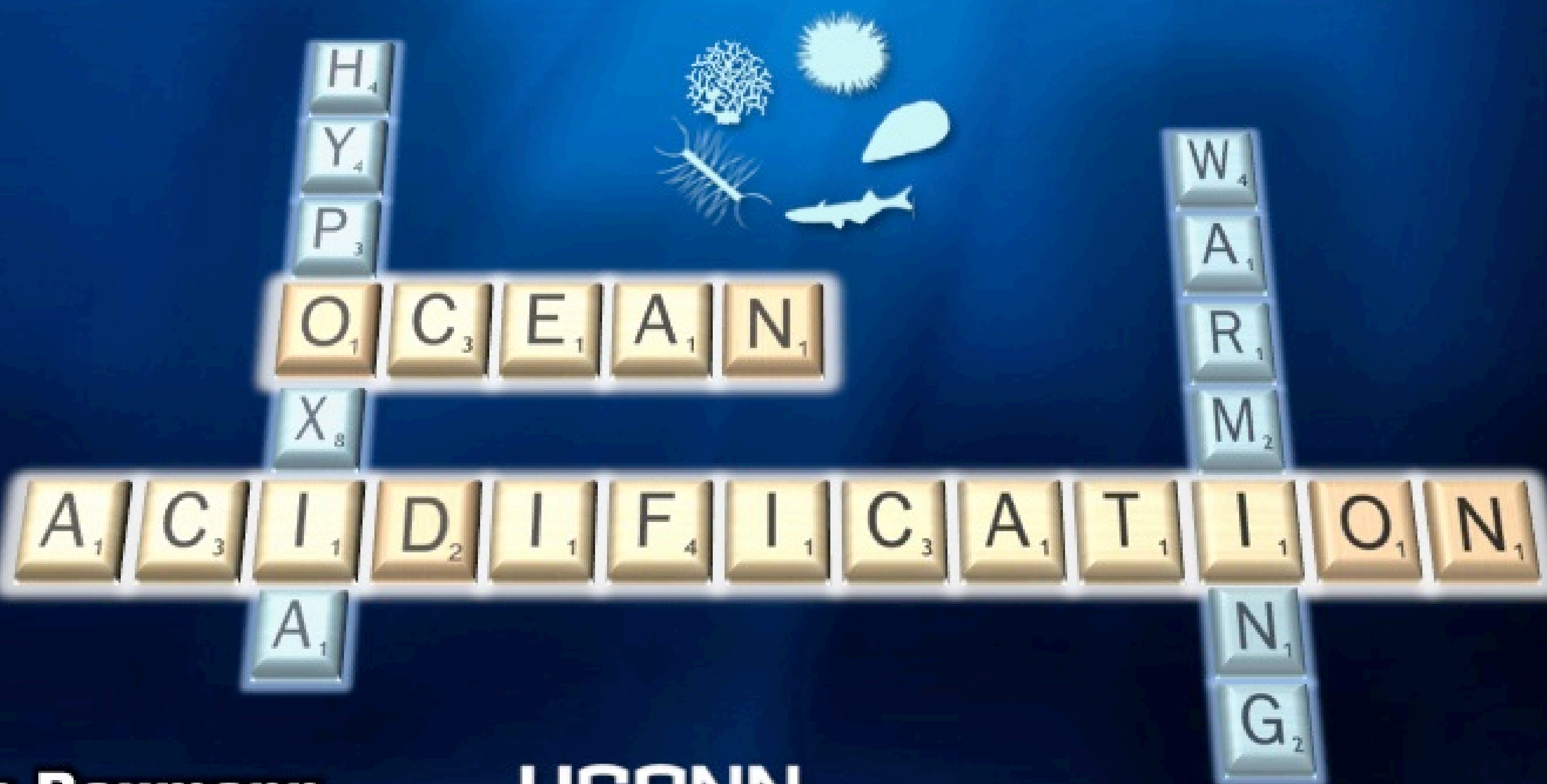
LIMNOLOGY AND OCEANOGRAPHY

ASLO e-Lectures

Combined Effects of Ocean Acidification, Warming, and Hypoxia on Marine Organisms



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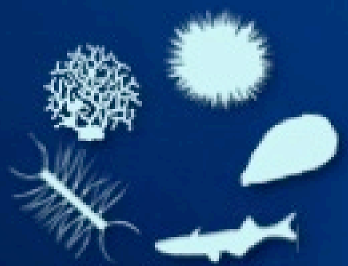
A multistressor perspective of OA: key concepts

T + CO_2 + O_2 = Climate Change Syndrome

1 + 1 > 2

OA, hypoxia, and warming *combined* often have stronger negative effects on marine organisms than OA alone.



Single-stressor research underestimates the true impact of marine climate change.

Stressor interactions are not understood. Multi-stressor research is urgently needed.

STRESSOR: A physical or biological variable altered by human activities that makes negative physiological or ecological responses more likely.

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doi:10.1002/loe2.10002

Human activity disturbs many global systems

Ocean acidification is accompanied by other stressors

Rockstroem et al. *Nature* 2009

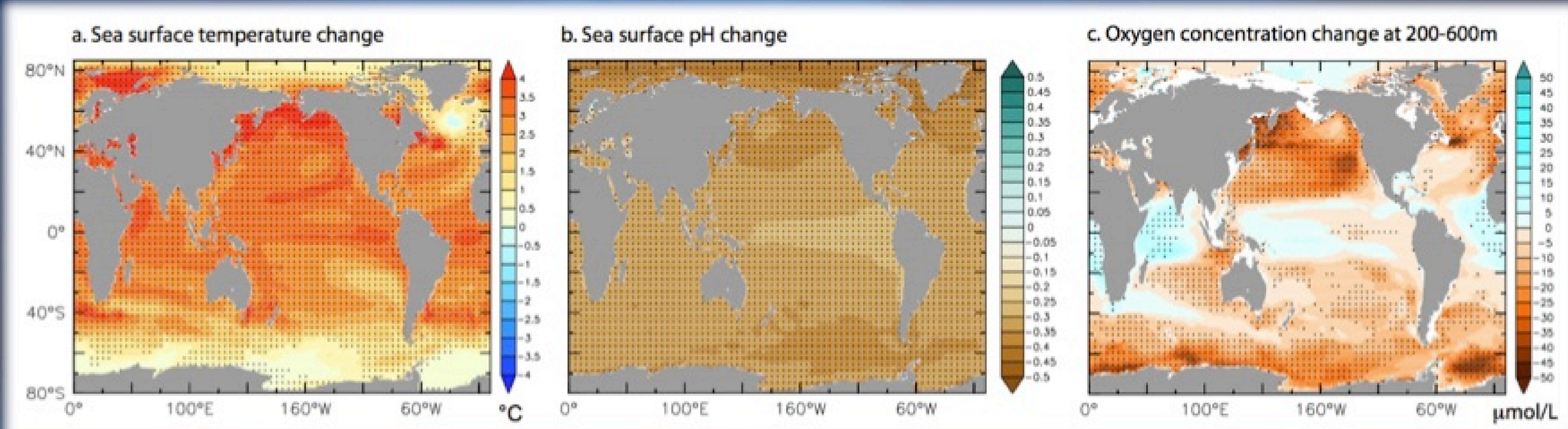
1. Freshwater use
2. **Reactive N & P emissions**
3. Ocean acidification
4. Chemical pollution
5. **Climate change**
6. Ozone depletion
7. Land use
8. Biodiversity loss

Two processes are particularly relevant in combination with OA

CO_2: the global driver of marine climate change

Ultimate cause	*Proximate cause*	*Physical principle*	*Effect / stressor*
Fossil fuel combustion + Deforestation →	**Increasing atmospheric CO_2 levels** →	**Greenhouse effect** →	**Warming**
		CO_2 dissolution in seawater →	**Acidification**
		O_2 decreases as temperature and stratification of the ocean increase →	**Deoxygenation**

Global processes advance at regionally different rates



Bopp et al. Biogeosciences 2013

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doi:10.1002/loe2.10002

ASLO *e-Lectures*

Regional drivers of change in coastal waters

Ultimate cause	*Proximate cause*	*Physical principle*	*Effect / stressor*

Industrial agriculture, land use, population growth → Eutrophication

↓

Increased phytoplankton growth

→ **Increased microbial respiration**

→ **Consumes the dissolved O_2 in water** → **Deoxygenation/ Hypoxia**

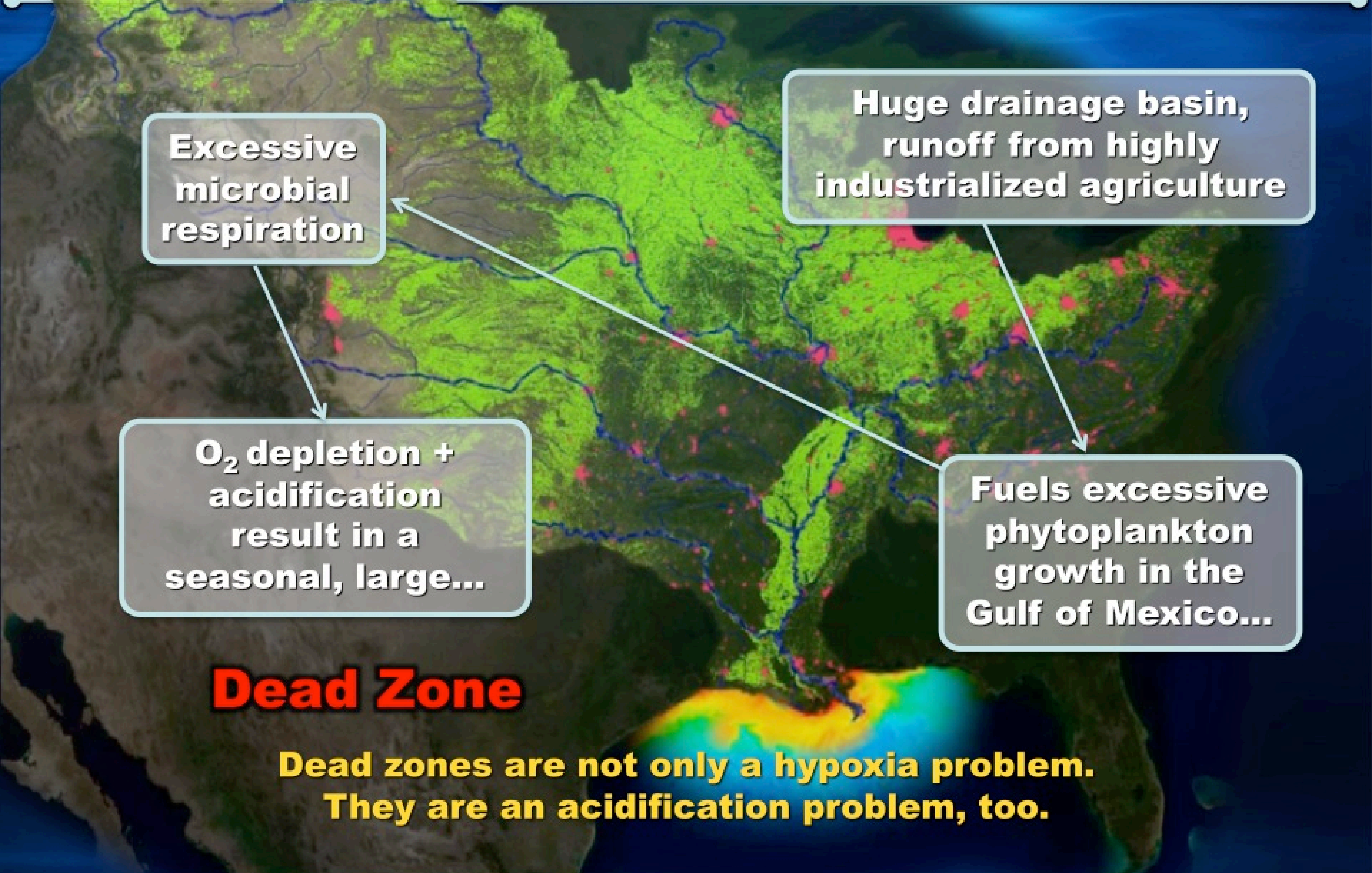
→ **Produces CO_2 that dissolves in water** → **Acidification**

Eutrophication-induced ***HYPOXIA*** *has long been recognized as a* ***global problem****.*

Coastal ***ACIDIFICATION*** *is* ***the other eutrophication problem!***

doi:10.1002/loe2.10002

The Mississippi Delta: a spigot of excessive nutrients



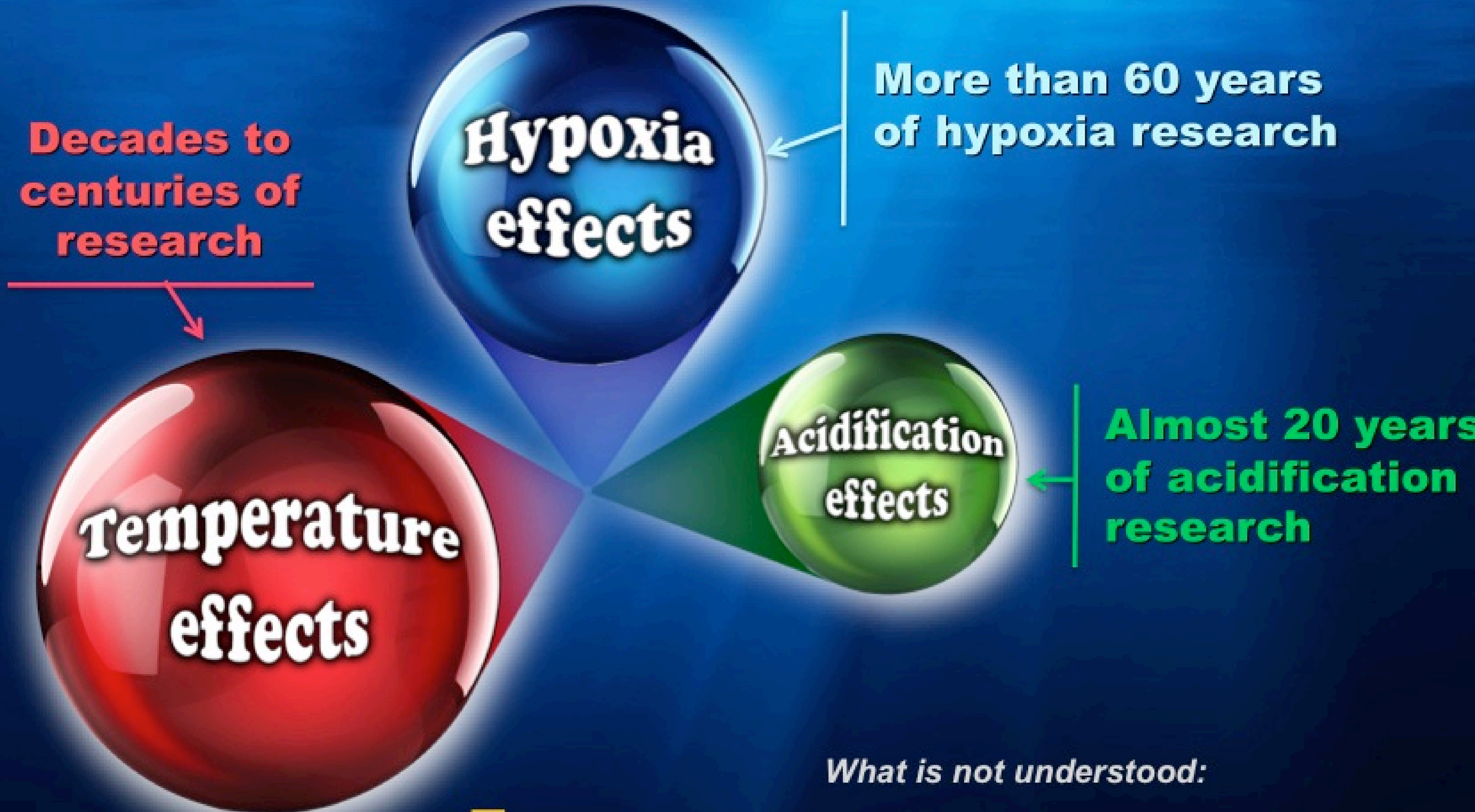
doi:10.1002/loe2.10002

Temperature and oxygen as major co-stressors

- **Warming + increasing O_2 levels: major co-stressors of ocean acidification**
- **They can result from humans emitting excessive amounts of CO_2 and reactive nitrogen & phosphorus**
- **Rates of change, severity, and consequences for marine life vary regionally and over time**
- **Other factors contribute to local changes**

doi:10.1002/loe2.10002

After decades of research, what gaps remain?

