Unifying principles of ocean acidification effects on marine ectotherms?

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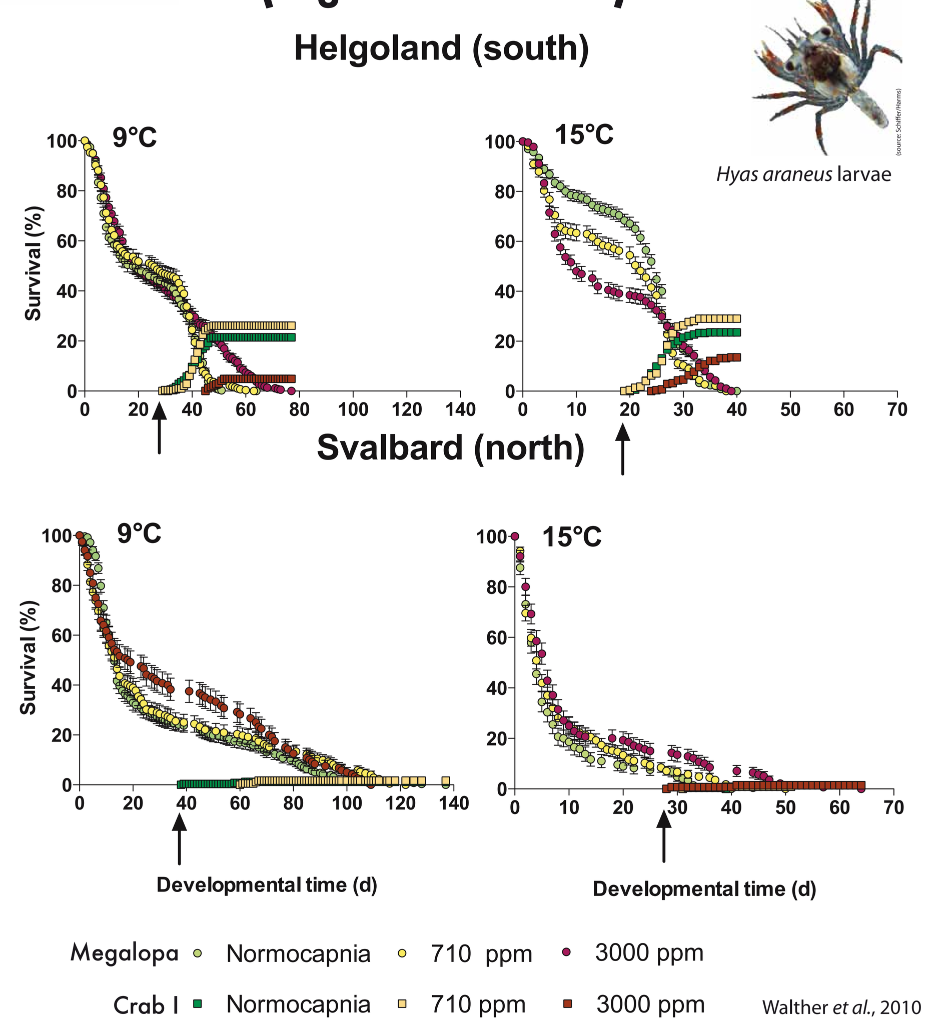
Introduction

Atmospheric CO_2 accumulation elicits climate change and associated impacts on marine ecosystems, emphasizing the need for an integrative understanding of the driving forces and their specific and synergistic effects. Besides indirectly inducing ocean warming, CO_2 directly causes ocean acidification, but the specific contribution of this process to ongoing ecosystem change is not yet clear. Learning about the principles involved can benefit from the observed organism and ecosystem responses to the warming trend. Understanding the specific effects of CO_2 and the synergisms with temperature requires the identification of sensitive physiological mechanisms.

