Modelling harmful algal growth under climate change

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What are Models?

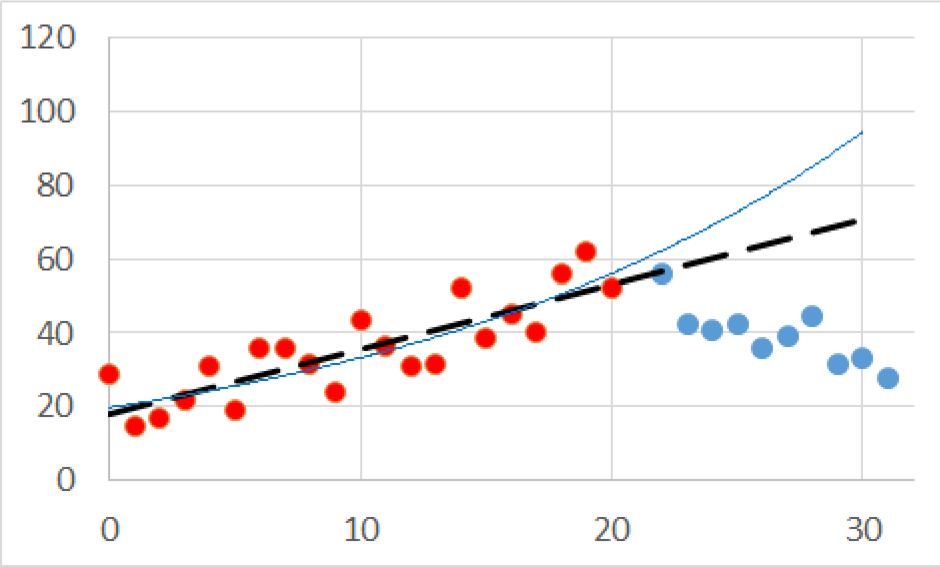
- Models are simplifications of reality
- Deciding on where & how to simplify is a critical step, depending in part on the type and role of the model,
- … and depends in part upon our understanding of the system

What are models for?

- Integrate knowledge **(dynamic conceptual models)**
- Used to explore theory through to prediction
- An inability to match model output to reality can tell us much …
- but we need to establish whether failure reflects an ignorance of reality &/or a failure in transcribing knowledge into equations

Into the future

- Simple models may be likened to regression statistics
- Typically they do not offer a sound base for prediction beyond the data series used for their construction
- Climate change takes us beyond our experience



Prediction underpinned by understanding requires a careful balance between model simplicity and complexity

Prediction requires a sound understanding of the system

- What is “the system”?
- How well do we understand the system?
- known knowns; things we know we know.
- known unknowns; things we know we do not know.
- unknown unknowns – things we don't know we don't know
- **And one more ….**

the unknown knowns …

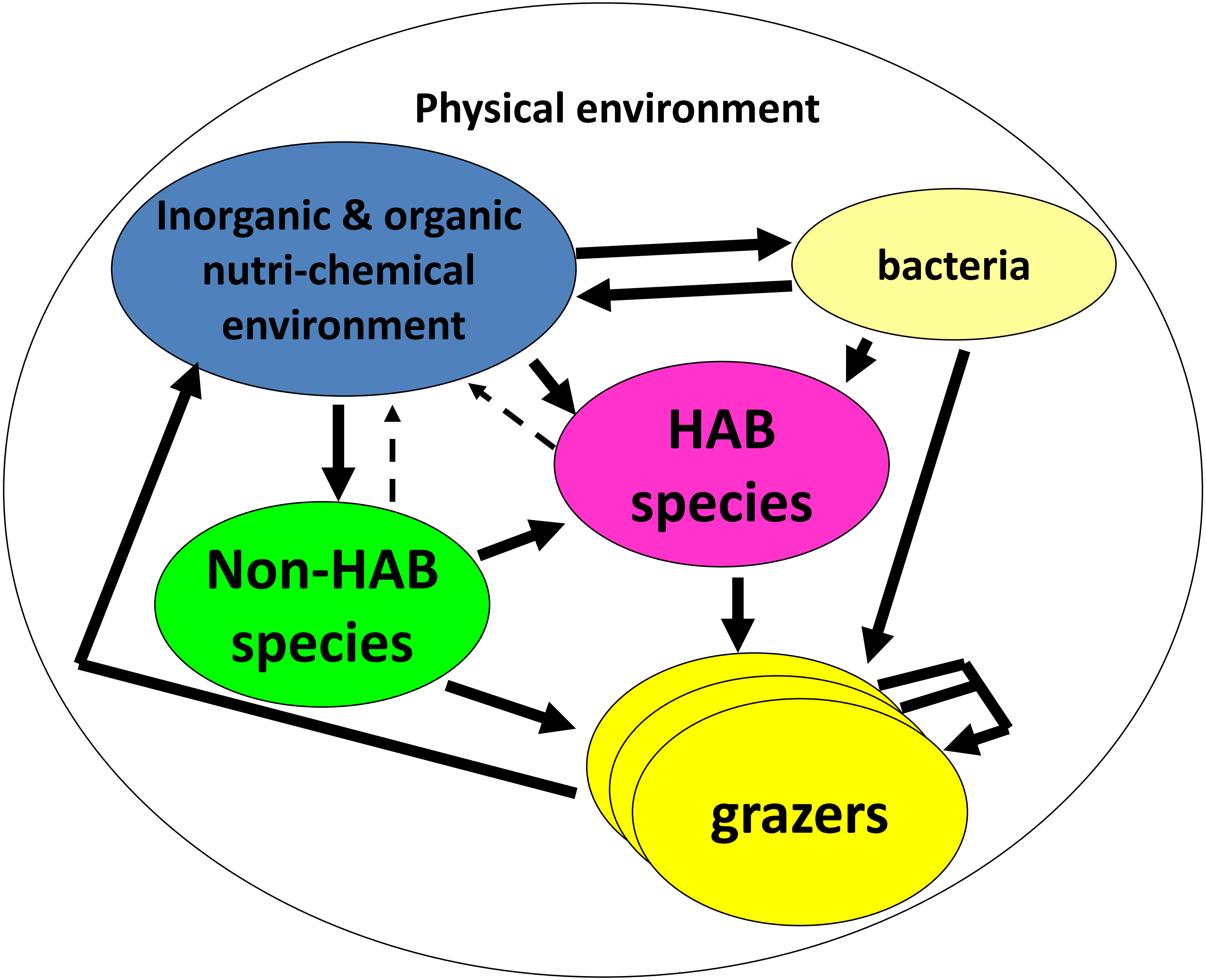
- …. things that we intentionally refuse to acknowledge that we know
- This is a common issue in modelling, driven by the need to simplify

These may include….

- Climate change, "weather" inc. cloudiness, rainfall, temperature; salinity; OA; etc.
- Aspects of ecology such as cysts, mixotrophy, allelopathy, role of DOM/mucus, aggregation, vertical migration, grazers (inc. selectivity) & trophic cascades, virus & parasites, etc.

What is so special about HAB species?

- What is a weed?
- .. “a plant in the wrong place”
- So are HABs species just **(too much of)** an “unwanted” species in the wrong place?
- Studies of HABs from a holistic standpoint appear little different to studies of plankton in general terms
- **HABs models have more in common with end-2-end fisheries models than with biogeochemical models**



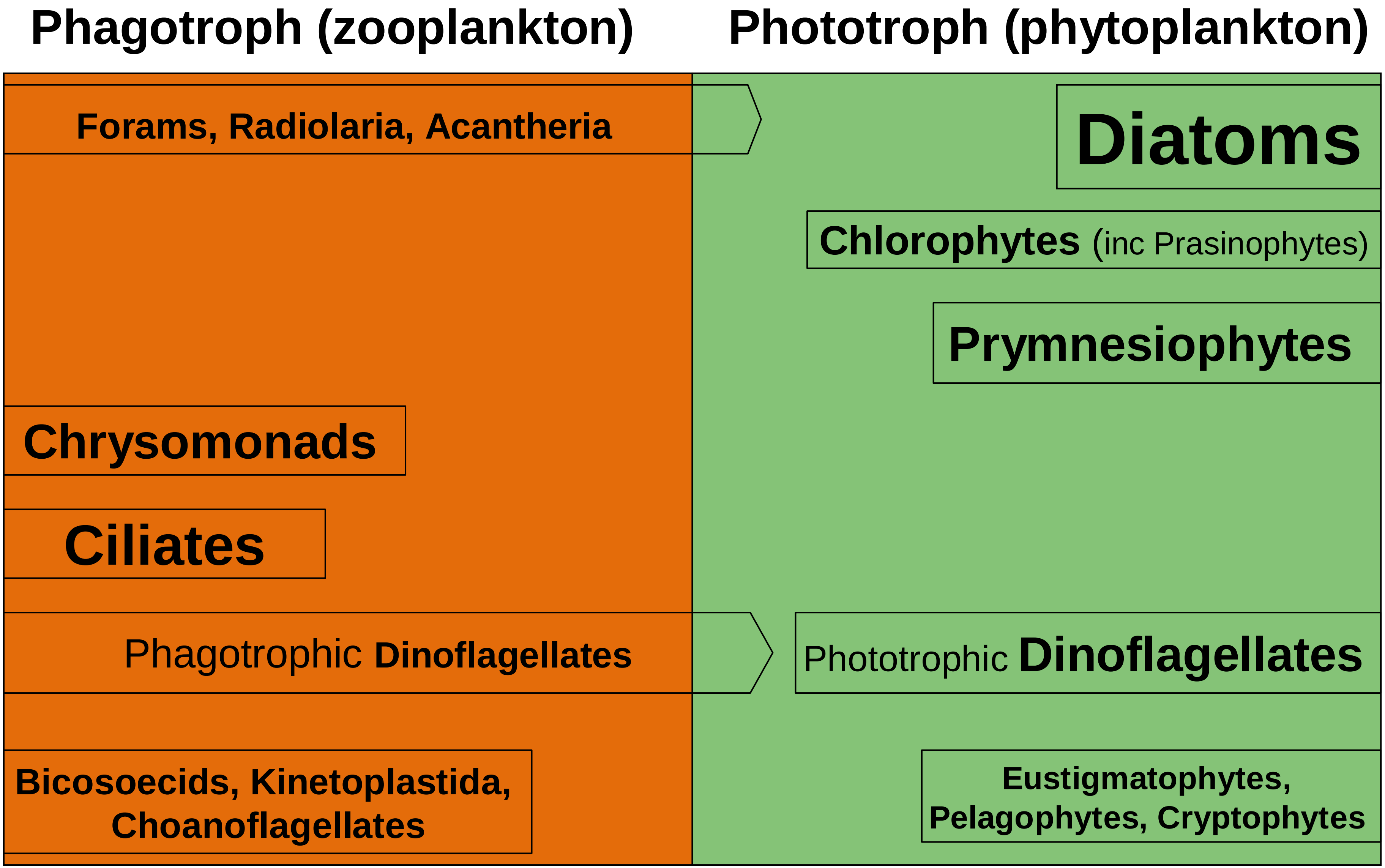
Physical environment
Inorganic & organic nutri-chemical environment
bacteria
HAB species
Non-HAB species
grazers