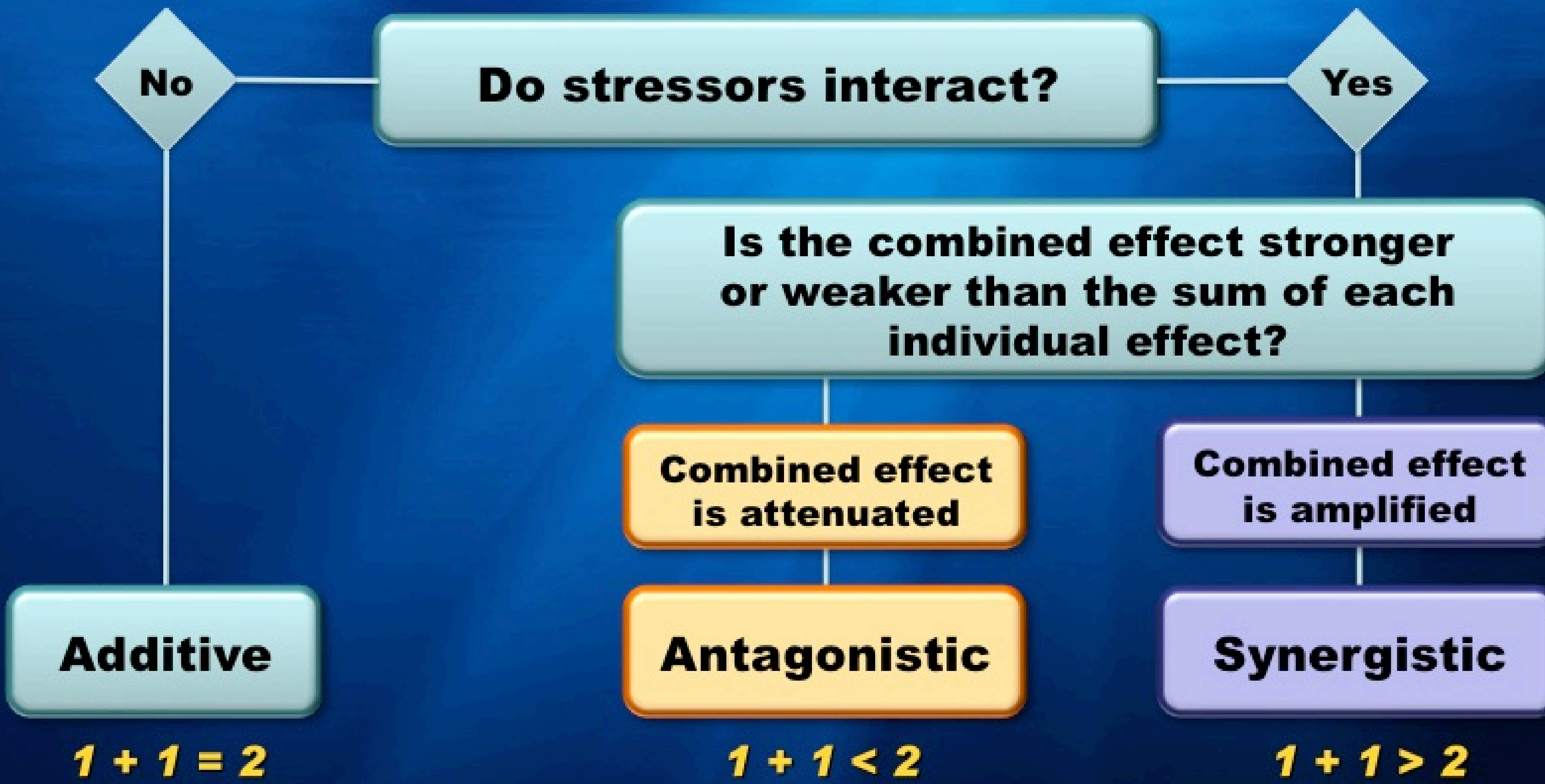


What is not understood:

[What are the combined effects of these stressors on organisms and their fitness relevant traits?]

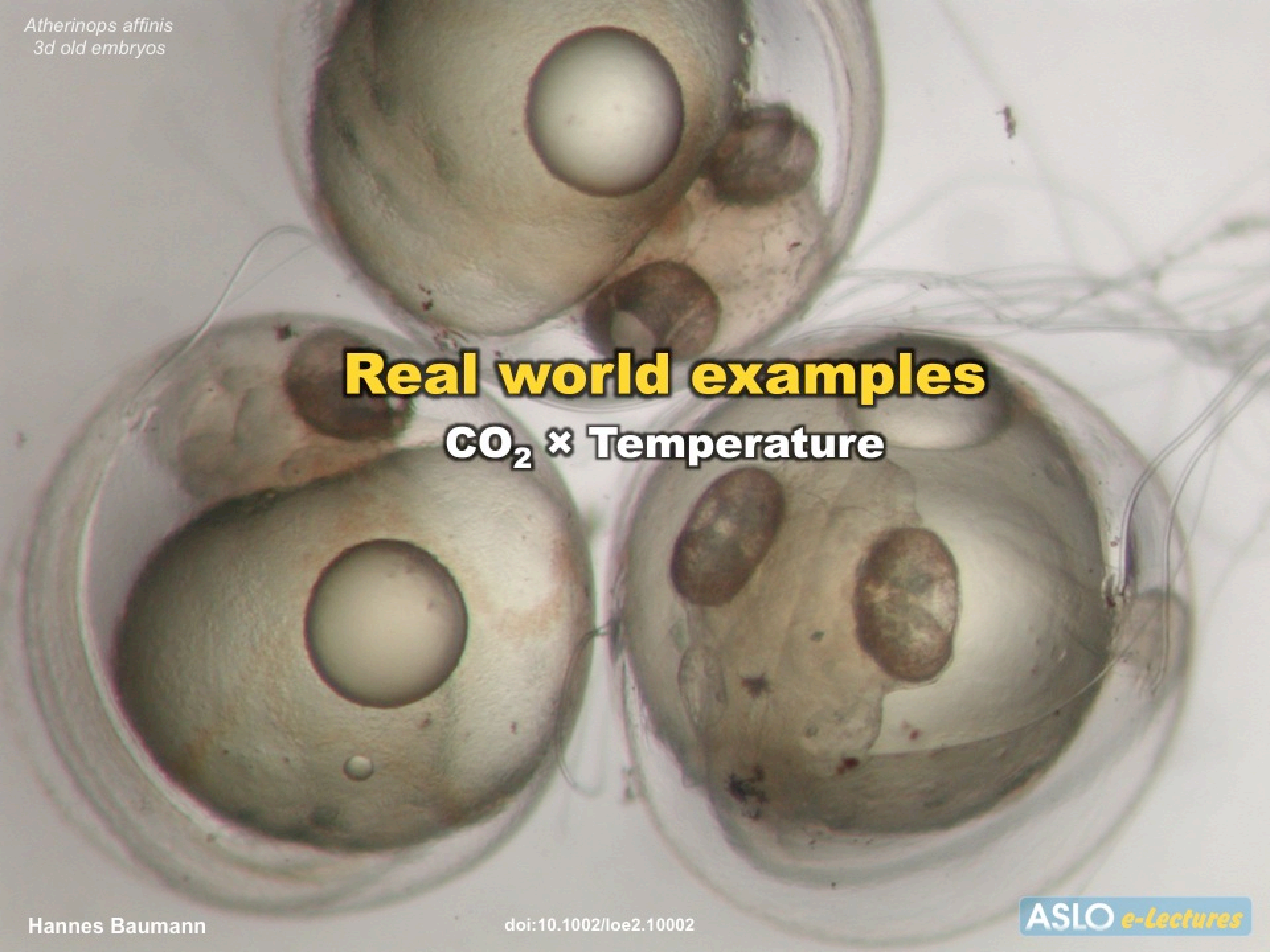
doi:10.1002/loe2.10002

Three possible outcomes when stressors co-occur



Interactions will vary between traits, species, populations, ...individuals?

doi:10.1002/loe2.10002



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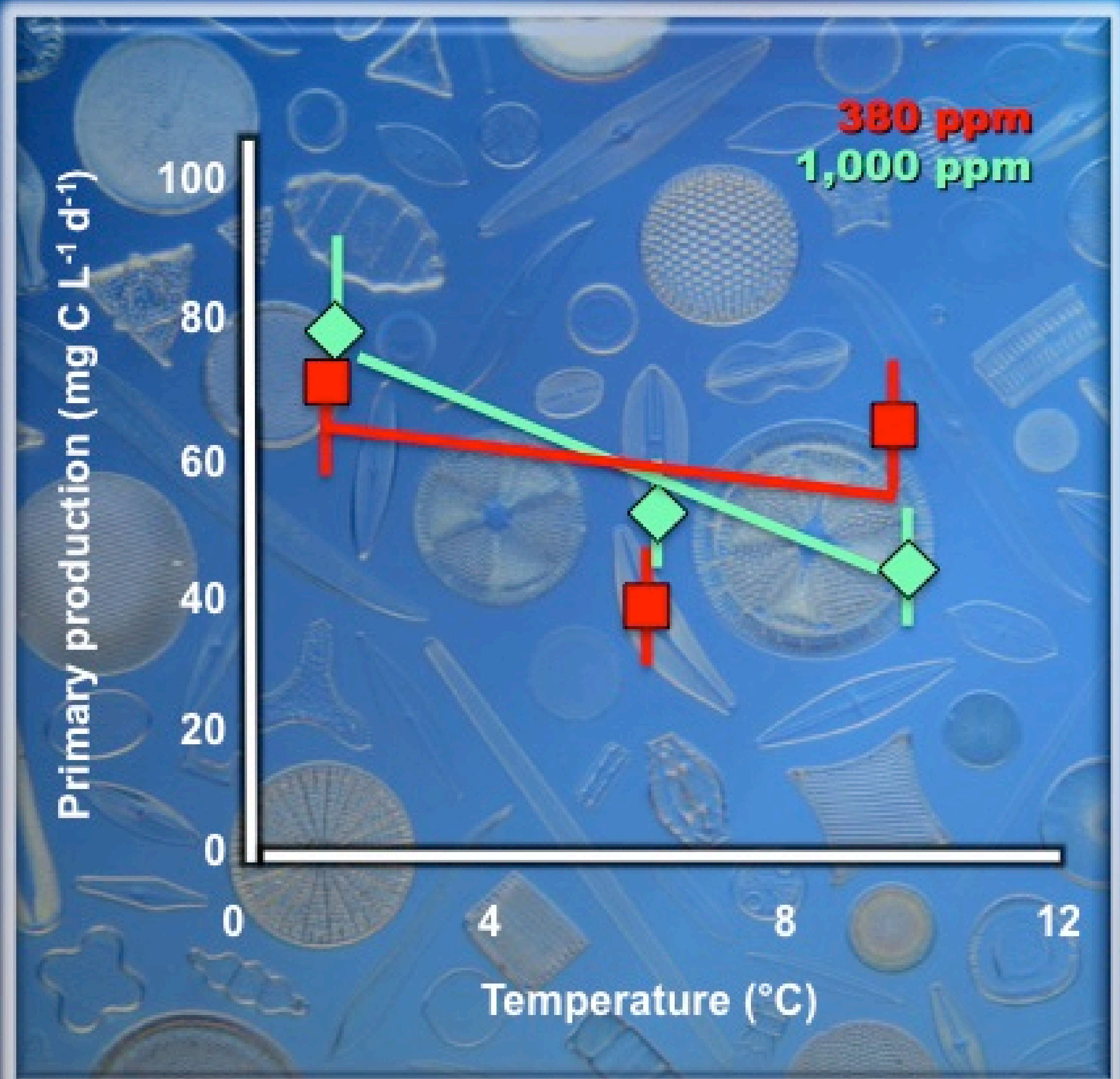
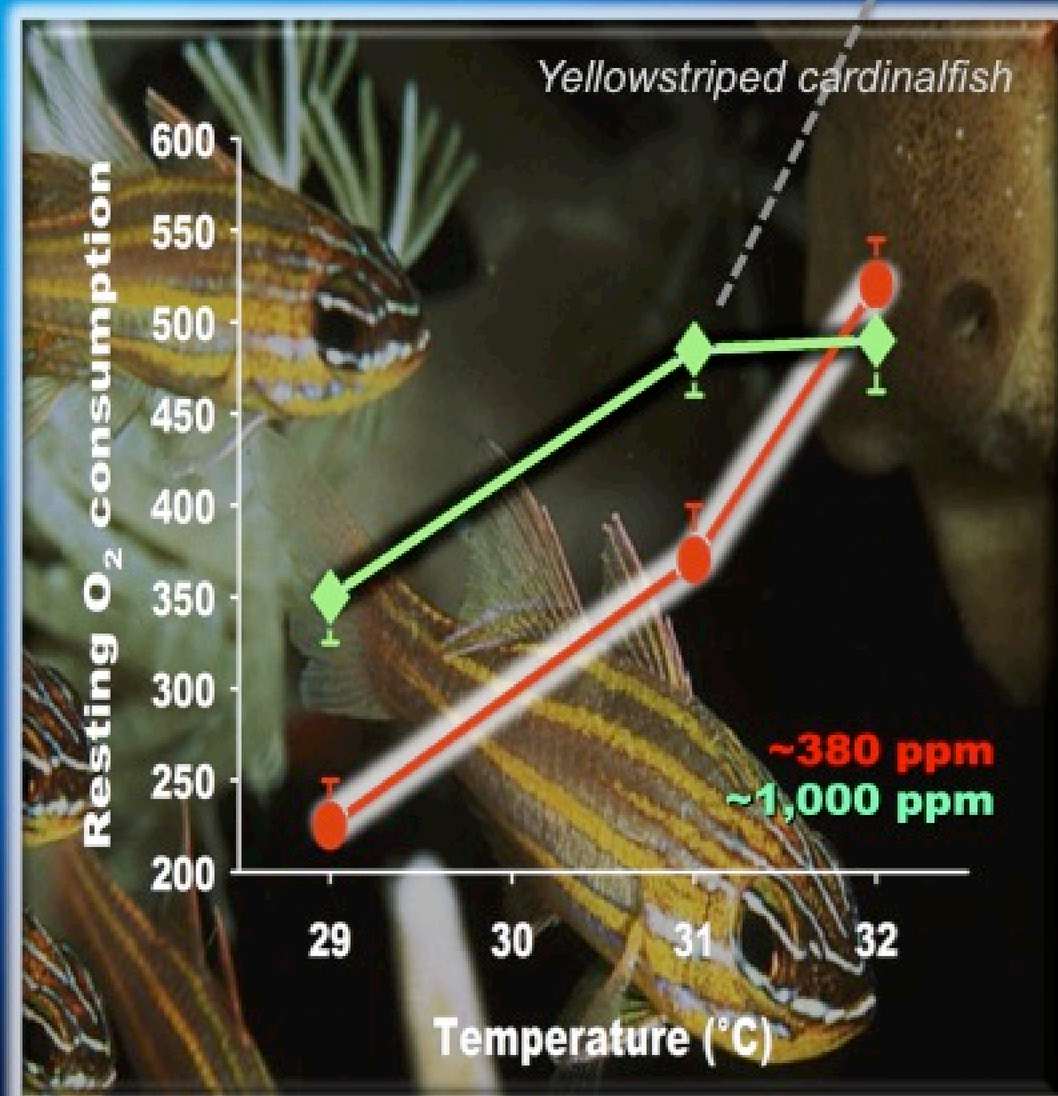
When 1 + 1 ≠ 2: real world examples for stressor interaction

Primary production of Arctic diatoms



Coello-Camba et al. Frontiers of Marine Science 2014

Metabolism in a tropical reef fish



Munday et al. MEPS 2009

Traits changed with temperature, but differently under ambient vs. high CO_2 regimes.

Unpredictable from single-stressor experiments.

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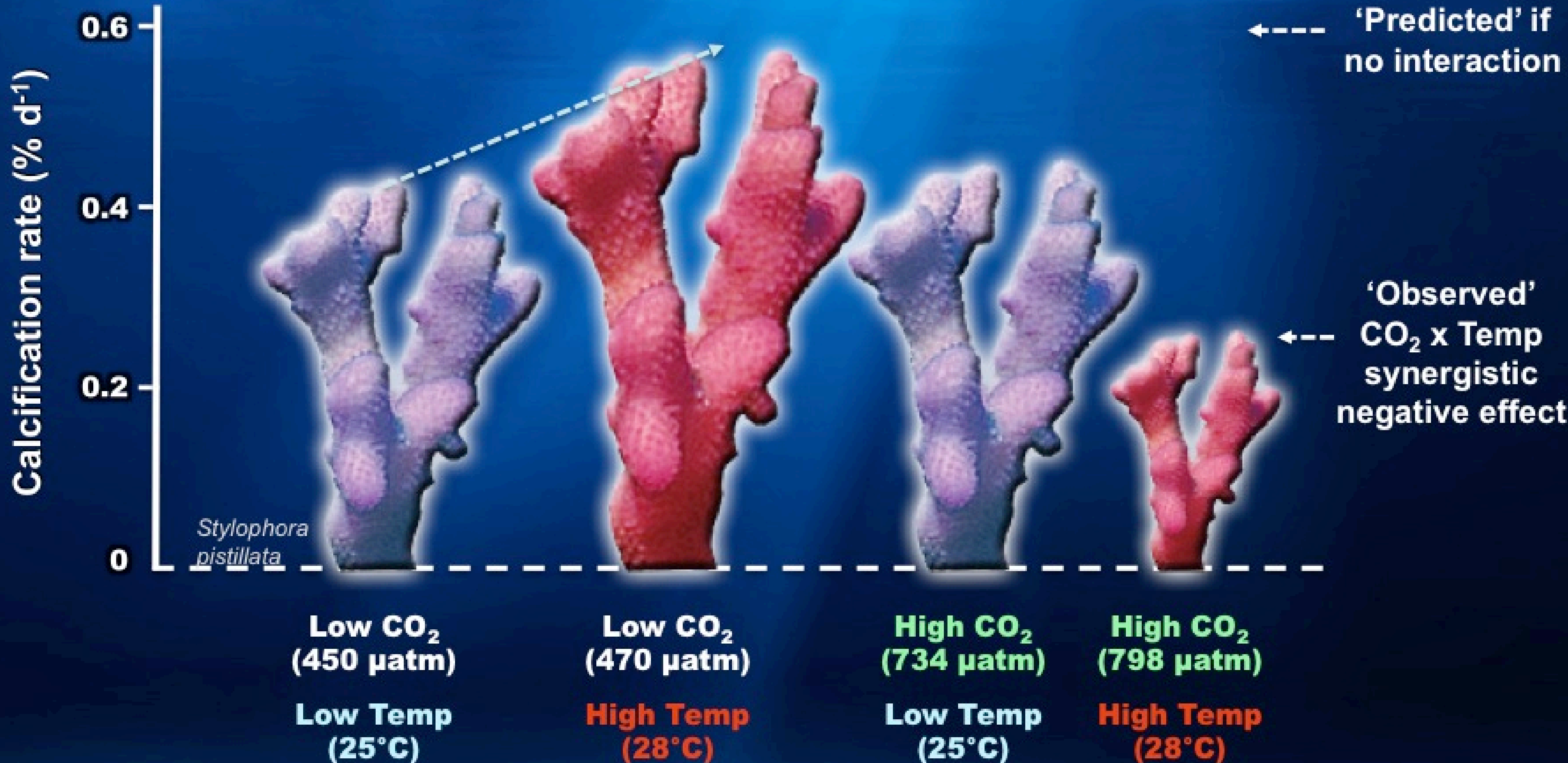
Synergistic CO_2 × temperature effects in a coral

