From phytoplankton to fish: global patterns in energy flow through marine ecosystems

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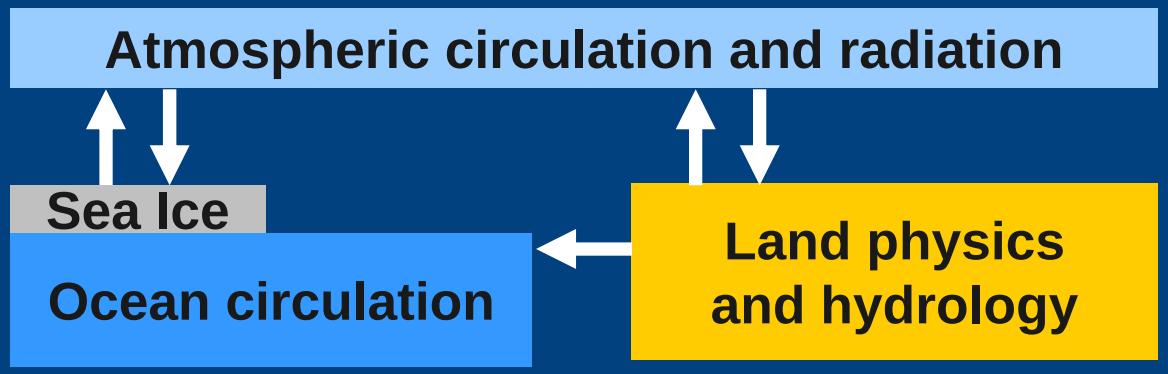
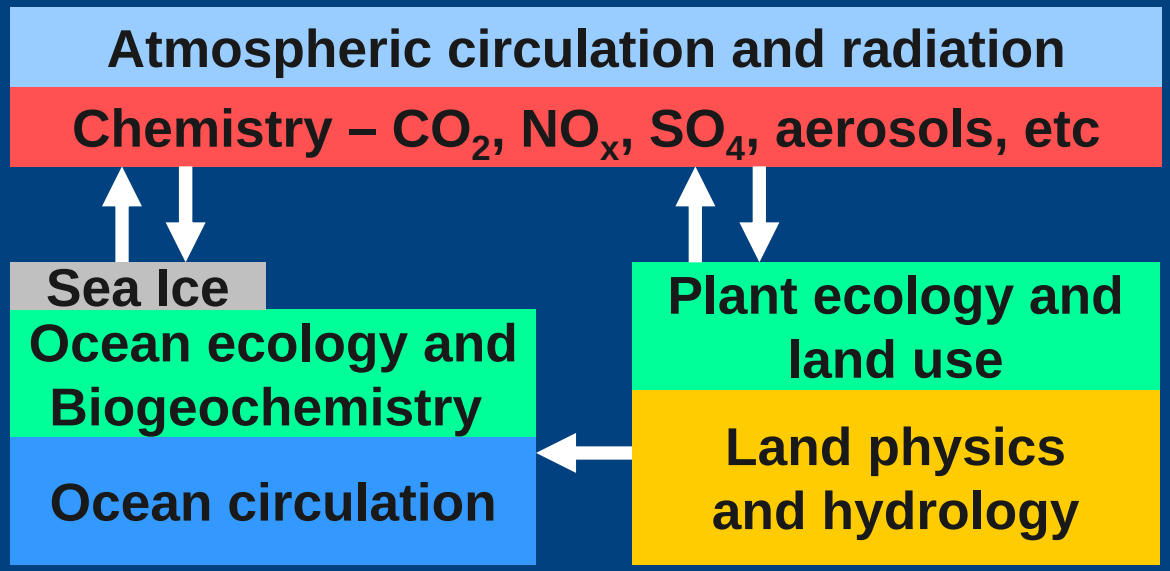
Earth System Model (ESM)

Climate Model



Earth System Model

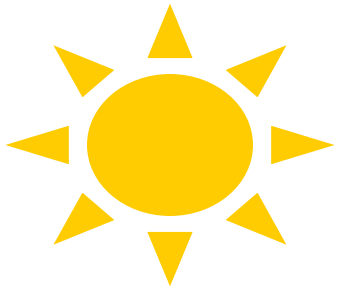


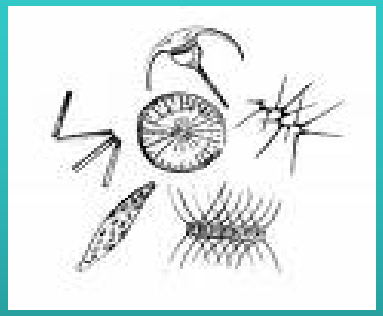
How will climate change impact global fisheries production?

we have low confidence in predictions of future fisheries production because of uncertainty over future global primary production and the transfer of this production through the food chain for human consumption

Paraphrased from K.M. Brander, PNAS, 2007

Primary productivity: the foundation of marine ecosystems



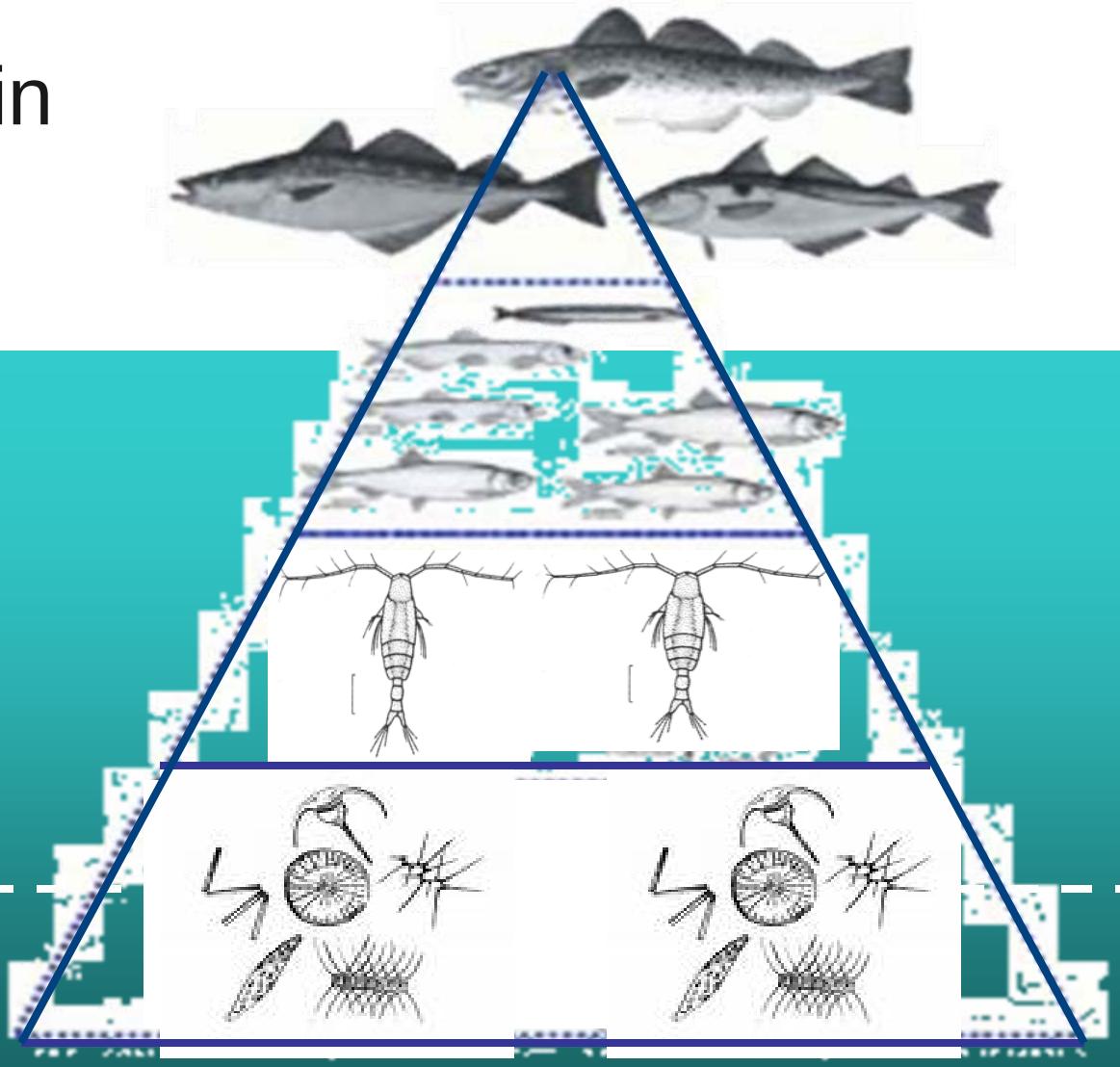


$$106CO_2+16HNO_3+H_3PO_4+78H_2O \rightarrow C_{106}H_{175}O_{42}N_{16}P+150O_2$$

Nutrients

Old view:

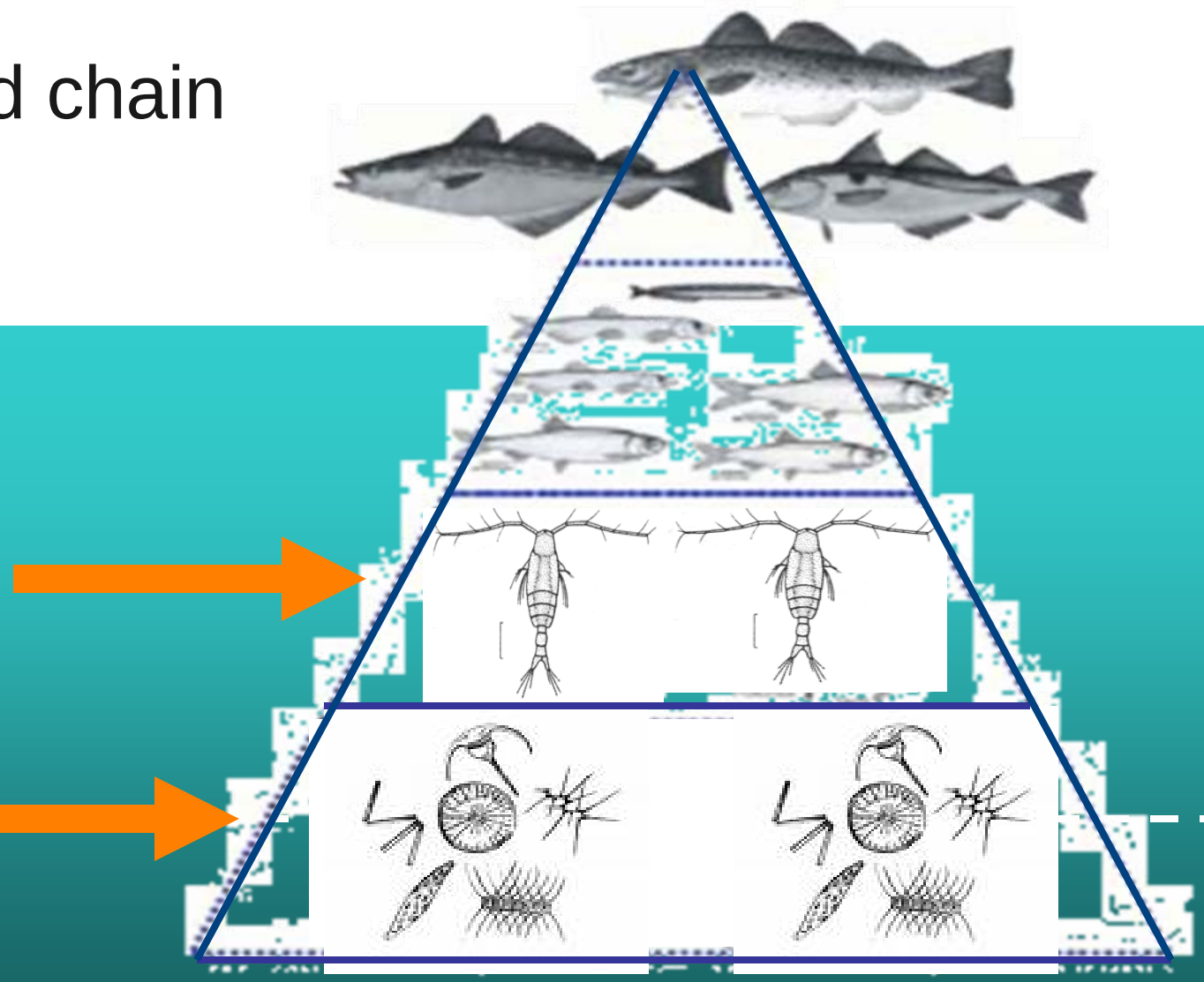
a simple food chain



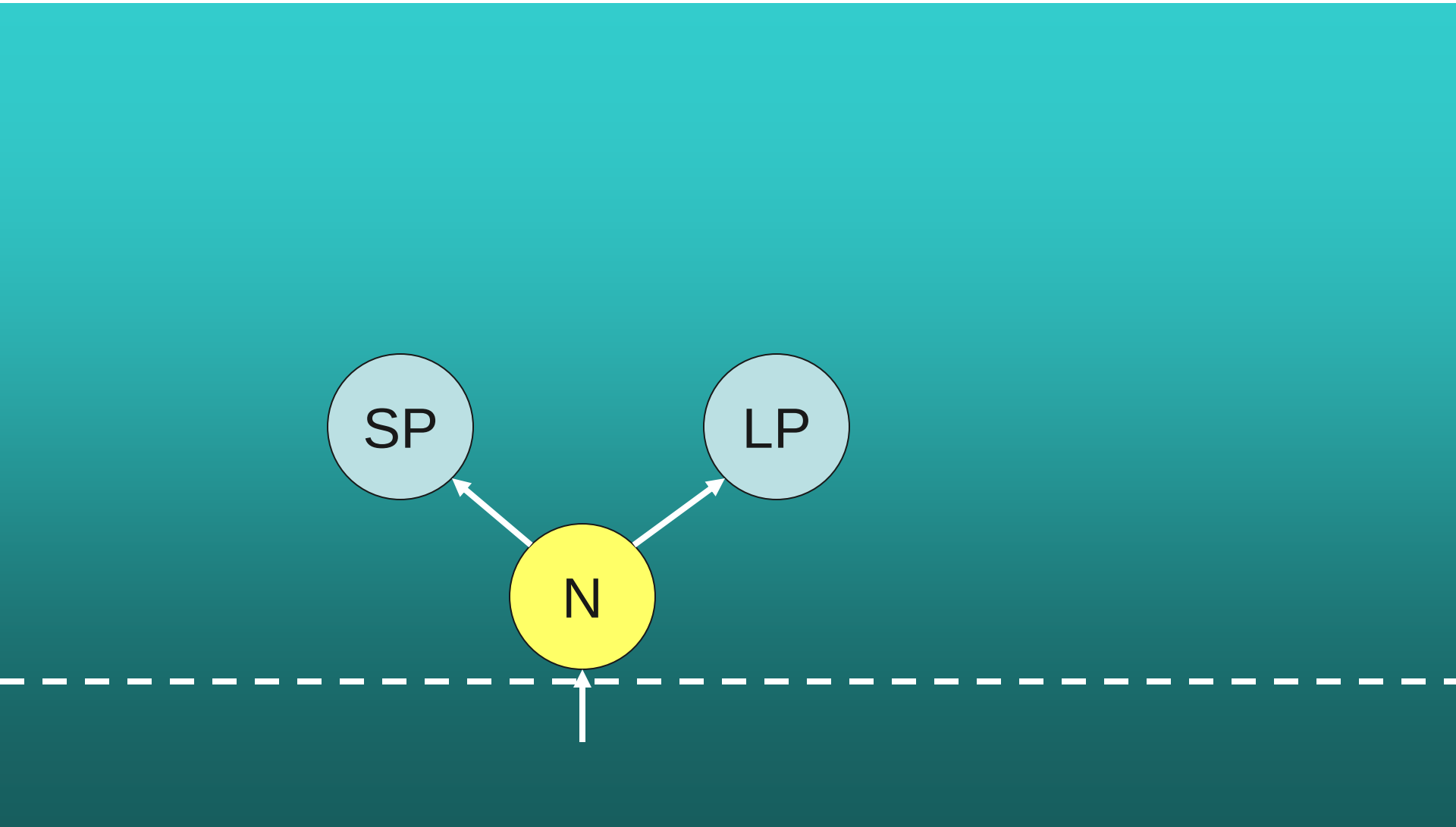
Graphics from Frank et al. (2005)

Old view:

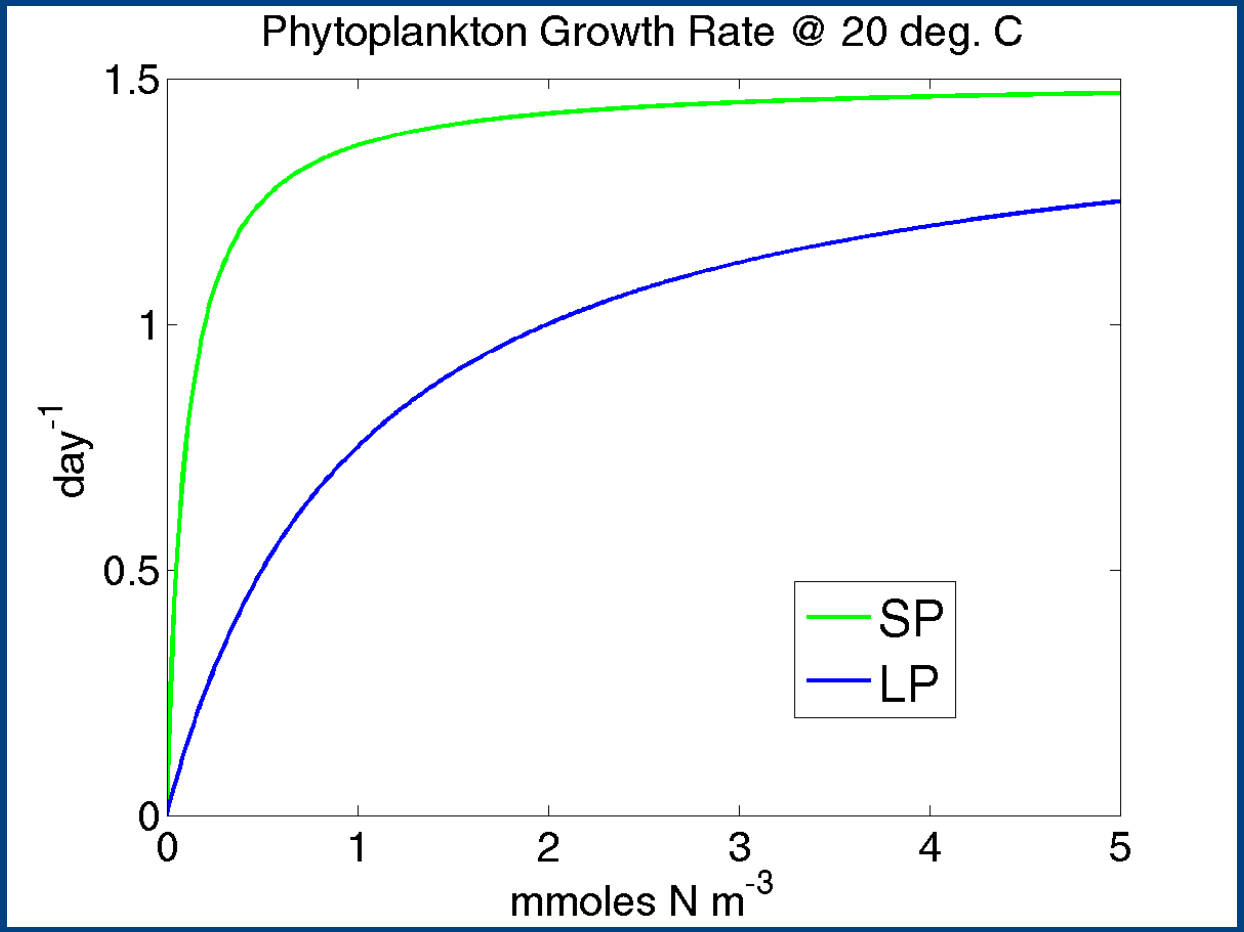
a simple food chain



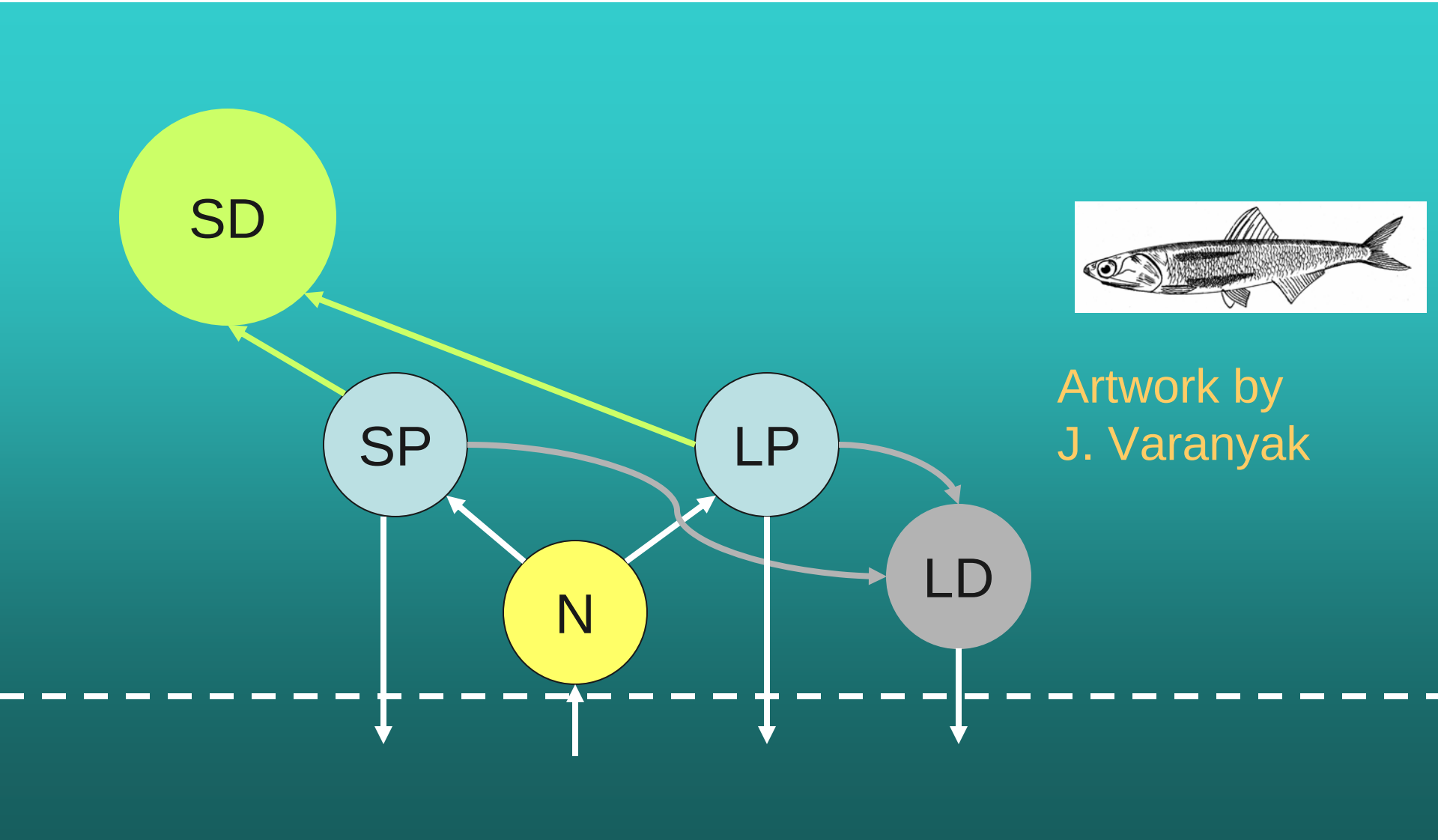
Different phytoplankton groups spanning a broad range of sizes compete for nutrients



Small phytoplankton are adapted to low nutrient environments

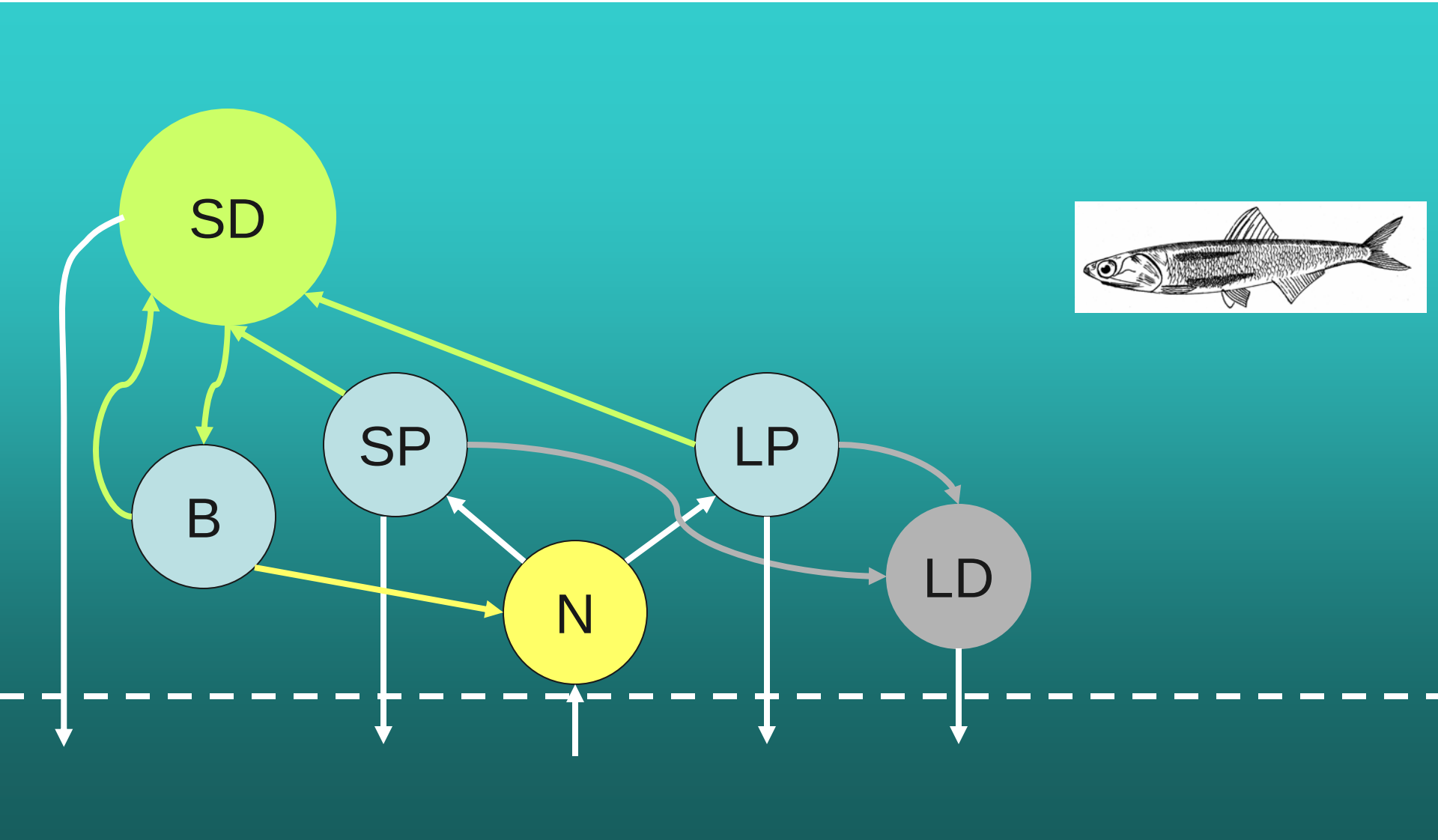


Phytoplankton can sink, be lost to viral lysis, exude dissolved nutrients or aggregate into large detritus