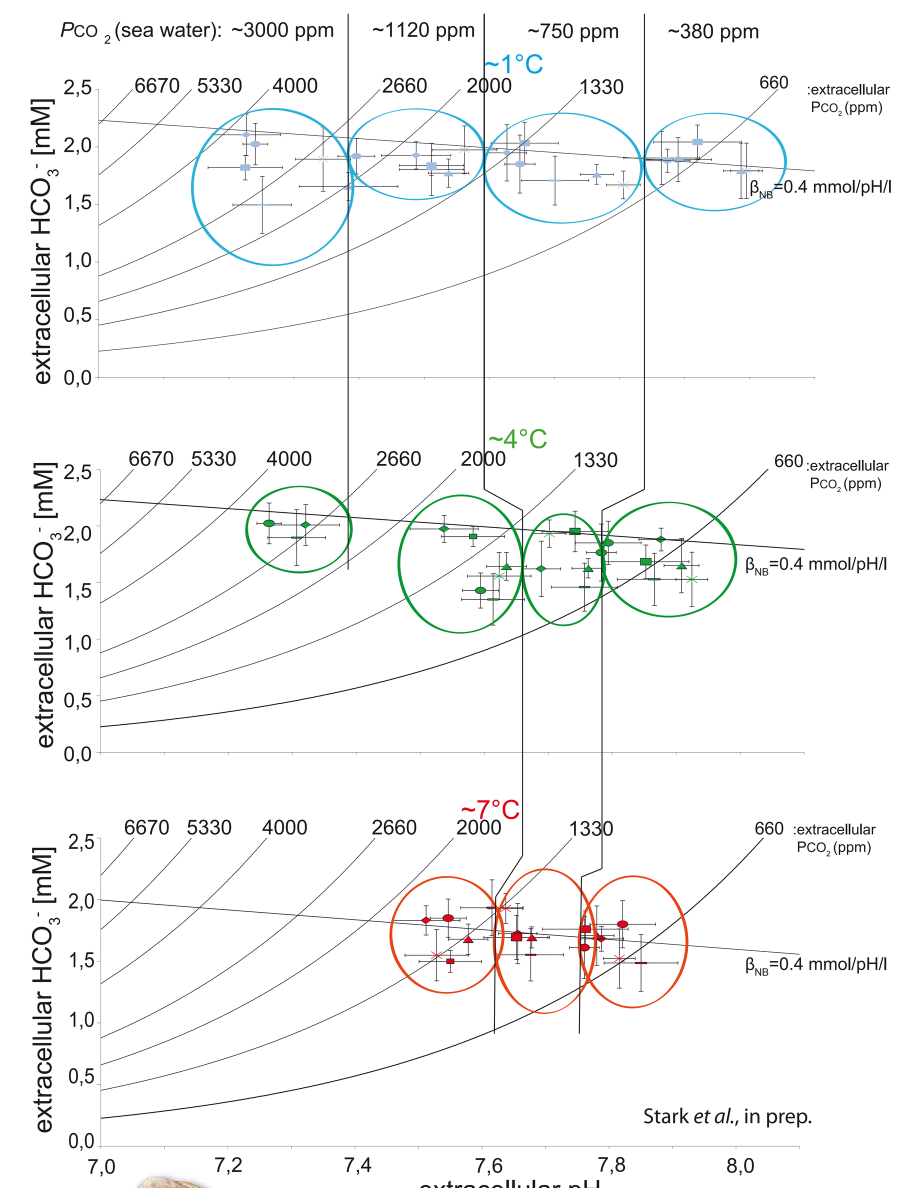
1. Whole Organism Synergistic Effects (e.g. crab larvae)

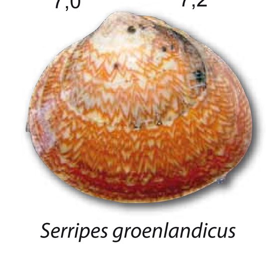


In Megalopae and post larvae of the spider crab Hyas araneus from Arctic and temperate regions, hypercapnia leads to developmental delay and enhanced mortality, illustrating the high sensitivity of early life stages[3].