- Calcification at 25°C robust against high CO_2
- At 28°C and elevated CO_2 decrease by 50%



Reynaud et al.
Global Change Biology 2003

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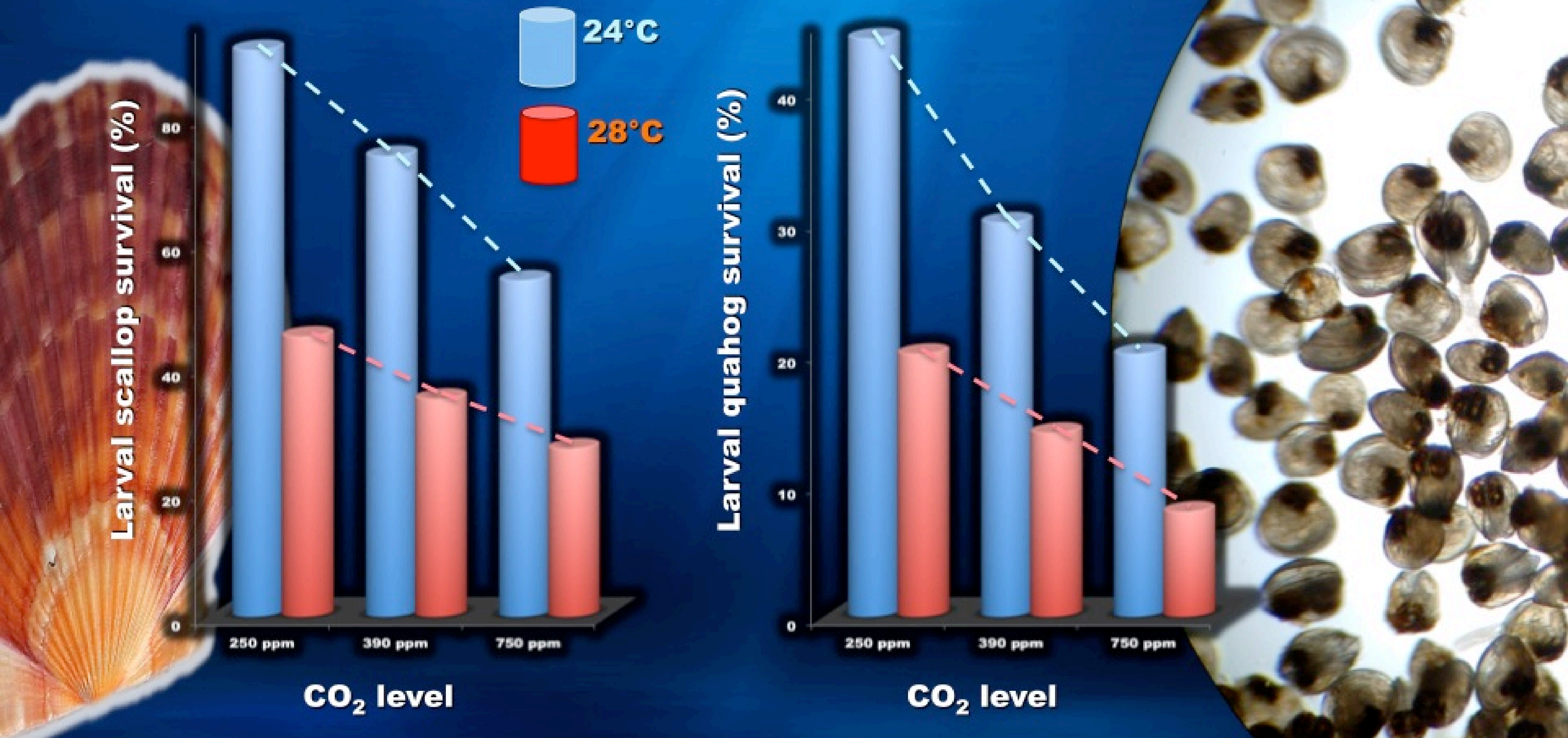
doi:10.1002/loe2.10002

Additive CO_2 × temperature effects in two shellfish species

Additive negative effects of warming and acidification on survival in *Quahog* and *Scallop* larvae

Talmage & Gobler PLoS One 2011



doi:10.1002/loe2.10002

CO_2 effects on thermal tolerance in spider crab life stages

Thermal tolerance in spider crabs lower at high CO_2 levels, but...

Megalopae: narrowest window, unaffected by high CO_2.

Zoeae: high CO_2 narrowed the window, caused respiration and heart rate failure at a lower temperature compared to controls.

Schiffer et al. Frontiers in Zoology 2014

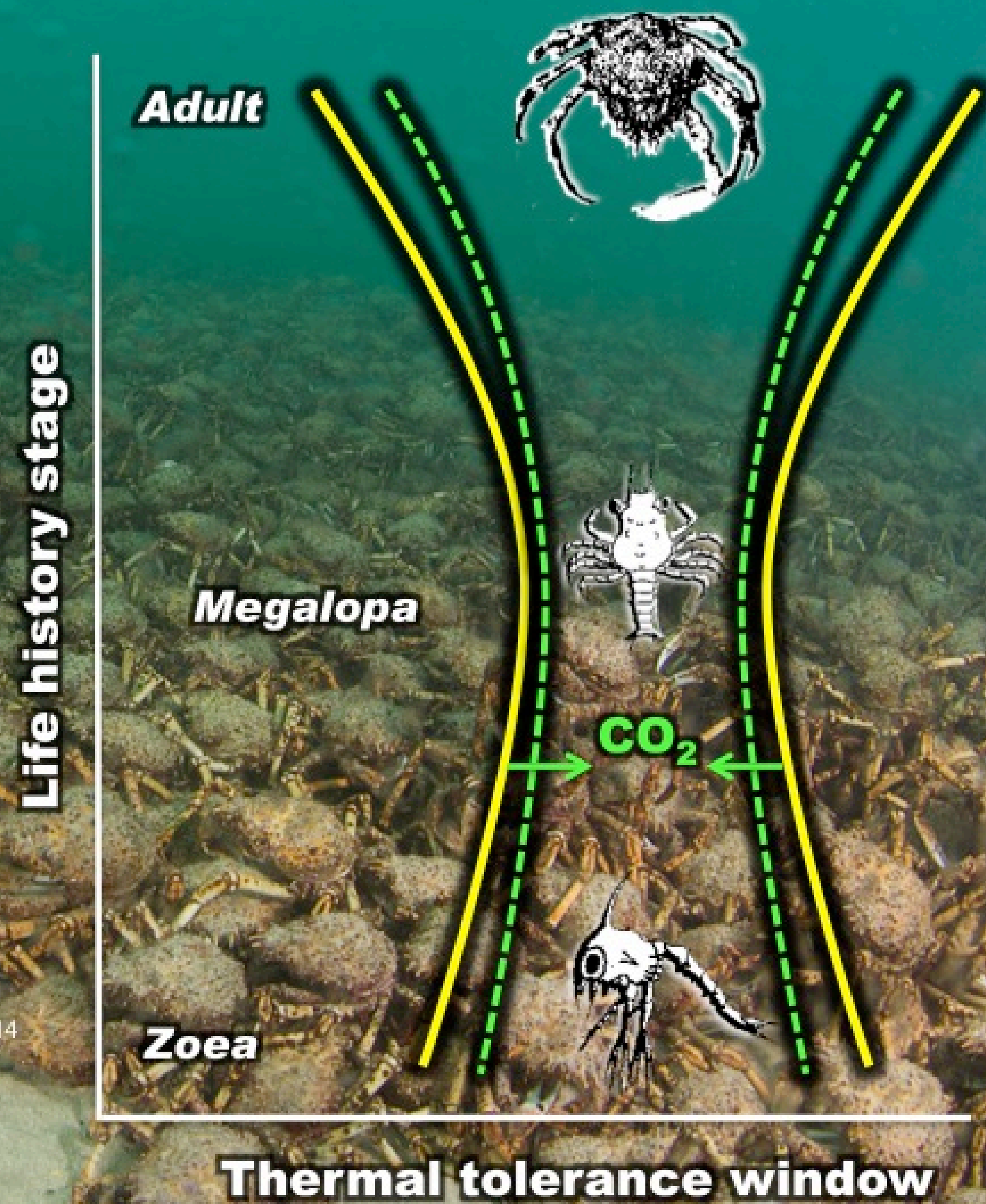
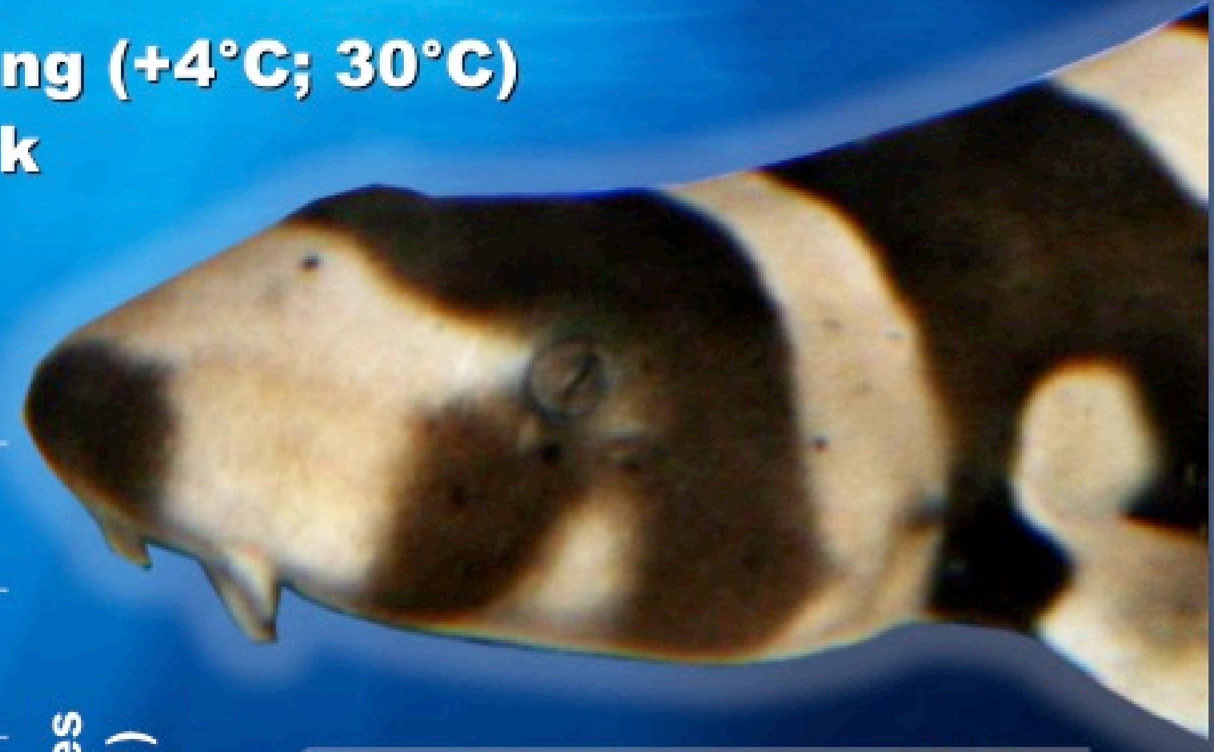


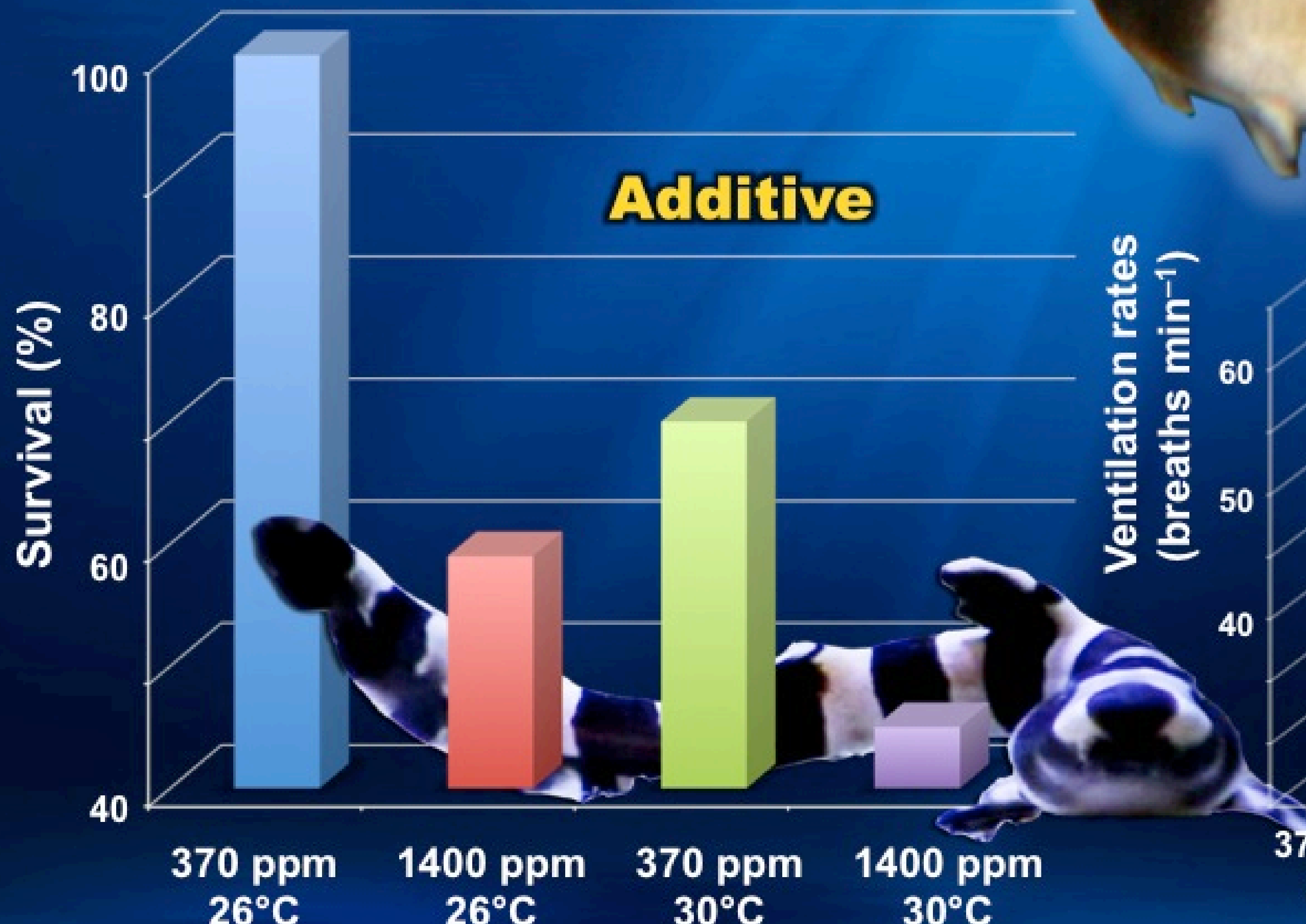
Image: Matti Tornio 2012

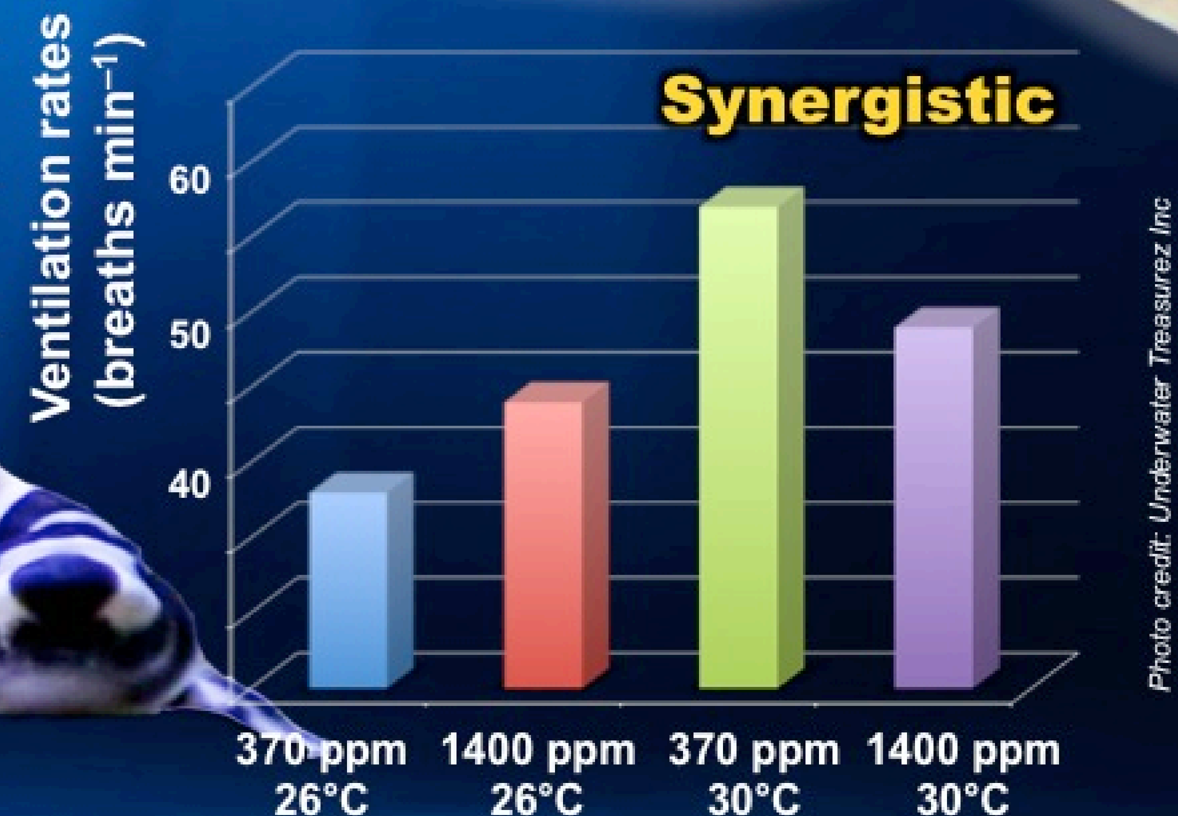
doi:10.1002/loe2.10002

CO_2 × temperature effects, even in sharks

Acidification (ΔpH = 0.5) and warming (+4°C; 30°C) significantly impaired juvenile shark condition and survival. *Rosa et al. PRSB 2014*