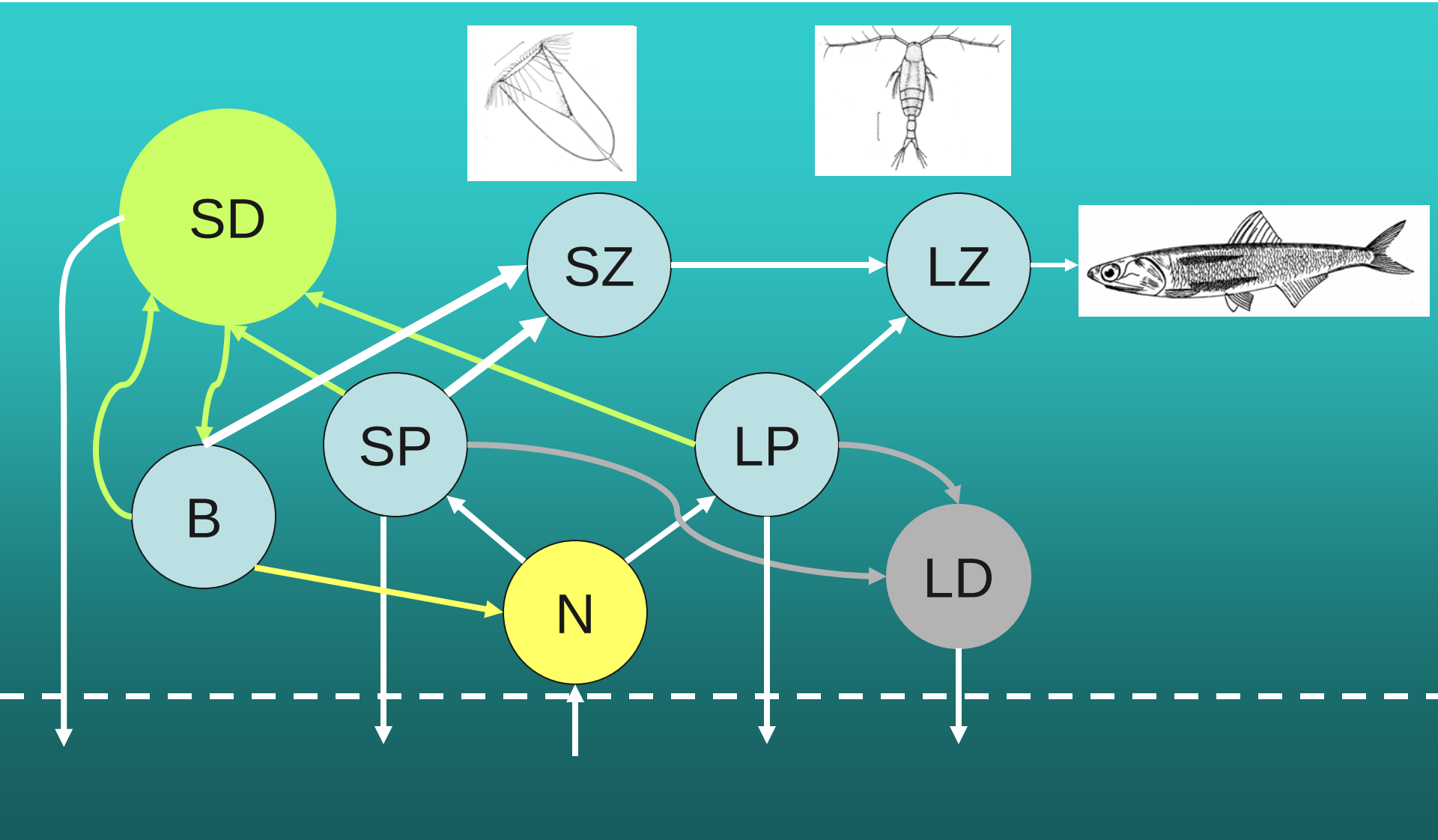


Artwork by
J. Varanyak

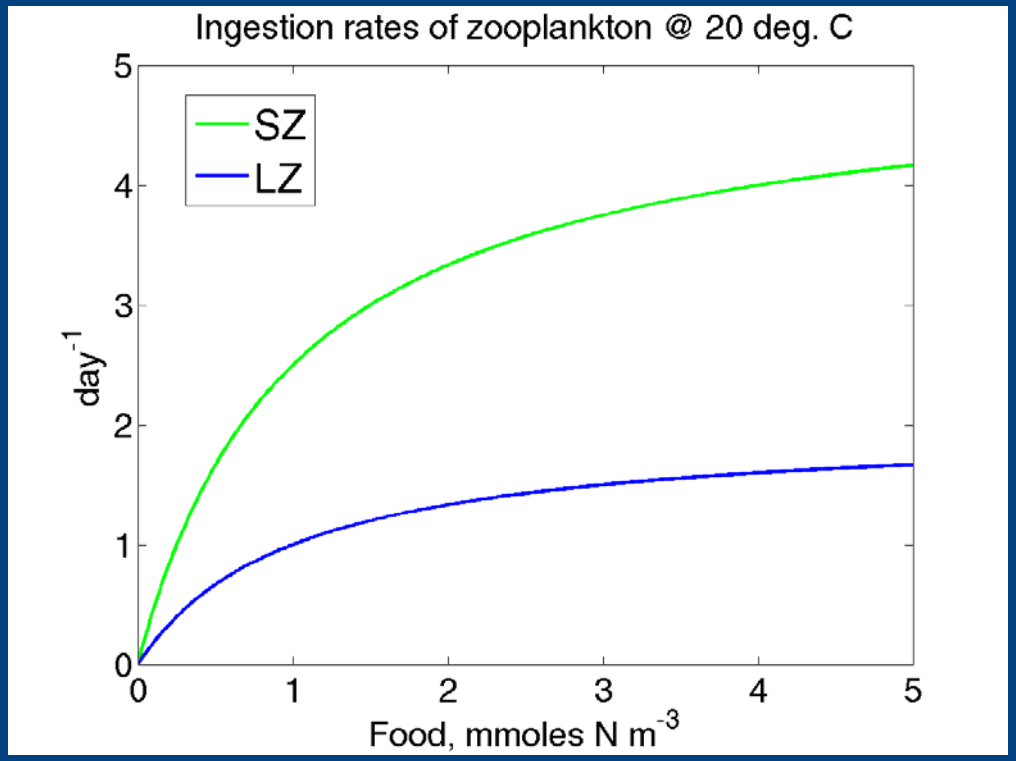
Small detritus (SD) can be mixed to deeper water or consumed by bacteria. Bacteria can remineralize SD to N, or be lysed by viruses and returned to SD



Zooplankton must "compete" for primary production with other phytoplankton loss mechanisms

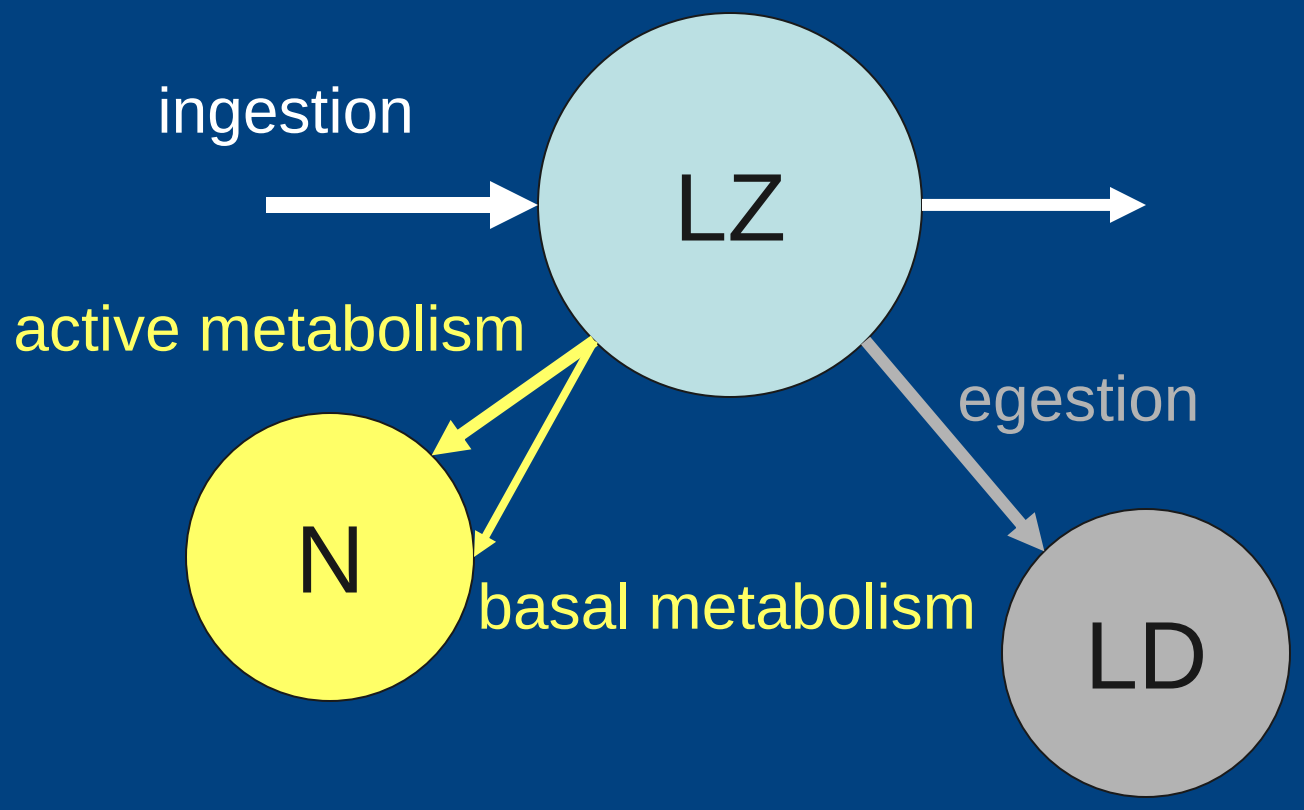


Small zooplankton are voracious consumers



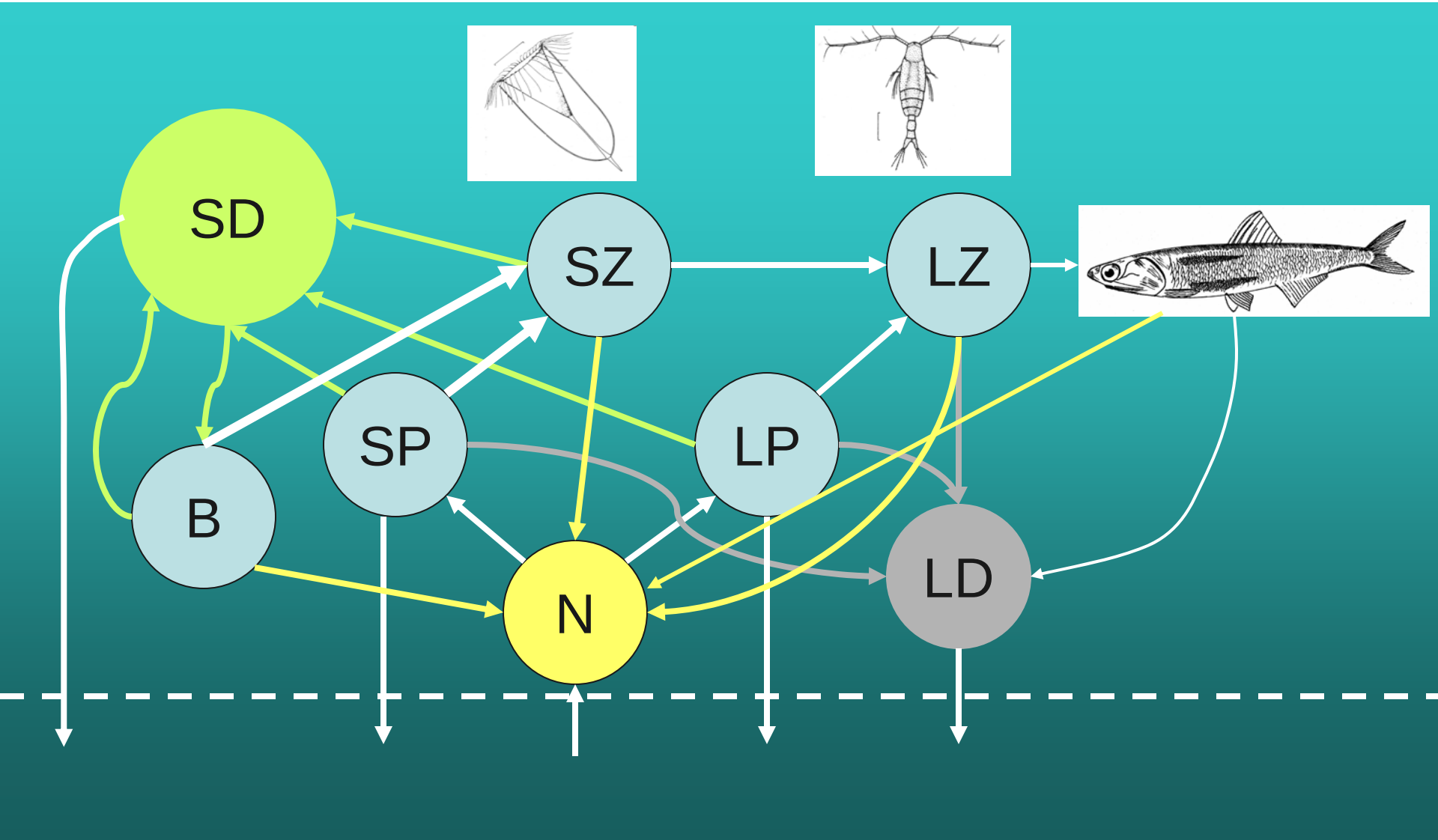
The nutrient uptake advantage of small phytoplankton is counteracted by their susceptibility to small zooplankton grazing

