Ocean Acidification International Coordination Centre

IAEA OA-ICC

OA ALLIANCE — INTERNATIONAL ALLIANCE TO COMBAT OCEAN ACIDIFICATION

Basic Training Course on Ocean Acidification

9 - 13 September 2024

EVT2205463

hosted by

United Methodist University (UMU)

From chemistry to biology

On the menu today

- What part of the carbonate chemistry is biologically relevant?
- What part of the local carbonate chemistry shall we monitor to infer biological response?
- Shall we care about variability in itself?
- How long shall we monitor to see biological impacts?

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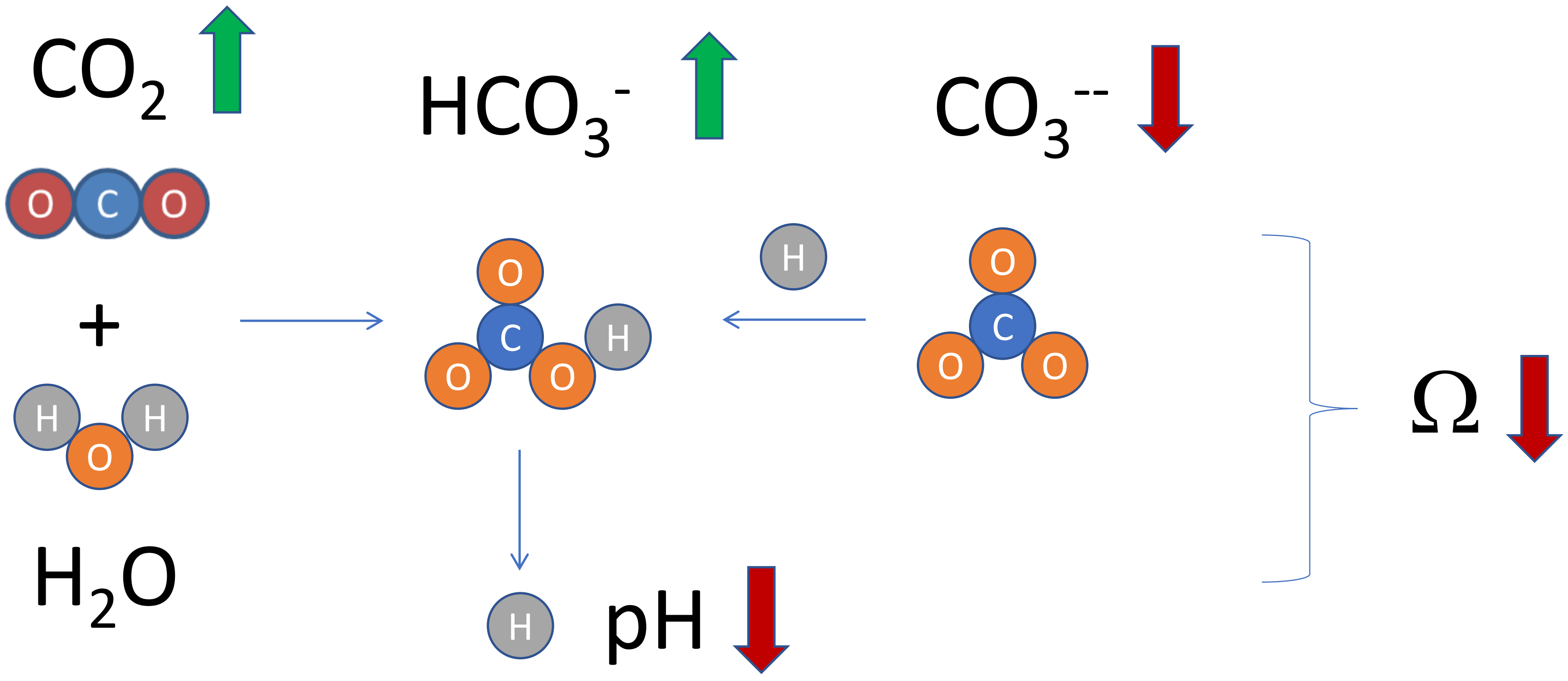
Ocean acidification in a nutshell



What is driving biological changes?

Is it Ω?

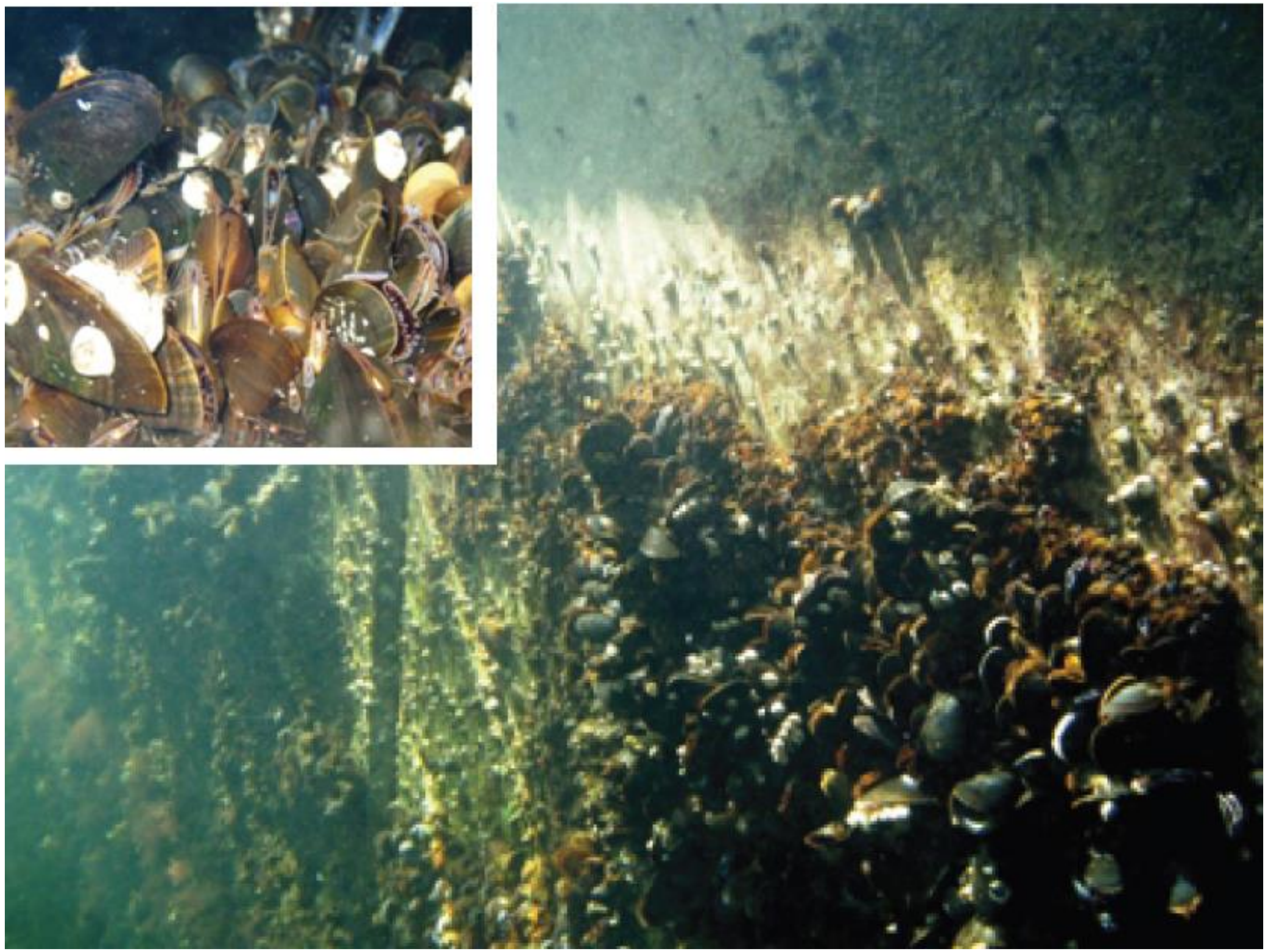
nature climate change
PERSPECTIVE
PUBLISHED ONLINE: 23 FEBRUARY 2015 | DOI: 10.1038/NCLIMATE2508

Vulnerability and adaptation of US shellfisheries to ocean acidification

Julia A. Ekstrom[1*†], Lisa Suatoni[2], Sarah R. Cooley[3], Linwood H. Pendleton[4,5], George G. Waldbusser[6], Josh E. Cinner[7], Jessica Ritter[8], Chris Langdon[9], Ruben van Hooidonk[10], Dwight Gledhill[11], Katharine Wellman[12], Michael W. Beck[13], Luke M. Brander[14], Dan Rittschof[8], Carolyn Doherty[8], Peter E. T. Edwards[15,16] and Rosimeiry Portela[17]

e.g. Threshold: $\Omega < 1.5$ for calcifiers
e.g. 80% of present

Organisms are not pieces of calcium carbonate



pH 7.5, Ωara=0.35

(Thomsen et al. 2010)

Acid-base regulatory mechanisms

Concept of threshold

Temperature: 0°C

How do you make ice at >0°C

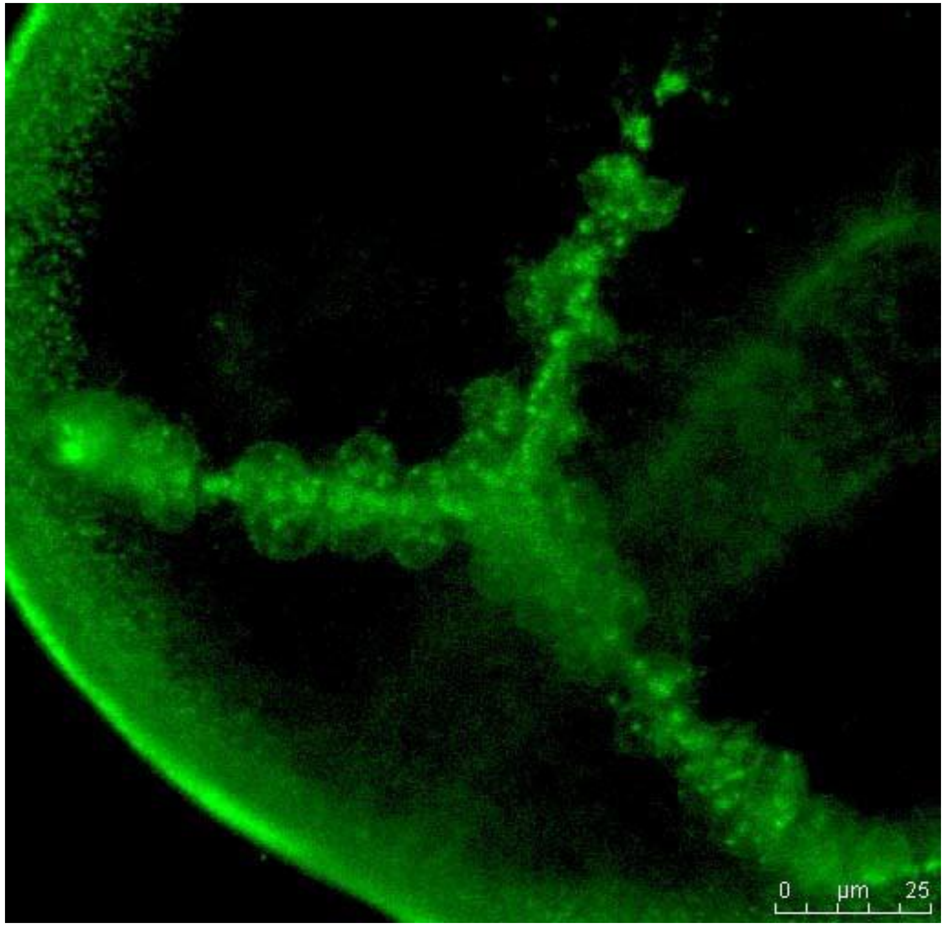
A freezer

Energy cost

Concept of threshold

$$\Omega=1$$

Physiological mechanisms



How to make $CaCO_3$ at $\Omega<1$?

$\Omega>1$ at the calcification site

Life adapts to its environment

pH 5.36, Ωara=0.01

(Tunnicliffe et al. 2009)

Omega myth… but…

ICES Journal of Marine Science

ICES CIEM International Council for the Exploration of the Sea / Conseil International pour l'Exploration de la Mer

ICES Journal of Marine Science (2016), 73(3), 563–568. doi:10.1093/icesjms/fsv174

Contribution to Special Issue: 'Towards a Broader Perspective on Ocean Acidification Research'

Comment

Calcium carbonate saturation state: on myths and this or that stories

George G. Waldbusser*, Burke Hales, and Brian A. Haley

ICES Journal of Marine Science

ICES CIEM International Council for the Exploration of the Sea / Conseil International pour l'Exploration de la Mer

ICES Journal of Marine Science (2016), 73(3), 558–562. doi:10.1093/icesjms/fsv075

Contribution to Special Issue: 'Towards a Broader Perspective on Ocean Acidification Research'

Food for Thought

The Omega myth: what really drives lower calcification rates in an acidifying ocean

Tyler Cyronak[1]*, Kai G. Schulz[2], and Paul L. Jokiel[3]

Ω can be important for organisms with:

- Exposed skeletal structure (dissolution) e.g. corals
- Periods of fast calcification (kinetic constrains) e.g. larval bivalves

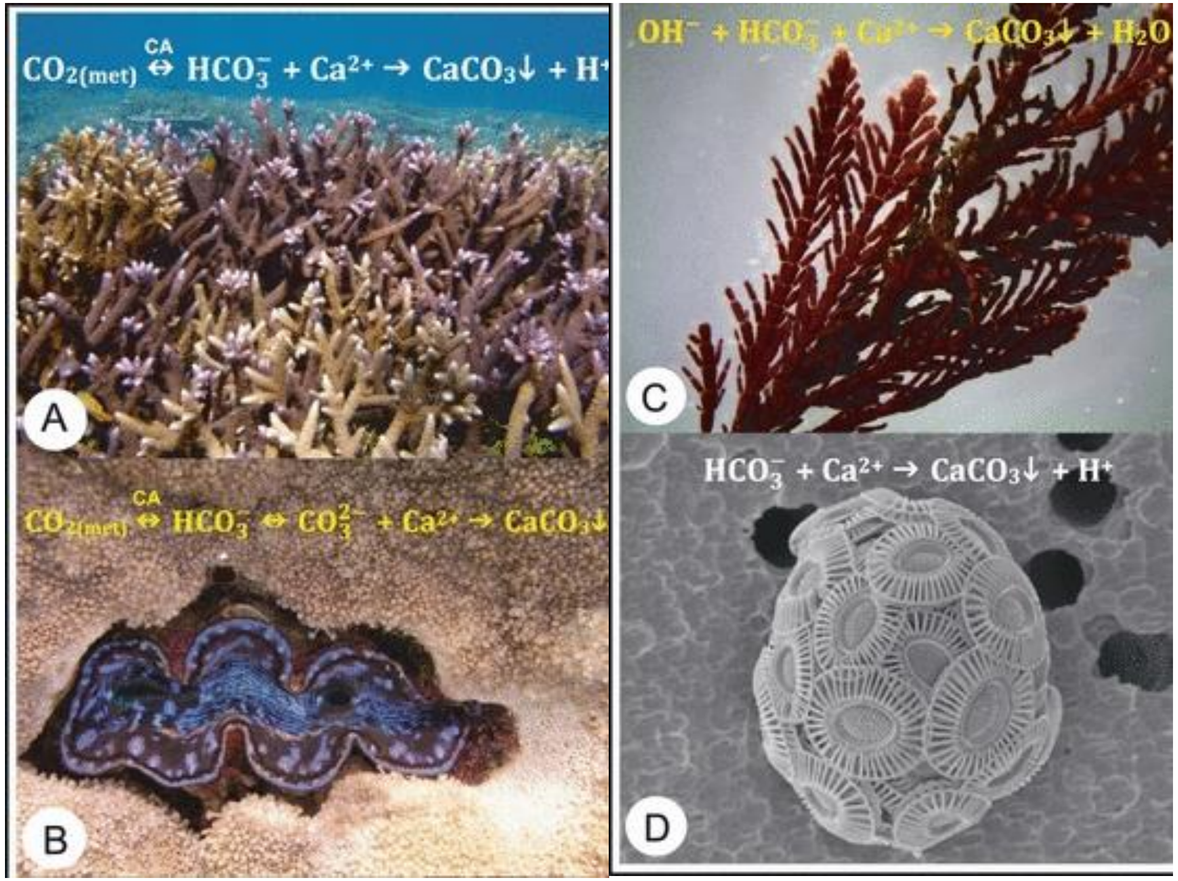
Is it CO_3^{2-}?

Calcification:

~~$Ca^{++} + CO_3^{--} \rightarrow CaCO_3$~~

$Ca^{++} + 2HCO_3^{-} \rightarrow CaCO_3 + H_2O + \mathbf{CO_2}$

Is it CO_3^{2-}?



Seawater CO_3^{2-} not main bricks for calcification

Roleda et al. 2012

Why science matters?

Mussels and oysters aquaculture as a CO_2 capture method

Received: 14 March 2024 | Revised: 10 July 2024 | Accepted: 11 July 2024
DOI: 10.1111/raq.12954