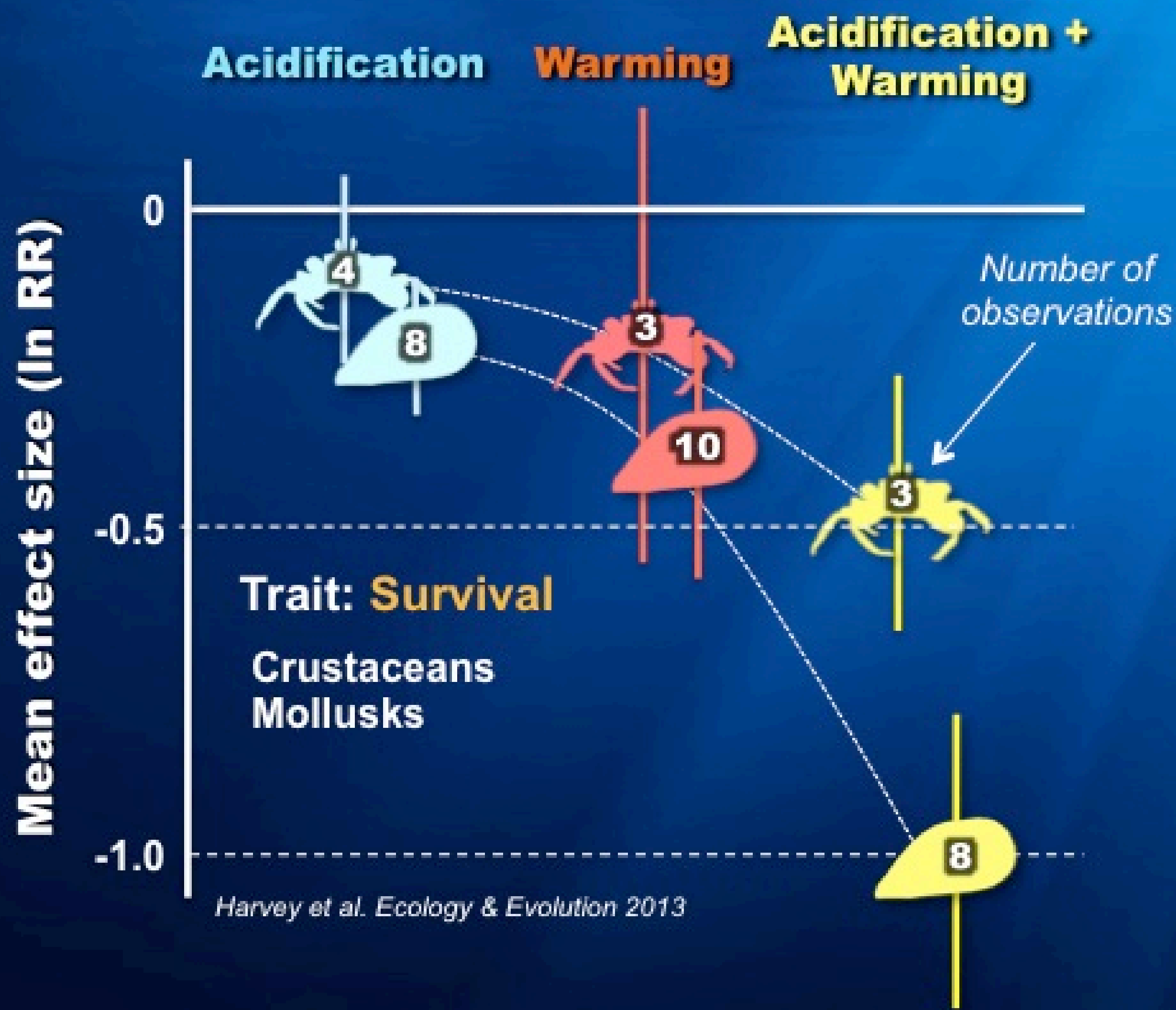


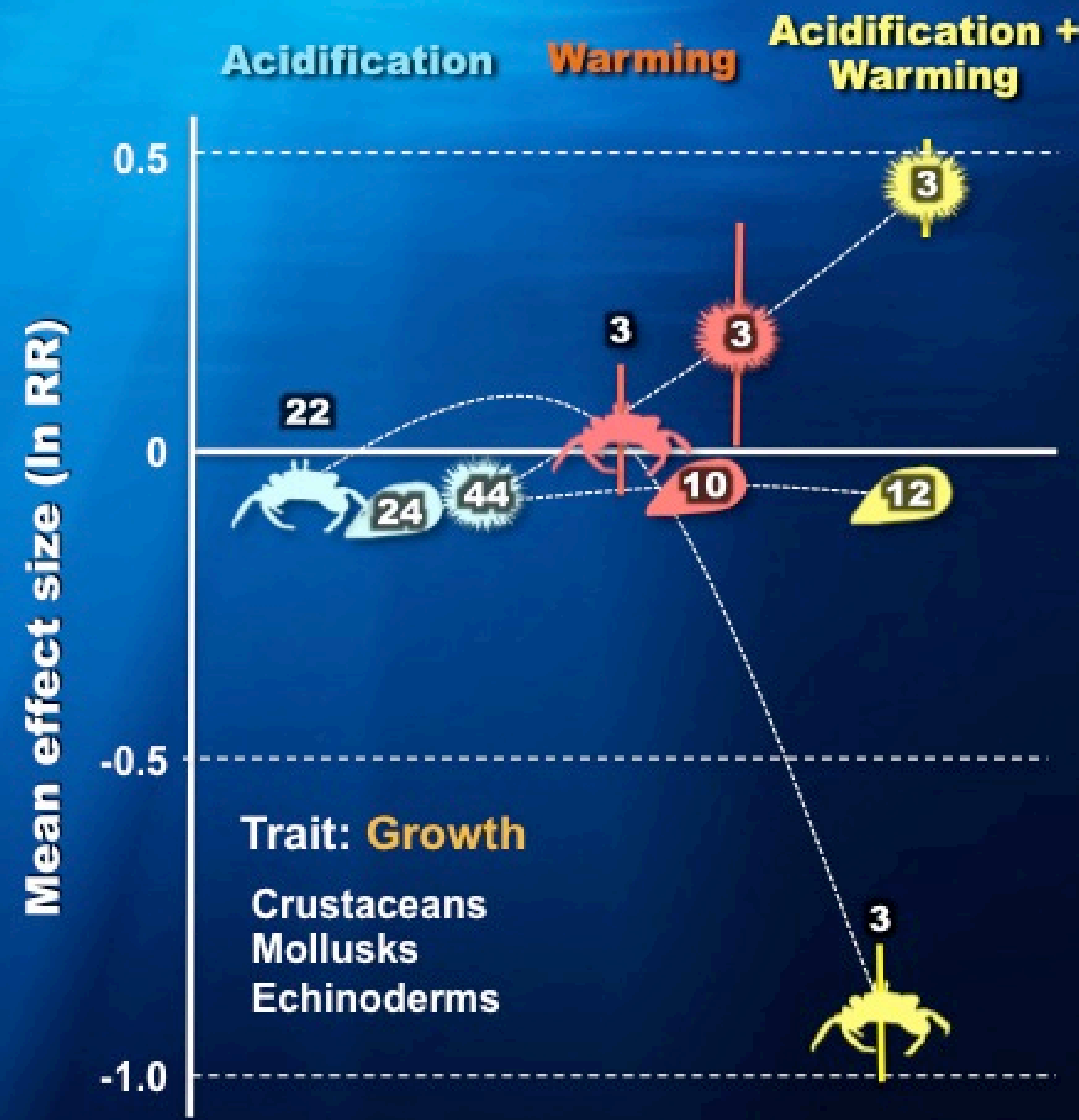


doi:10.1002/loe2.10002

CO_2 × temperature: a meta-analysis

Combining empirical data across studies





- **Biological responses vary across taxa, stages, and trophic levels**
- **Combined stressors generally cause stronger (positive or negative) effects**

doi:10.1002/loe2.10002

CO_2 × temperature: conclusions from two meta-analyses

(1) Larval stages are more sensitive

(2) Calcifiers sensitive to warming + acidification, non-calcifiers more sensitive to warming.

(2) Fertilization appears robust

(2) Significant combined effects of warming + acidification (70% of species)

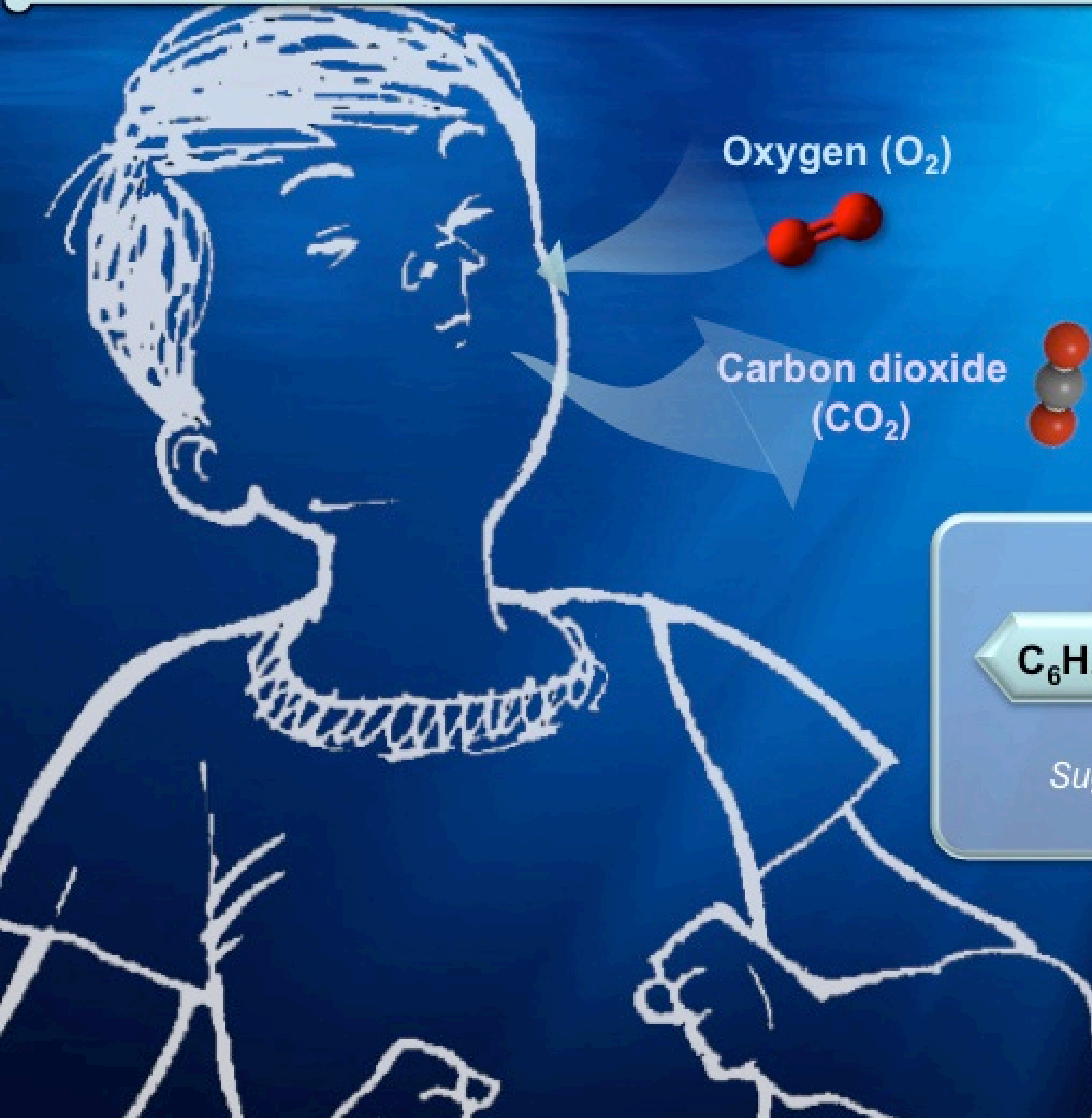
Additive negative effects most common

(1) Reproduction affected positively in autotrophs, negatively in heterotrophs

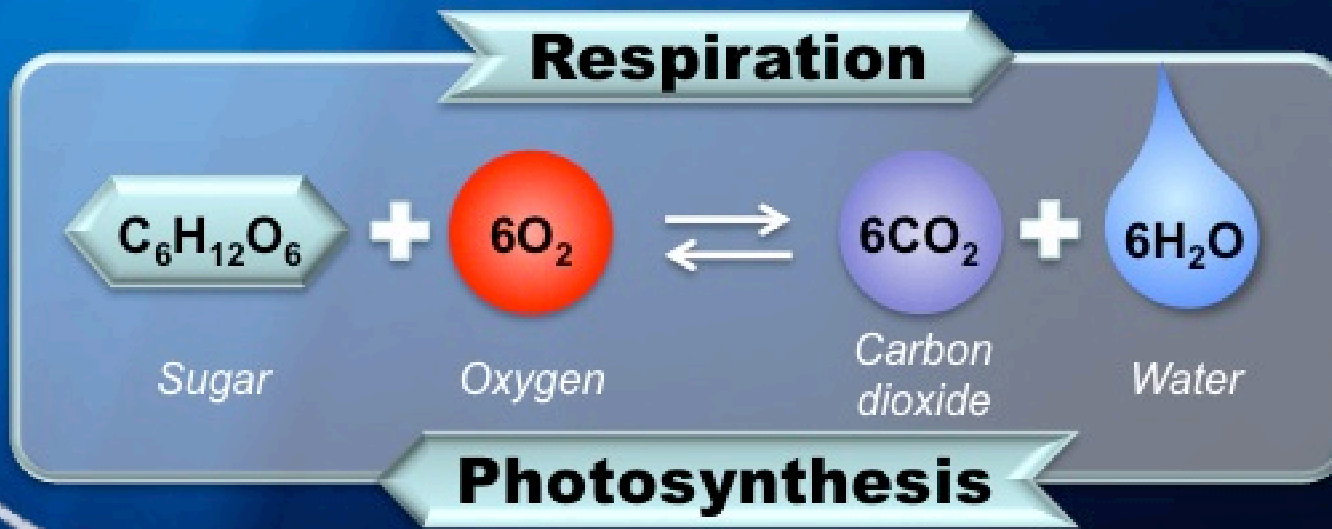
(1) Calcification, photosynthesis, reproduction, survival: synergistic interactions between acidification and warming can occur

(1) Harvey et al. Ecology & Evolution 2013

(2) Byrne & Przeslawski ICB 2013



Now take a deep breath...