Not all of the energy zooplankton consume is available to the next trophic level



New view:

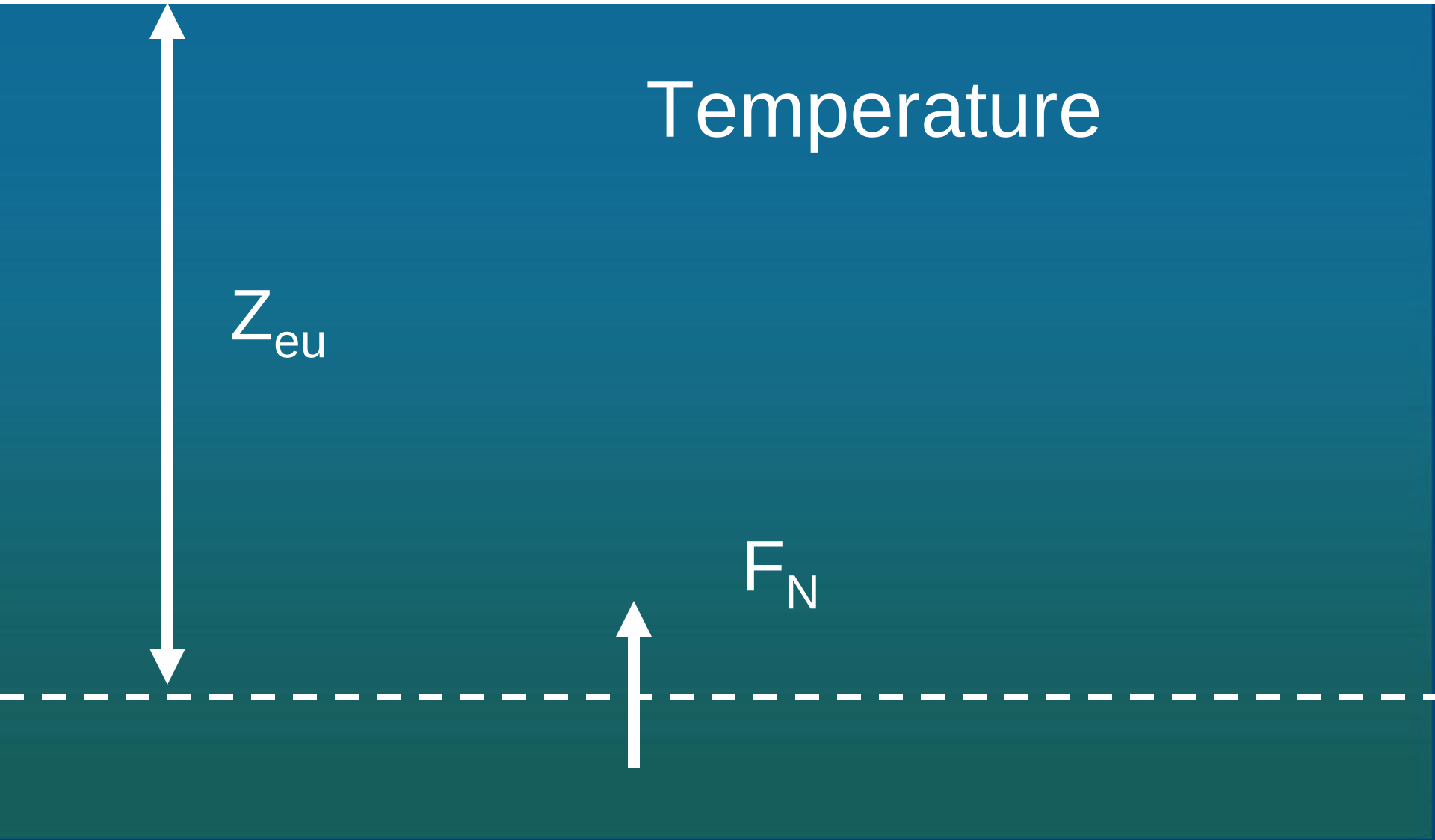
A complex food web



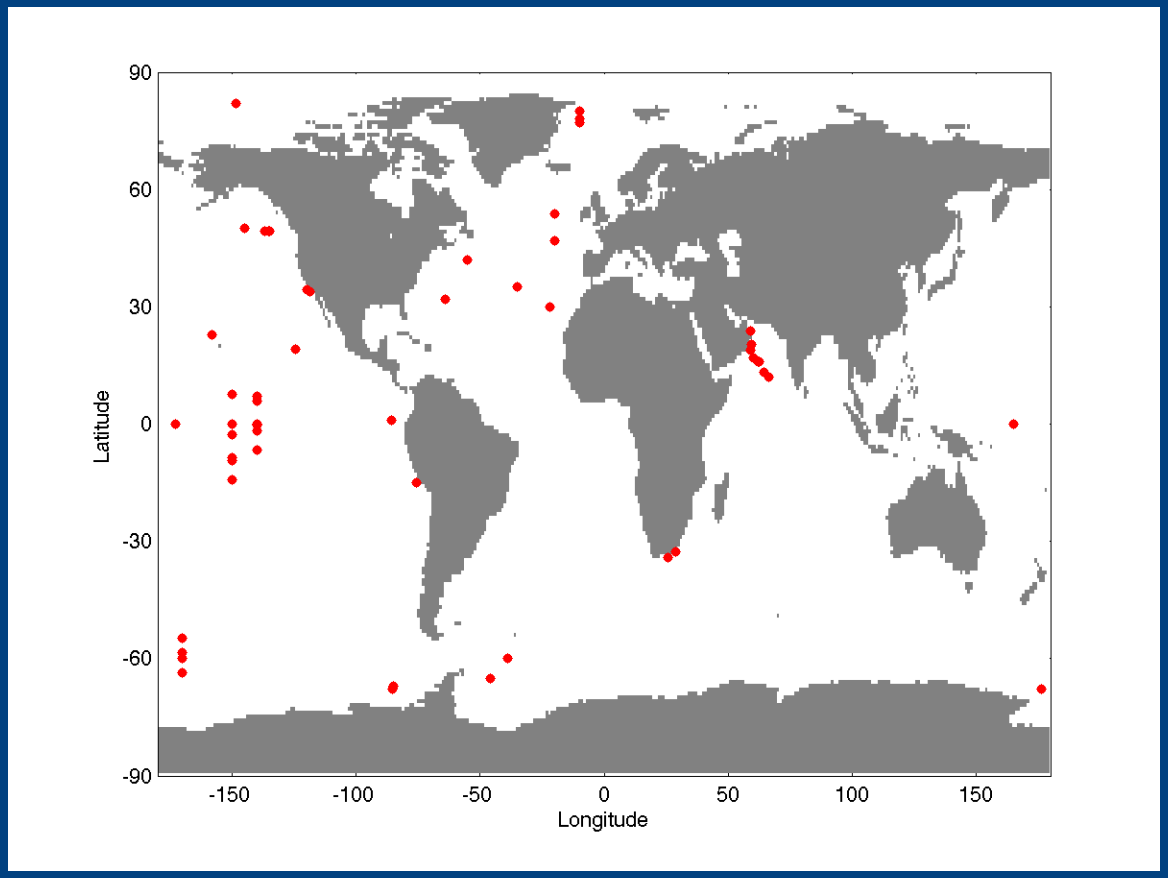
Specific questions:

- Do observed global cross-ecosystem patterns in phytoplankton and mesozooplankton biomass and productivity emerge from the equilibrium solutions of the model?
- What are the mechanisms and parameters that control the ratio of mesozooplankton production to primary production?

Classify ecosystems based on flux on nutrient enrichment, temperature, and euphotic zone depth



Calibrate based on data from a wide range of oceanic ecosystems

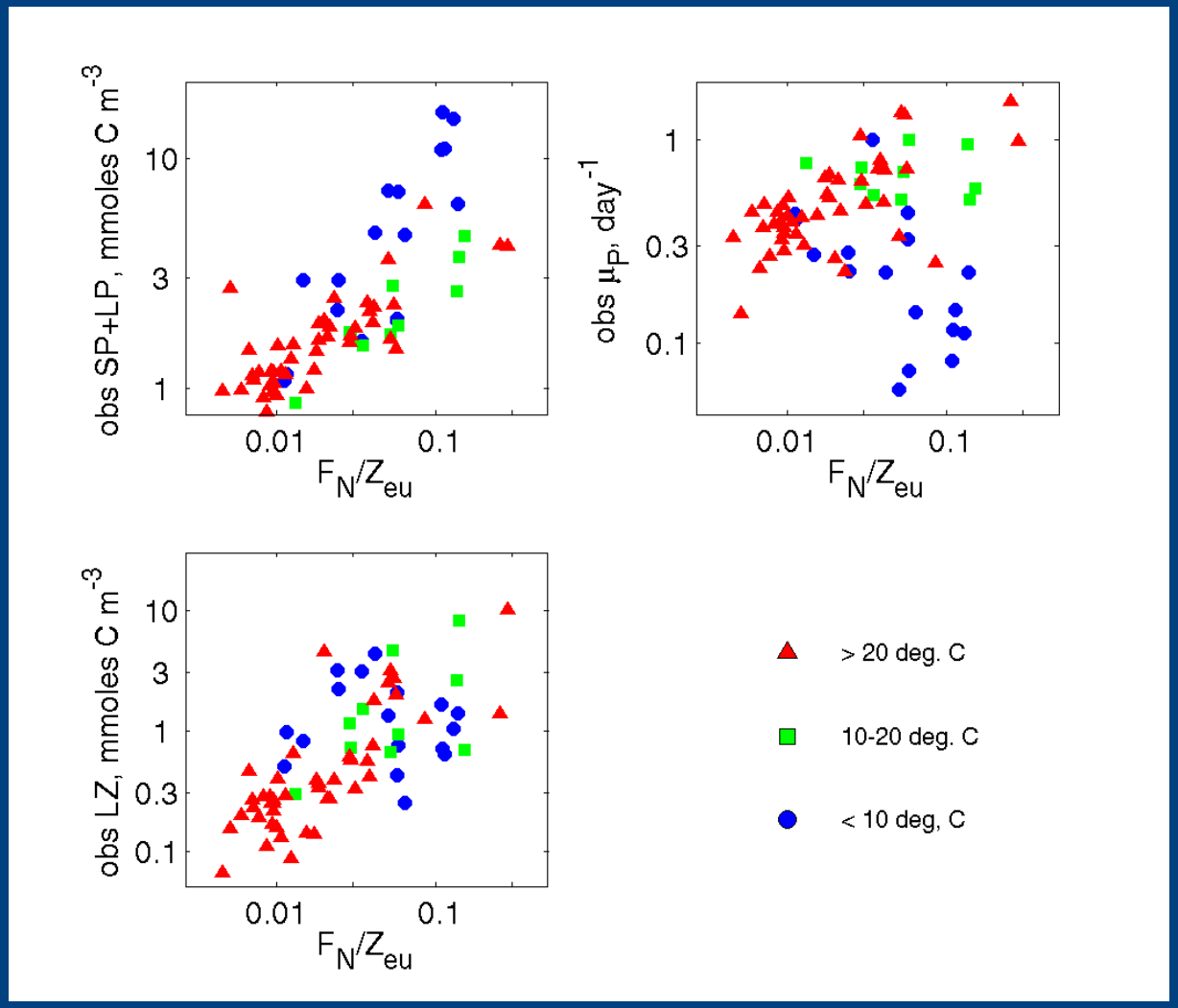


- temperature
- euphotic zone depth
- export or nutrient flux into the euphotic zone