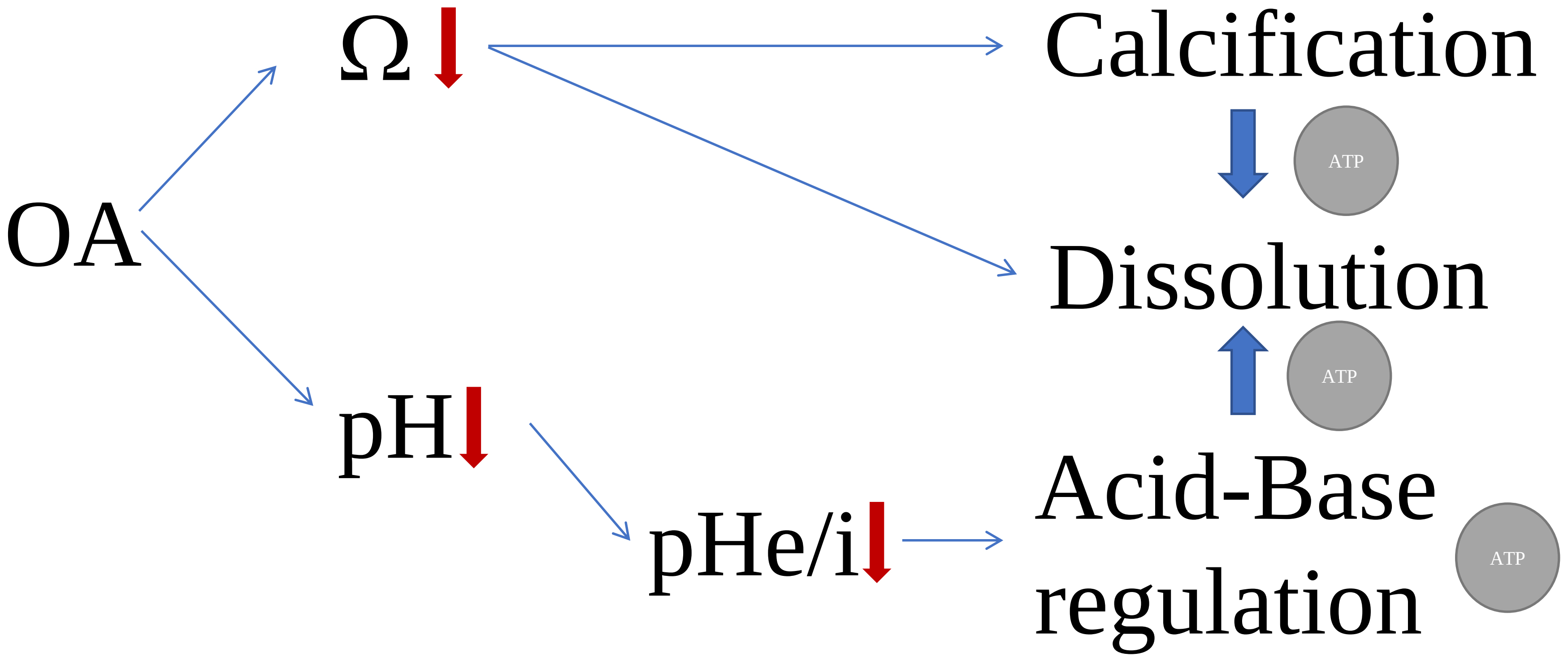
REVIEW

REVIEWS IN Aquaculture

Cracking the myth: Bivalve farming is not a CO_2 sink

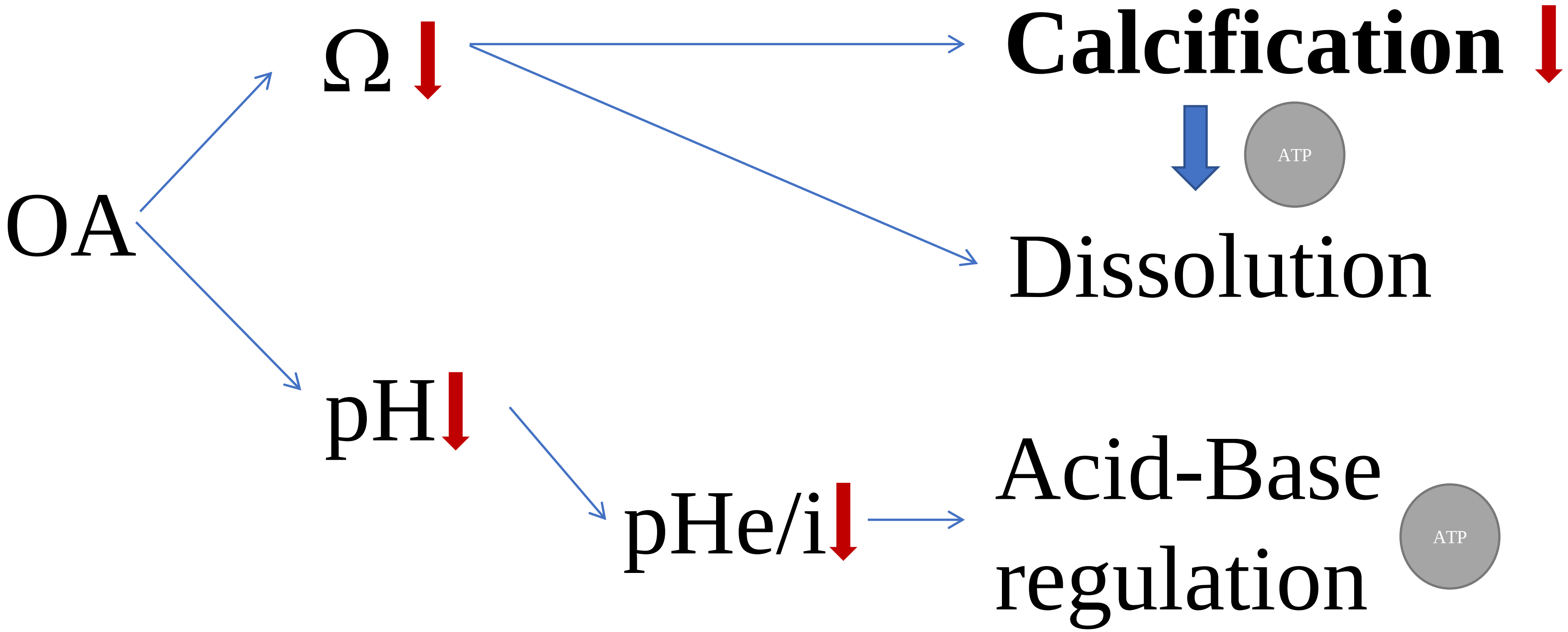
Fabrice Pernet[1] | Sam Dupont[2,3] | Jean-Pierre Gattuso[4,5] | Marc Metian[3] | Frédéric Gazeau[4]

(Many) animal exposed to ocean acidification?



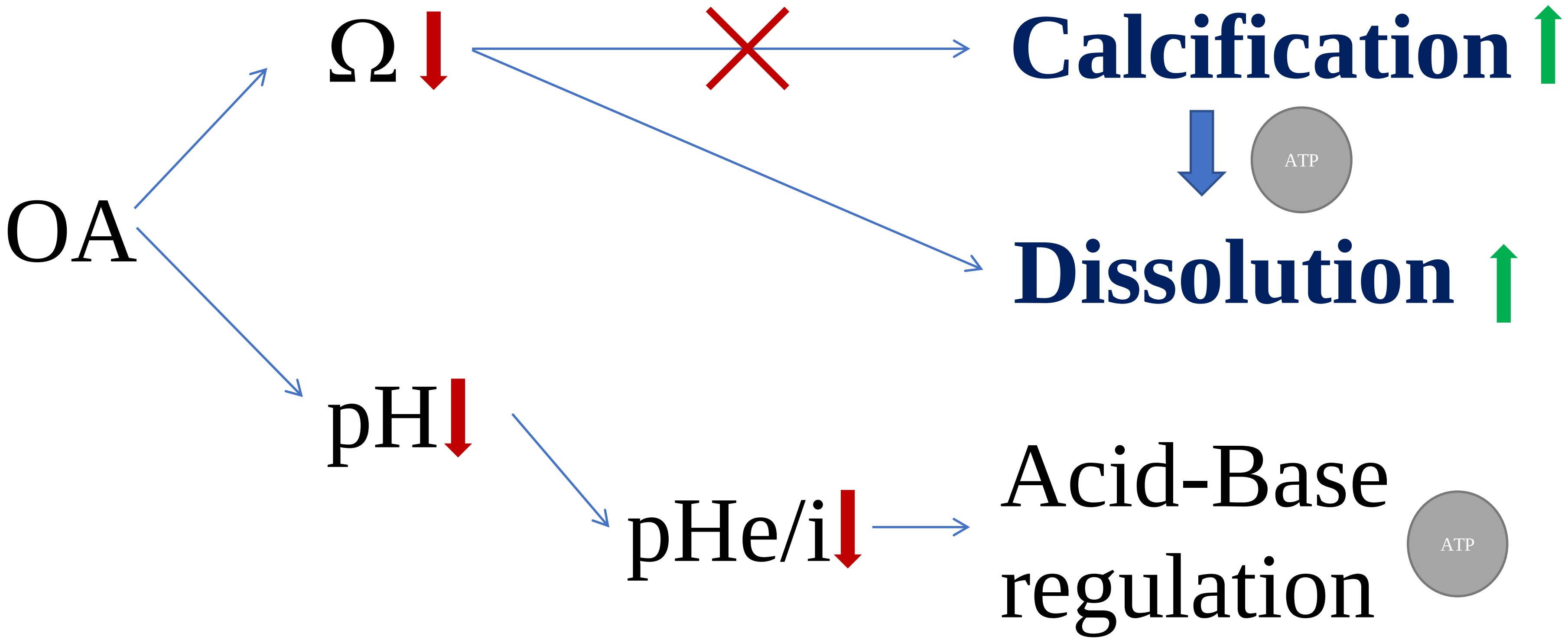
Species sensitivity relates to: ability to protect/compensate & energy

Early oyster larvae

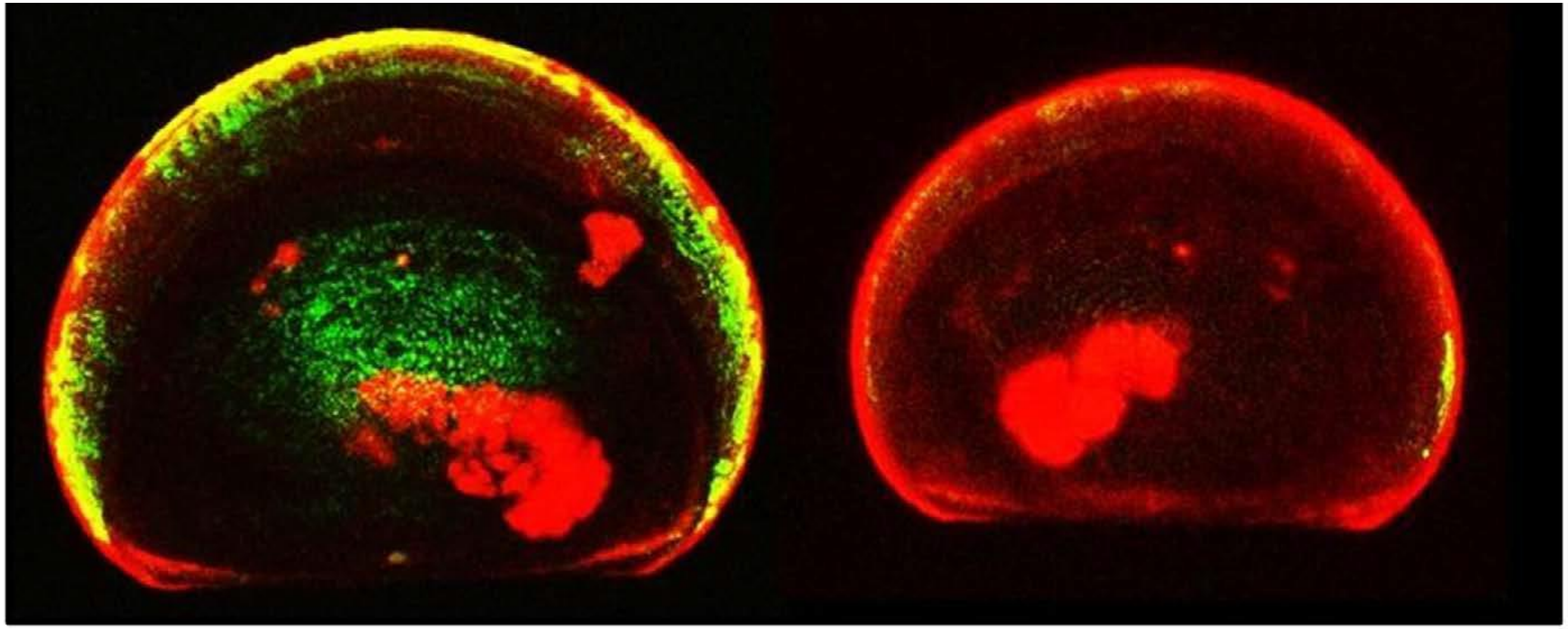


Ω main driver (kinetic constrains)

Mussels


OA
Ω
pH
pHe/i
Calcification
ATP
Dissolution
Acid-Base regulation
ATP

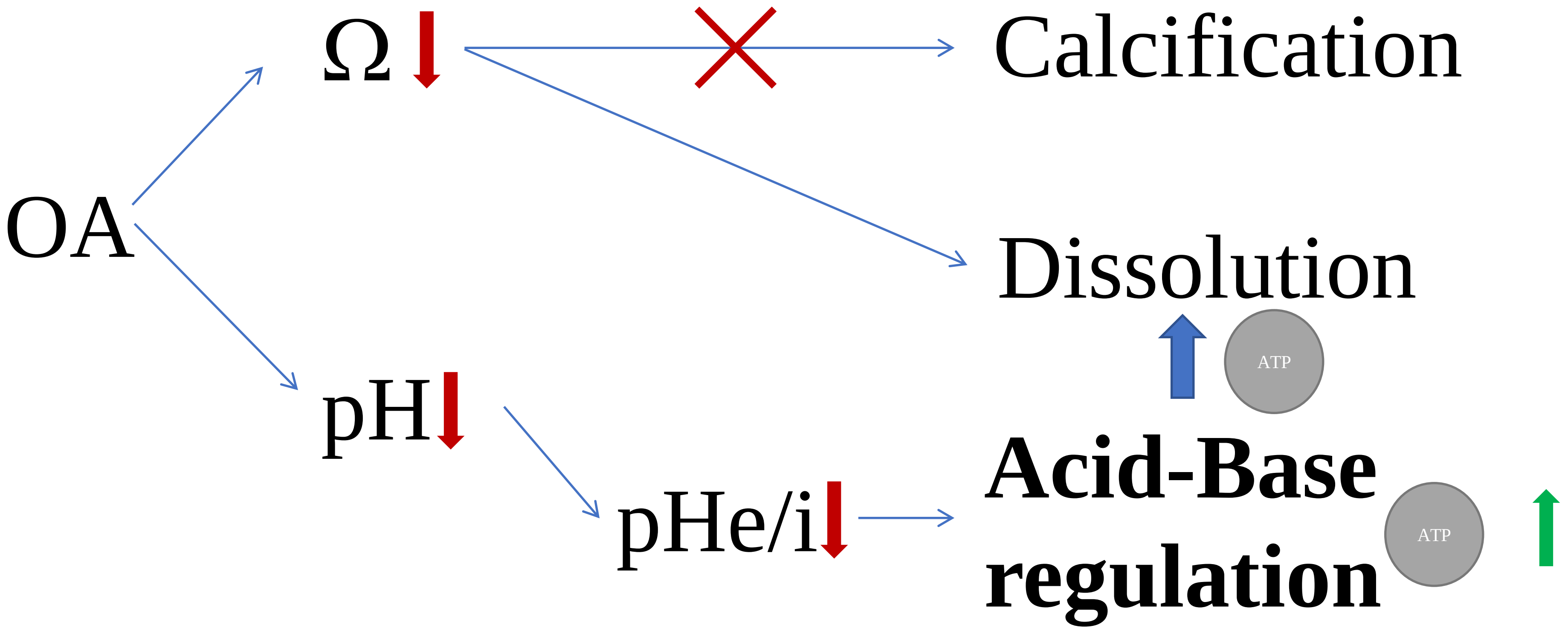
Mussels



Compensatory calcification

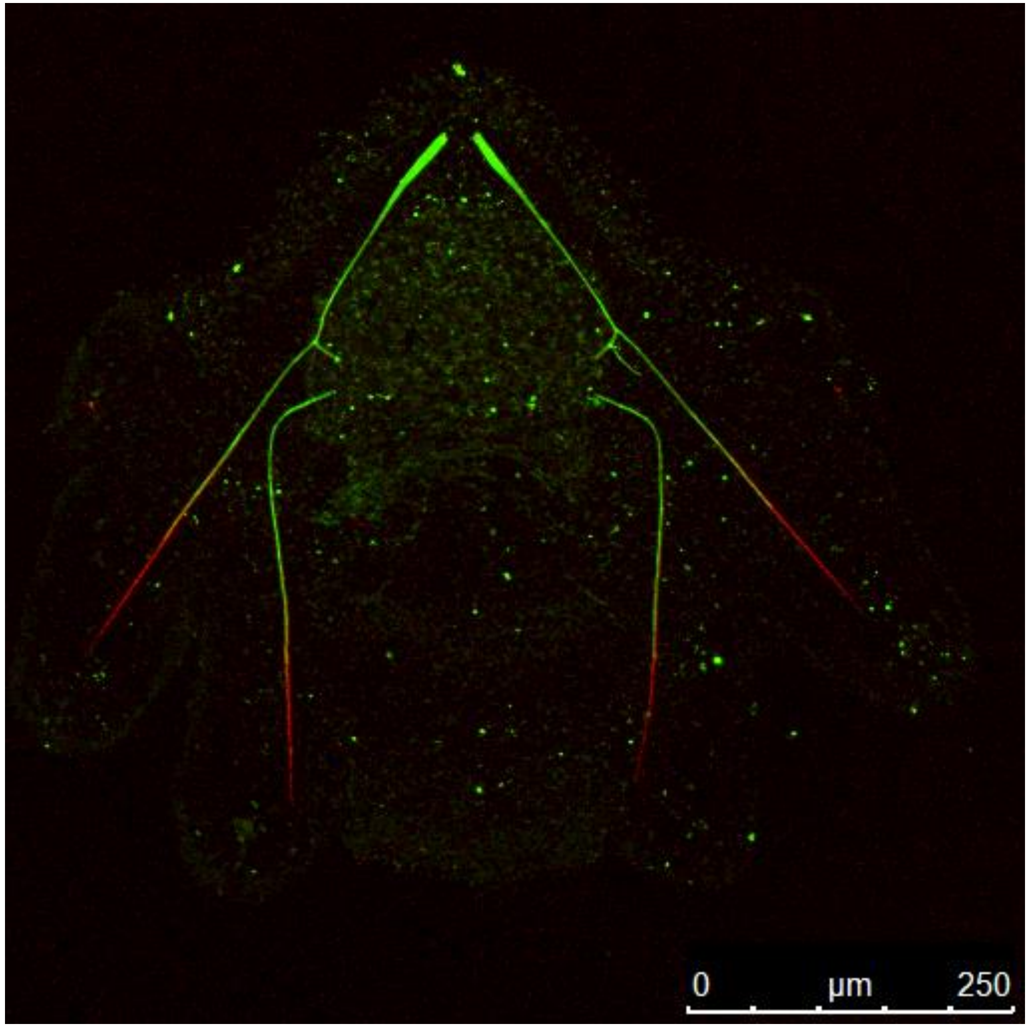
Ventura et al. (2016)

Echinoderms



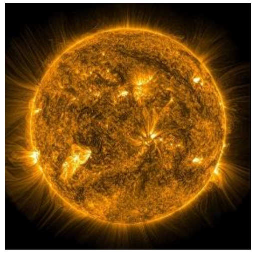
pH main driver (regulation)

Echinoderms



Is it CO_2?

$$6CO_2 + 6H_2O \text{ ------> } C_6H_{12}O_6 + 6O_2$$



Photosynthesis

Summary

- Understand your biology to define the key driver(s)

On the menu today

- What part of the carbonate chemistry is biologically relevant?
- **What part of the local carbonate chemistry shall we monitor to infer biological response?**
- Shall we care about variability in itself?
- How long shall we monitor to see biological impacts?

Species- / population- specific

Population 1

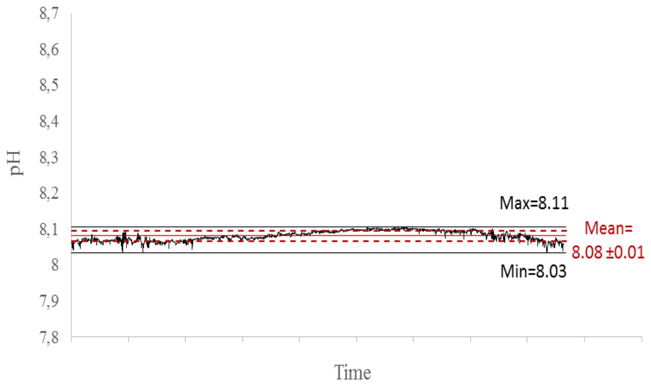
Population 2

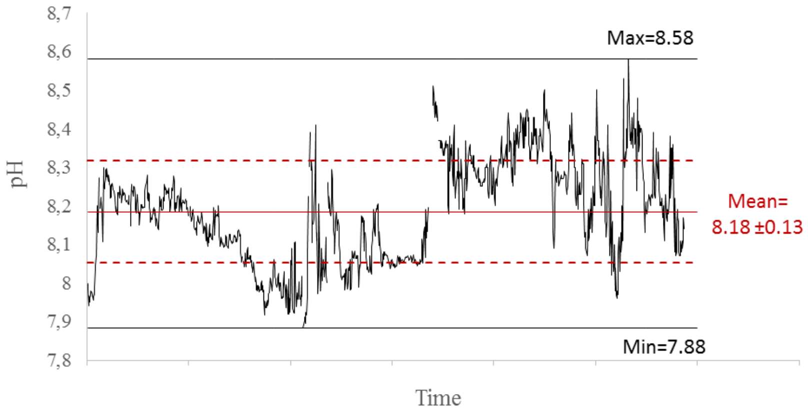
=

Species- / population- specific

Population 1

Population 2





Need local data

$$P(CO_2)atm = p(CO_2)sw$$

CO_2 400ppm

Atmosphere

Seawater

CO_2 400µatm → pH 8.1

Equilibrium true for open ocean

Present: 8.1
OA – 2100: 7.7 (ΔpH: 0.4)

Other parameters are influencing the carbonate chemistry in the ocean

- ✓ Mixing/upwelling
- ✓ Interaction with other parameters (e.g. temperature, salinity)
- ✓ Other sources of acidification (nutrients, SOx/NOx)
- ✓ Biology (photosynthesis, respiration, calcification, etc.)