Two major challenges in modelling of HABs, and of plankton in general

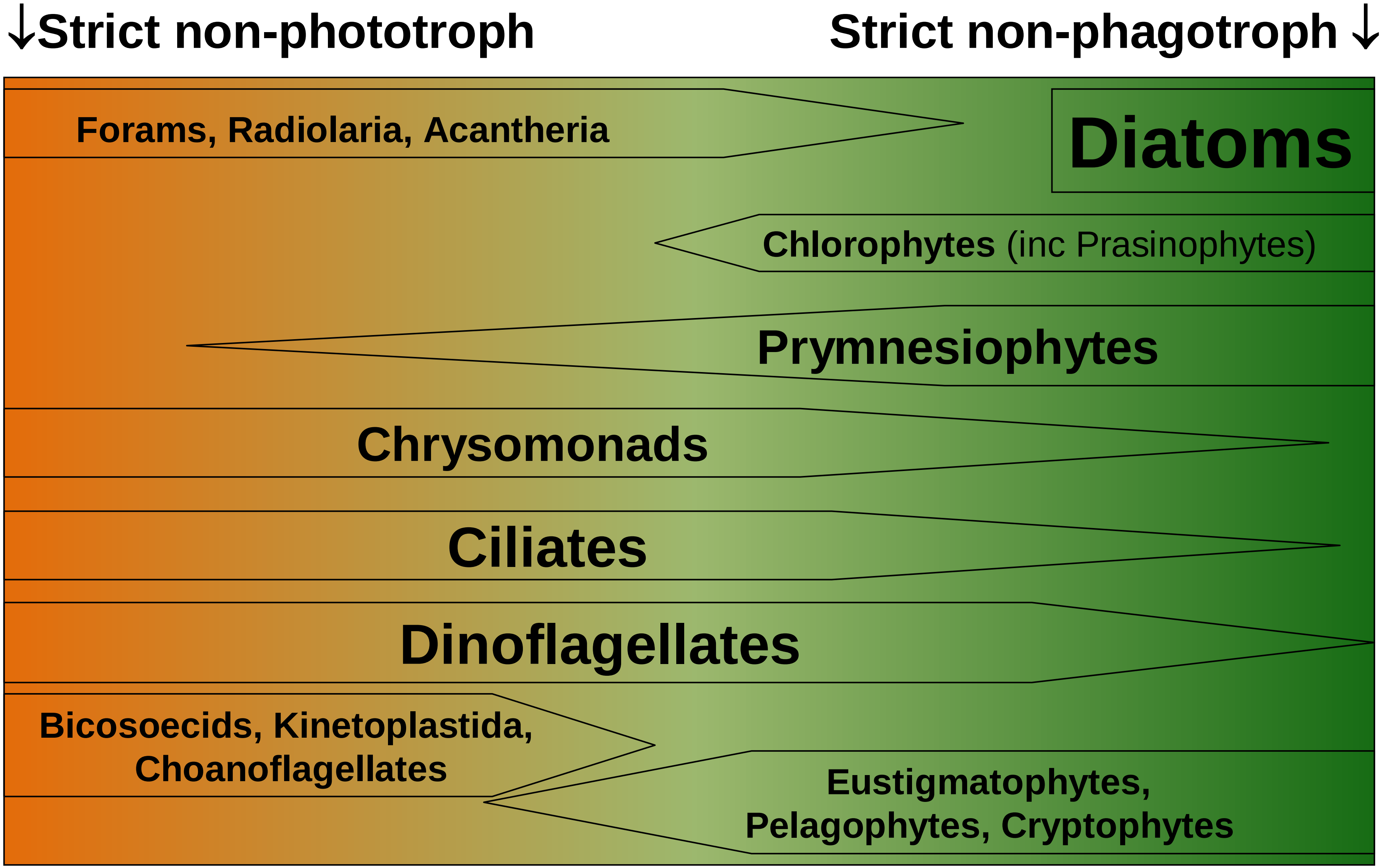
- Mixotrophy in protists **(CF emphasis on classic phytoplankton, light and inorganic nutrients)**
- Grazing activity **(blooms can only occur in the absence of grazing, &/or presence of selective grazing, which may relate to the mixotrophic capacity of the HAB species)**

Harmful ***Algal Blooms***

- The term “algal blooms” invokes notions of **(only)** photoautotrophy
- In reality, and other than cyanobacteria and diatoms, most HAB species are likely phago-mixotrophic
- ... not just phototrophic **(CF. the emphasis in HAB models on phototrophy and the use of inorganic nutrients)**



Flynn et al. (2013) JPR doi:10.1093/plankt/fbs062

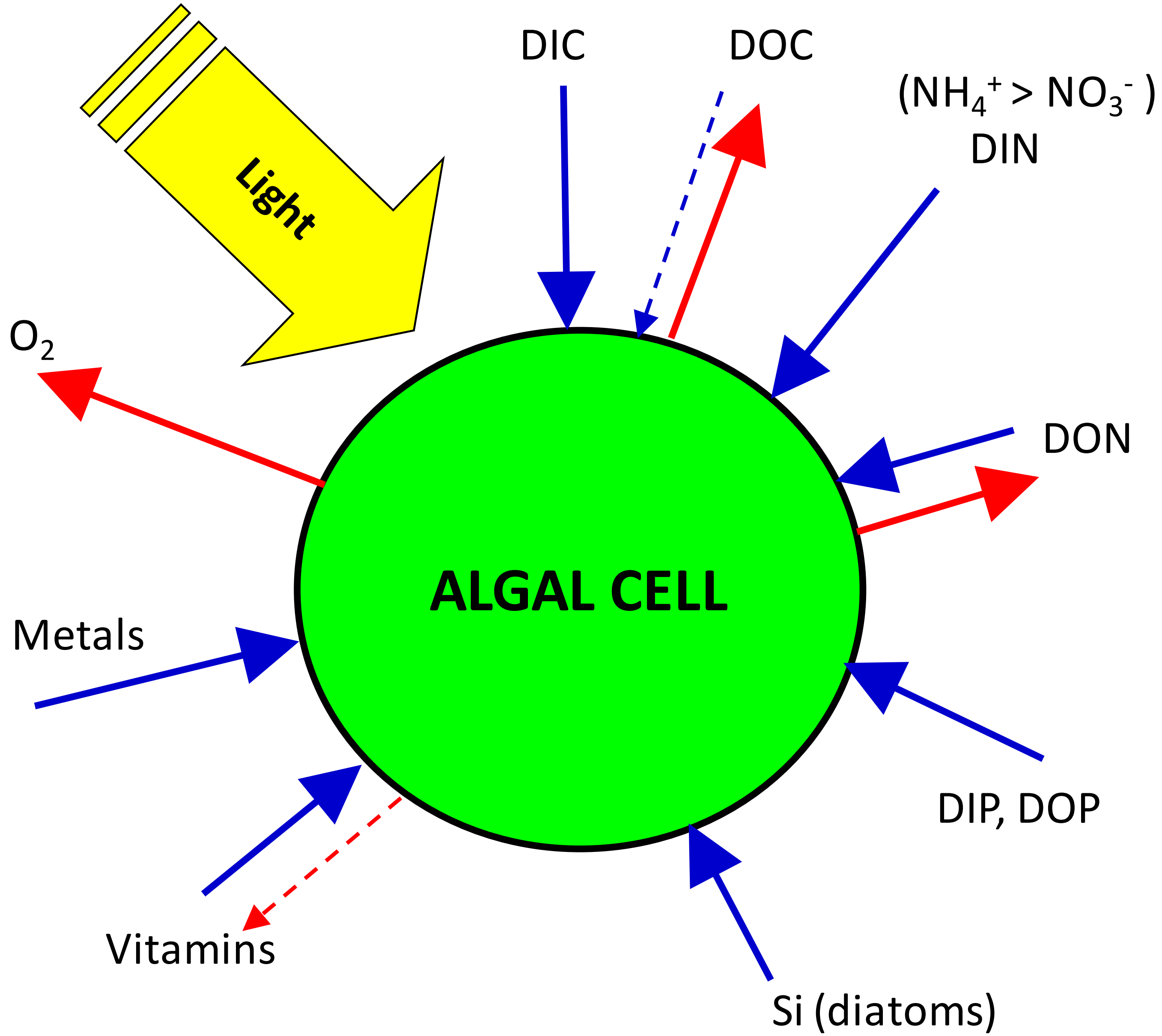


Flynn et al. (2013) JPR doi:10.1093/plankt/fbs062

Photo-phago Mixotrophy

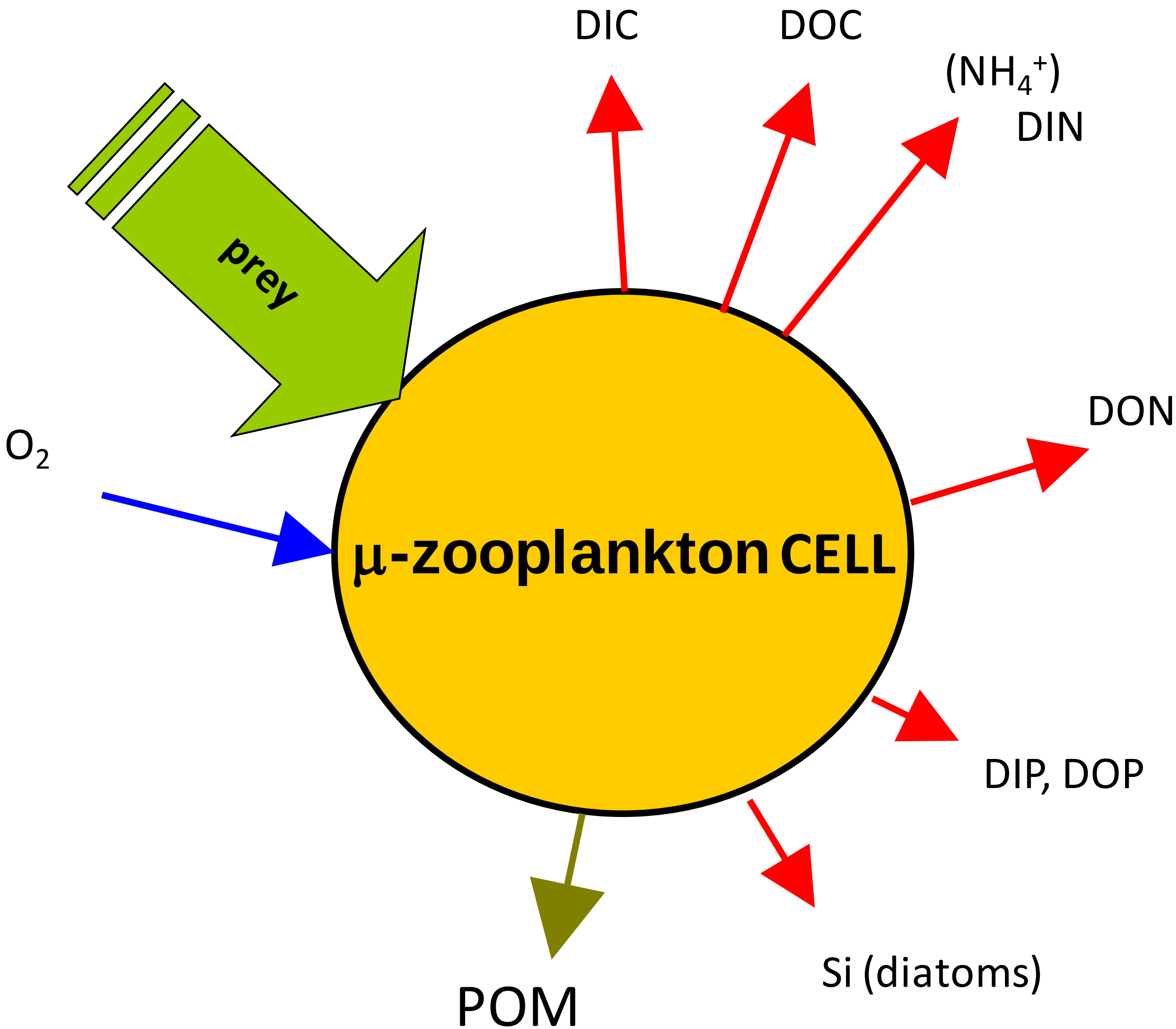
- The biggest *known unknown*, or is it actually an *unknown known* **(deliberately ignored)**?
- Mixotrophy is common in protists, and esp. common in HAB species
- Modelling mixotrophy is particularly challenging, combining the processes of phototrophy and phagotrophy **(grazing)**

