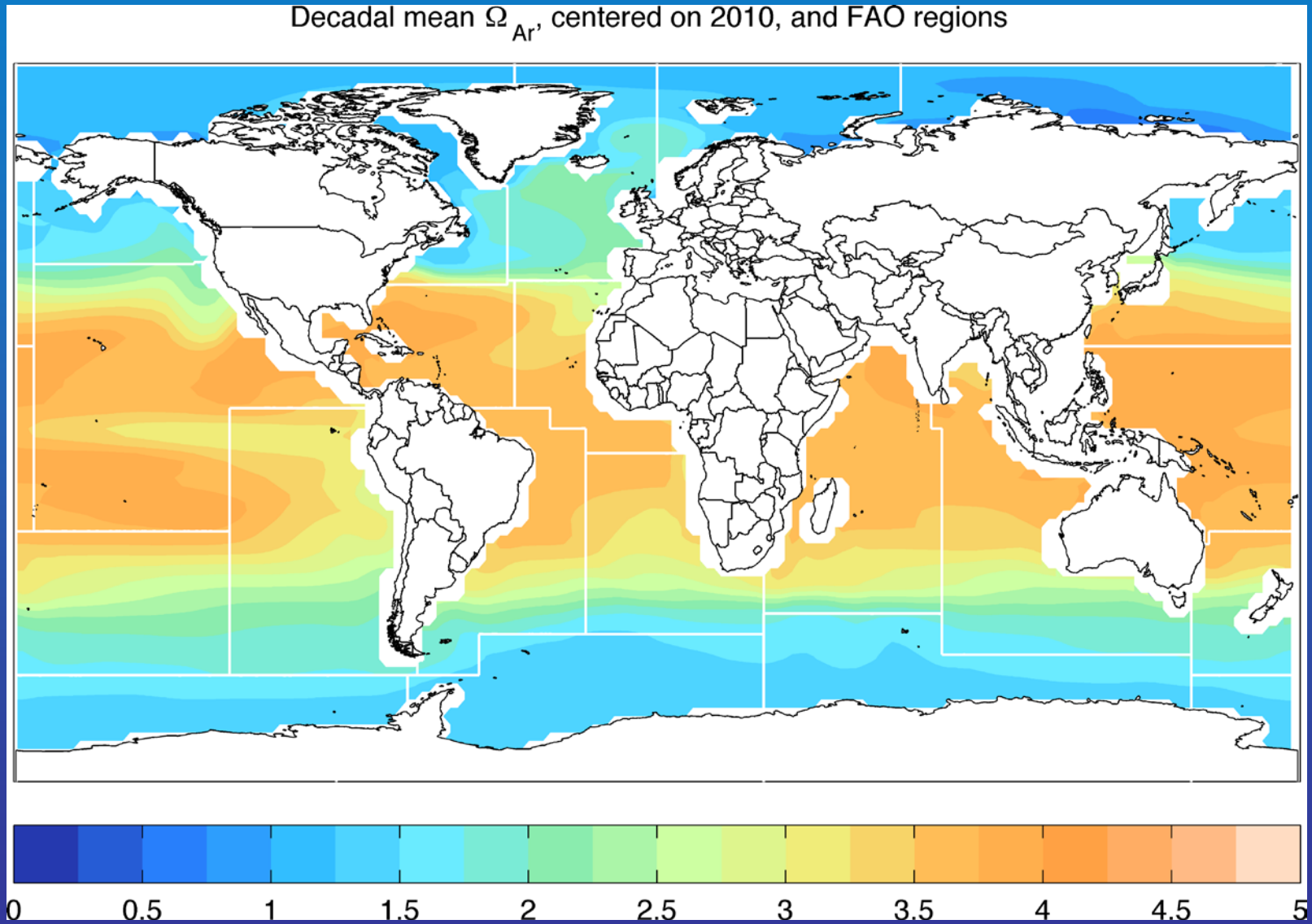
Cooley, Kite-Powell, and Doney, Oceanography 2009

2007 mollusk production (per capita)



