# Effects of $CO_2$ on marine animals

## Time scales, processes, and limits of adaptation

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Interactions with temperature and hypoxia regimes

Scenarios:
- Business as usual,
- Direct disposal,
- Indirect disposal
(Fe fertilization)

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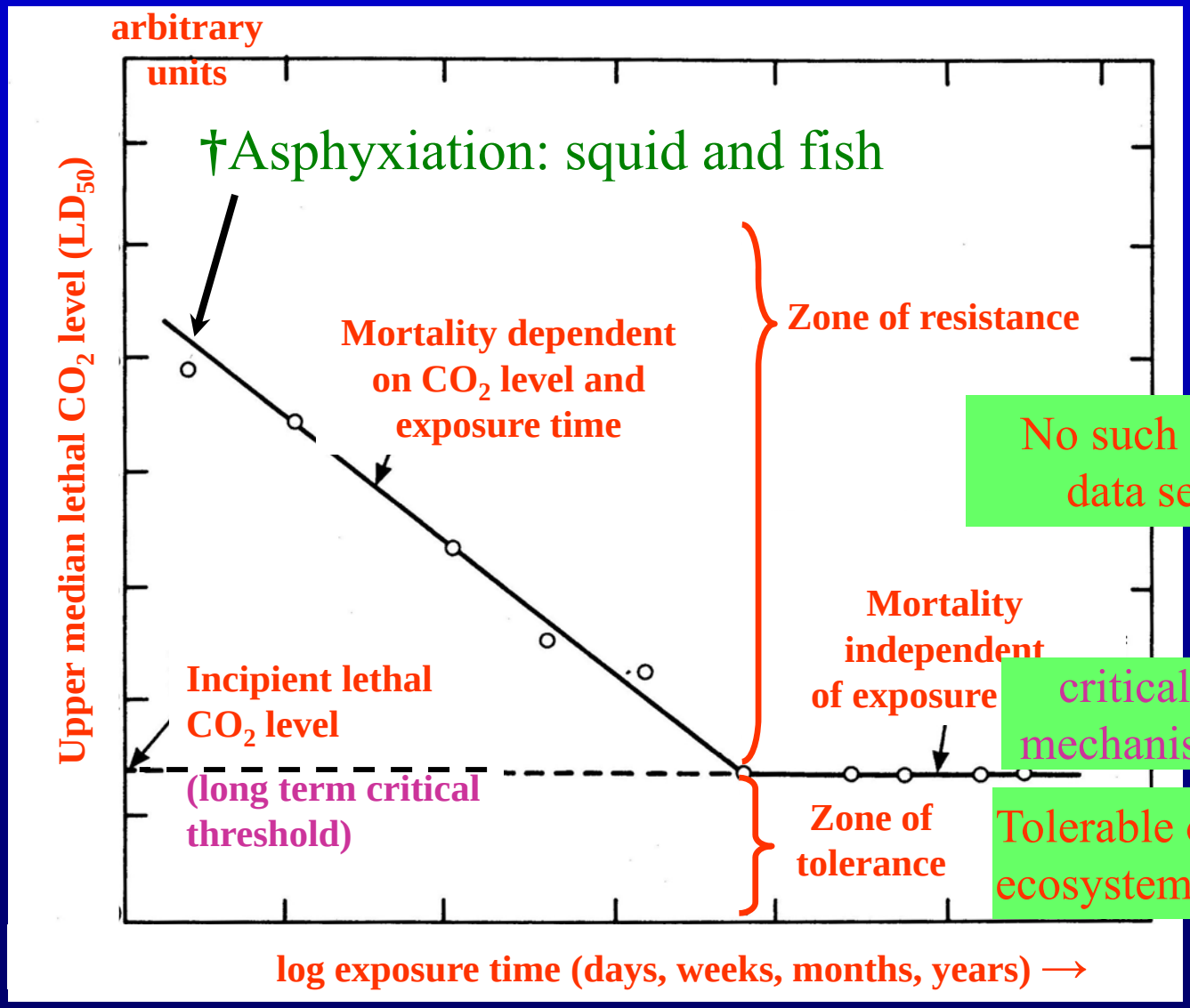
# Principle considerations:
# Role of time scales in $CO_2$ exposure experiments




No such complete data set exists

critical level and mechanism unknown

Tolerable organism and ecosystem (?) responses

Pörtner, in prep.

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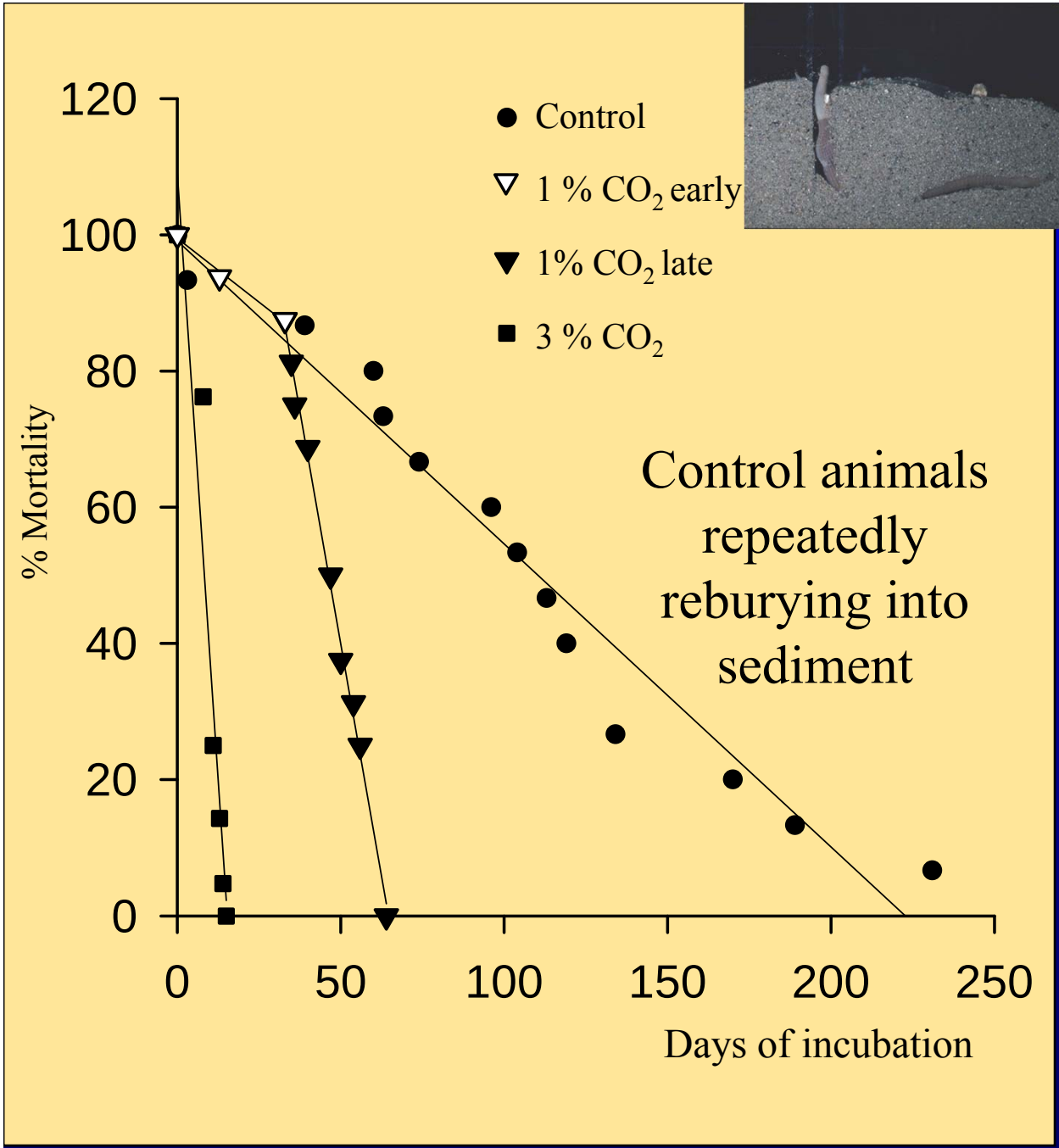
# Example of an animal species tolerant to $CO_2$ oscillations: *Sipunculus nudus*

eurybathic:
found between 0 and 2300 m depths




However, tolerance is limited: Delayed onset of enhanced mortality during long term „disturbed“ maintenance under 1 % $CO_2$ in *S. nudus*

