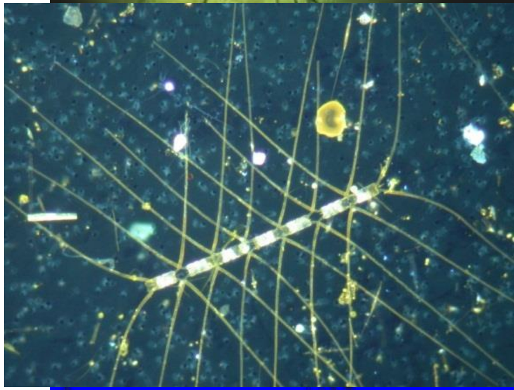
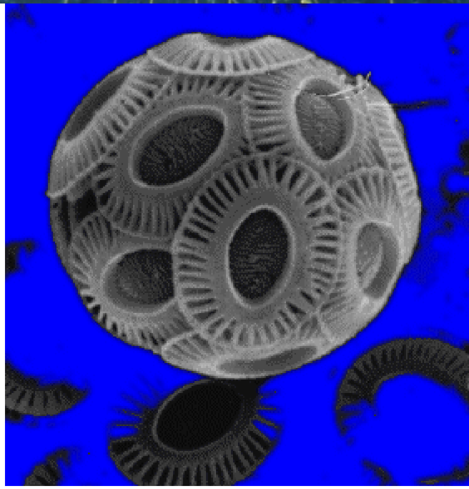
Plankton biogeochemistry in a future ocean





Philip Boyd

Institute for Marine and Antarctic Studies

OUTLINE

What will the future ocean look like?

Phytoplankton and Biogeochemistry

Environmental controls on phytoplankton

Influence of individual environmental drivers

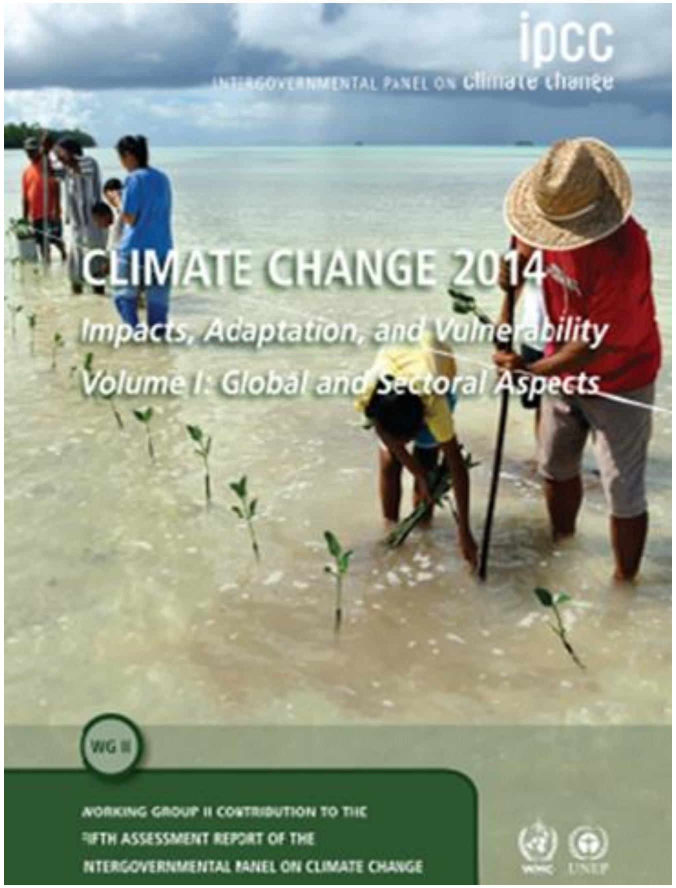
Ramifications of the interplay between individual drivers

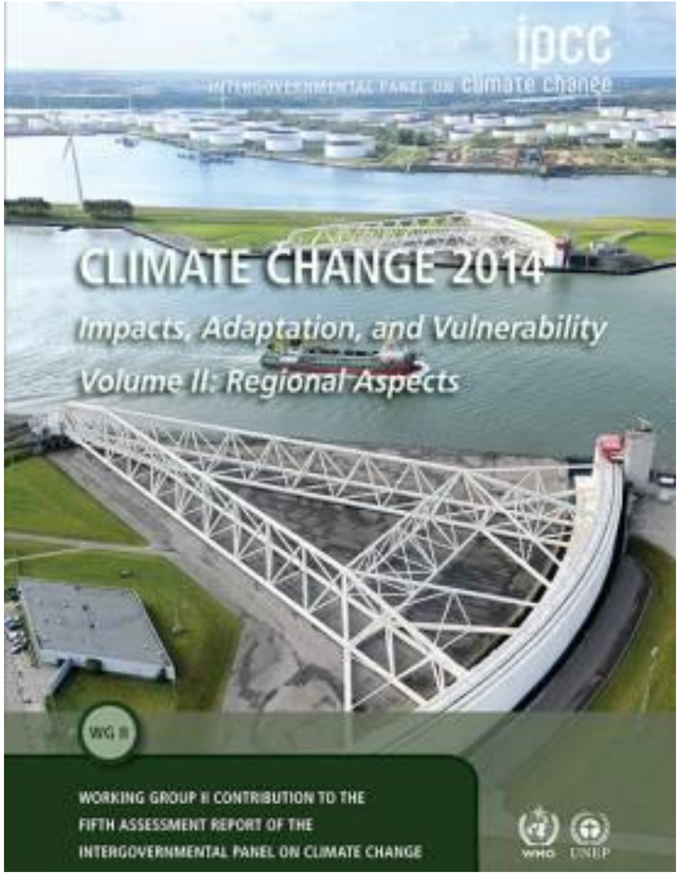
Acclimation and adaptation

Foodwebs and differential susceptibility

Methodological challenges

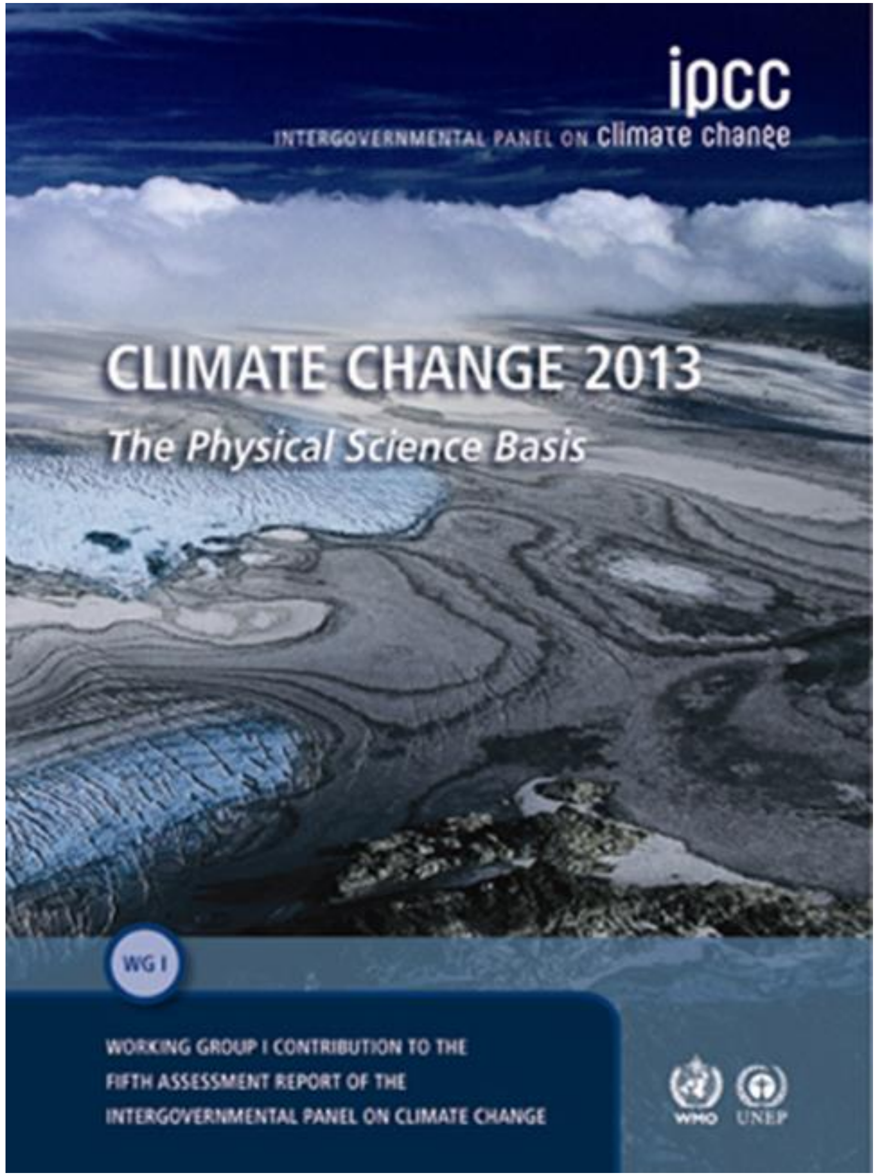
IPCC AR5 WG II released on the www in April 2014

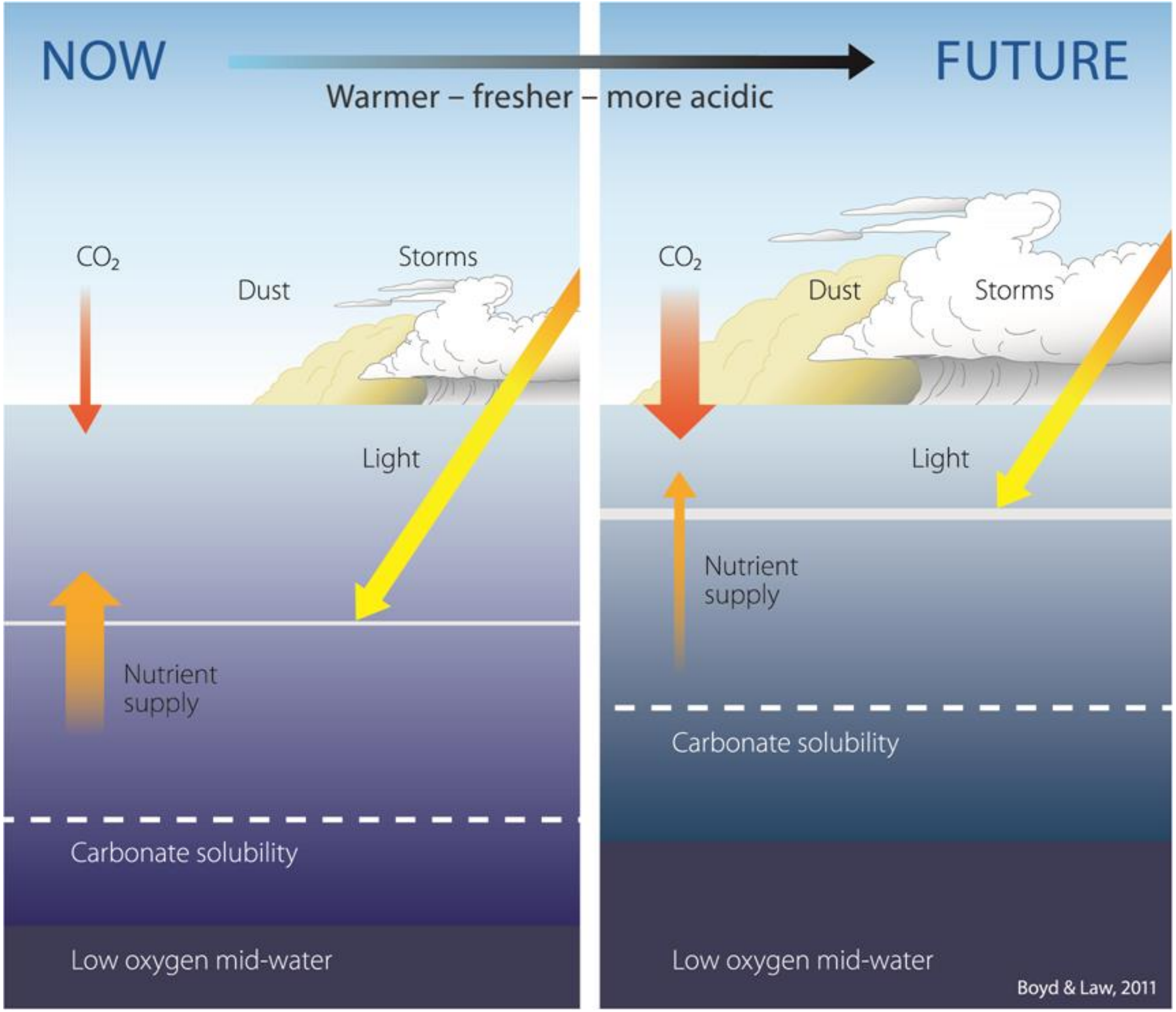




The assessed information is considered by sectors (oceans, water resources; ecosystems; food & forests; coastal systems; industry; human health) and regions (Africa; Asia; Australia & New Zealand; Europe; Latin America; North America; Polar Regions; Small Islands, oceans).

What will the future ocean look like?