Two sides of the same coin:

[In most ecosystems, CO_2 and O_2 dynamics mirror each other because they are connected by community metabolism]

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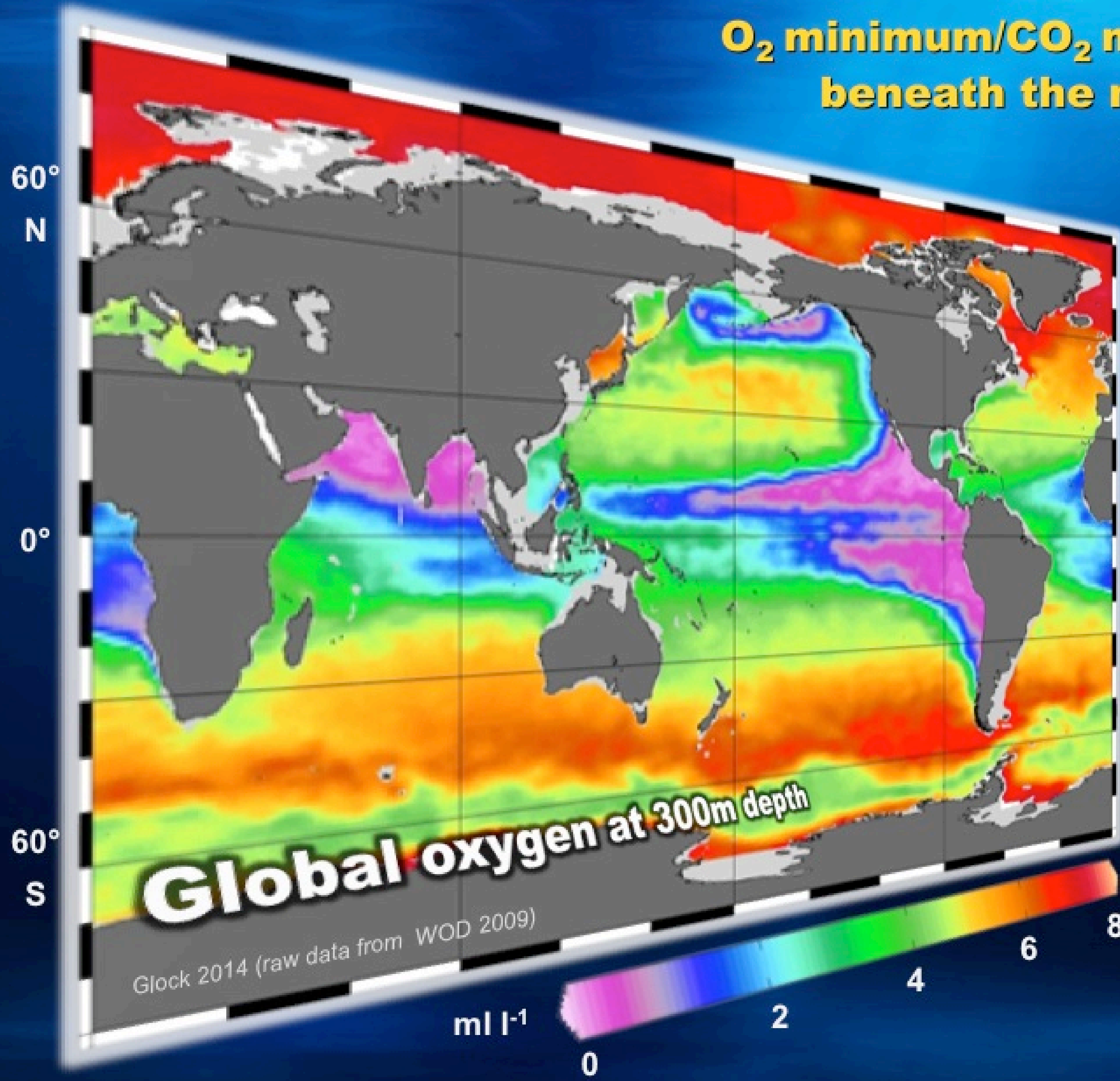
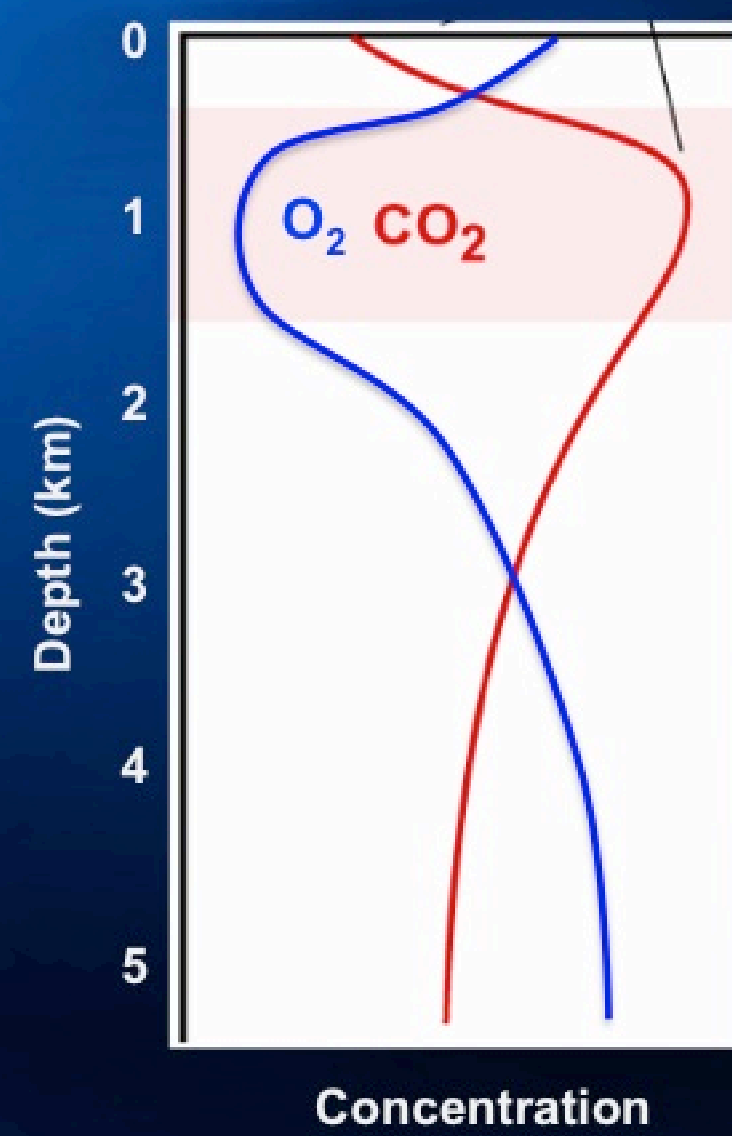
Co-occurrence of acidification and hypoxia in the mid-ocean

O_2 minimum/CO_2 maximum zones occur beneath the most productive parts of the world's oceans





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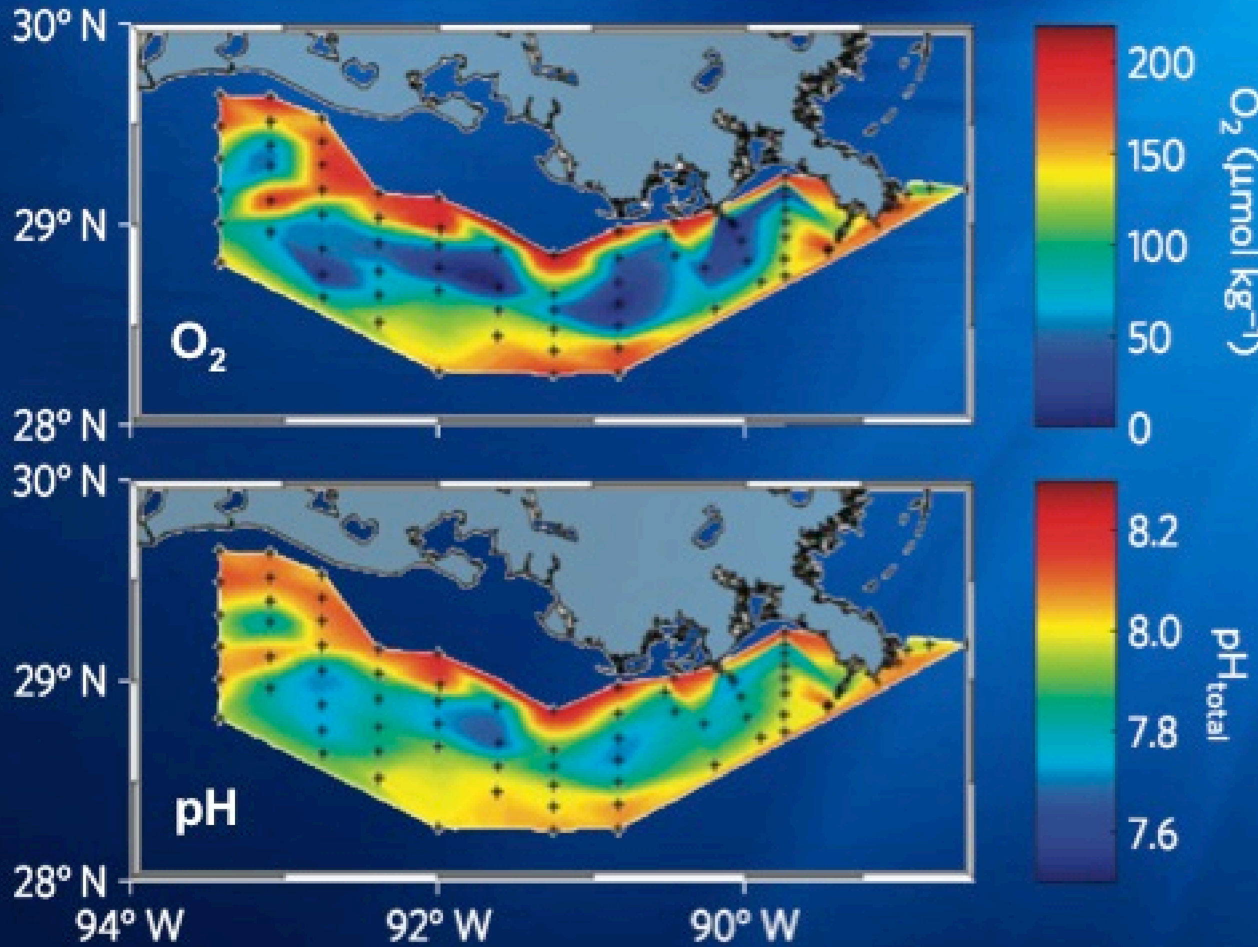
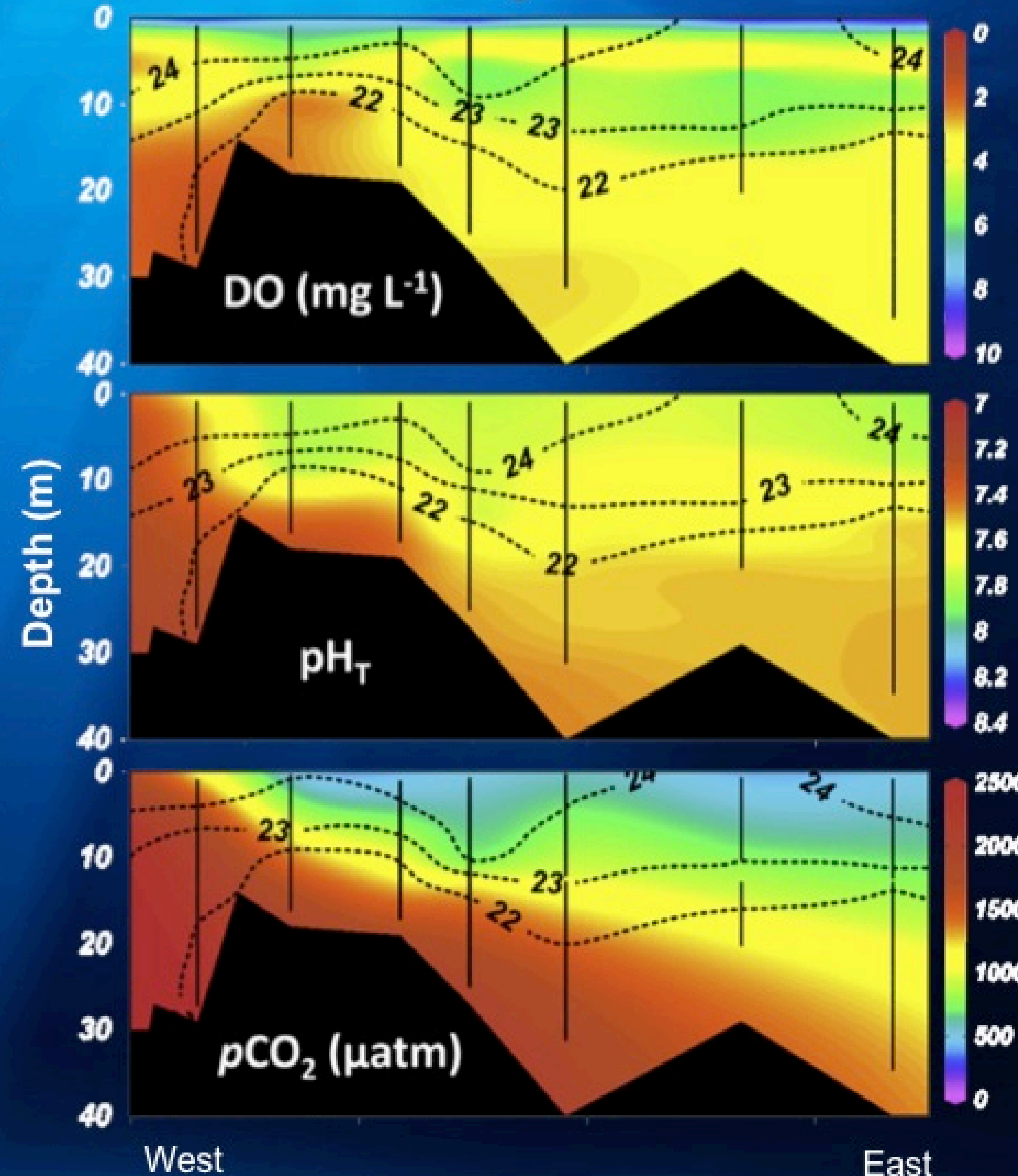
Co-occurrence of acidification and hypoxia II: coasts

Summer situation in the Northern Gulf of Mexico



Cai et al. Nat Geoscience 2011

Western Long Island Sound

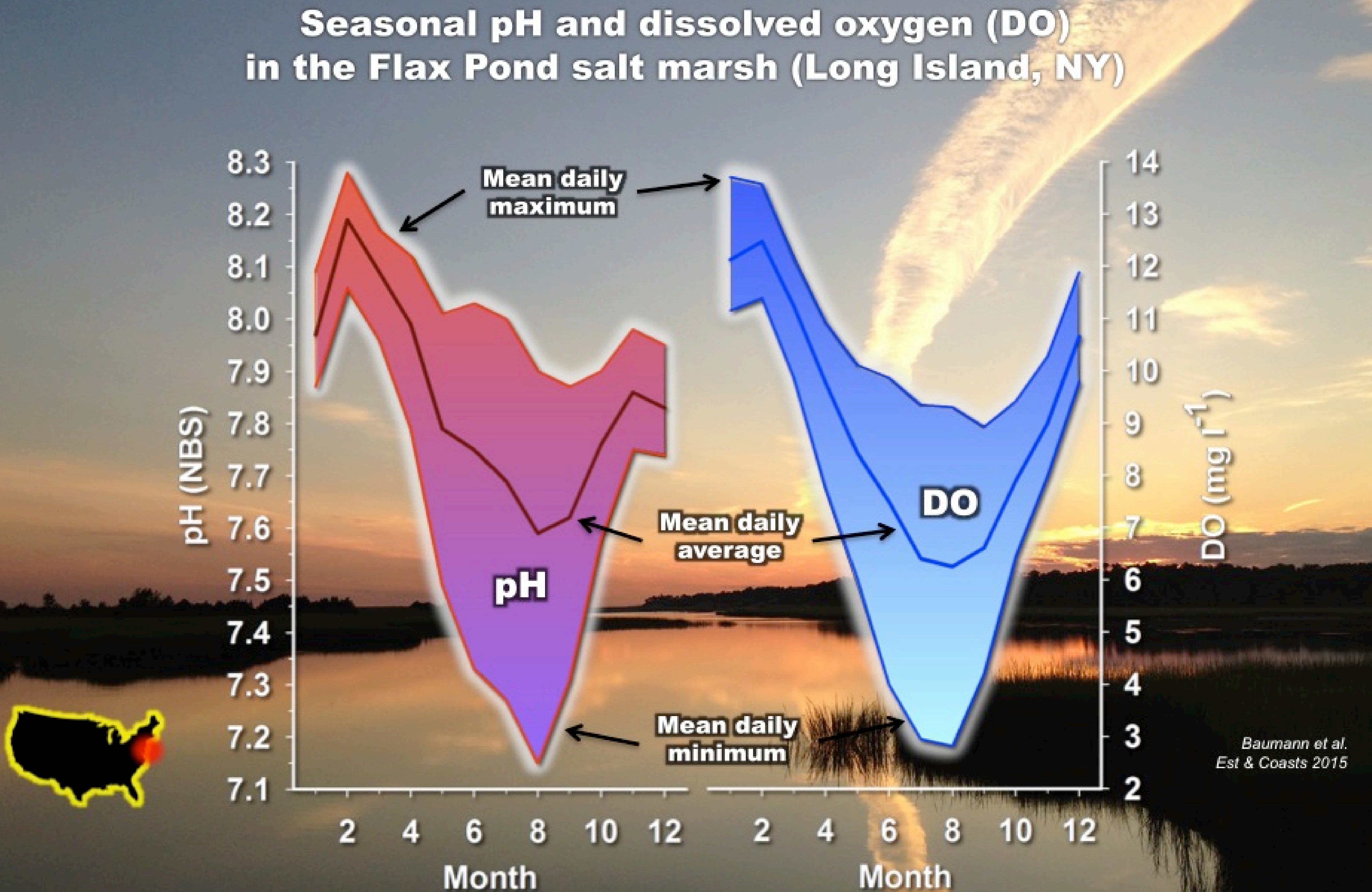


Wallace et al. Est Coast Shelf Sci 2014

- **In coastal habitats, metabolism dominates the O_2 and CO_2 dynamics**
- **Hence low pH and low O_2 conditions co-occur in time and space**