Phototroph



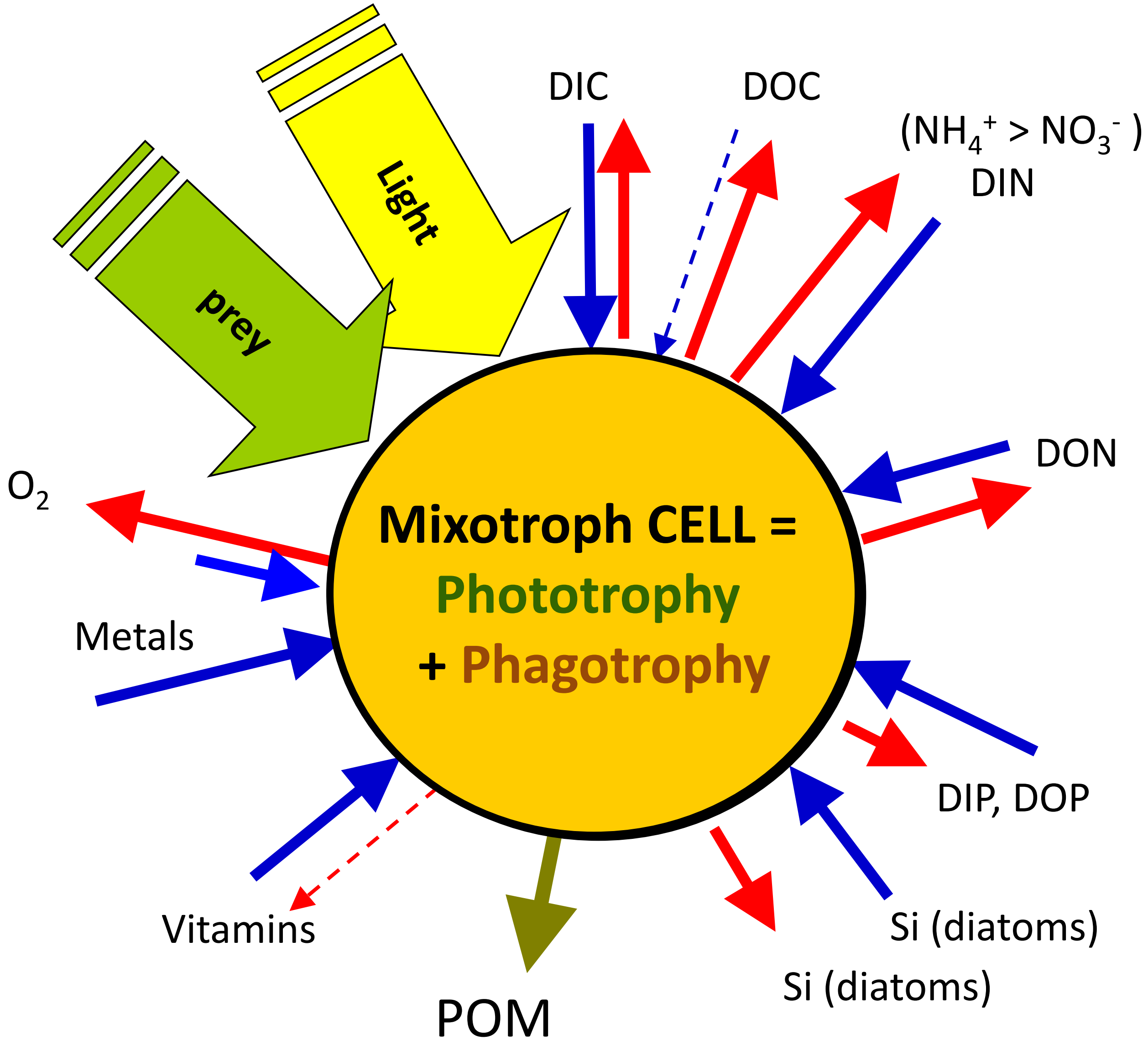
Light
DIC
DOC
$(NH_4^+ > NO_3^-)$
DIN
O_2
DON
ALGAL CELL
Metals
DIP, DOP
Vitamins
Si (diatoms)

Phagotroph

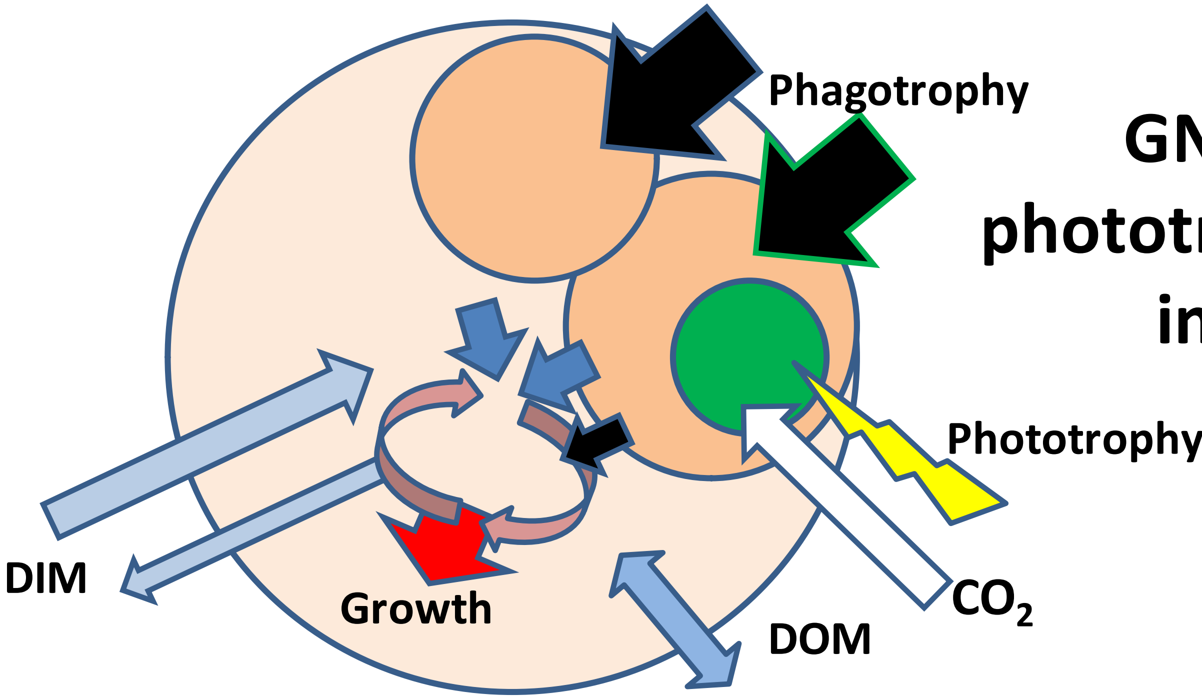


DIC
DOC
(NH_4^+)
DIN
prey
O_2
μ-zooplankton CELL
DON
DIP, DOP
POM
Si (diatoms)

Mixotrophy = Phototrophy + Phagotrophy



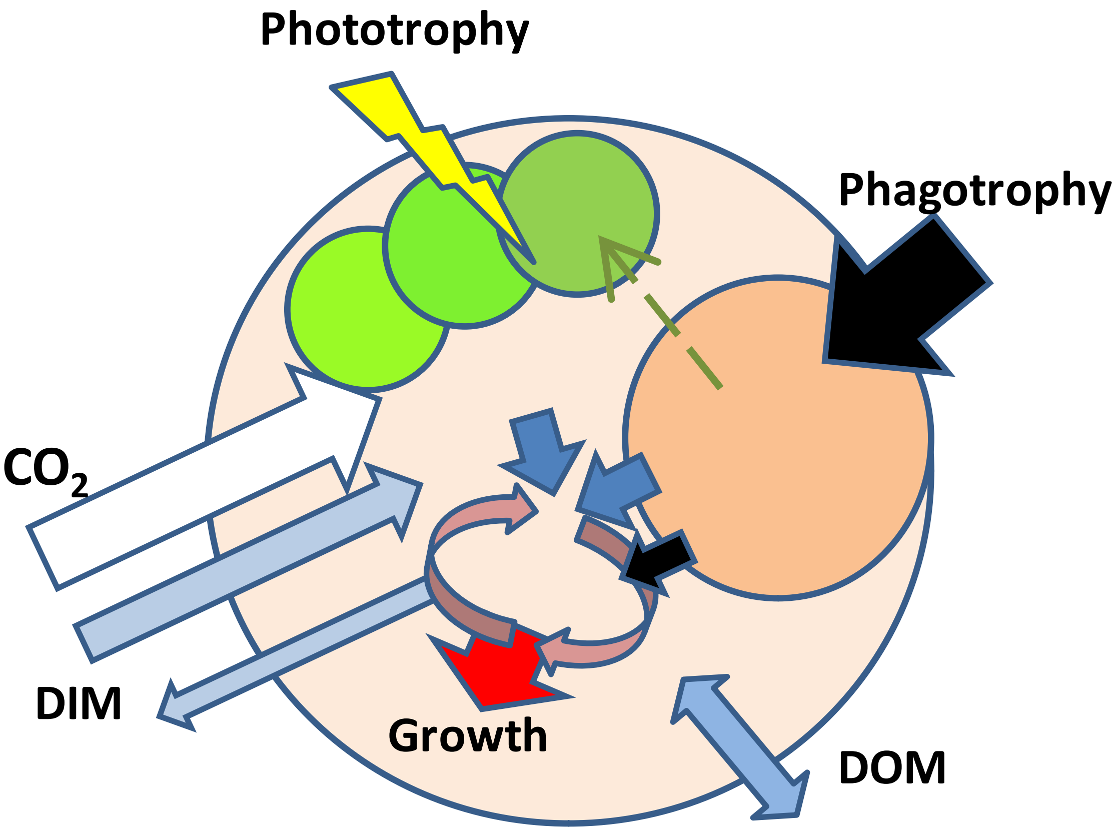
Mixotroph functional type: Generalist Non-Constitutives