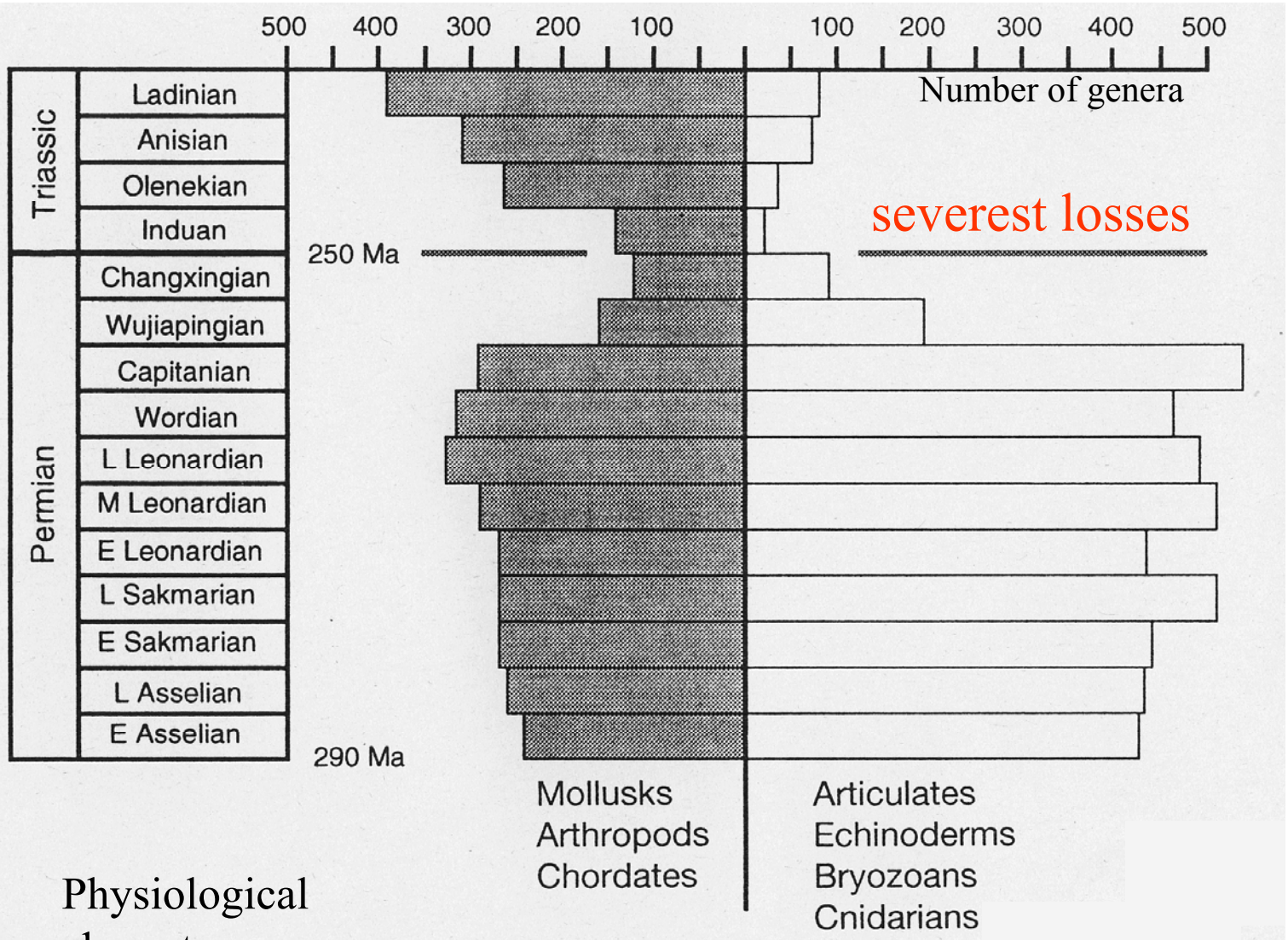
- no decrease in body energy stores
- behavioral incapacitation involved

Langenbuch et al. (2004)

# $CO_2$ limitations relevant in evolution?

Permian-Triassic mass extinctions

Loss of marine invertebrate genera due to $CO_2$?