Cooley et al. submitted

Mollusk harvests don't depend on Ω_{ar}

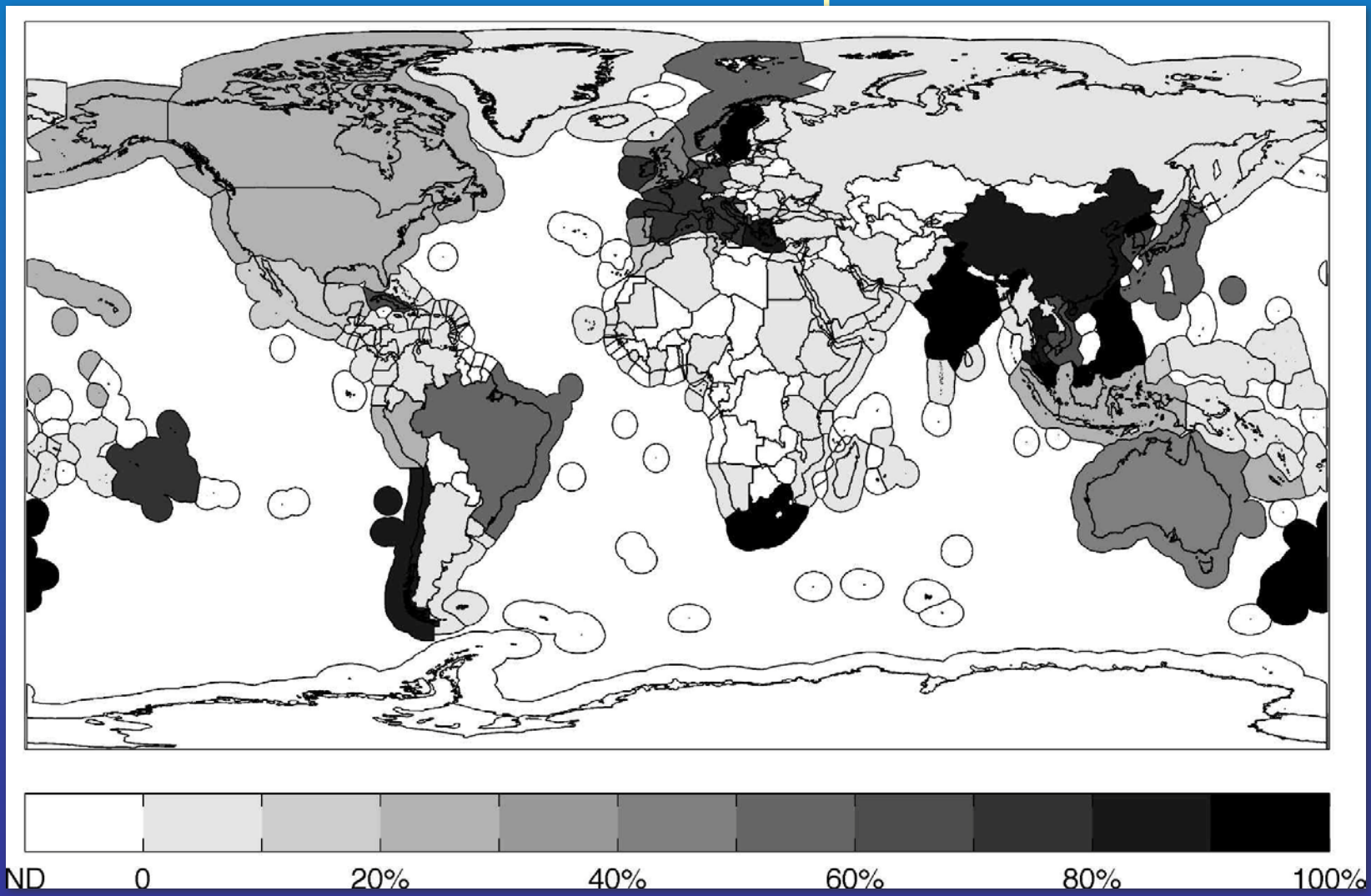


Cooley et al. submitted

Calculated from CCSM3 output fields

Present oceanic conditions

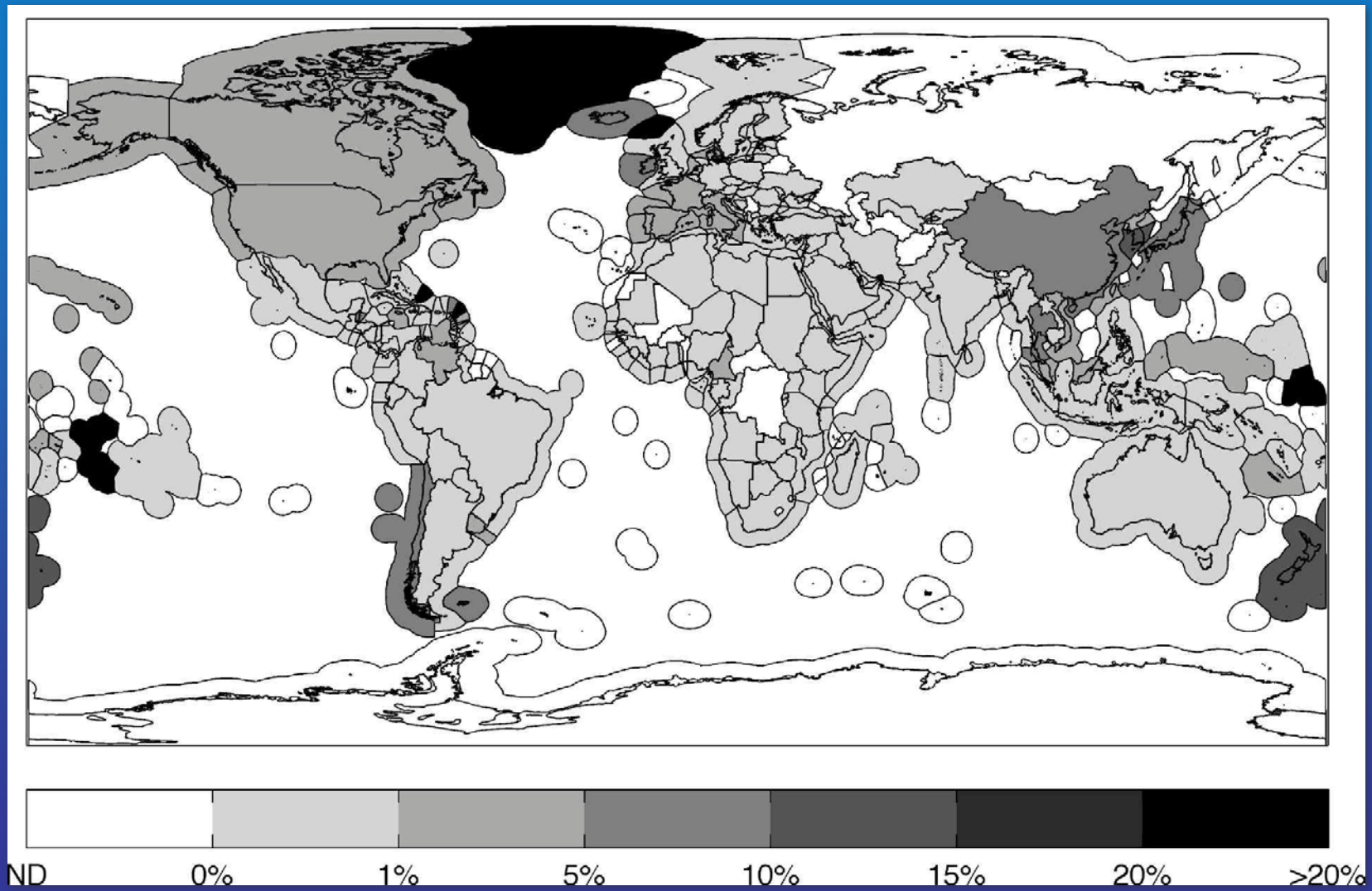
% of harvest from aquaculture



2007 data from U.N. FAO;
Cooley et al. submitted to *Fish and Fisheries*

Present socioeconomic conditions

% of protein from mollusks



Calculated from from U.N. FAO data;
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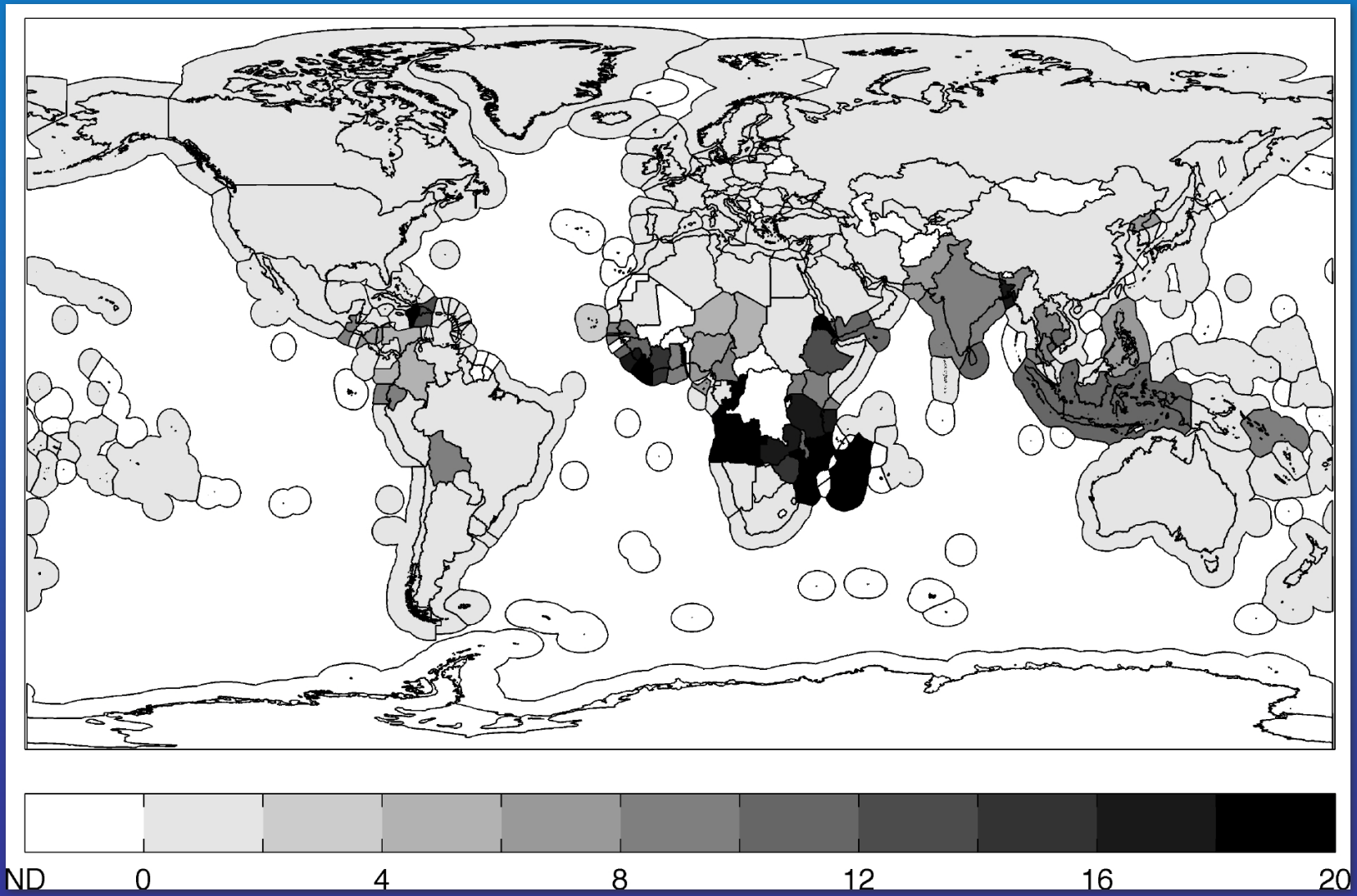
Present socioeconomic conditions