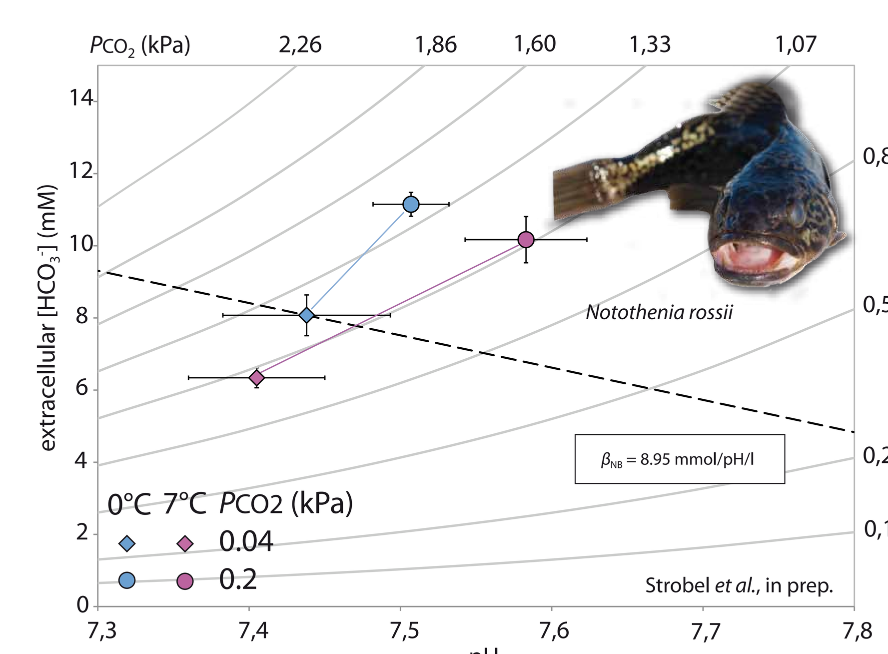
2. Specific effects: Acid-base Regulation in Polar Organisms

Organisms from polar areas are exposed to the largest changes in P_{CO_2} and may be most sensitive due to low capacities of physiological functions and low metabolic rates.



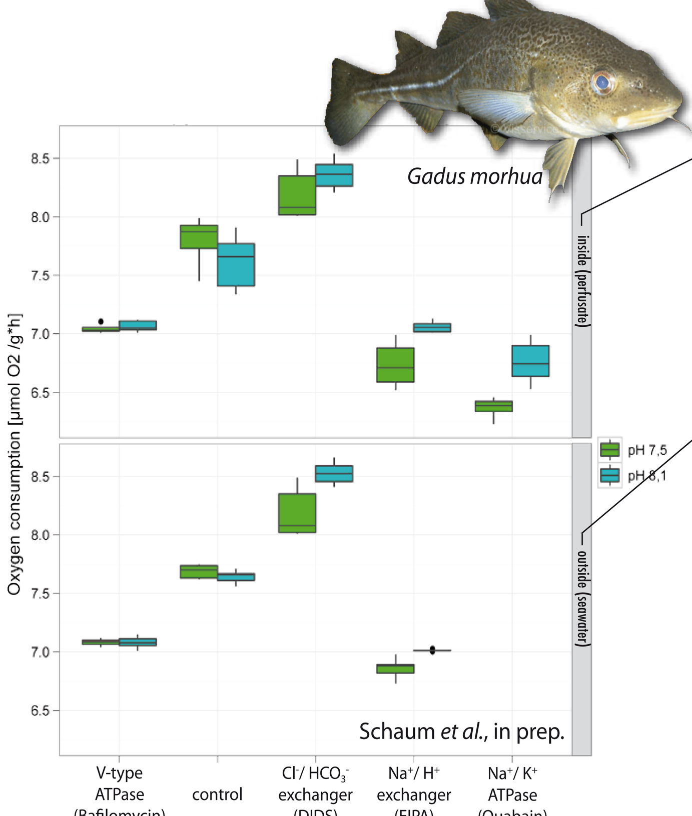


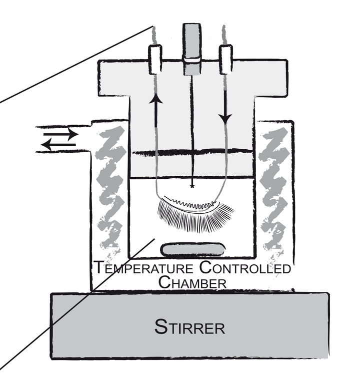
Bivalves like the Greenland Smoothcockle (Serripes groenlandicus) only passively regulate extracellular pH regardless of temperature.



Antarctic fish (Notothenia rossii) show a compensation of blood pH by active HCO_3^- uptake at low temperatures and even overcompensation at warm temperatures.

