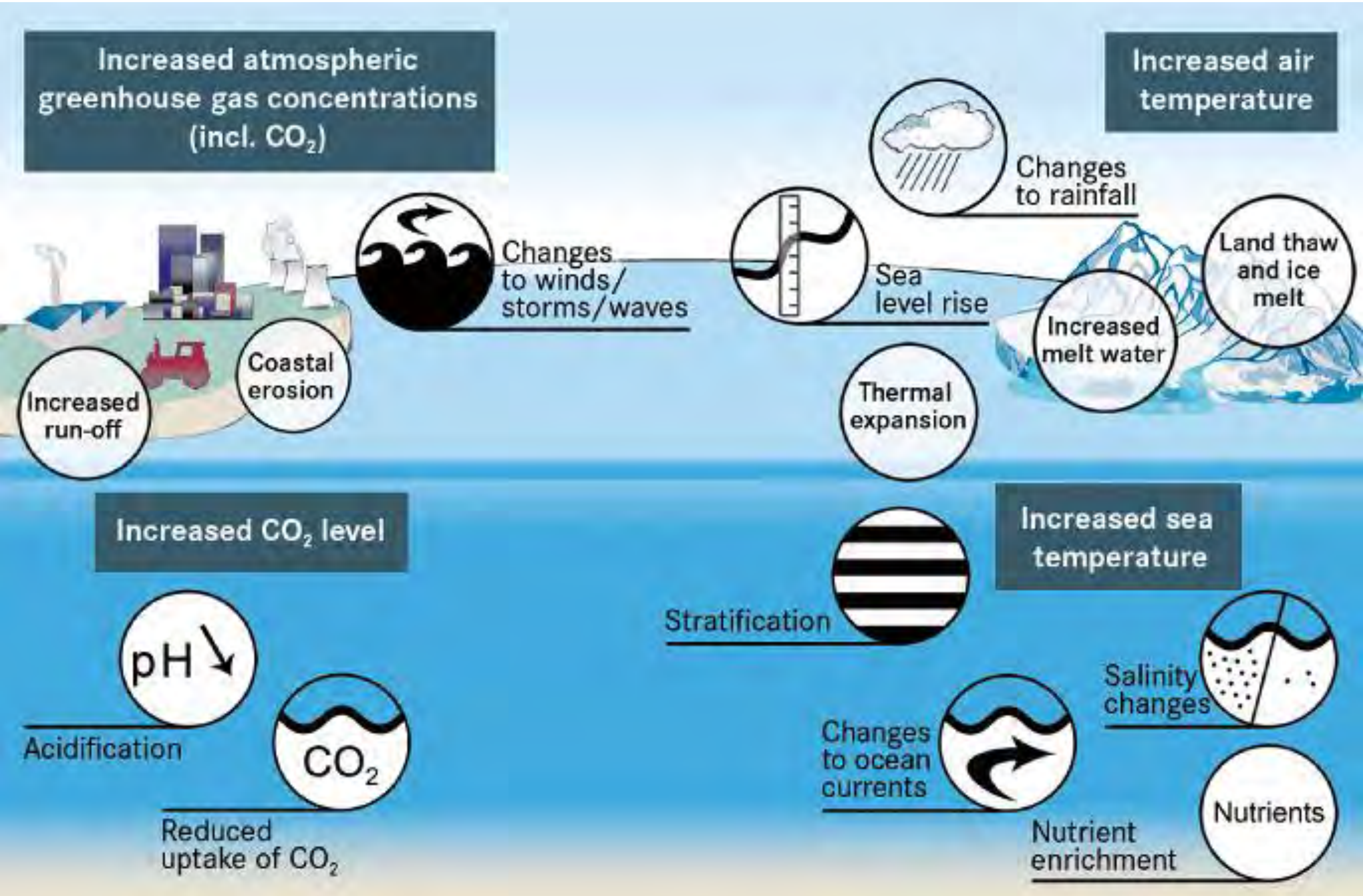
ARC CENTRE OF EXCELLENCE
Coral Reef Studies

Predicting evolutionary responses to climate change in the sea: Progress and challenges

Philip Munday, James Cook University

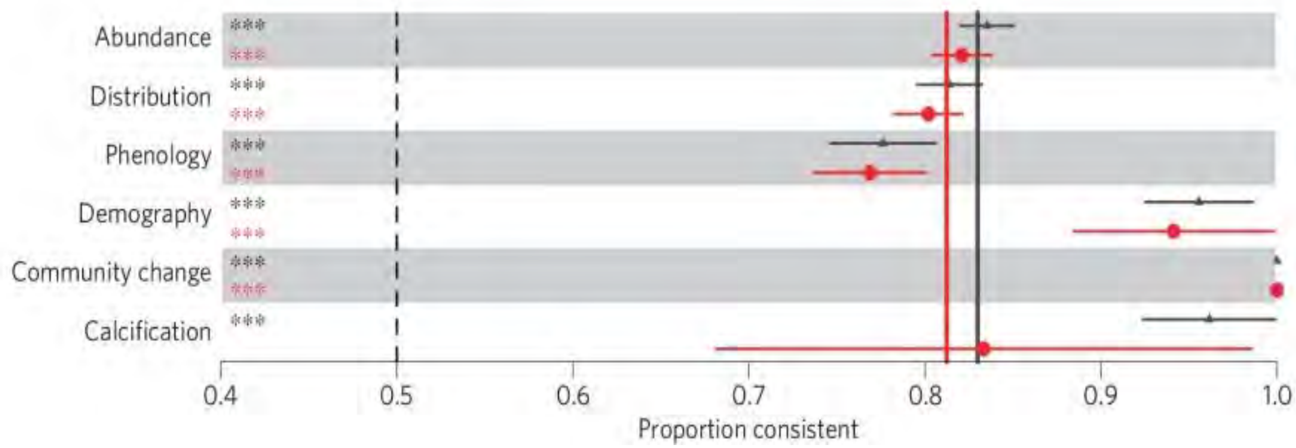
www.coralcoe.org.au


Increased atmospheric greenhouse gas concentrations (incl. CO_2)
Increased air temperature
Changes to rainfall
Changes to winds/ storms/waves
Sea level rise
Land thaw and ice melt
Increased melt water
Coastal erosion
Increased run-off
Thermal expansion
Increased CO_2 level
Increased sea temperature
Stratification
pH
Salinity changes
Acidification
CO_2
Changes to ocean currents
Nutrients
Reduced uptake of CO_2
Nutrient enrichment

Biological consequences

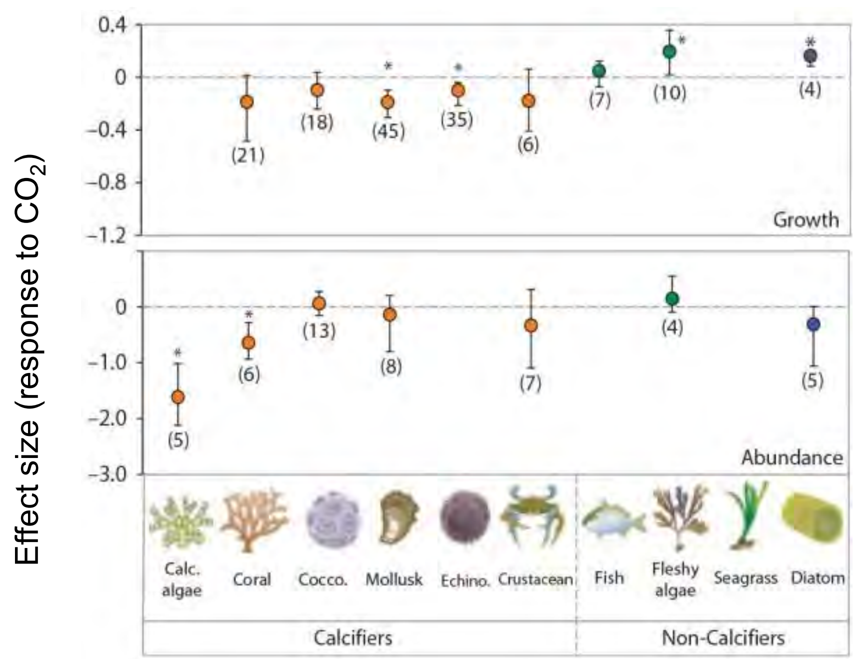
Observations

Poloczanska et al. 2013 NCC



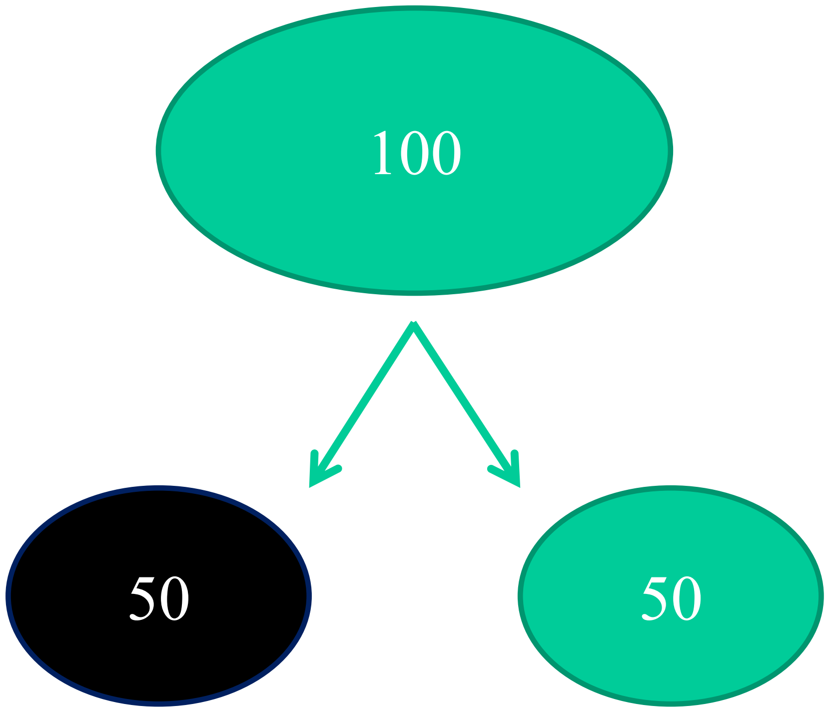
Experiments

Kroeker et al. 2012 GCB



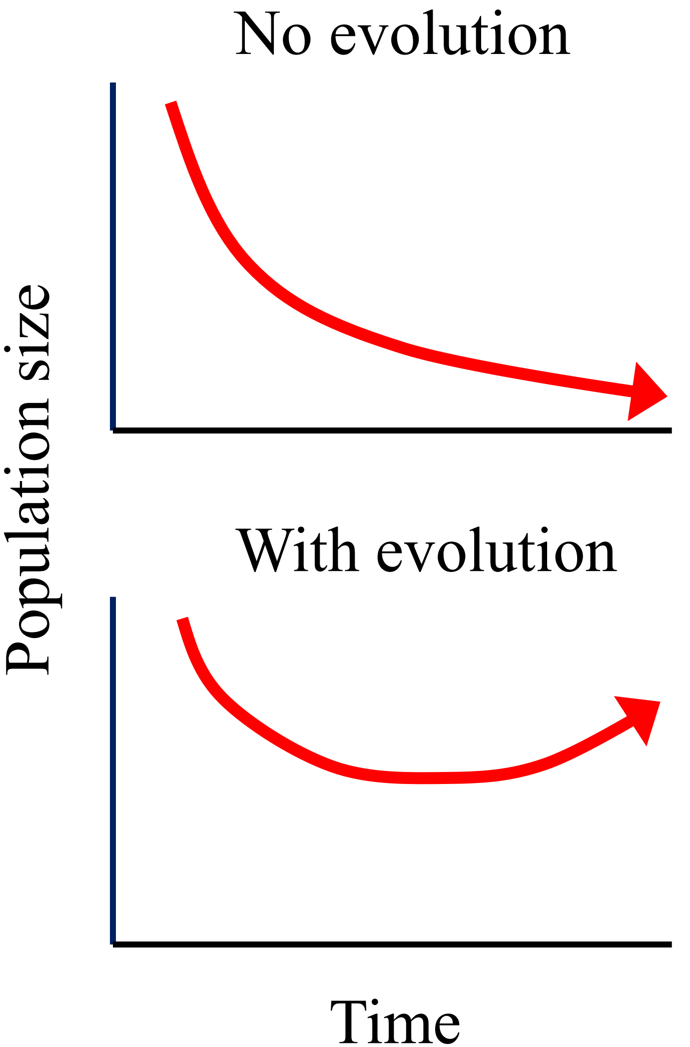
Evolutionary perspective

Extrapolations from short-term experiments risk overestimating impacts



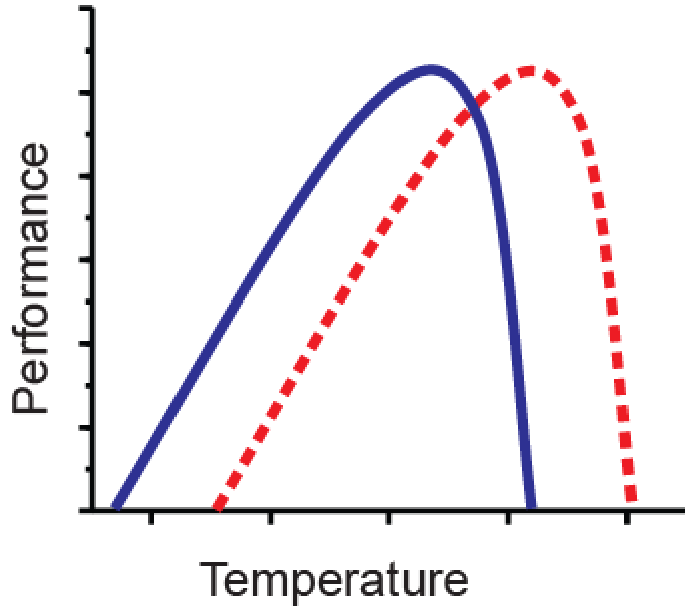
Evolutionary perspective

- Projections that include evolutionary potential
- Models that incorporate demographic effects of climate change and adaptive potential
- Evolution and ecology