doi:10.1002/loe2.10002

Seasonal coupling of pH and oxygen dynamics: salt marsh



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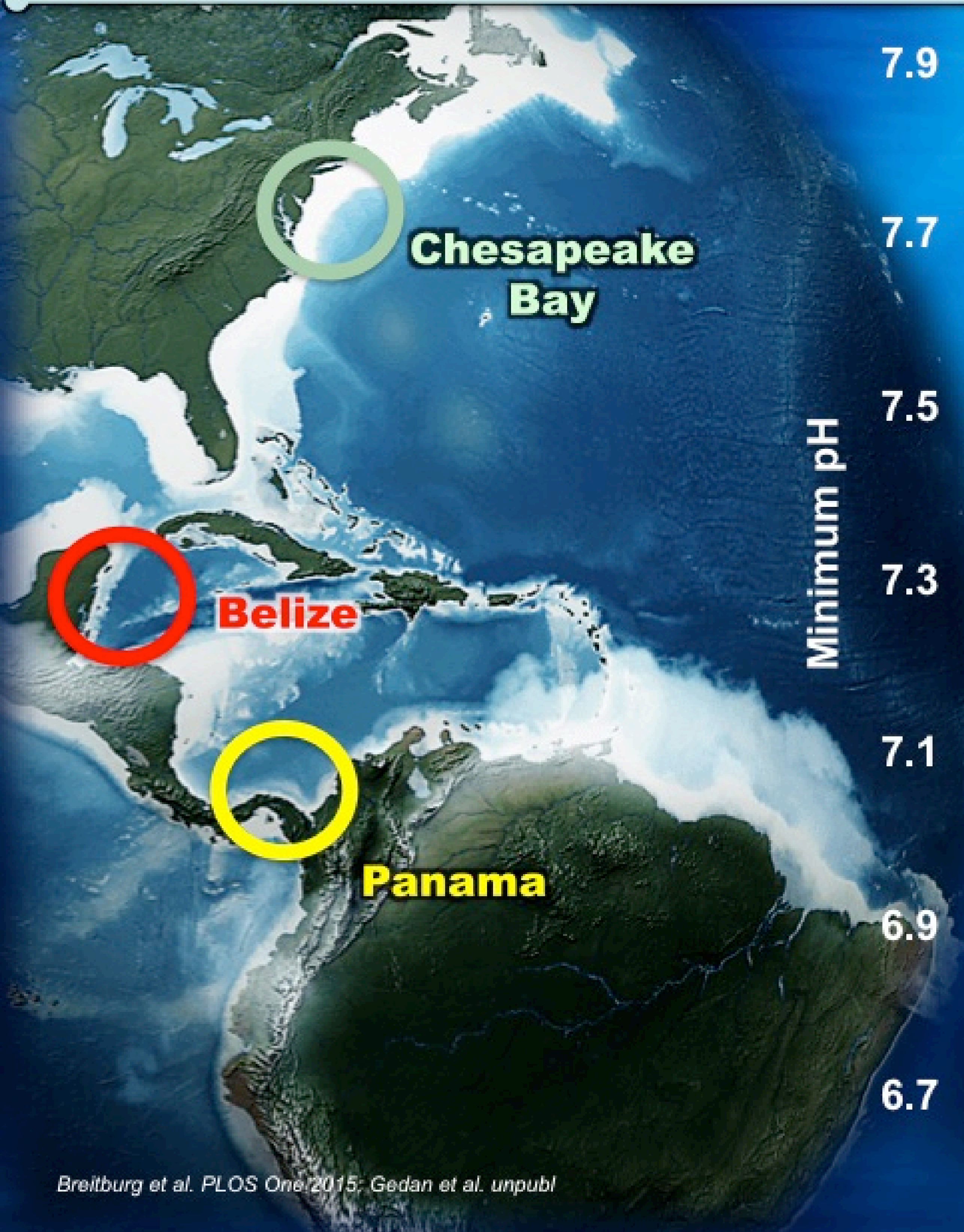
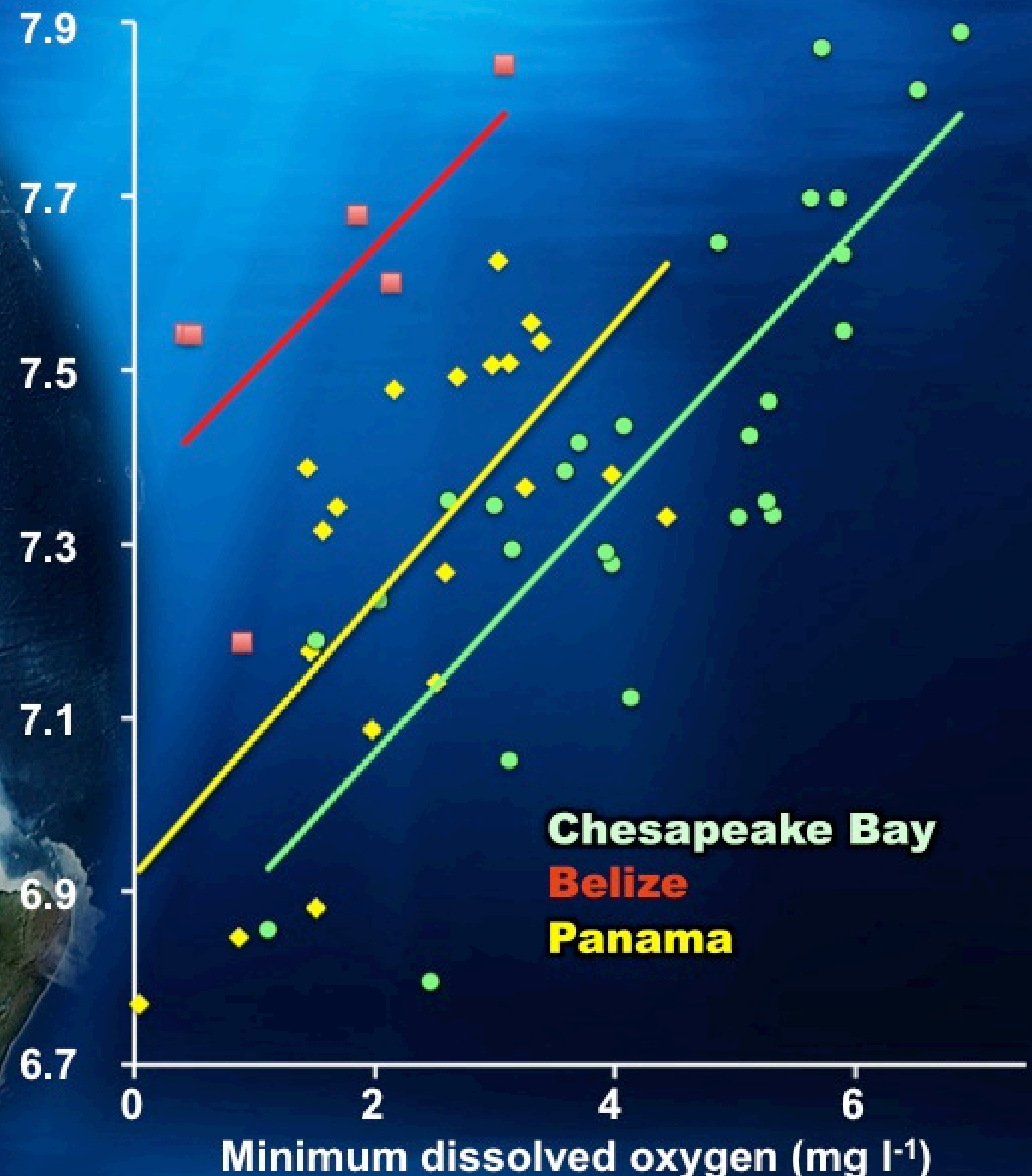
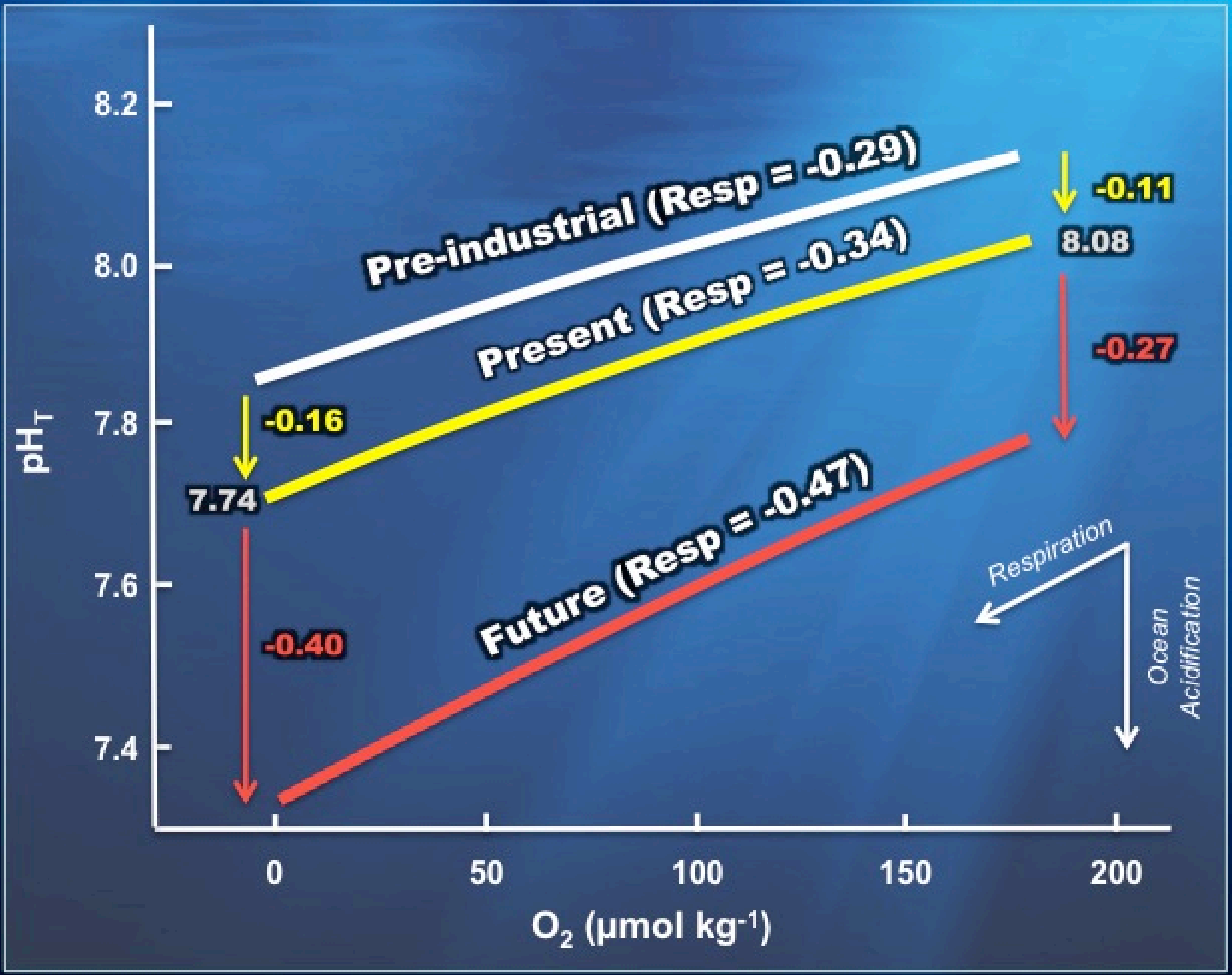
pH:DO relationships: similar slopes, different intercepts





doi:10.1002/loe2.10002

The relationship between O_2 and pH. Past. Present. Future?



Will the relationship between pH and O_2 change with ongoing ocean acidification?

Cai et al. Nat Geoscience 2011

Yes. Low O_2 conditions will be associated with disproportionally lower pH conditions.

Real world examples

$CO_2 \times O_2$

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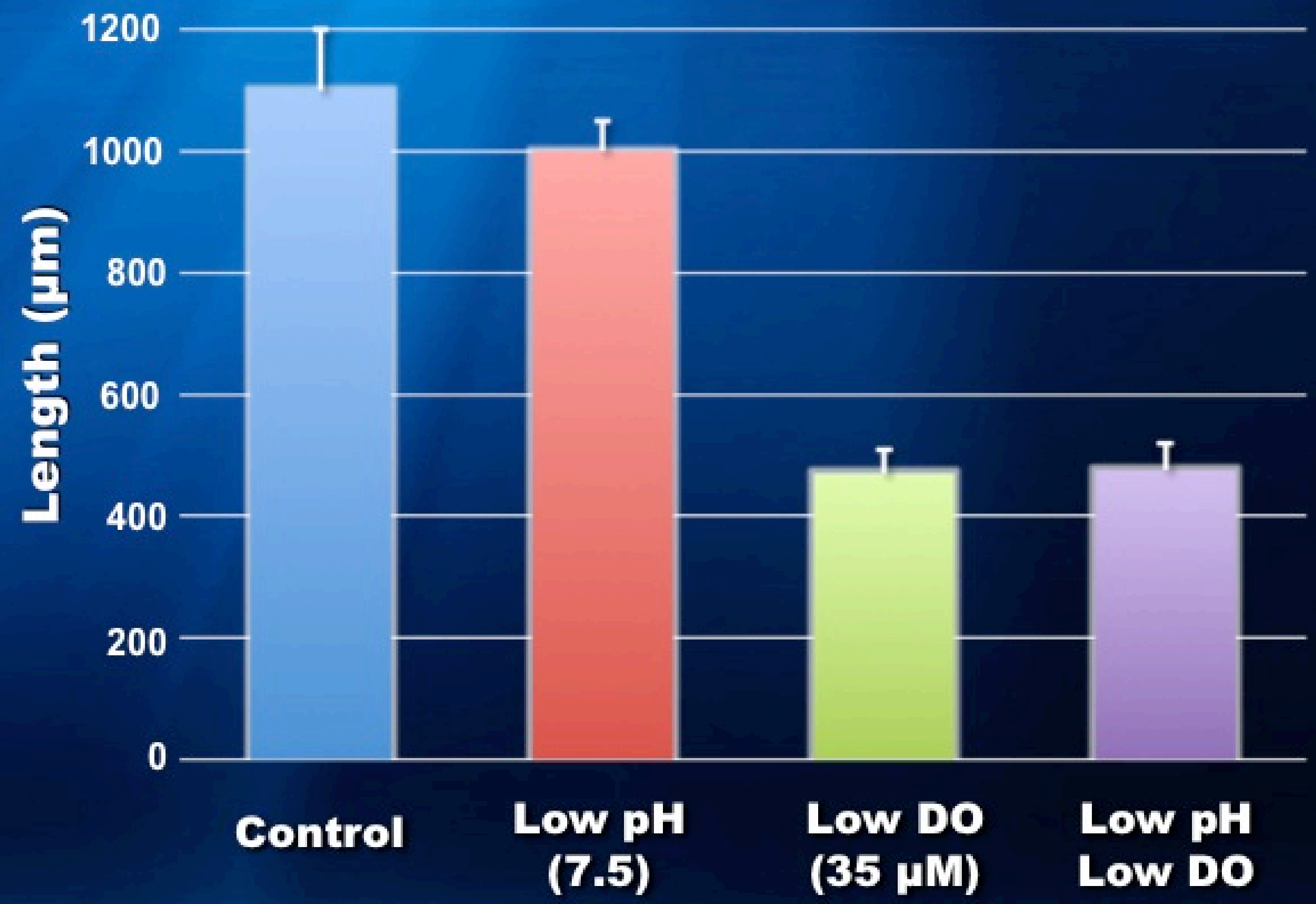
Additive CO_2 × O_2 effects on bay scallop growth

Argopecten irradians

Low oxygen → reduced growth
Low pH → no effect
No interaction of stressors



Gobler et al. PLOS One 2014

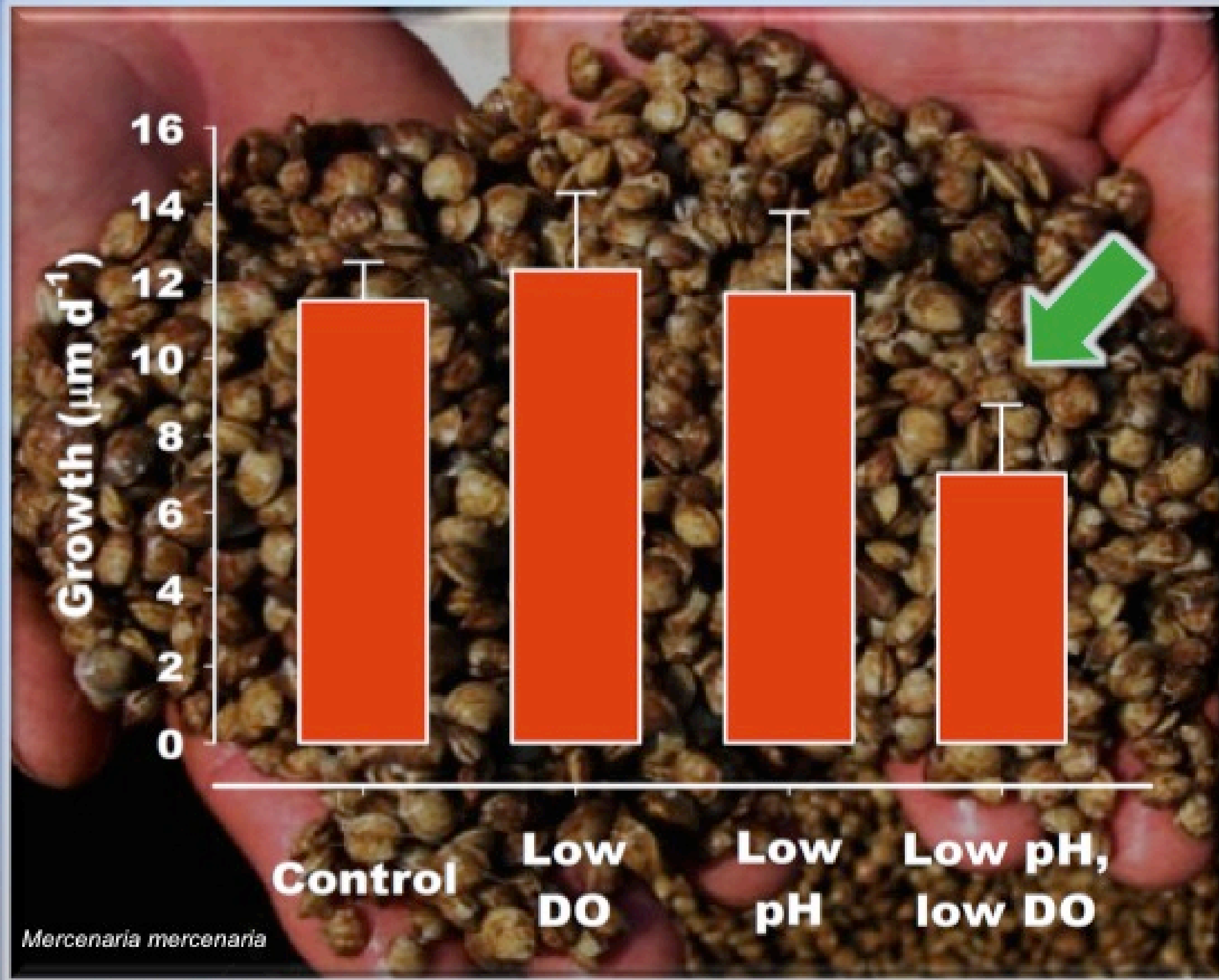
doi:10.1002/loe2.10002

Synergistic CO_2 × O_2 effects on juvenile bivalve growth

Low DO → no effect
Low pH → no effect

Both stressors combined
↓
Synergistic negative effect!