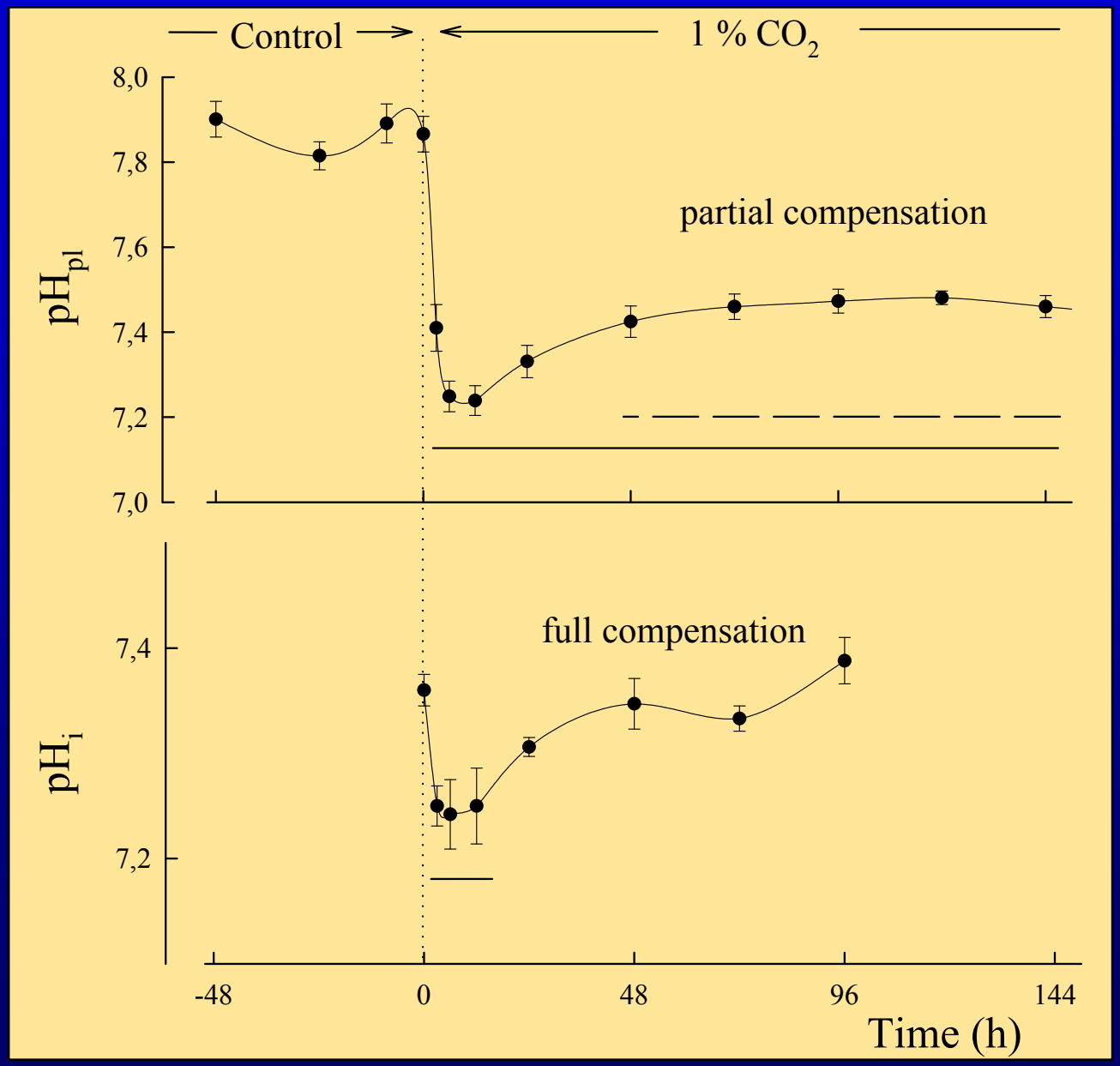

Physiological characters of eliminated forms?

moderately active, moderate calcification

sessile, hypometabolic, calcified: larger effect?

after Knoll *et al.*, 1996

# Physiological background??




*S. nudus*: Extra- and intracellular acid-base status during hypercapnia *in vivo*

Partial compensation of extracellular acidosis: A typical finding in invertebrates?

after Pörtner et al. 1998

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# 55 % (!) growth reduction in *Mytilus galloprovincialis* under hypercapnia (permanent extracellular acidosis!!)

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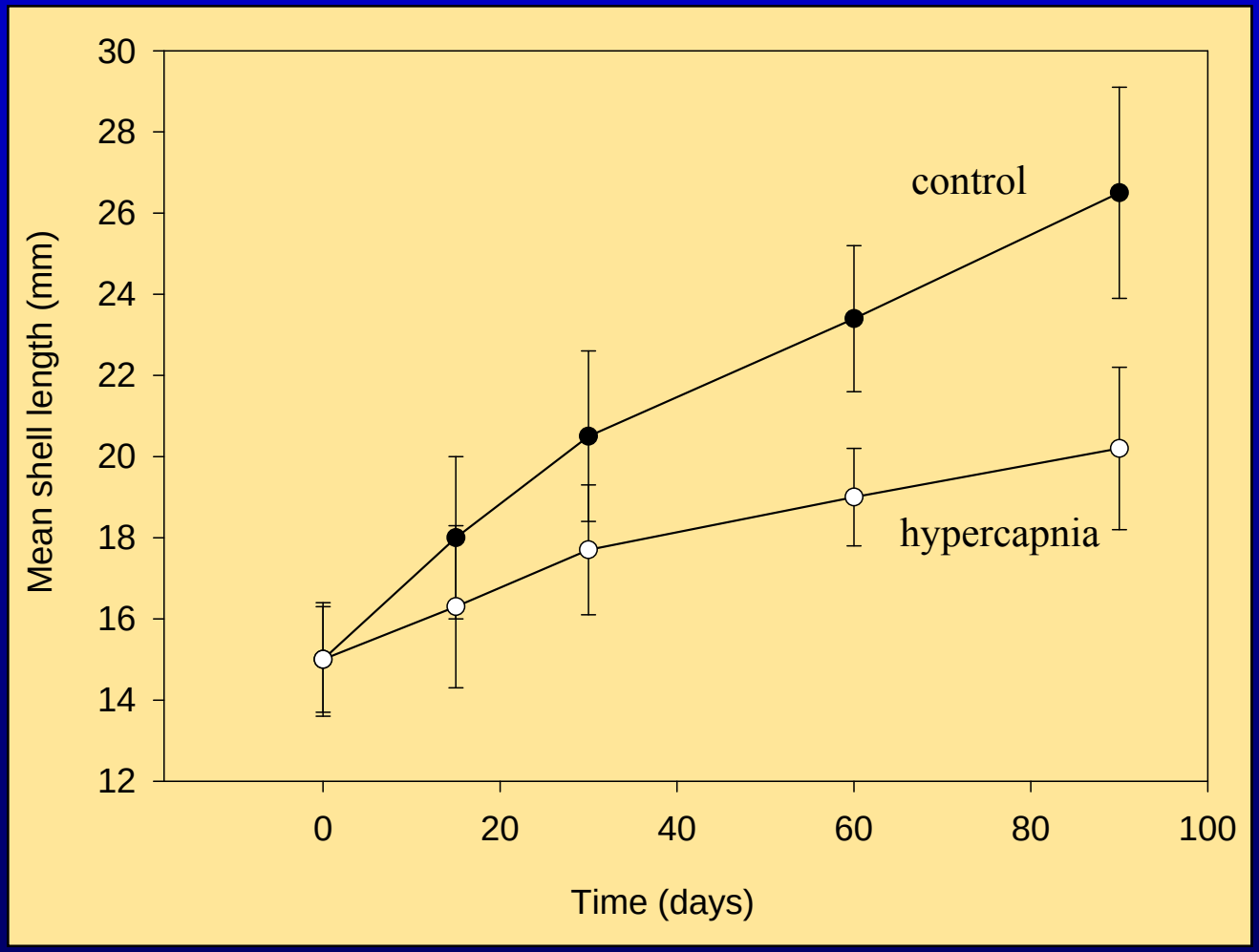


Water pH 7.3: Maximum pH drop as expected from business as usual scenarios by 2300 (Caldeira and Wickett, 2003)

Michailidis et al. (2004)

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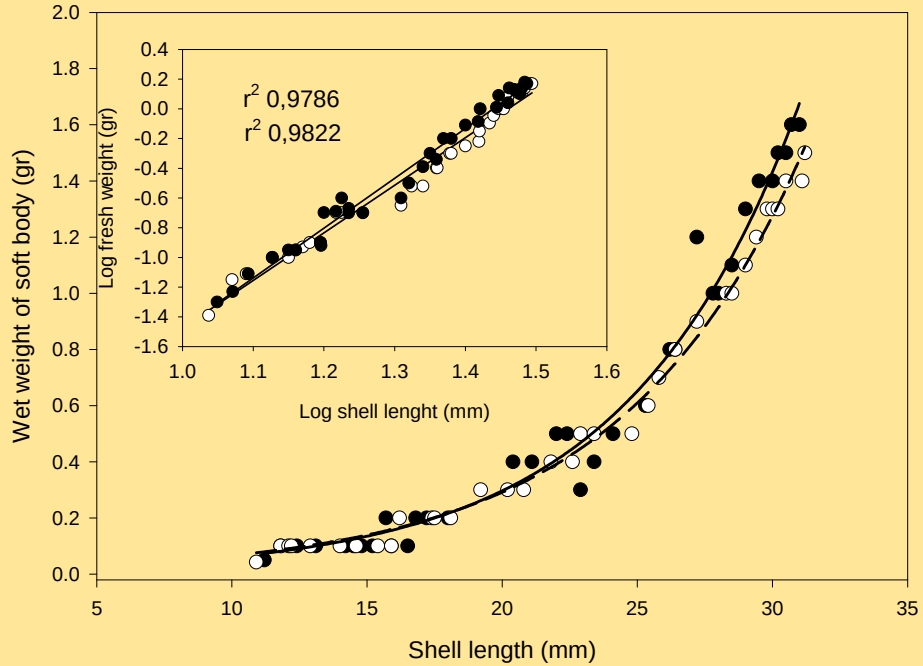