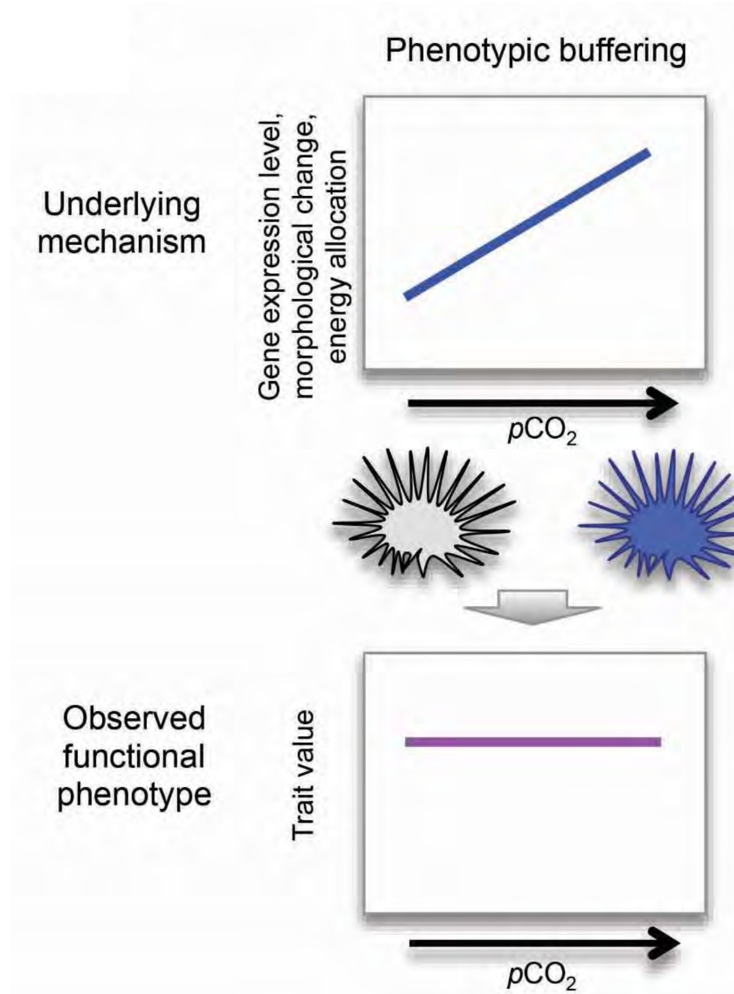
Acclimation and adaptation

- Acclimation (acclimatization)
  - Physiological, behavioural or morphological adjustment without genetic selection (plasticity)
- Genetic Adaptation (evolution)
  - Selection on genetic variation that is inherited from one generation to the next



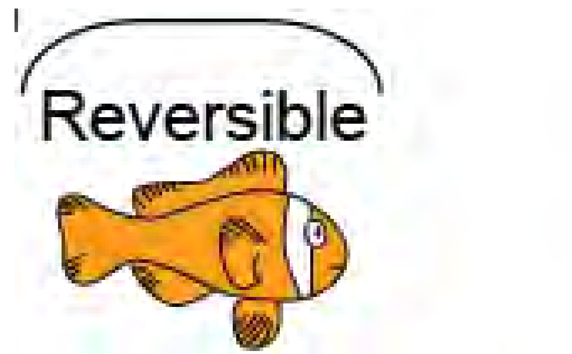
Plasticity

- Rapid phenotypic response to environmental change
- Enable performance to be maintained in a new environment
- Time for adaptation to catch up



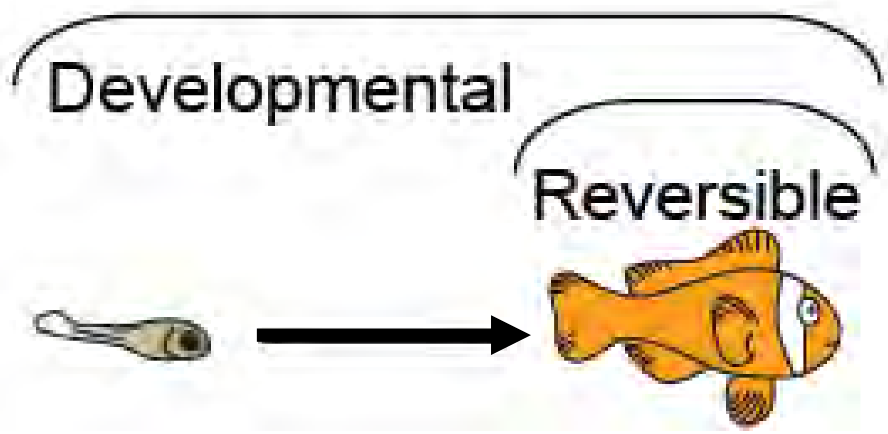
Sunday et al. 2014 *TREE, 29:117-125*

Plasticity



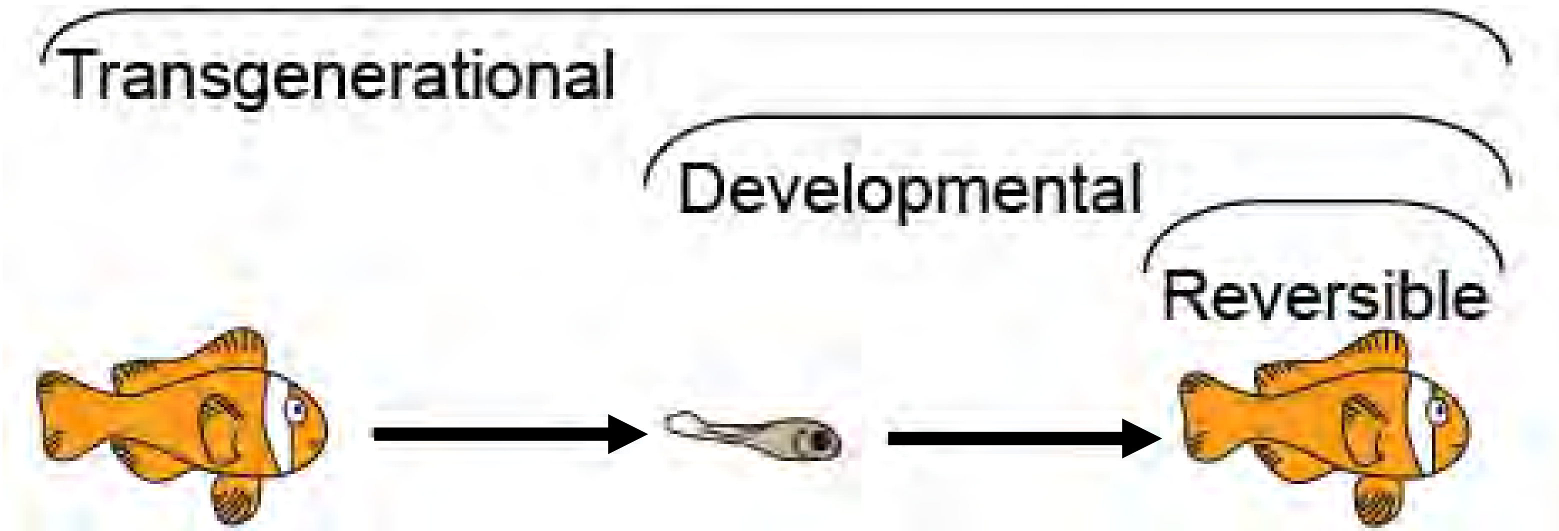
- Short-term regulated responses to environmental variation: e.g. diel & seasonal variation
- Species that live in variable environments

Plasticity



- Irreversible response to environmental conditions experienced during ontogeny
- Influences response of later life stages

Plasticity

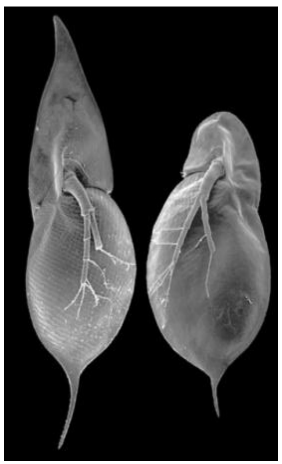


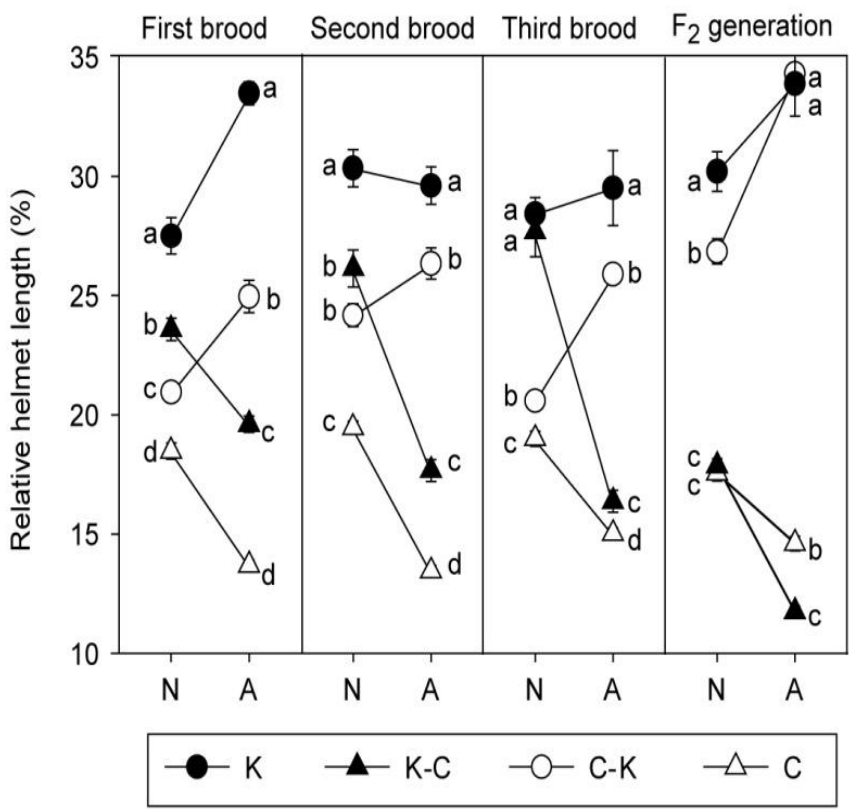
- Environment experienced by the parents (or earlier generations) influences the offsprings' response to environmental conditions
- Relevant to climate change

Munday 2014 F1000Prime Reports, 6:99

Transgenerational Plasticity

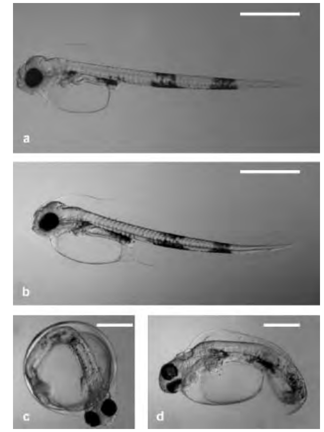
Daphnia (waterflea) response to predator chemical cues