CO_2 ⬇ CO_2 ⬆ CO_2 ⬆

$P(CO_2)atm \neq p(CO_2)sw$ E.g. coastal zone

CO_2 400ppm

Atmosphere

Seawater

CO_2 200-1400 µatm → pH 8.7 - 7.6

↑

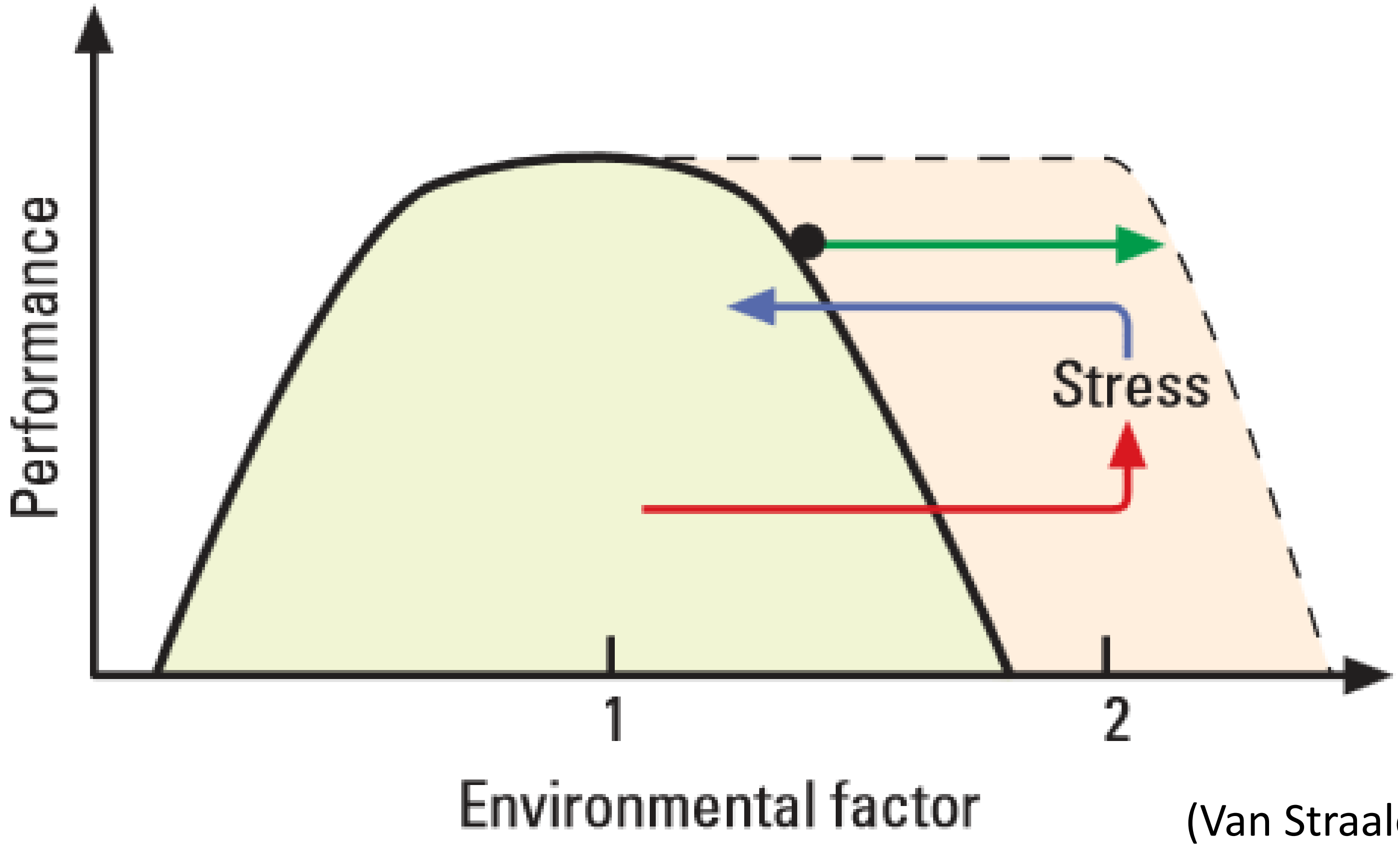
Biology

Not in equilibrium

Present: 8.7-7.6

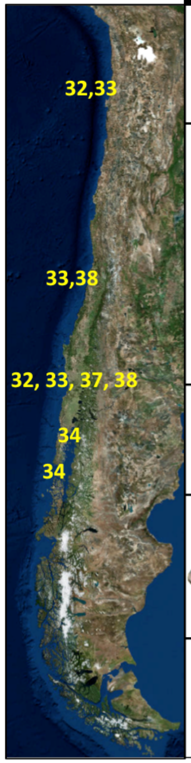
OA – 2100: 8.3-7.2 (ΔpH: 0.4)

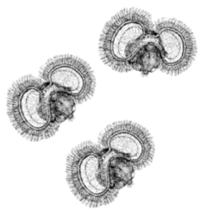
Global stressors



(Van Straalen 2007)

Population effect



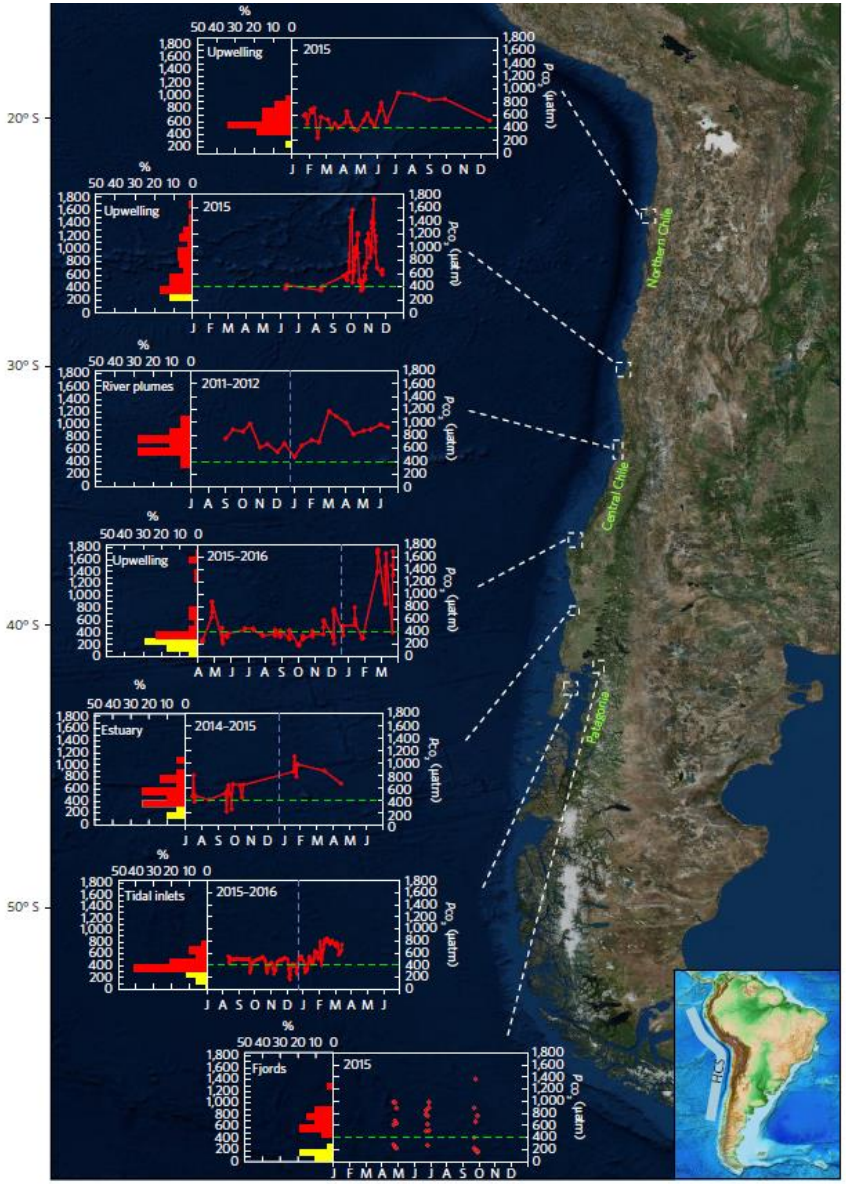
Taxa	Environment	Mean ± SD environmental pCO_2 levels (μatm)	Control pCO_2 levels (μatm)	Experimental pCO_2 levels (μatm)	Response	Mean effect	Reference
	Coastal ocean	555.6 ± 157.5	380	1500	Respiration	+ 213%	32
	Estuarine	623.42 ± 233.68	380	1500	Respiration	+147%	32
	Coastal ocean	555.6 ± 157.5	376	980 -1100	Ingestion	-47%	33
	Estuarine	623.42 ± 233.68	376	980 -1100	Ingestion	-33%	33
	River-plume area	811.0 ± 185.7	376	980 -1100	Ingestion	-17%	33
	Estuarine	623.42 ± 233.68	365 - 398	979 - 1077	Larval survival	-60%	38
	River-plume area	811.0 ± 185.7	365 - 398	979 - 1077	Larval survival	-17	38
	Estuarine	623.42 ± 233.68	347 - 377	910 - 960	Ingestion	-60%	33
	River-plume area	811.0 ± 185.7	347 - 377	910 - 960	Ingestion	-13%	33
	Tidal inlet	500.8 ± 140.2	388	979	Calcification Growth	-37% -35%	34
	Freshwater-influenced tidal inlet	608.9 ± 319.3	388	979	Calcification Growth	-4% -13%	34
	Coastal ocean	405.9 ± 95.4	398 - 405	1255	Ingestion	-72%	37
	Estuarine	623.42 ± 233.68	398 - 405	1255	Ingestion	+ 5%	37

nature ecology & evolution ANALYSIS
PUBLISHED: 13 MARCH 2017 | VOLUME: 1 | ARTICLE NUMBER: 0084

Species-specific responses to ocean acidification should account for local adaptation and adaptive plasticity

Cristian A. Vargas[1,2,3*], Nelson A. Lagos[3,4], Marco A. Lardies[3,5], Cristian Duarte[3,6], Patricio H. Manríquez[7], Victor M. Aguilera[2,8], Bernardo Broitman[3,7], Steve Widdicombe[9] and Sam Dupont[10]

Local adaptation



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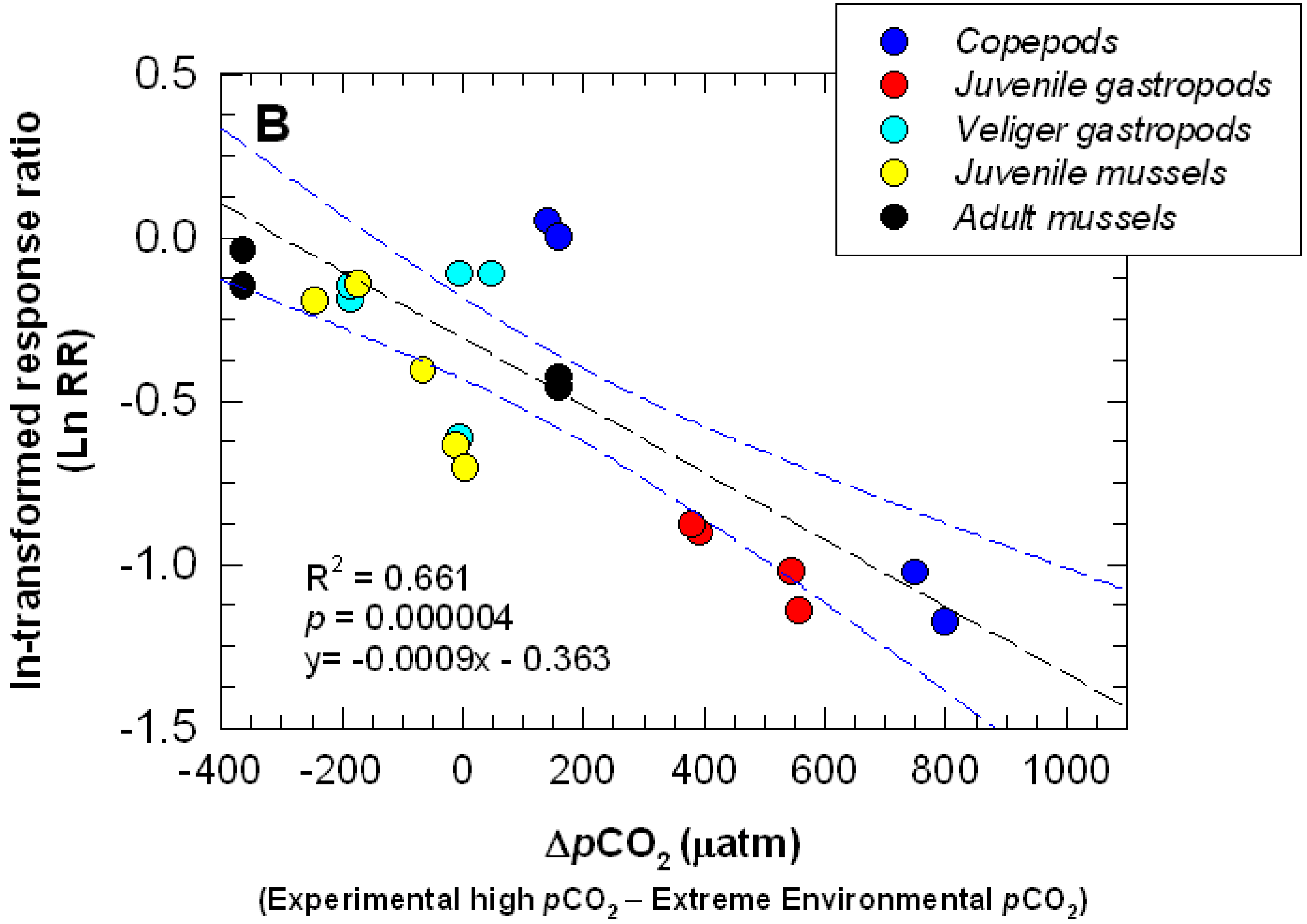
Local adaptation



The more you deviate from today, the more negative impact

If you know the present variability, you can predict the threshold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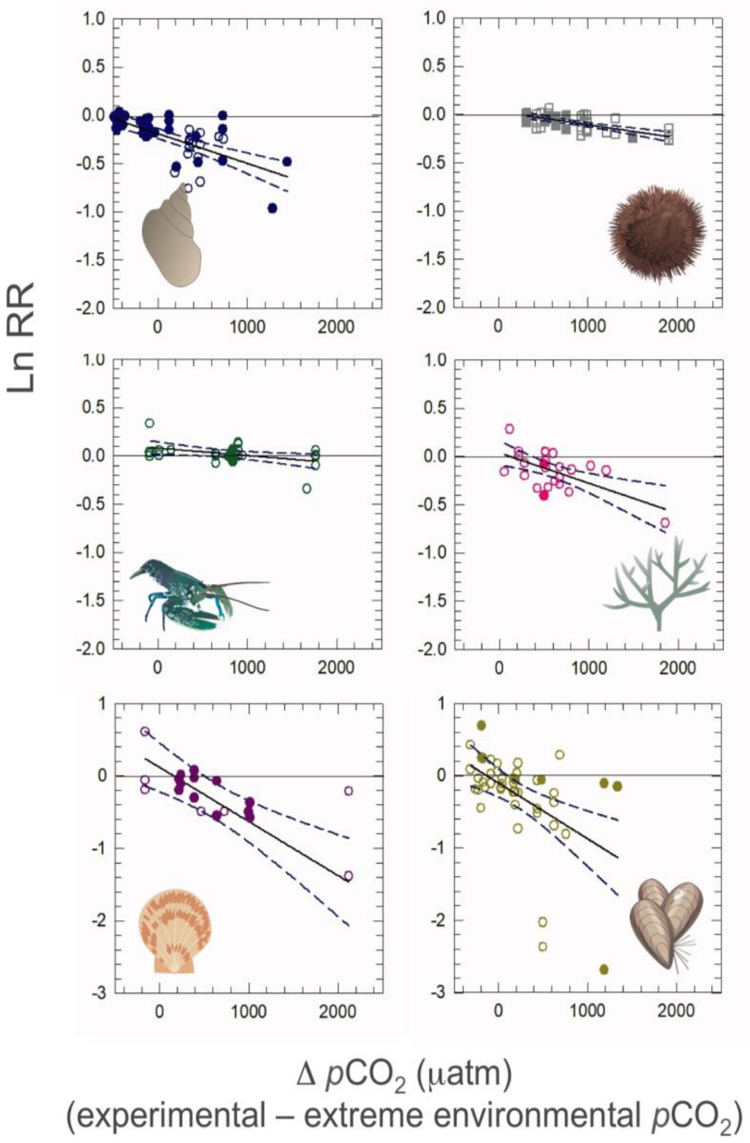
Upscale to the world



Same global trends

Differences between phyla

ANALYSIS

https://doi.org/10.1038/s41558-021-01269-2

nature climate change

Check for updates

Upper environmental pCO_2 drives sensitivity to ocean acidification in marine invertebrates

Cristian A. Vargas[1,2,3], L. Antonio Cuevas[1,3], Bernardo R. Broitman[3,4], Valeska A. San Martin[3], Nelson A. Lagos[3,5], Juan Diego Gaitán-Espitia[6] and Sam Dupont[7,8]

Summary

- Understand your biology to define the key driver(s)
- Need to capture the short-term variability and extremes

Biology is complicated

What are the physico-chemical conditions experienced by my organism/ecosystem?

Important to take into account:

- ✓ Microhabitats

Microhabitats

250 mmol O_2
pH 8.00

50 mmol O_2
pH 7.67

Before starting your experiment

What are the physico-chemical conditions experienced by my organism/ecosystem?

Important to take into account:

- ✓ Microhabitats
- ✓ Behaviour
- ✓ Life-history stages

The picture can't be displayed.

Behaviour

The picture can't be displayed.

Life-history stages

Summary

- Understand your biology to define the key driver(s)

- Need to capture the short-term variability and extremes

… experienced by the organism / ecosystem

On the menu today

- What part of the carbonate chemistry is biologically relevant?
- What part of the local carbonate chemistry shall we monitor to infer biological response?
- **Shall we care about variability in itself?**
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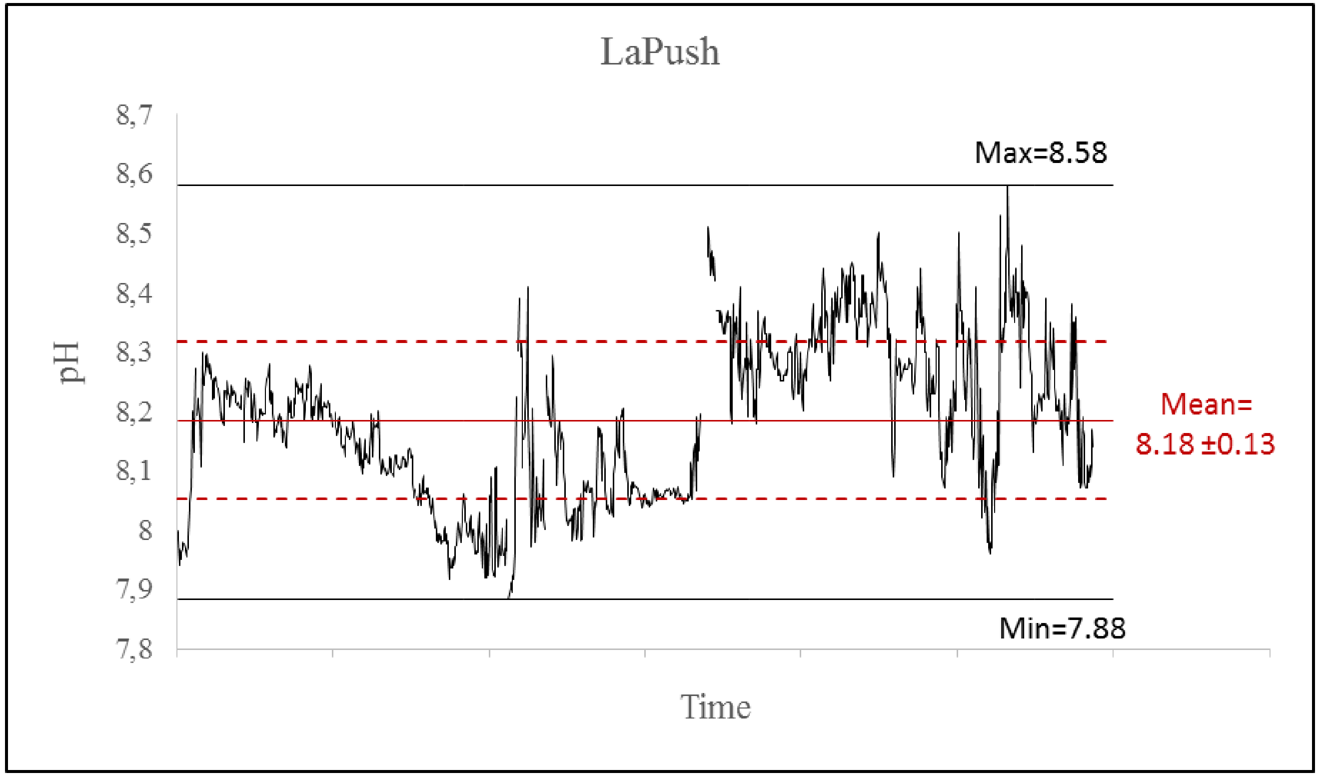
Scales of time and variability



Variability:

- **Predictable** (cycles)
- **Unpredictable** (extreme events)

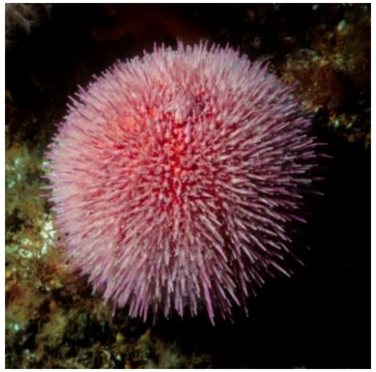
Exposure:

- **Duration** (time, life-cycles, generations)

Adaptation: ecosystem protection & restoration (e.g. seagrass)

- Increase biodiversity
- Increase resilience
- Capture carbon

Short term natural variability



Echinus esculentus

Damboia Cossa

Create variability

Day: light
= Photosynthesis + respiration

O_2 ↑ CO_2 ↓ pH ↑

Night: dark
= respiration

O_2 ↓ CO_2 ↑ pH ↓

How will organism respond to this variability?