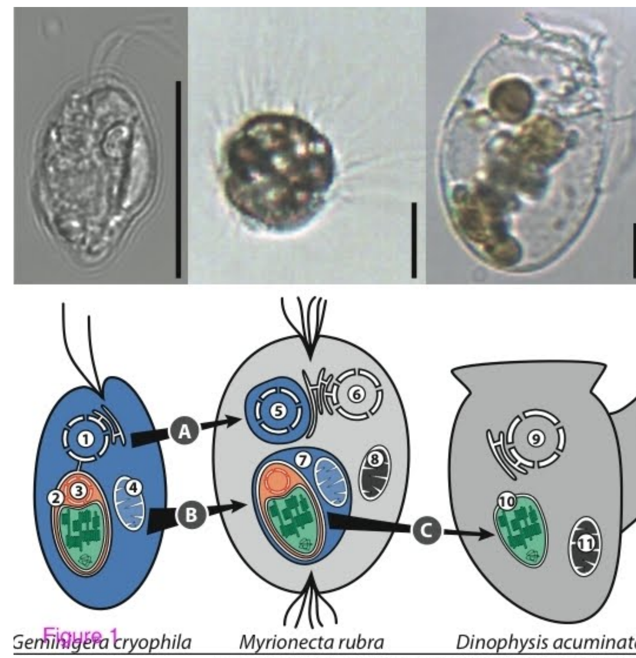
GNC-mixotroph phototrophy provided by ingested prey

Example:
plastidic ciliates – 1/3rd of photic zone µZoo

Mixotroph functional type:
Specialist Non-Constitutives (kleptoplasty)



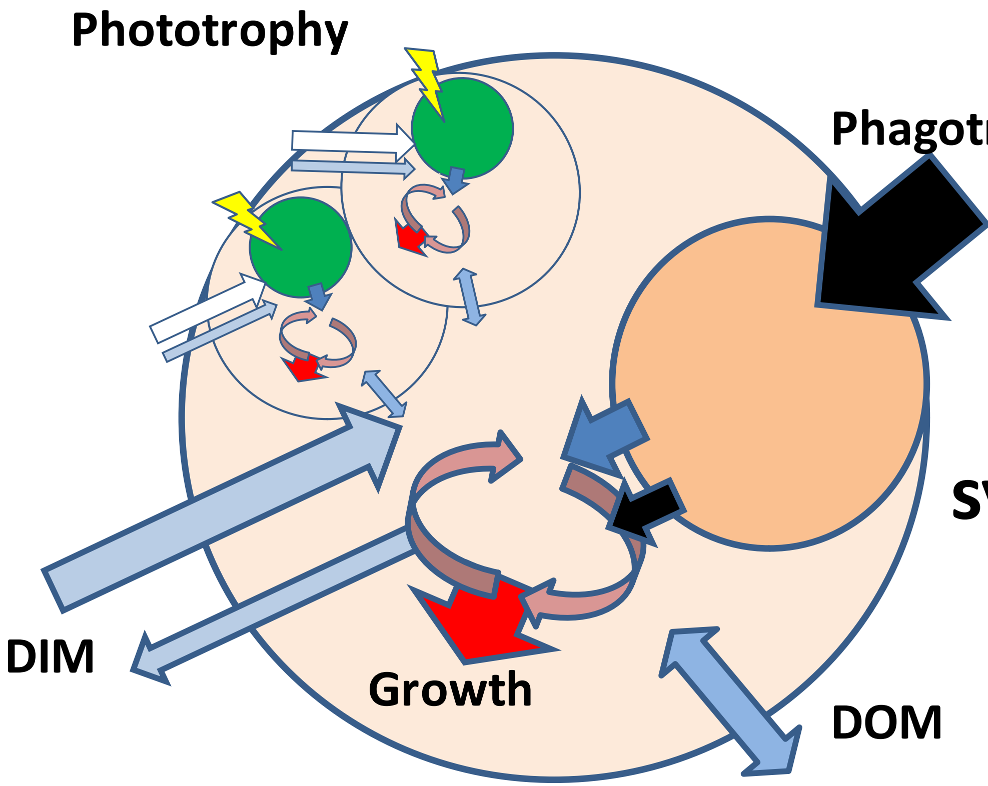
Examples:
Mesodinium,
Dinophysis



Wisecaver & Hackett 2010 BMC Genomics

SNC-mixotroph
partial integration of phototrophy

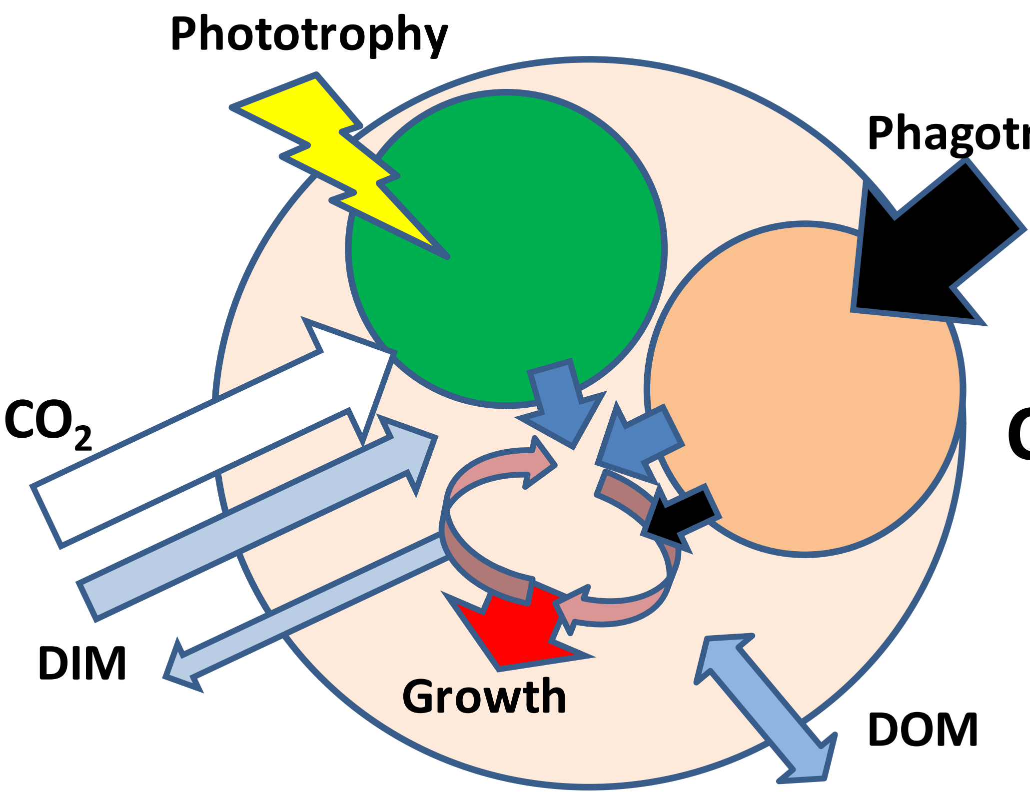
Mixotroph functional type:
Specialist Non-Constitutives (endosymbionts)



SNC-mixotroph symbiotic phototrophy

Examples:
green *Noctiluca,*
foraminiferans

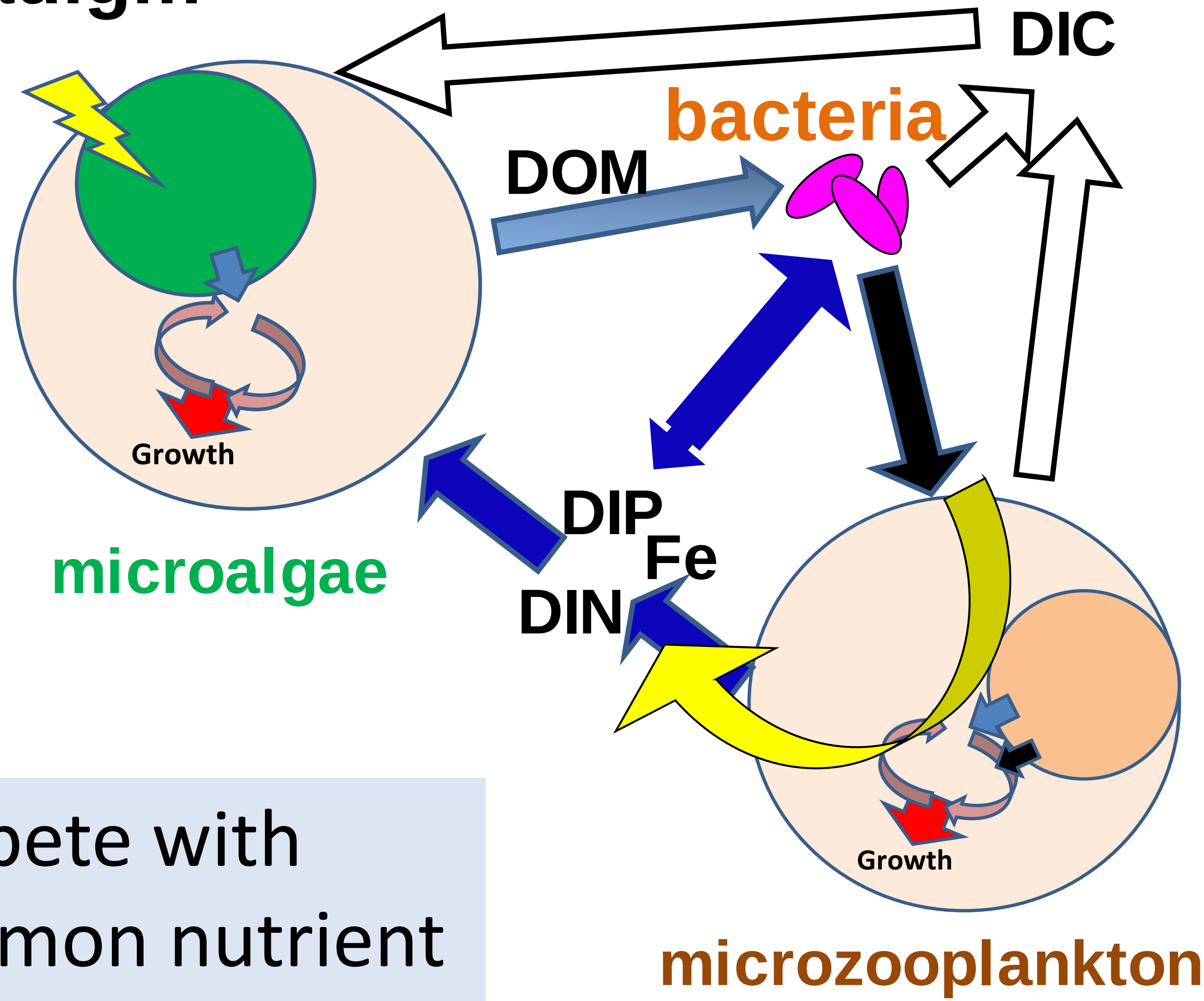
Mixotroph functional type: Constitutives