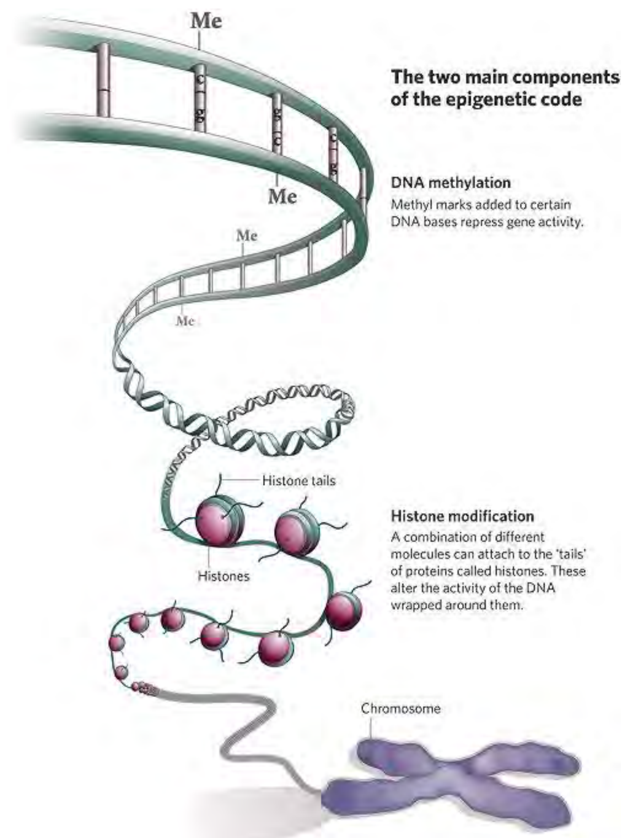




Argrawal et al. 1999 Nature

- Nutrients
  - Yolk
- Cytoplasmic factors
  - Hormones and proteins
- Epigenetic marks
  - DNA methylation
  - Chromatin structure
  - Modify the activation of genes
  - Influenced by the environment
  - Potentially heritable



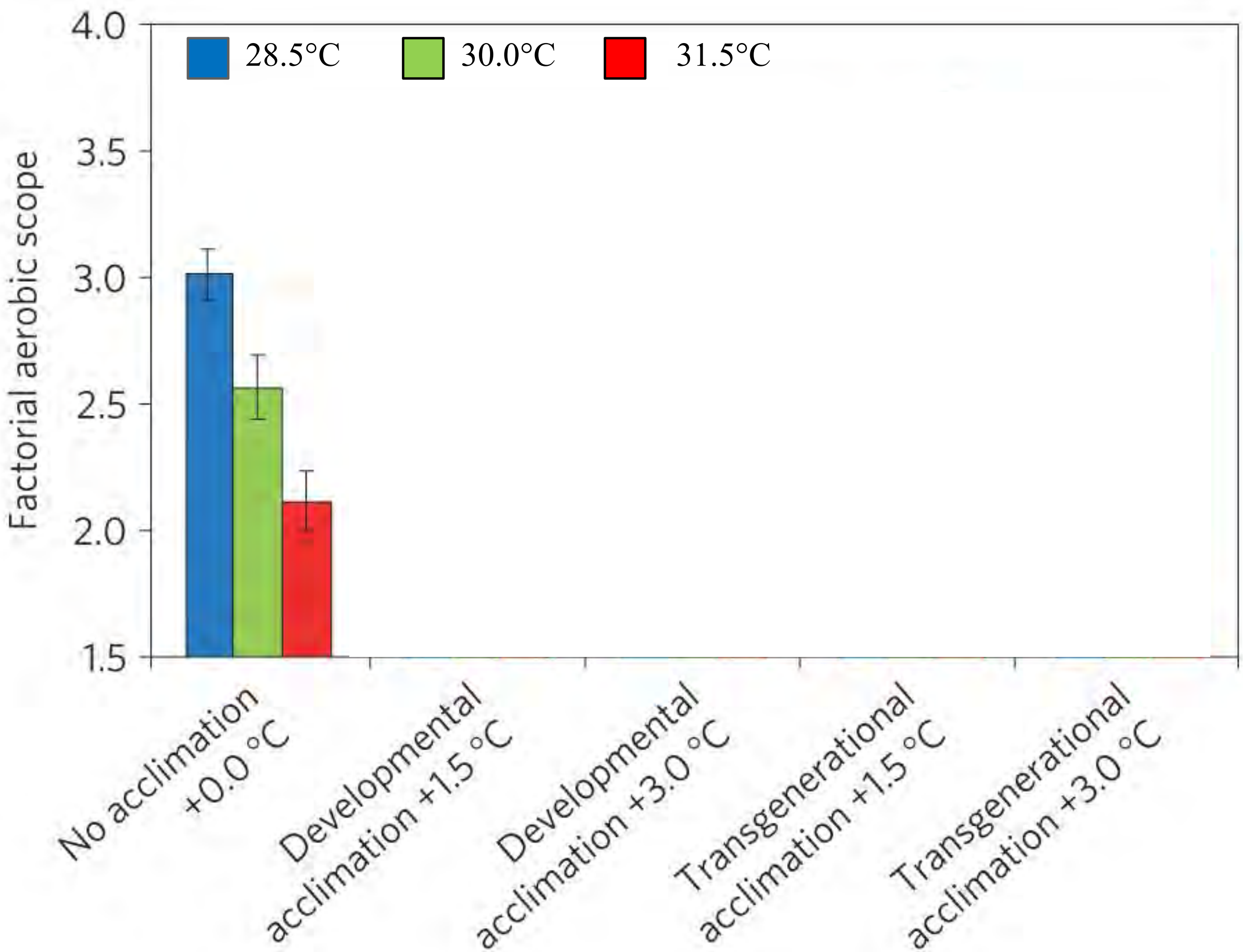


Transgenerational Plasticity

- Limited capacity for reversible acclimation
- + 1.5- 3°C affects:
  - growth, reproduction, aerobic performance
- Rearing fish over multiple generations
  - Developmental
  - Transgenerational

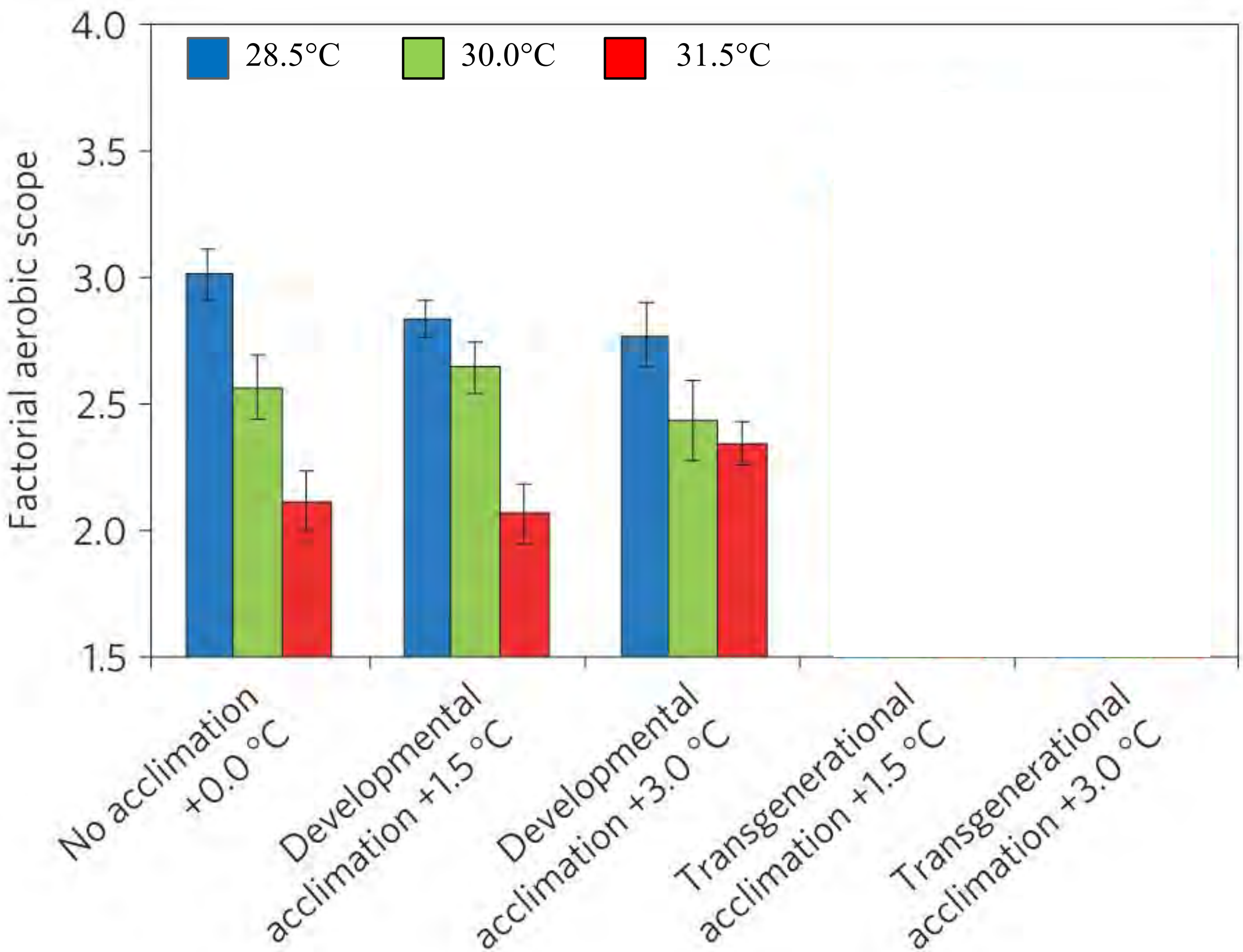
Spiny damselfish

Acute effects



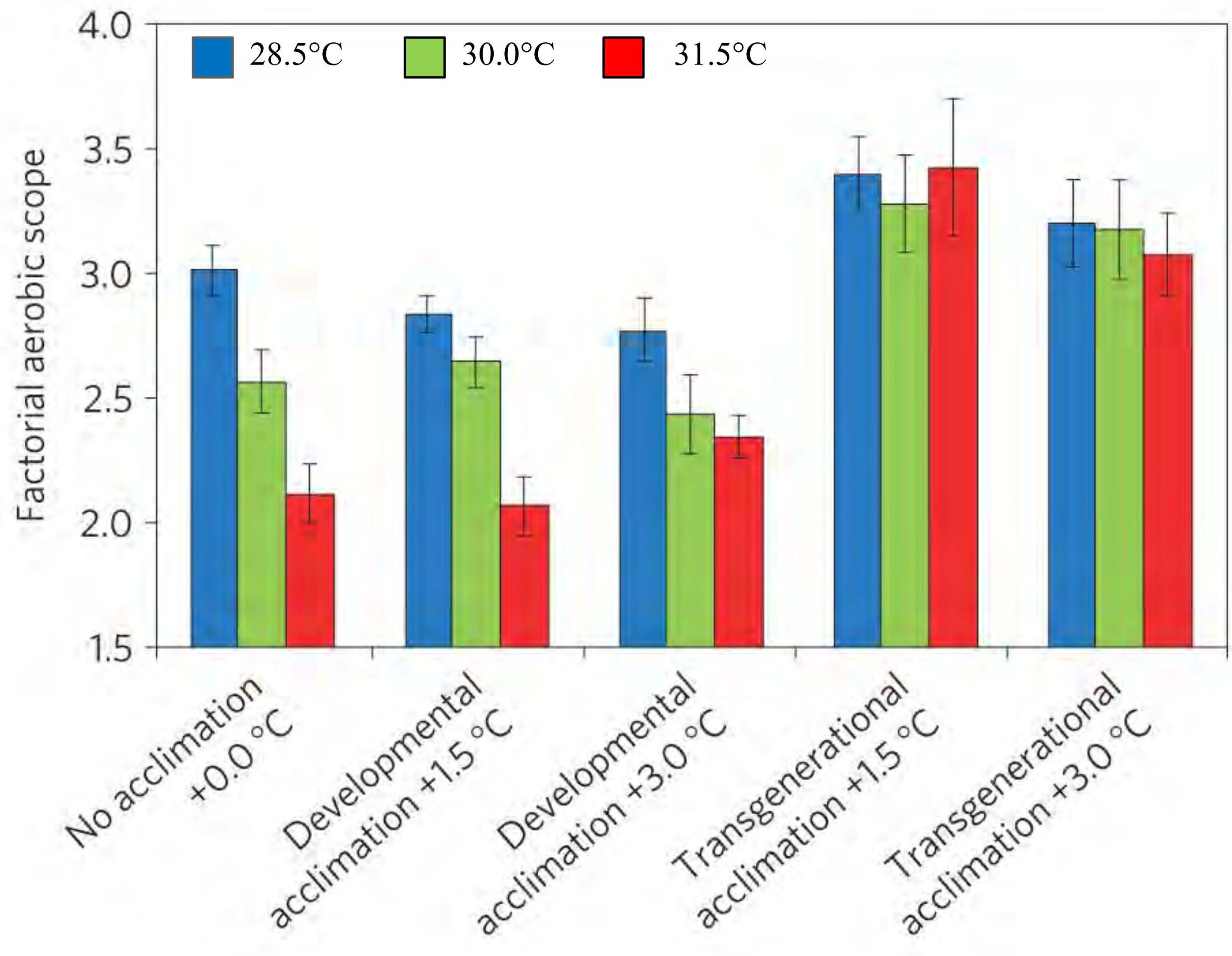
Donelson et al. 2012 *Nature Climate Change* 2: 30-32