Design – experimental system

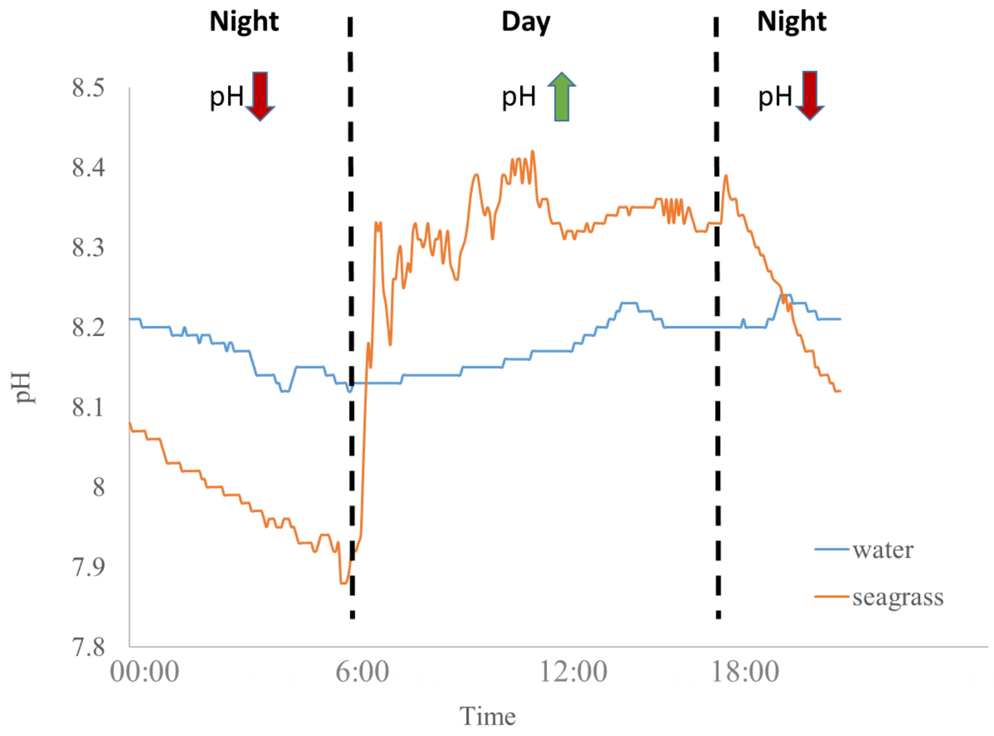
Water +sediment	Water +sediment +seagrass
n=3	n=3

(X 4 pH)
(8.3 to 7.5)

- *Natural flowing surface seawater*
- *12:12 light*
- *True replication*

- *Discrete + continuous measurements (temperature, salinity, oxygen, alkalinity, pH)*

Chemistry

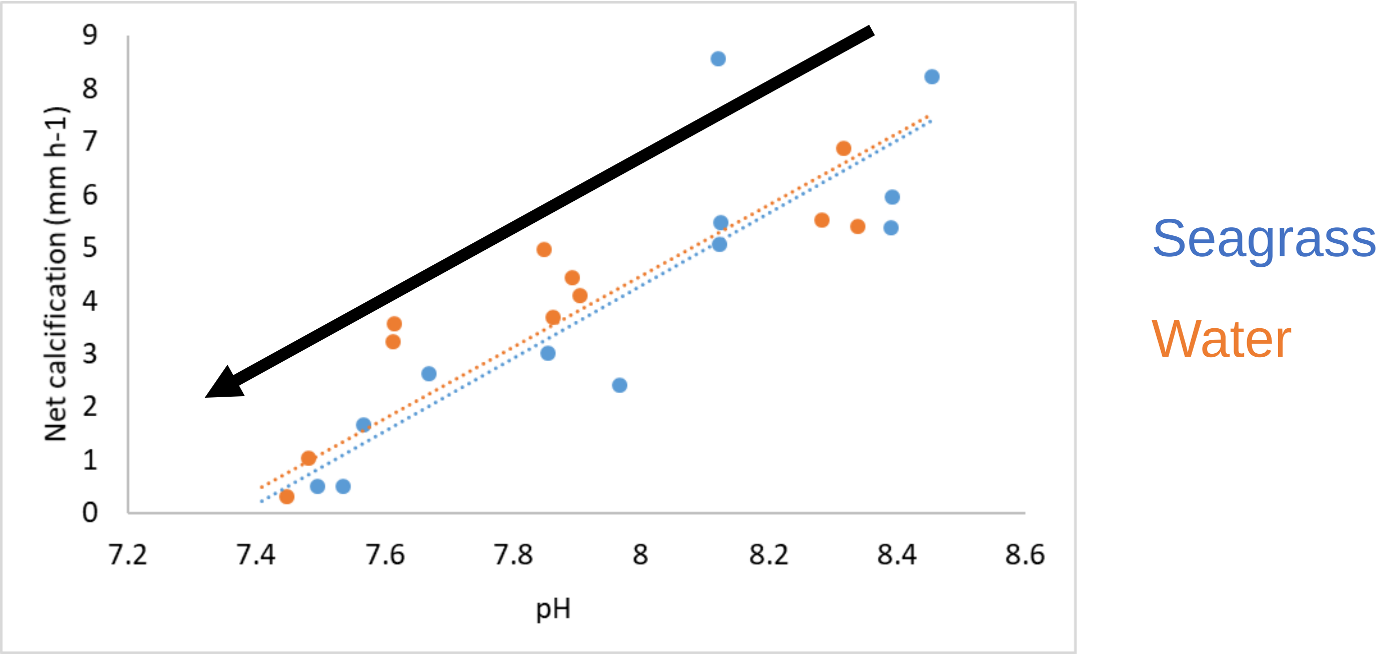


Seagrass increases the variability in pH through photosynthesis / respiration

4 different starting pH

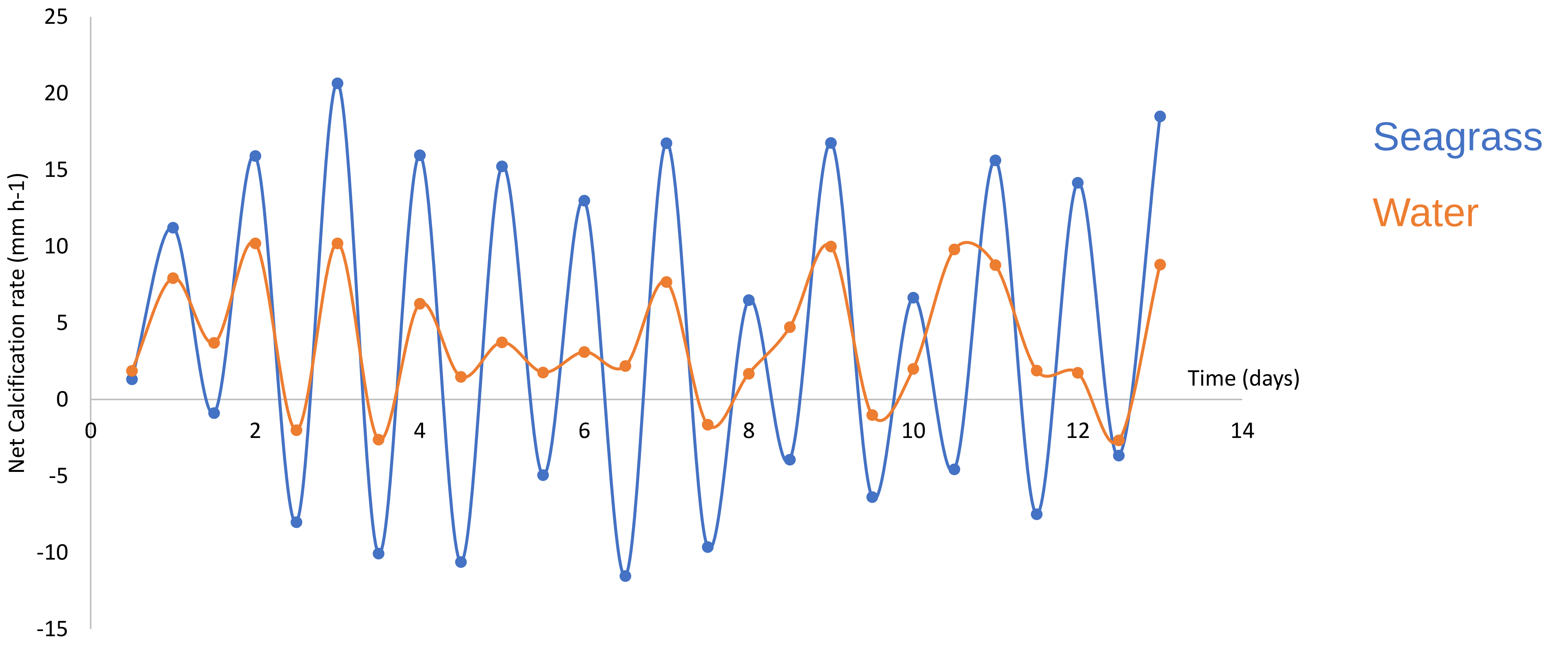
4-8x more variability when seagrass is present

Daily net calcification



Decreasing calcification with decreasing pH
Same daily calcification

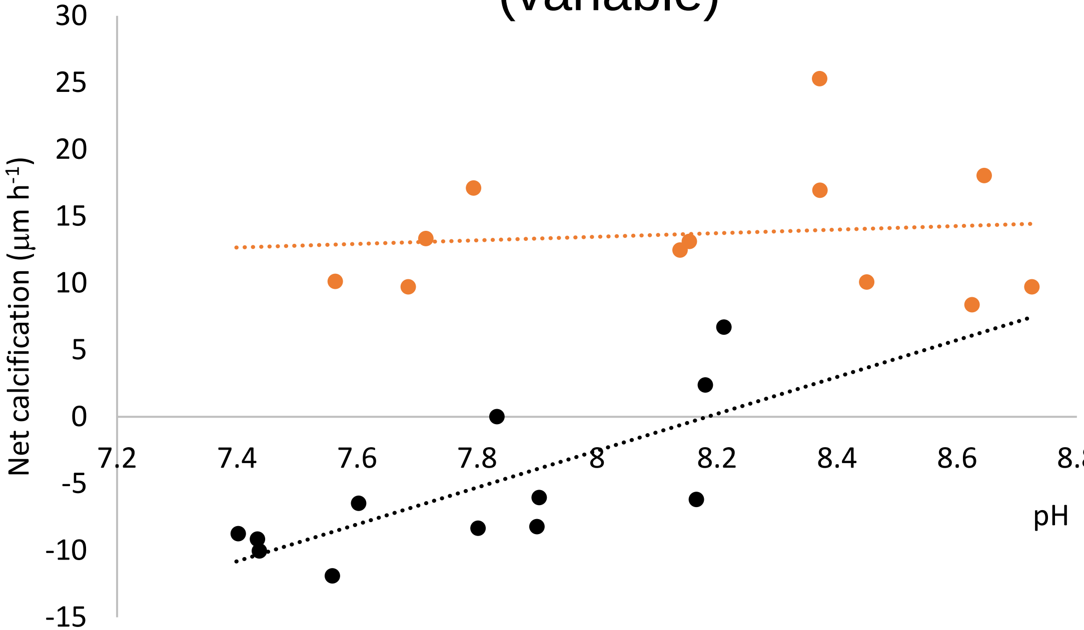
Day-Night net calcification



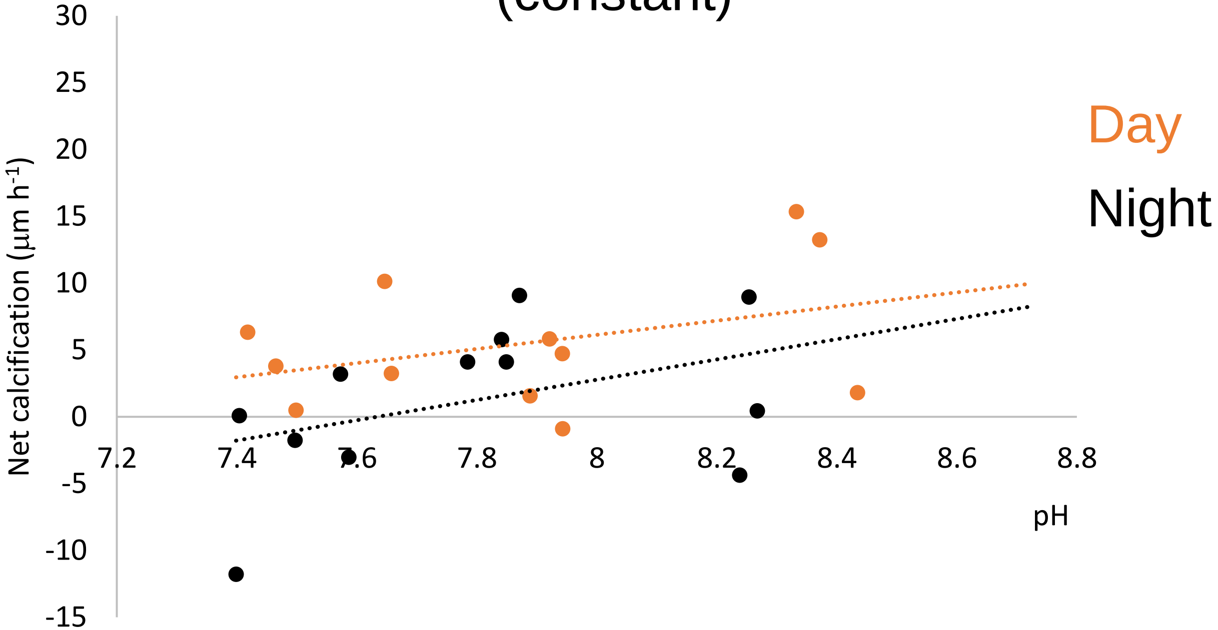
Cycle of calcification (⬆ day - ⬇ night)
Stronger and more regular in variable / seagrass environment

Day-Night net calcification

Seagrass
(variable)



Seawater
(constant)



Maximum calcification during the day

Constant calcification

Two different environments -> two different strategies

Summary

- Understand your biology to define the key driver(s)

- Need to capture the short-term variability and extremes
… experienced by the organism / ecosystem

- Variability is important in itself

On the menu today

- What part of the carbonate chemistry is biologically relevant?

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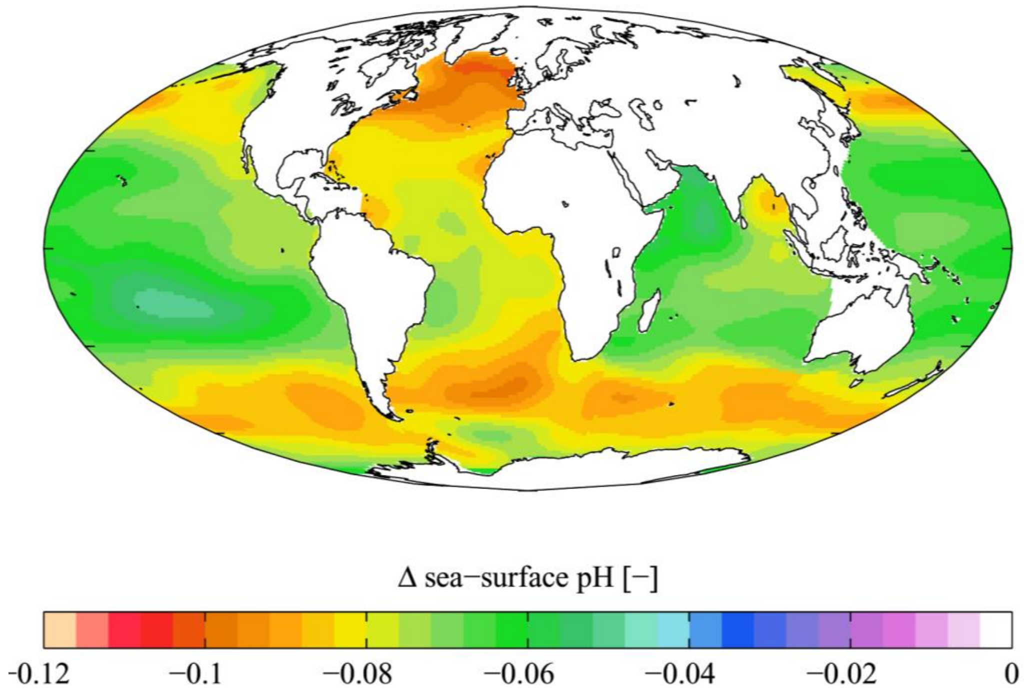
- **How long shall we monitor to see biological impacts?**

Factors modulating biological rate of change

- ✓ Biological sensitivity
- ✓ Chemical rate of change

Where to monitor to see biological changes?