Constitutive Mixotroph

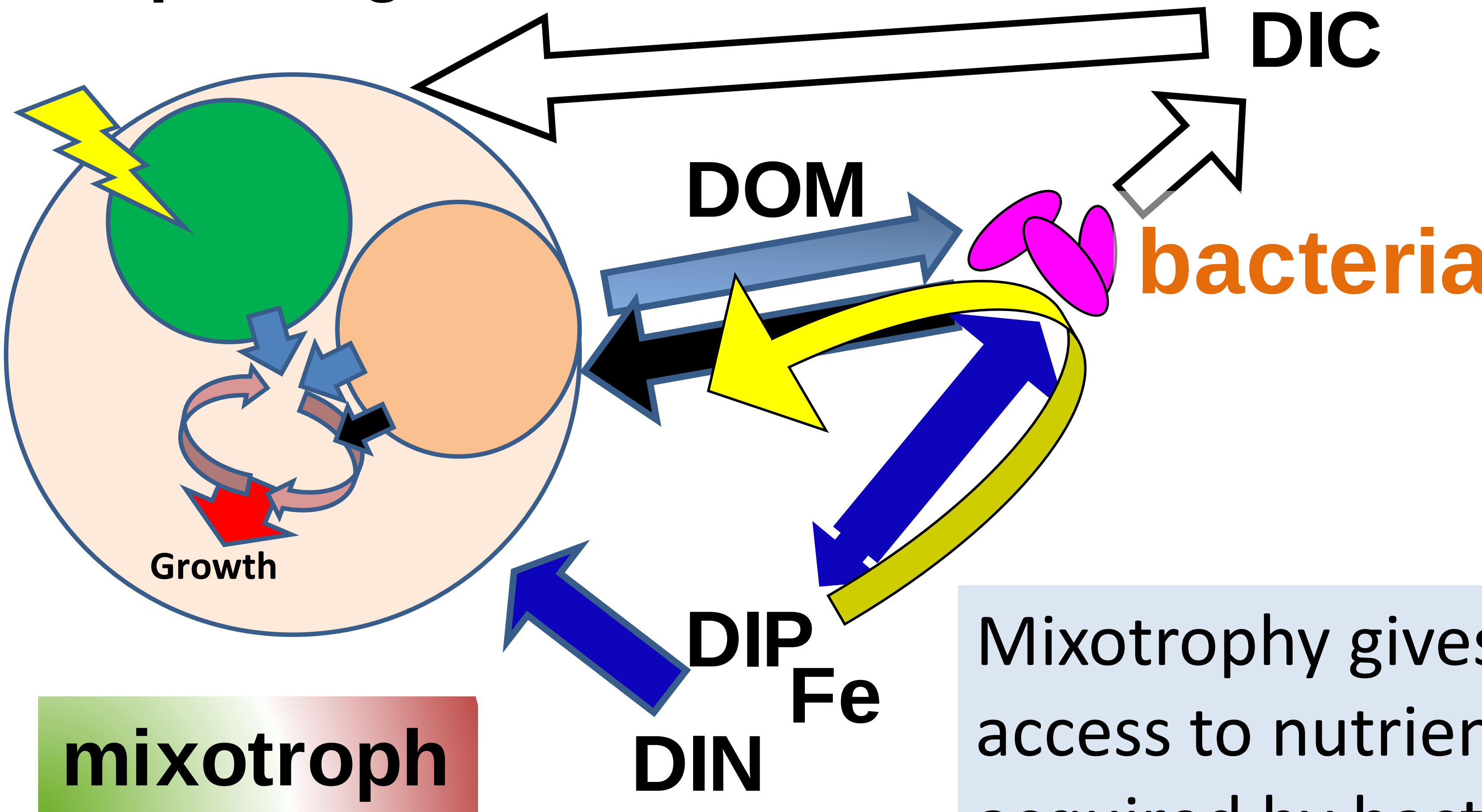
Examples:
Karlodinium,
Prymnesium

Traditional paradigm



Microalgae compete with bacteria for common nutrient needs, with grazers controlling the outcome

New paradigm

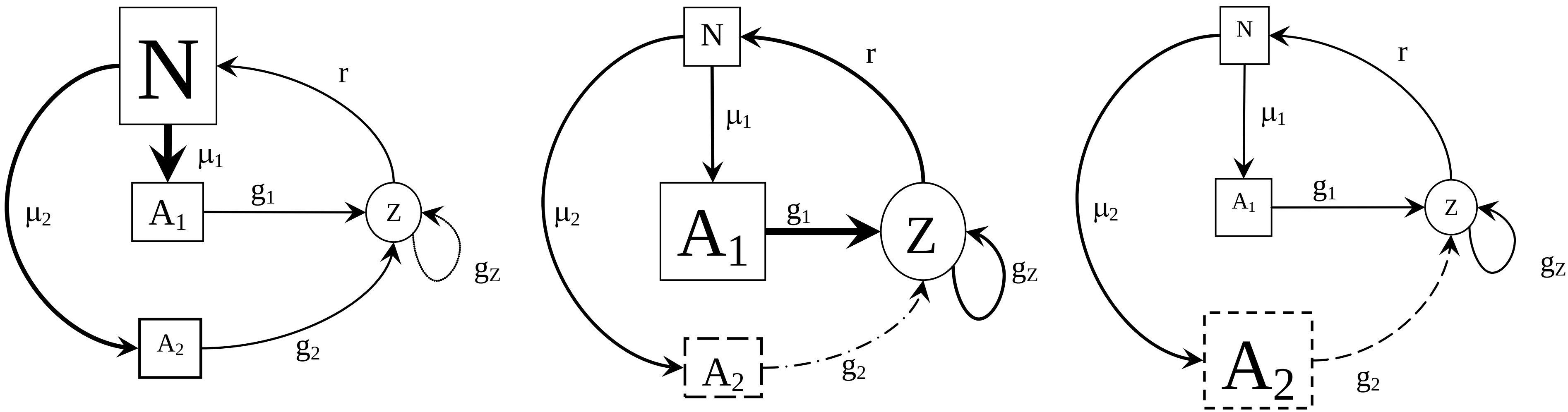


Mixotrophy gives access to nutrients acquired by bacteria, and not otherwise directly available to support C-fixation

Fig.6(b), Mitra et al. (2014) Biogeosciences
doi:10.5194/bg-11-1-2014

Moving on to grazers …

Scope for zooplankton (Z) act as a vector transferring nutrients (N) from first bloom (A_1) to a second (A_2) which forms an EDAB

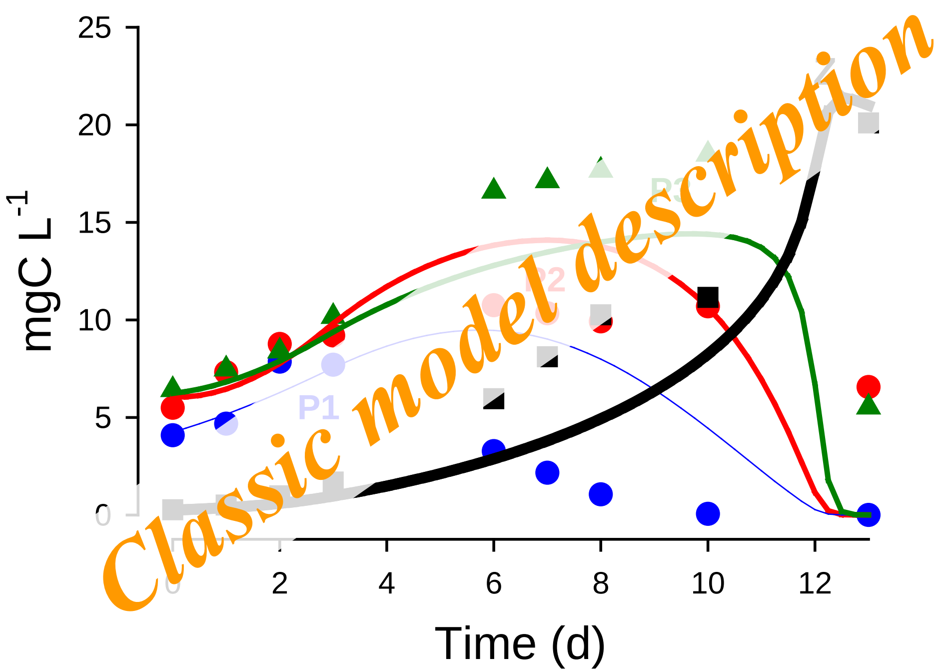


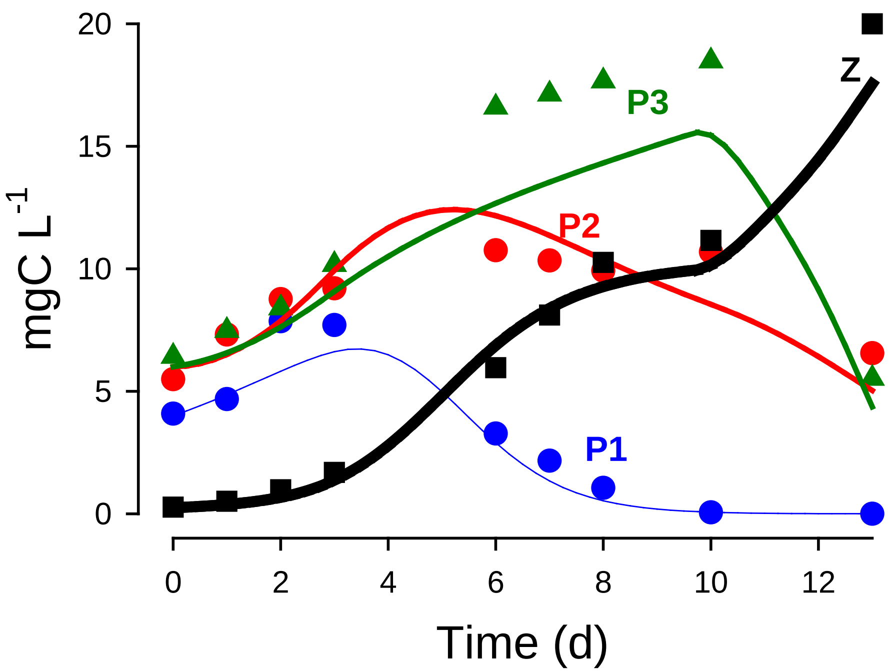
Growth using regenerated nutrients becomes rate limiting;
A_2 becomes nutrient stressed and hence becomes poor quality feed for grazers (de-selected) or perhaps noxious