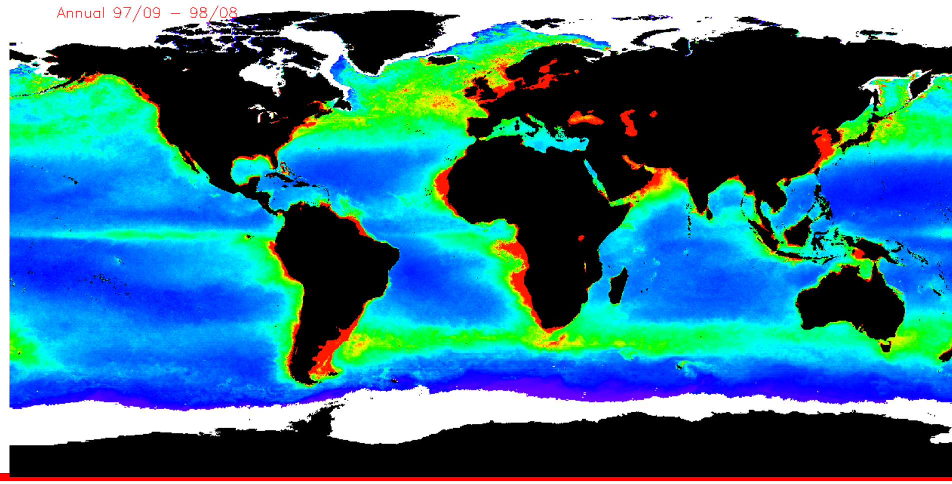


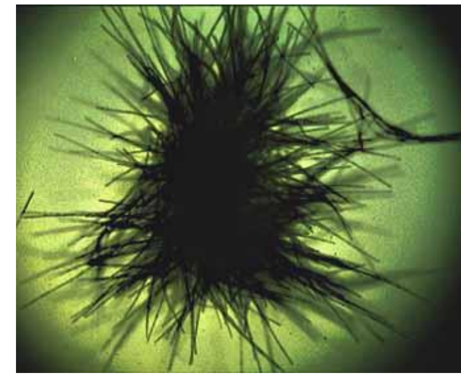
Multi-stressors - Boyd & Law 2011

The rates of change are also important Boyd et al. (2008)

Property	**Rate of change per decade (climate change)**
Temperature deg. C	+0.03 to +0.17
Salinity psu	-.014 to -.042
Mixed layer depth m	-0.3 to -0.8
Stratification kg/m^4 x 10^{-4}	+0.28 to +1.49
Surface PO_4 μmol/l	+.001 to -.004
Surface Fe nmol/l x 10^{-3}	-1.89 to -5.58
pCO_2 ppmv	+37.4 to +41.0
Light climate (mixed layer)	0.003 to 0.005 W/m2
Ice fraction	-.003 to -.013

Interactions between climate, phytoplankton, ecosystems and ocean biogeochemistry





CHANGING CLIMATE

Altered upper ocean properties

BIODIVERSITY
BIOGEOGRAPHY
PHYSIOLOGY

ECOSYSTEMS
Cycling of organic matter

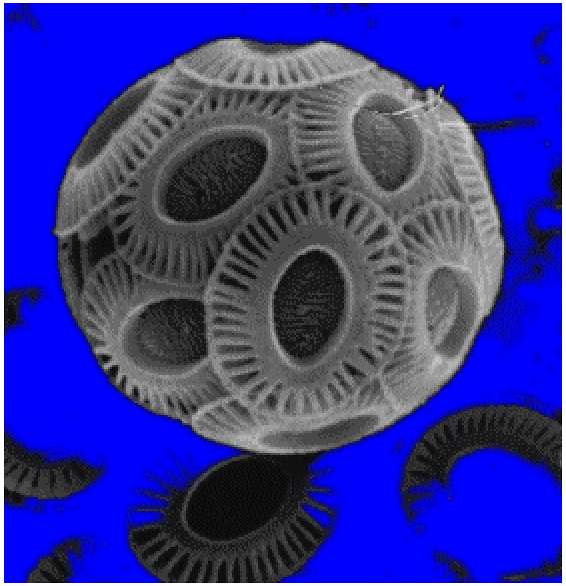
BIOGEOCHEMISTRY
Elemental fluxes

Modified from Legendre and Rivkin (2005)

Different bloom-formers impact a range of oceanic biogeochemical cycles

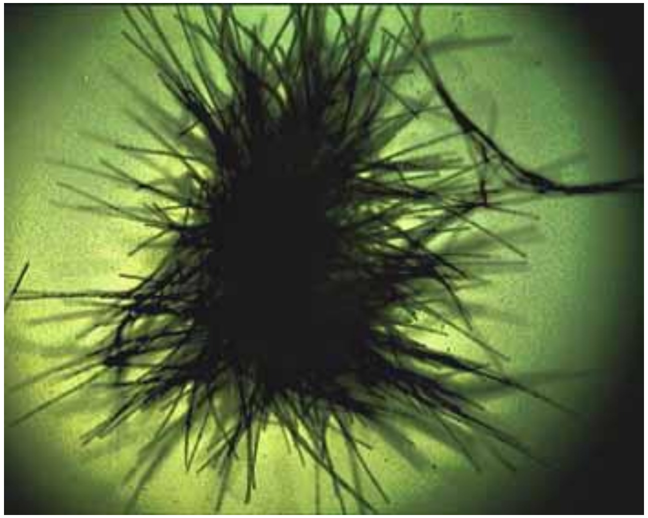
(C, Fe, N)

Diatoms



(C, S)

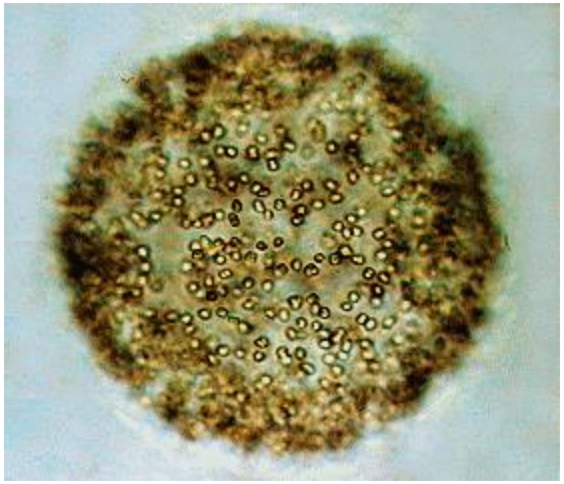
Coccolithophores



(Fe, N ,P)

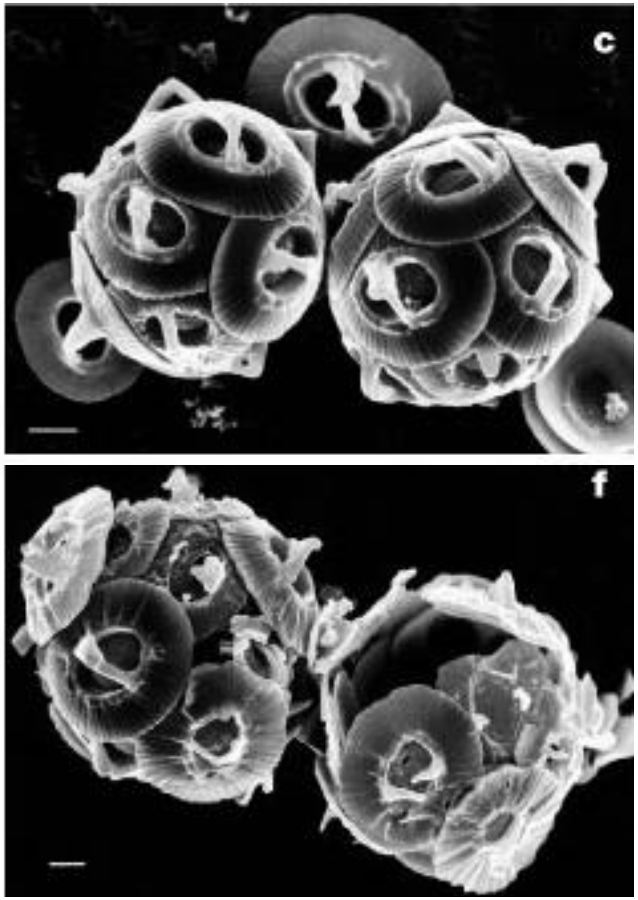
N-fixers *Trichodesmium*

(S, C, P)

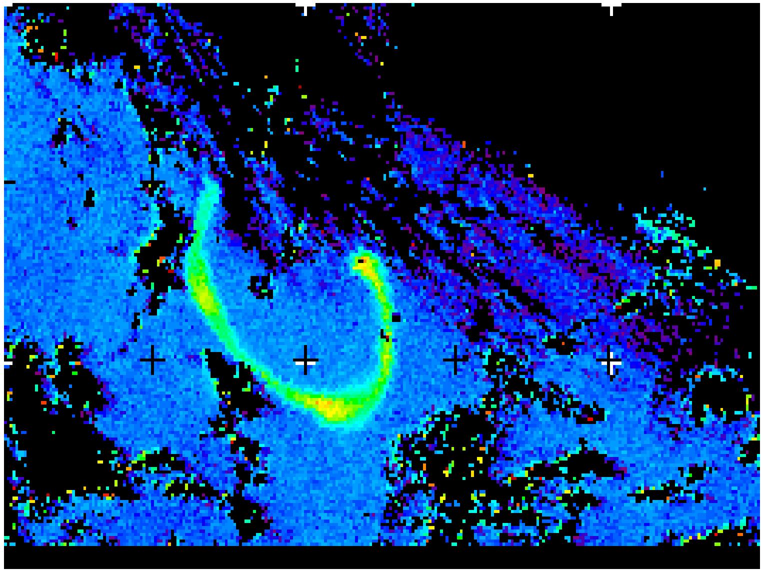


Phaeocystis

Environmental controls on phytoplankton

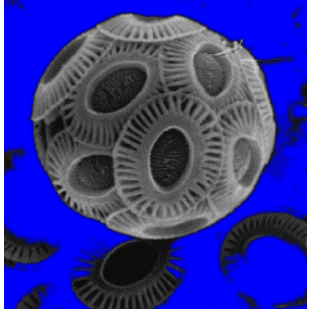


Riebesell et al. (2000)



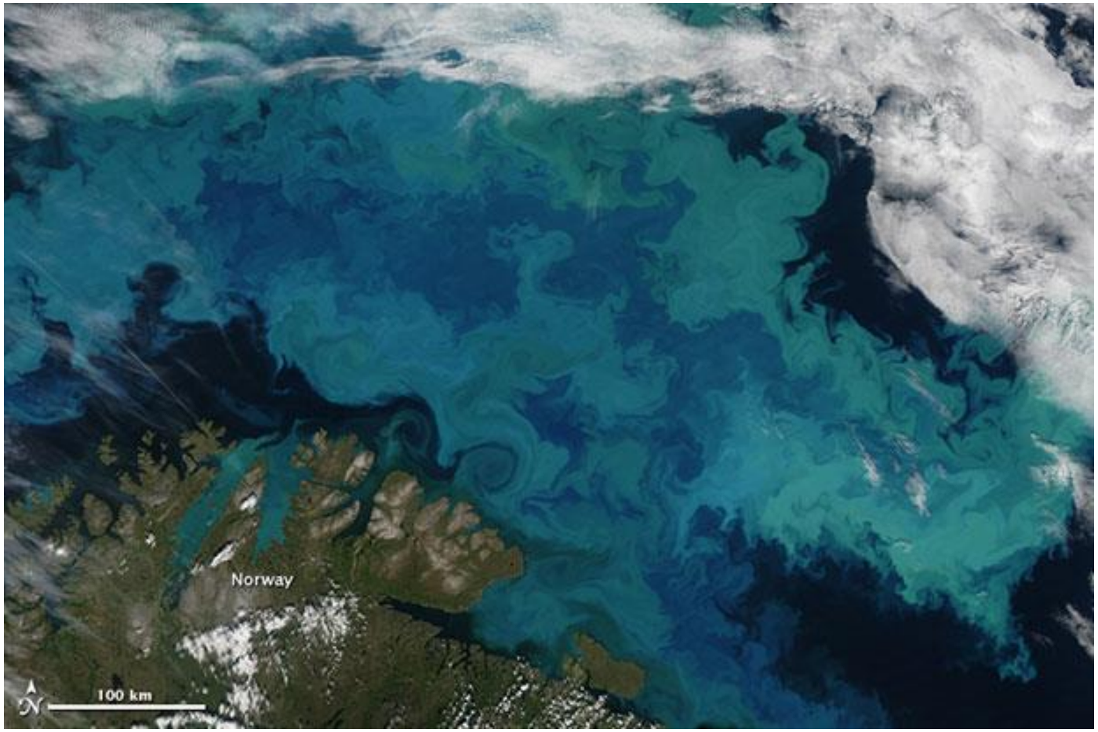
Boyd et al. (2000)

Ocean time-series observations also point to environmental drivers on oceanic biota

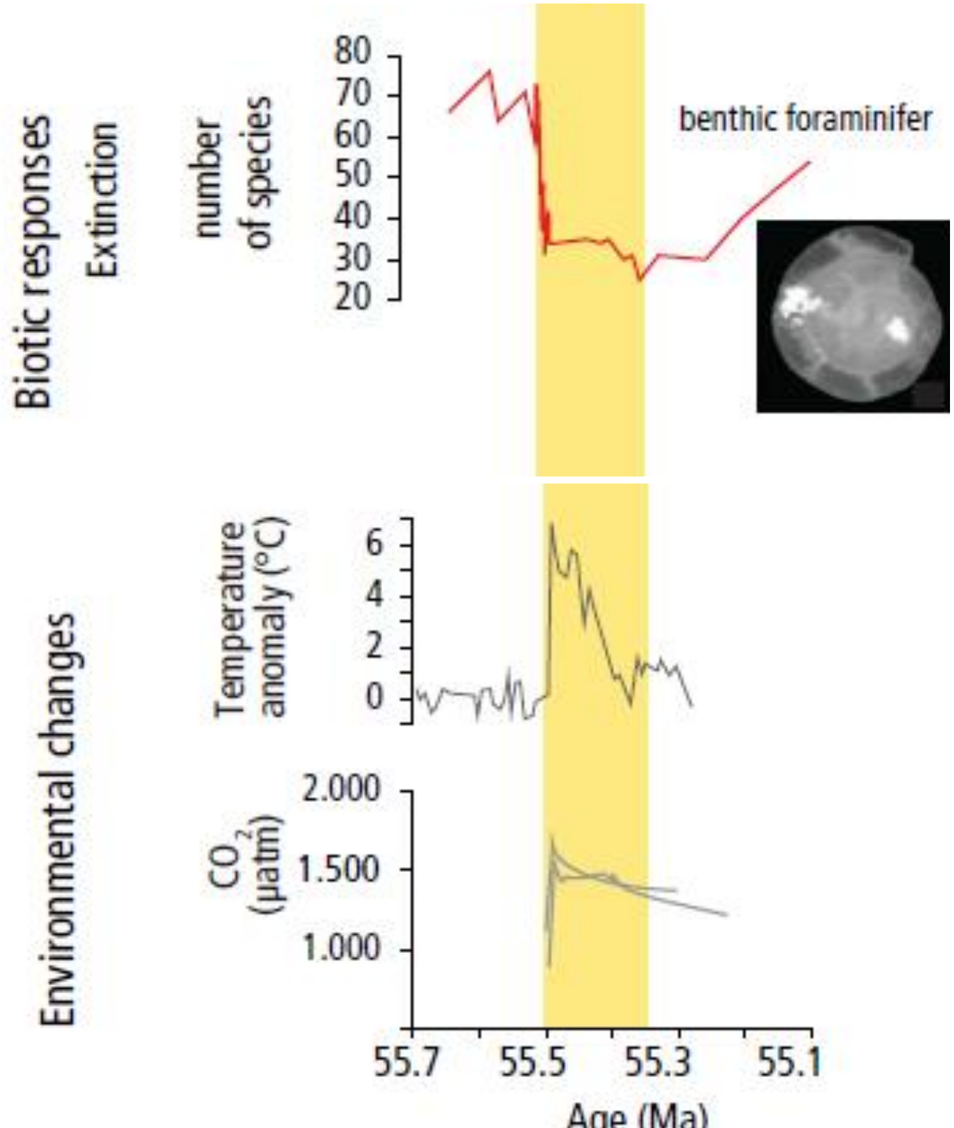


Increases in spatial extent of coccolithophores in Bering
& Barents Sea linked to warming and stratification (Smyth et al, 2004).

