New models, new data: can DNA barcoding help with the development of General Ecosystem Models?

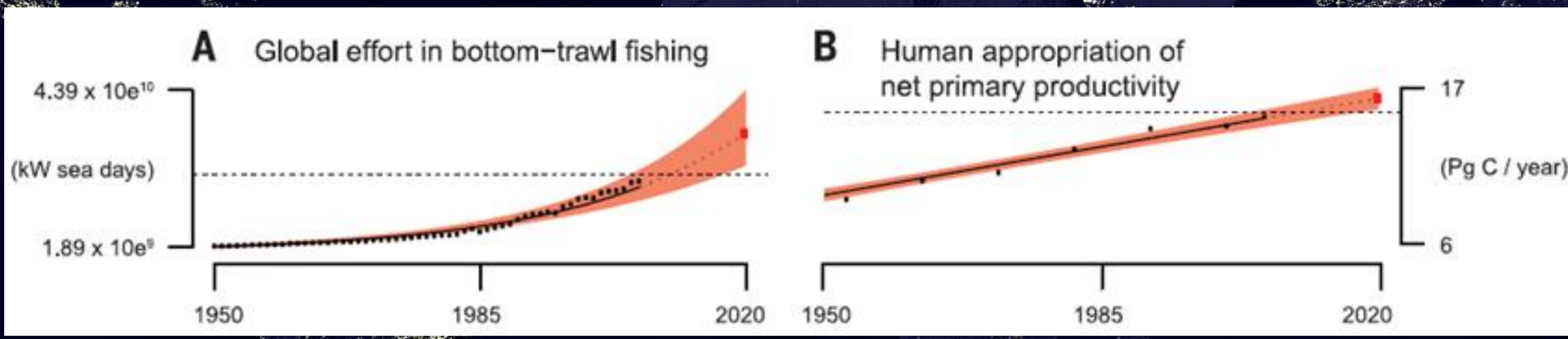
Derek P. Tittensor

6th iBOL conference

1. Why we need new models

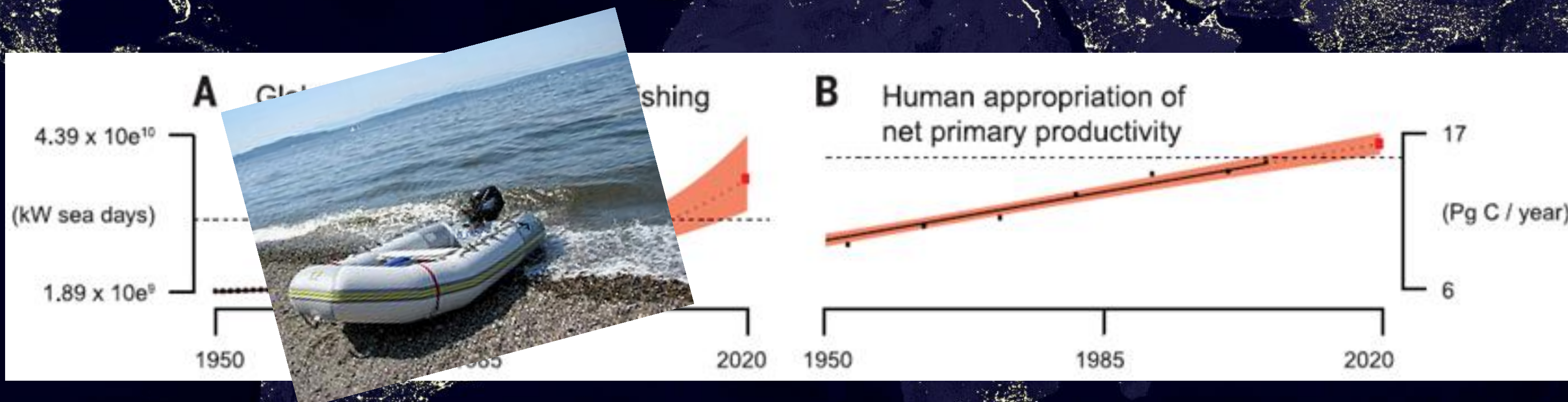
The Anthropocene

The Anthropocene



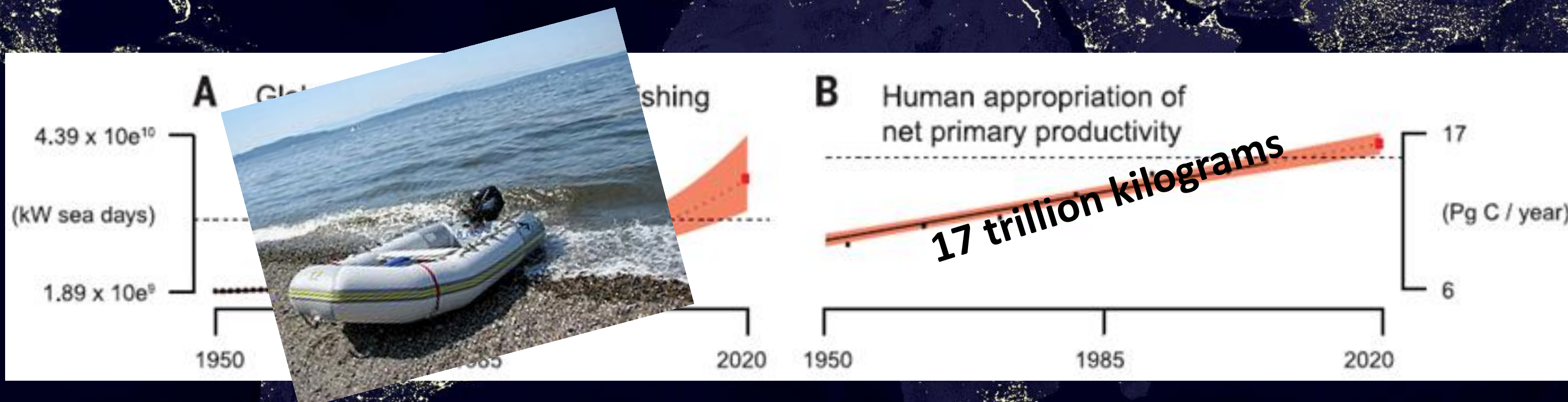
Tittensor *et al*. (2014), Science

The Anthropocene



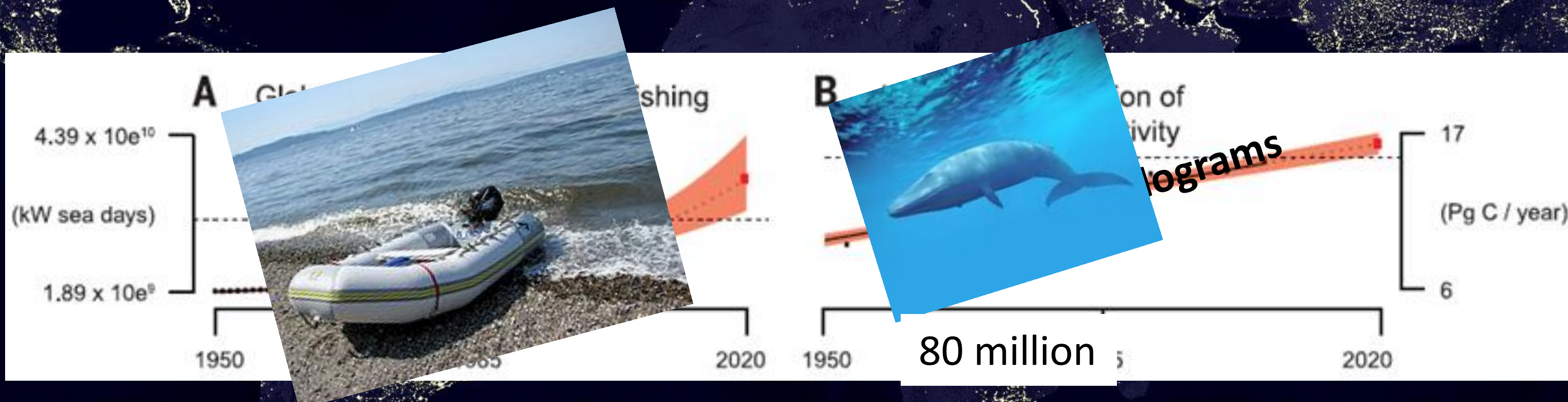
Tittensor *et al*. (2014), Science

The Anthropocene



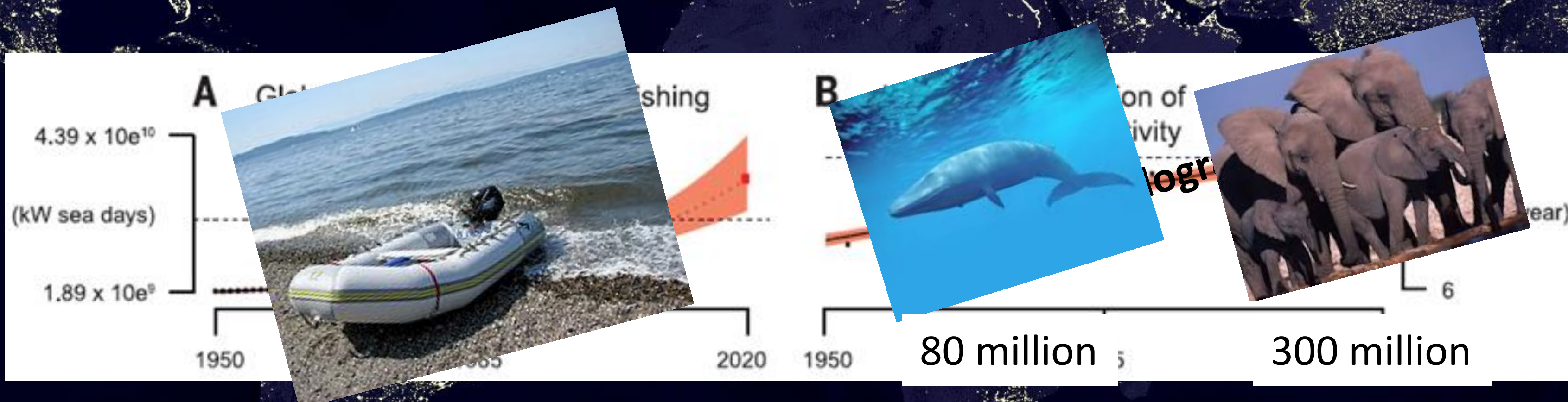
Tittensor *et al*. (2014), Science

The Anthropocene

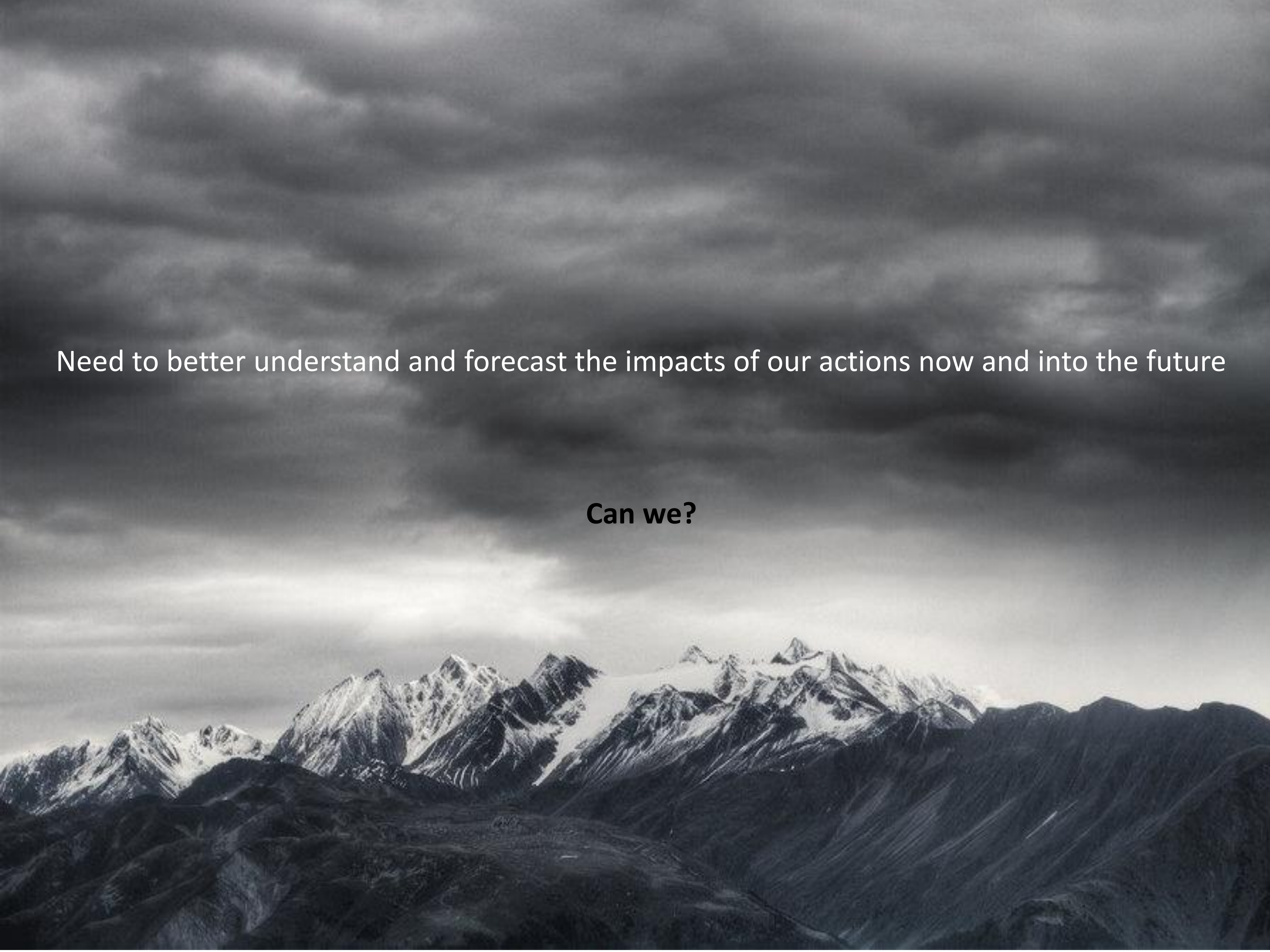


Tittensor *et al*. (2014), Science

The Anthropocene



Tittensor *et al*. (2014), Science


Need to better understand and forecast the impacts of our actions now and into the future
Can we?

SUSTAINABILITY

Prediction, precaution, and policy under global change

Emphasize robustness, monitoring, and flexibility

By **Daniel E. Schindler*** *and* **Ray Hilborn**