Developmental plasticity



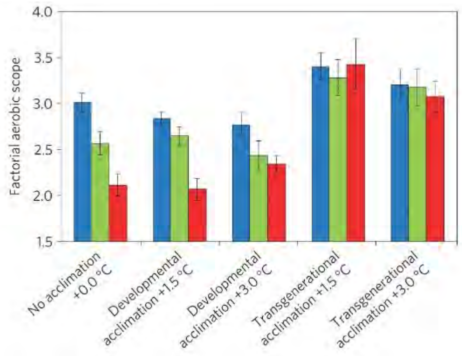
Donelson et al. 2012 *Nature Climate Change* 2: 30-32

Transgenerational plasticity

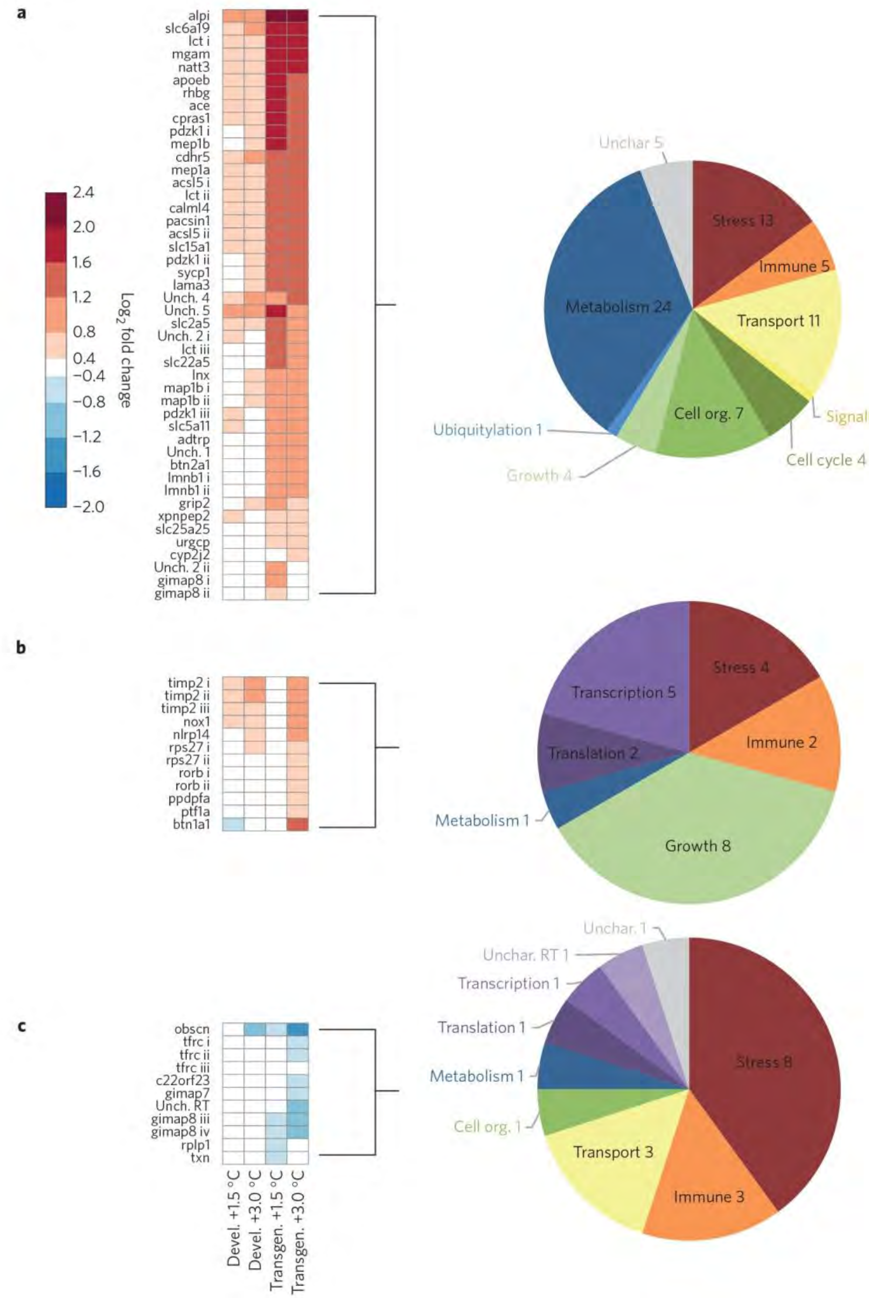


Donelson et al. 2012 *Nature Climate Change* 2: 30-32

Mechanism



- 53 key genes
- Metabolism – shifts in energy production
- Immunity and stress
- Tissue development and transcriptional regulation



Veilleux et al. 2015 *Nature Climate Change*, 5:1074-1078

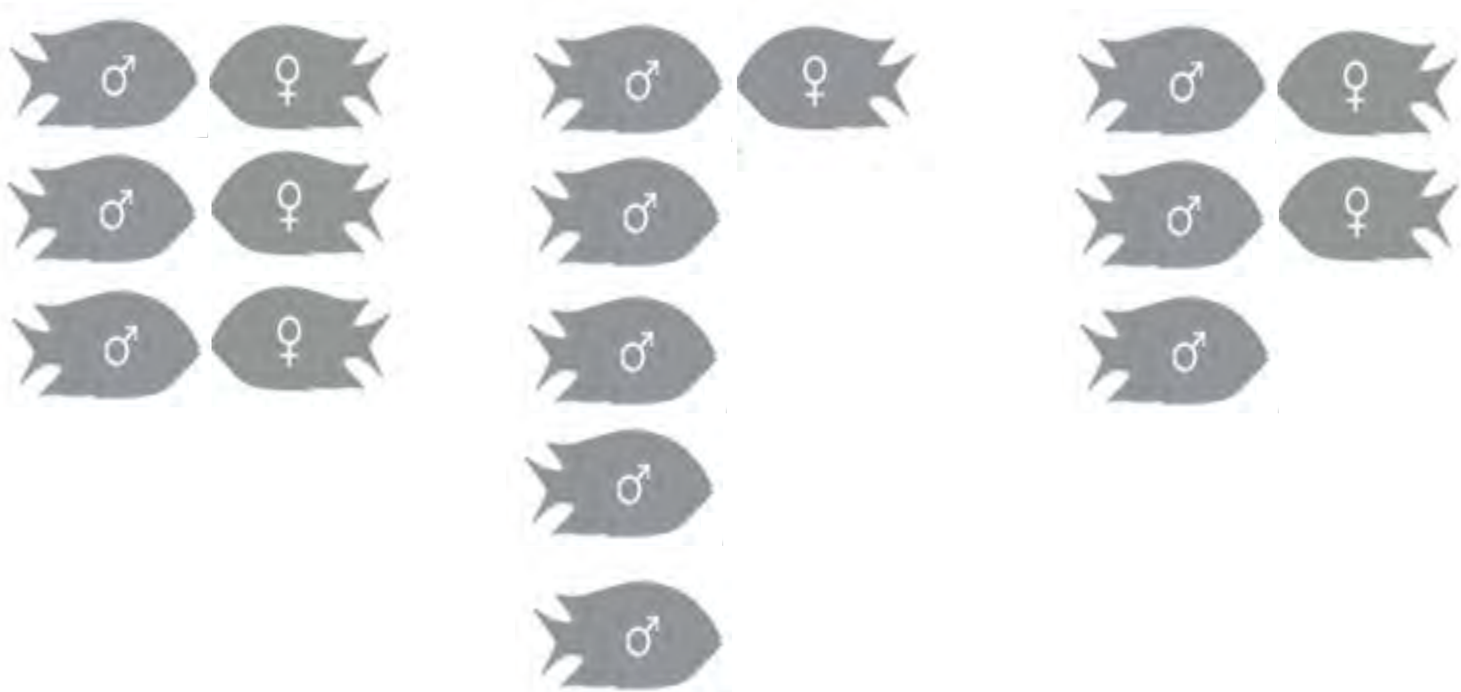
Sex ratios

Ambient | +1.5°C developmental | +1.5°C transgenerational

Donelson & Munday 2016 *Global Change Biology 21:2954-62*

Sex ratios

Ambient | +3°C developmental | +3°C transgenerational



Donelson & Munday 2016 *Global Change Biology 21:2954-62*

- Temperature and growth
  - Sheepshead minnow
  - Stickleback

Salinas & Munch 2012. *Ecology Letters* 15:159

Shama et al. 2014 *Functional Ecology,* 28: 1482-1493

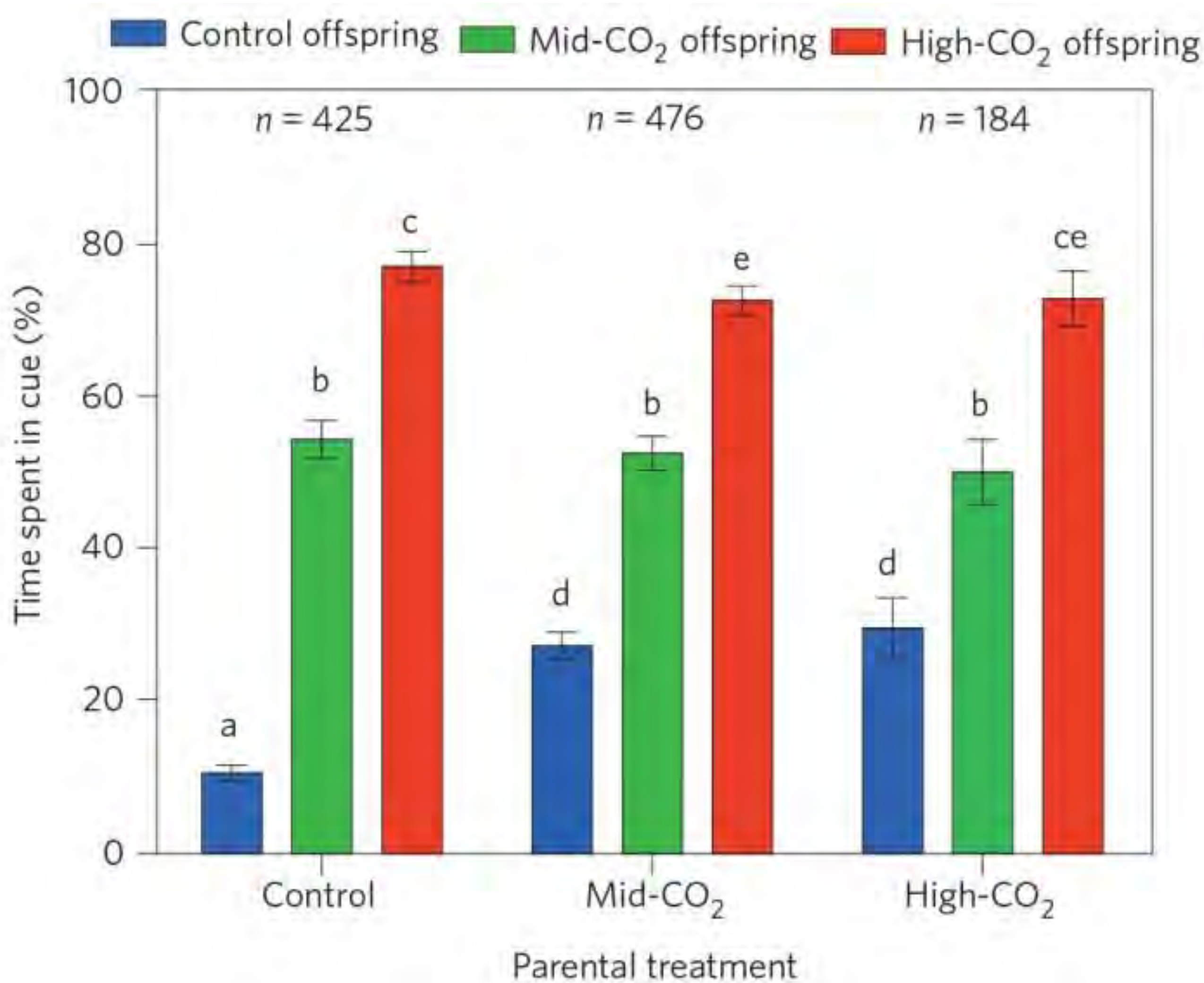
- High CO_2 and survival
  - Atlantic silverside