Protein gap (g d^{-1} $capita^{-1}$)



Data from U.N. FAO;
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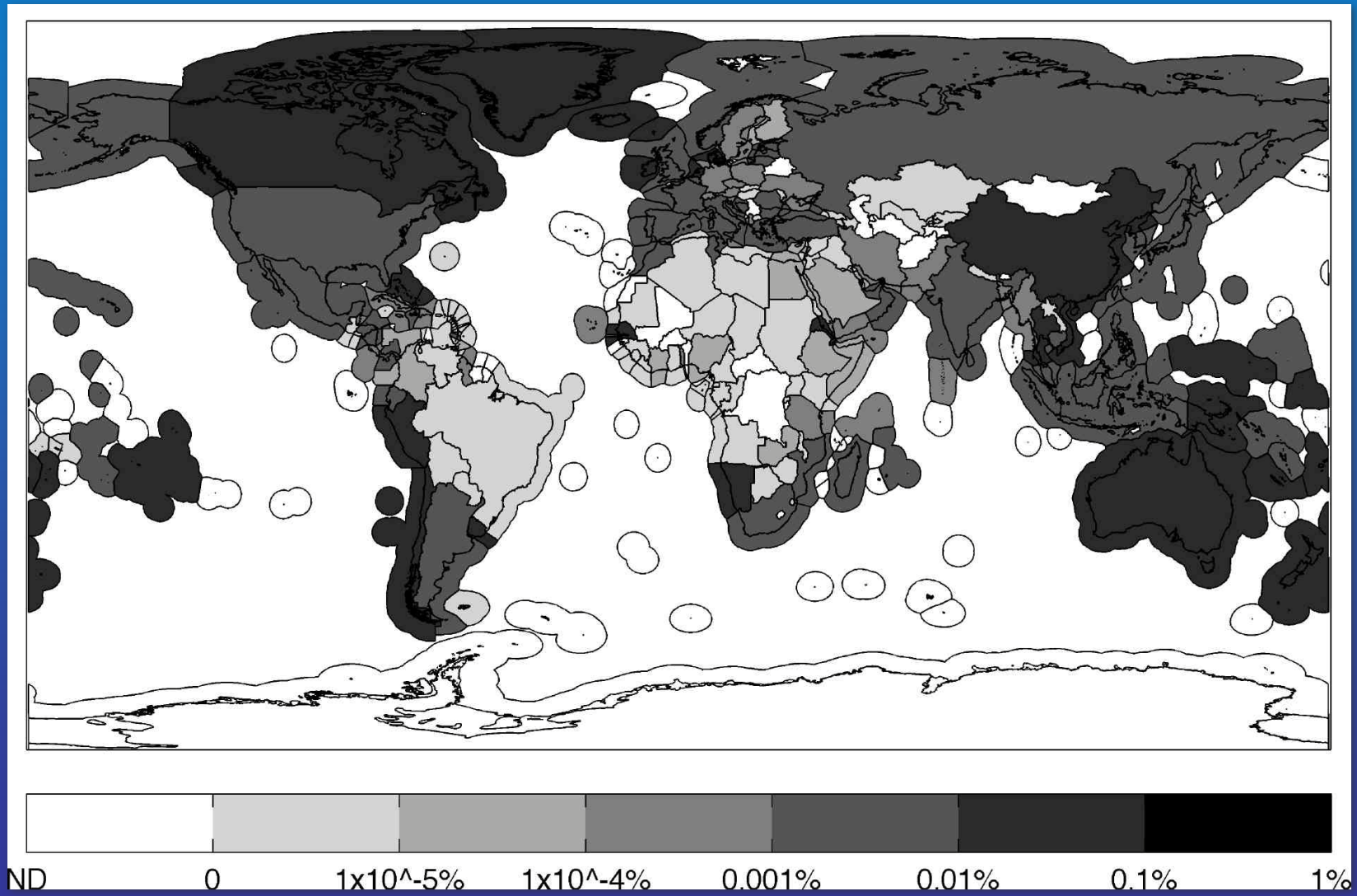
Present socioeconomic conditions

Mollusk export as % of GDP

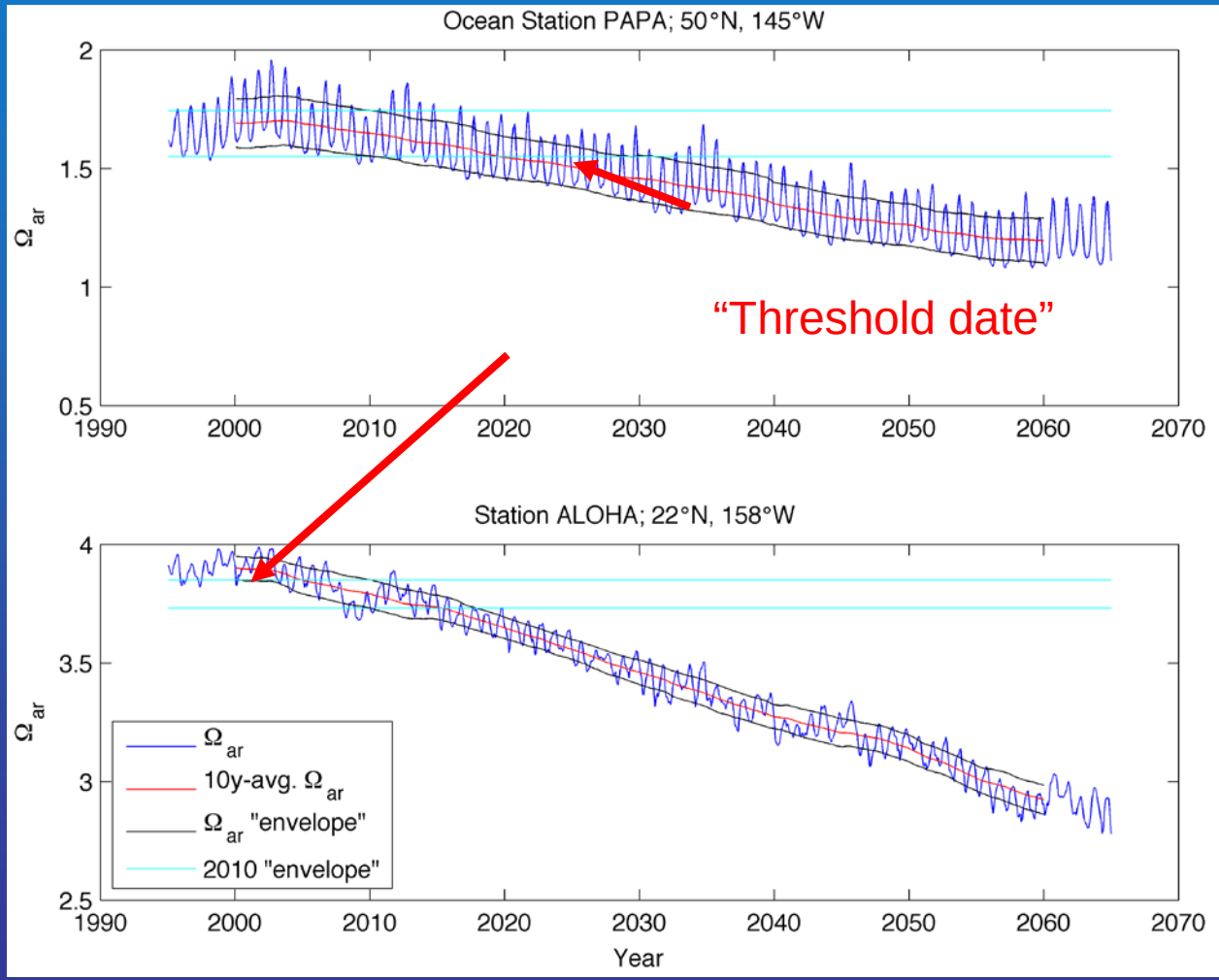


Data from U.N. FAO;
Cooley et al. submitted to *Fish and Fisheries*

When is Ω_{ar} significantly different from today?