Likewise for Subantarctic waters (Cubillos et al. 2009)



The fossil record and present field and laboratory observations confirm links between key environmental drivers and responses of ocean ecosystems to climate change (*high confidence*). For millions of years in Earth history, natural climate change at rates slower than today's anthropogenic change has led to significant ecosystem shifts (*high confidence*), including species emergences and extinctions (*high confidence*). Contemporary multidecadal natural climate variations associated with regional transient warming periods by 1°C have led to fundamental restructuring of ecosystems and large socioeconomic implications (*high confidence*). [6.1.2, 6.3.1, 6.4]



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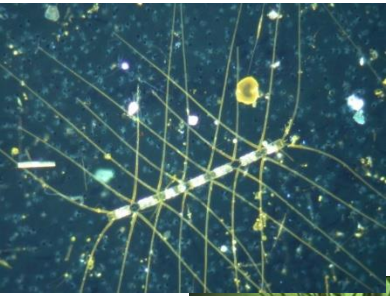
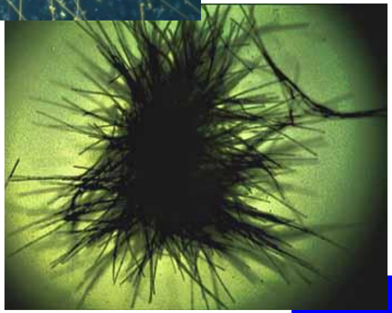
Report card of our understanding of environmental controls on phytoplankton groups



8

Conceptual framework in place – but issues with groups (Strzepek & Harrison, Marchetti et al.) – let alone species



3

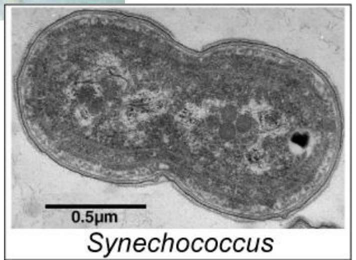
No general consensus, preoccupation with Tricho? Control of other diazotroph groups, life-cycle issue

4

No general consensus, preoccupation with E. hux. Large differences in responses of other coccos to perturbation

6

Framework in place – but cues to drive life cycle are missing



9

Lab results & field observations agree. Role of nitrate and TM's

From Boyd et al. (2010)

Can we formulate a ranking order of environmental controls on different algal groups?

Algal group	Temperature	PAR	Nitrogen	Phosphorus	Silicon	Iron	CO_2
Diatoms	?[a]	4[be]	1[c]	n.s.	3[d]	2[abcde]	5[e]
Phaeocystis antarctica	?	1[f]	n.s.	n.s.	n.s.	2[f]	3
Coccolithophores	1[g]	2 ?	3 ?[h]	3 ?[h]	n.s.	n.s.	4 ?[g]
N_2 fixers	1	2[i]	n.s.	3[jk]	n.s.	3[ikl]	?[jl]
Picocyanobacteria ***Prochlorococcus***	1	1	2[m]	n.s.	n.s.	?[o]	?
Synechococcus	3[n] ?	1 ?	2 ?	2 ?	n.s.	?[o]	4 ?[n]

(Boyd et al. 2010)

Limnol. Oceanogr., 55(3), 2010, 1353–1376

doi:10.4319/lo.2010.55.3.1353

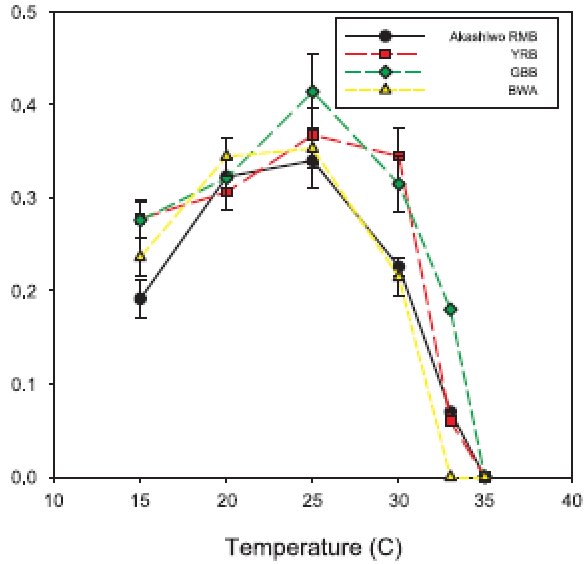
Environmental control of open-ocean phytoplankton groups: Now and in the future

Philip W. Boyd,[a,*] Robert Strzepek,[b] Feixue Fu,[c] and David A. Hutchins[c]

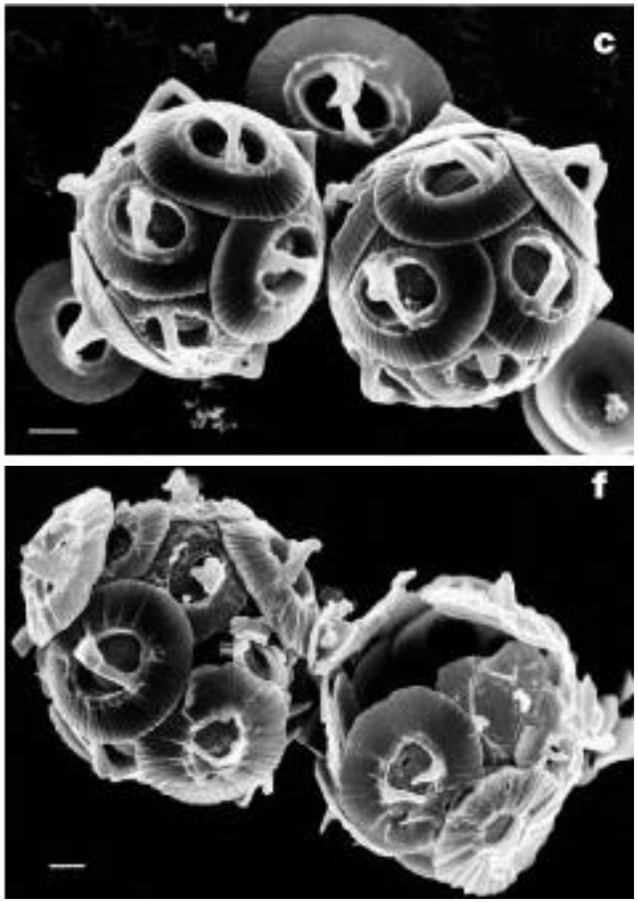
Algal group	Temperature	PAR	Nitrogen	Phosphorus	Silicon	Iron	CO_2
Diatoms	?[a]	4[bc]	1[d]	n.s.	3[e]	2[abcde]	5[c]
Phaeocystis antarctica	?	1[f]	n.s.	n.s.	n.s.	2[f]	3
Coccolithophores	1[g]	2 ?	3 ?[h]	3 ?[h]	n.s.	n.s.	4 ?[g]
N_2 fixers	1	2[i]	n.s.	3[jk]	n.s.	3[ikl]	?[jl]
Picocyanobacteria							
Prochlorococcus	1	1	2[m]	n.s.	n.s.	?[n]	?
Synechococcus	3[o] ?	1 ?	2 ?	2 ?	n.s.	?[n]	4 ?[o]

[a] Temperature and iron have been shown to have marked synergisms on diatom abundance in the Ross Sea (Fig. 1C; Rose et al. 2009).
[b] Numerous laboratory and field studies have demonstrated co-limitation of diatoms by light and iron (Sunda and Huntsman 1998; Maldonado et al. 1999; Fig. 5).
[c] CO_2, light, and iron have a three-way interactive effect on diatom community structure in the Ross Sea (Feng et al. 2010).
[d] Nitrogen and iron are also potentially co-limiting for diatoms (Price et al. 1991; DiTullio et al. 1993).
[e] Silicon and iron requirements are antagonistic in diatoms (Hutchins and Bruland 1998).
[f] Light and iron have synergistic effects on the abundance of colonial *Phaeocystis antarctica* (Fig. 1D; Feng et al. 2010).
[g] Coccolithophore abundance in the North Atlantic spring bloom is synergistically affected by both temperature and CO_2 (Fig. 3C; Feng et al. 2009). In general, such interactions between multiple variables may be especially important for this group, making a hierarchical ranking especially problematic for coccolithophores (uncertainties indicated by the question marks after each number).
[h] The ratio of nitrogen to phosphorus has been suggested to be a significant control on coccolithophore blooms (Tyrrell and Taylor 1996).
[i] The high iron and light requirements of nitrogen fixers may make them especially vulnerable to iron and light co-limitation.
[j] Co-limitation of *Trichodesmium* by phosphorus and CO_2 has been reported (Hutchins et al. 2007).
[k] Iron and phosphorus co-limitation of N_2 fixation has been demonstrated in the North Atlantic (Mills et al. 2004).
[l] Iron limitation has an antagonistic effect on stimulation of *Crocosphaera* by increasing CO_2 (Fig. 3A,B; Fu et al. 2008).
[m] Some strains of *Prochlorococcus* cannot use nitrate and so must rely on reduced nitrogen sources, including ammonium and nitrite (Rocap et al. 2003).
[n] Picocyanobacterial stocks have exhibited transient increases following iron supply during mesoscale iron enrichments in polar, subpolar, and tropical HNLC waters (Boyd et al. 2005).
[o] CO_2 and temperature synergisms have been reported for *Synechococcus* (Fu et al. 2007).

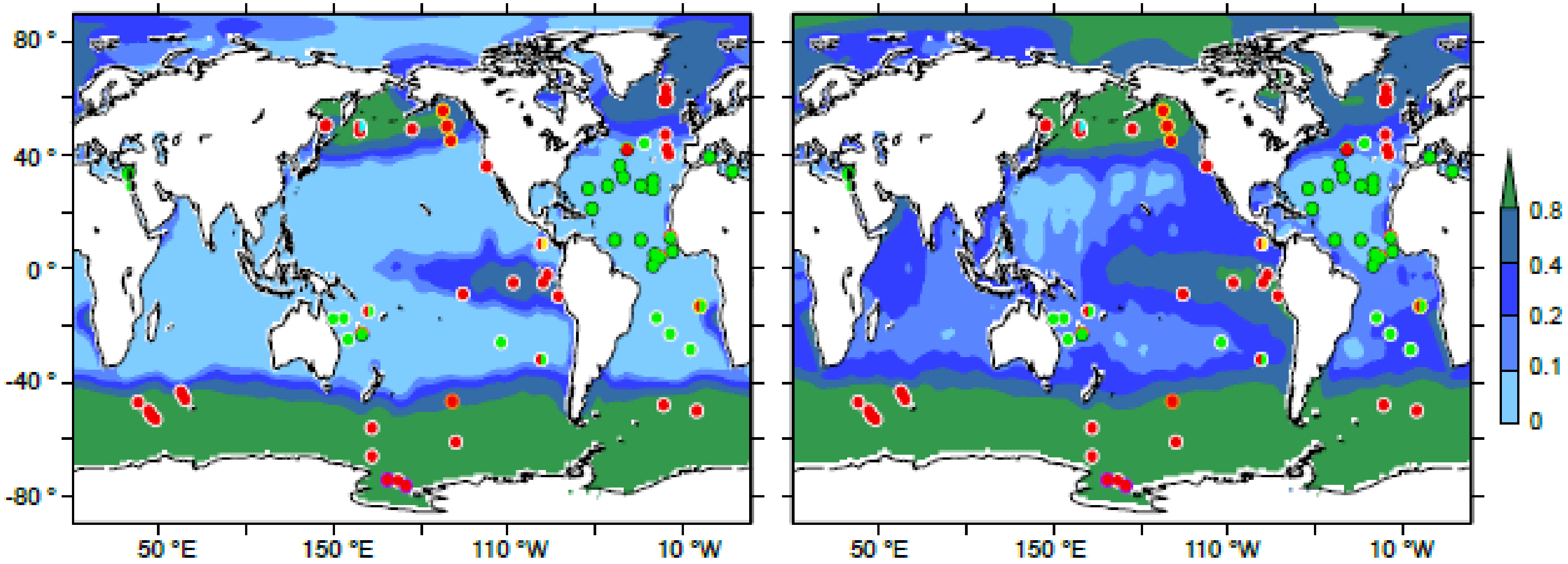
Influence of individual environmental drivers