- phytoplankton biomass
- primary production
- mesozooplankton biomass

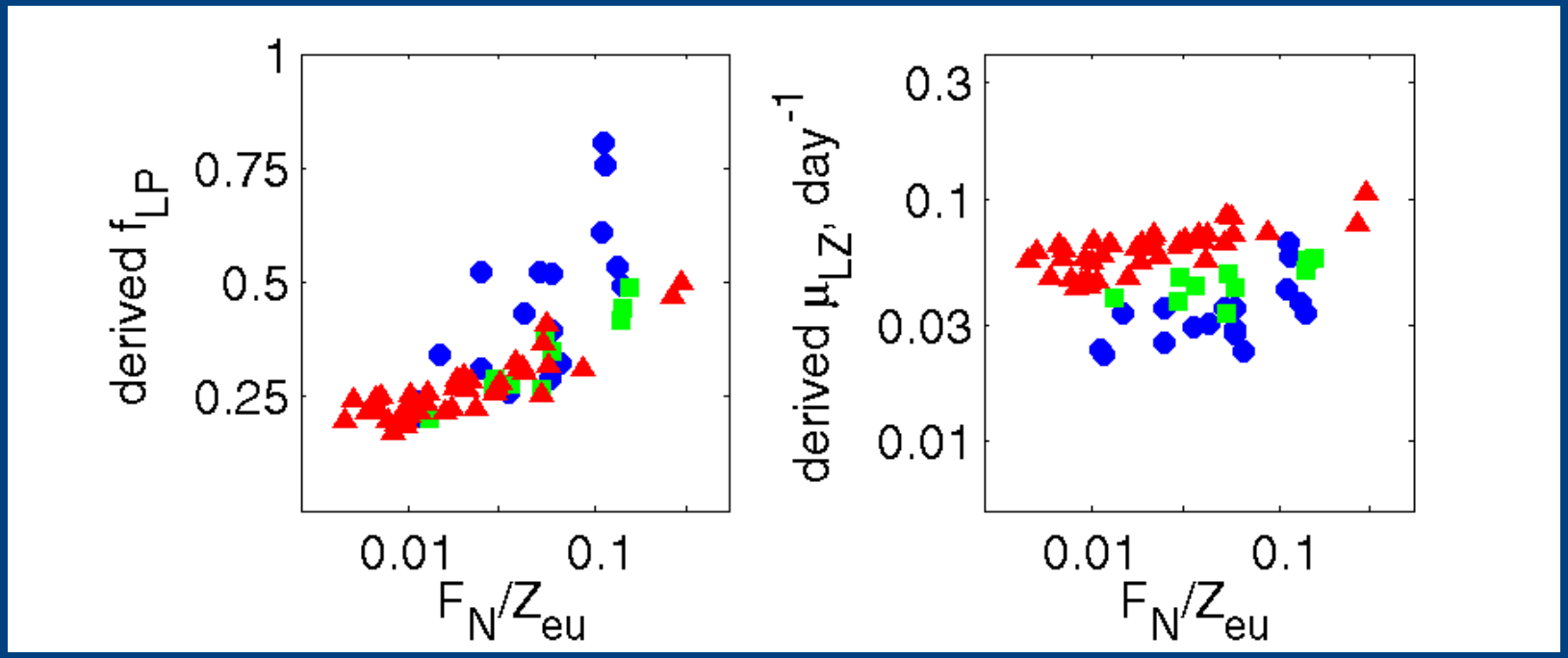
Dunne et al. (2005); Stock and Dunne (submitted)

Calibration dataset



Empirical constraints for phyto size distribution and mesozooplankton growth rate

$f_{LP} = f(chl)$ $\mu_{LZ} = f(chl,sst)$

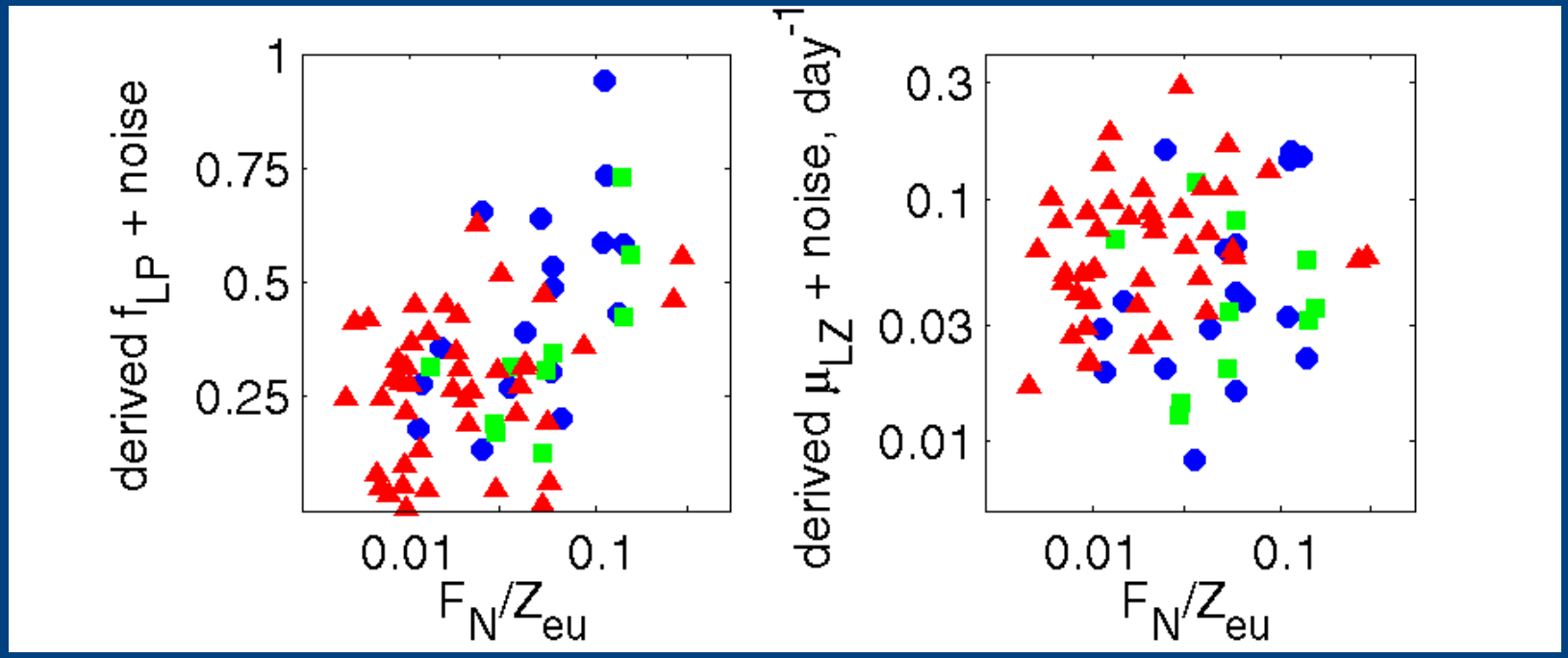


Dunne et al., 2005
Denman and Pena, 2002

Hirst and Bunker, 2003

Add variability to empirical functions to weight consistently during calibration

$f_{LP} = f(chl)$ $\mu_{LZ} = f(chl,sst)$

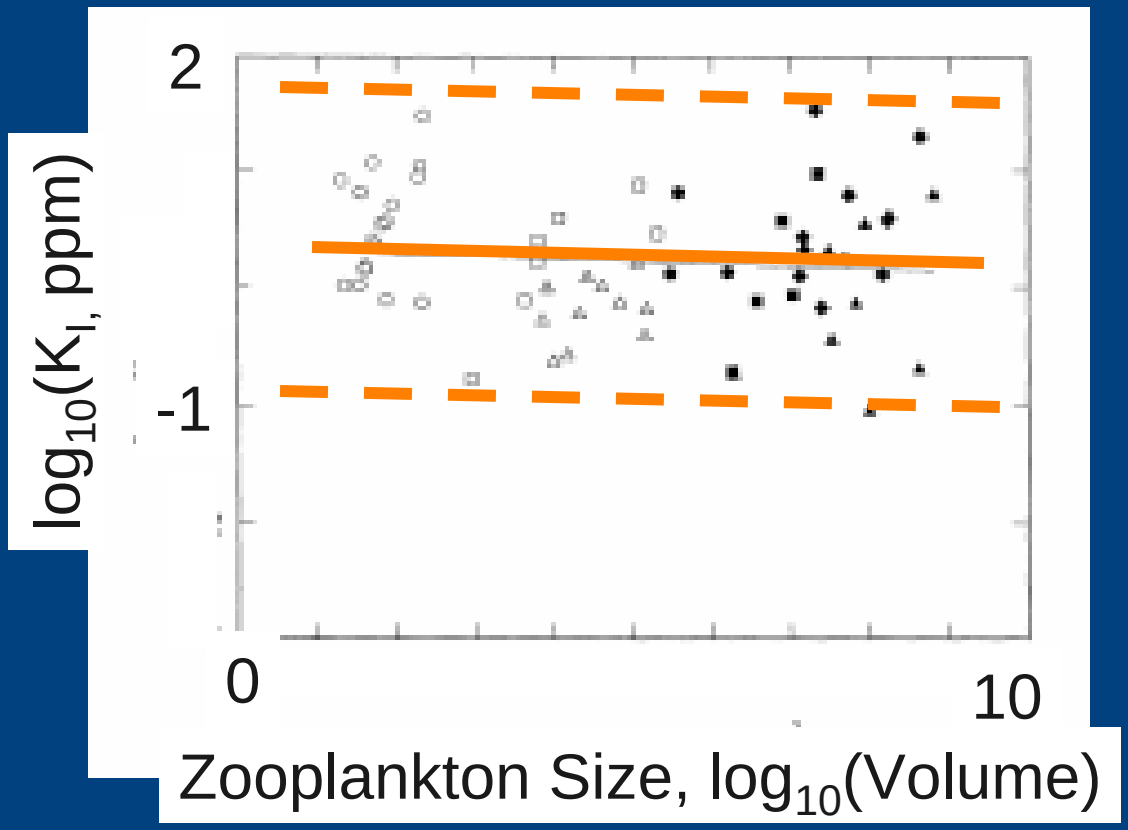


Dunne et al., 2005
Denman and Pena, 2002

Hirst and Bunker, 2003

Model calibration

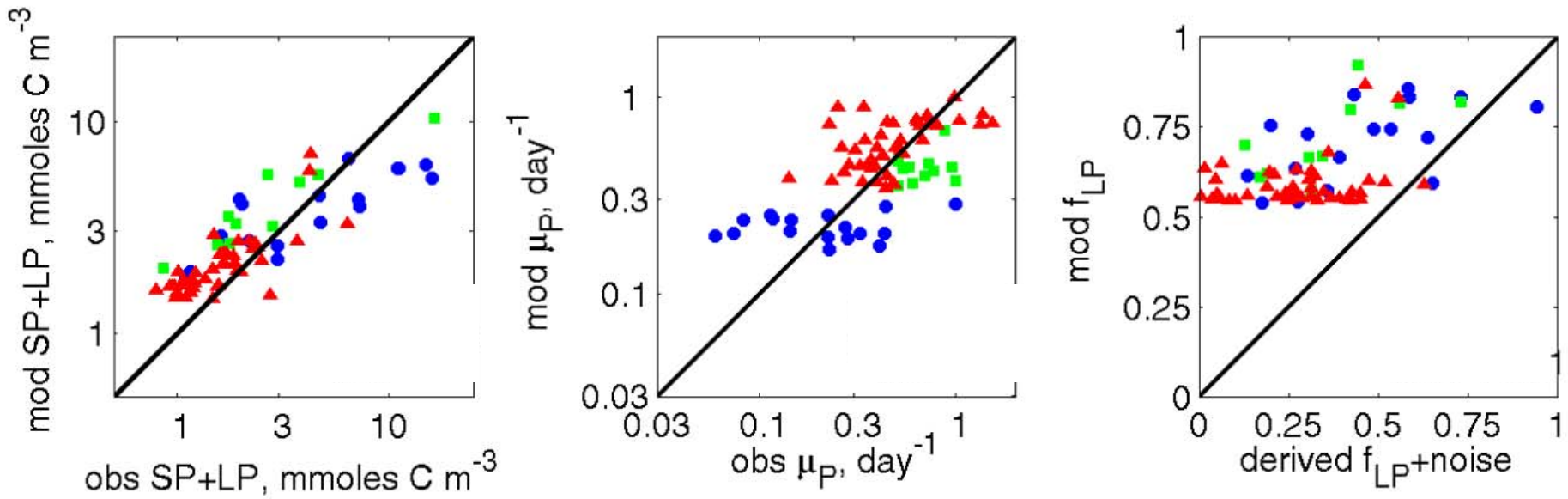
Start with one calibration parameter: Half-saturation constants zooplankton feeding (K_I)



- Lab measurements vary over 3 orders of magnitude
- No empirical or strong theoretical evidence to expect first order changes in K_I with organism size