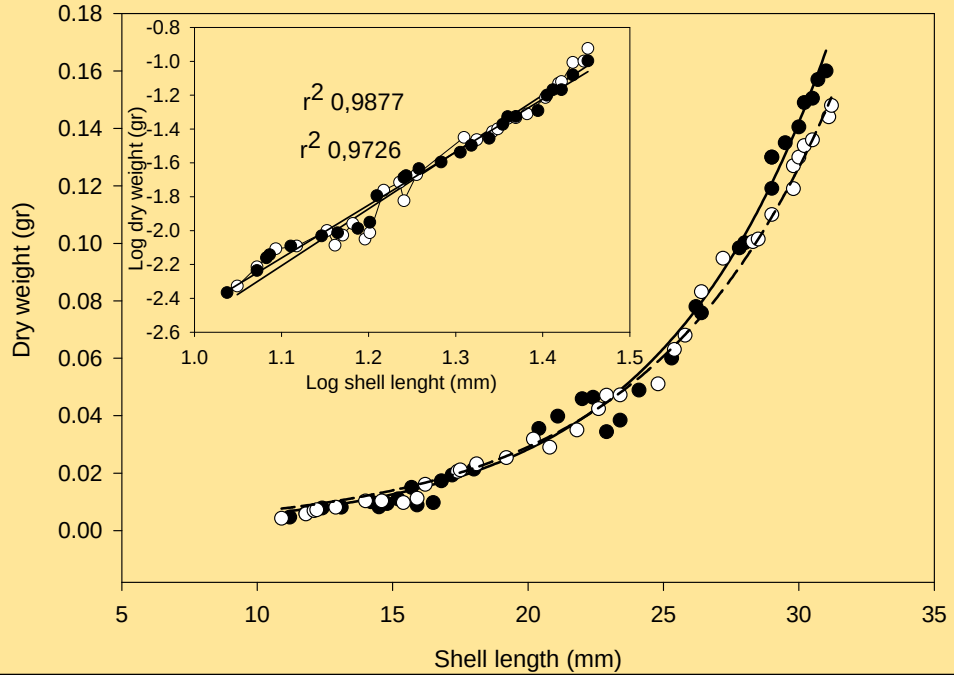


# Close correlation between dry / wet weight and shell length

Reduced growth affects shell and soft body alike

Michailidis et al. (2004)

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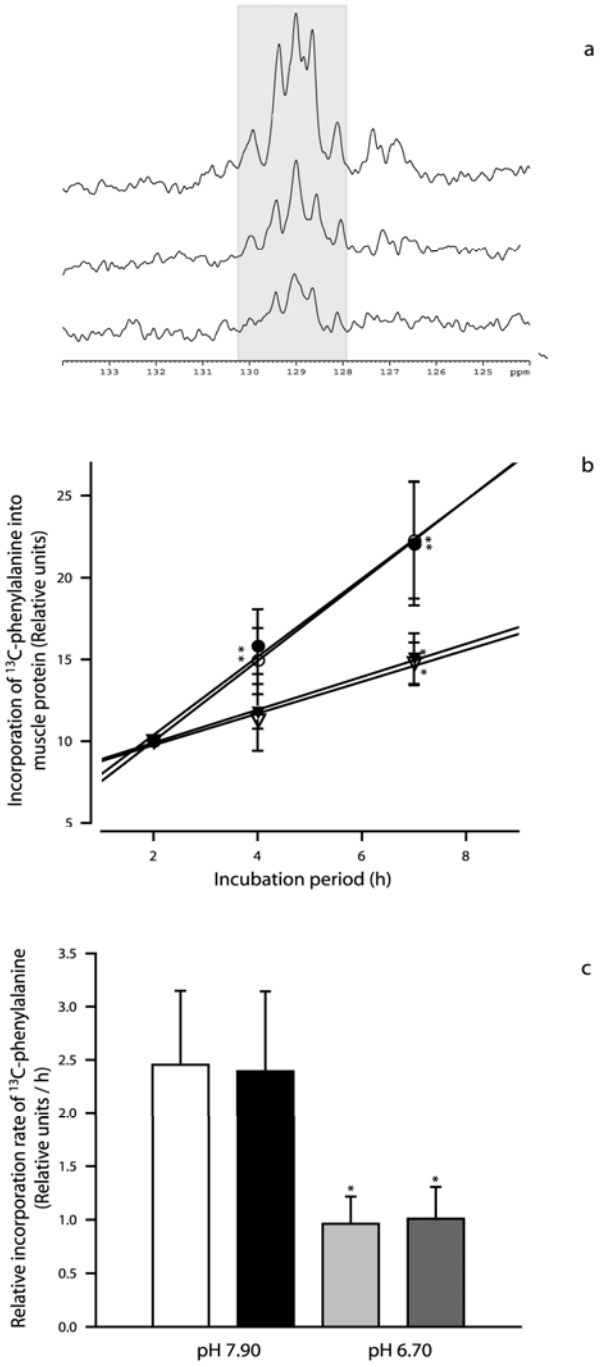


# Reduced cellular protein synthesis during acidosis favouring amino acid catabolism in *S. nudus*

….likely causing reduced growth rates

Langenbuch et al. 2004.