Murray et al. 2014 *MEPS* 504:1-11

- High CO_2 and growth
  - Cinammon clownfish

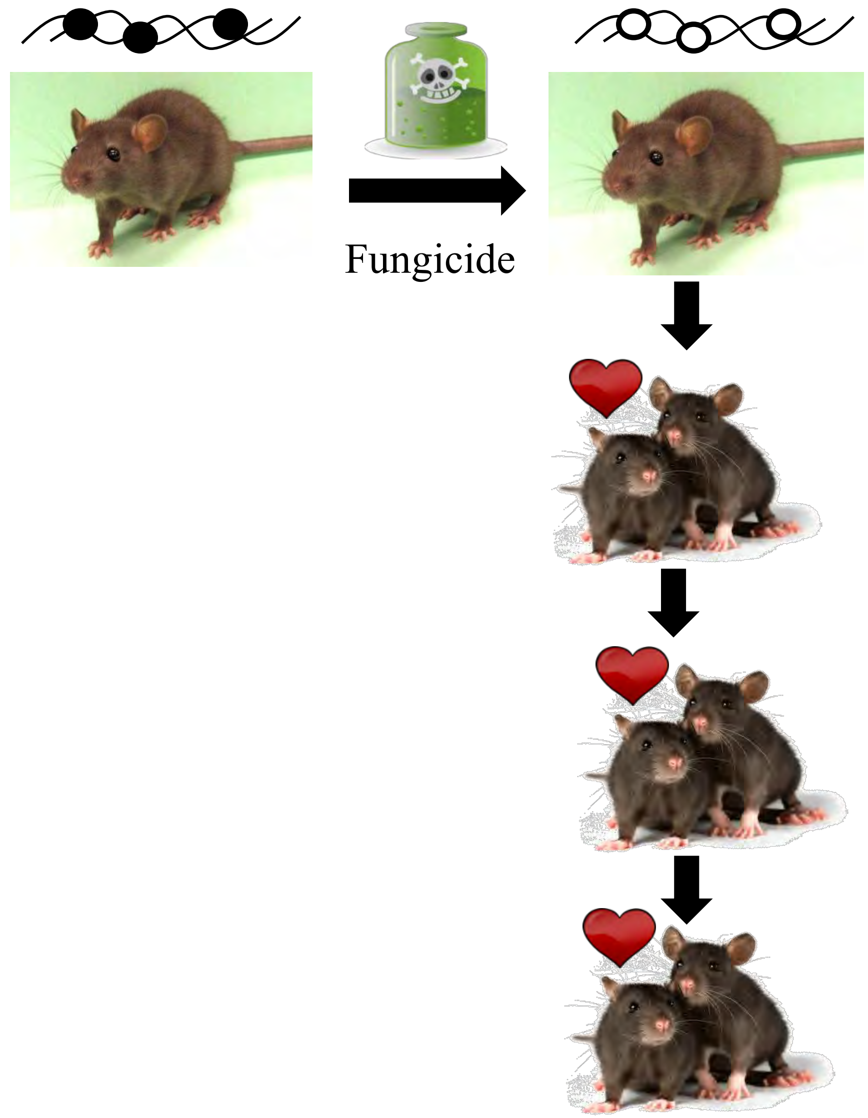
Miller et al. 2012. *Nature Climate Change*, 2: 858-861

No transgenerational plasticity



Welch et al. 2014. *Nature Climate Change*, 4: 1086-1089

Maladaptive effects



Altered DNA methylation in sperm

F1

F2

F3

Mate choice

Disease prevalence

Stress response

Crews et al. 2007 PNAS 104: 5942

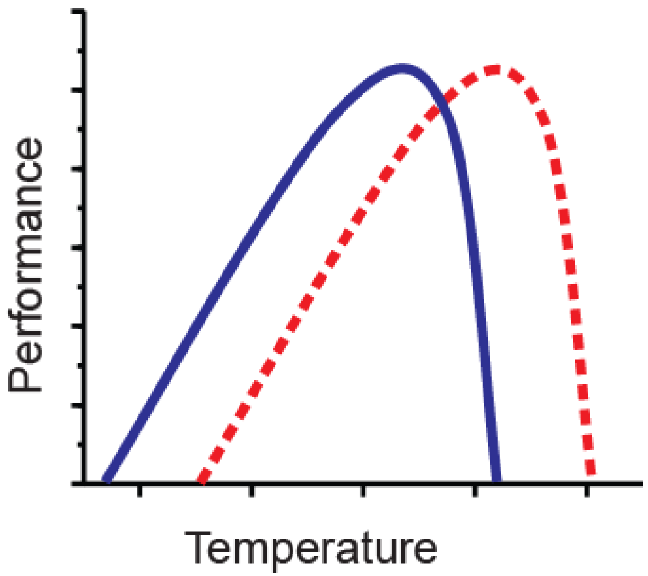
Crews et al. 2012 PNAS 109: 9143

Future directions

- Longer-term experiments that account for plasticity within and between generations
- What are the costs or trade-offs?
- Does plasticity translate to persistence?
- Can we predict which species will exhibit TGP or other forms of plasticity?

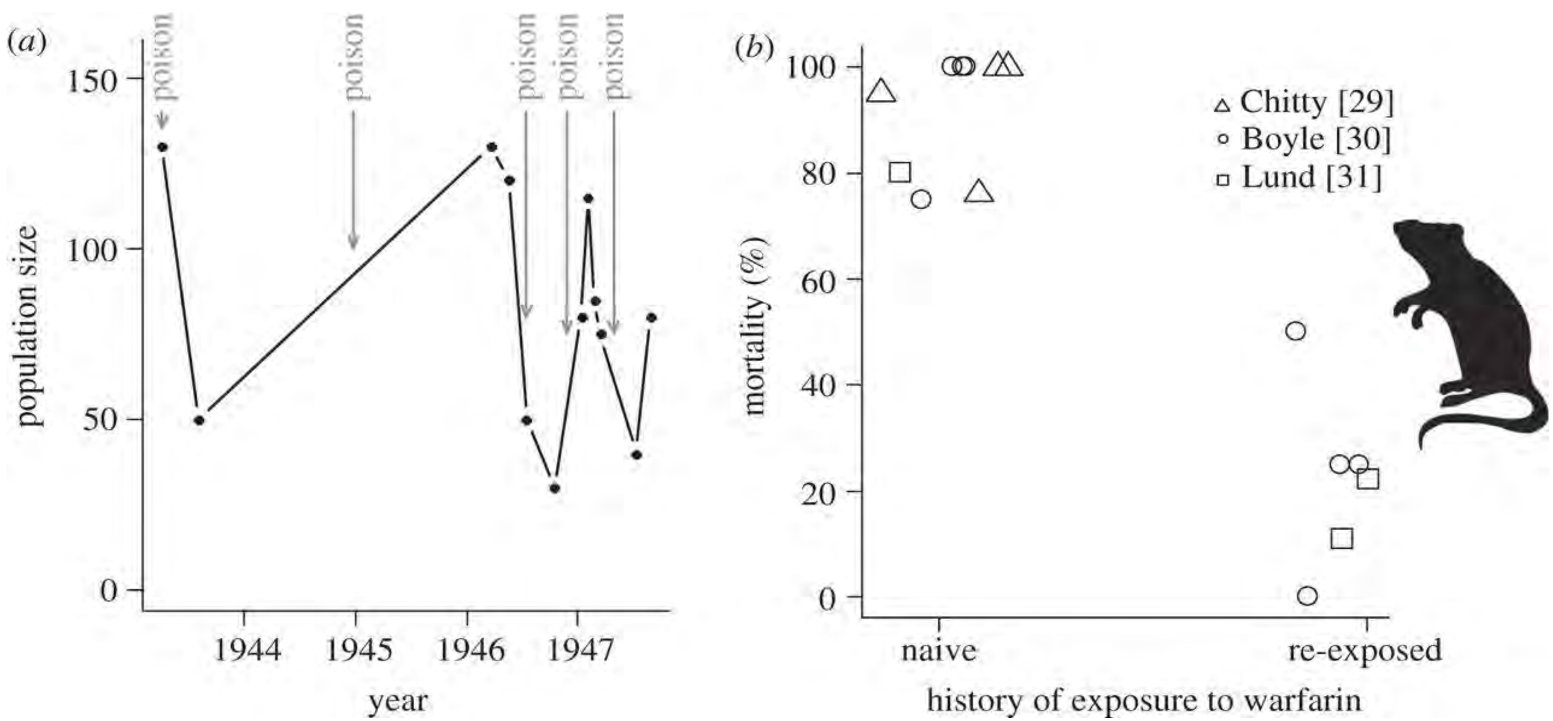
Adaptation

- Acclimation
  - Physiological, behavioural or morphological adjustment without genetic selection (plasticity)
- Genetic Adaptation
  - Selection on genetic variation that is inherited from one generation to the next



Adaptation

- Genetic adaptation can sometimes be surprisingly rapid



Vander Wal et al. 2013 *Phil. Trans. R. Soc. B,* 368:20120090

Assessing evolutionary potential

- Field studies
- Experimental evolution
- Quantitative genetics
- Molecular approaches
- Combined
  - molecular and experimental

ECOLOGY LETTERS

Ecology Letters, (2013) doi: 10.1111/ele.12185

REVIEW AND SYNTHESIS

Predicting evolutionary responses to climate change in the sea

Philip L. Munday,[1]* Robert R. Warner,[2] Keyne Monro,[3] John M. Pandolfi[4] and Dustin J. Marshall[3]

Abstract

An increasing number of short-term experimental studies show significant effects of projected ocean warming and ocean acidification on the performance on marine organisms. Yet, it remains unclear if we can reliably predict the impact of climate change on marine populations and ecosystems, because we lack sufficient understanding of the capacity for marine organisms to adapt to rapid climate change. In this review, we emphasise why an evolutionary perspective is crucial to understanding climate change impacts in the sea and examine the approaches that may be useful for addressing this challenge. We first consider what the geological record and present-day analogues of future climate conditions can tell us about the potential for adaptation to climate change. We also examine evidence that phenotypic plasticity may assist marine species to persist in a rapidly changing climate. We then outline the various experimental approaches that can be used to estimate evolutionary potential, focusing on molecular tools, quantitative genetics, and experimental evolution, and we describe the benefits of combining different approaches to gain a deeper understanding of evolutionary potential. Our goal is to provide a platform for future research addressing the evolutionary potential for marine organisms to cope with climate change.

Review Cell PRESS

Evolution in an acidifying ocean

Jennifer M. Sunday[1,2], Piero Calosi[3], Sam Dupont[4], Philip L. Munday[5,6], Jonathon H. Stillman[7,8], and Thorsten B.H. Reusch[9]

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[7] Romberg Tiburon Center and Department of Biology, San Francisco State University, Tiburon, CA 94920, USA
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Ocean acidification poses a global threat to biodiversity, yet species might have the capacity to adapt through evolutionary change. Here we summarize tools available to determine species' capacity for evolutionary adaptation to future ocean change and review the progress made to date with respect to ocean acidification. We focus on two key approaches: measuring standing genetic variation within populations and experimental evolution. We highlight benefits and challenges of each approach and recommend future research directions for understanding the modulating role of evolution in a changing ocean.