Boyd et al. 2013

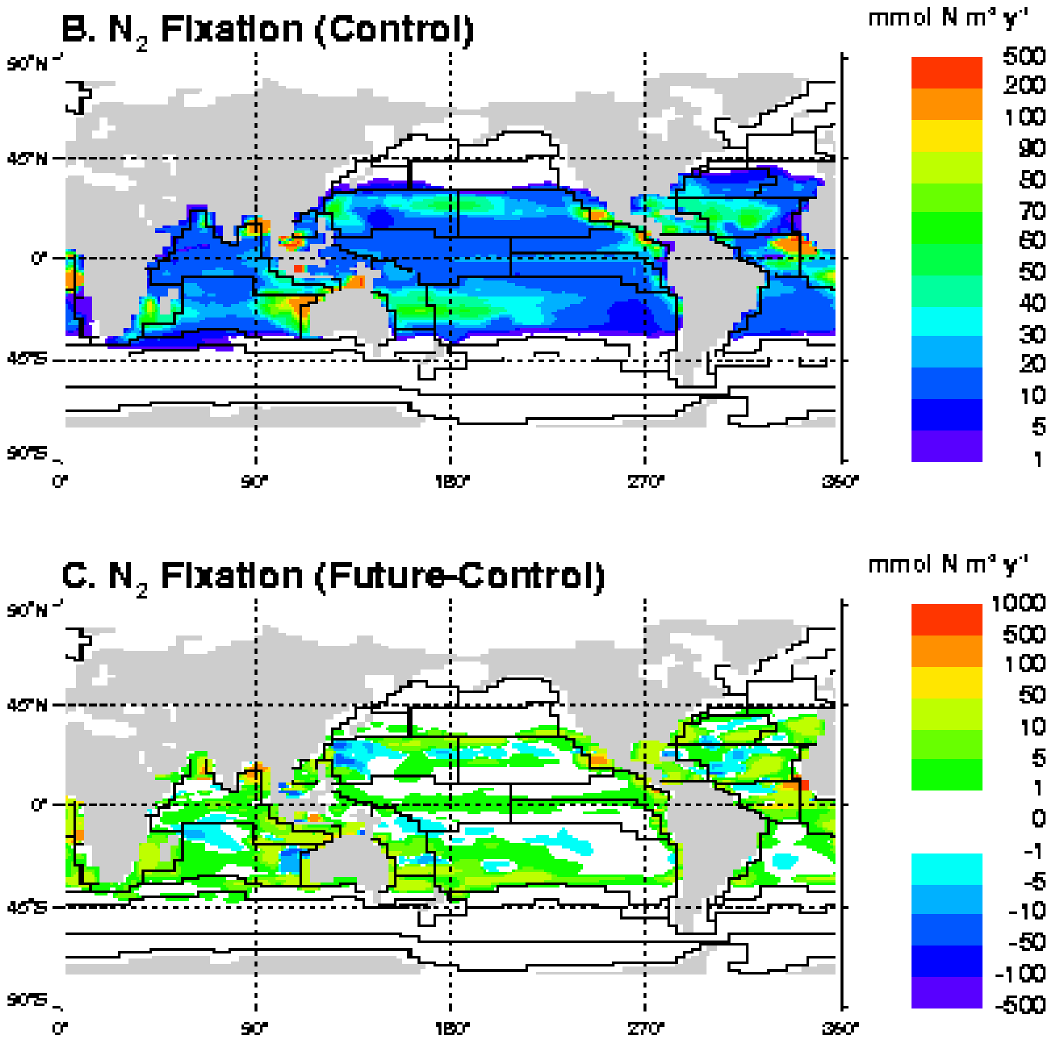


Riebesell et al. 2000



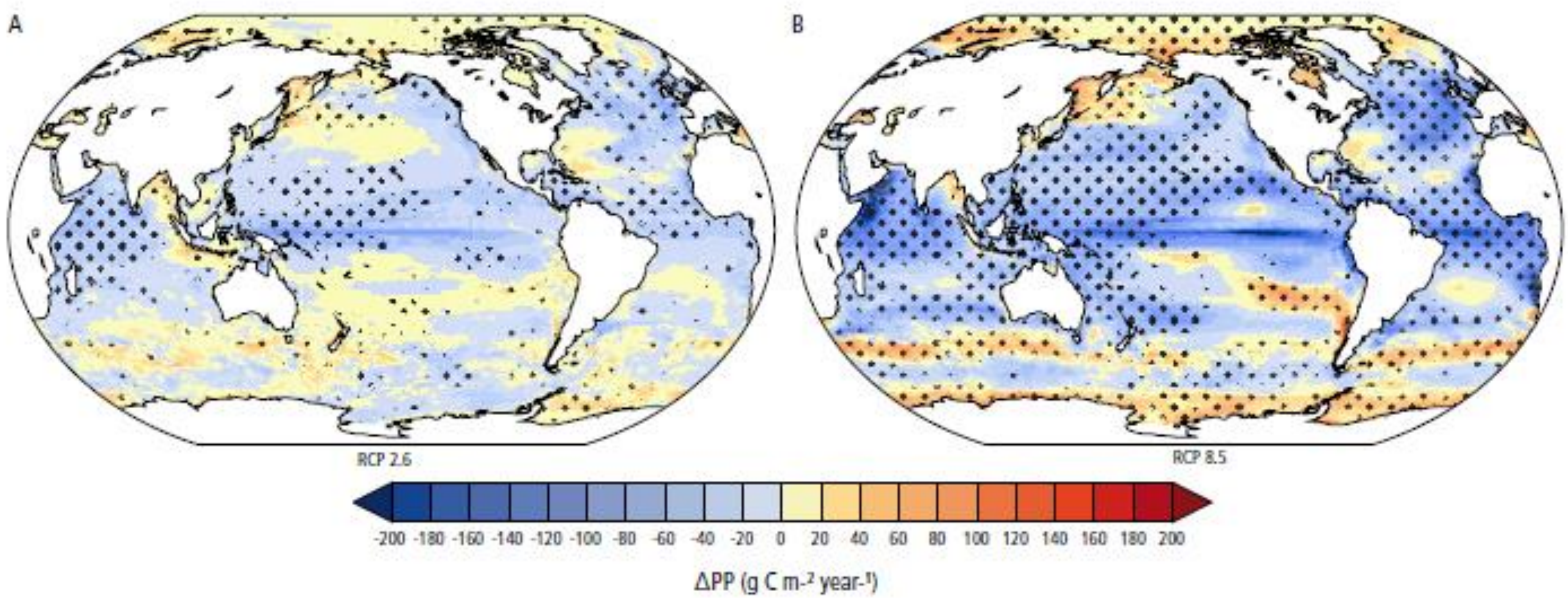
Moore et al. (2013)

Influence of environmental drivers can be explored in models



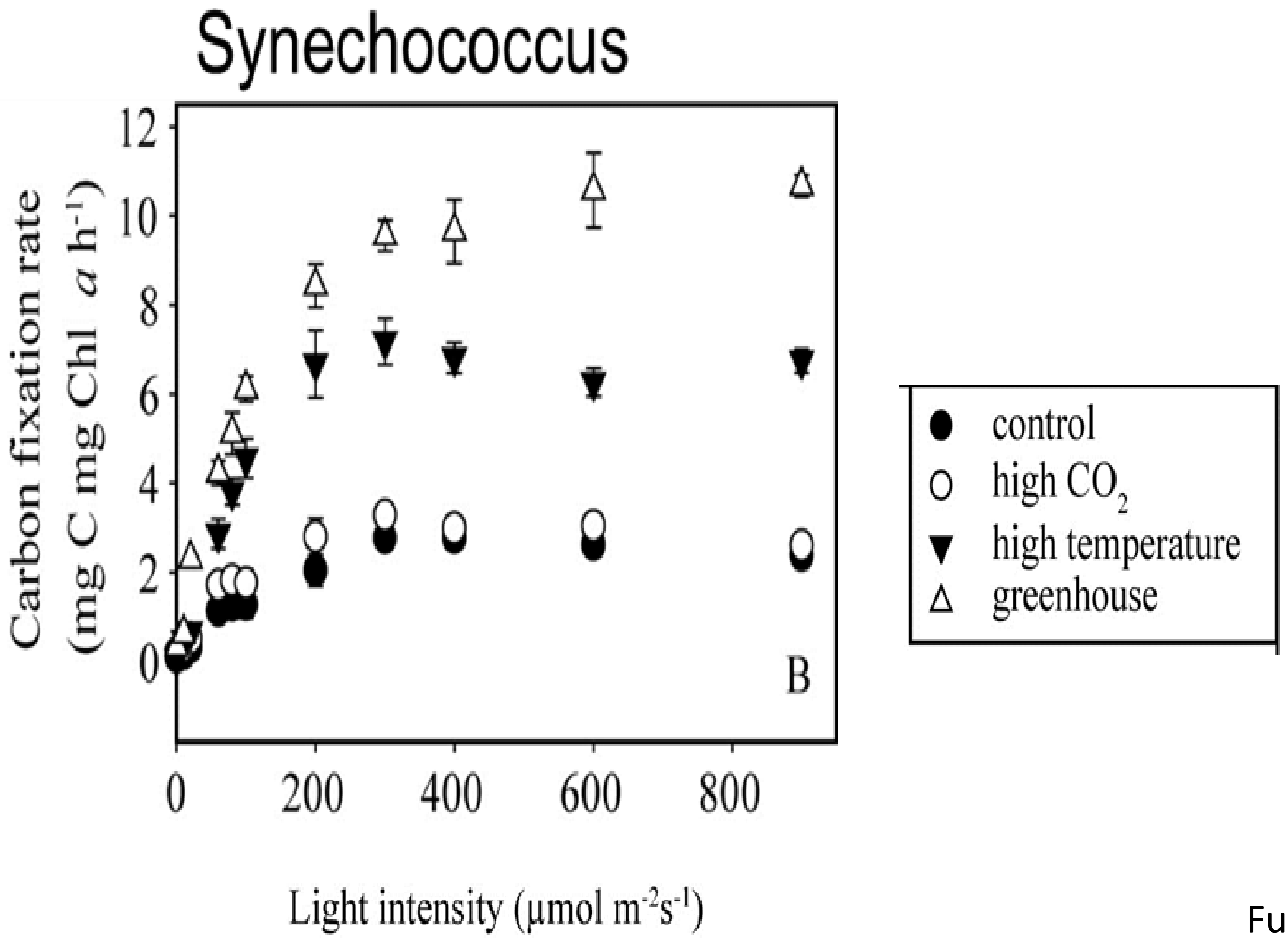
Boyd & Doney (2002)

Towards consensus in biological modelling

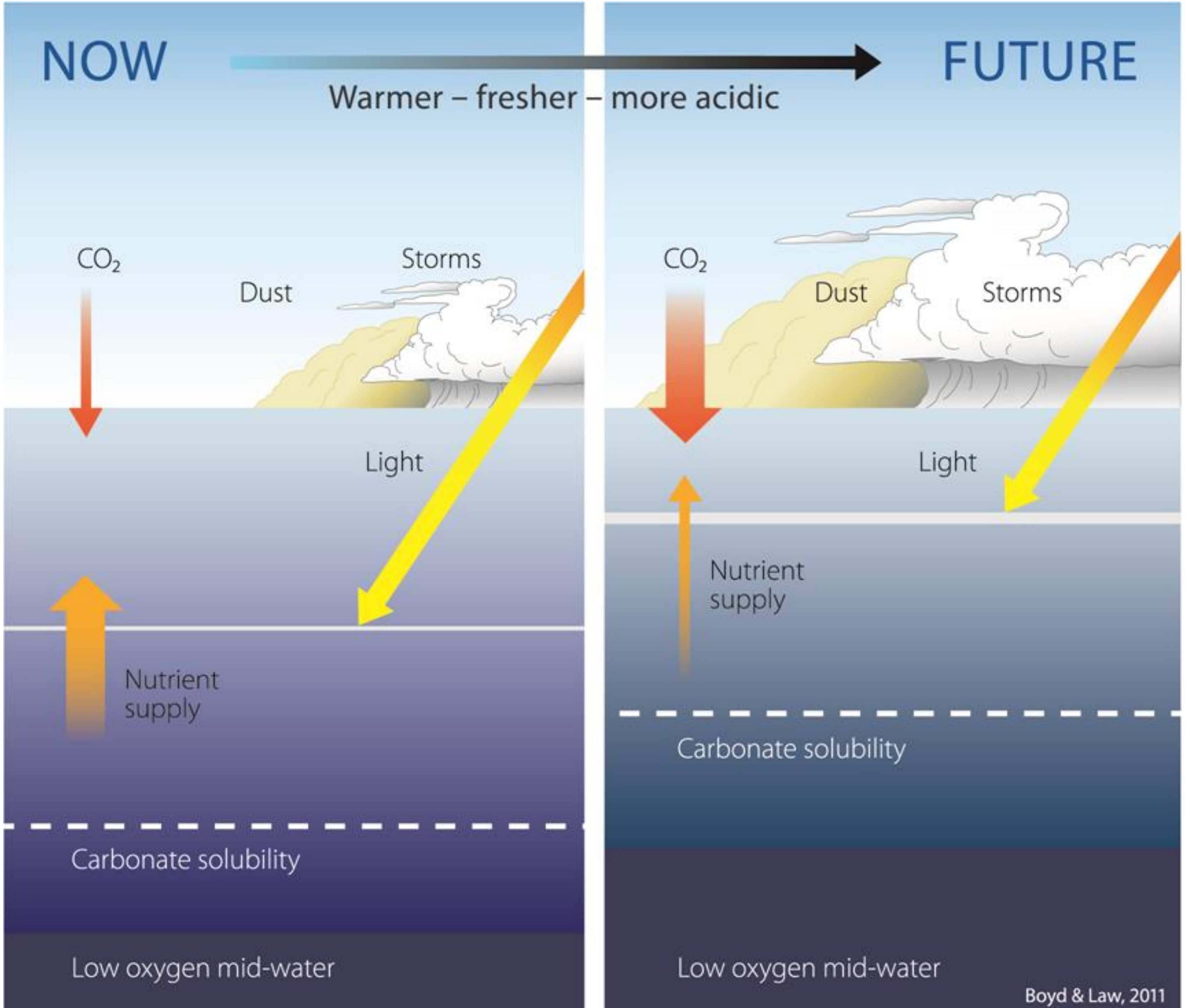


IPCC 2014 – from Bopp et al. (2013)

Ramifications of the interplay between individual drivers



Fu et al. (2007)



Multi-stressors

Clusters of environmental change

Property	(a) Seasonal	(b) la Niňa climate variability	(c) SAM climate variability	(d) Future climate change
Temperature	↑	↓	↓	↑
Iron	↓	↑	↑ ?	?
Nutrients	↓	↑	↑	↓
Mixed layer depth	↓	↑	↑	↓
CO_2	↓	↑	↑	↑
Incident irradiance	↑	NC	NC	?

Boyd et al. 2010

Clusters of environmental properties

An unprecedented suite of permutations

Seasonal progression

Temp	↑
Fe	↓
Nuts	↓
MLD	↑
CO2	↓
PAR	↑

Variability (ENSO)

Temp	↓
Fe	↑
Nuts	↑
MLD	↑
CO2	↑
PAR	NC

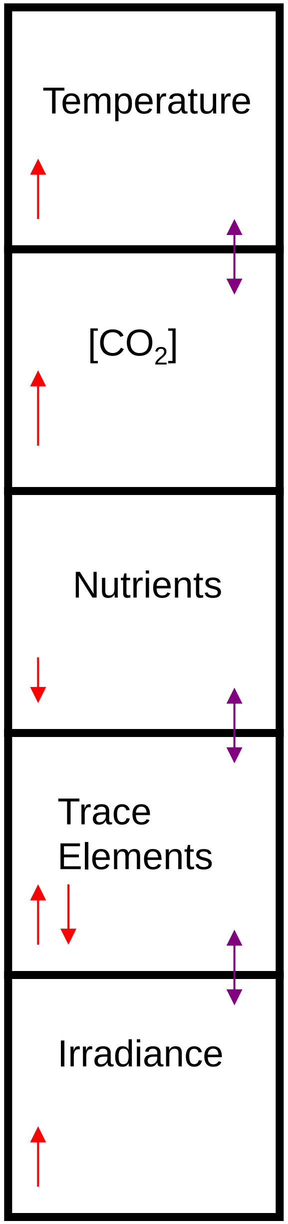
Climate Change

Temp	↑
Fe	↓
Nuts	↓
MLD	↑
CO2	↑
PAR	??