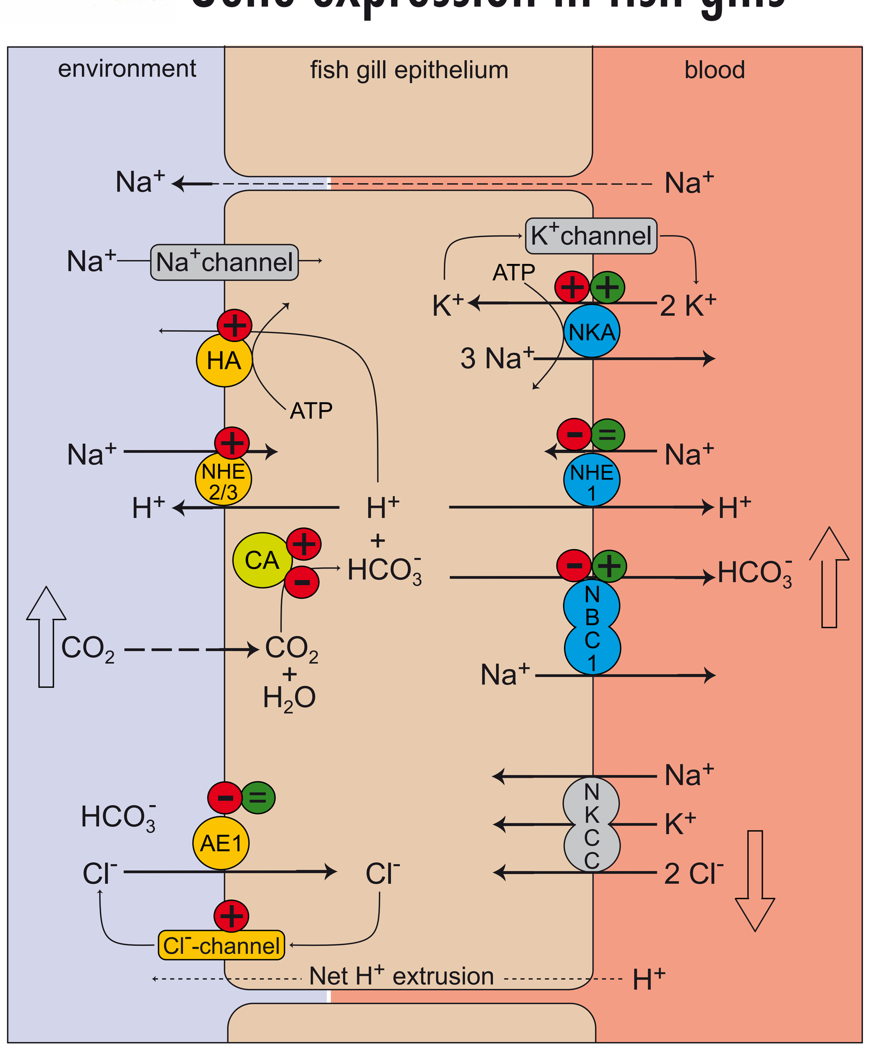
3. Specific effects: Energy budget of fish gills