Mitra & Flynn 2006 BiolLet

Prey de-selection by grazers is an important enabler of bloom formation

Experimental data of grazer Z on 3 prey options





Ratio-based selection term
uses relative preference terms

Selective feeding function, linked to prey quality & quantity

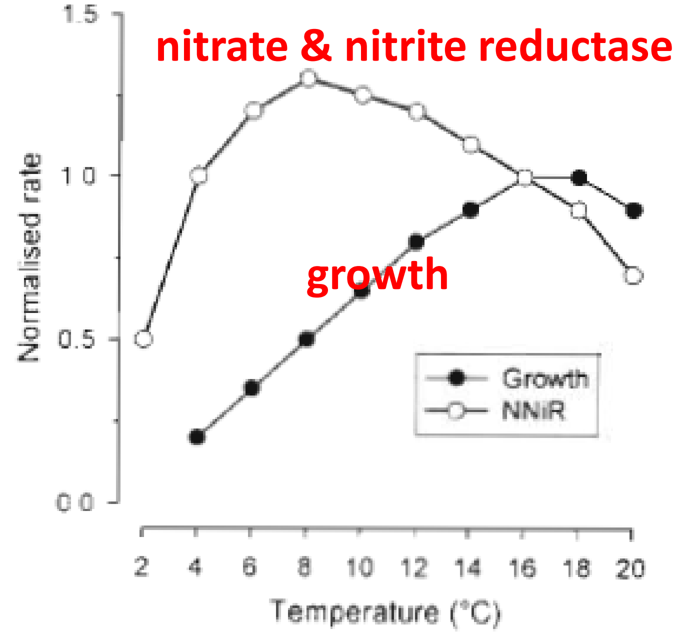
Mitra & Flynn 2006 EcolMod

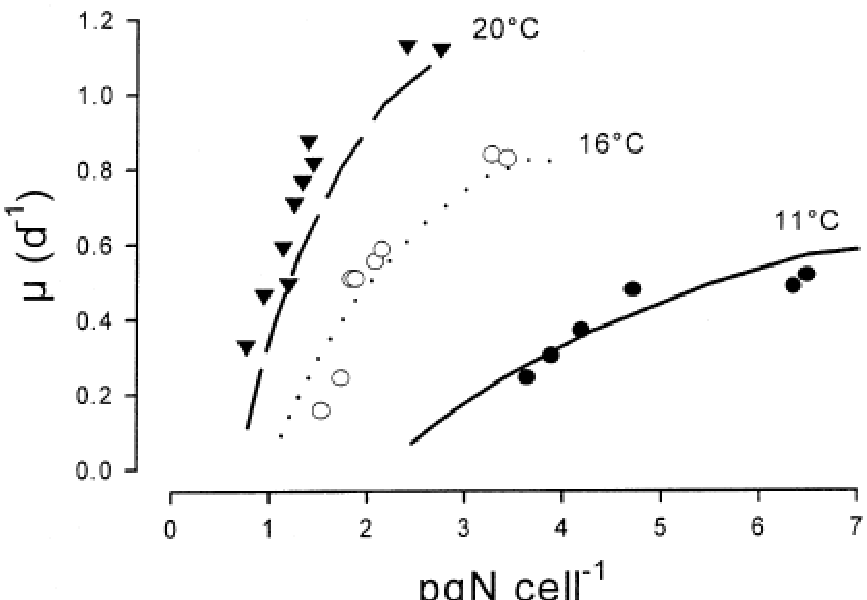
Climate change for HABs

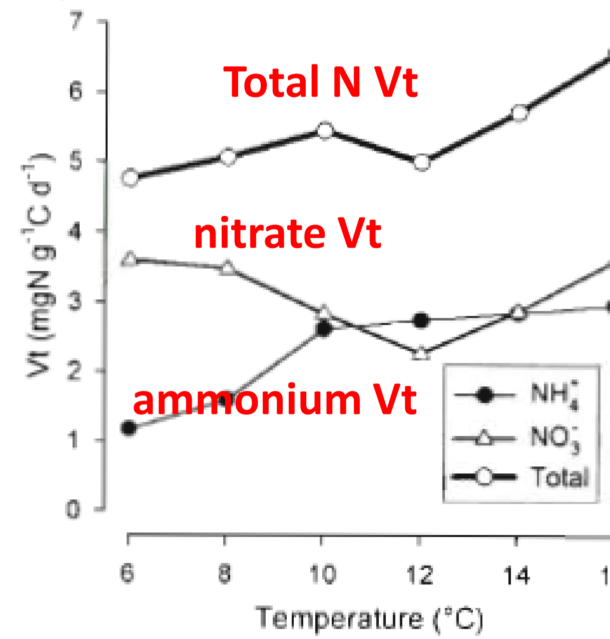
- What we consider climate change need not align simply with what organisms "see"
- These organisms encounter generational changes in their climate every season
- .. in part that they cause through their own activity.
- The environment proximal to the cells may also differ from bulk environmental conditions **(varies with organism size, growth rates, vertical migration)**
- Models can help us better appreciate such issues

Temperature affects more than growth rate

- It affects physiology
- It affects organism size (and thence predator-prey interactions, and cell count-biomass transforms)







nature climate change

LETTERS

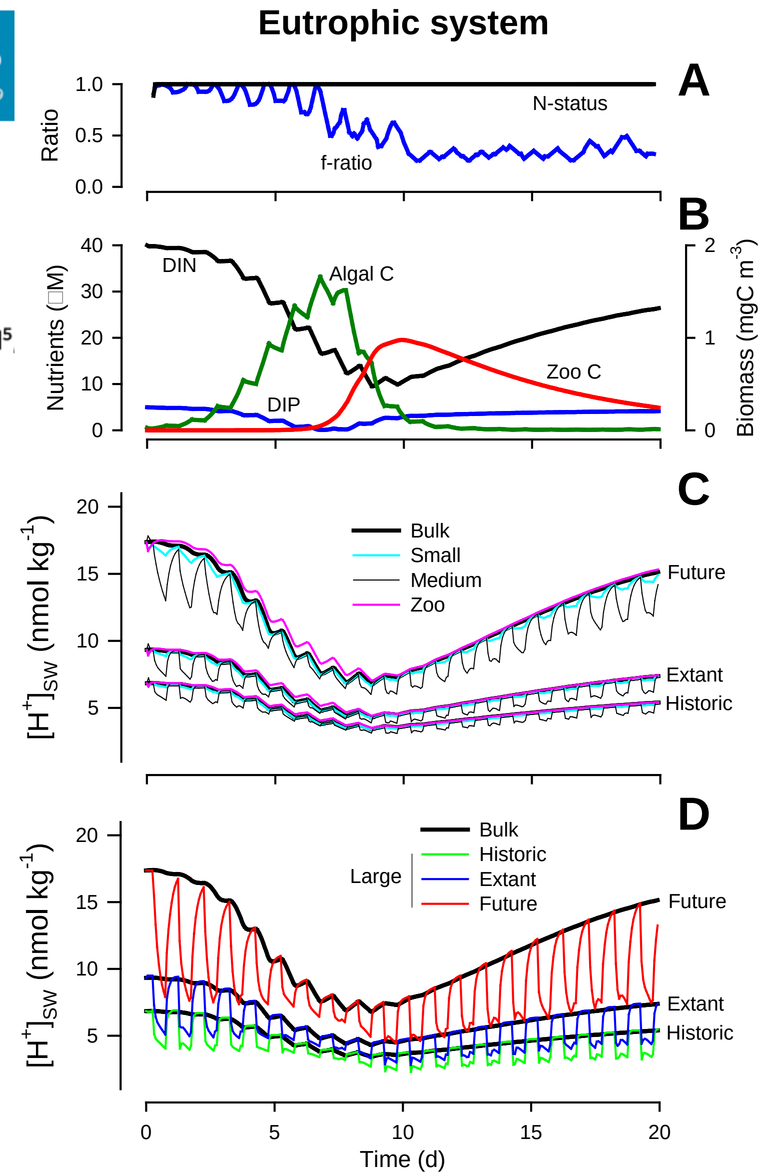
PUBLISHED ONLINE: 15 APRIL 2012 | DOI: 10.1038/NCLIMATE1489

Changes in pH at the exterior surface of plankton with ocean acidification

Kevin J. Flynn[1]★, Jerry C. Blackford[2], Mark E. Baird[3], John A. Raven[4], Darren R. Clark[2], John Beardall[5], Colin Brownlee[6], Heiner Fabian[1] and Glen L. Wheeler[2,6]

- With OA, $[H^+]$ **(hence pH)** is less stable as buffering is less
- Bulk pH tells only part of the story
- particle-surface pH changes over the day, increasing with size and activity
- OA & basification stresses will be greater for larger organisms and those in aggregates

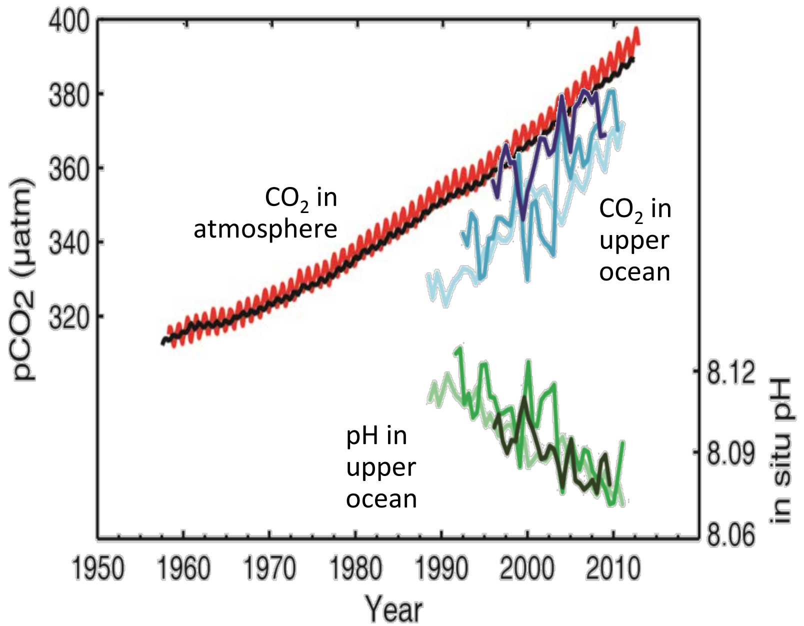
(but those may be better adapted)

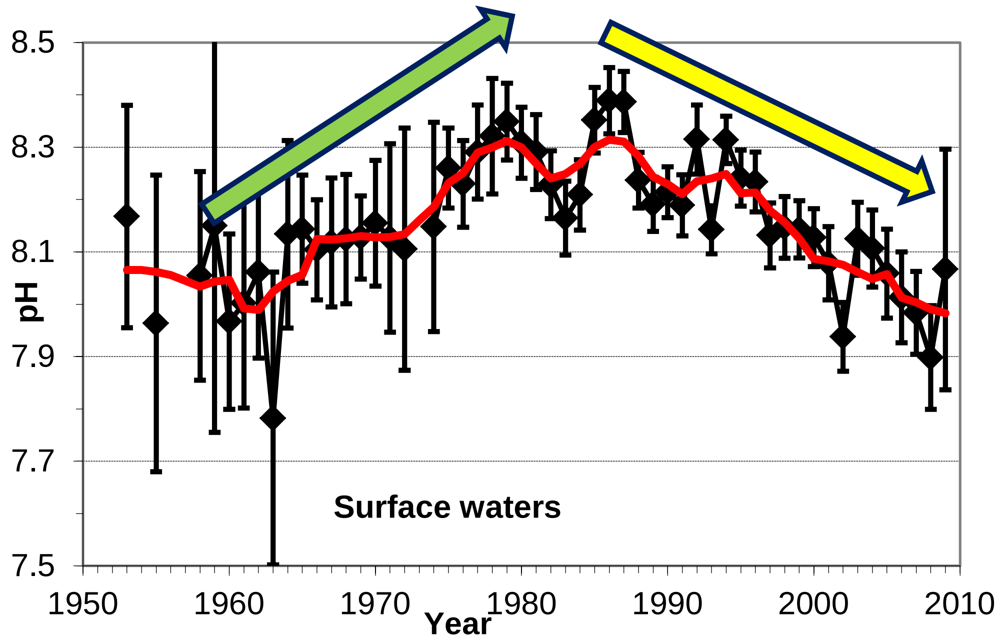


Particle ESD 25, 75, 150µm; zoo 200 µm

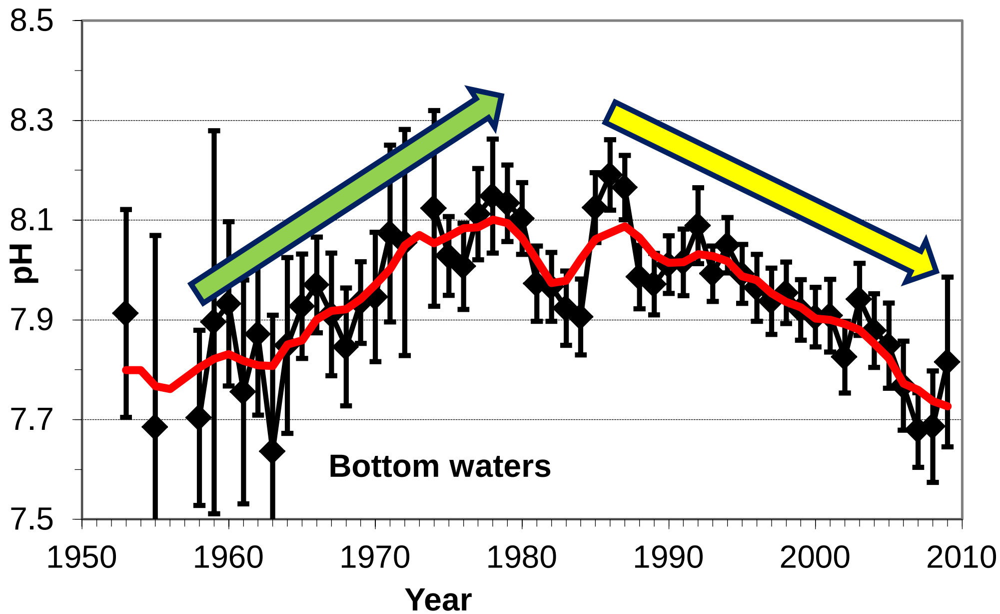
Ocean Acidification (OA) – an example of biotic-abiotic interactions