Chemical rate of change depends on where you are

Factors modulating biological rate of change

- ✓ Biological sensitivity ↑
- ✓ Chemical rate of change ↑

→ Rate of change ↑

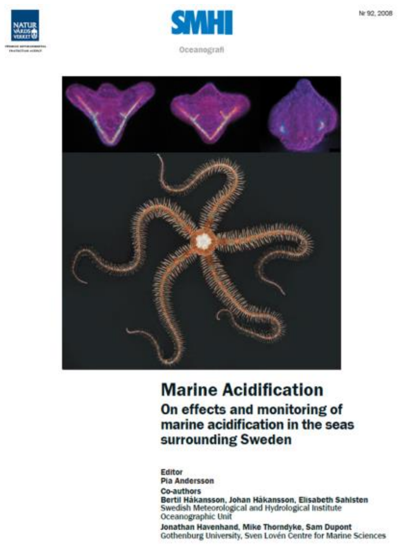
→ Shorter you need to monitor to see an effect and collect robust data

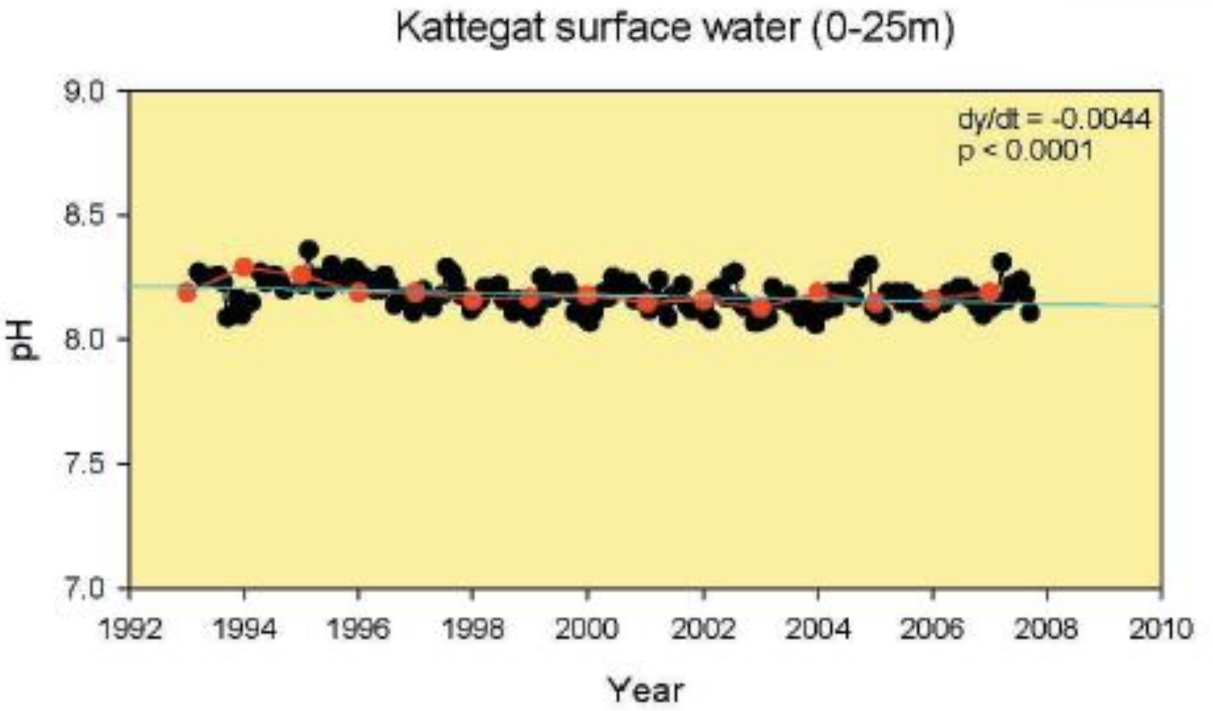
How to estimate how long to monitor to see (robust) changes?

Use experimental data

Example: Gullmarsfjord, Sweden

Rate of chemical change

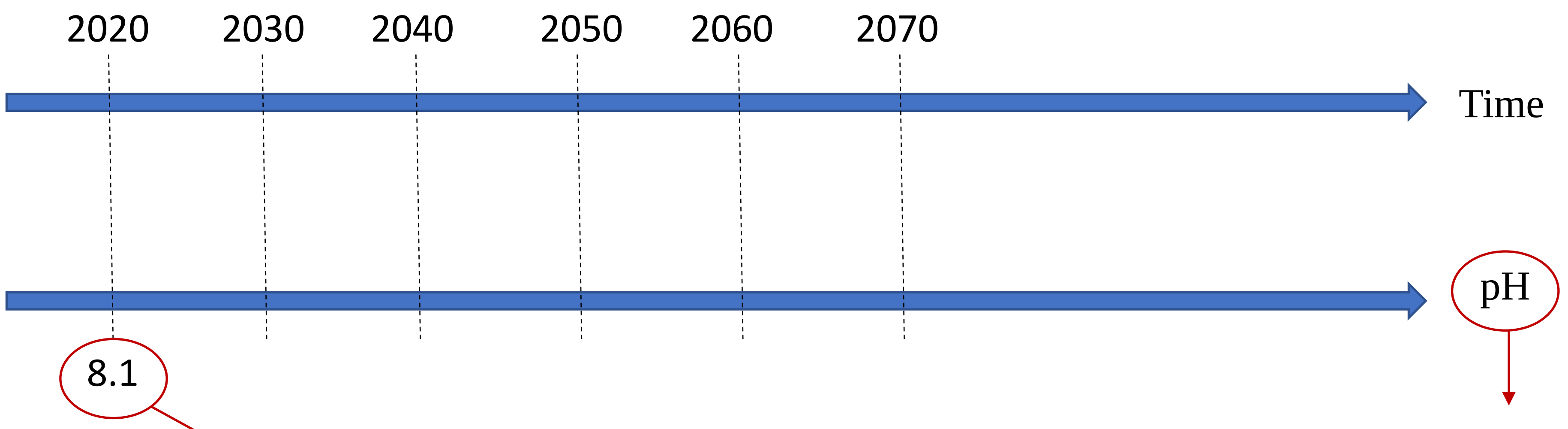




-0.0044 pH unit / year

Combine these data

Step 1: turn time into pH

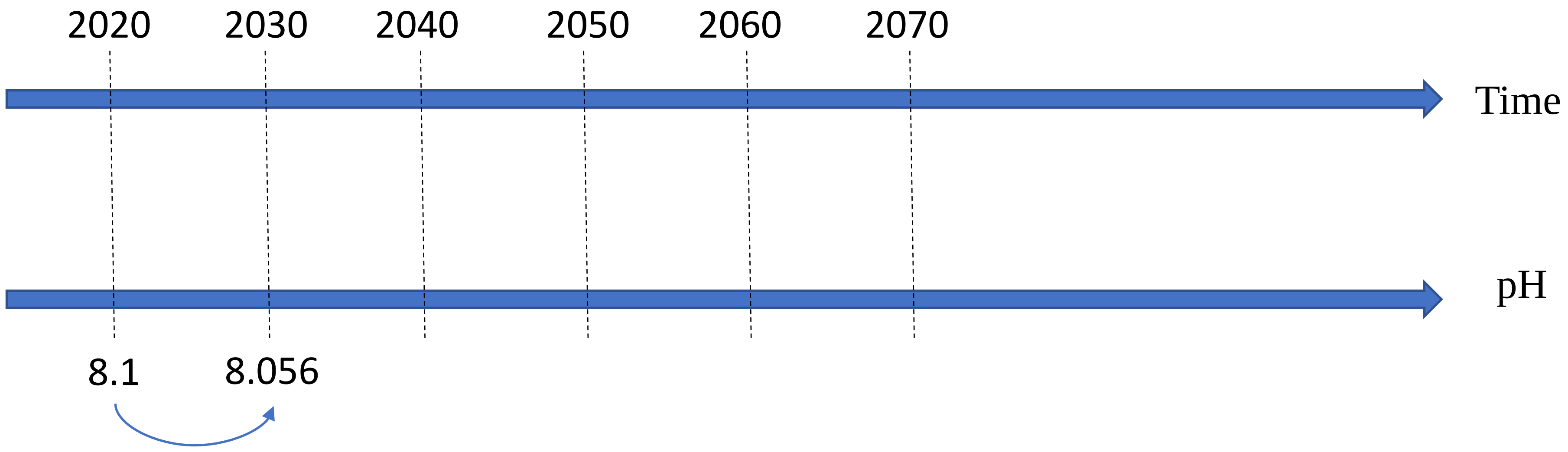


- Present pH (observed)
- Average/extreme/etc. depends on what is biologically relevant

Or any biologically relevant parameter of the carbonate chemistry

Combine these data

Step 1: turn time into pH



$pH_{2030} = pH_{2020}$ + Rate of chemical change x (2030 – 2020)

Rate of chemical change = -0.0044 pH unit / year

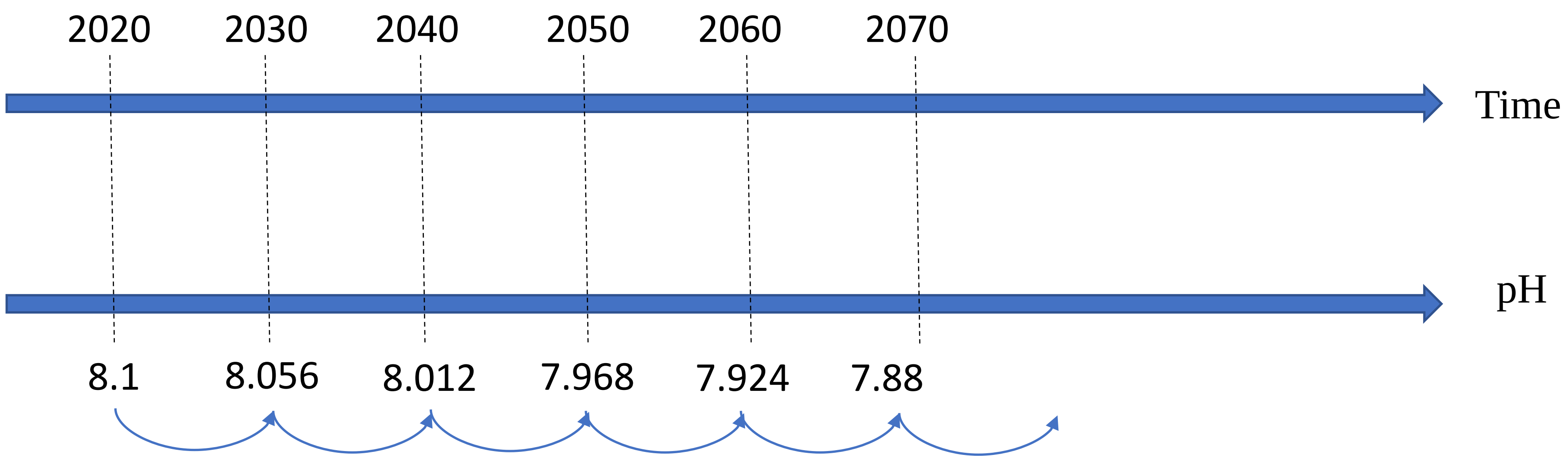
$pH_{2030} = 8.1 - 0.0044 \times 10 = \mathbf{8.056}$

Limitations:

- Rate not constant (mitigation, modulating factors)

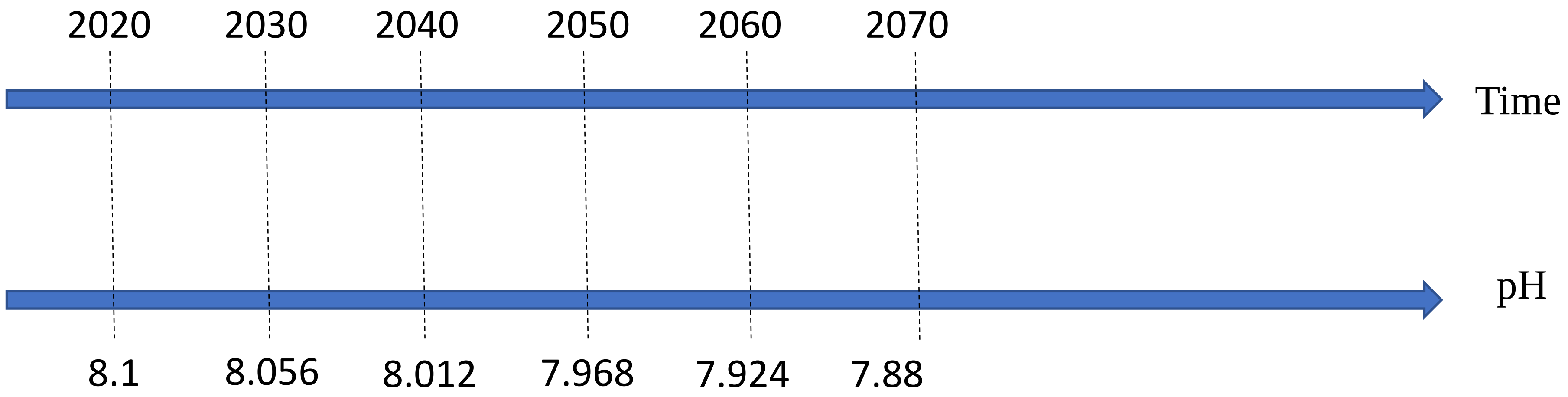
Combine these data

Step 1: turn time into pH



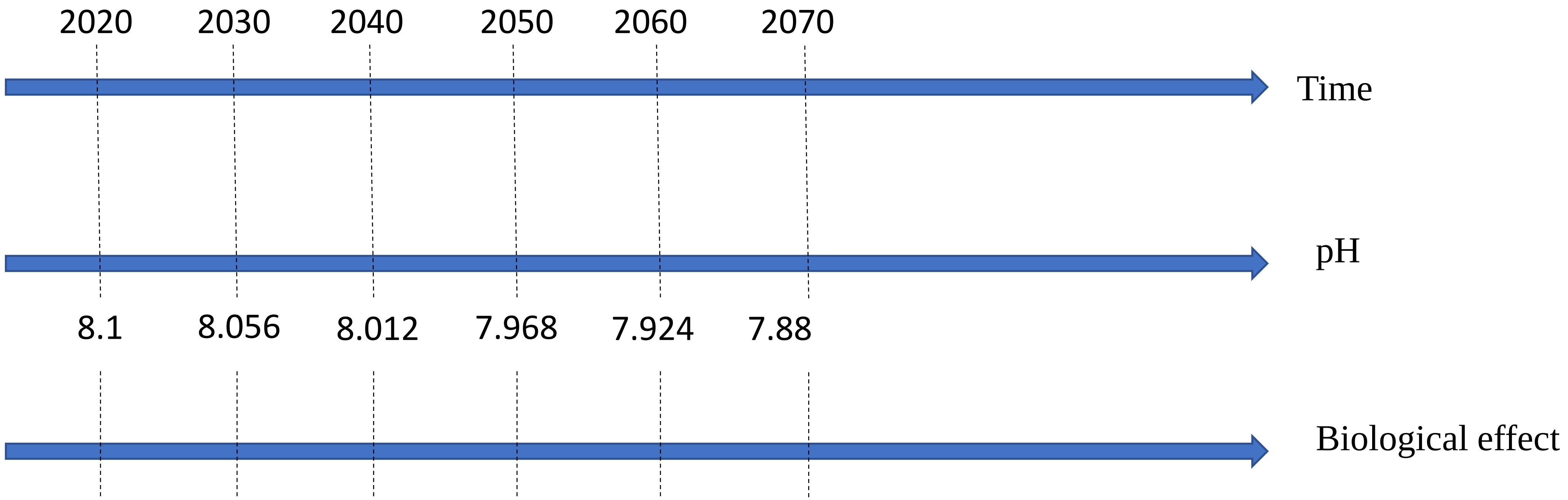
Combine these data

Step 2: turn pH into biological effects

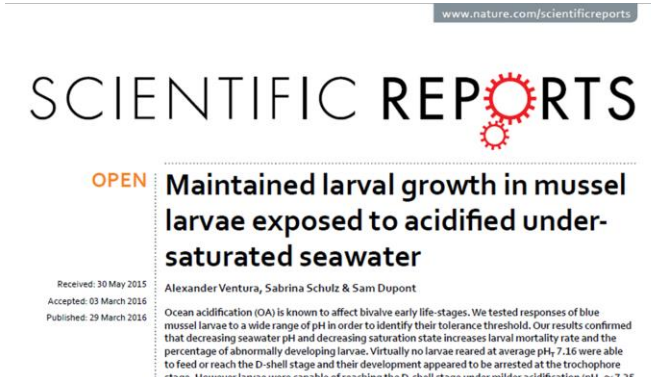


Combine these data

Step 2: turn pH into biological effects



Biological sensitivity (e.g. blue mussels)



www.nature.com/scientificreports

SCIENTIFIC REPORTS

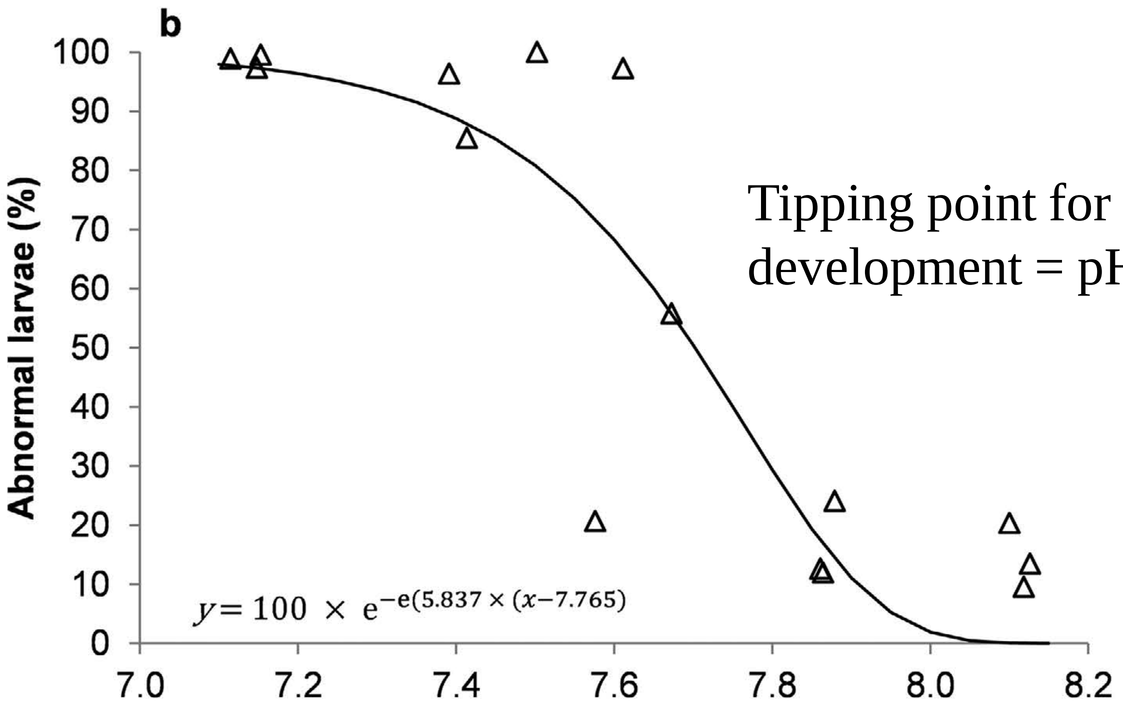
OPEN

Maintained larval growth in mussel larvae exposed to acidified under-saturated seawater

Received: 30 May 2015
Accepted: 03 March 2016
Published: 29 March 2016

Alexander Ventura, Sabrina Schulz & Sam Dupont

Ocean acidification (OA) is known to affect bivalve early life-stages. We tested responses of blue mussel larvae to a wide range of pH in order to identify their tolerance threshold. Our results confirmed that decreasing seawater pH and decreasing saturation state increases larval mortality rate and the percentage of abnormally developing larvae. Virtually no larvae reared at average pH_T 7.16 were able to feed or reach the D-shell stage and their development appeared to be arrested at the trochophore



Tipping point for normal development = pH_T 7.765.

Limitations:

- Experimental design
- Adaptation / Acclimation
- Ecological interactions
- Modulating factors
- Etc.