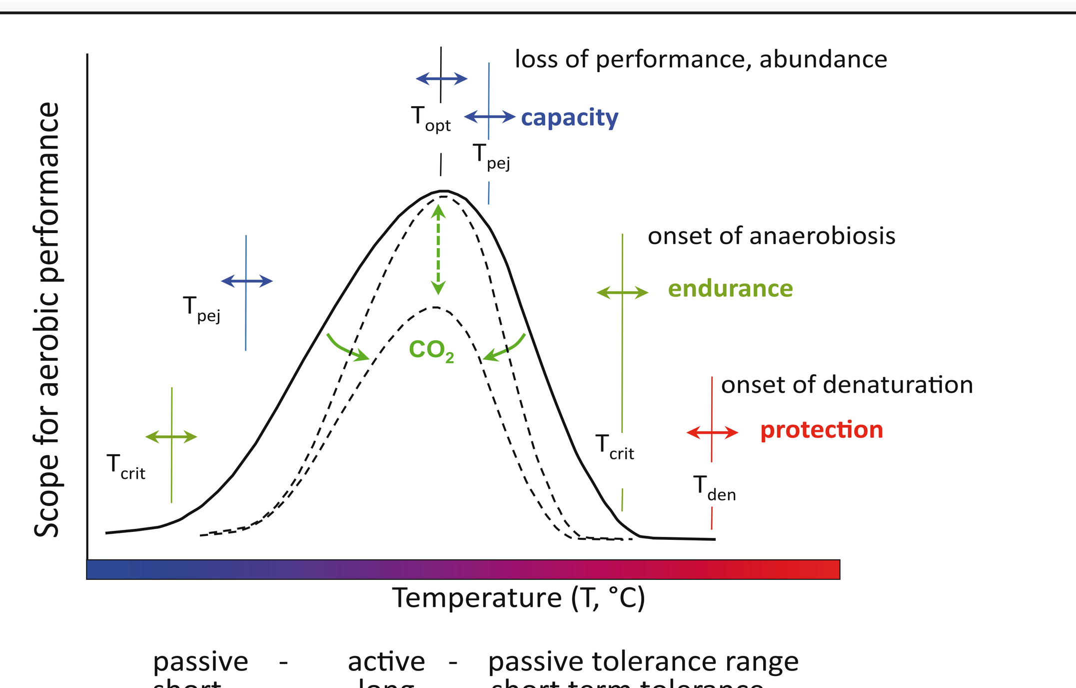
With full compensation of acid-base status, some ion transporters in perfused cod gills display enhanced turnover rates indicating elevated energy demand and a shift in gill energy budget elicited by changes in P_{CO_2}.

4. Specific effects: Gene expression in fish gills



Working model for acid-base regulation under hypercapnia in the gills of the marine teleost Zoarces viviparus[4]. Red circles: gene expression during short-term hypercapnia (24 to 96 h), green circles: long-term response (6wks). mRNA levels were found to be up-regulated (+), down-regulated (-) or unchanged (=). HA: H^+-ATPase, NHE1/2/3: Na^+/H^+-exchanger isoforms, CA: Carbonic anhydrase, AE1: Cl^-/HCO_3^--exchanger, NKA: Na^+/K^+-ATPase, NBC1: Na^+/HCO_3^- co-transporter, NKCC: $Na^+/K^+/2Cl^-$ co-transporter. Open arrows: changes in substrate concentrations.

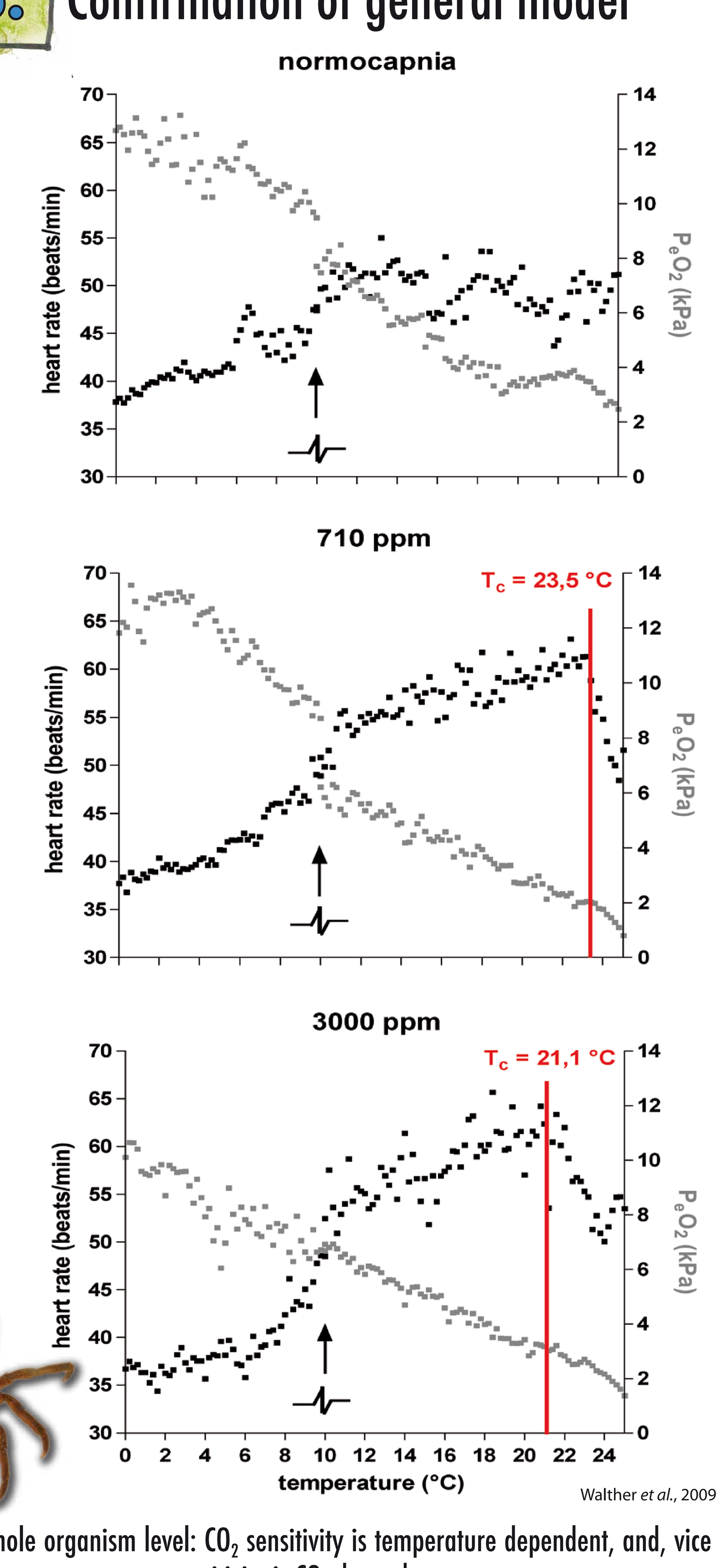
5. Ecosystem effects involve multiple stressors: General Model