Bringing evolution into the forecast of an acidified ocean

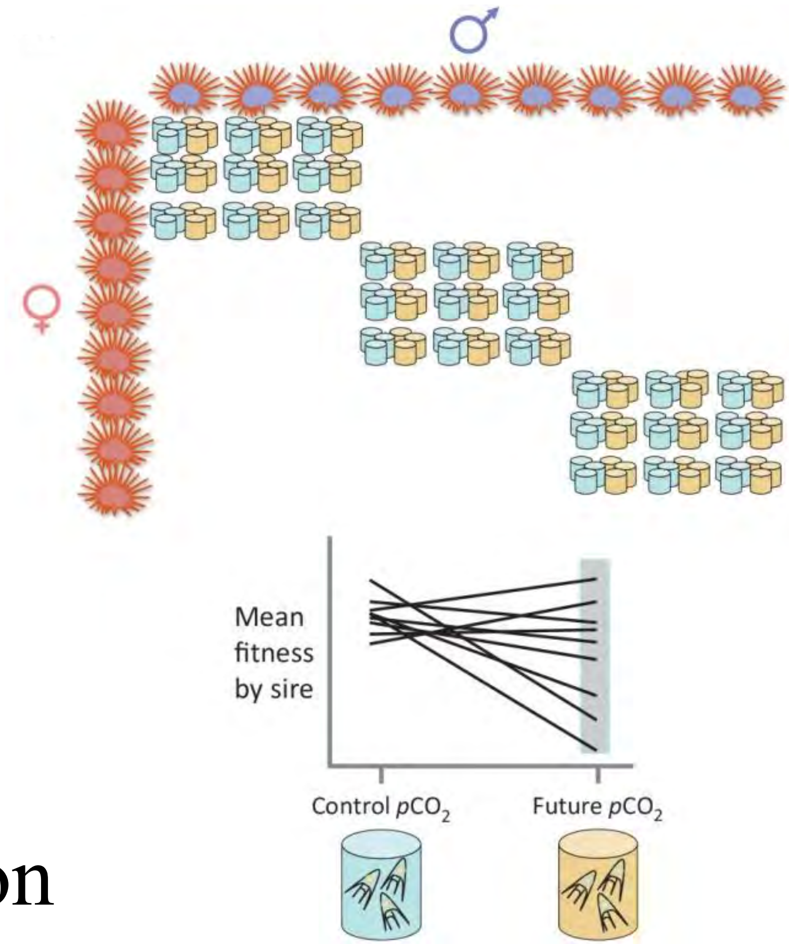
The ocean environment is changing rapidly, with surface waters changing in temperature and acidity at geologically unprecedented rates [1]. Projecting the fate of marine biodiversity requires not only understanding how these changes will affect populations, but also how populations will respond via acclimation and adaptive evolu-

Ocean acidification – the increase in partial pressure of CO_2 (pCO_2) and reduction in pH associated with uptake of fossil fuel-derived CO_2 from the atmosphere – profoundly alters the inorganic conditions of the oceans. Although increased pCO_2 can enhance photosynthesis and growth of photoautotrophic organisms, ocean acidification is a stressor for many organisms (i.e., decreases fitness, reviewed in [4]). Because spatial gradients in pCO_2 are relatively low and unstructured relative to the temporal change predicted [5], species are less likely to find refuge through migration (as has been observed across thermal gradients [6]). Evolutionary adaptation could hence be a particularly important response to this widespread change.

Although the possibility for evolutionary adaptation to ocean acidification is increasingly recognized [7–9], the field is at a nascent stage. Here we summarize approaches that can be used to address the potential for evolutionary adaptation in order to guide future work with an evolutionary focus. Although we use ocean acidification as a case study, the methods reviewed are equally applicable to other aspects of ocean change and we highlight the utility

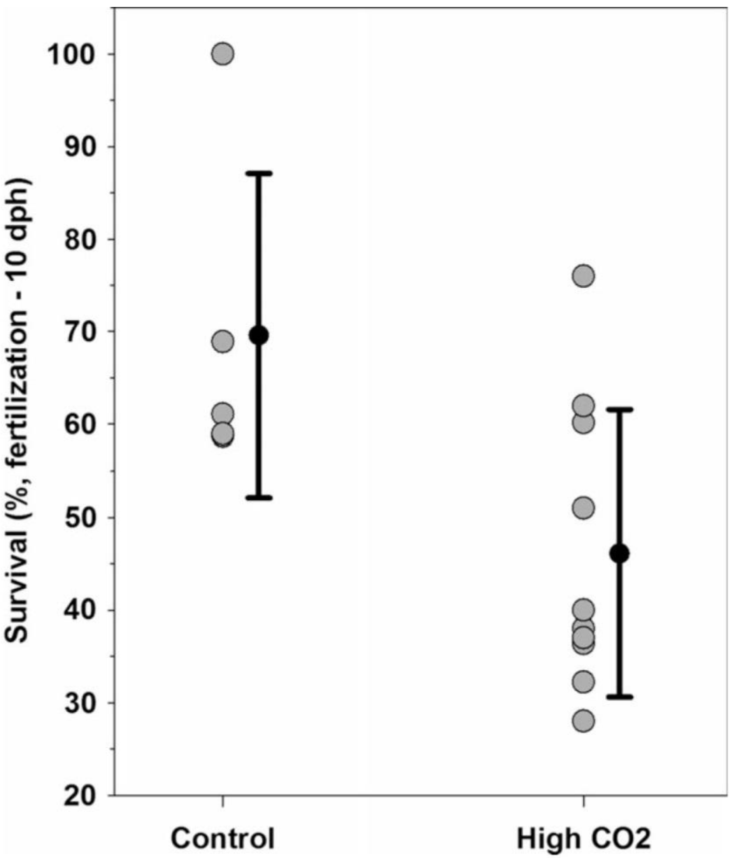
Quantitative genetics

- Parent-offspring correlations
- Pedigree mapping
- Breeding designs
  - partition phenotypic variation
    - fathers
    - mothers
    - fathers*mothers
    - environment
- Heritable genetic variation



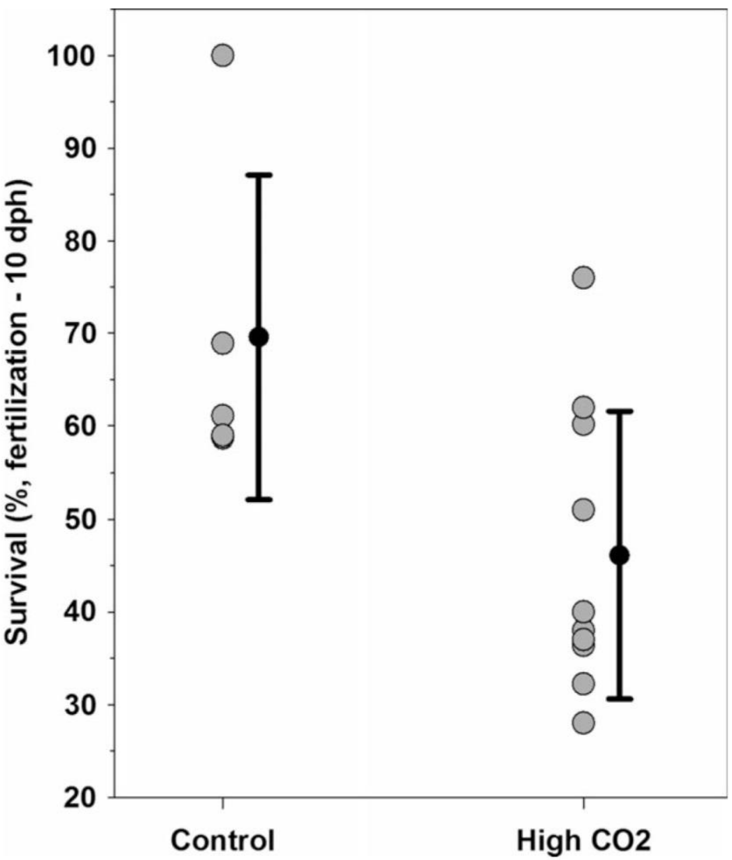
Sunday et al. 2014 *TREE, 29:117-125*

Quantitative genetics



Malvezzi et al. 2015 *Evolutionary Applications* 8:352-362

Quantitative genetics



Additive genetic variation for survival in high CO_2

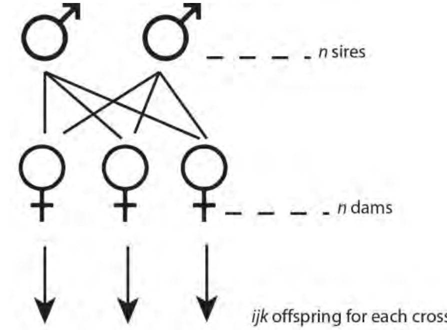
- Cross-fertilized 42 males & 29 females
- Constructed a parent-offspring pedigree using microsatellites
- The Animal Model to partition phenotypic variance

Model	Variance component	Estimate	Standard error
$DS_i = ID + \alpha_i + \varepsilon_i$	V_{DS}	29.145	1.685
	V_A	5.716	2.102
	V_R	23.428	1.925
Heritability	$h^2 = V_A/V_{DS}$	0.196	0.067

V_{DS}, total phenotypic variance of *DS*; V_A, additive genetic variance (genotype); V_R, residual variance.