Boyd et al. (2010)

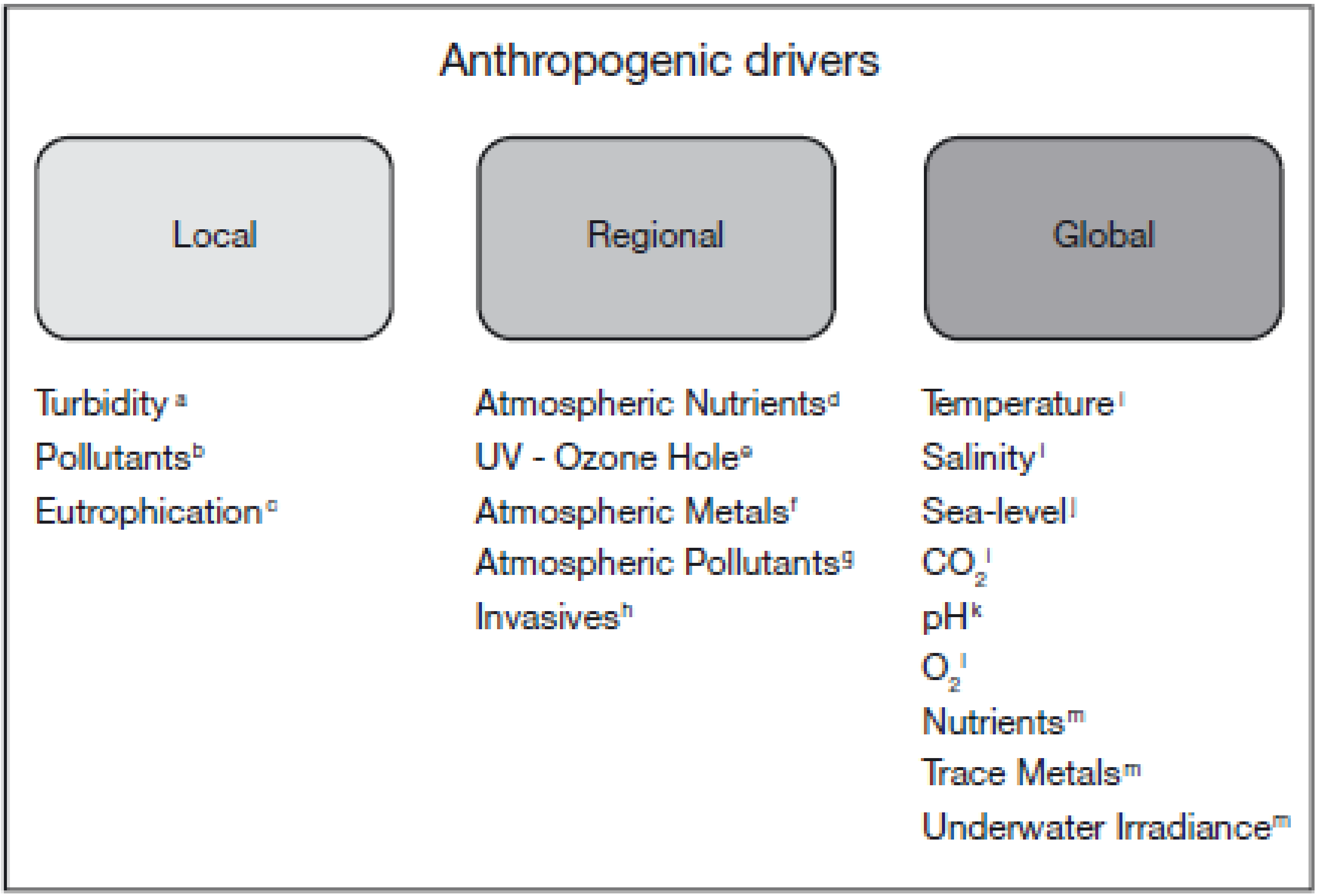
Climate Change
Environmental Clusters

Are further confounded
By interactive effects



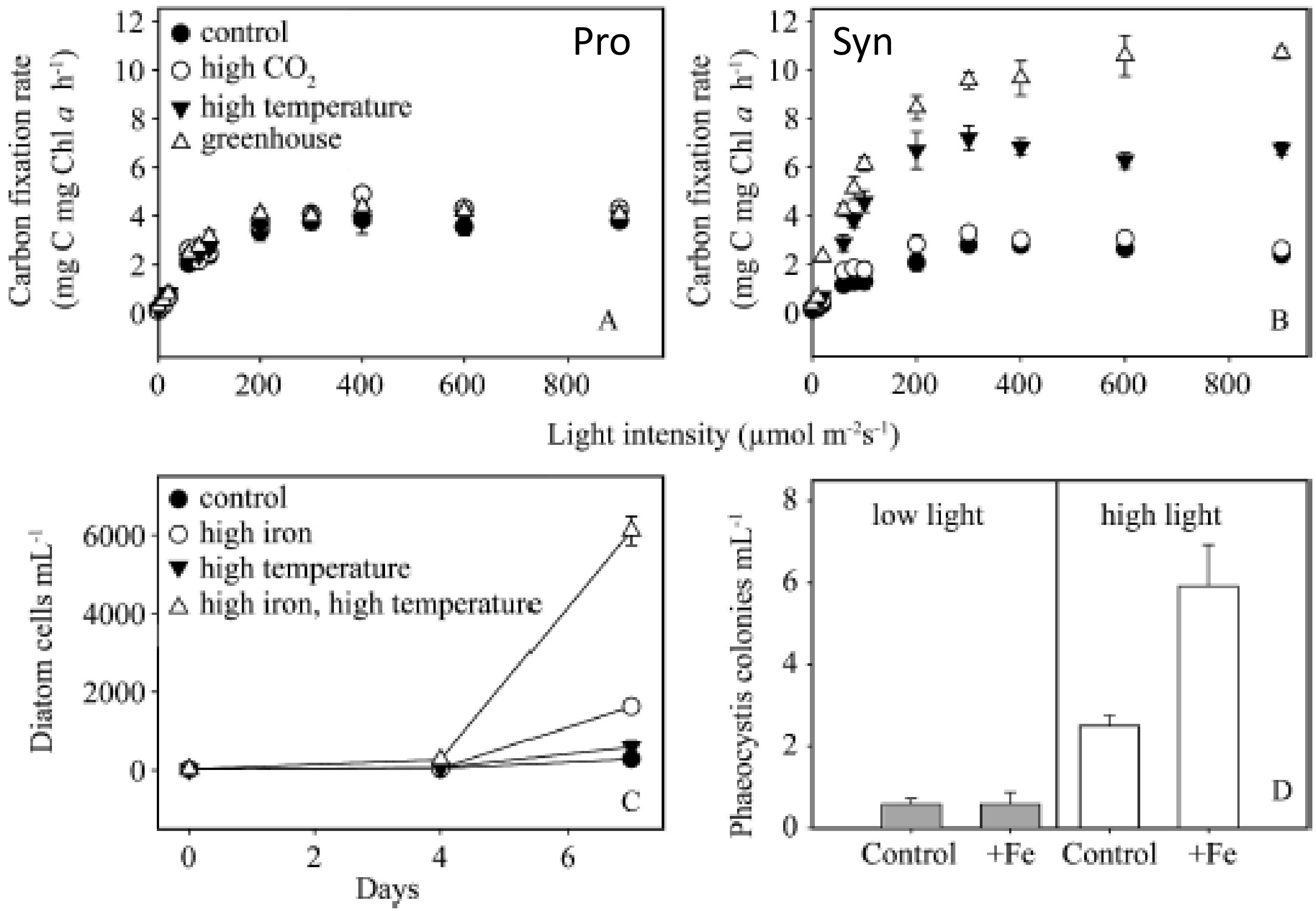
Boyd & Hutchins
2012

A complex matrix of cumulative anthropogenic change



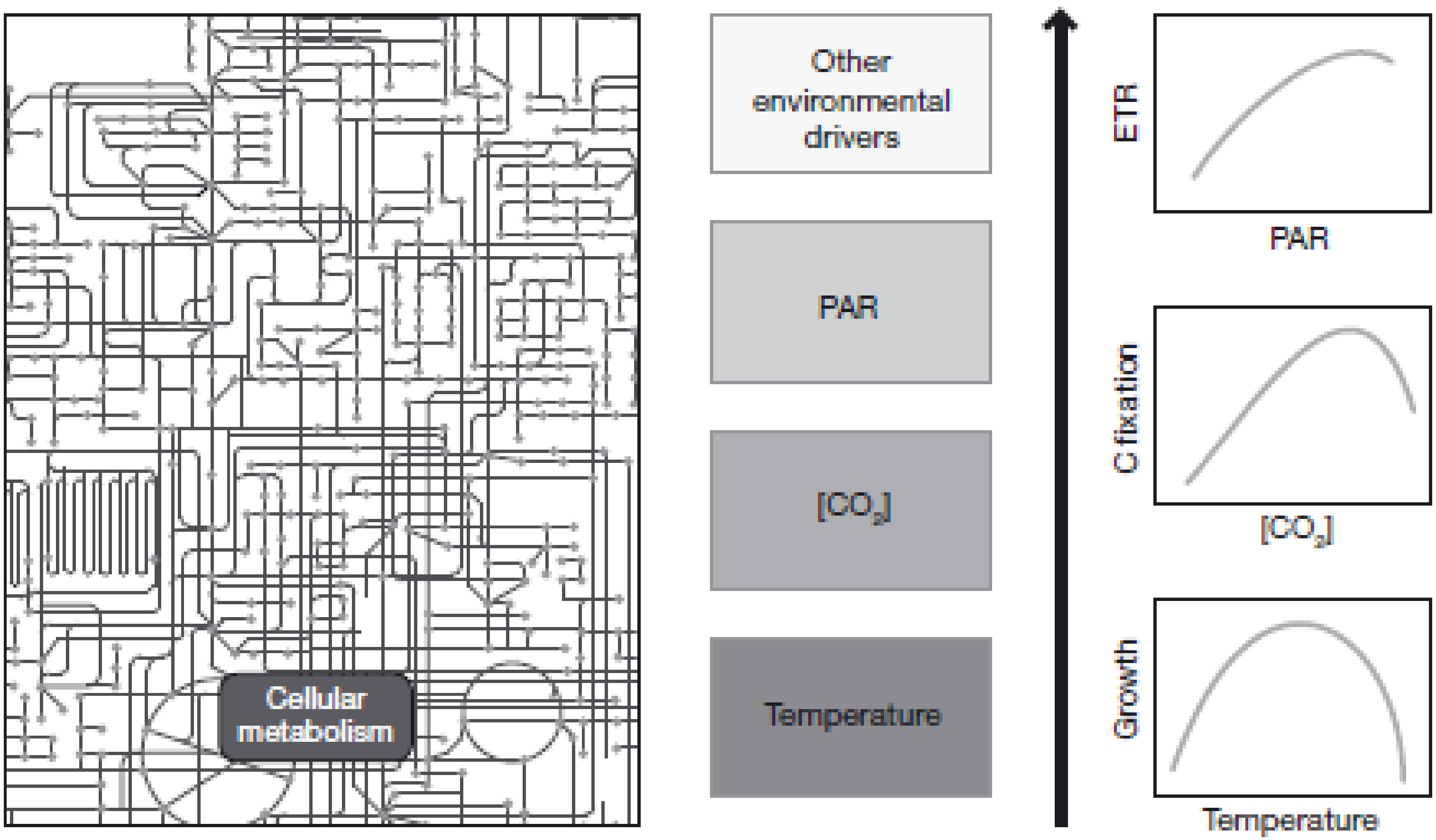
Boyd & Hutchins 2012

Synergisms & Antagonisms



Boyd et al. (2010)

Cumulative environmental stress



Boyd & Hutchins 2012

Temperature Modulates Coccolithophorid Sensitivity of Growth, Photosynthesis and Calcification to Increasing Seawater pCO_2

Scarlett Sett[1*], Lennart T. Bach[1], Kai G. Schulz[1,2], Signe Koch-Klavsen[1], Mario Lebrato[1], Ulf Riebesell[1]

Iron Limitation Modulates Ocean Acidification Effects on Southern Ocean Phytoplankton Communities

Clara J. M. Hoppe[1*], Christel S. Hassler[2¤], Christopher D. Payne[3], Philippe D. Tortell[3], Björn Rost[1], Scarlett Trimborn[1]

Light-Modulated Responses of Growth and Photosynthetic Performance to Ocean Acidification in the Model Diatom *Phaeodactylum tricornutum*

Yahe Li[1], Juntian Xu[2], Kunshan Gao[1*]

INTRODUCTION

Understanding the responses of ocean biota to a complex matrix of cumulative anthropogenic change

Philip W. Boyd[1,*], David A. Hutchins[2]

CONTENTS

Can Conceptual and modelling approaches Guide us through this maze?

Limnol. Oceanogr., 55(3), 2010, 1353–1376

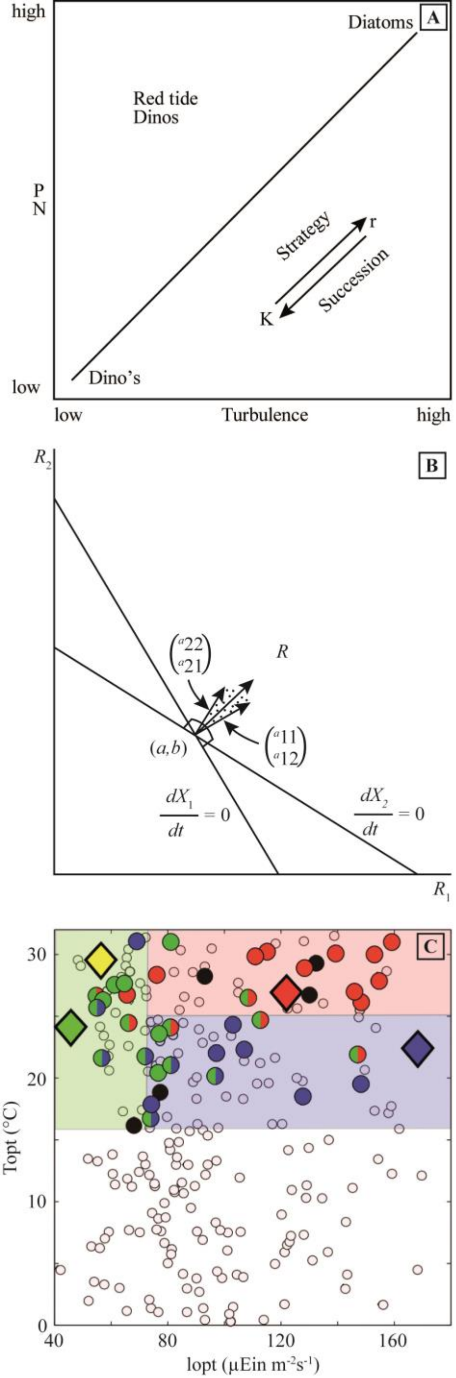
doi:10.4319/lo.2010.55.3.1353

Environmental control of open-ocean phytoplankton groups: Now and in the future

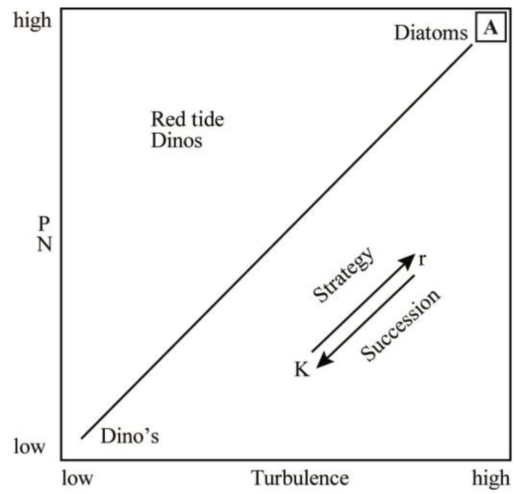
Philip W. Boyd,[a,*] Robert Strzepek,[b] Feixue Fu,[c] and David A. Hutchins[c]

Reviewed conceptual approaches including Margalef’s Mandala, resource ratio theory, functional traits & Follows emergent biogeography

Compared & contrasted the projections of coupled ocean atmosphere climate models with results from experimental manipulation studies



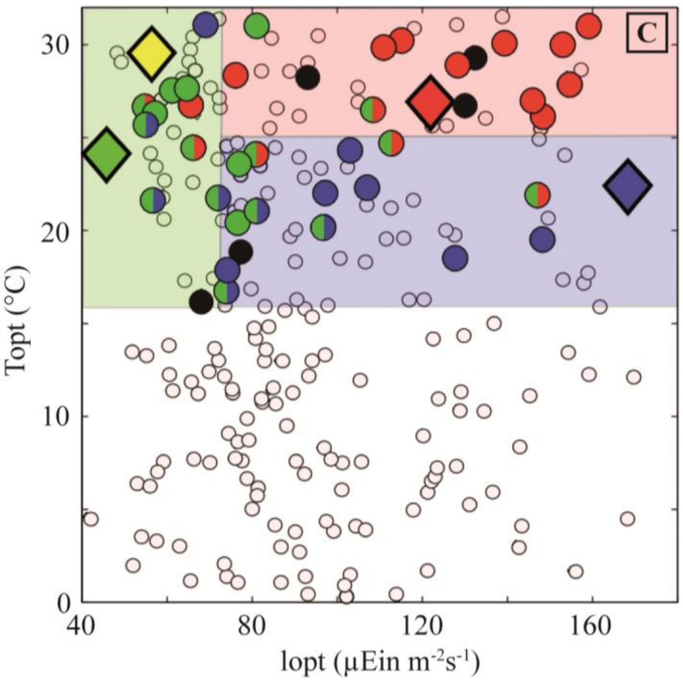
Can theoretical approaches adequately represent the effects of climate change?