The concept of oxygen and capacity limitation of thermal tolerance (OCLT) provides a matrix integrating the synergistic effects of environmental stressors including ocean acidification. The thermal window is narrowed through CO_2 specific effects on molecular to whole organism functions. Available evidence suggests that the OCLT concept closely defines the sensitivity and response of individuals to climate change at ecosystem level. It also provides causality and quantifies the levels and changes of organism performance and resistance as a reason for changes in species interactions[1]. An understanding of ecosystem-level processes results as needed to achieve more realistic estimates of species and ecosystem sensitivities to environmental change.

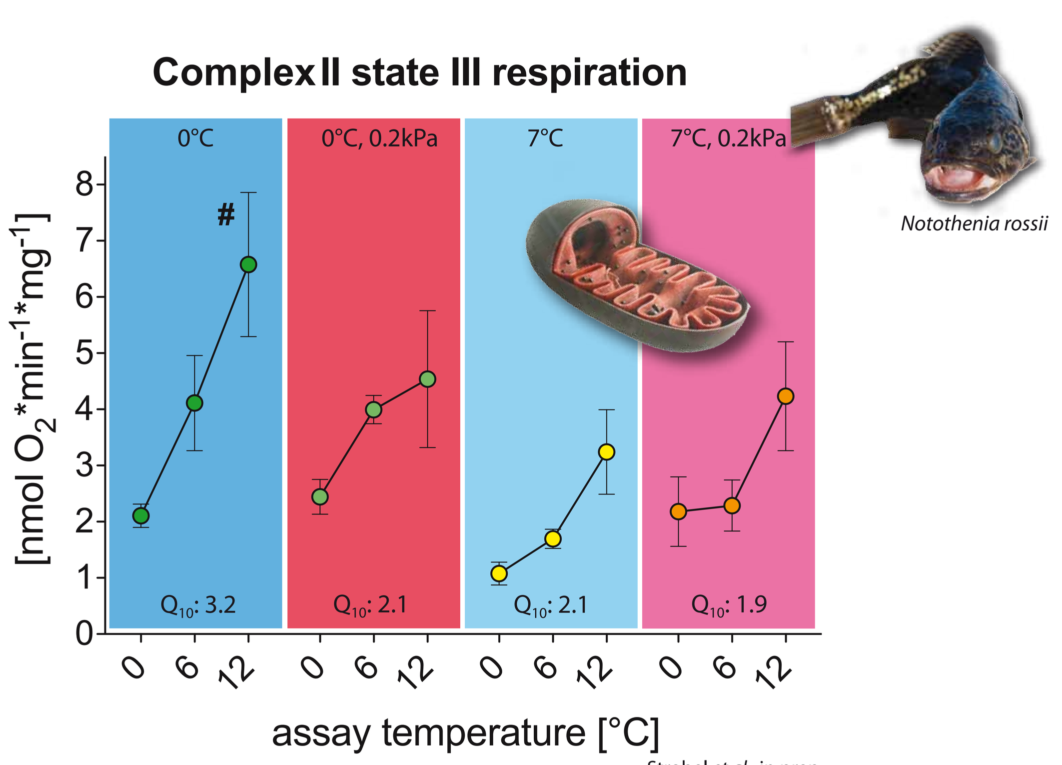
Which physiological mechanisms explain the different sensitivities and synergistic effects observed?