Only multi-stressor experiments can detect this!

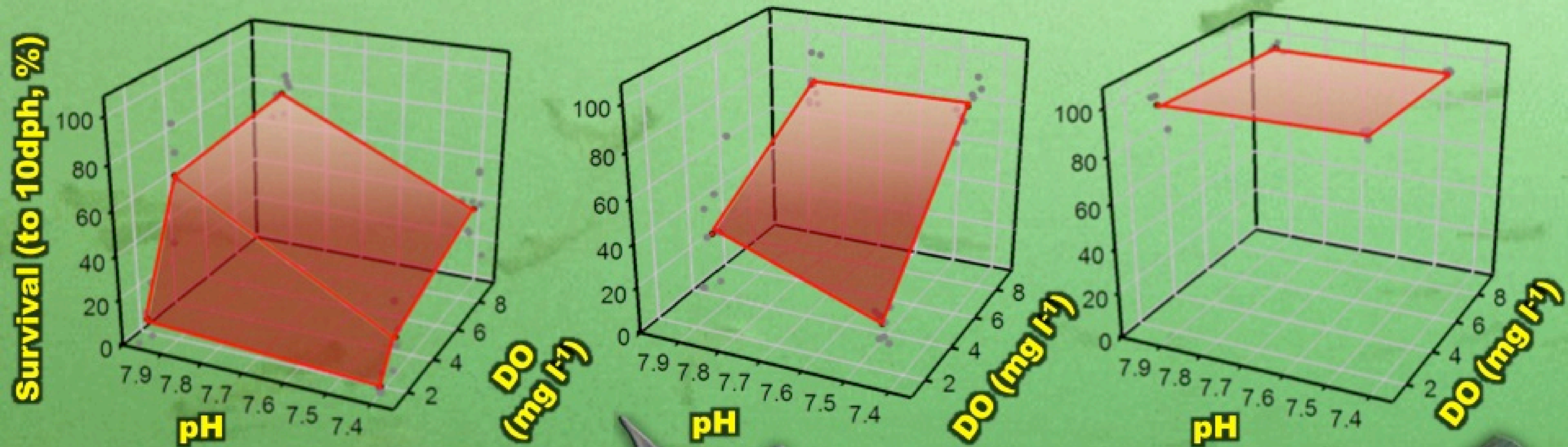


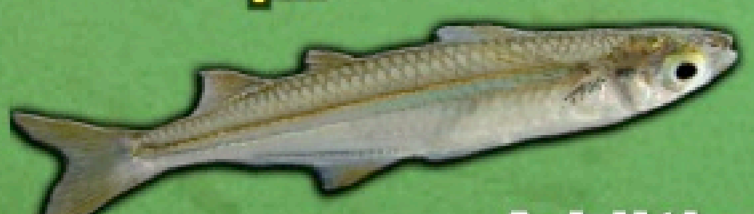
Gobler et al. PLOS One 2014

doi:10.1002/loe2.10002

CO_2 × O_2 effects on post-hatch survival in 3 coastal marine fish

Trait: Survival





Additive DO and pH effects on Inland silversides (interaction non-significant)

Synergistic Negative DO × pH effect on Atlantic silversides

No DO and no pH effect on sheepshead minnows

Depasquale et al. MEPS 2015

doi:10.1002/loe2.10002

CO_2 × O_2: urgent need for empirical data

1

Only a handful of studies on CO_2 × O_2 interactions available to date

Meta-analyses not possible yet

2

Robust conclusions or predictions have yet to emerge

3

Bivalves and fish:

Both additive and synergistically negative effects observed

Fish less tolerant to low DO than low pH

Sensitivities in bivalves life-stage dependent

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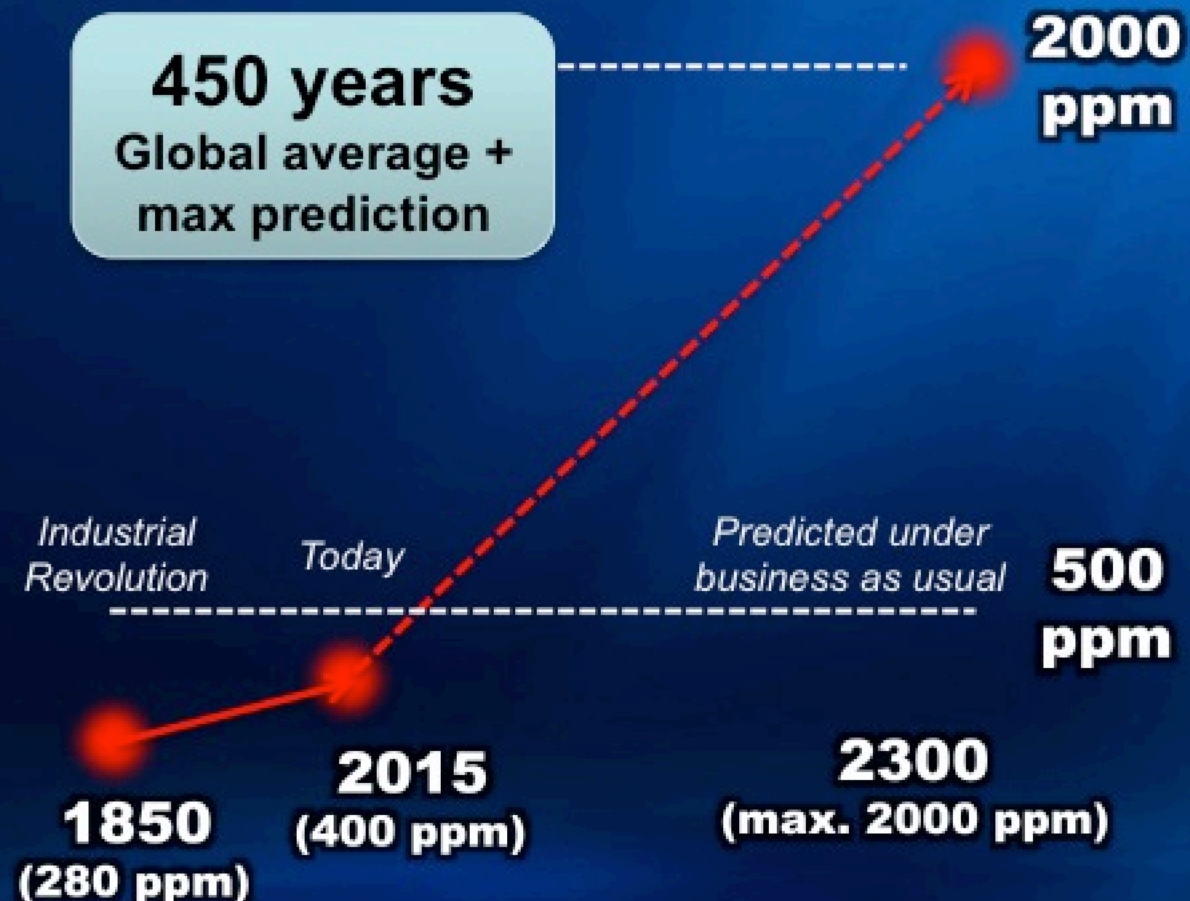
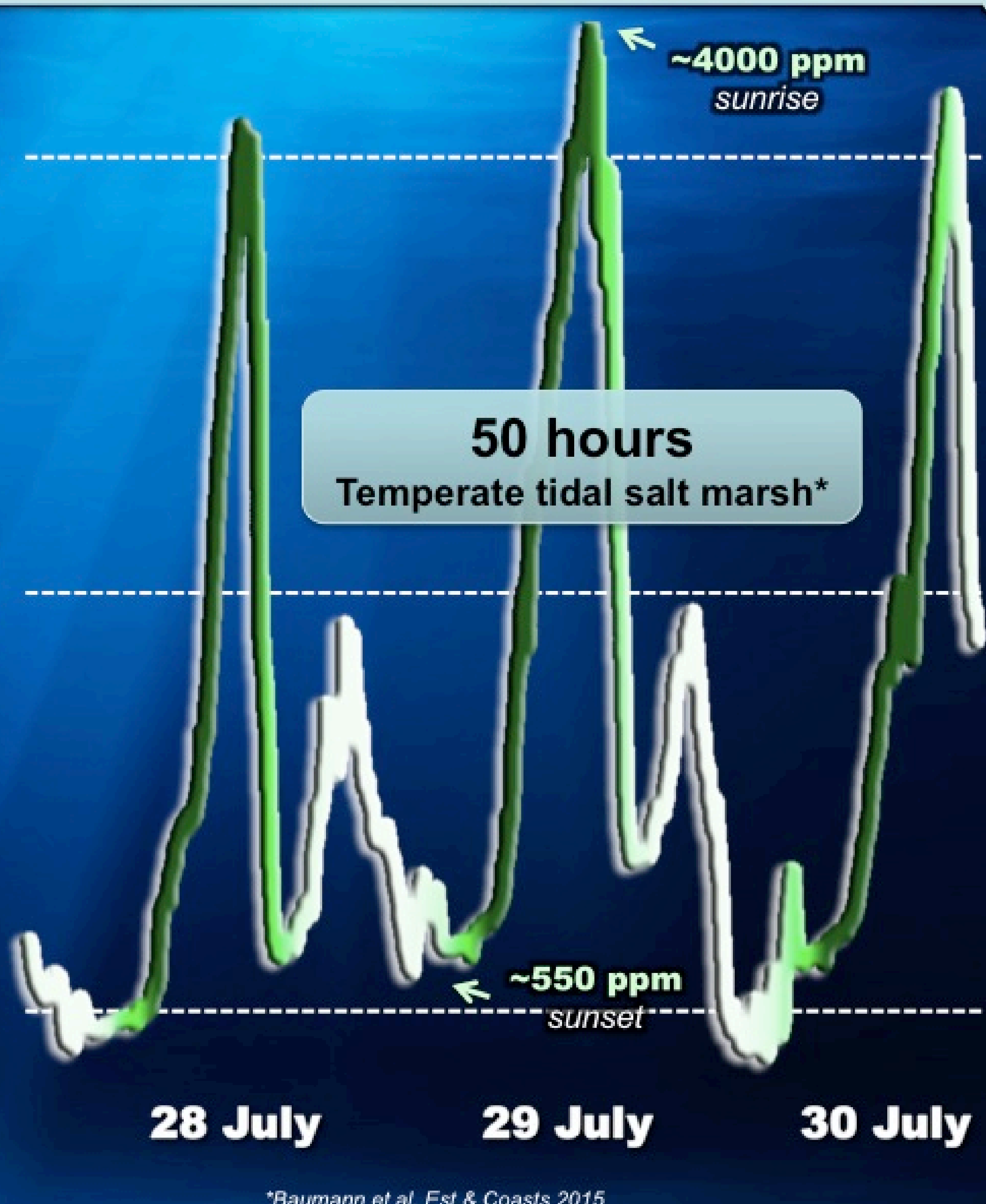
Coastal variability vs. long-term projected change

Do extreme short-term $CO_2 \times O_2$ fluctuations in some nearshore habitats act as temporary relief or added stressor to coastal organisms?





*Baumann et al. Est & Coasts 2015

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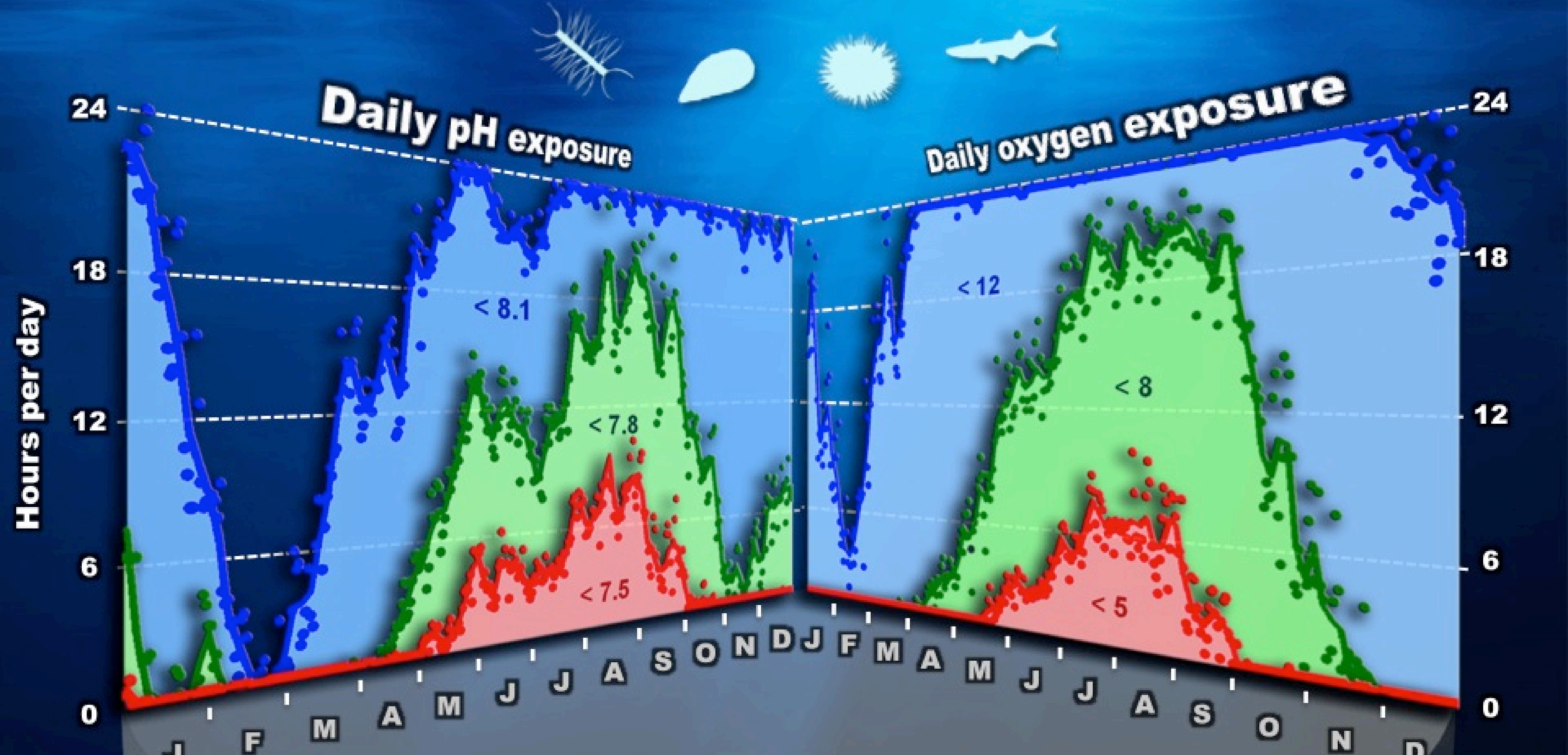
Seasonal exposure to low pH and DO in a salt marsh



Average exposure of salt marsh organisms to waters below pH/DO = 8.1/12, 7.8/8, and 7.5/5.

Baumann et al. Est & Coasts 2015

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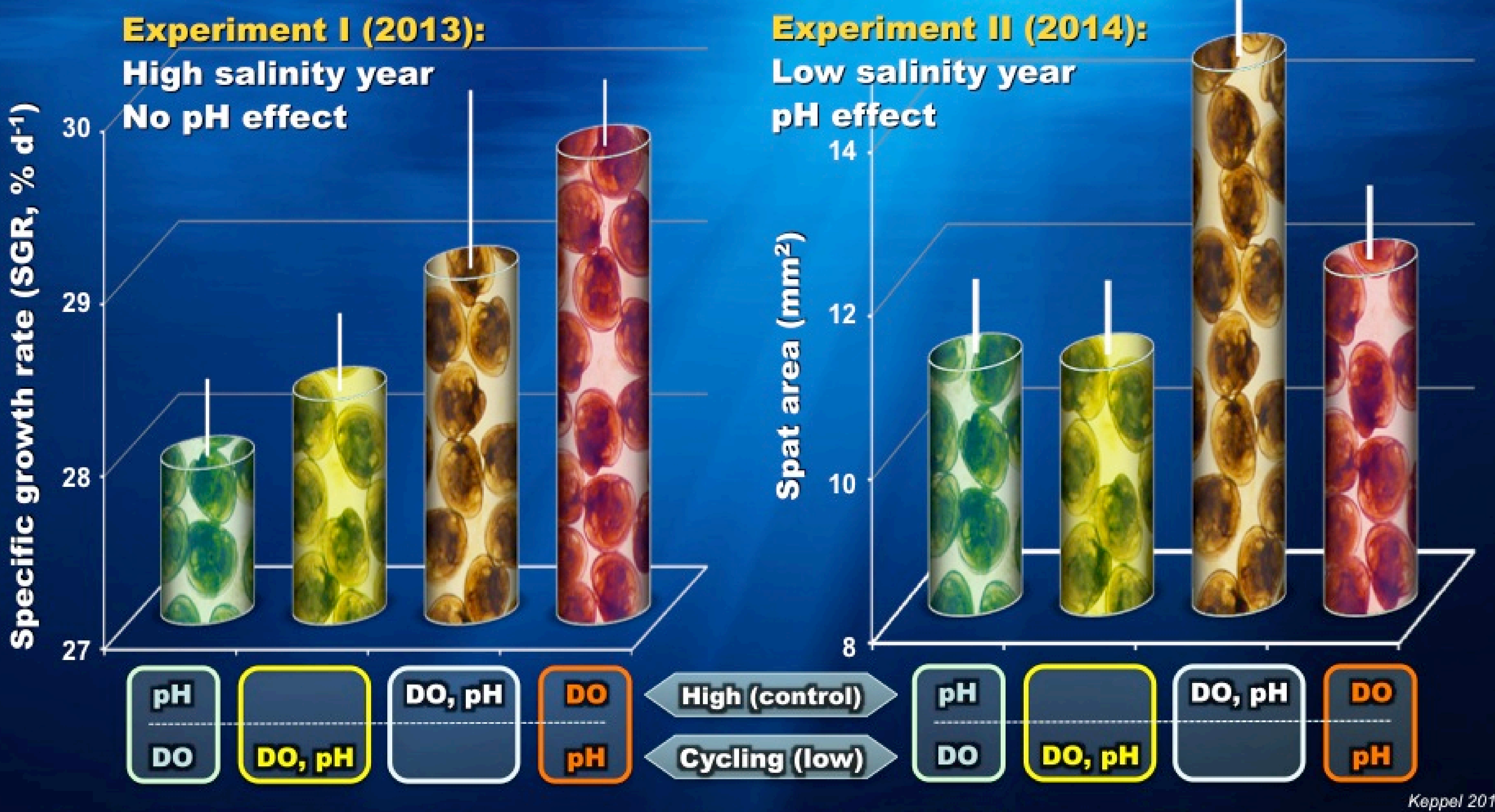
Effects of fluctuating CO_2 × O_2 on oyster spat



Cycling pH had no effect on growth (SGR) in 2013 (high salinity).