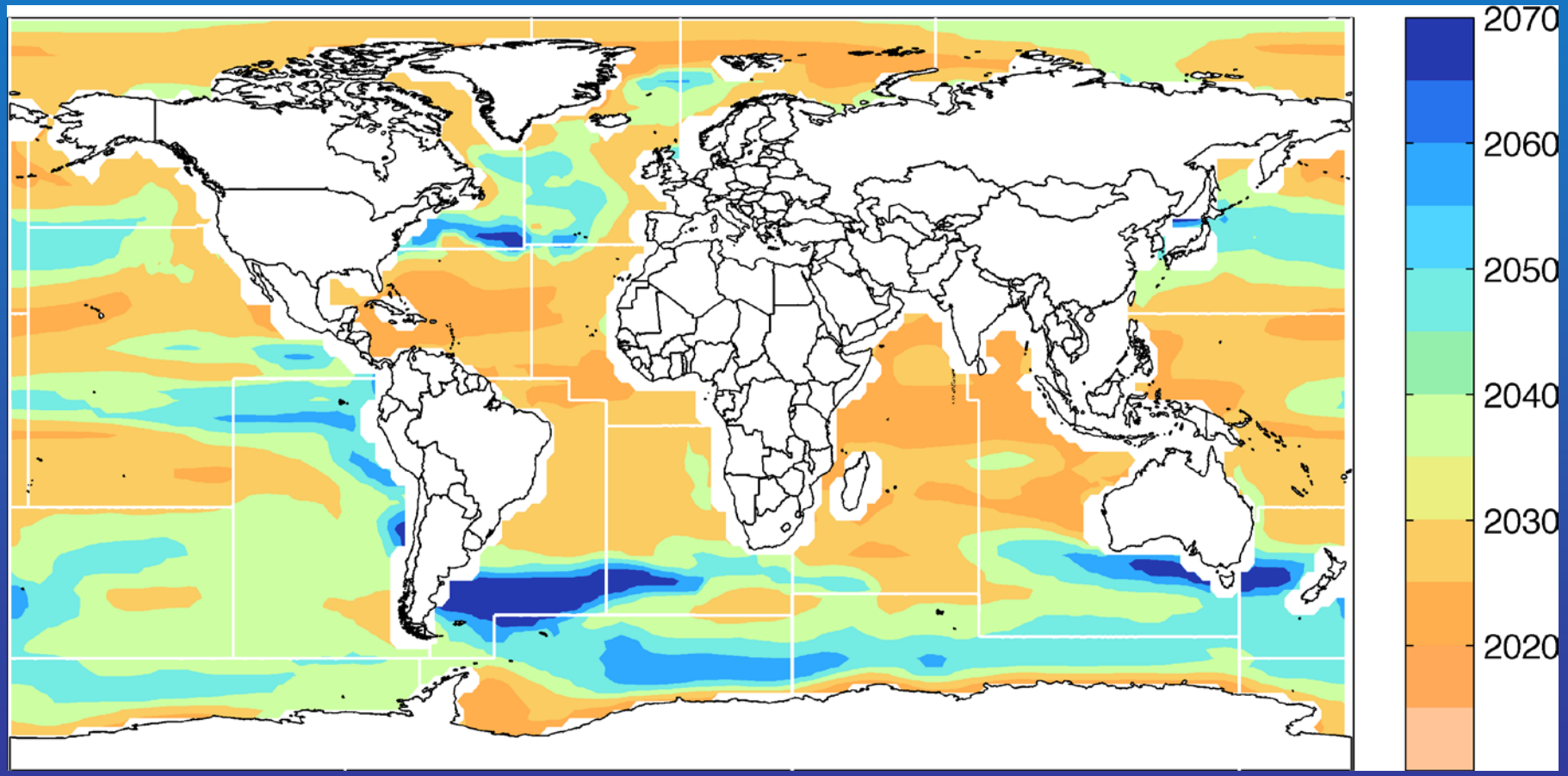
Monthly mean Ω_{ar}
Decadal mean Ω_{ar}
2010 Ω_{ar} envelope
Running Ω_{ar} envelope

"envelope" =
mean ± RMS



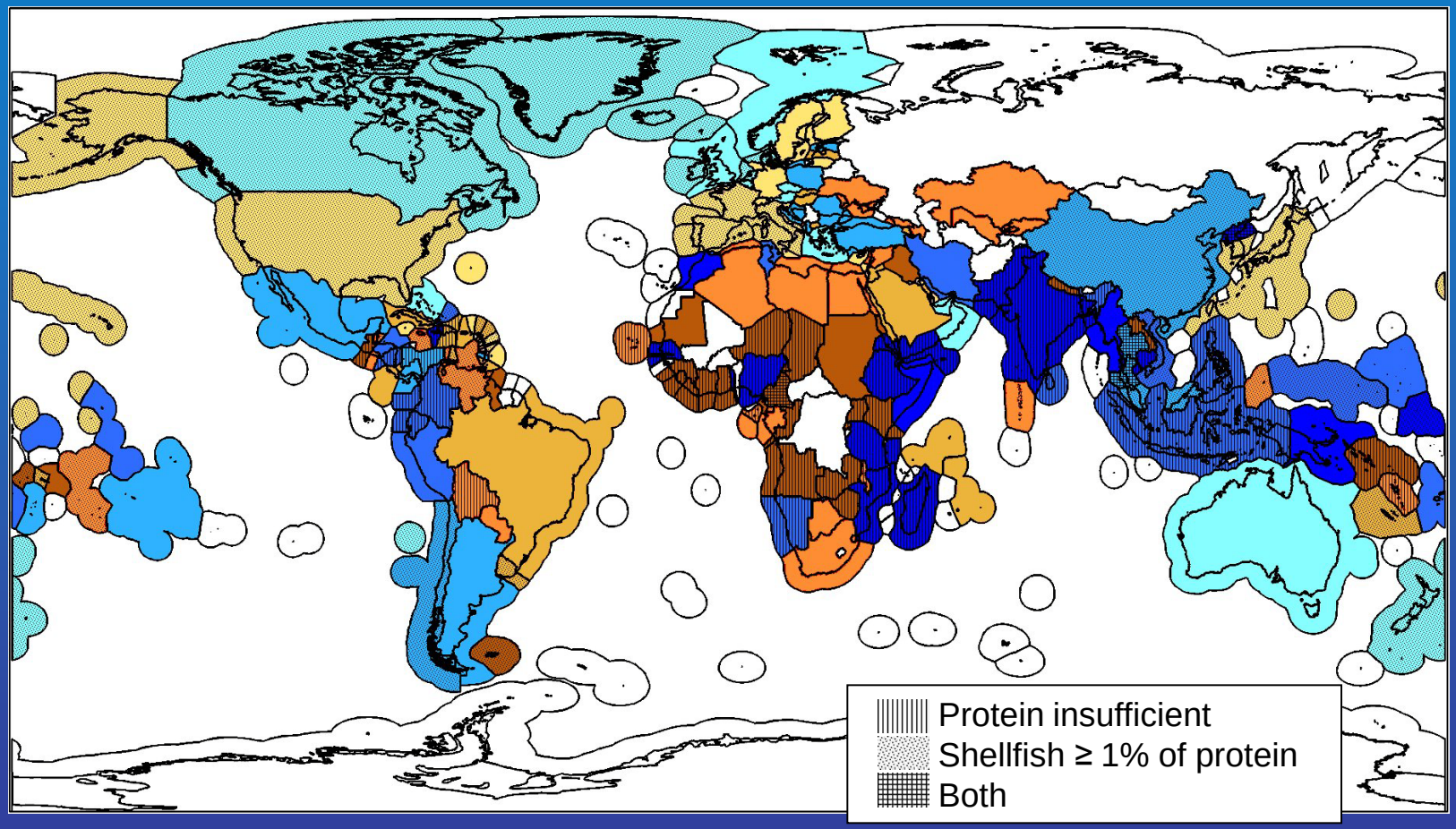
Calculated from Community Climate System Model 3.1 output;
Cooley et al. submitted to *Fish and Fisheries*