Hansen et al., L&O, 1997

Initial model-data comparison: phytoplankton quantities

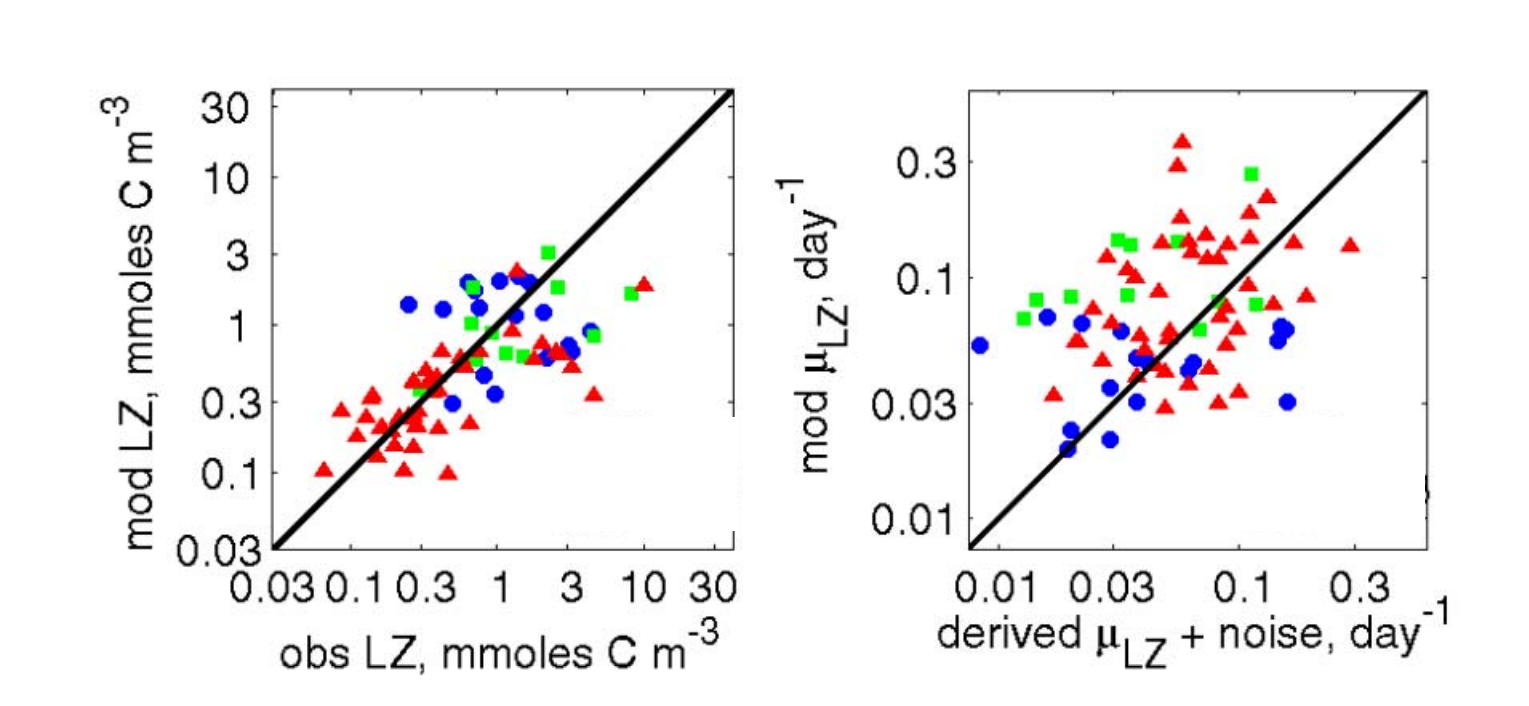


r = 0.85
F_{med} = 1.37

r = 0.60
F_{med} = 1.10

r = 0.56
bias = +.31

Initial model-data comparison: mesozooplankton quantities



r =0.67
F_{med}=0.90

r =0.29
F_{med}=1.28

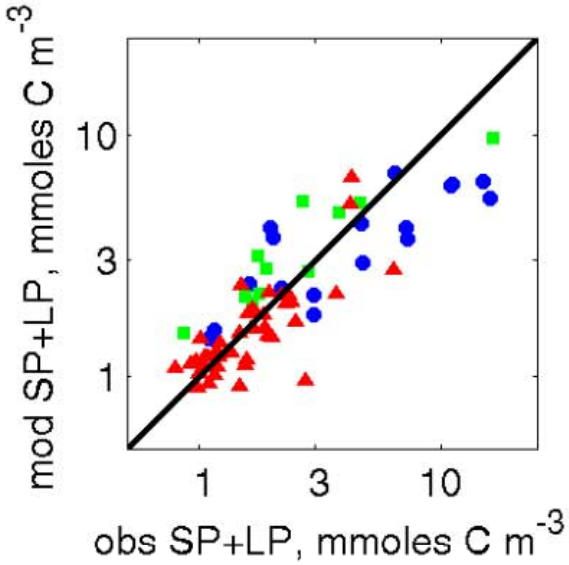
Model calibration

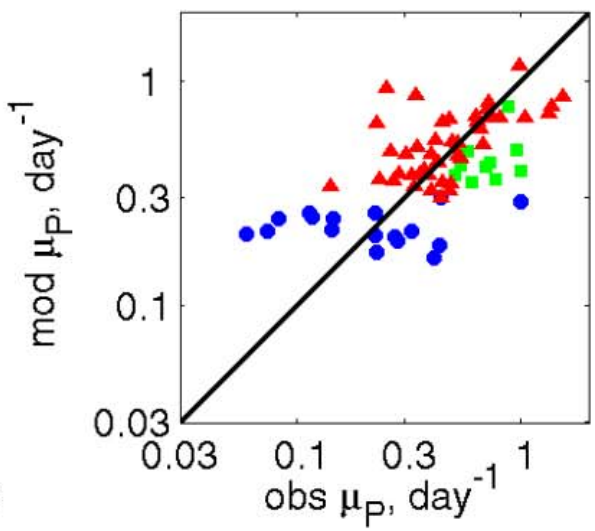
- Perturbation analysis to identify parameters w/large impact over uncertainty range
- Sequential addition of additional tuning parameters until changes in likelihood become insignificant

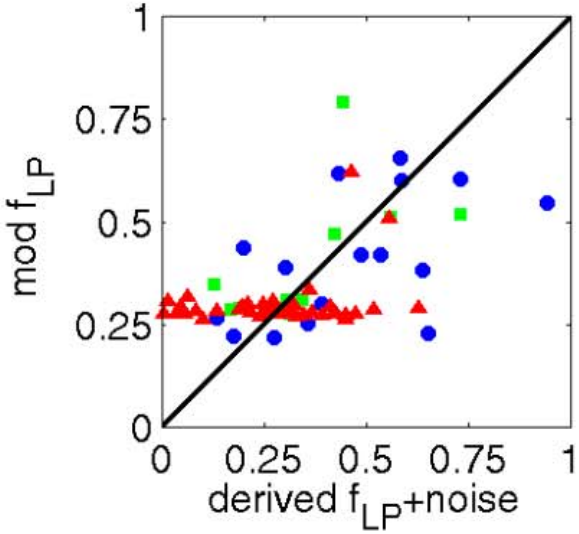
Two primary changes:

- Zooplankton basal metabolic rates had to be decreased to capture conditions in oligotrophic ecosystems
- Some egestion by small zooplankton redirected to large, sinking detritus to eliminate high productivity bias across systems