Effect size (in this case, same thing)

Effect size (%) = 100 x e $^{-e\ (5.837\ x\ (pH\ -\ 7.765))}$

Combine these data

Step 2: turn pH into biological effects

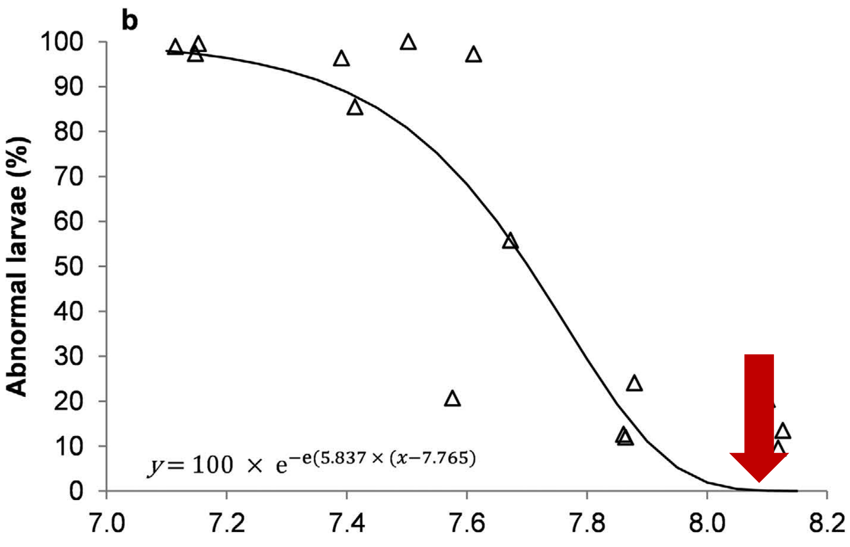
2020 2030 2040 2050 2060 2070

Time

8.1 8.056 8.012 7.968 7.924 7.88

0.085

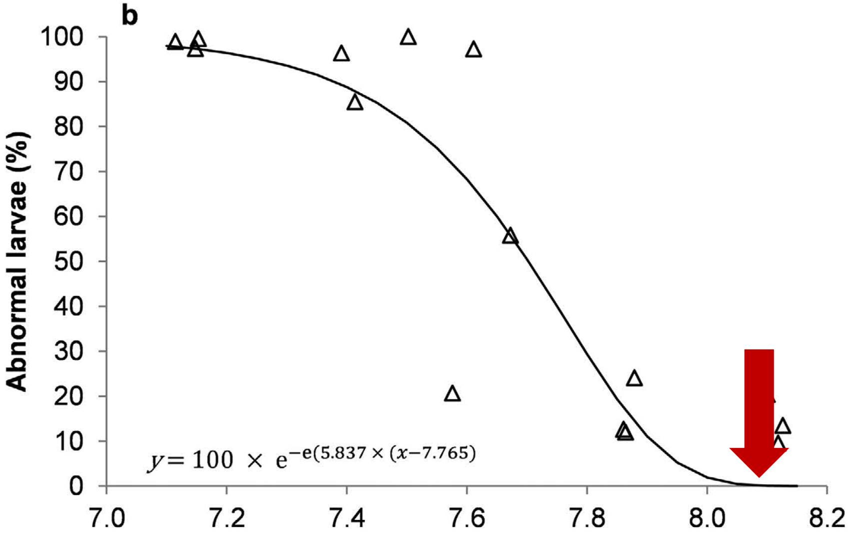
$$0.085303513 = 100 \times e^{-e\,(5.837 \times (8.056 - 7.765))}$$



Combine these data

Step 2: turn pH into biological effects

2020	2030	2040	2050	2060	2070	Time
8.1	8.056	8.012	7.968	7.924	7.88	
0.085	0.423					



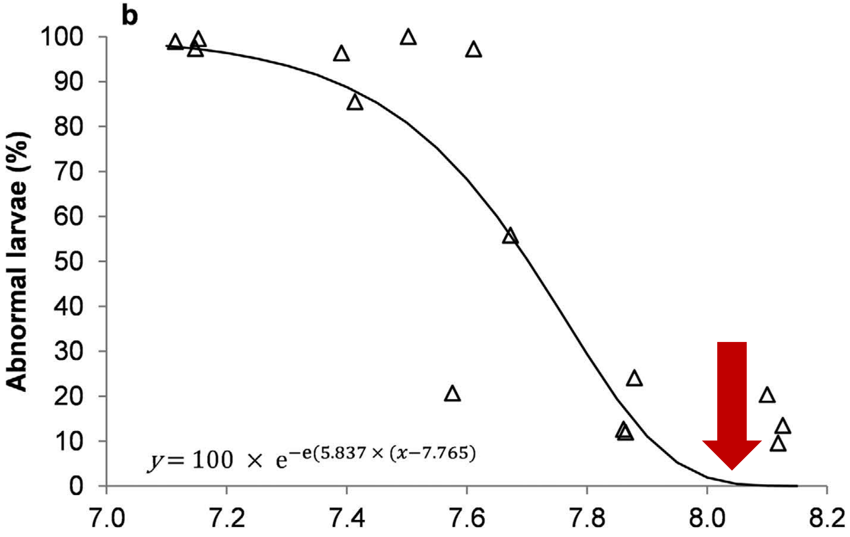
$$0.422765065 = 100 \text{ x } e^{-e\,(5.837 \text{ x } (8.056 - 7.765))}$$

Combine these data

Step 2: turn pH into biological effects

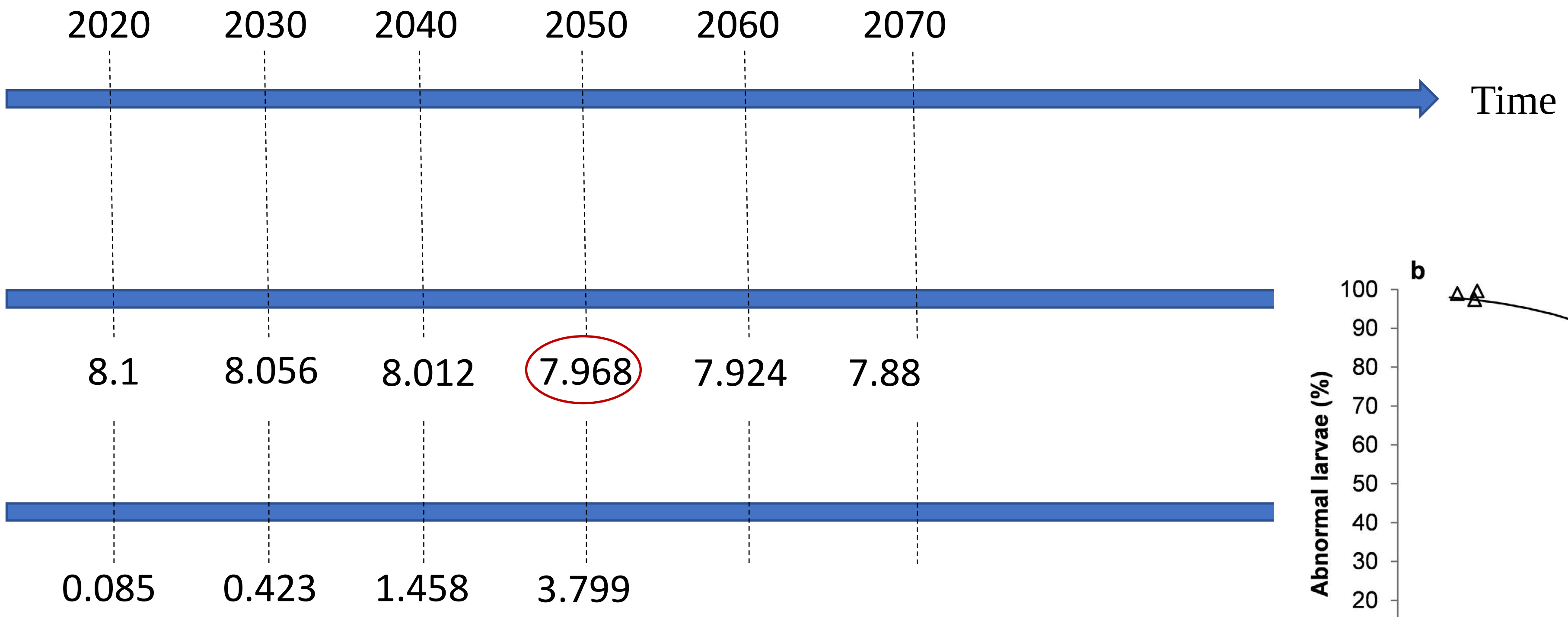
Time

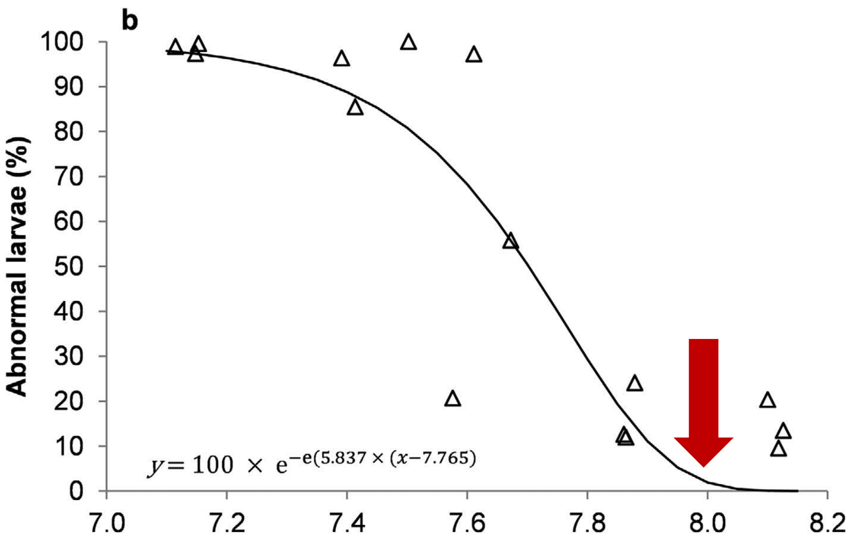
2020	2030	2040	2050	2060	2070
8.1	8.056	8.012	7.968	7.924	7.88
0.085	0.423	1.458			