Issues

Margalef's Mandala has insufficient dimensions to take into account seasonal changes in the multiple limiting and co-limiting factors that control a phytoplankton group.

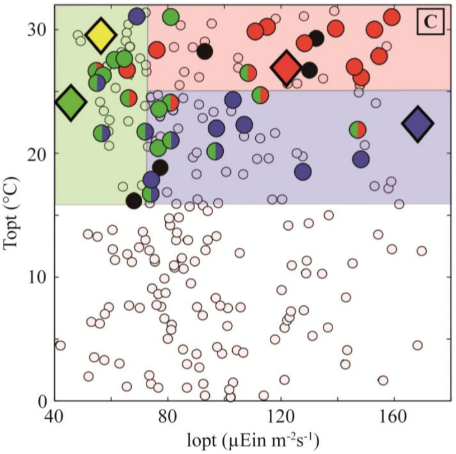
Boyd et al. (2010)



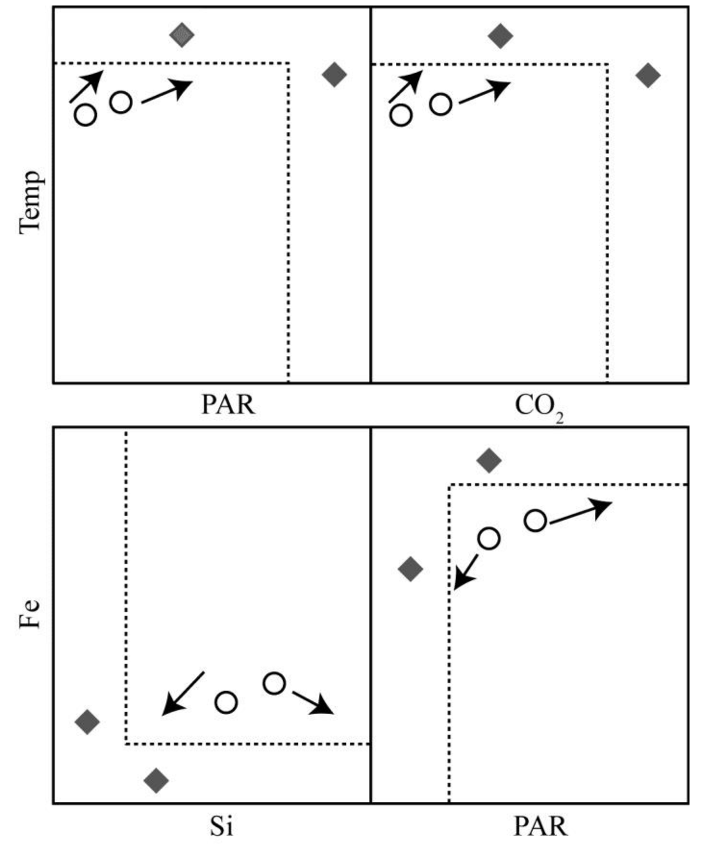
Modelling emergent phytoplankton biogeography

Follows et al. (2007)

- ❑ Formulated an ecosystem model with 78 potentially viable phytoplankton types.
- ❑ Physiological characteristics were determined stochastically.
- ❑ Initialized organism types interacted and evolved into a sustainable ecosystem.
- ❑ Community structure and diversity were emergent properties.



The Follows model was populated with phytoplankton types that exhibited a wide range of physiological permutations based on <u>published data</u>.



However, climate change will modify both the property-property space and may also alter the physiological permutations available.

The response of phytoplankton will depend upon:

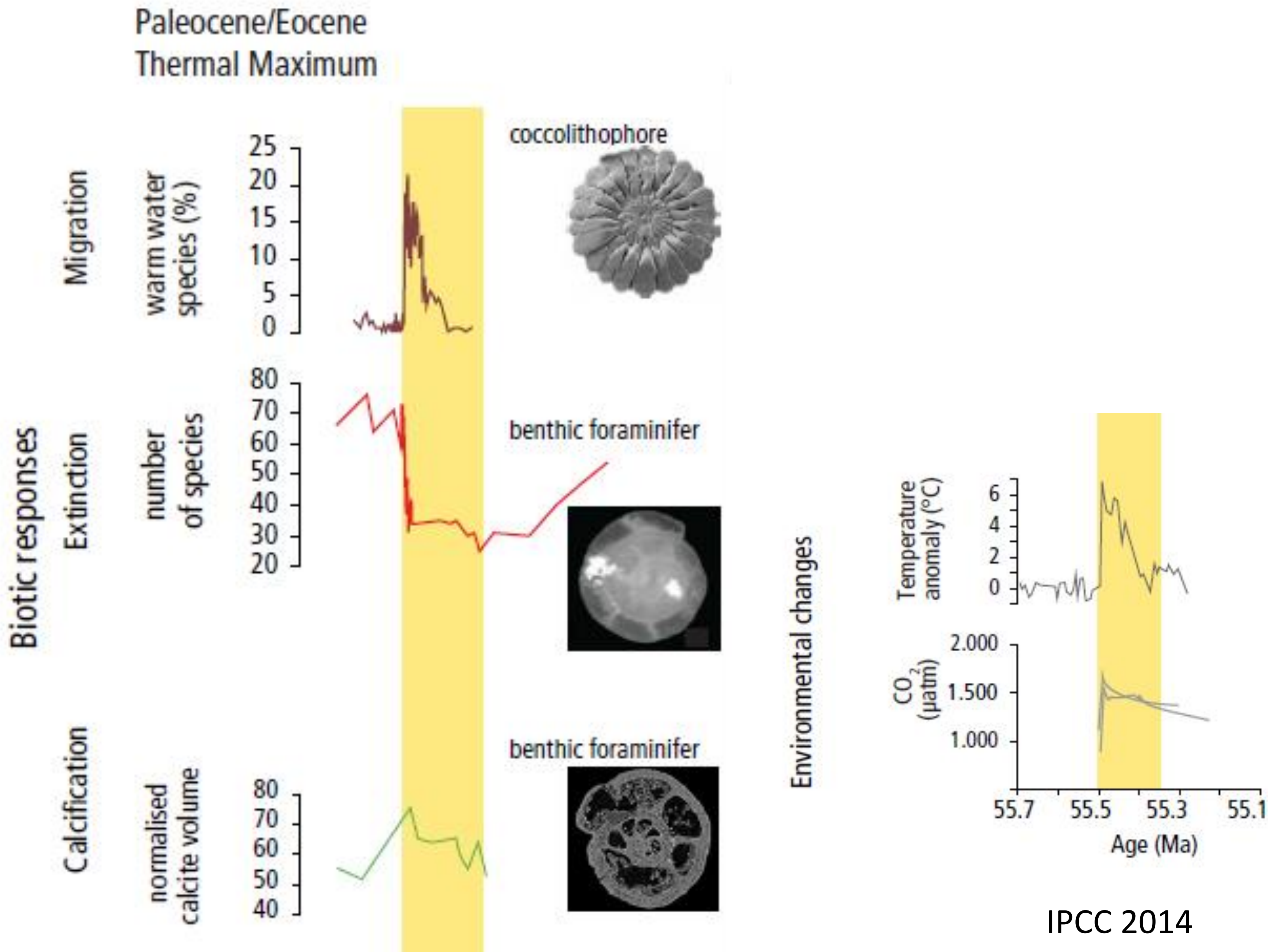
Physiological acclimation
Adaptation by existing dominant spp.
Succession by other spp./ecotypes

Boyd et al. (2010)

Acclimation and adaptation (Boyd et al. (2008)

Property	**Rate of change per decade (climate change)**
Temperature deg. C	+0.03 to +0.17
Salinity psu	-.014 to -.042
Mixed layer depth m	-0.3 to -0.8
Stratification kg/m^4 x 10^{-4}	+0.28 to +1.49
Surface PO_4 µmol/l	+.001 to -.004
Surface Fe nmol/l x 10^{-3}	-1.89 to -5.58
pCO_2 ppmv	+37.4 to +41.0
Light climate (mixed layer)	0.003 to 0.005 W/m2
Ice fraction	-.003 to -.013

Lessons from deep time – emergences and extinctions



IPCC 2014

We can now compute rates of change in upper ocean properties due to climate change – and compare them to what have been used experimentally – Boyd et al 2008

Property	Rate of change (decadal)	Experimental approaches	Response detected
Temp (C)	+0.10 to +0.31	**+1 to +4**	**yes**
pCO_2 (ppmv)	+33.9 to +44.6	**+480 to +600**	**yes**
Iron (pmol/l)	-0.32 to -1.30	**100 to 400**	**yes**

NSF workshop May 2010 Catalina Island

Gene expression changes in the coccolithophore *Emiliania huxleyi* after 500 generations of selection to ocean acidification

Kai T. Lohbeck Ulf Riebesell Thorsten B. H. Reusch1

Special issues

Evolutionary Rescue – Graham Bell – Proc Royal Soc 2013

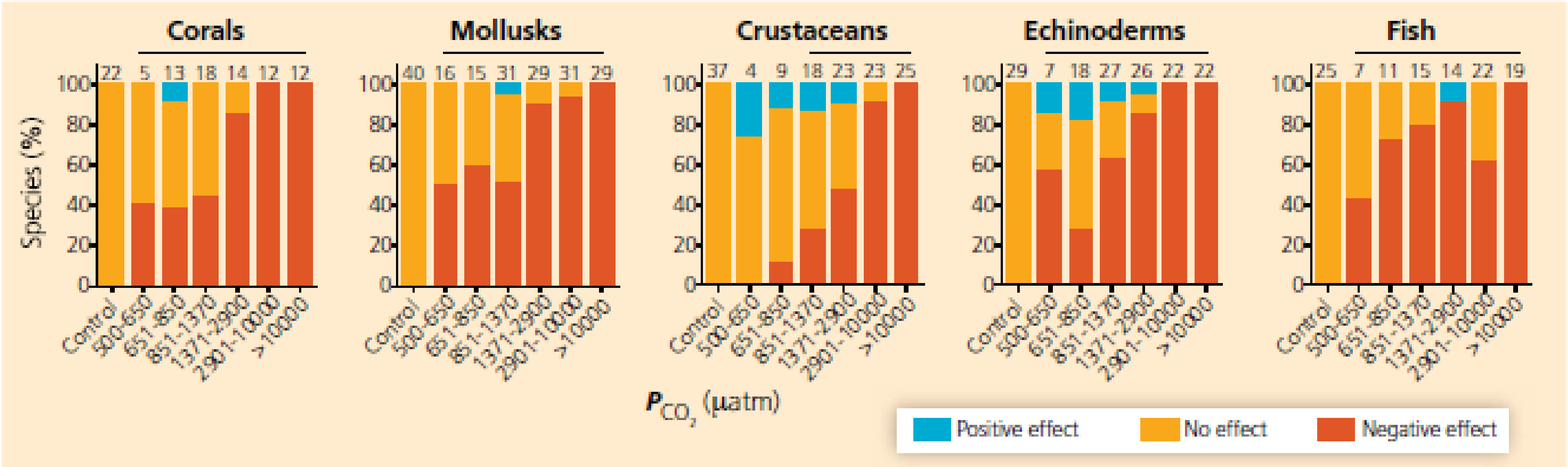
Evolutionary biology & Oceanography - Sinead Collins 2013

doi:10.1111/evo.12035

EXPERIMENTAL EVOLUTION MEETS MARINE PHYTOPLANKTON

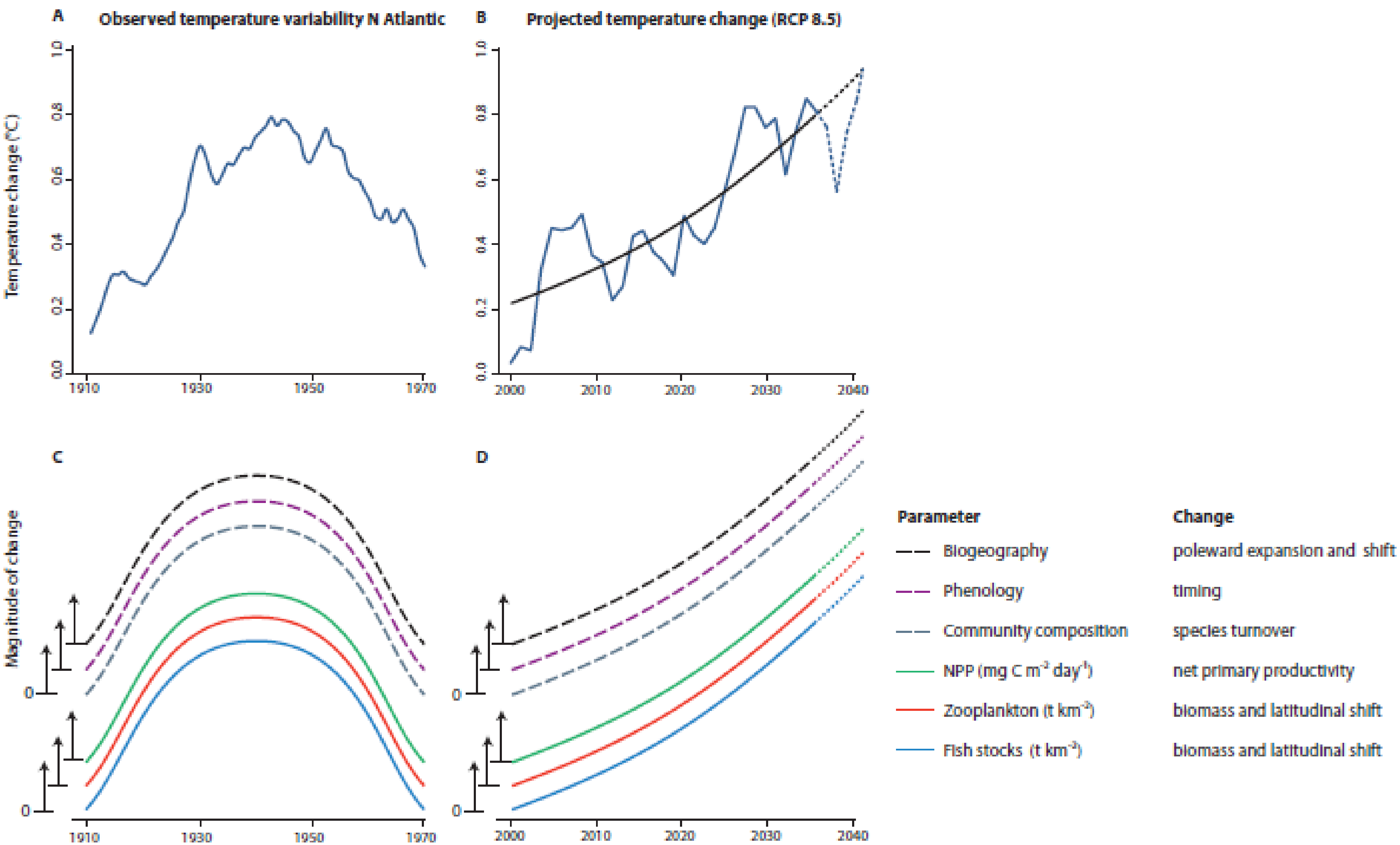
Thorsten B. H. Reusch[1,2] and Philip W. Boyd[3]