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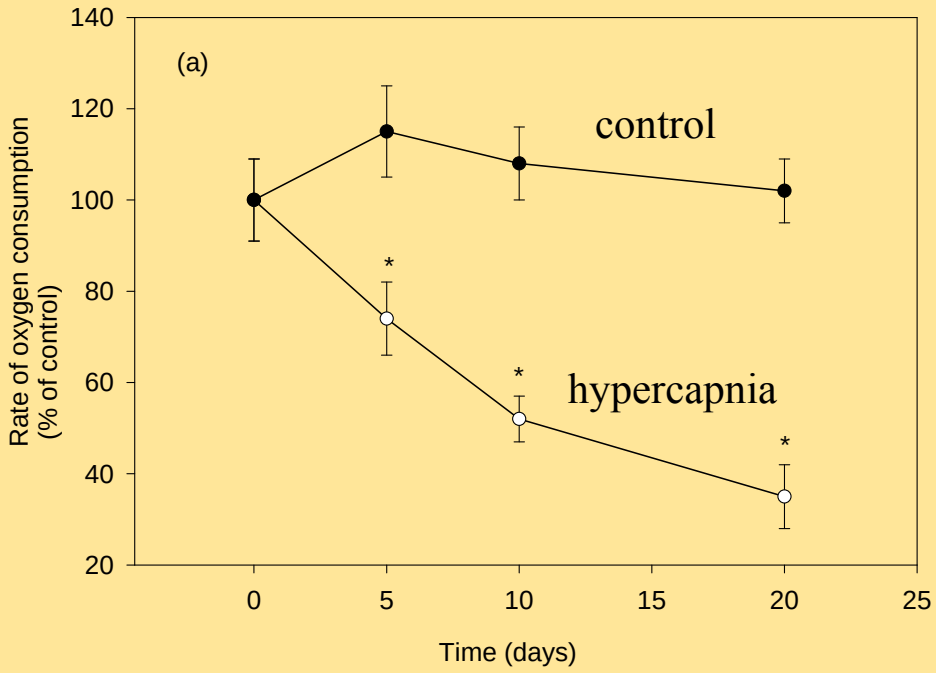
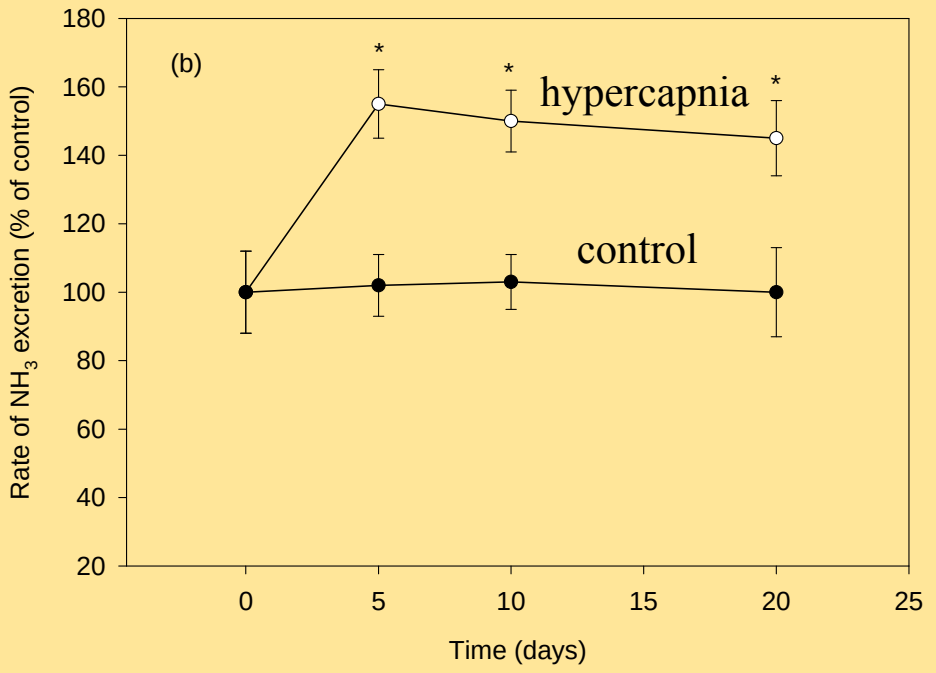


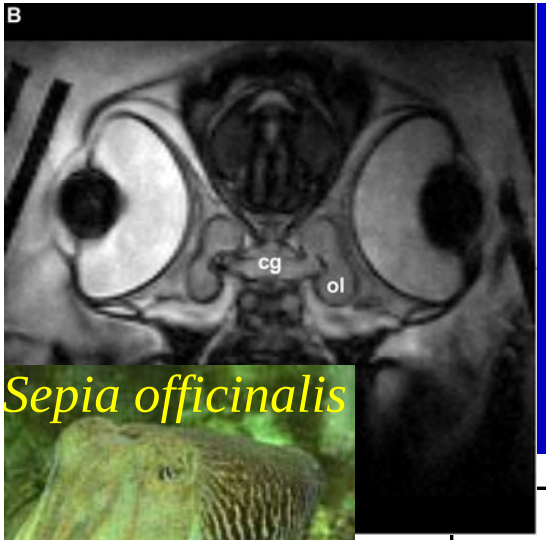



*Mytilus galloprovincialis* under hypercapnia (water pH 7.3):

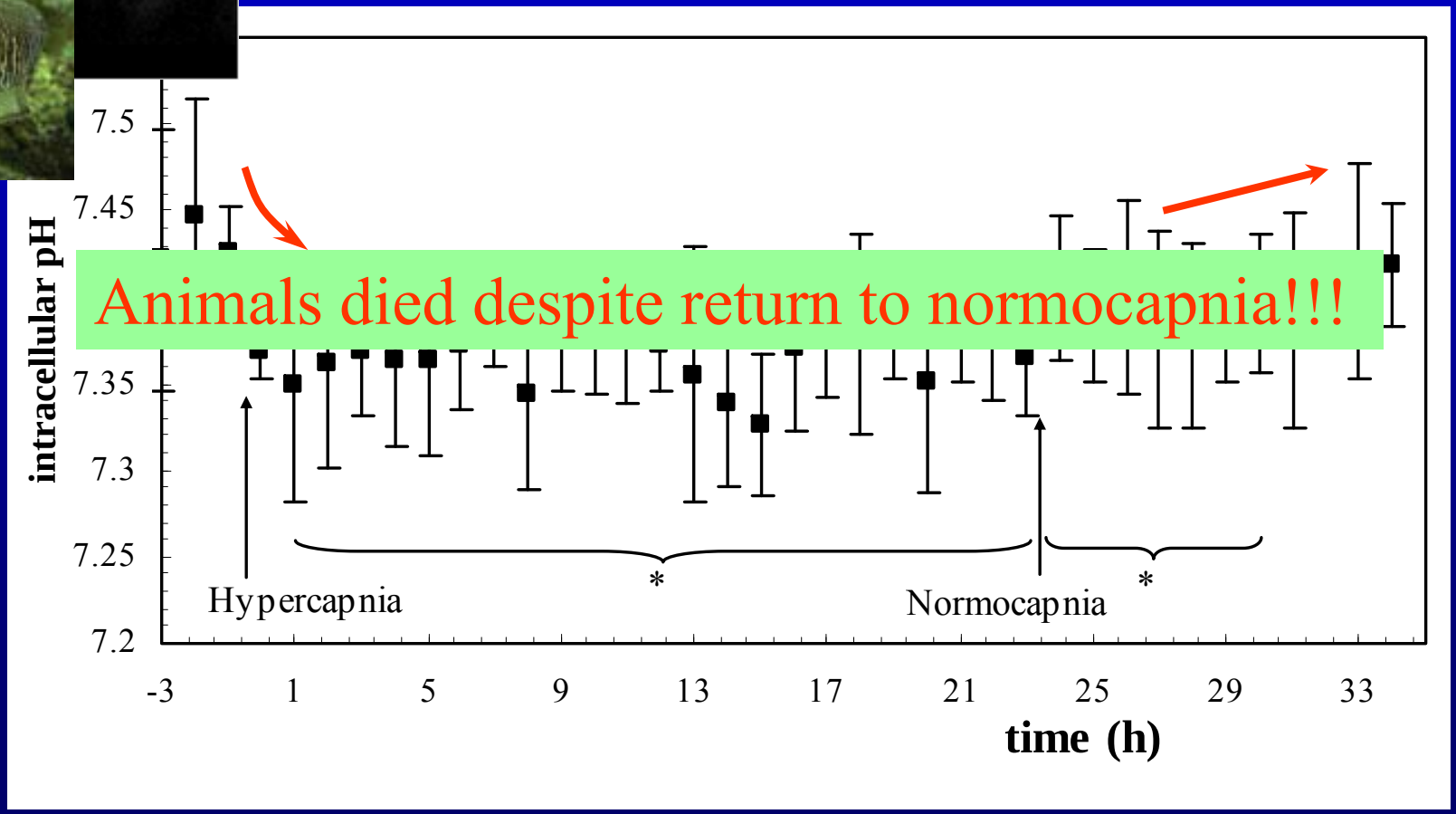
65% (!) metabolic depression associated with enhanced N excretion, i.e. protein degradation during permanent (extracellular) acidosis (as seen in *S. nudus*)

Michailidis et al. (2004)

# Uncompensated intracellular acidosis in cuttlefish (*S. officinalis*) brain under 24 h of hypercapnia (1%)








S. Schmidt, C. Bock, H.O. Pörtner, unpubl.

# Uncompensated acidosis
# and metabolic depression in several invertebrates

…contributing to lower resistance and enhanced mortality?