- Dissolution of atmospheric CO_2 in the oceans leads to OA
- Primary production consumes CO_2, resulting in pH increasing **("basification" – the opposite of acidification)**
- **Basification adversely and selectively affects plankton growth**





In some coastal waters, home to most fisheries, nutrient pollution **(eutrophication)** until the 1980's stimulated phytoplankton growth, countering OA **(pH increased)**

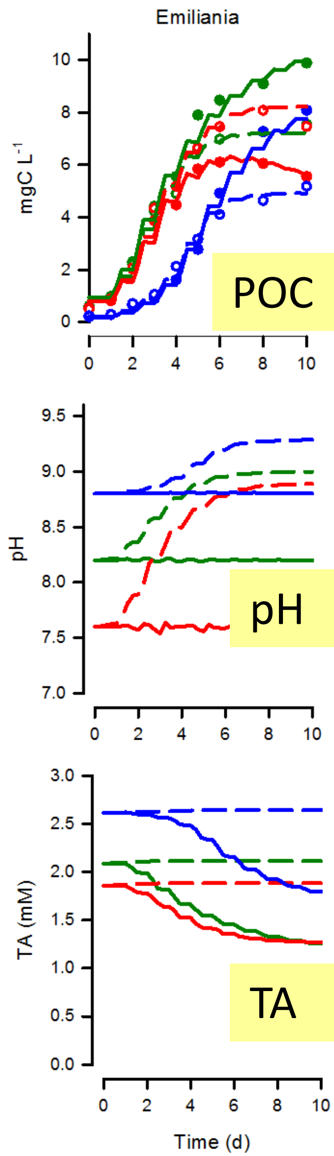


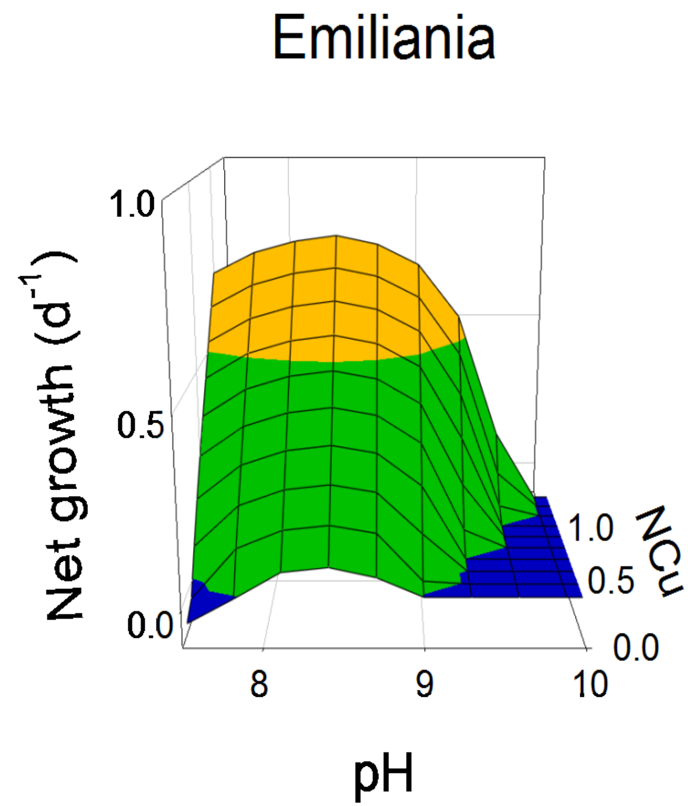
…the impact of OA may now be faster in such waters because of <u>de</u>-eutrophication starting in the 1980's

Variations in seawater pH in inner Danish waters Data from NJ Carstensen, Dept. of Biosciences, AU, Denmark

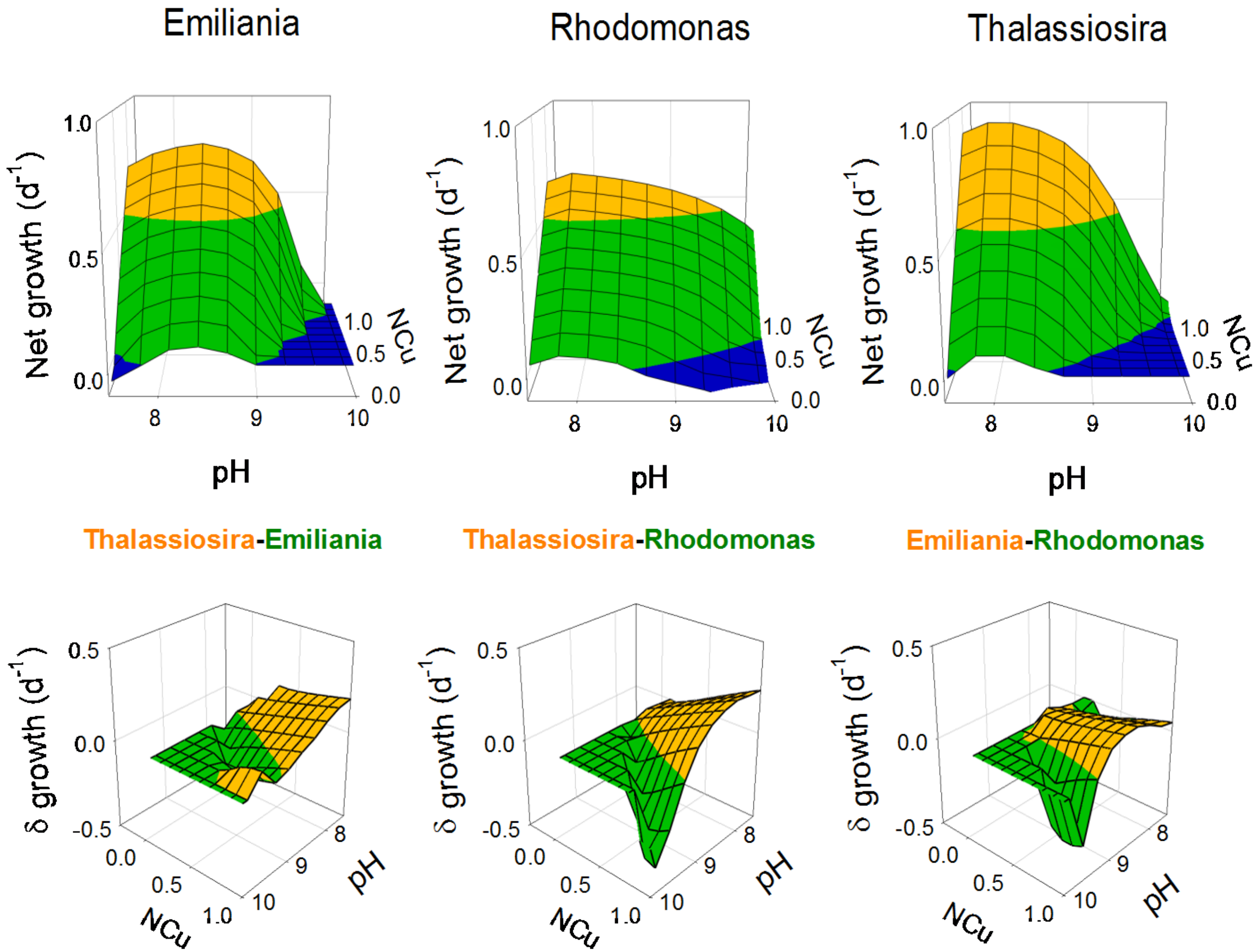
An example of linking nutrients, pH, algal growth, and models

- Unialgal cultures grown in fixed/drift pH used to parameterise CNPChl aclimative models …
- … generating response curves linking pH and nutrient status to growth and death rates