Foodwebs and differential susceptibility



IPCC 2014

Regime Shifts provide ecological detail of what we can expect in the coming decades



IPCC 2014

Methodological challenges

Single stressor vs. Multiple stressor research

Research facet	Single Stressor	Multiple Stressor
Implementation	Less difficult	Difficult
Communication	Interpretation is less complex	Complex findings
Funding	Long term	Longer term
Outreach	Readily conveyed	Difficult to simplify
Scope	Broad	Broadest
Pertinence	High	Highest

Boyd & Hutchins 2013

Challenges

Nebulous

Daunting

Building a research community & developing methodologies

Engaging research & government agencies

Modelling

Benefits

'The real deal' - the most pertinent and holistic research

Confounding issues

Different responses between species and strains

Study	Strain	PIC production	POC production
Feng et *al*. 2008	CCMP371^{C}	╲	—
Iglesias-Rodriguez et *al*. 2008	NZEH$_{R}$	╱	╱
Langer et *al*. 2009	RCC1212$_{B}^{O}$	╲	—
	RCC1216$_{R}^{O}$	╲	—
	RCC1238$_{A}^{C}$	—	⌒
	RCC1256$_{A}^{C}$	⌒	⌒
Riebesell et *al*. 2000	PLYB92/11$_{A}^{C}$	╲	╱
Sciandra et *al*. 2003	TW1		
Shi et *al*. 2009	NZEH$_{R}$	╱	╱
This study	RCC1256$_{A}^{C}$	╲	—
	NZEH$_{R}$	╲	

E. huxleyi
(Hoppe et al, 2011)

How can we model their response to an altered environment?

Cross-referencing biological responses to ocean change

COMMENTARY:

Framing biological responses to a changing ocean

Philip W Boyd   2013 Nature CC

Paradoxically, there is a real danger that as we conduct more complex experiments to attempt to understand biological responses to a changing ocean that we will decrease our understanding due to too many incompatible approaches and experimental designs

This points to the need for a co-ordinated approach from our community

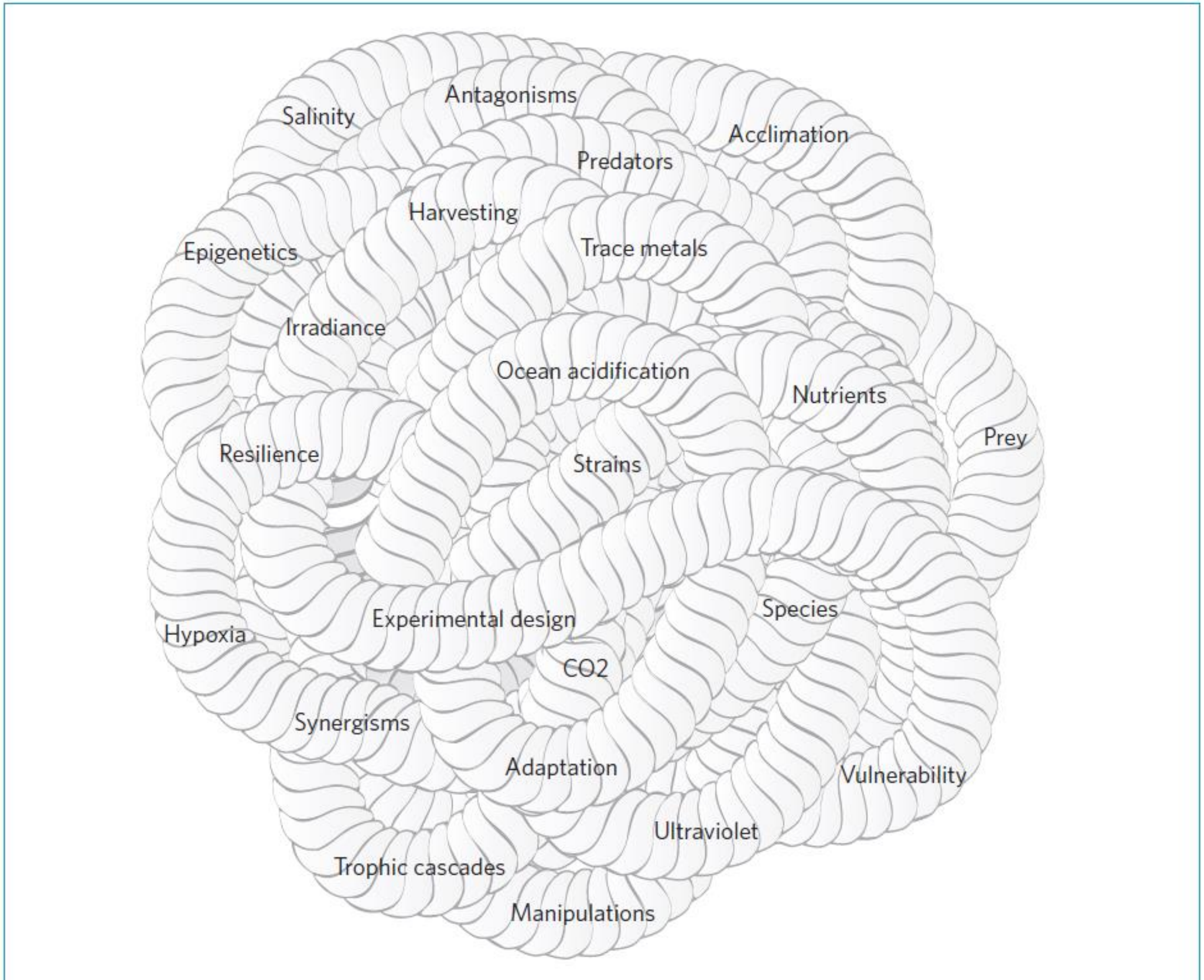


Figure 1 | A Gordian Knot made up of differing thematic information, indicating the wide range of research issues associated with the study of the response of biota to changing oceanic conditions.

Boyd 2013

Learning from other research communities - the success of the OA community

commentary

Beyond ocean acidification

Philip W. Boyd

Research into the biological threat of reduced ocean pH has yielded many insights over the past decade. Further progress requires a better understanding of how the interplay between ocean acidification and other anthropogenic stresses impacts marine biota.

Boyd (2011)

A research community
Standardised protocols
Public Outreach

Integration into Global Ocean Change
Conceptual and technological advances
OA as the public vanguard for GEC

2000 | 2010 | 2020…….

OPEN ACCESS Freely available online

PLOS | ONE

Marine Phytoplankton Temperature versus Growth Responses from Polar to Tropical Waters – Outcome of a Scientific Community-Wide Study

Philip W. Boyd[1,2*¤a], Tatiana A. Rynearson[3], Evelyn A. Armstrong[1], Feixue Fu[4], Kendra Hayashi[5], Zhangxi Hu[6], David A. Hutchins[4], Raphael M. Kudela[5], Elena Litchman[7], Margaret R. Mulholland[6], Uta Passow[8], Robert F. Strzepek[9¤b], Kerry A. Whittaker[3], Elizabeth Yu[4], Mridul K. Thomas[7]

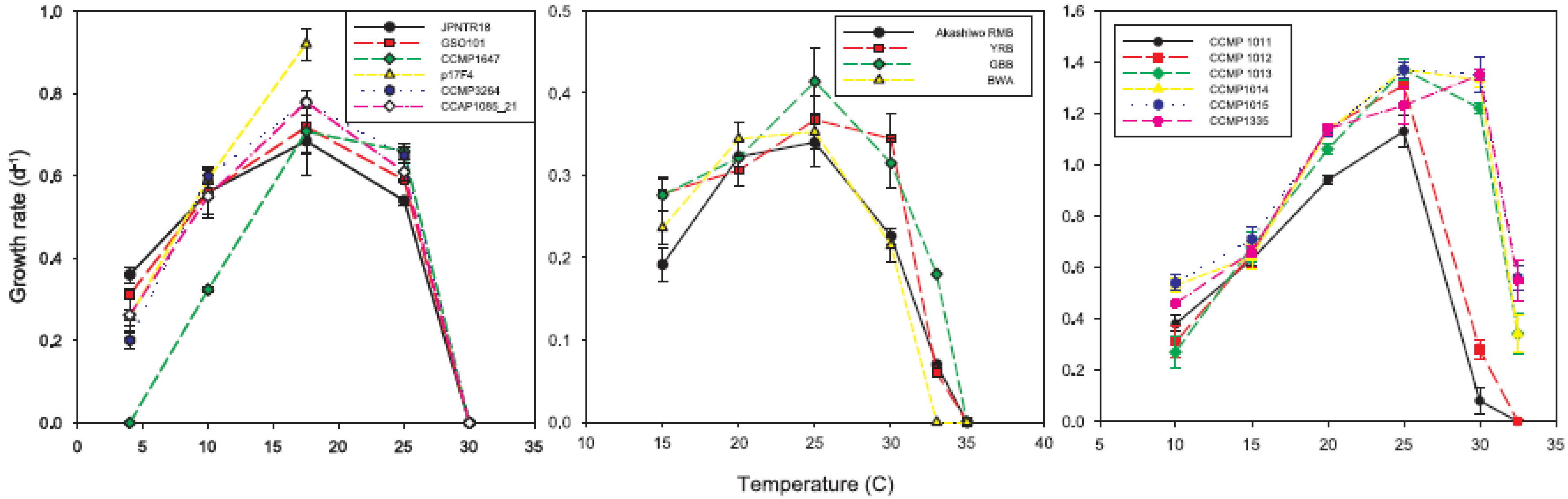


Figure 2. Thermal reaction norms for multiple strains of *Thalassiosira rotula* (left panel) *Akashiwo sanguinea* (central panel) and *Thalassiosira pseudonana* (right panel) used in our study.
doi:10.1371/journal.pone.0063091.g002

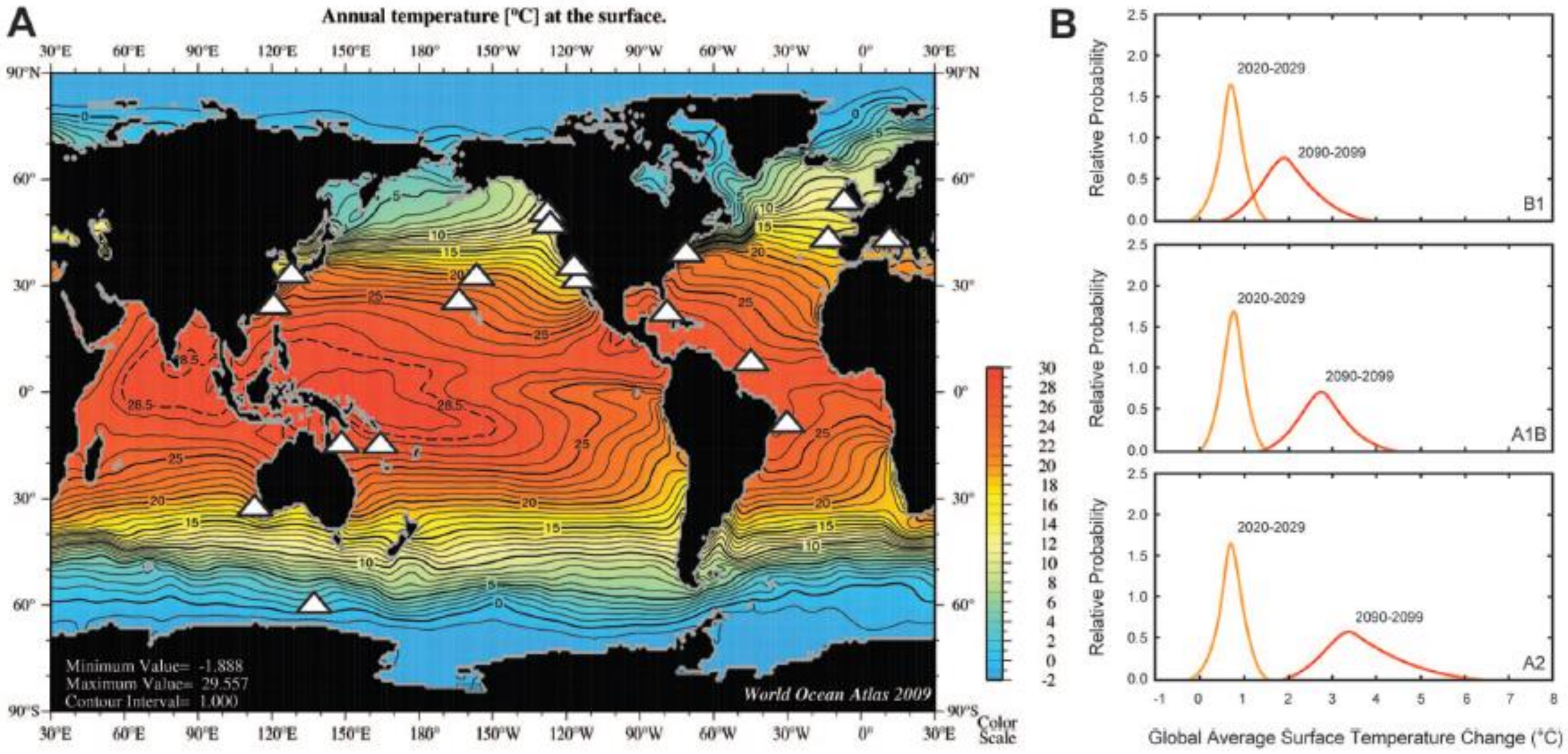


Figure 1. Summary of the locations at which the species/strains were initially isolated. A) Overlaid (locales denoted by white stars) on a