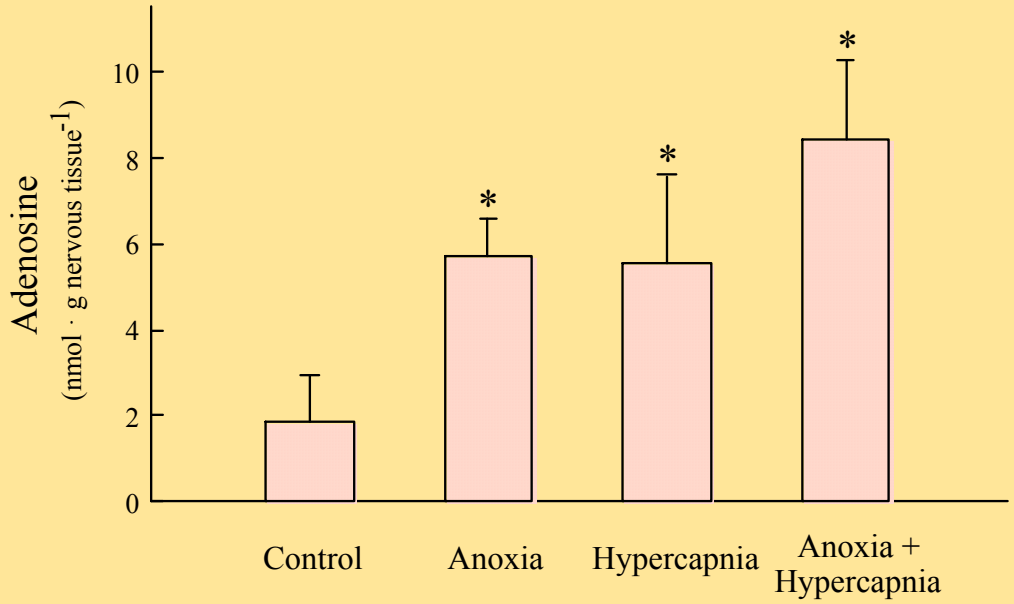

# Compensated acidosis
# and, therefore, no metabolic depression in most fish

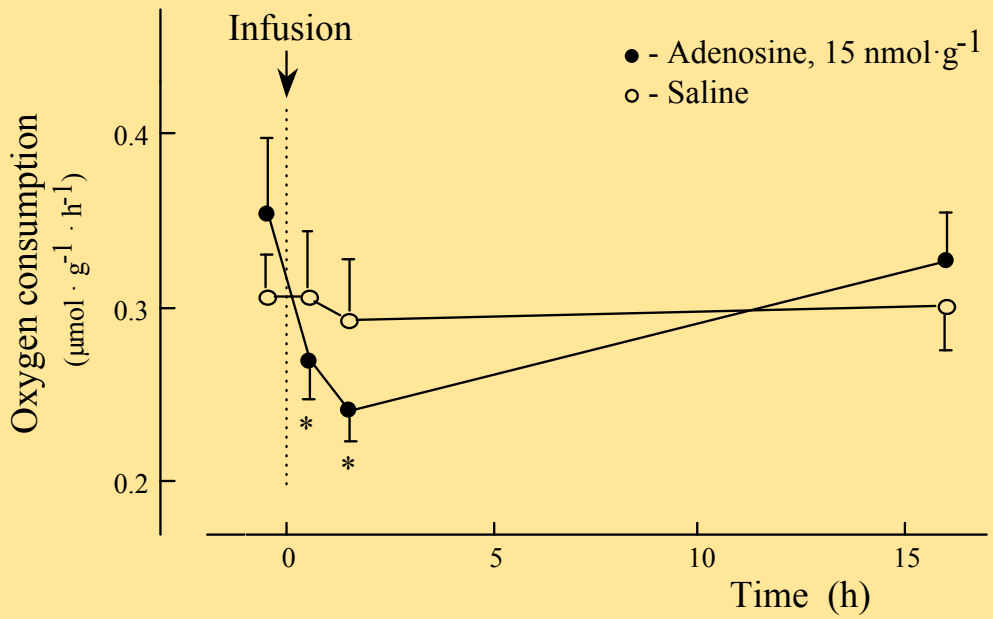
…a reason for enhanced resistance to high $CO_2$?



Heisler, 1986, Larsen et al. 1997, Ishimatsu et al., 2004

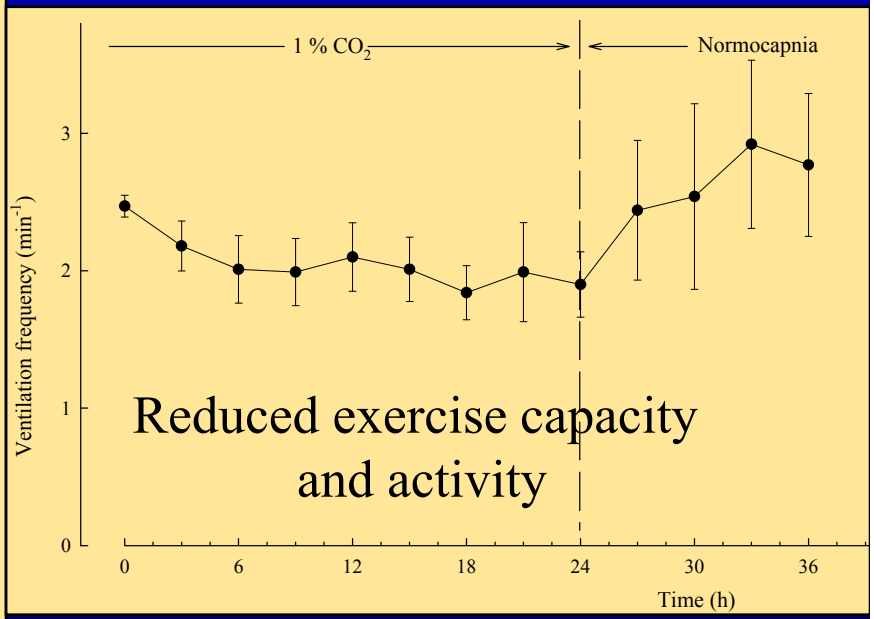
# A role for adenosine in metabolic depression