Malvezzi et al. 2015 *Evolutionary Applications* 8:352-362

Quantitative genetics



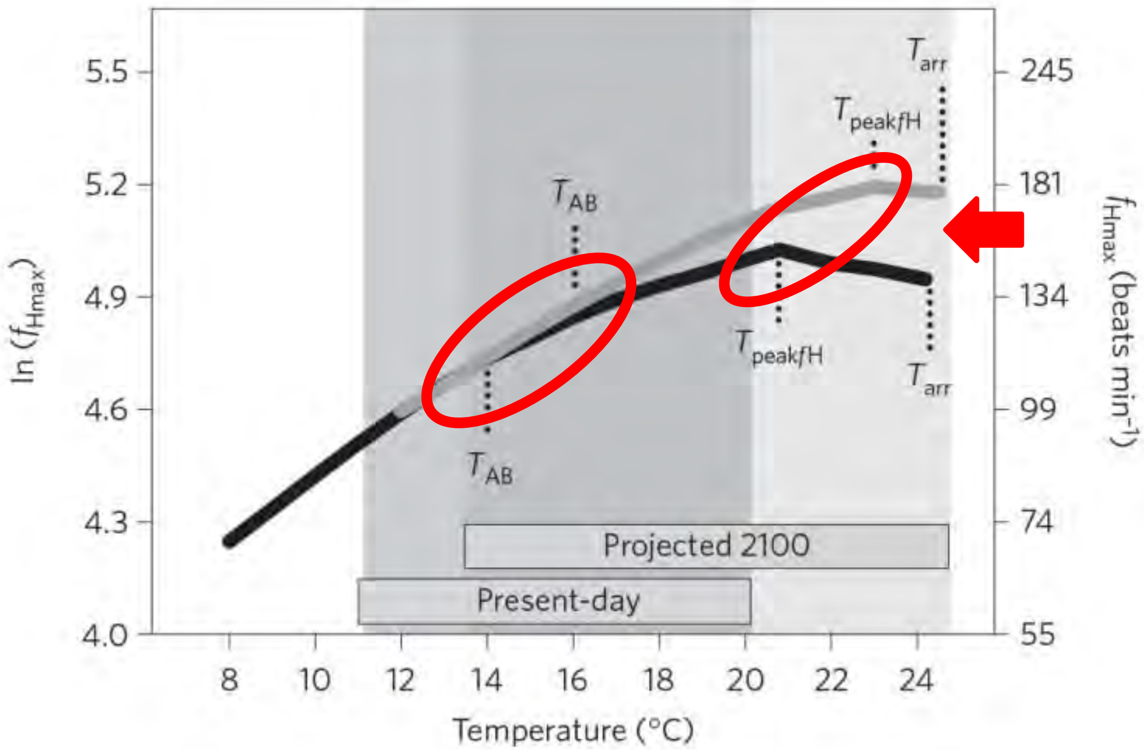


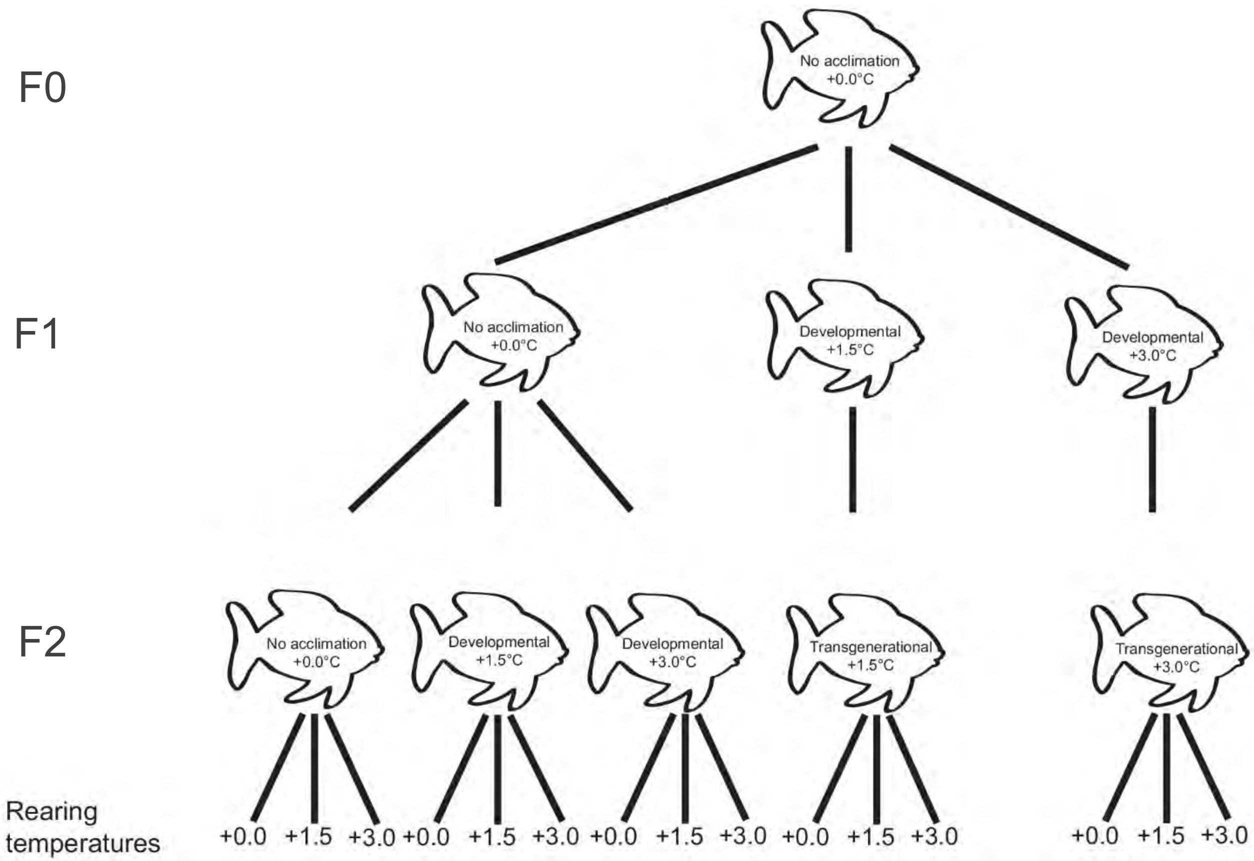
Table 1 | The plastic and genetic effects contributing to cardiac performance and thermal tolerance in Quinsam River chinook salmon (*O. tshawytscha*).

	DF	SS	*F*	*P*	σ^2	% phenotypic var	
T_{AB}							
Treatment	1	235	267	<0.001	0.84	Plastic	42
Dam	4	3.04	0.87	0.485	0.01		
Sire	4	12.3	3.49	0.009	0.04	Additive	9
Sire × Dam	4	3.99	1.14	0.340	0.01		
Treatment × Dam	4	7.26	2.07	0.086	0.03		
Treatment × Sire	4	8.19	2.33	0.057	0.03		
Residual	260	228			0.82		
T_{peakfH}							
Treatment	1	101.6	26.9	<0.001	0.36	Plastic	7
Dam	4	30.0	1.98	0.098	0.11		
Sire	4	23.4	1.54	0.191	0.08		
Sire × Dam	4	9.37	0.62	0.650	0.03		
Treatment × Dam	4	7.24	0.48	0.752	0.03		
Treatment × Sire	4	5.83	0.38	0.819	0.02		
Residual	260	985			3.52		
T_{arr}							
Treatment	1	2.30	0.68	0.411	0.01		
Dam	4	35.2	2.59	0.037	0.13	Maternal	4
Sire	4	24.1	1.77	0.134	0.09		
Sire × Dam	4	6.70	0.49	0.740	0.02		
Treatment × Dam	4	1.47	0.11	0.980	0.01		
Treatment × Sire	4	9.66	0.71	0.585	0.03		
Residual	260	882			3.15		

Munoz et al. 2015 *Nature Climate Change*, 5: 163-166

Quantitative genetics

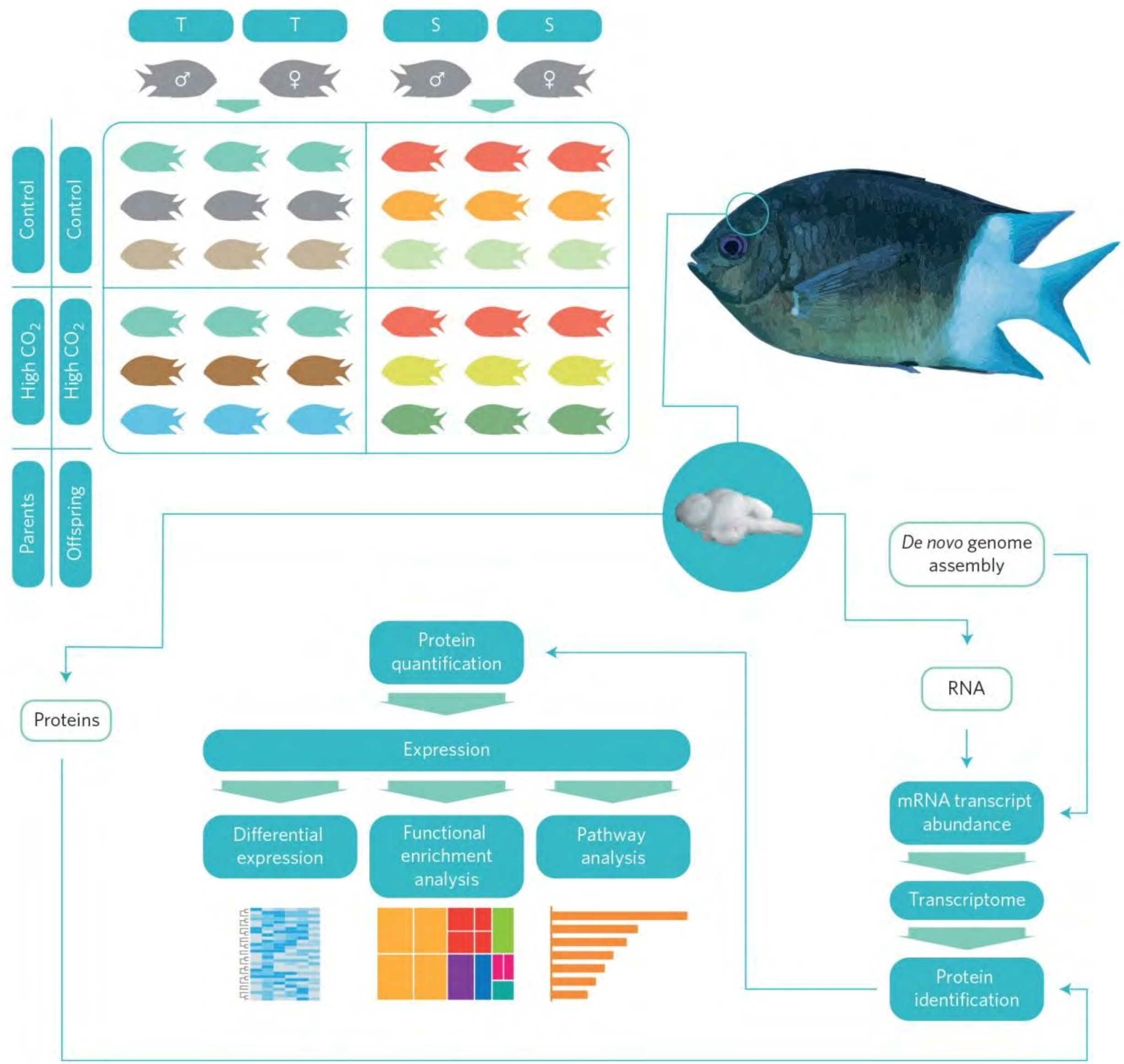
Multigenerational pedigree



- High heritability of growth and metabolism
- G x E imply capacity for adaptation

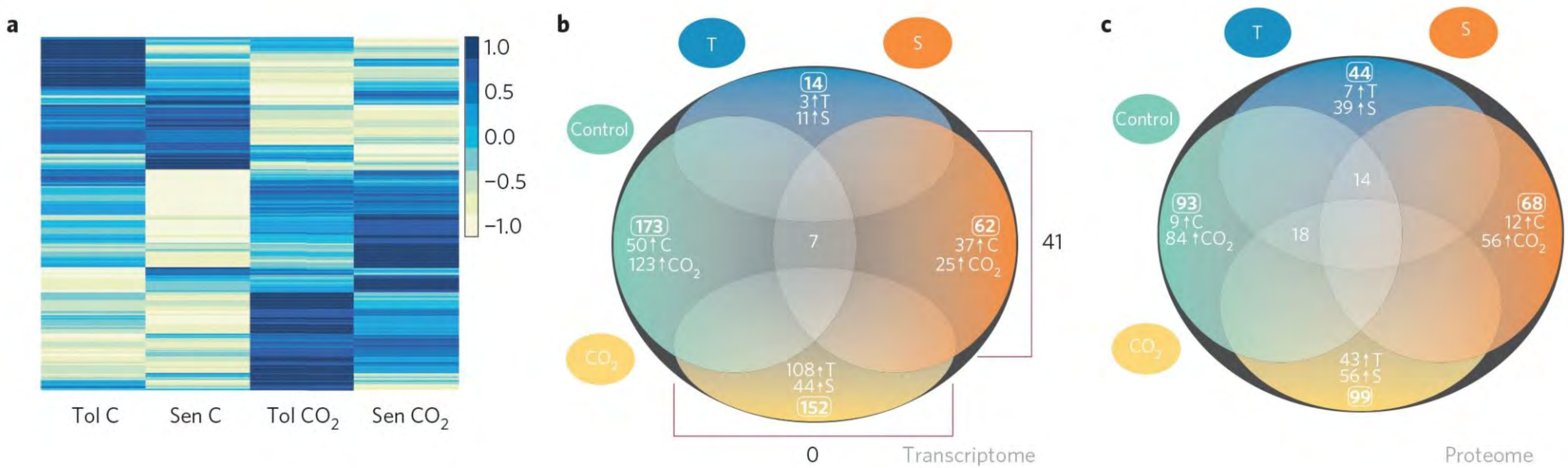
Munday et al. 2016 *Global Change Biology* doi: 10.1111/gcb.13419

Experimental molecular approaches



Experimental molecular approaches

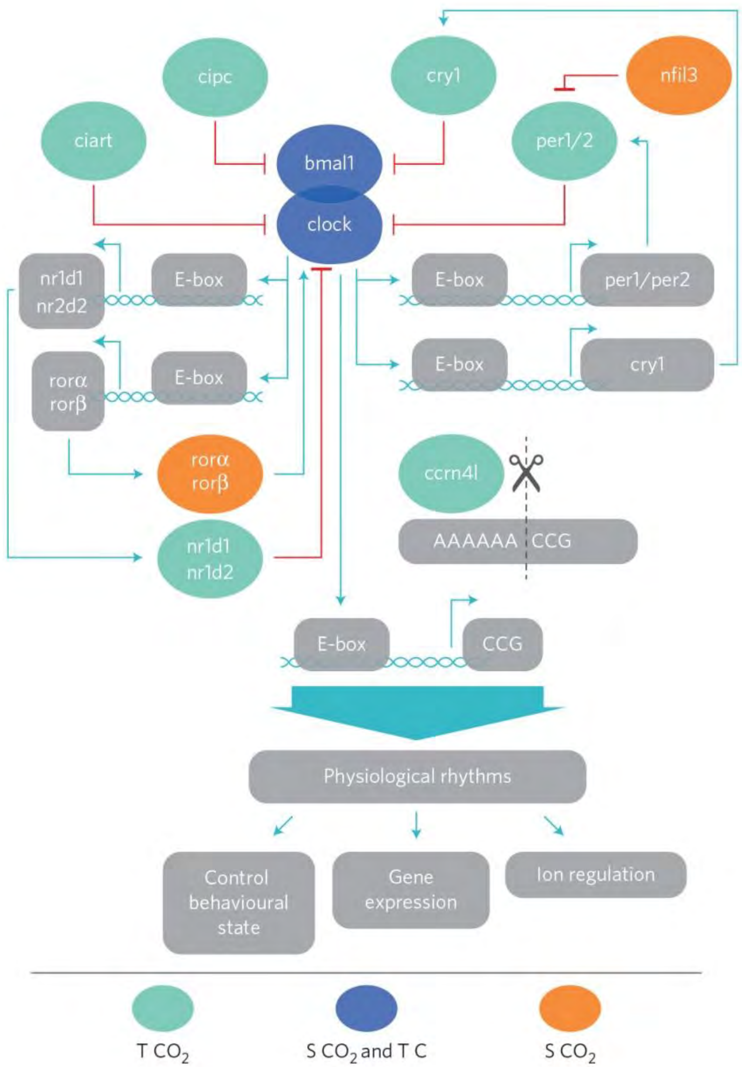
Molecular signature of parental tolerance to high CO_2