Combine these data

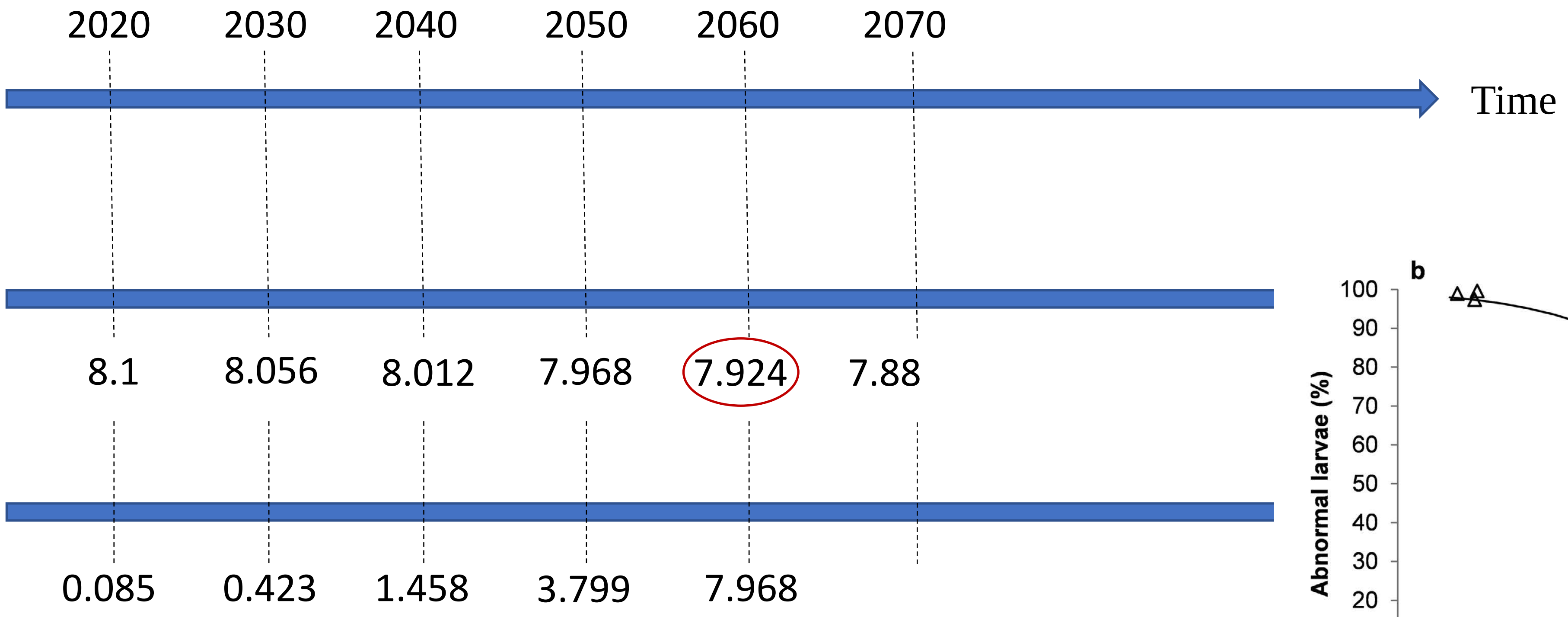
Step 2: turn pH into biological effects

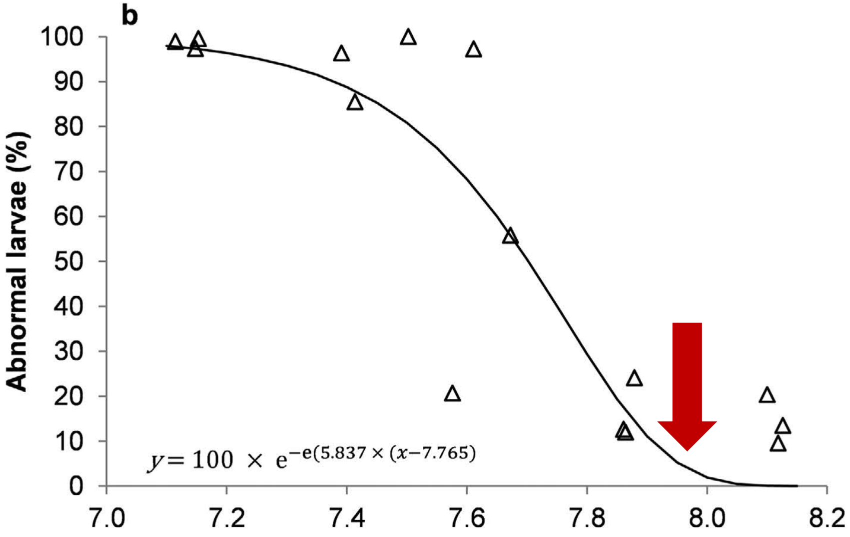




Combine these data

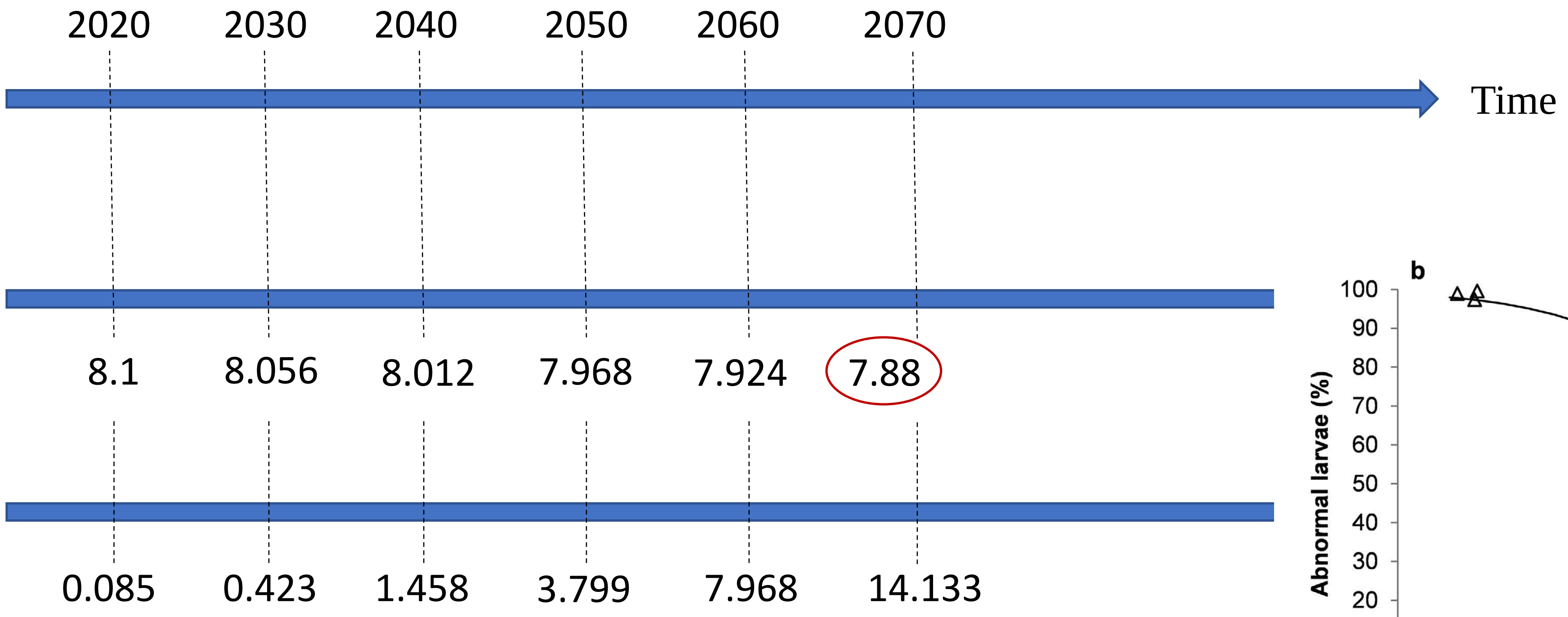
Step 2: turn pH into biological effects

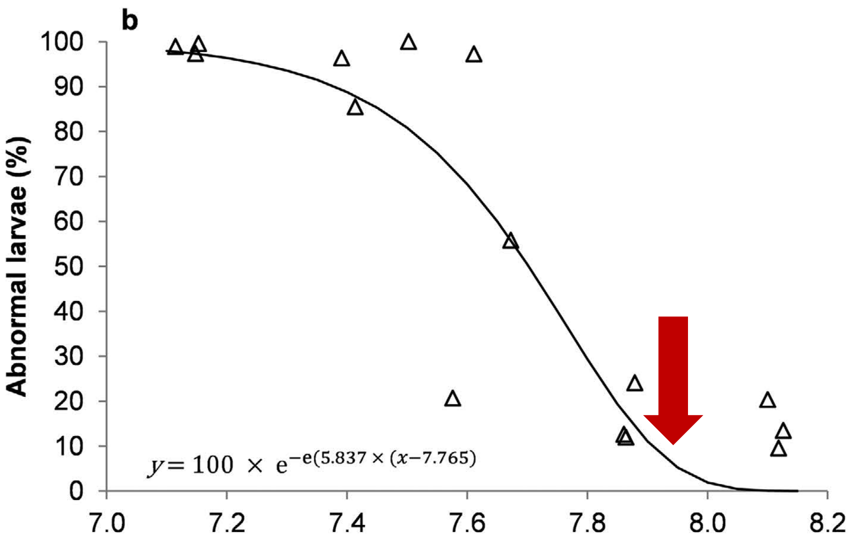




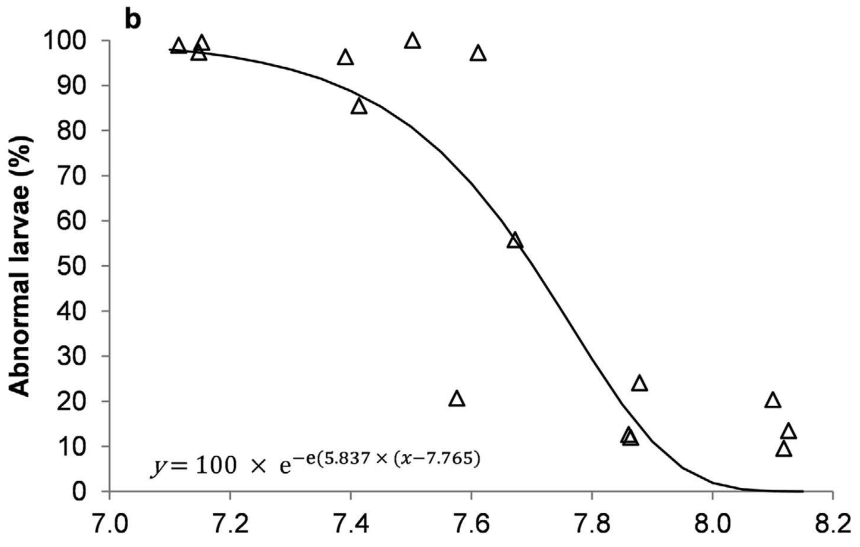
Combine these data

Step 2: turn pH into biological effects



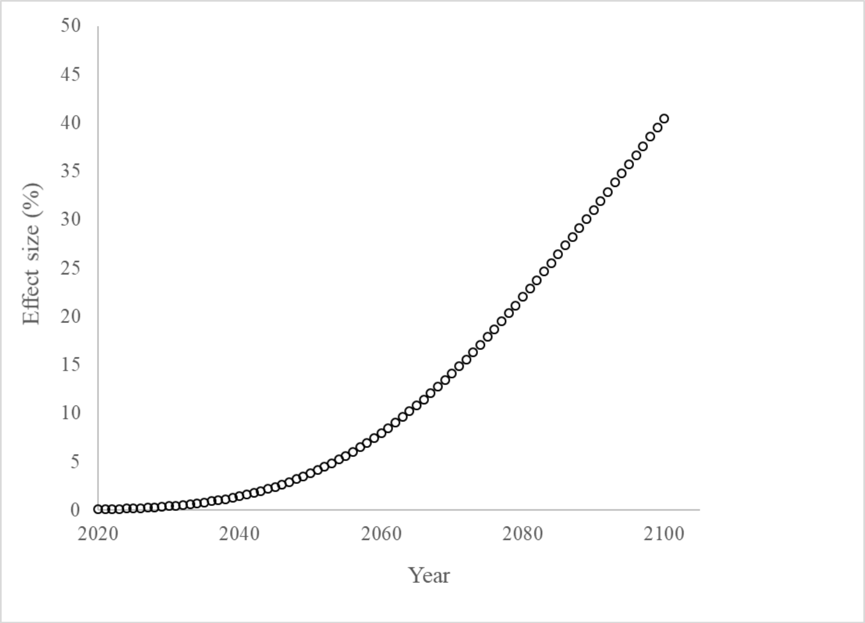


What can be expected



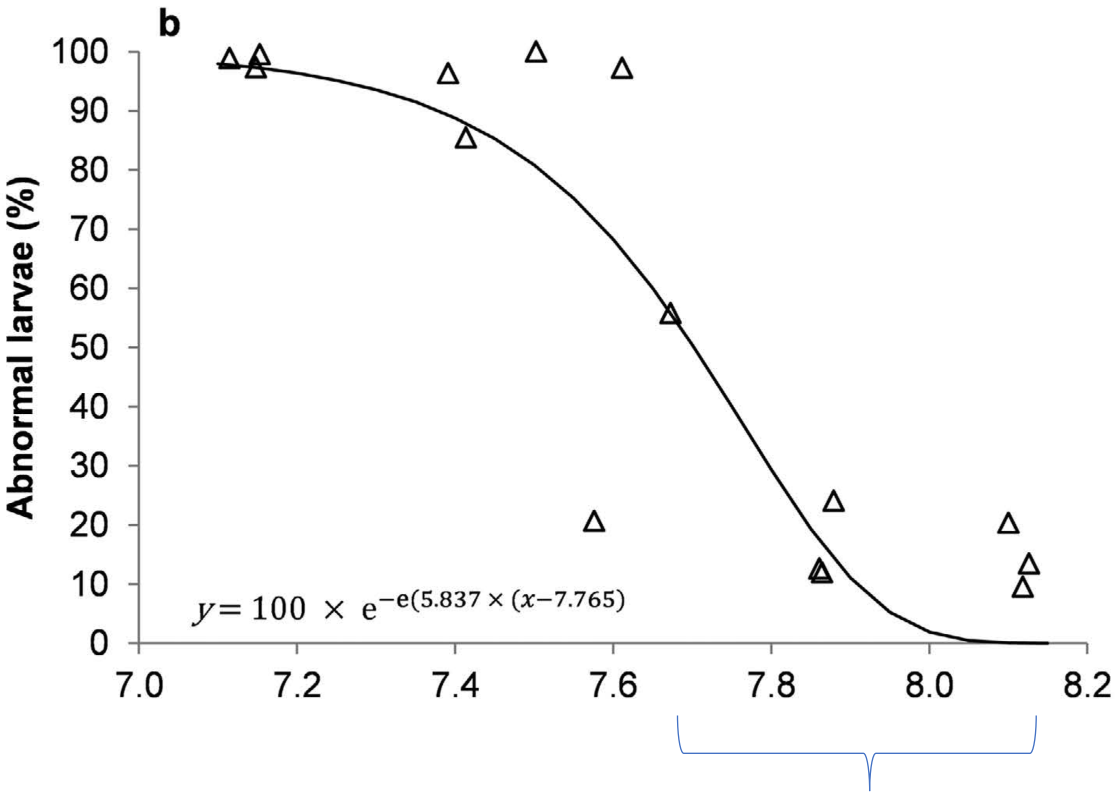
Biological response

Chemical rate of change



Biological observation (projected)

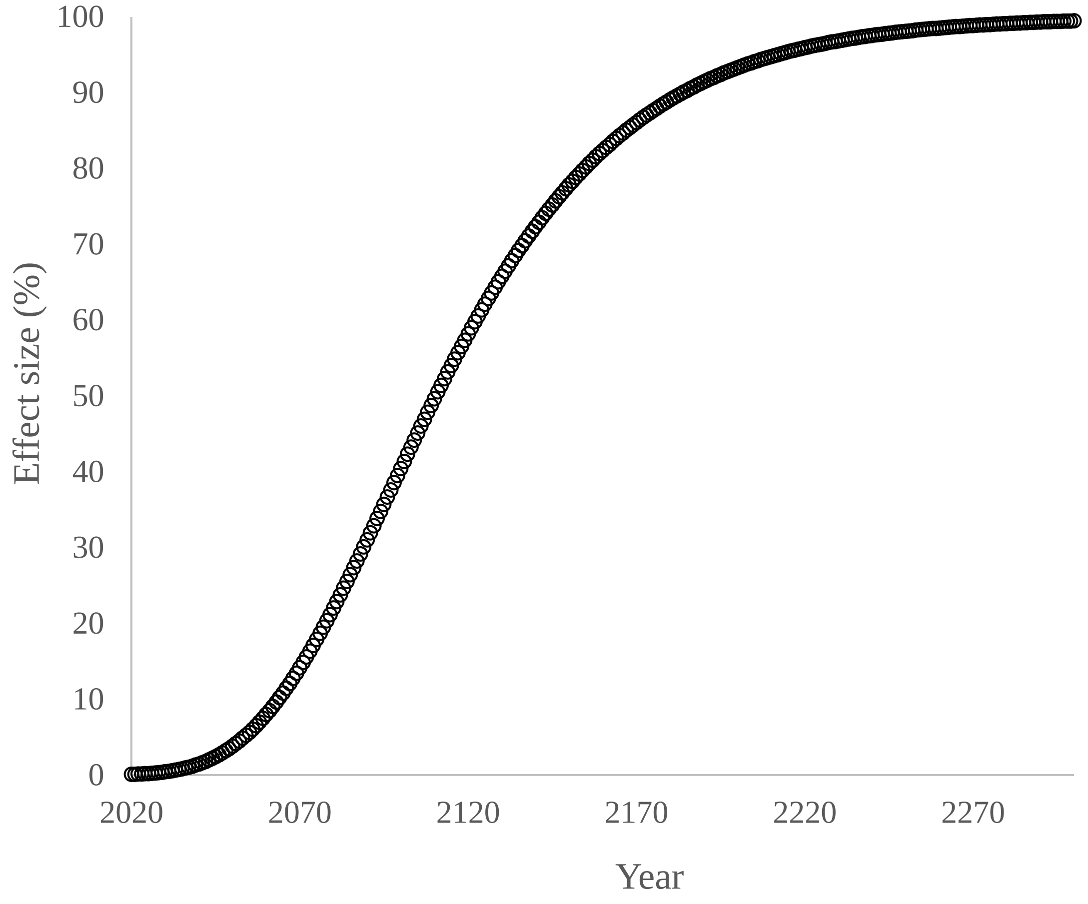
Step 3: estimate the rate of biological change



Range covered by 2100

- Not linear
- Need a wide range of pH to have the full curve

Step 3: estimate the rate of biological change

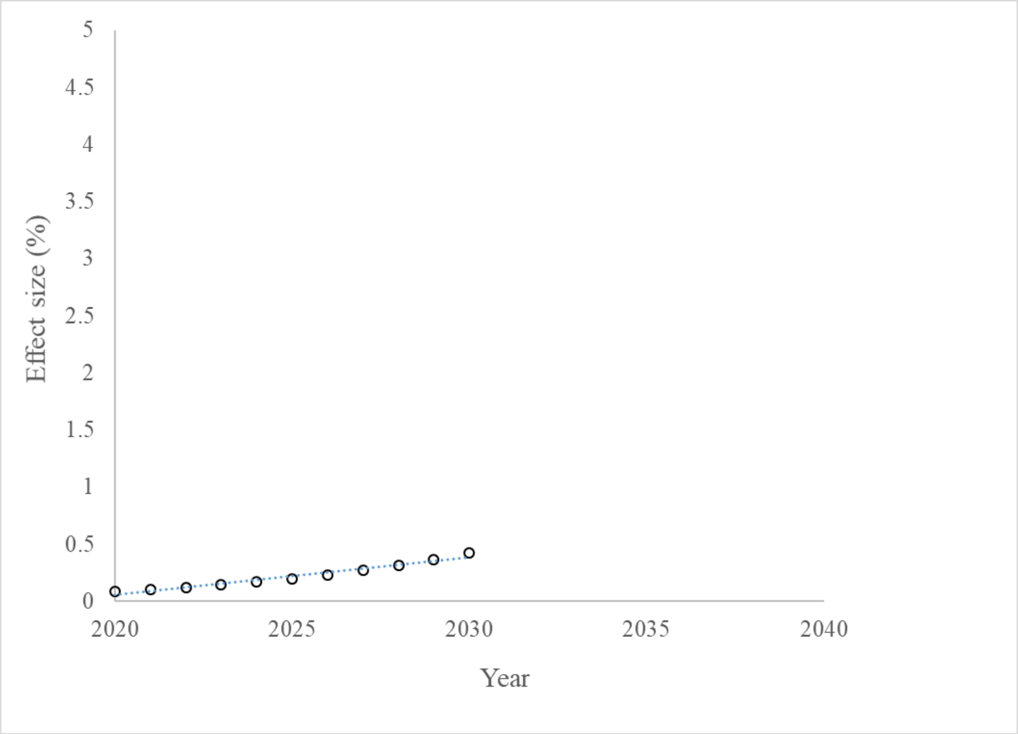


Not possible to calculate real non-linear rate of change with incomplete dataset

In that example, need 200 years of data

Step 3: estimate the rate of biological change

10 years of data



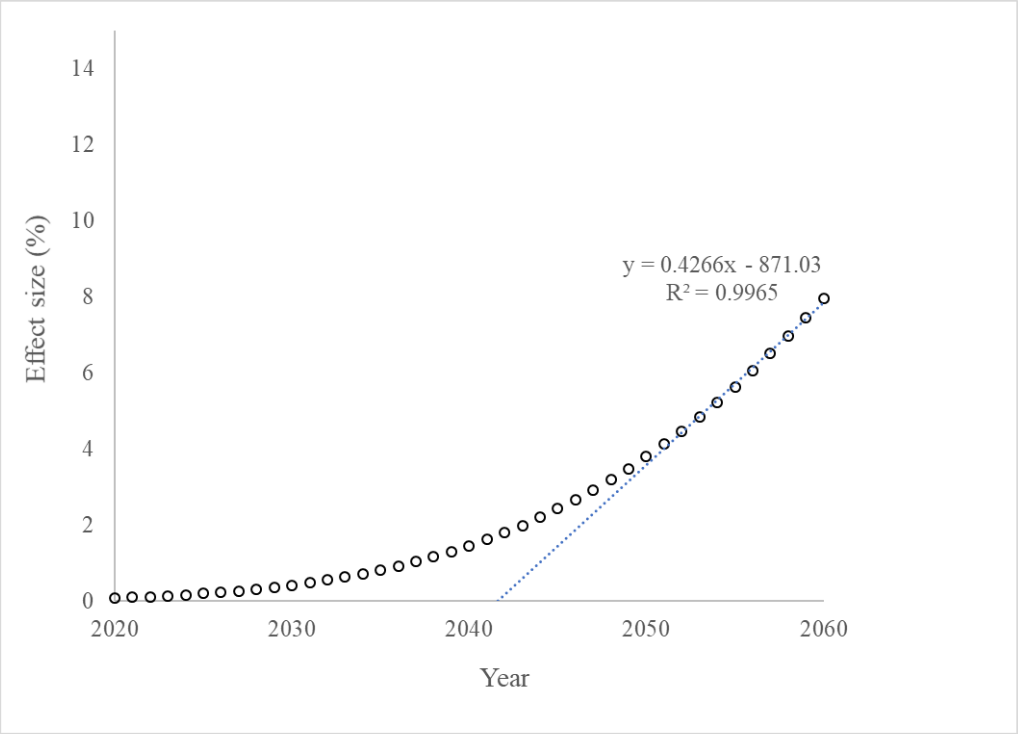
Linear regression (R^2=0.97)

Effect size = 0.0332 x Time – 67.043

Biological rate: 0.033 % / year

Step 3: estimate the rate of biological change

40 years of data



Linear regression (R^2=0.99)

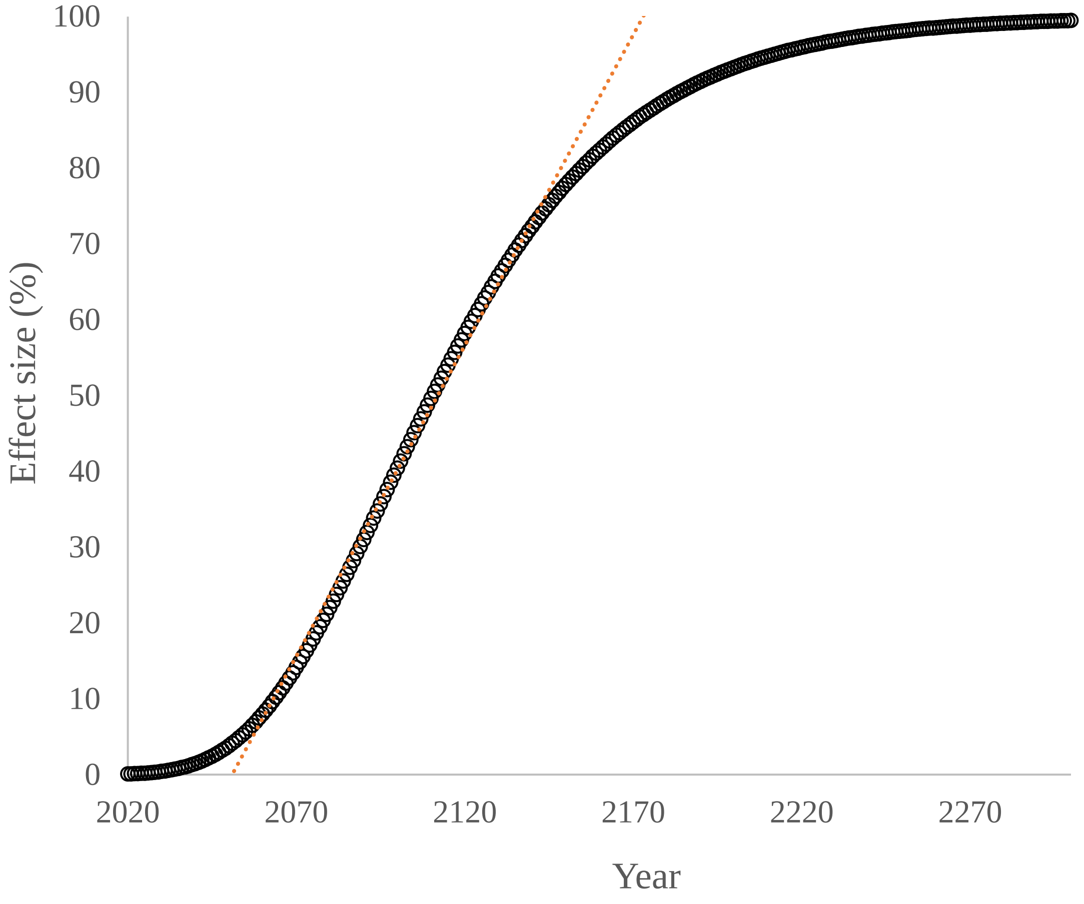
Effect size = 0.4266 x Time – 871.03

Biological rate: 0.427 % / year

”Maximum” linear growth

Step 3: estimate the rate of biological change

All curve

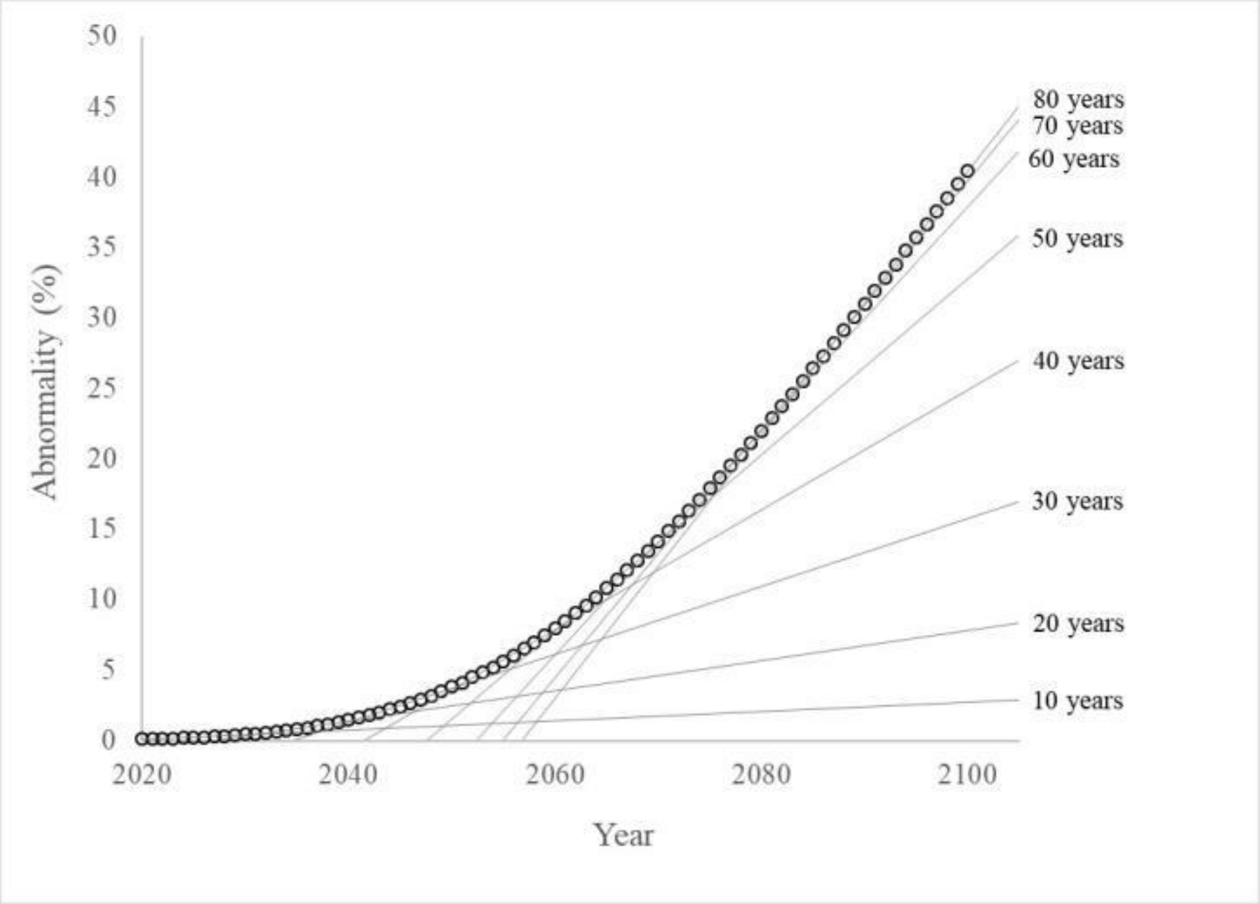


Linear regression (R^2=0.99)