Threshold date: when Ω_{ar} is significantly different



Cooley et al. submitted

Vulnerability from socioeconomic links to shellfish



Net importers

Net exporters

Least adaptable

Most adaptable

Cooley et al. submitted

National vulnerability index

Points	Reason
+1	Mollusks provide > 0.001% of GDP
+1	Country is protein insufficient
+1	Mollusks provide > 1% of citizens' protein
+1	Required production increase by 2050 > 100%
+1	Country has no mollusk aquaculture
+0-3	Adaptability score percentile
+0-1	Normalized years until threshold date

Nations ranked by total vulnerability points

Cooley et al. submitted to *Fish and Fisheries*

Vulnerabilities to decreased mollusk harvests

Net mollusk exporters

Most vulnerable	Least vulnerable
1. Senegal	1. Hong Kong
2. Madagascar	2. United Kingdom
3. Gambia	3. Greece
4. Togo	4. Australia
5. Ethiopia	5. Norway

Net mollusk importers

Most vulnerable	Least vulnerable
1. Solomon Isl.	1. Sweden
2. Ivory Coast	2. Germany
3. Jamaica	3. Brunei
4. Dominican Rep.	4. Slovenia
5. Belize	5. Brazil

Exporters may have an edge if mollusk scarcity increases prices.

Cooley et al. submitted to *Fish and Fisheries*

OA as a geohazard acting through mollusks

- Mollusks provide protein, income for many nations
- Threshold date soon + mollusks socioeconomically important = greatest vulnerability
- Good adaptive solutions will include
  the timescales of expected change and
  socioeconomic importance of mollusks to citizens

OA: Human causes, human effects

Industrial activities

Ocean CO_2 uptake

Ecosystem consequences?

Socioeconomic dimensions?

Greater investment, less reward?

Future possibilities

Consequences?

- Stress particular species?
- Biogeographic shifts?
- Food web shifts
- Altered ecosystem svcs. (food, income, protection)
- Need for protein sources

Adaptations?

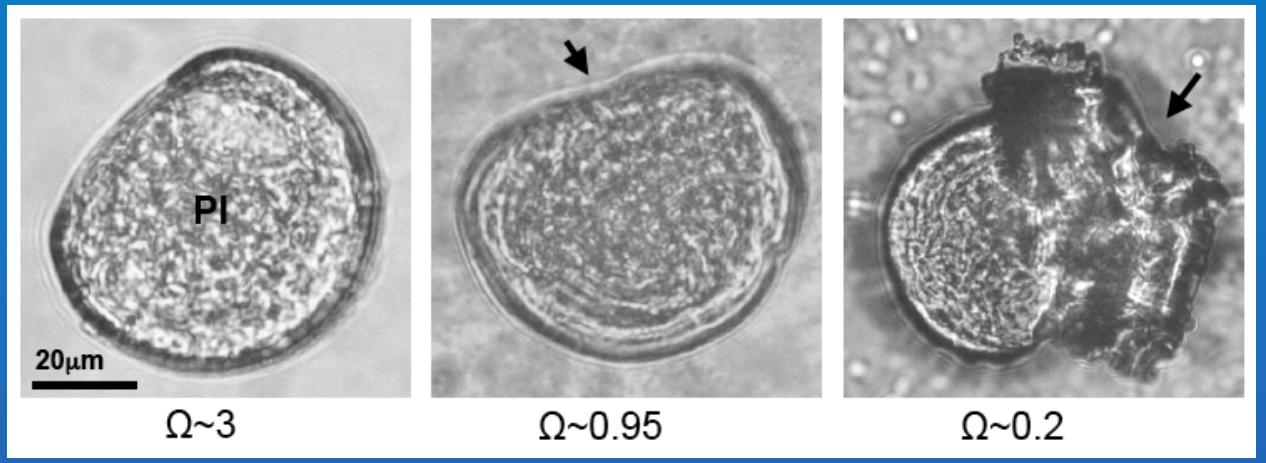
- Ecosystem-based management
- Fisheries switching/buyouts
- Protected areas
- Support communities through changing economies
- Technology transfer to developing nations

(Research) Needs

- Regionally targeted research
- Natural science studies
  - Chemical time-series
  - Organisms to ecosystems
- Economic and social science studies
  - Valuation
  - Integrating over time
- Coupled chemo-eco-socioeconomic models (if-then assessments)

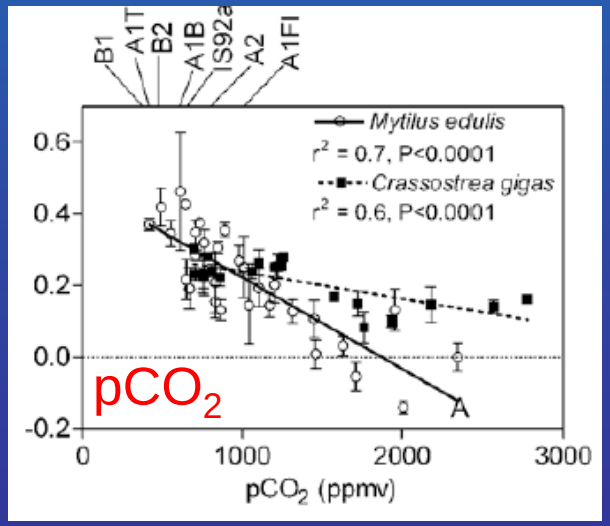
Thank you!

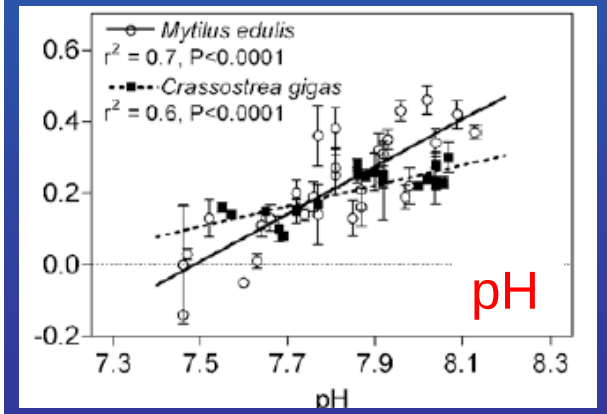
Mollusks develop, calcify differently



Larval Eastern Oyster (*Crassostrea virginica*)
Anne Cohen and Dan McCorkle, WHOI, 2007