Final model-data comparison: phytoplankton quantities





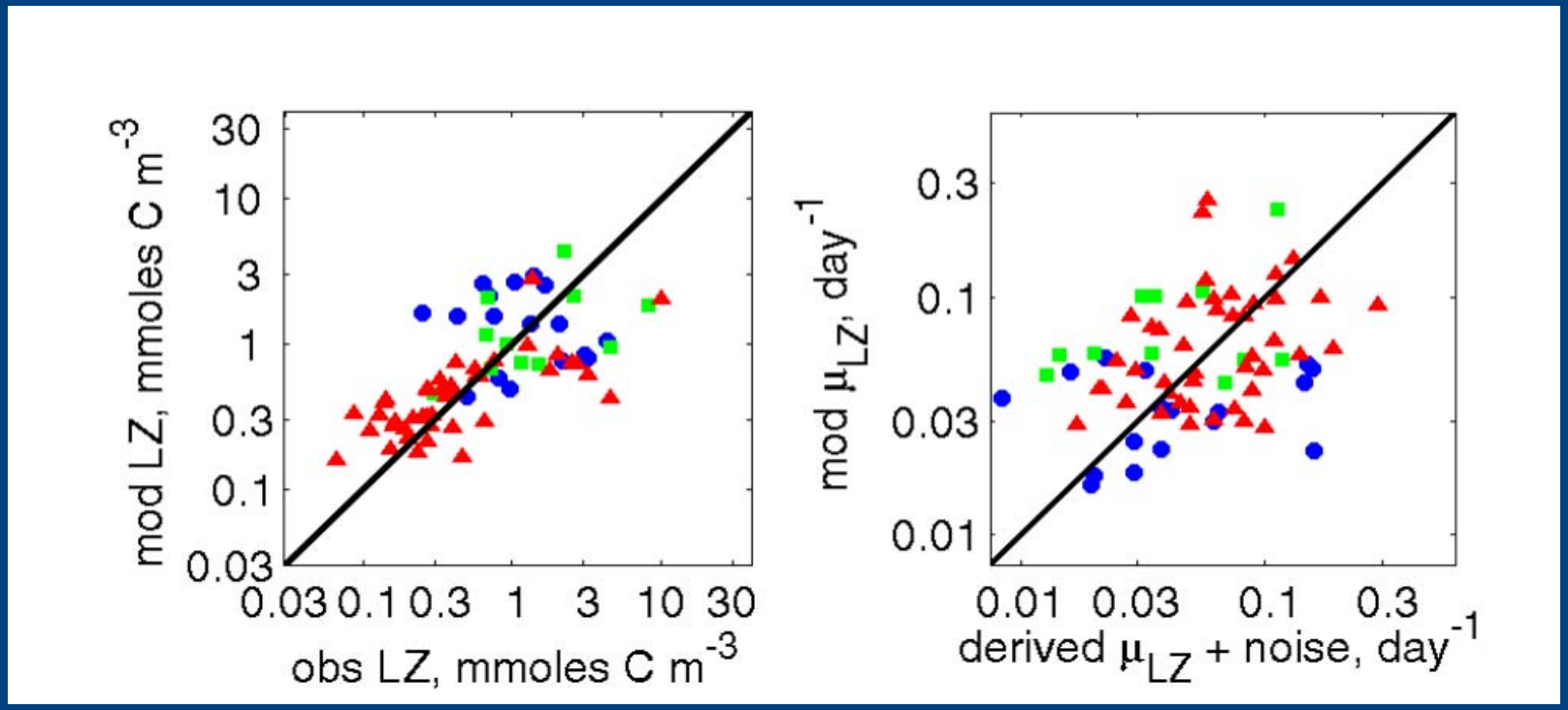


r = 0.85
F_{med}=1.03

r = 0.62
F_{med}=1.01

r = 0.54
bias = +0.01

Final model-data comparison: mesozooplankton quantities



$r = 0.65$
$F_{med} = 1.13$

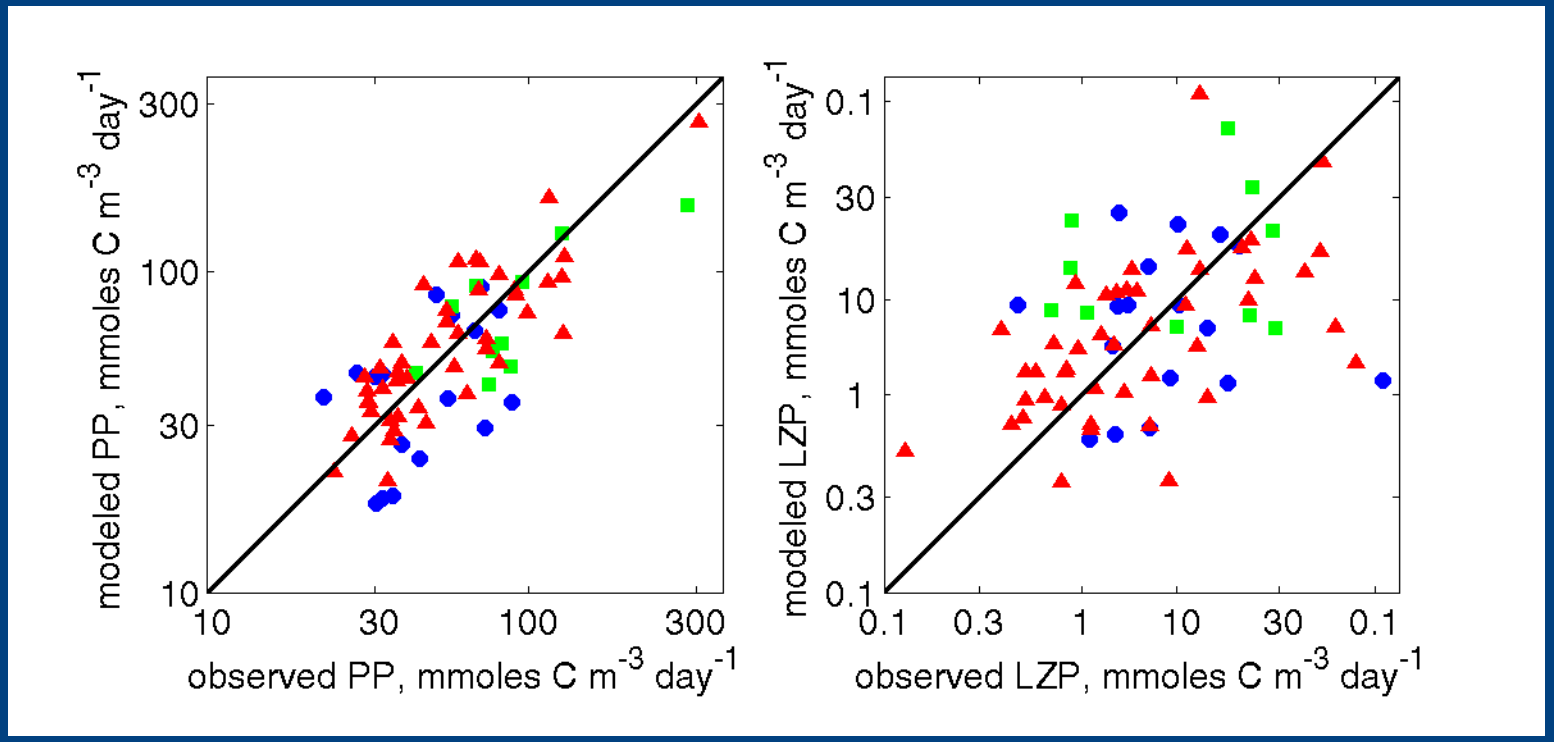
$r = 0.31$
$F_{med} = 0.95$

The ratio of large production to primary production

$$z = \frac{\mu_{LZ} \times LZ}{PP}$$

Metric for the flow of primary production up the marine food web

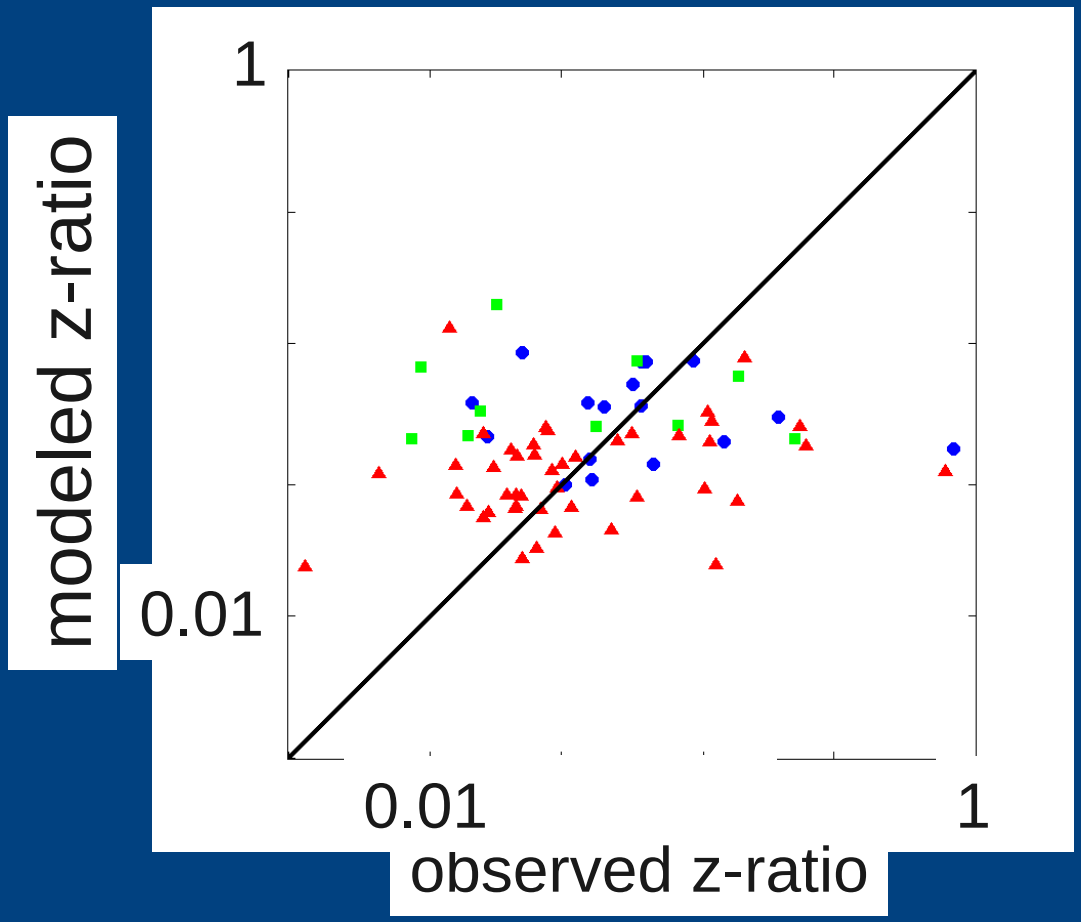
Trends in both primary prod. and mesozooplankton prod. emerge....



r = 0.76
F_{med} = 0.97

r = 0.43
F_{med} = 1.18

But the model has no predictive power for the z-ratio??



$r = 0.17$

$F_{med} = 1.22$

Independent global z-ratio estimates: mesozooplankton biomass

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

20 200

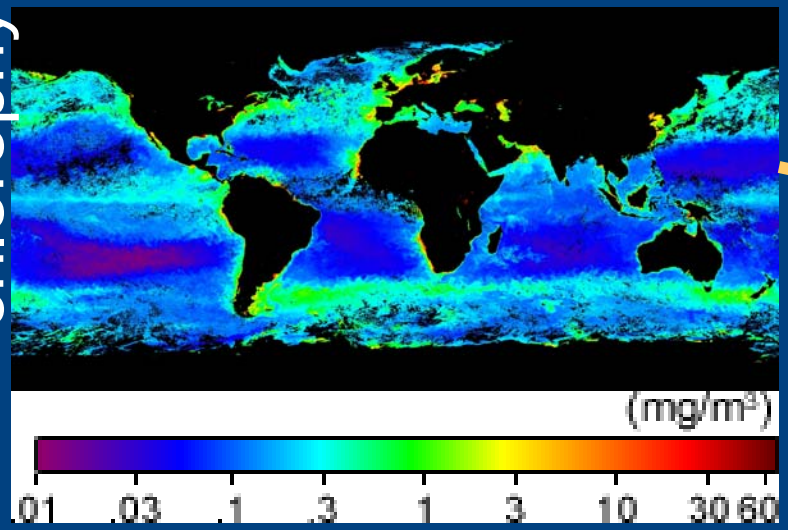
Mesozooplankton biomass (mg C m^{-2})

$$z = \frac{\mu_{LZ} \times LZ}{PP}$$

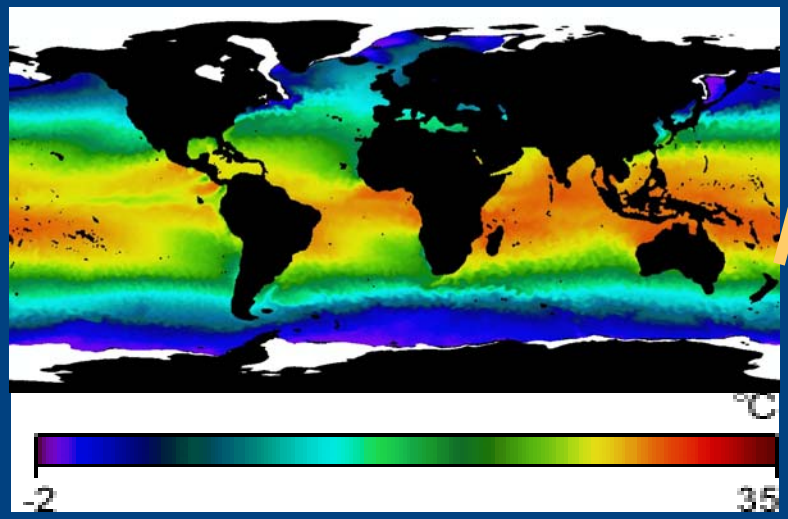
Global average from many net tows
NOAA/NMFS COPEPOD database (O'Brien, 2005)

Independent global z-ratio estimates: mesozooplankton growth rate

chlorophyll



SST

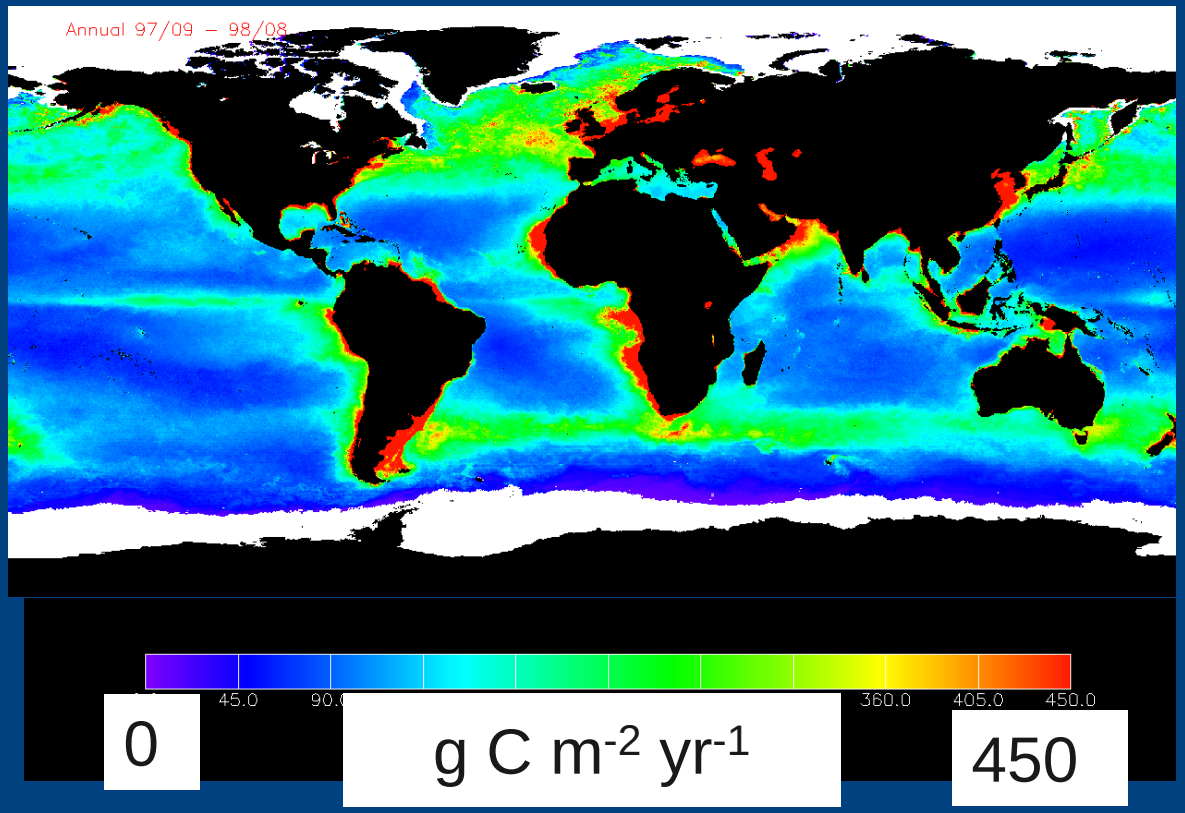


$$\mu_{LZ} = f(chl, sst)$$

$$z = \frac{\mu_{LZ} \times LZ}{PP}$$

Hirst and Bunker, 2003

Independent global z-ratio estimates: primary production

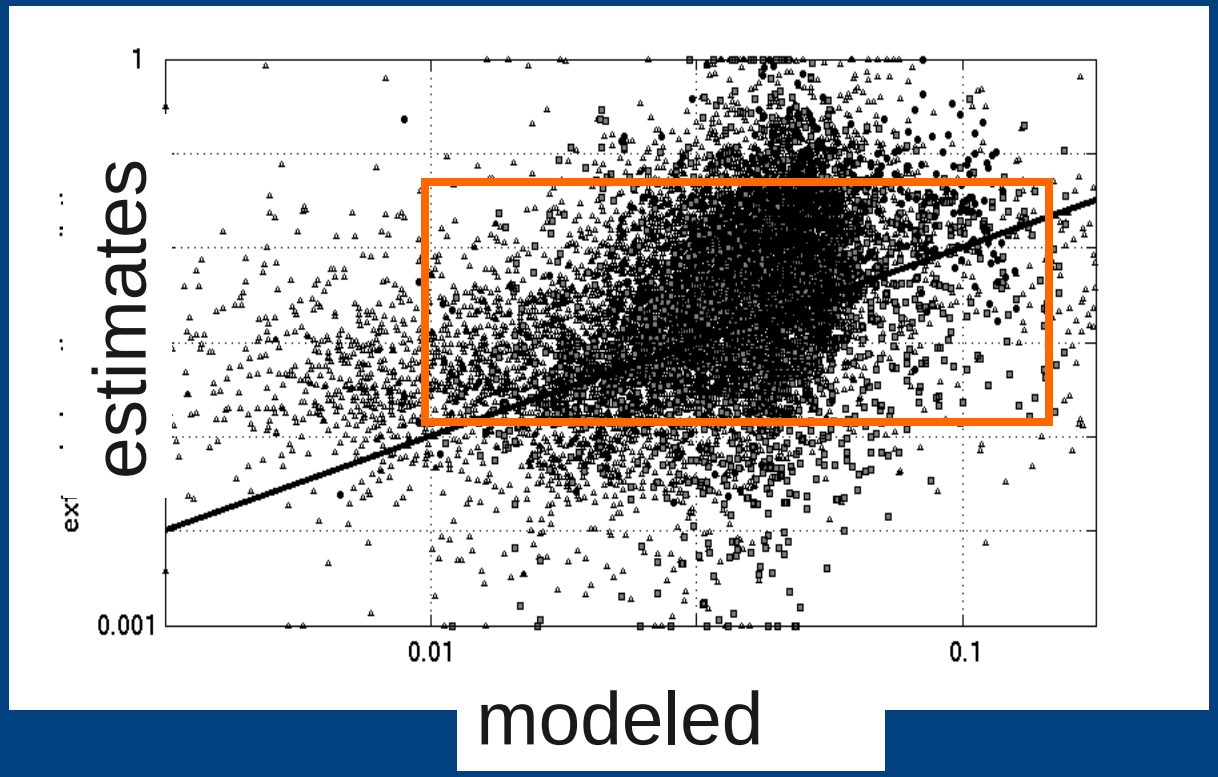


Sattelite-derived primary production

$$z = \frac{\mu_{LZ} \times LZ}{PP}$$

Restrict analysis to 50S-50N

Model comparison to estimates (1)