Cycling pH reduced SGR under control DO conditions in 2014 (low salinity).

Severe cycling hypoxia reduced juvenile oyster growth in both years.

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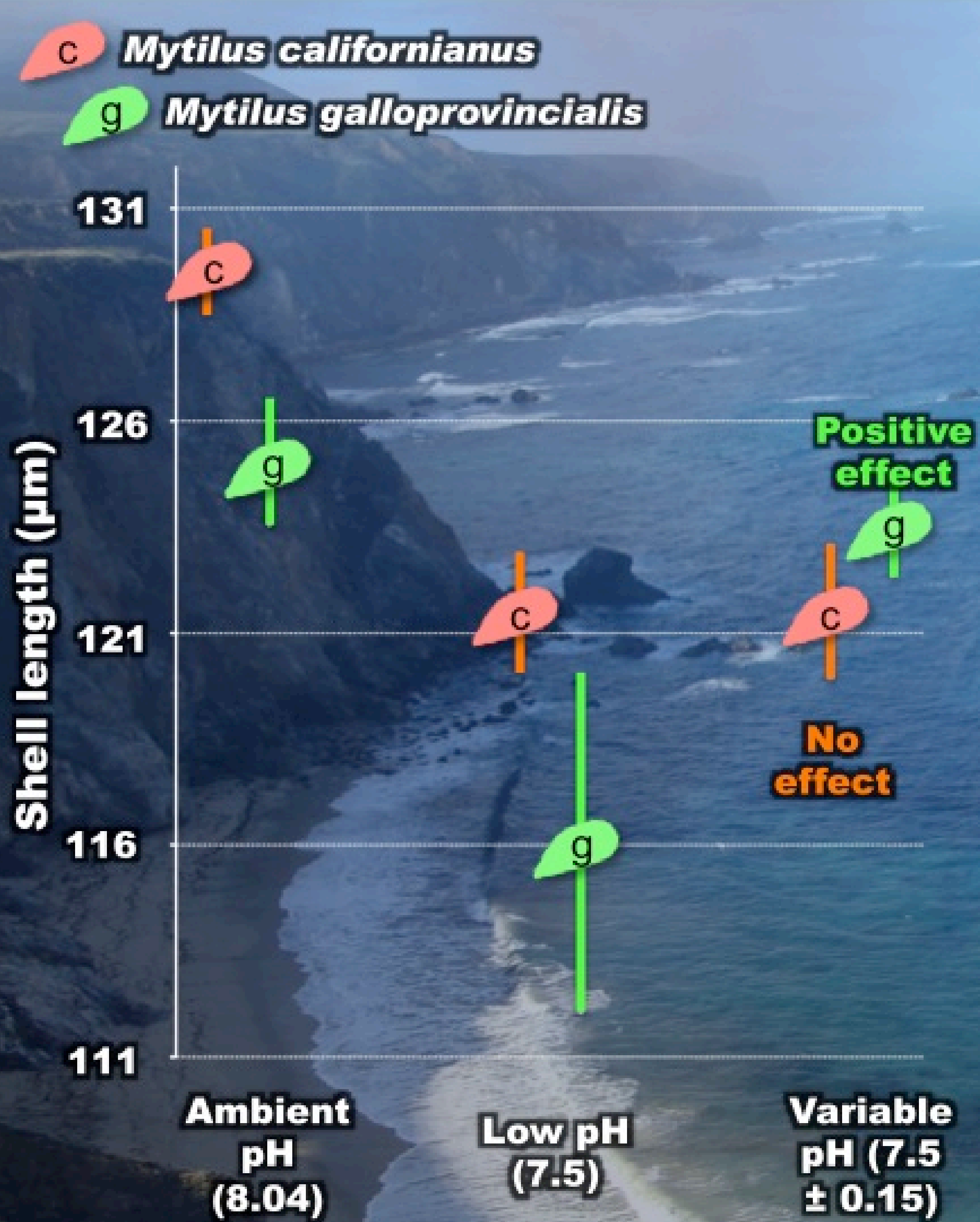
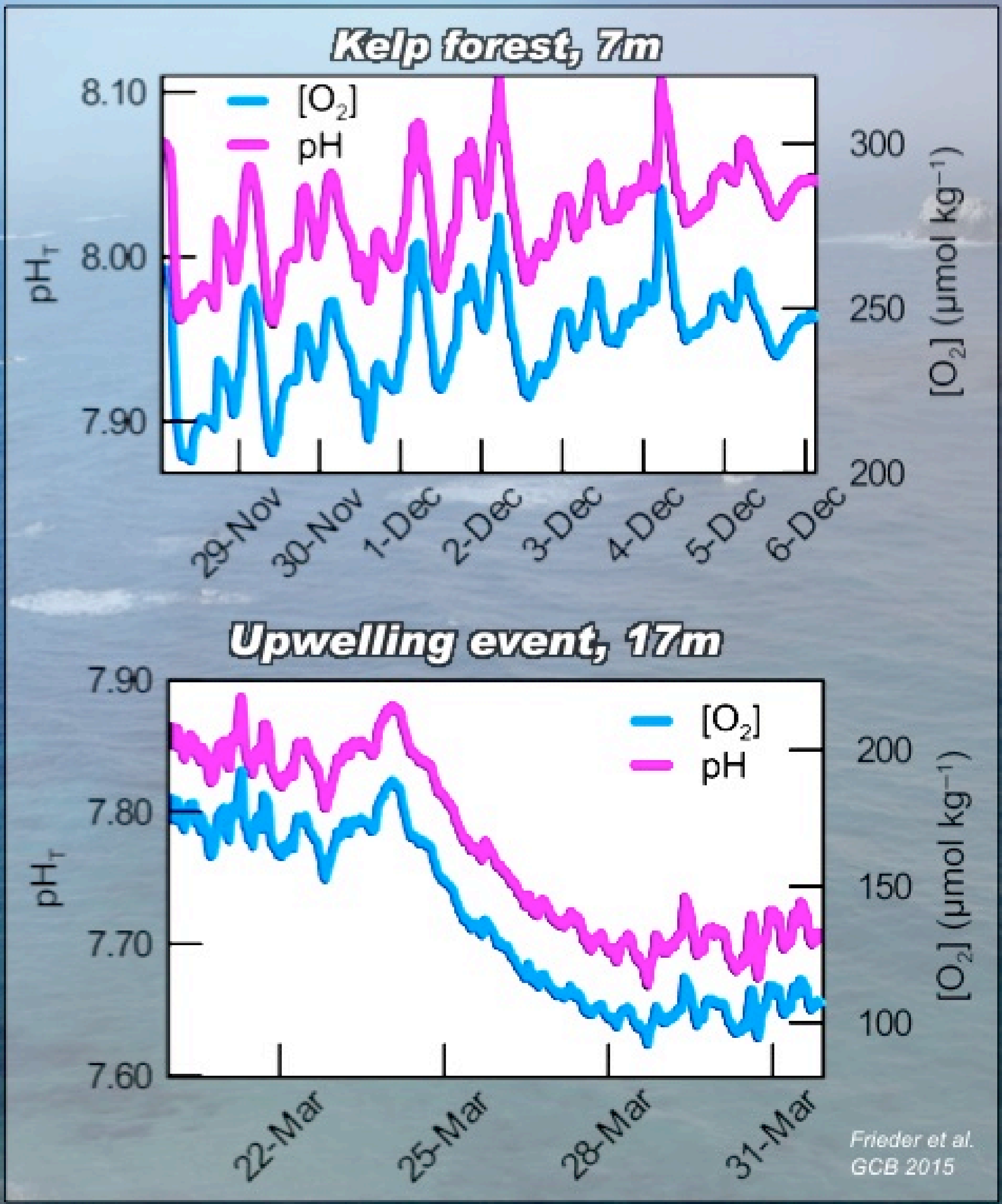
doi:10.1002/loe2.10002

Differential growth effects of variable pH in mussels





Low pH reduced shell growth.
Variable pH reduced the negative effect on *M. galloprovincialis* growth.

From data to concepts *and* The way forward

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doi:10.1002/loe2.10002

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A physiological framework to predict O_2 × CO_2 × Temp effects

Oxygen- and capacity-limited thermal tolerance

H.-O. Pörtner

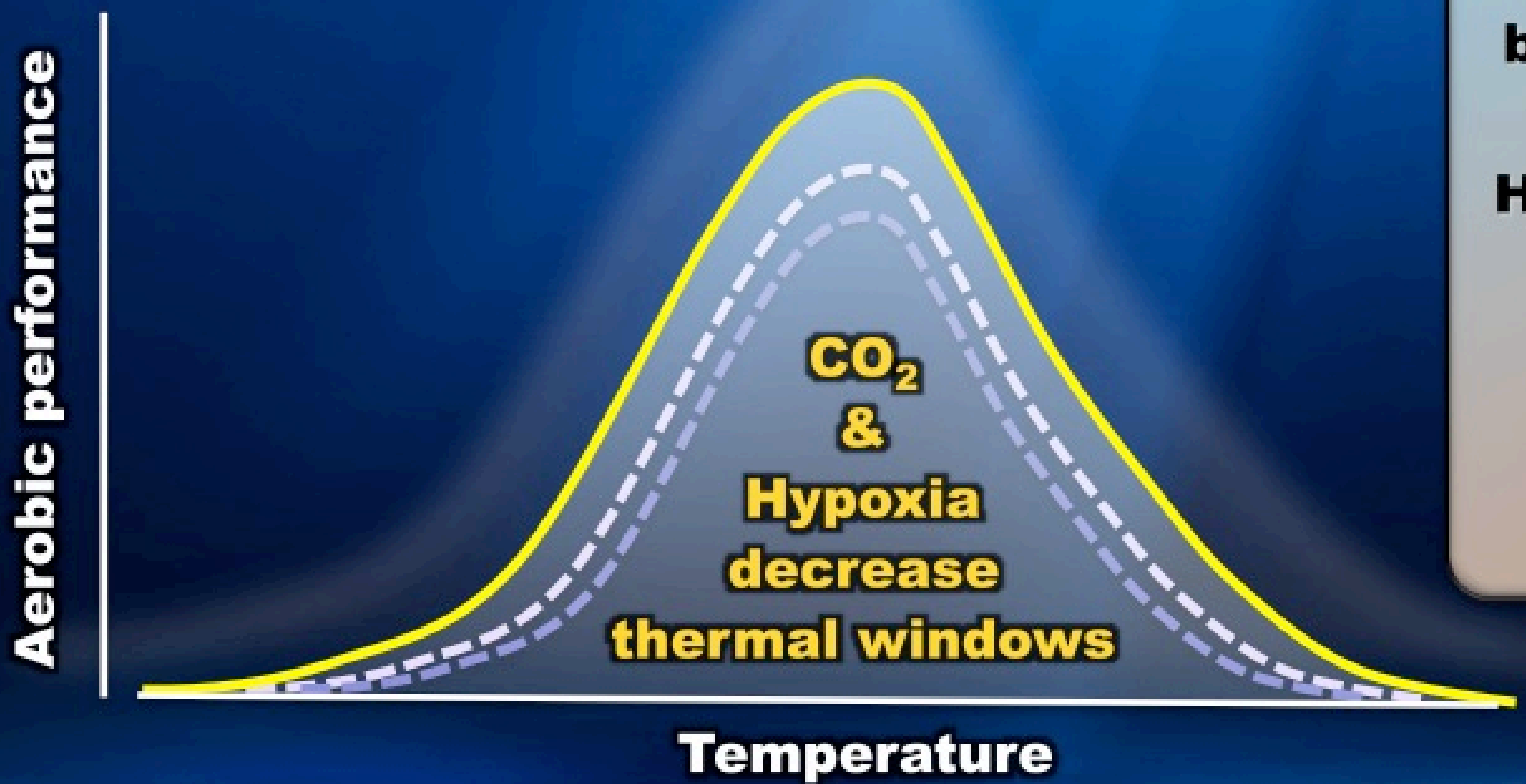
1. For every species and life-stage there is a thermal window of aerobic performance

2. Temperature, hypoxia and CO_2 all affect energy turnover in organisms.

3. Hypoxia decreases blood oxygen content → window shrinks

   High CO_2 can reduce the function of blood pigments → window shrinks

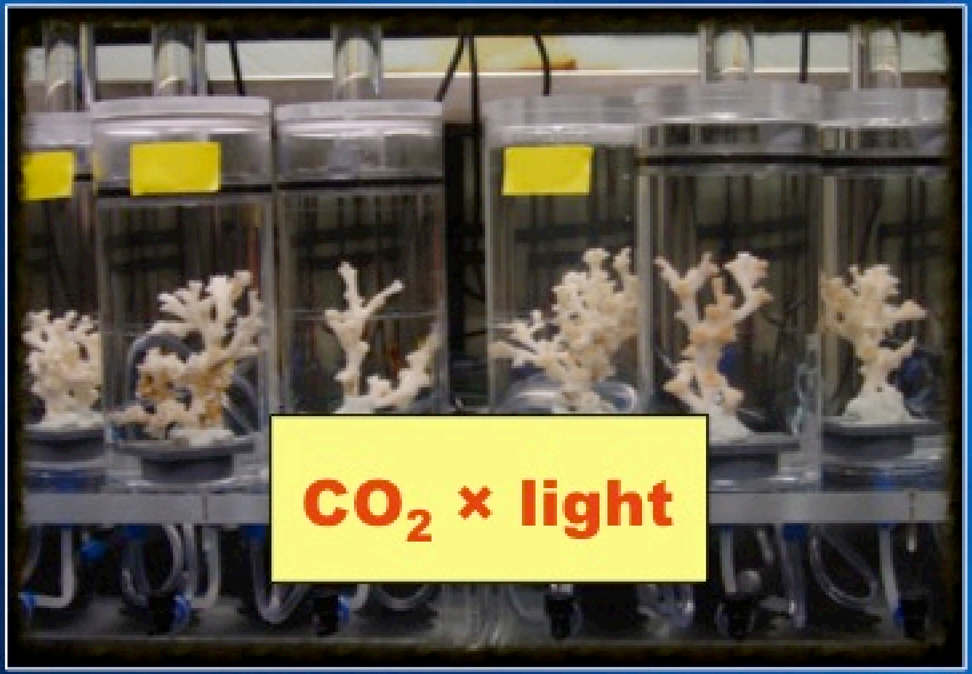
   Effects strongest at thermal extremes.



Poertner et al. MEPS 2012

doi:10.1002/loe2.10002

The way forward I: beware of confounding CO_2 interactions



Increasing CO_2 sensitivity with decreasing light levels

"…OA studies must better account for the potential moderating role of light upon growth/diversity if we are to move beyond the current…" Suggett et al. *Coral Reefs* 2013

Ad libitum food may disguise CO_2 effects on growth in survivors

"This could also explain the mostly neutral or positive growth effects of increasing CO_2 levels reported by other studies on fish early life stages…" Murray et al. *MEPS* 2014

doi:10.1002/loe2.10002

The way forward II: methods-approaches

Realistic simulations of hypoxia need to include ACIDIFICATION.

Multi-stressor experiments should be FACTORIAL

Move beyond 'control-treatment' designs, include at least 3 levels of a particular factor

Take advantage of natural existing gradients in CO_2, O_2, temperature conditions

Field manipulations add to laboratory experiments

doi:10.1002/loe2.10002

Take home messages

T + CO_2 + O_2 = climate change syndrome

1. The addition of OA's main co-stressors (*hypoxia, temperature*) results, in most cases, in stronger negative effects on marine organisms than OA alone.

2. Hence, single-stressor research likely underestimates the true impact of marine climate change.

3. In combination, CO_2, temperature, and O_2 effects are mostly additive (no interaction) – or synergistically negative (interaction).

4. We currently don't have the ability to predict the occurrence or the strength of stressor interaction on a given trait.

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SUNY RF The Research Foundation for The State University of New York

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UCONN

NSF

Grant #1097840

One tidal cycle at Flax Pond salt marsh, Long Island, NY

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