Oyster & mussel calcification rates decline from OA

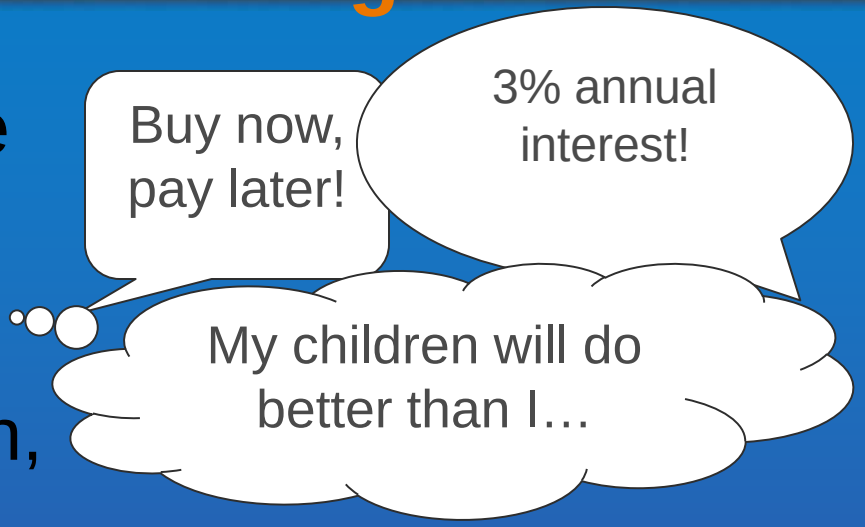




Gazeau et al., GRL 2007

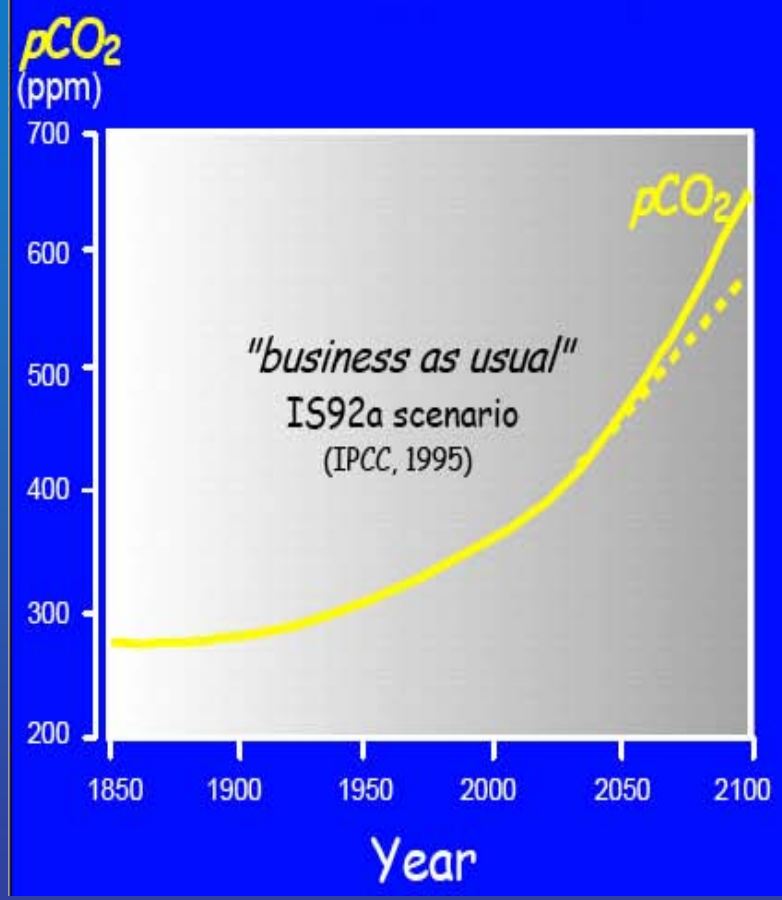
Another difficulty: discounting the future

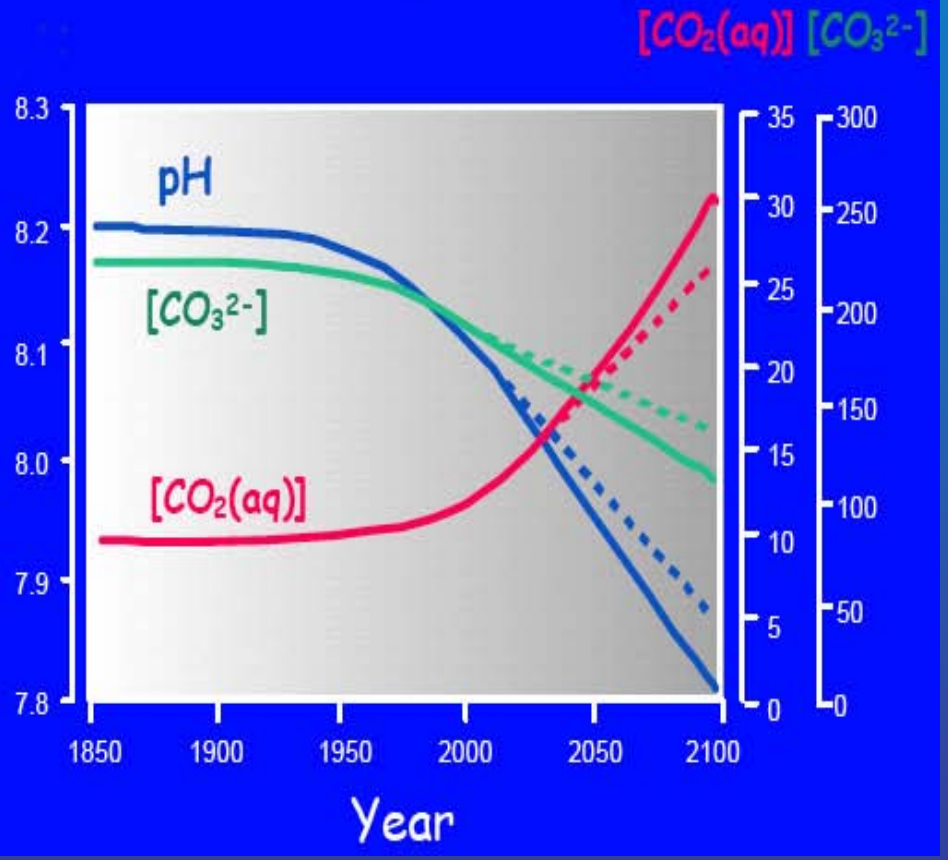
- Summing values over time involves discounting
- Assumes economic growth, constant social values
- Debate over discount rate
- Need other decision-making currency?



Discussed at length in Stern 2009, *The Global Deal*.