Quantitative genetics to confirm and estimate heritability

Schunter et al. 2016 *Nature Climate Change 6:1014-1018*

Experimental molecular approaches



Mechanism

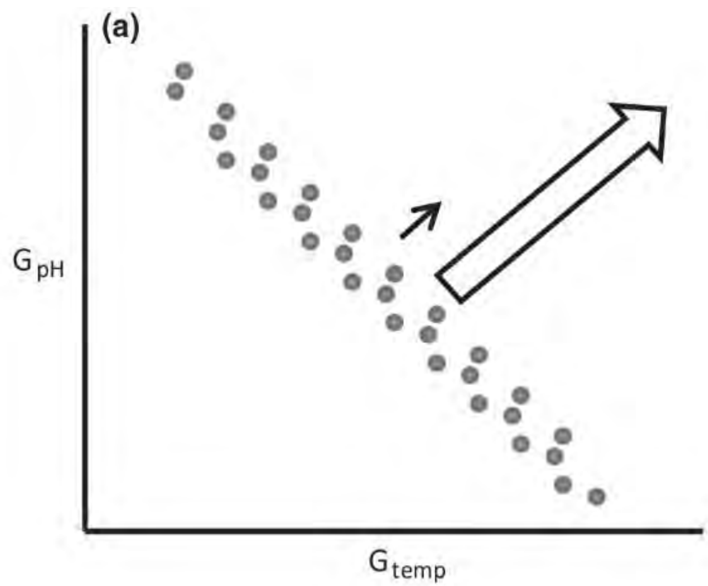
- Tolerance to high CO_2 defined by regulation of circadian rhythm
- Tolerant individuals less pronounced ion-regulation
- Less interference with neurotransmitter function

Schunter et al. 2016 *Nature Climate Change 6:1014-1018*

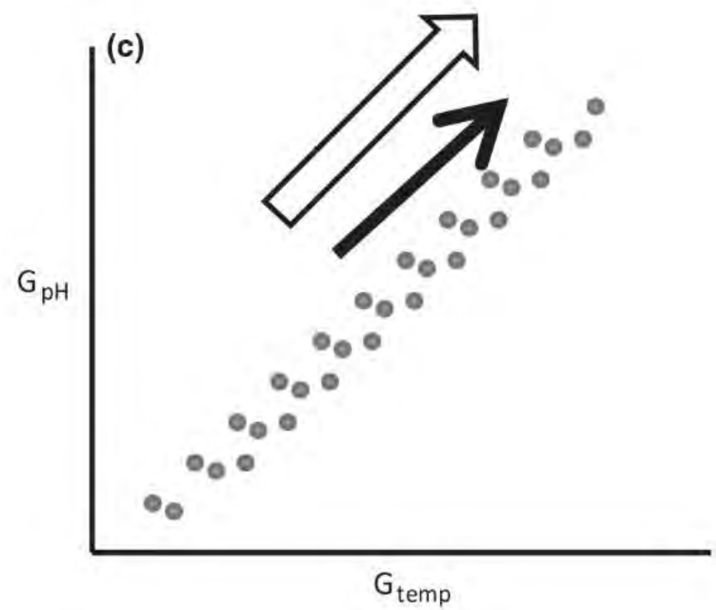
Future directions

- Genetic correlations between traits

Negative correlation:
Weak evolutionary response



Positive correlation:
Strong evolutionary response



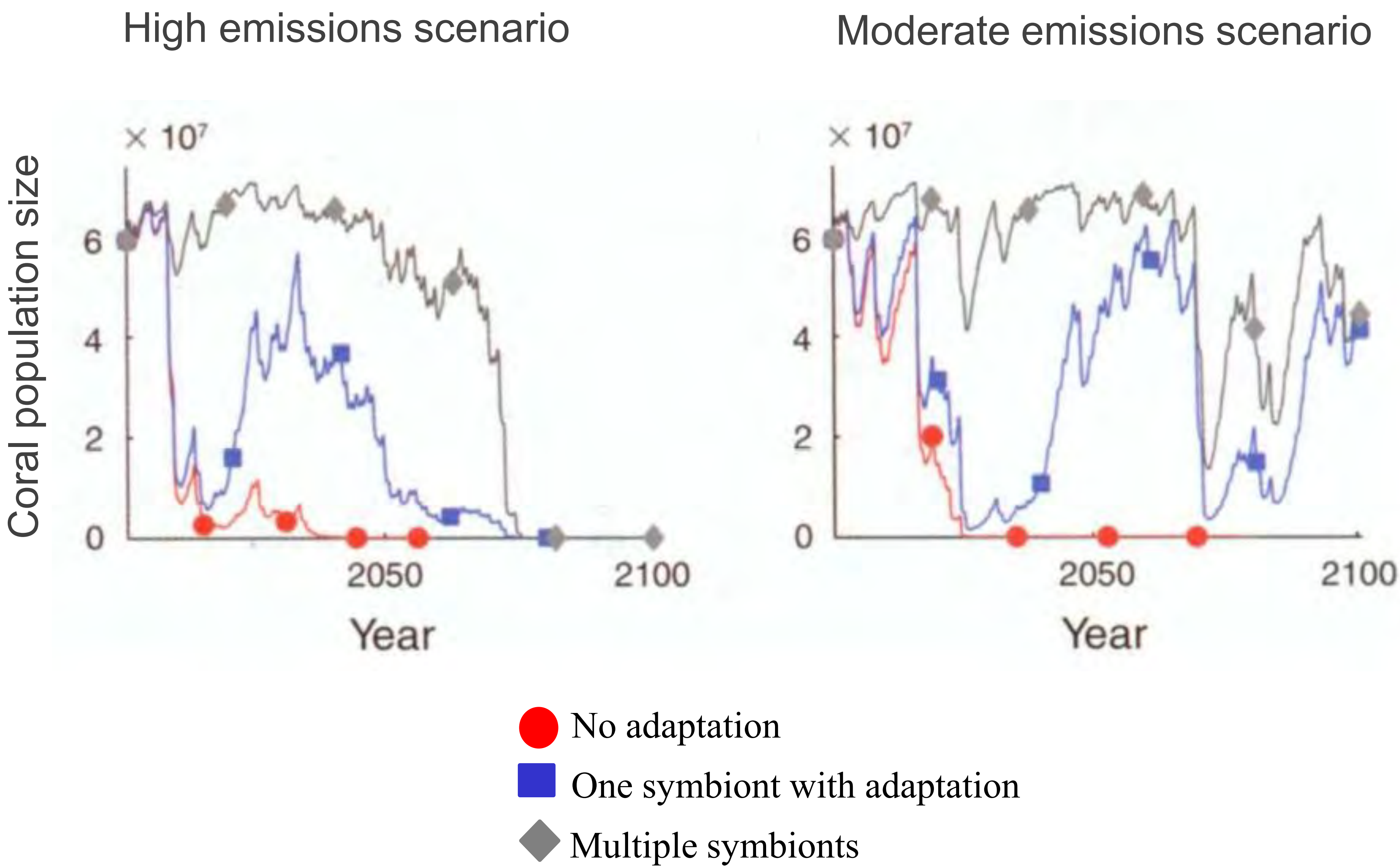
Munday et al. 2013 *Ecology Letters 16:1488-1500*

Future directions

- Genetic correlations between traits
- Understanding the interaction between plasticity and genetic adaptation
- Does plasticity affect genetic adaptation?
  - retard by shifting phenotype without selection?
  - accelerate by genetic assimilation?

Future directions

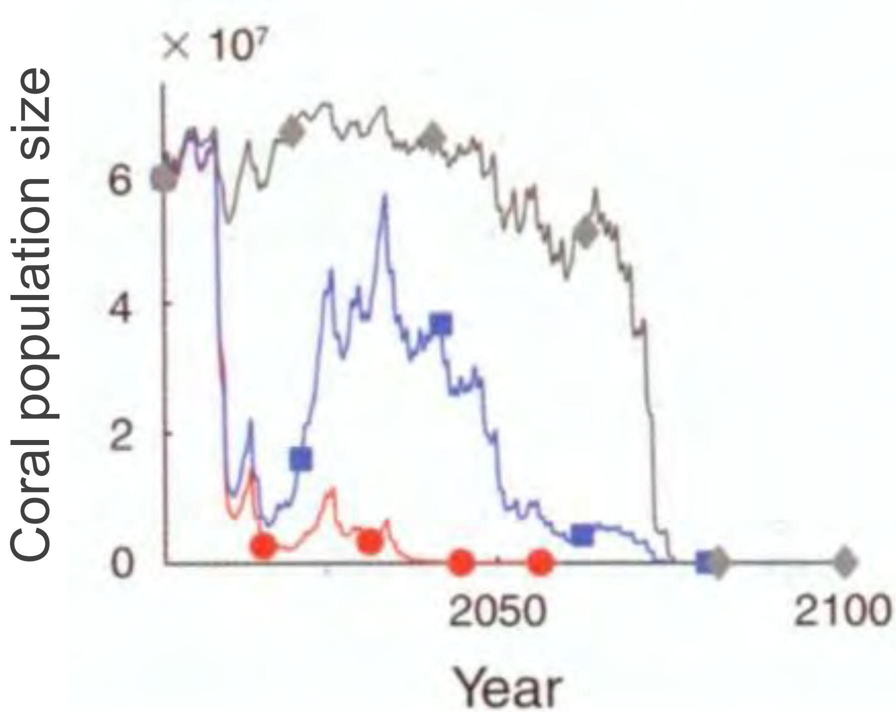
- Genetic correlations between traits
- Understanding the interaction between plasticity and genetic adaptation
- Does acclimation affect genetic adaptation?
- Include evolutionary potential in demographic models (evolutionary rescue)

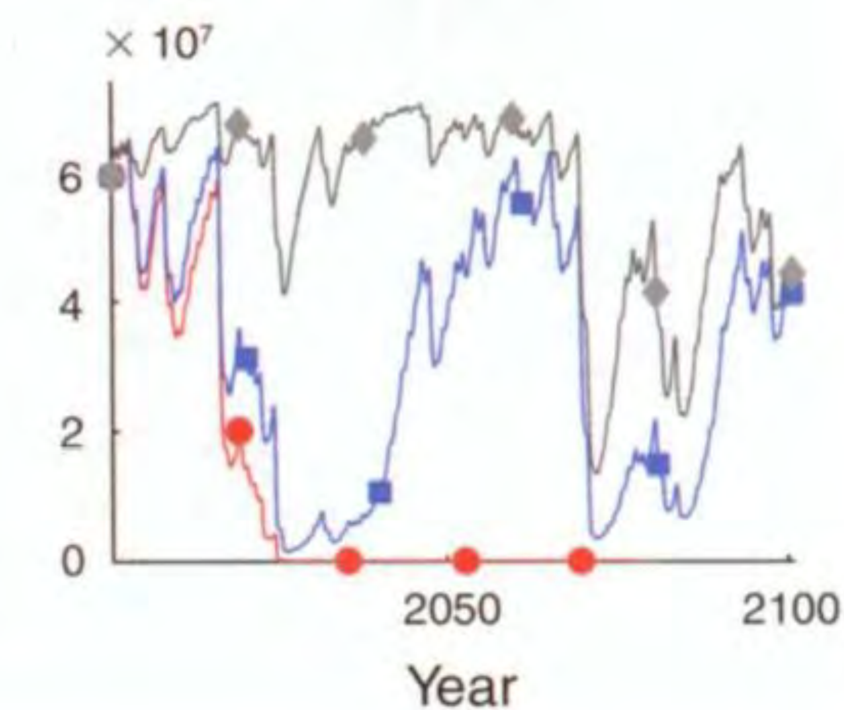


Basket et al. 2009 *Ecological Applications* 19: 3-17

High emissions scenario

Moderate emissions scenario





All populations go extinct

Adaptation and diversity promote persistence

Basket et al. 2009 *Ecological Applications* 19: 3-17

Thanks

- ARC Centre of Excellence for Coral Reef Studies
- Australian Research Council
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Jennifer Donelson

Gabrielle Miller

Megan Welch

Heather Veilleux

Celia Schunter