Effect size = 0.9196 x Time – 1681

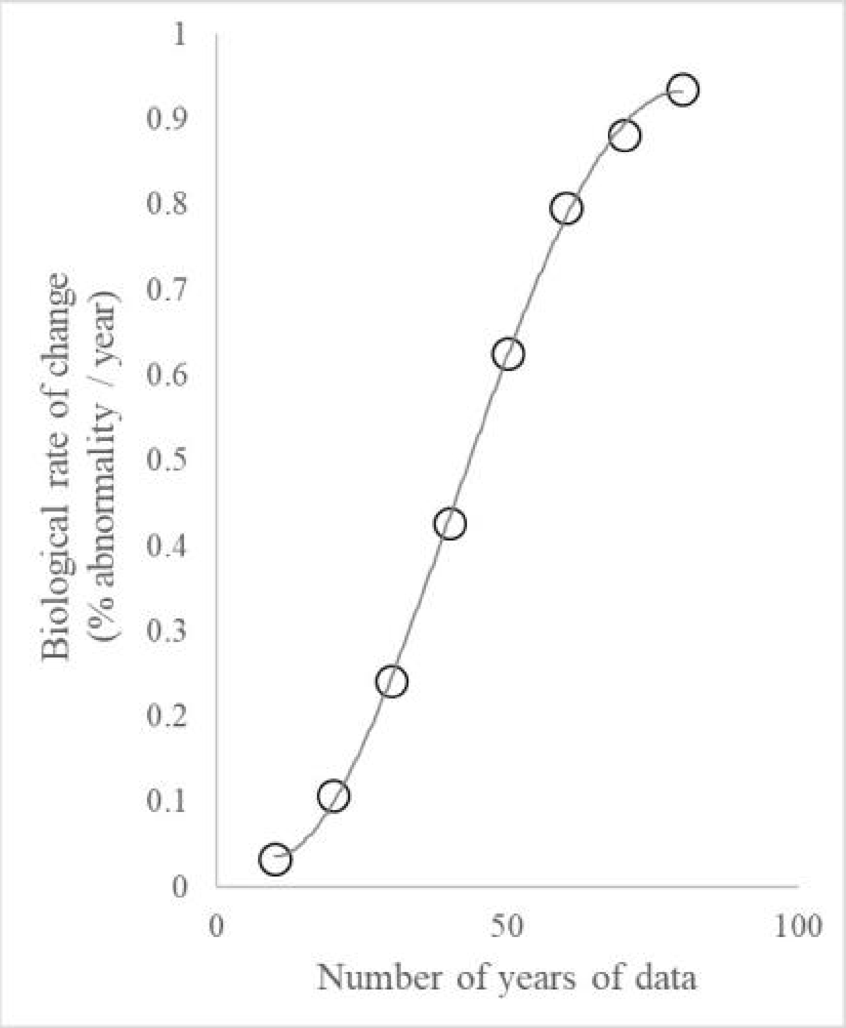
Max biological rate: 0.9196 % / year (linear)

Step 3: estimate the rate of biological change



Estimate the observed maximum rate of change after different duration of biological monitoring

Rate of biological change vs duration of monitoring



Reach saturation

Need >80 years of data for a robust evaluation

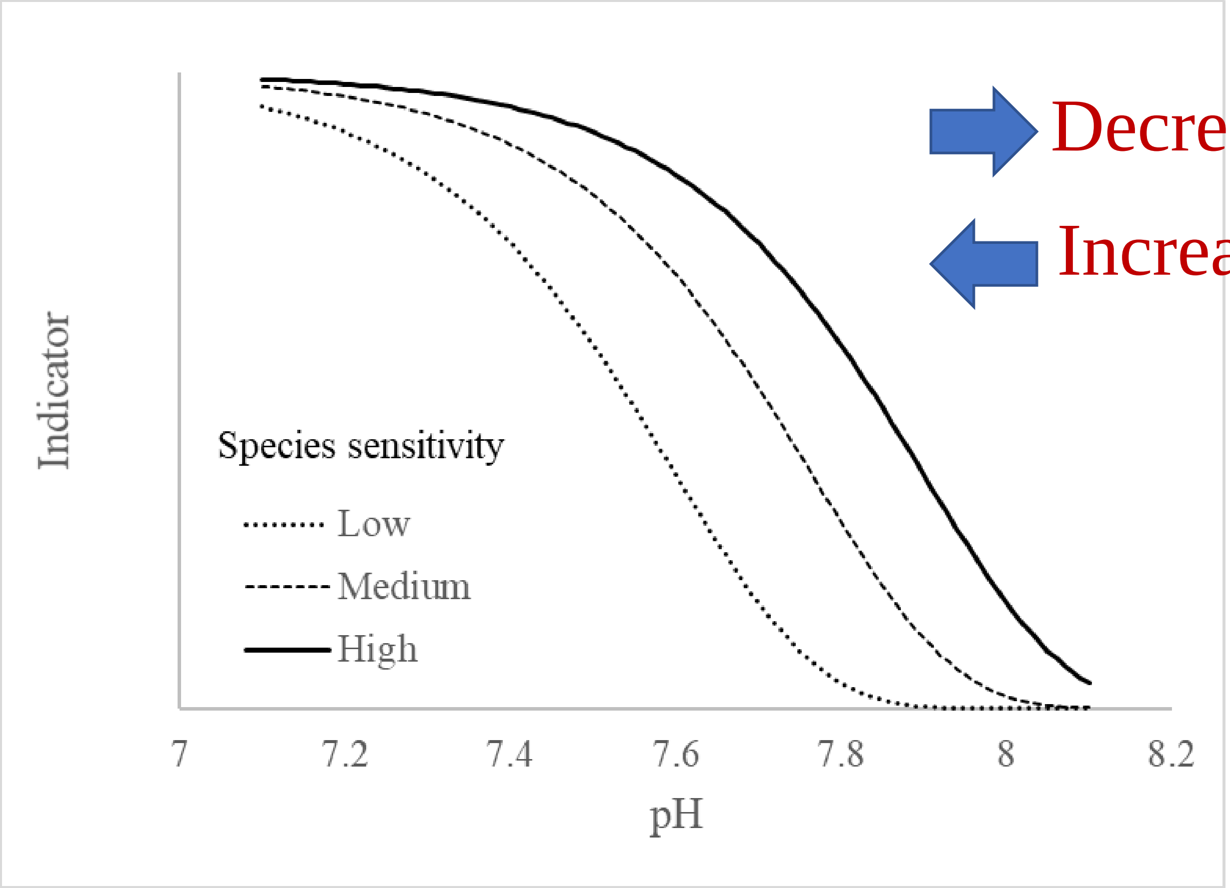
Caution: Factors modulating biological rate of change

- ✓ Biological sensitivity
- ✓ Chemical rate of change

→ Rate of change

For this exercise we assumed that both were **constants** BUT both can vary over time

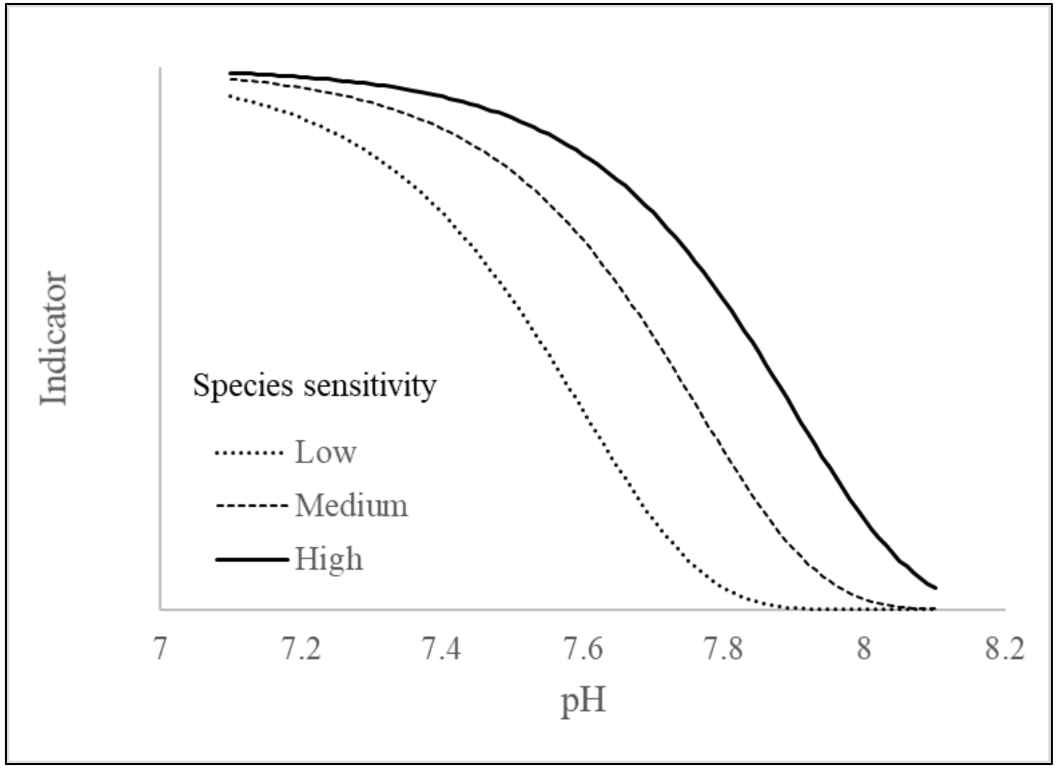
Biological sensitivity

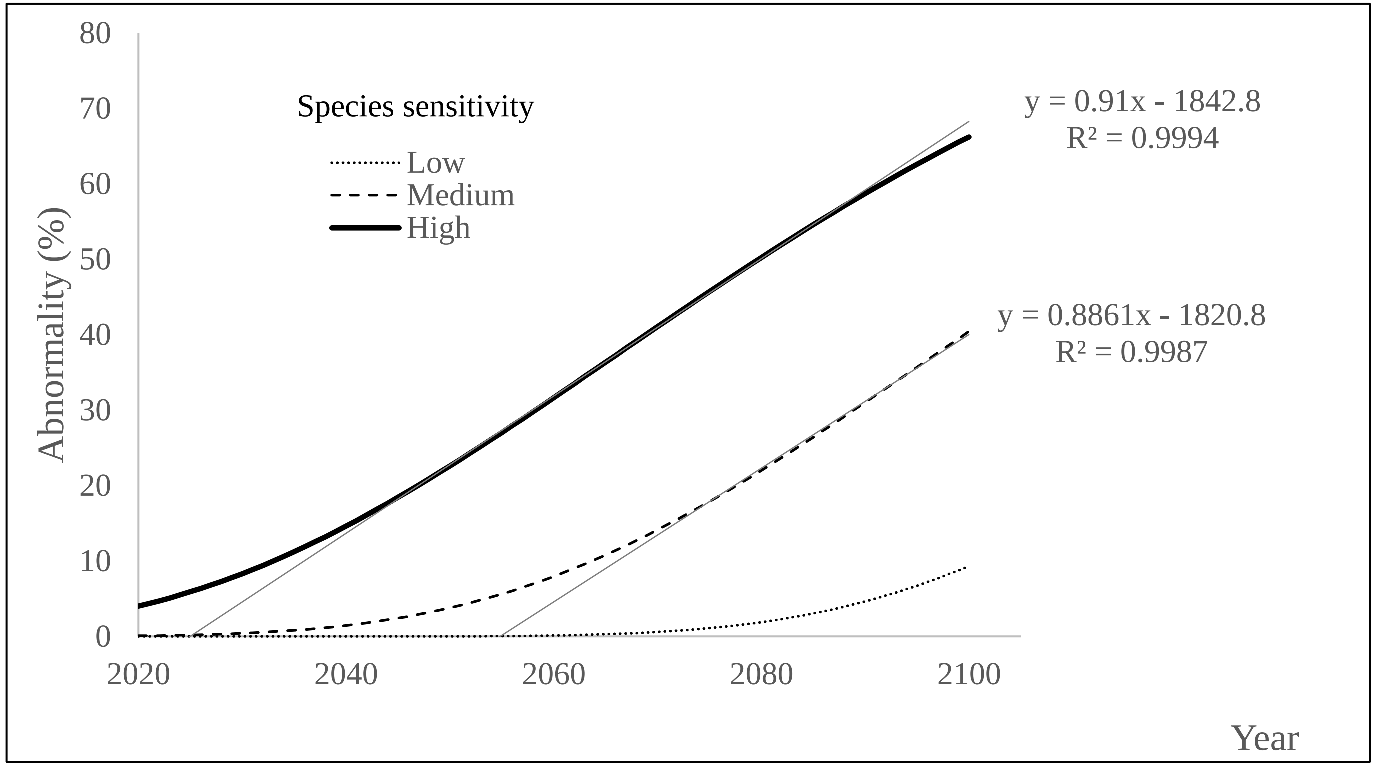


Decreased sensitivity (e.g. Adaptation)

Increased sensitivity (e.g. multiple stressors)

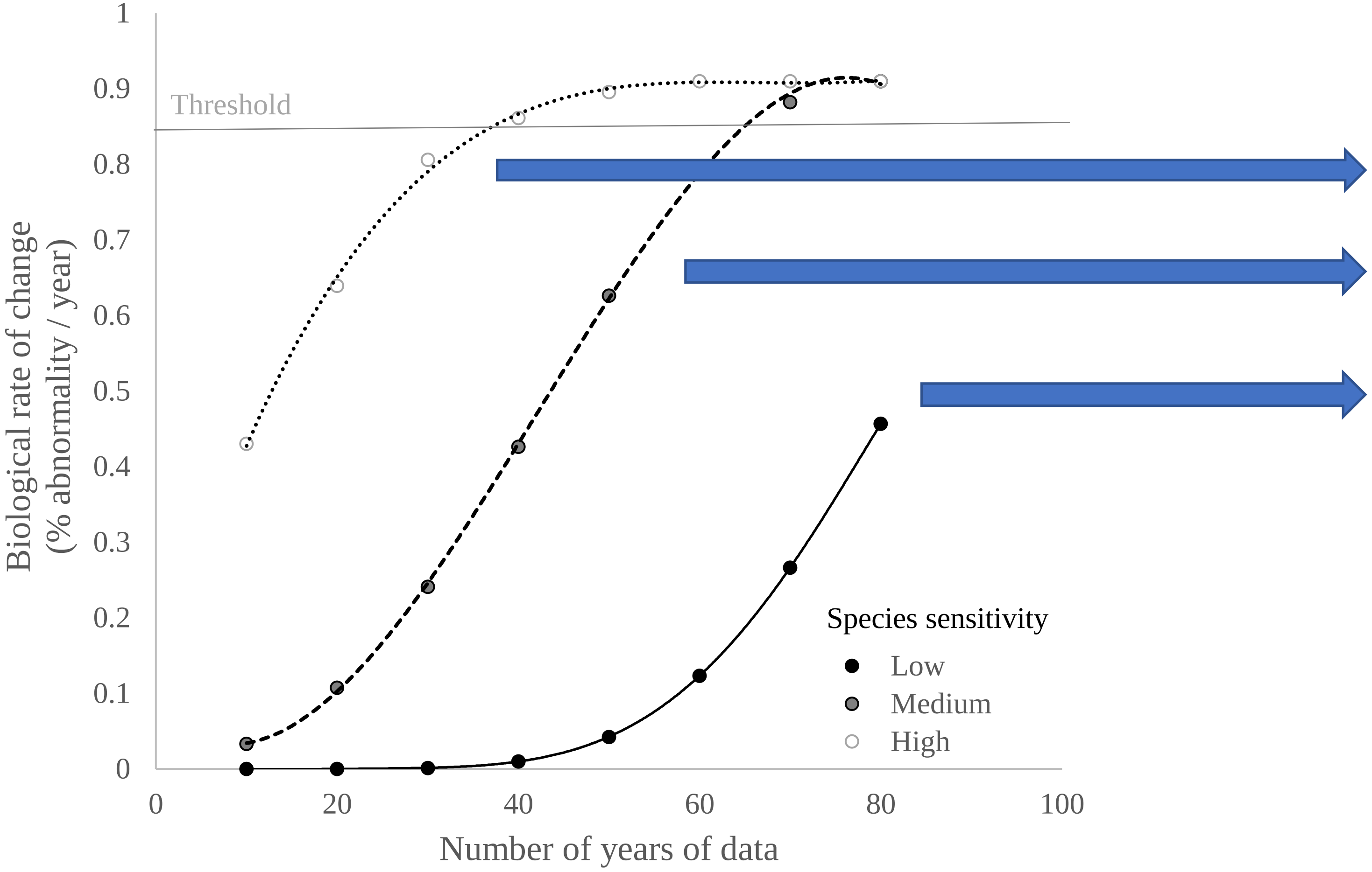
Higher the sensitivity = shorter the monitoring





The higher the species sensitivity, the faster you observe a robust rate of change

Higher the sensitivity = shorter the monitoring



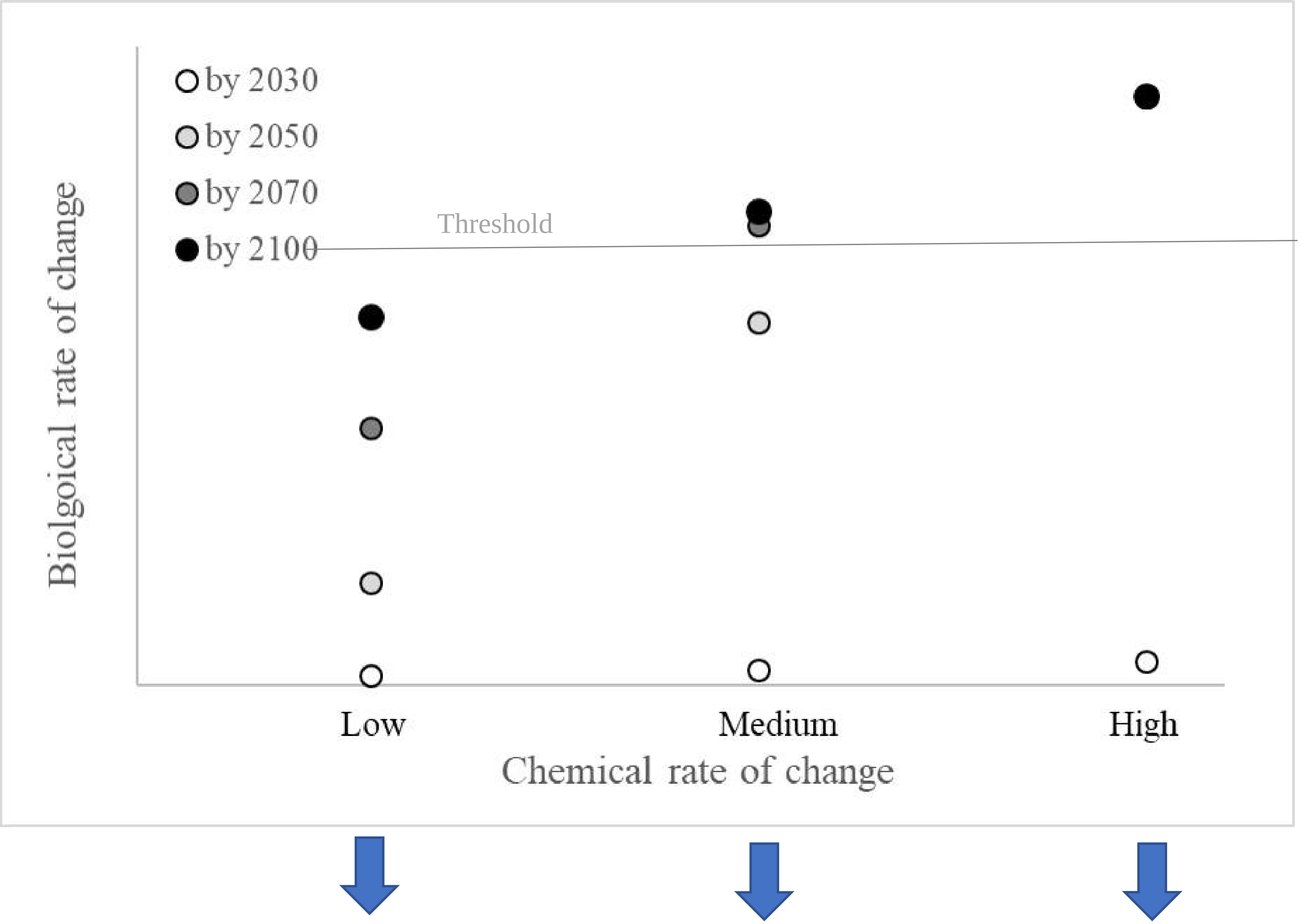
Robust data after:

40y

80y

?

Faster the chemical rate = shorter the monitoring



Date to reach robust data: 2100 2070 2050

Summary

- ✓ Biological sensitivity ↑
- ✓ Chemical rate of change ↑

→ Rate of change ↑

IF the goal is to observe robust estimate of biological rate of change, prioritize locations with high biological sensitivity and high chemical rate of change

Summary

- Understand your biology to define the key driver(s)

- Need to capture the short-term variability and extremes
… experienced by the organism / ecosystem

- Variability is important in itself

- Depending on you question and/or your capacities, chose location / strategy accordingly