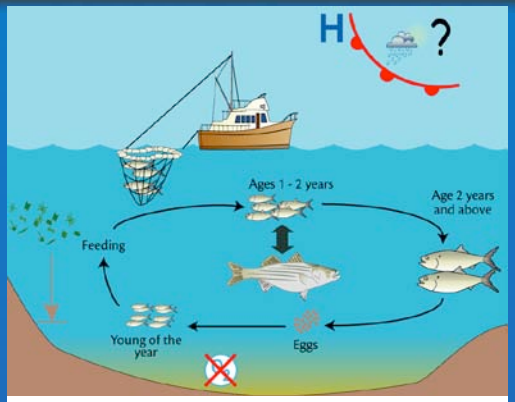
Accelerating Trends over 21st Century



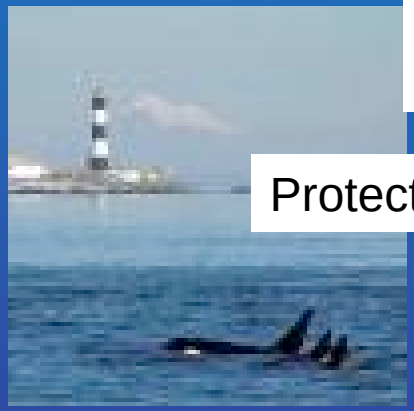


Adaptation & mitigation needed

Aquaculture



Ecosystem-based management



Protected areas

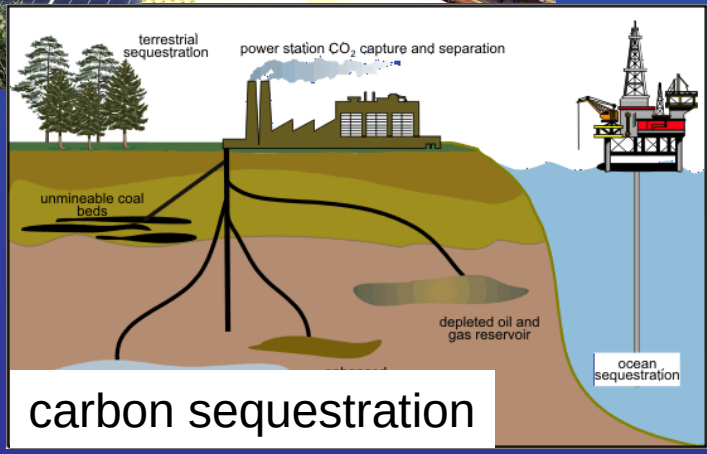
Harvest resilient species

Retrain workers

energy conservation

renewable energy

vehicles & buildings



carbon sequestration

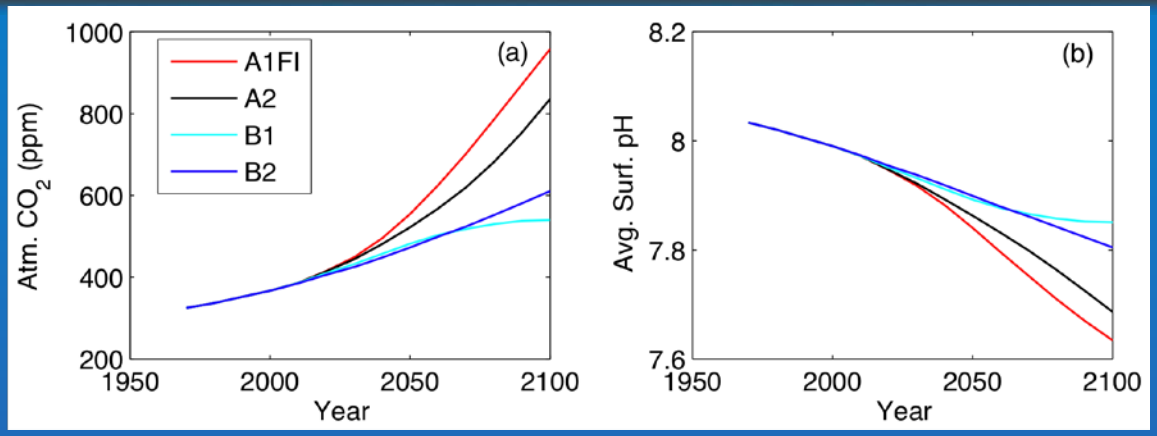
What could OA do?

Results:

-Annual harvest decreases of 6%(B1)-25% (A1FI) by 2060

-Mollusks = $748 M of U.S. ex-vessel revenues (2007)

-10-25% harvest decreases = $75-187 M ex-vessel losses each year



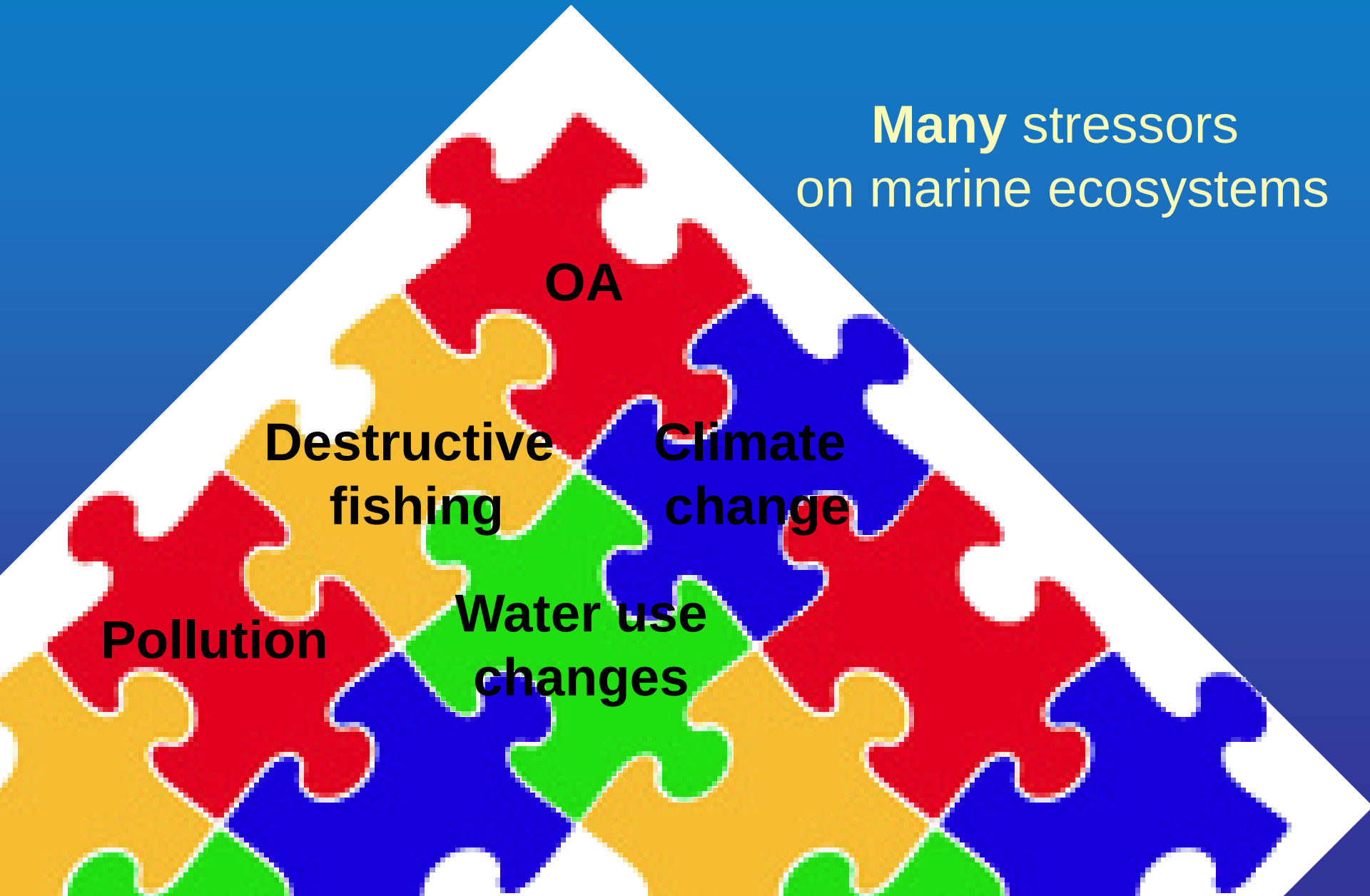
NPV by 2060 (millions, U.S. $)

Discount rate	*4%*	*2%*	*0%*
Losses, Low CO_2 (B1)	324-809	610-1,523	1,226-3,063
Losses, High CO_2 (A1FI)	543-1,358	1,023-2,557	2,058-5,144
Fishery NPV, no losses	17,115	25,063	40,406