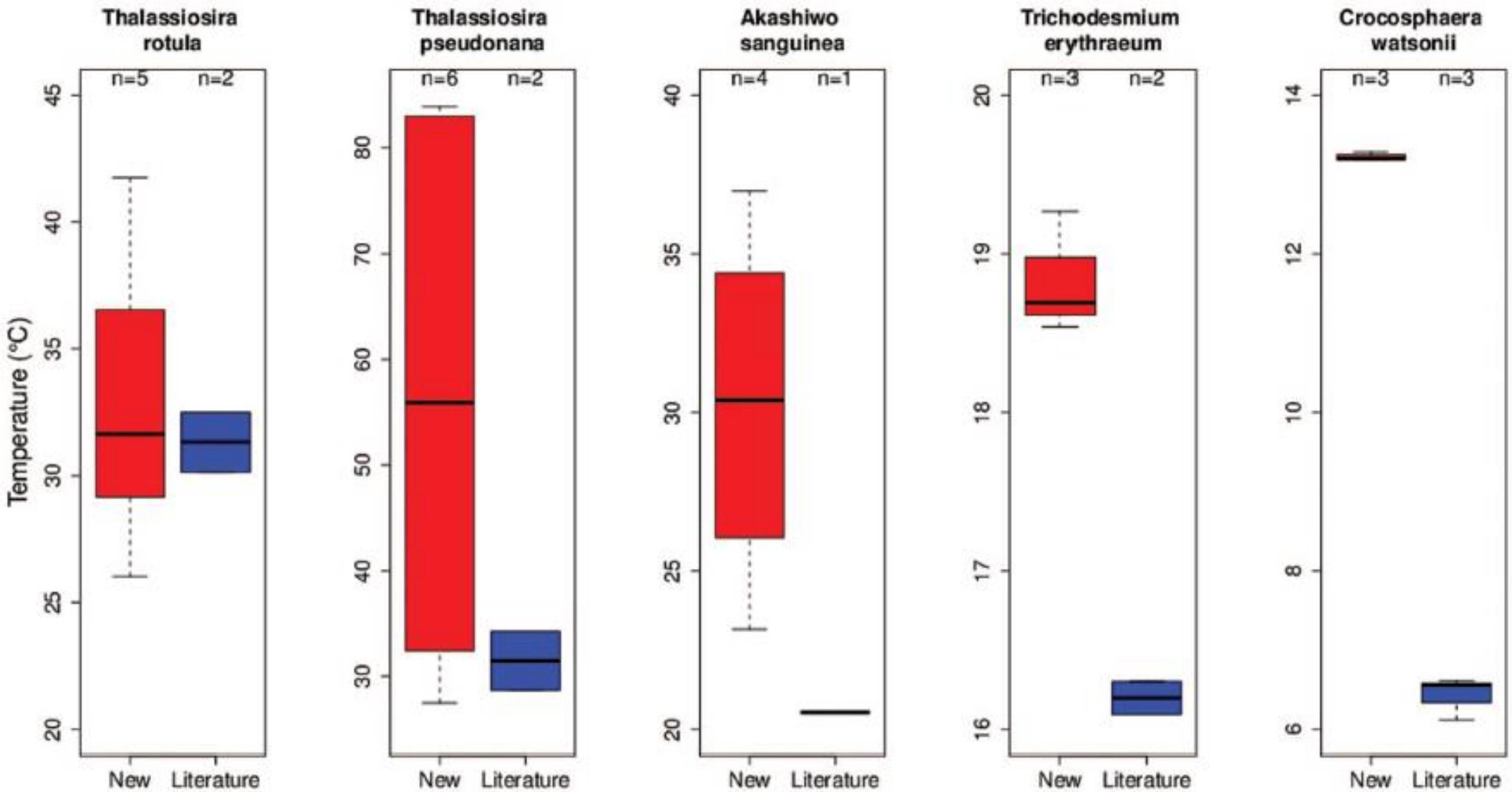
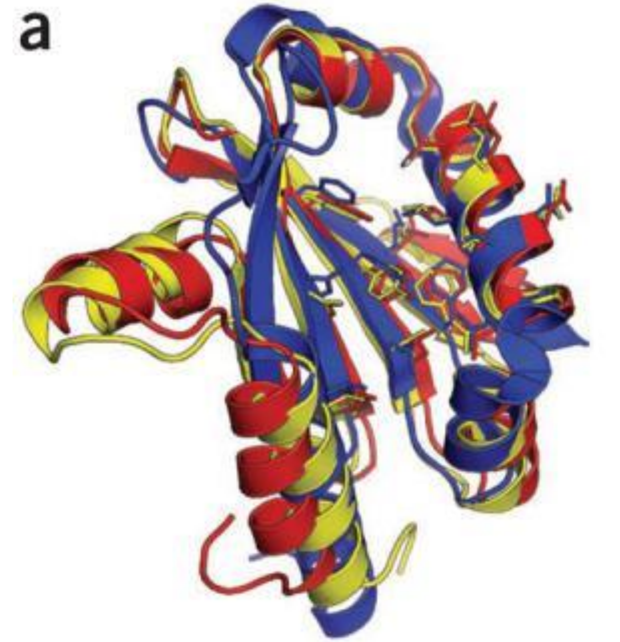


Figure 5. A comparison of the thermal trait, niche width (°C) using box and whisker plots, between previously published studies (using a wide range of experimental protocols, see [43]) and the species/strains used in the present study. The black bands denote the

Boyd et al. 2013



Crystal structure of a monomeric retroviral protease solved by protein folding game players

Khatib F, DiMaio F; Foldit Contenders Group;
Foldit Void Crushers Group, et al. (2011) Nat Struct Mol Biol.

Following the failure of a wide range of attempts to solve the crystal structure of M-PMV retroviral protease by molecular replacement, we challenged players of the protein folding game Foldit to produce accurate models of the protein.

Remarkably, Foldit players were able to generate models of sufficient quality for successful molecular replacement and subsequent structure determination. The refined structure provides new insights for the design of antiretroviral drugs.

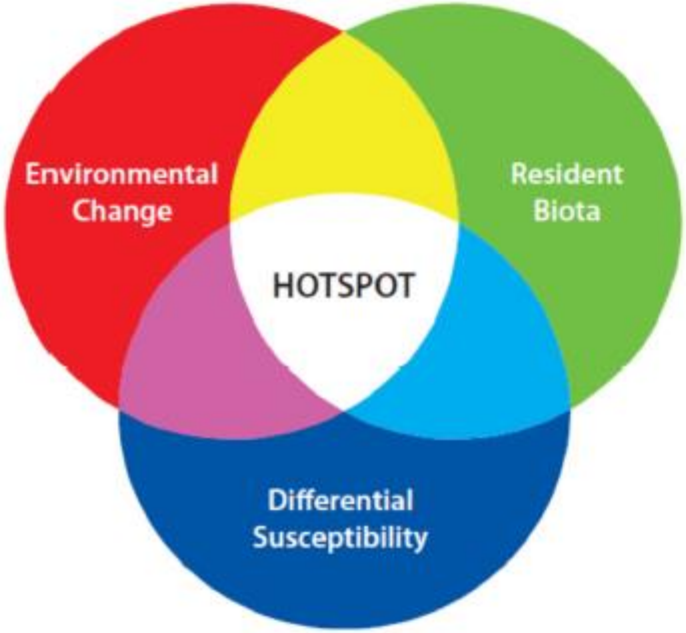
Communities Under Climate Change
David Nogués-Bravo and Carsten Rahbek
Science **334**, 1070 (2011);
DOI: 10.1126/science.1214833

Such a change from the traditional research and funding structure in ecological disciplines, from small individual grants to large global consortia, is by no means trivial.

It would require substantial, if not dramatic, changes in the distribution of funds, the criteria by which they are awarded, how researchers collaborate, and (not least) how scientific credit is partitioned between groups and individuals.

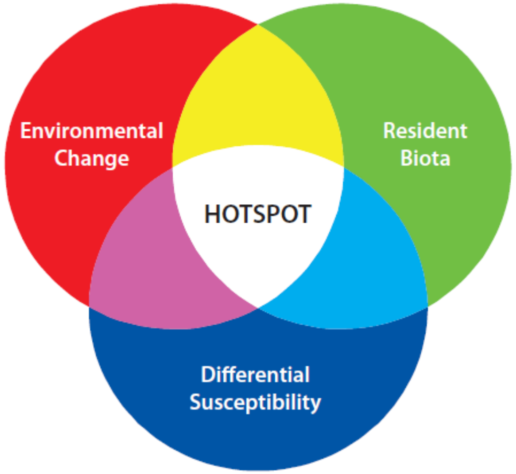
Communicating the implications of multiple stressor research to policy makers

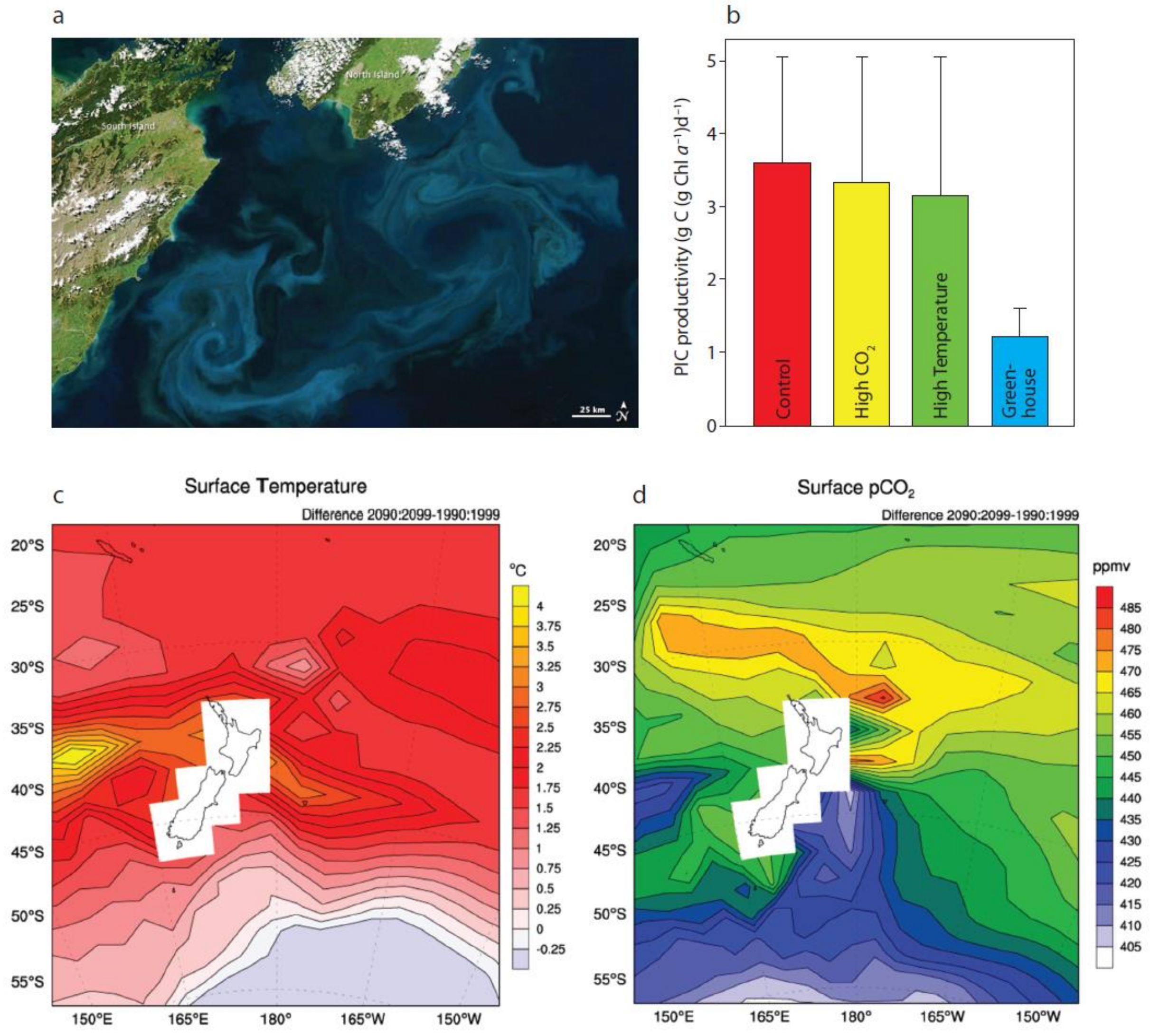
A Climate Change Atlas for the Ocean



Boyd, Law & Doney (2011)

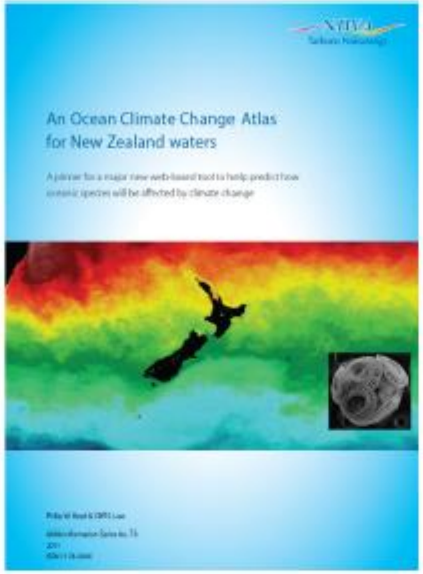
Preliminary evidence of a climate change HOTSPOT east of New Zealand





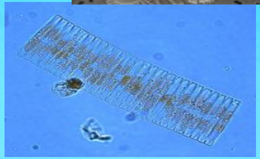
We propose a Climate Change Atlas as such an integrator

The multi-faceted roles of a www.atlas



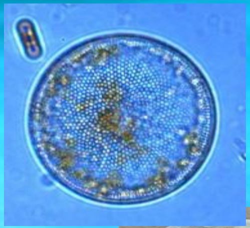
- An archive of previously funded research findings
- A repository for future datasets and conceptual advances
- An umbrella for different ocean interest groups
- A record to compare new findings with
- A catalogue to fuel question-driven policy issues
- A tool to reveal important research gaps





Announcing the 1st

Ocean Global Change Biology Gordon Research Conference



Dave Hutchins (chair), Philip Boyd (vice-chair)

Adina Paytan and Shannon Meseck (co-organizers)

July 6-11, 2014 at the Waterville Valley Resort, New Hampshire

Sessions:

1. Lessons learned from the ocean acidification field
2. Feedbacks between ocean acidification, warming and hypoxia
3. Paleo proxies for multiple environmental stressors
4. Biogeochemical consequences of multi-variable global change processes
5. Acclimation, plasticity and adaptation
6. Physiological and genetic responses to interacting anthropogenic stressors
7. Ecosystem modeling of multiple stressors
8. Developing and comparing ocean global change experimental methods
9. Temporal and spatial scales of biological responses to environmental chang



For more information or to apply, go to the GRC website:

www.grc.org/programs.aspx?year=2014&program=oceanglob

Or contact Dave Hutchins (dahutch@usc.edu) or Phil Boyd (Philip.Boyd@utas.edu.au)

Gordon Research Conferences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