6. Confirmation of general model

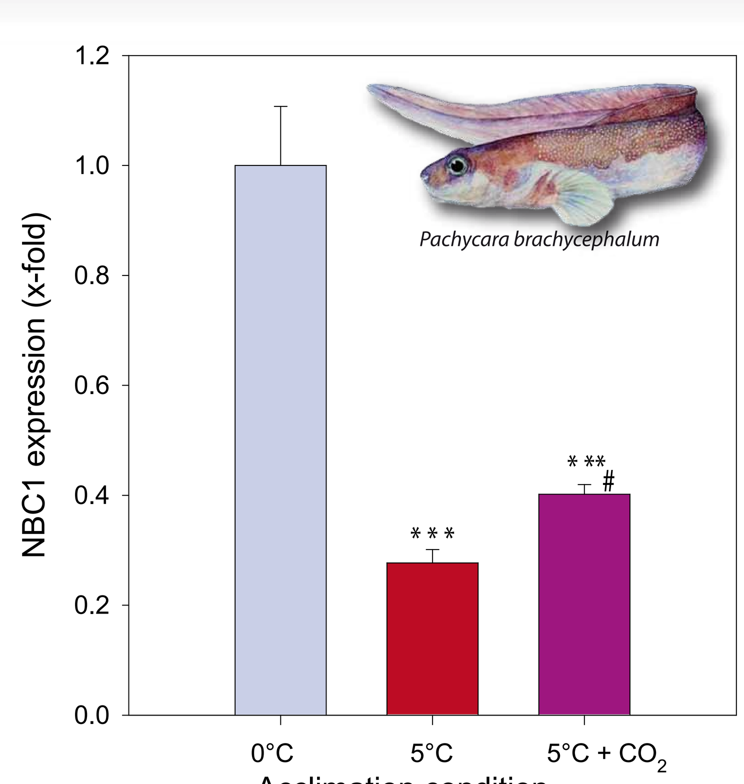


Whole organism level: CO_2 sensitivity is temperature dependent, and, vice versa, temperature sensitivity is CO_2 dependent.
The thermal window of the spider crab Hyas araneus is progressively narrowed by elevated CO_2 levels, indicated by the shift in upper critical temperature (Tc) to lower values[2].

7. Synergistic effects: Mechanisms underneath



Mitochondrial level: Mitochondrial capacities that generally are in excess of whole organism functional capacities and energy turnover are thermally less responsive under elevated P_{CO_2} in Antarctic notothenioids.
At thermal extremes, mitochondria may not display sufficient capacity to meet whole organism energy demand causing an earlier onset of thermal stress.



Genetic level: mRNA expression (x-fold) of gill Na^+/HCO_3^- cotransporter (NBC1) is reduced in long-term warm acclimated Antarctic eelpout P. brachycephalum. Expression was normalized to β-actin and given relative to the expression of the respective control group animals.
CO_2 may reduce the capacity of the warm acclimation response in Antarctic fish gills and thereby contribute to an earlier onset of thermal stress.

References: 1) Pörtner (2010) J Exp Biol 213:881-893 2) Walther et al. (2009) Biogeosciences 6:2207-2215 3) Walther et al. (2010) Mar Ecol Prog Ser 417:159-170 4) Deigweiher et al. (2008) Am J Physiol 295:R1660-1670

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