Cooley and Doney *ERL* 2009

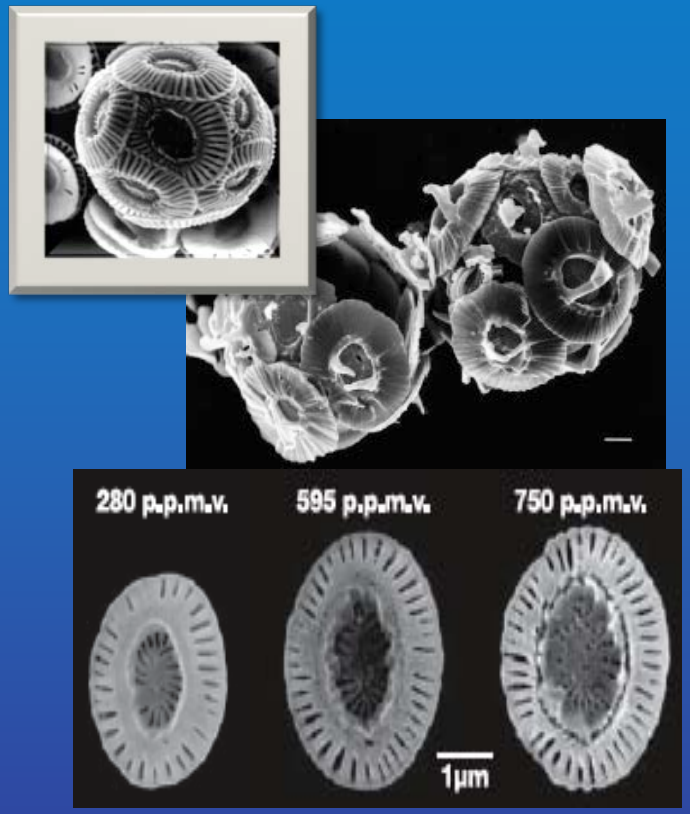
OA's not acting in a vacuum

Many stressors
on marine ecosystems

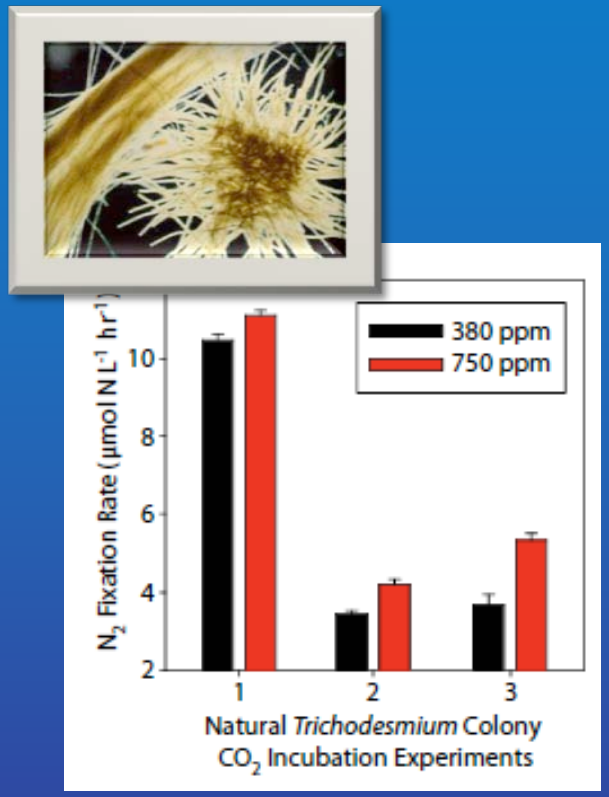


Plankton respond to elevated CO_2

Pteropods
finfish prey



Coccolithophores
photosynthesis,
$CaCO_3$ export



Trichodesmium
photosynthesis,
nitrogen fixers

Orr et al., 2005; Riebesell et al. 2000; Iglesias-Rodriguez et al. 2008; Hutchins et al. 2009

Observed ecosystem responses

Near a volcanic CO_2 vent,

- adult mollusks damaged
- juvenile mollusks absent
- corals, coralline algae absent
- abundant macroalgae & seagrasses

Hall-Spencer et al., *Nature* 2008

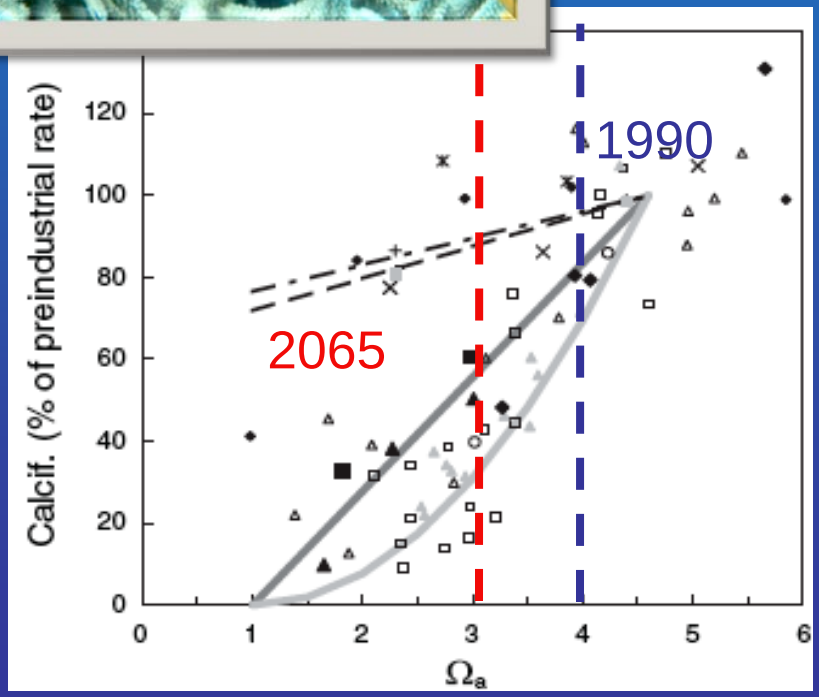
In a coastal lagoon,

noncalcifiers replaced calcifiers over an 8-y pH drop (8.41-7.99)

Wootton et al. *PNAS* 2008; Photo, U. Washington

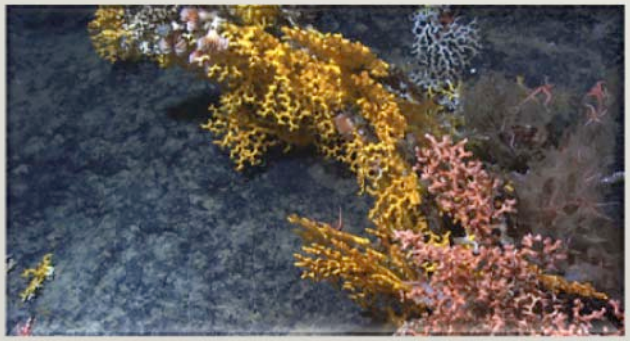
Coral calcification & range respond to Ω

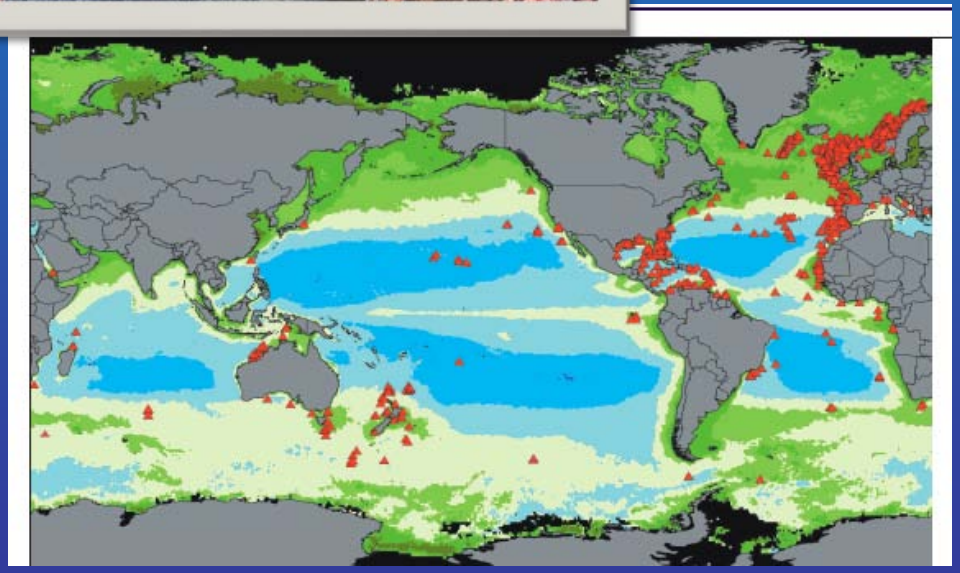
Warm corals



Langdon & Atkinson, GBC 2004

Cold corals





Guinotte et al. Frontiers Ecol. Environ. (2006)