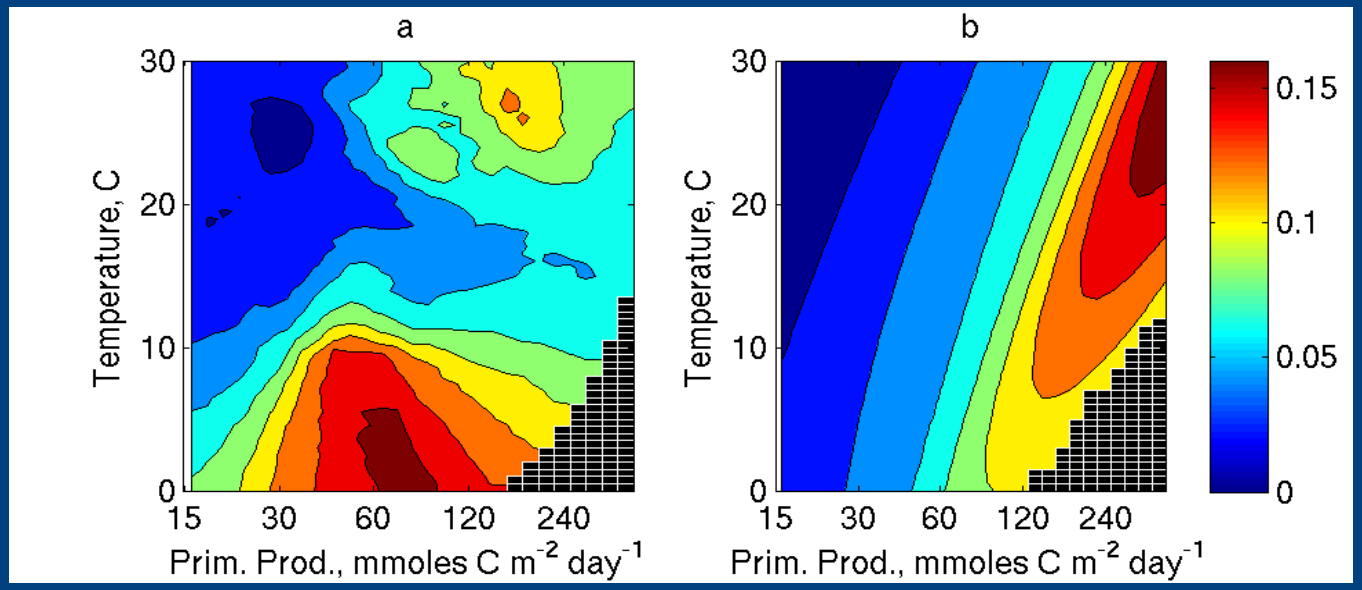


- majority of points between 0.01-0.2
- "low frequency" trend overlain by substantial unexplained variability

correlation = 0.4

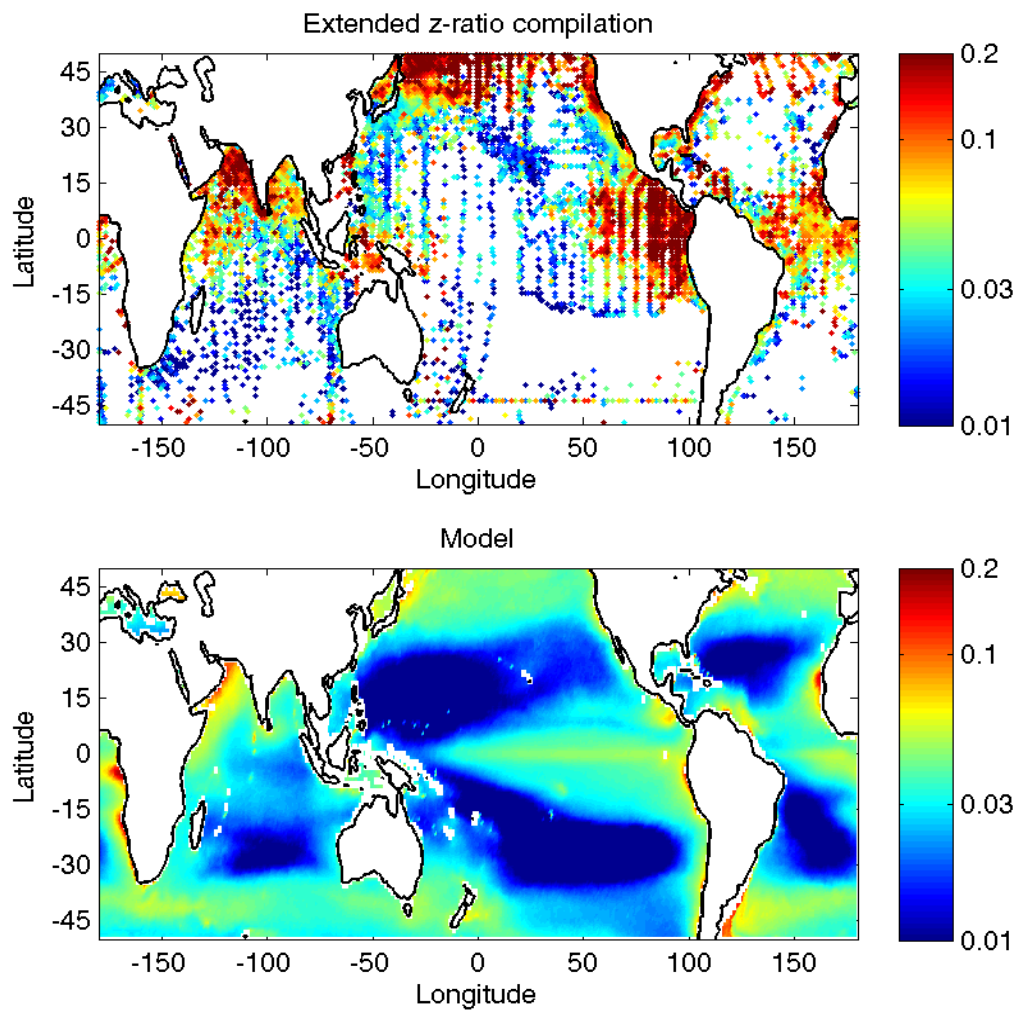
Model comparison to estimates (2)

estimated z-ratio model z-ratio



mean z-ratio increases from 0.01-0.03 to 0.1-0.2
as primary productivity increases, transition to high values occur earlier in cold water systems

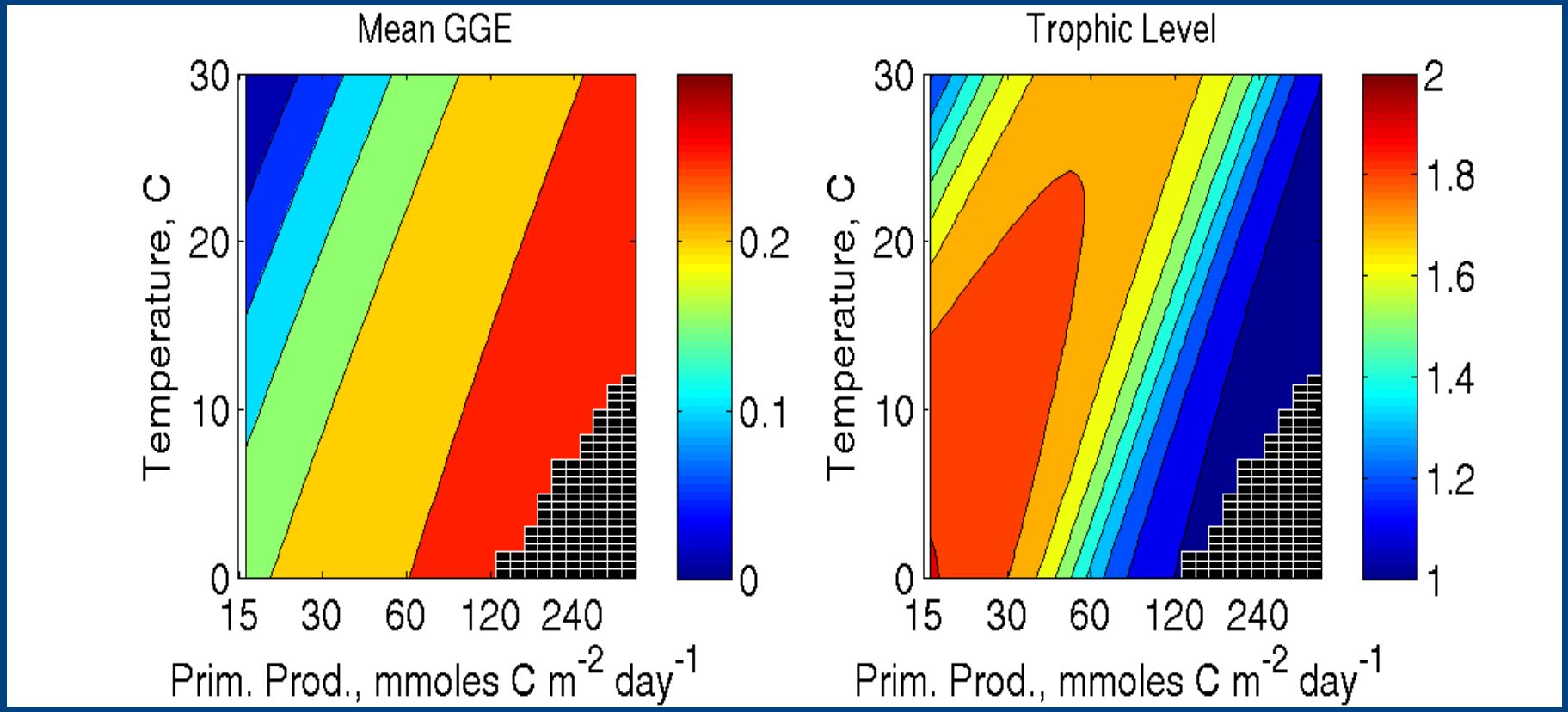
Model comparison to estimates (3)



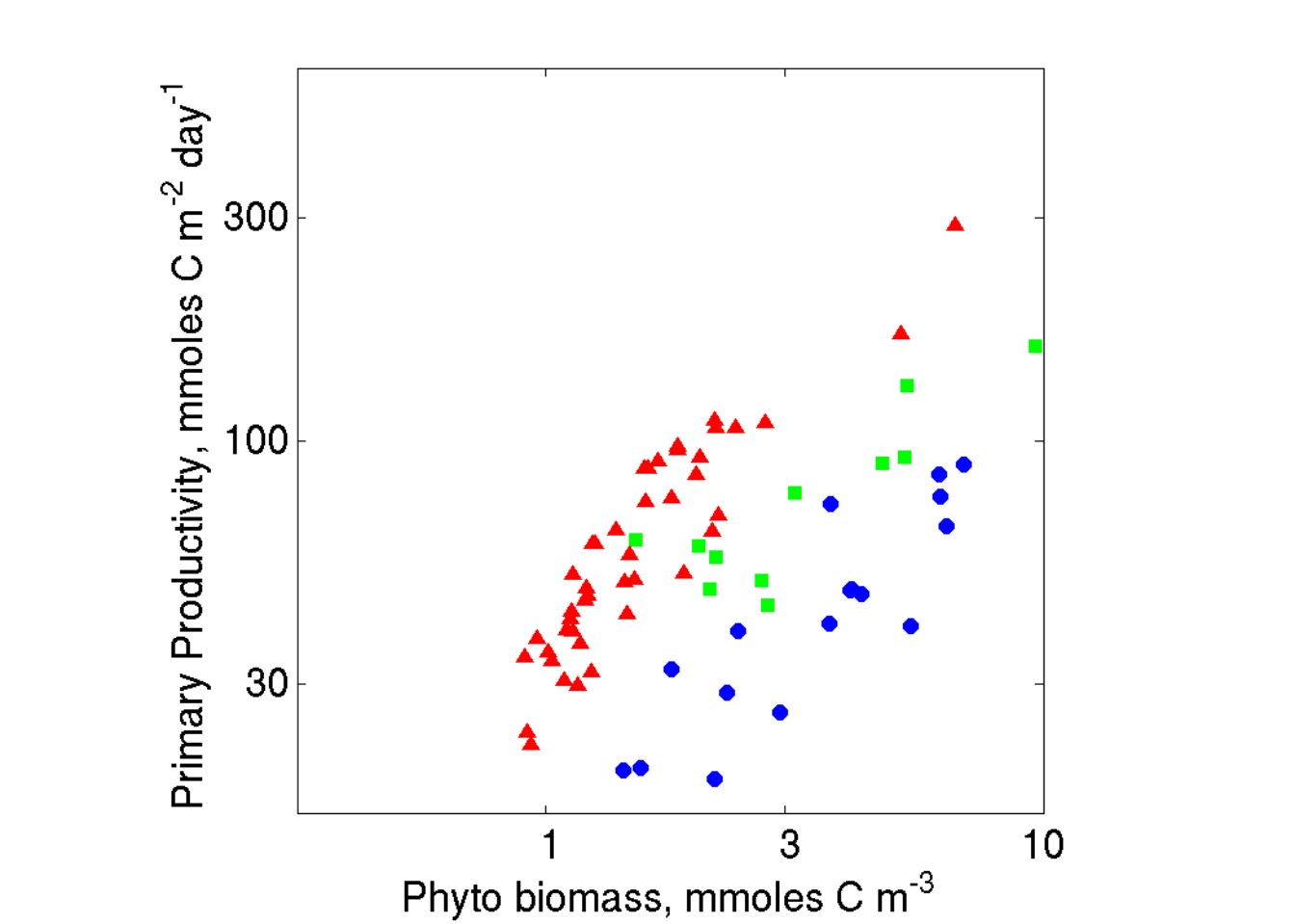
- z-ratio ~0.1-0.2 in highly productive upwelling regions
- 0.01-0.03 in subtropical gyres (the ocean's deserts)

Two mechanisms:

1) growth efficiency increases with prey biomass
2) mesozooplankton become more herbivorous in high productivity regions dominated by LP



Transition to high z-ratio occurs at lower primary productivity in low temperature ecosystems because these are "high biomass, low turnover" systems



Summary (1)

- Cross-ecosystem scaling of phytoplankton and zooplankton biomass and productivity emerged from model equilibria
- Zooplankton basal metabolic rates must be reduced to match the conditions in oligotrophic ecosystems

Summary (2)

- The mean z-ratio varies from ~0.01-0.03 in oligotrophic ecosystems to ~0.1-0.2 in highly productive ecosystems.
- The transition to high z-ratios occurs at lower primary production in cold-water systems
- A fractional change in primary production causes a larger fractional change in mesozooplankton production

Important caveats:

- The mean changes are a low-frequency trend that is overlain by substantial high frequency variation
- Some more systematic departures of model and data need to be addressed

Toward marine resource prediction at interannual to centennial time-scales

- Incorporate enhanced ecosystem dynamics into:
  - historical ocean/ice simulations forced with atmospheric reanalysis
  - Century-scale climate simulations
  - Interannual and decadal scale "initial value" simulations

- Develop capacity to link with explicit fisheries models

- Engage marine resource community through postdocs and workshops to develop new and innovative applications of GFDL models to marine resource prediction

Workshop to develop new GFDL model applications to fisheries prediction

Applying IPCC-class Models of Global Warming to Fisheries Prediction

June 15-17, 2009

Princeton University

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