Poor nutrient status (low NCu) narrows the pH optima for growth

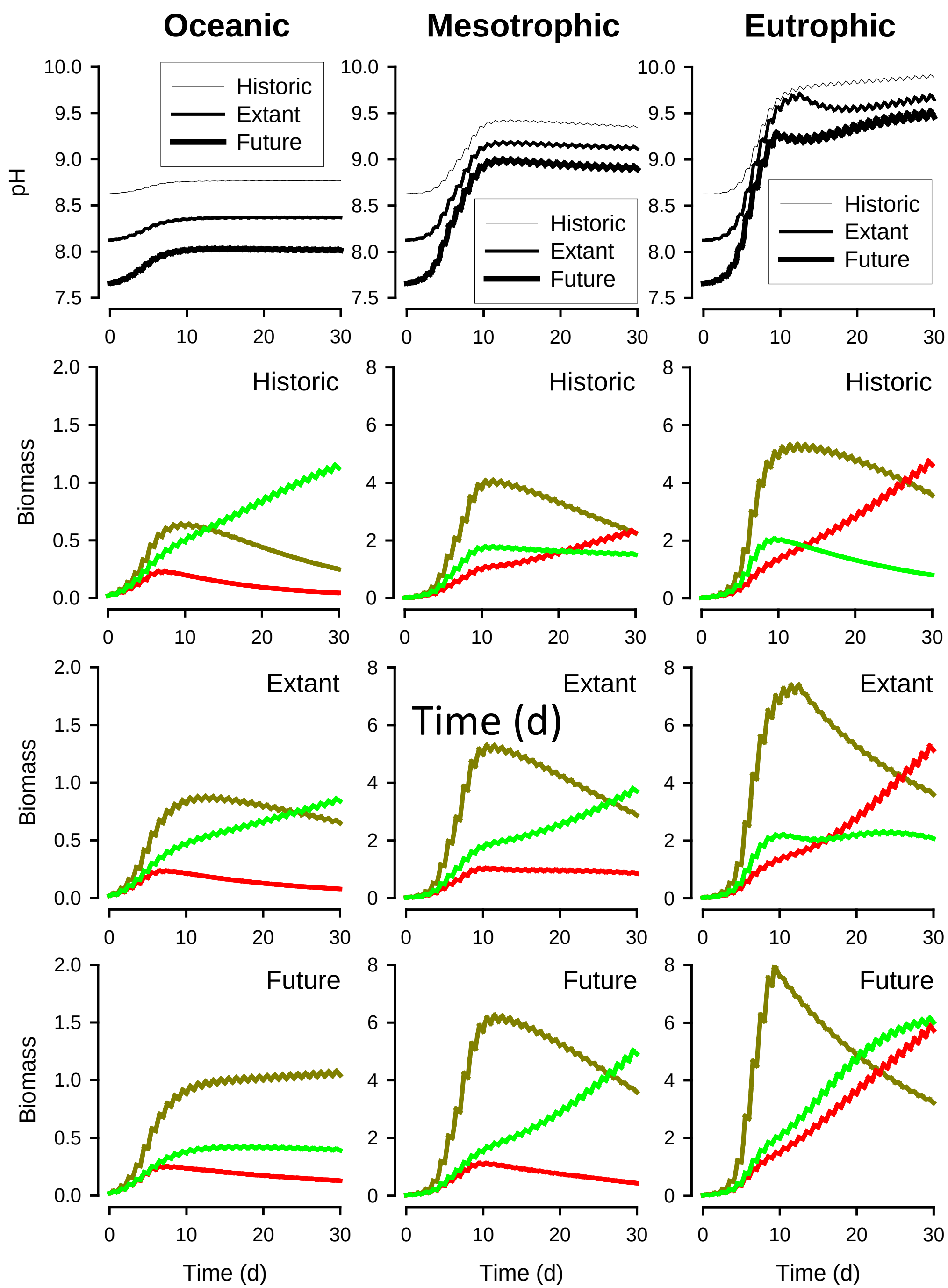


- Different species exhibit different response curves to pH and nutrient status, opening windows for competitive advantage
- NCu = cellular N-status (0 poor; 1 good)

Flynn et al. 2015 ProcRoySoc B

Simulation Scenarios

- Different oceanographic conditions (mixing depths, nutrient load)
- Different coloured lines for different phytoplankton configurations
- **Historic** (preindustrial) pCO_2 280 ppm
- **Extant** pCO_2 390 ppm
- **Future** (prediction for 2100) pCO_2 1000 ppm



Flynn et al. 2015 ProcRoySoc B

And we need to understand interactions far beyond this

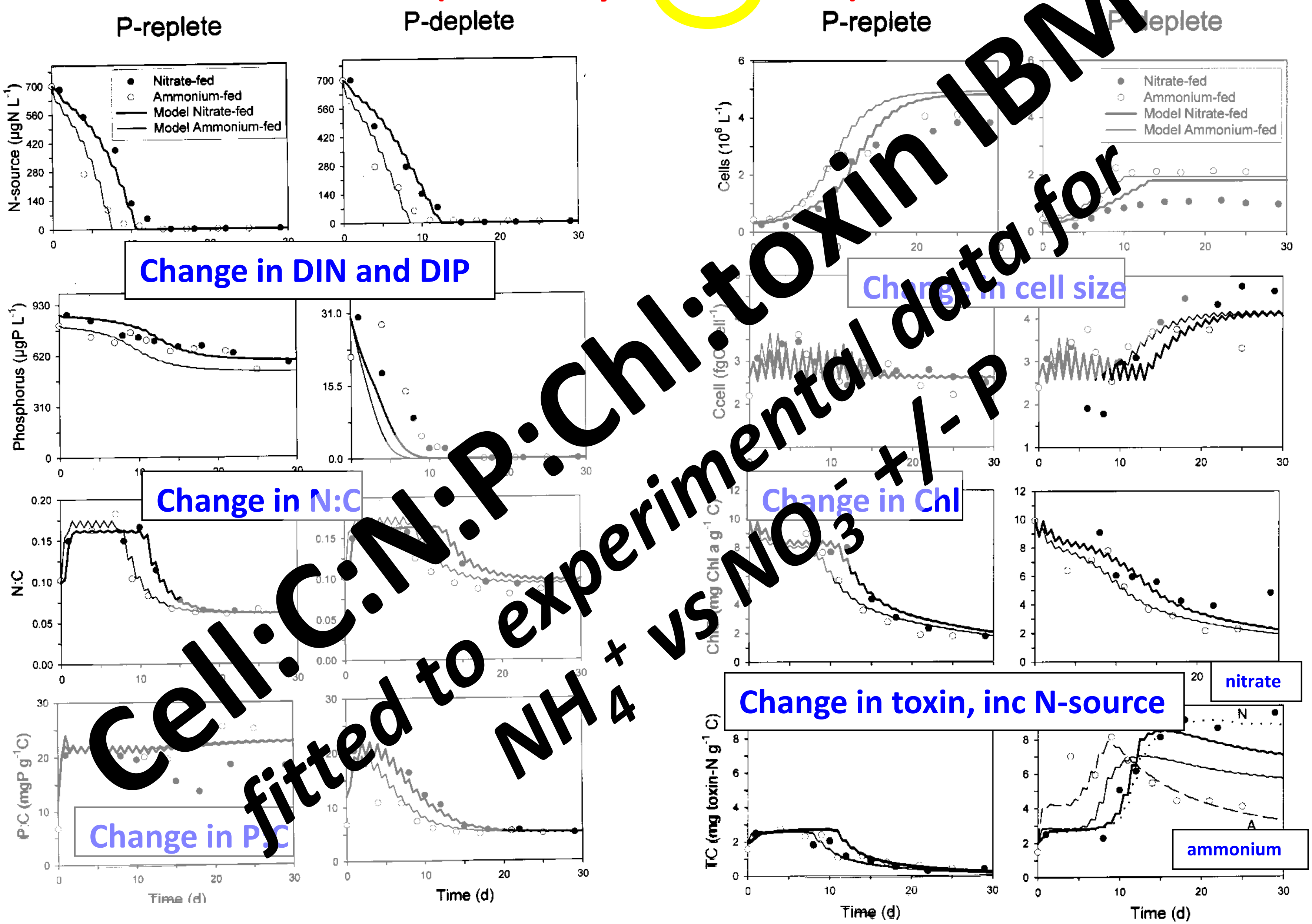
- Likely that similar optima curves as for pH also exist for temperature + nutrient-status, and likewise for prey and also grazers
- And these will all have knock-on impacts on trophic dynamics

Stoichiometric quality, toxins & grazing

- Stoichiometric quality **(C:N:P)** is key to trophic dynamics,
- yet variable stoichiometry is often not modelled **(nor measured in experiments of HAB or non-HAB plankton)**
- Grazing functions capable of properly describing feeding and switching between different prey types, C:N:P, sizes are also very rare **(nor well studied in exp.)**
- Implicit or explicit modelling of toxicity is typically very simplistic
- But then data collection is still too often **(often solely)** based upon organism counts, with little information on nutrient history (C:N:P)
- **Little seems to have advanced over the last decade that helps systems dynamics modelling ☹**

Alexandrium PSP with N and P-stress

(John & Flynn 2002 MEPS)



Models, nutrient ratios and Redfield

- Coupling variable stoichiometry studies and models reveals problems in interpreting N:P ratios and Redfield “optima”.
- External N and P concentrations, and Internal C:N and C:P are the drivers for growth **(links to external N:P or internal N:P are emergent)**

Journal of Marine Systems 83 (2010) 170–180

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Contents lists available at ScienceDirect

Journal of Marine Systems

journal homepage: www.elsevier.com/locate/jmarsys

Do external resource ratios matter?
Implications for modelling eutrophication events and controlling harmful algal blooms

Kevin J. Flynn *

Progress in Oceanography 84 (2010) 52–65

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Contents lists available at ScienceDirect

Progress in Oceanography

journal homepage: www.elsevier.com/locate/pocean

Ecological modelling in a sea of variable stoichiometry: Dysfunctionality and the legacy of Redfield and Monod

Kevin J. Flynn *

The optimal cellular C:N:P varies widely….

… P-ratios lower than Redfield can support good growth.

Conversely poly-P accumulation enables far higher P contents than may be expected and enables good growth in the absence of external P for many generations.

A Pragmatic Challenge

Molecular Biology vs Data For Models

- Molecular techniques identify immense variety in biological systems, and are frequently promoted as tools in monitoring impacts of climate change
- Models need to simplify, decrease/summarise all that variety into few ecological functional type descriptions
- But where € limits research, decisions need to be taken on the direction of studies .. Breadth of functional types vs comparison between strains .. Molecular vs biomass+rate measurements.
- Molecular techniques do not typically provide rate values of utility to systems dynamics models

Routes to the future

- HAB models require us to model much more than the HAB organisms
- Need to identify & describe the ecological plankton functional types across all trophic levels
- More emphasis needs to be placed on understanding causal interactions
- … rates, feedbacks, cascades etc are needed to aid model construction, and greater appreciation of variability and risks in model operation
- Systems modelling should be just as part and parcel of HAB science as ‘omics, statistics, toxin analysis etc.
- **If we can’t usefully model it, then we don’t understand it**

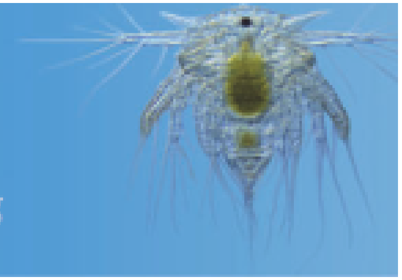
THE challenge ….

- .. is getting modelling and field/lab work really linked up
- Repeatedly stated as important, but little happens, complicated by semantics and other points of confusion between different researchers
- Typically takes 10yrs for advances in biology to progress to models
- Can we afford this delay, this waste of effort?

The role of the Expert Witness

- Collecting data is a major logistic challenge
- But there is a vast amount of phenomenological information – ***we need to exploit this***
- Modellers can engage the ecologist and biologist through "expert witness validation" …
- … *does the model do what the expert expects it to do under all plausible forcings?*

Journal of
Plankton Research
plankt.oxfordjournals.org



J. Plankton Res. (2015) 0(0): 1–9. doi:10.1093/plankt/fbv036

HORIZONS

Acclimation, adaptation, traits and trade-offs in plankton functional type models: reconciling terminology for biology and modelling

KEVIN J. FLYNN[1]*, MICHAEL ST JOHN[2], JOHN A. RAVEN[3,4], DAVID O.F. SKIBINSKI[5], J. ICARUS ALLEN[6], ADITEE MITRA[1] AND EILEEN E. HOFMANN[7]

.. And one final application of models for risk assessment for HABs in new climates

Interface Focus
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Research

Monster potential meets potential monster: pros and cons of deploying genetically modified microalgae for biofuels production

K. J. Flynn[1], A. Mitra[1], H. C. Greenwell[2] and J. Sui[1]
[1]Centre of Sustainable Aquatic Research, Swansea University, Swansea SA2 8PP, UK
[2]Department of Earth Sciences, Durham University, Durham DH1 3LE, UK

- much research is being conducted to generate GM microalgae
- there must be a risk that these organisms will escape **(especially biofuels algae from vast open ponds)**
- these could pose a very serious HAB threat, as all the features needed in a GM microalga also describe those for an EDAB **(rapid growth, efficient light & nutrient usage, resistant to grazers)**