# Mortality involves metabolic and **behavioral** depression

caused by adenosine accumulation in nervous tissue of *S. nudus*




Reduced exercise capacity and activity

Reipschläger et al., 1997

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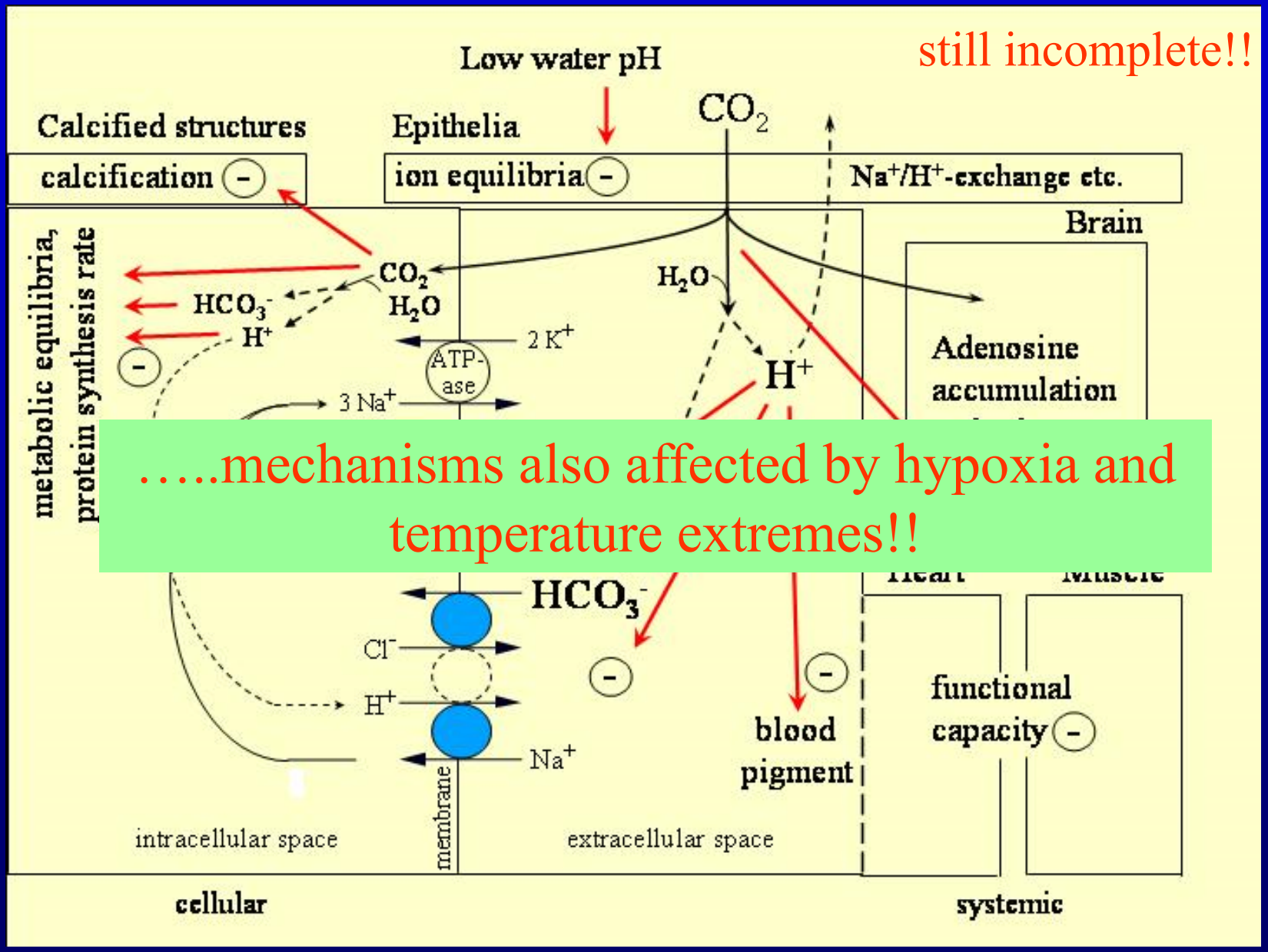
# Unifying principles of $CO_2$ effects in animals

still incomplete!!




…..mechanisms also affected by hypoxia and temperature extremes!!

Pörtner et al. 2004

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Temperature, hypoxia, $CO_2$ interactions?

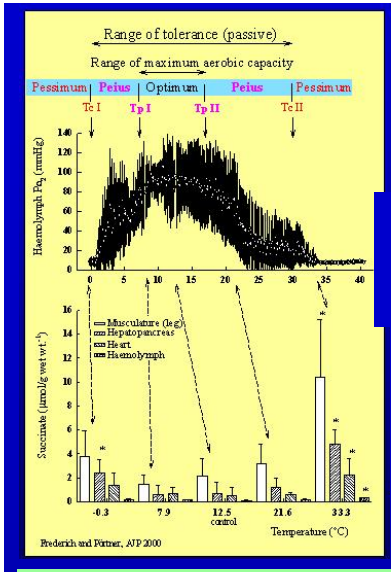
# A recent hypothesis:

The first level of thermal intolerance at low and high temperature extremes in METAZOA is a loss in whole organism aerobic scope,

a unifying principle in ectotherms (!) and endotherms (!?).

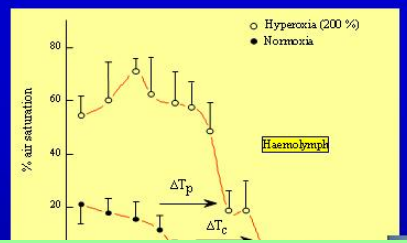
Am. J. Physiol 279, R1531-R1538, 2000.
Naturw. 88, 137-146, 2001
Am. J. Physiol. 283, R1254- R1262, 2002
Comp. Biochem. Physiol. 132A, 739-761, 2002

# EXAMPLES




Shelford's law of tolerance applicable to thermal limitations?

**Temperate crustacean, *Maja squinado***

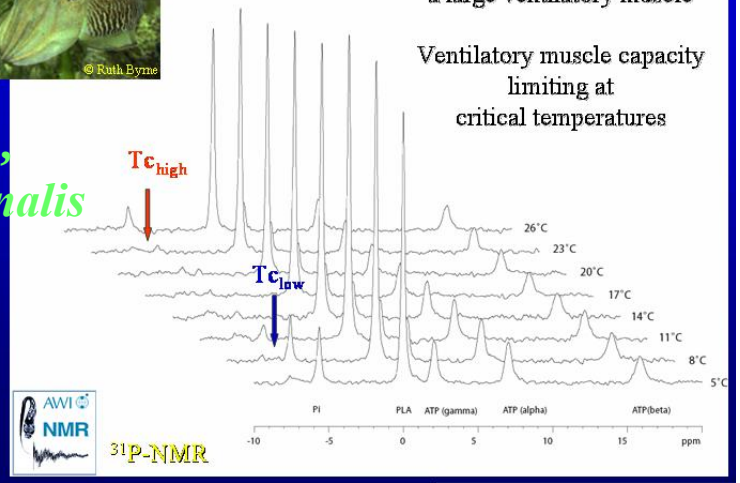



**Temperate cephalopod, *Sepia officinalis***


Oxygen limitation of thermal tolerance in the Antarctic bivalve, *Laternula elliptica* eliminated by hyperoxia?

Cephalopod mantle tissue, a large ventilatory muscle

Ventilatory muscle capacity limiting at critical temperatures




F. Melzner, C. Bock, H.O. Pörtner

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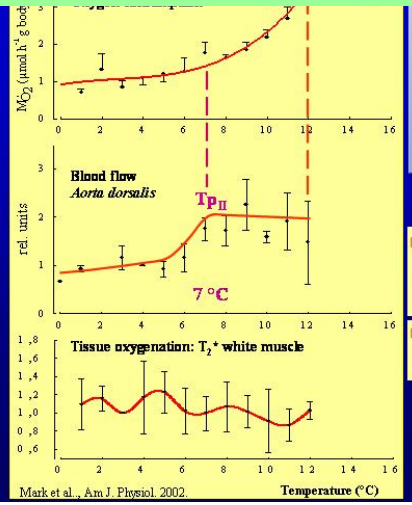
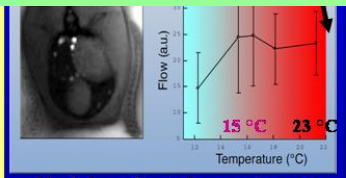
$O_2$ dependent temperature limits verified across phyla: annelids, sipunculids, molluscs (bivalves, cephalopods), crustaceans, fish and some air breathers, limited evidence in endotherms incl. man.




North Sea eelpout, *Zoarces viviparus*

**Do peius temperatures exist in fish?**

- Peius temperatures reflect limited capacity of the circulatory system in fish.
- Beyond $Tp_{II}$ aerobic scope falls at rising oxygen demand

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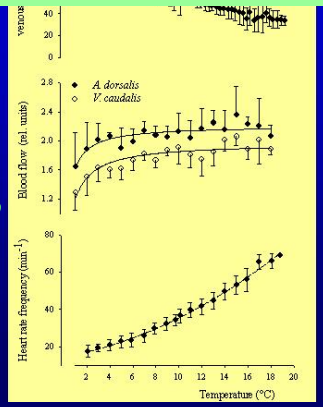
**Antarctic and temperate zoarcids, *Pachycara brachycephalum*, *Zoarces viviparus***




Atlantic cod (*Gadus morhua*).

indicated by falling venous oxygen tensions

Lannig et al. 2003

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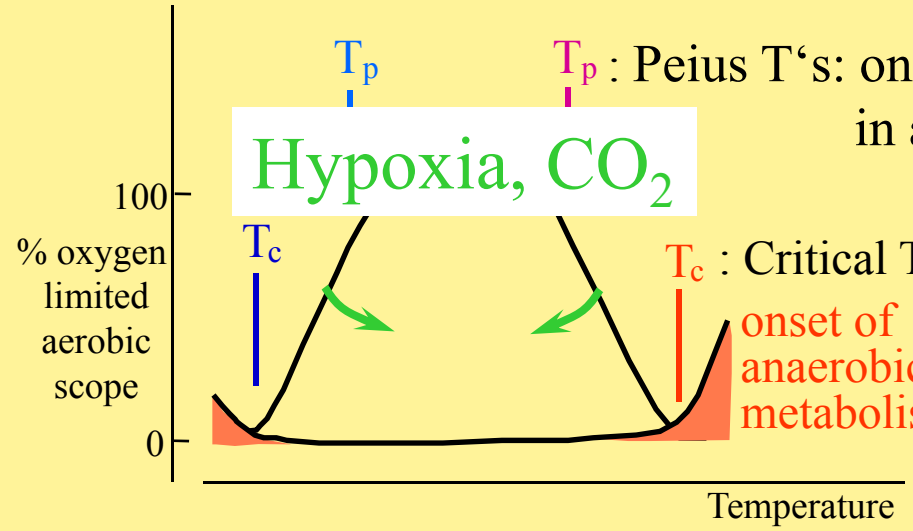
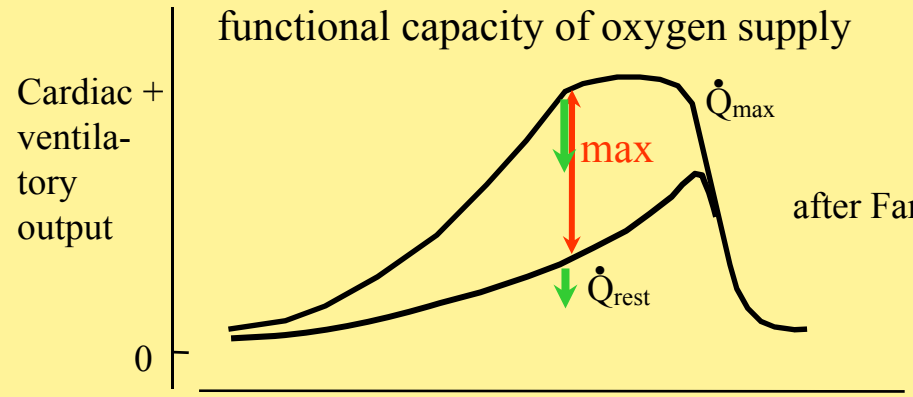
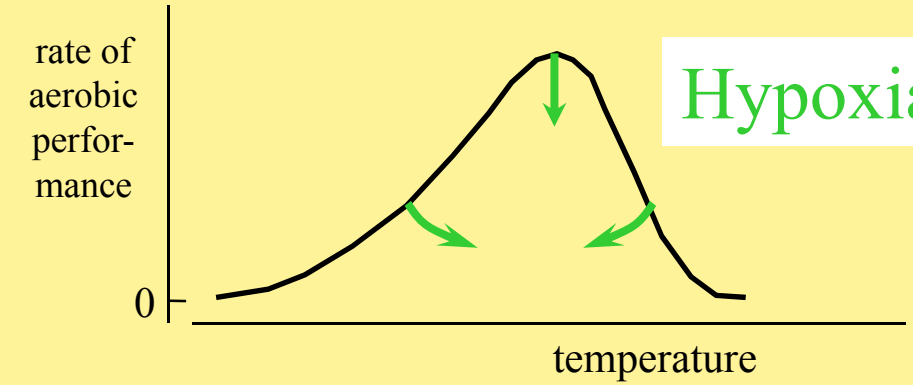



affecting growth, exercise, behaviours, reproduction, ….fitness




Aerobic scope and performance are maximal at the upper peius temperature.




Hypoxia, $CO_2$ and thermal extremes act synergistically via the same physiological mechanisms!!

after Frederich and Pörtner 2000, Mark et al. 2002
Pörtner et al. 2000, Pörtner 2001, 2002

# Processes and Limits:
# Effects of integrated $CO_2$, $O_2$ and temperature fluctuations

$CO_2$ impacts on:

Hypoxia tolerance ↑

→ Improved extension of passive survival (limited!)

BUT

Aerobic scope ↓

→ Long term performance and growth functions ↓

→ Thermal tolerance ↓

(tolerance to thermal fluctuations ↓)

These interactions and not $CO_2$ alone have likely shaped evolutionary scenarios!

Pörtner and Langenbuch, in prep.

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# Animal limitations in high $CO_2$ oceans

Progressive (not beyond critical thresholds?) effects already expected in 450 to 750 ppm surface ecosystems

shifted ecosystem equilibra caused by:

- reduced calcification rates
  - higher ratios of non-calcifiers over calcifiers
- reduced tolerance to thermal extremes
  - enhanced geographical distribution shifts
  - reduced distribution ranges
- reduced behavioral capacity, growth, productivity and life span*
  - food chain length and composition*
  - reduced population densities, ……biodiversity (critical!)?*

*effects transferred to deep with ocean disposal (direct and indirect)

Research needs to further identify mechanisms, titrate/quantify (lab and field) scenarios, address micro-evolutionary potential

Pörtner and Langenbuch, in prep.

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# Ocean $CO_2$ disposal: Are their methods of choice?

Preliminary insight from $CO_2$, T, hypoxia impact studies in animals

- Avoid business as usual scenarios
  - (thermal changes, direct impact of $CO_2$!)
- Avoid large scale disposal strategies
  - (towed pipe or Fe fertilization)
- If feasible, use $CO_2$ lake option in environments protected from physical disturbance („dump site“ strategy)
- Apply direct pH neutralization of injected $CO_2$?
- Dispose in thermally stable environments
- Avoid hypoxia aggravation (eutrophication)

Pörtner and Langenbuch, in prep.

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# CLIMATE CHANGE, $CO_2$ effects, ENERGY BUDGETS

Dr. Christian Bock
Carsten Burkhard
Dr. Martina Langenbuch
Dr. Anke Reipschläger
SusannSchmidt
Rolf-M. Wittig

Dr. Vasilis Michailidis


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