A great deal of research to inform environmental conservation and management takes a predict-and-prescribe strategy in which improving forecasts about future states of ecosystems is the primary goal. But sufficiently thorough understanding of ecosystems needed to reduce deep uncertainties is probably not achievable, seriously limiting the potential effectiveness of the predict-and-prescribe approach. Instead, research should integrate more closely with policy development to identify the range of alternative plausible futures and develop strategies that are robust across these scenarios and responsive to unpredictable ecosystem dynamics.

Calls for improving forecasts of future ecosystem states are common [e.g., (*1*)]. It is often assumed that poor performance of forecasting models (*2*) derives from weak understanding of ecological complexity and that developing richer mechanistic appreciation of ecological interactions outcome that is assumed to be predictable; policy developed under this premise will prepare us poorly for the unpredictable (*7*).

LIMITS OF MODELS. Ecosystems are organized around a seemingly infinite number of biological, chemical, and physical processes that play out across enormous ranges of space and time scales (*8*). Feedback mechanisms provide stability such that ecosystems appear stable during some time frames but can abruptly shift to express new structures in others (*9*). Our abilities to make observations are limited to a small range of space and time scales (*8*), limiting our capacity for understanding ecosystems and forecasting how they will respond to local and global

change. Thus, environmental management will always operate in a realm where uncertainties dominate (*10*). Although more detailed knowledge about ecological processes will certainly be produced, reliable forecasts will likely accumulate much slower than will be useful for contributing to effective policy for sustainability or conservation, and ecosystems will likely change faster than knowledge accumulates.

A wide range of modeling approaches is used to explore and forecast ecosystem dynamics. However, models are prone to errors that can mislead policy if not treated with appropriate skepticism (*11*). For example, in statistical models, historical time series are often compared to quantify cause-and-effect relationships between resources and environmental variables. Without controlled manipulations and appropriate reference systems, such comparisons can lead to false conclusions, based on spurious correlations, about cause-and-effect relationships. For example, a reanalysis of 47 previously published relationships between environmental variation and recruitment in marine fish—after including an additional decade of new data—revealed that only one of the previous statistically determined relationships was still used in management because the initial correlations failed to persist through time (*12*).

Nonstationarity in ecosystem relationships (i.e., evolution of parameters that quantify them) adds substantial uncertainty to models, even if statistical relationships are

Schindler & Hilborn (2015) Science

ECOLOGY

The Art of Ecological Modeling

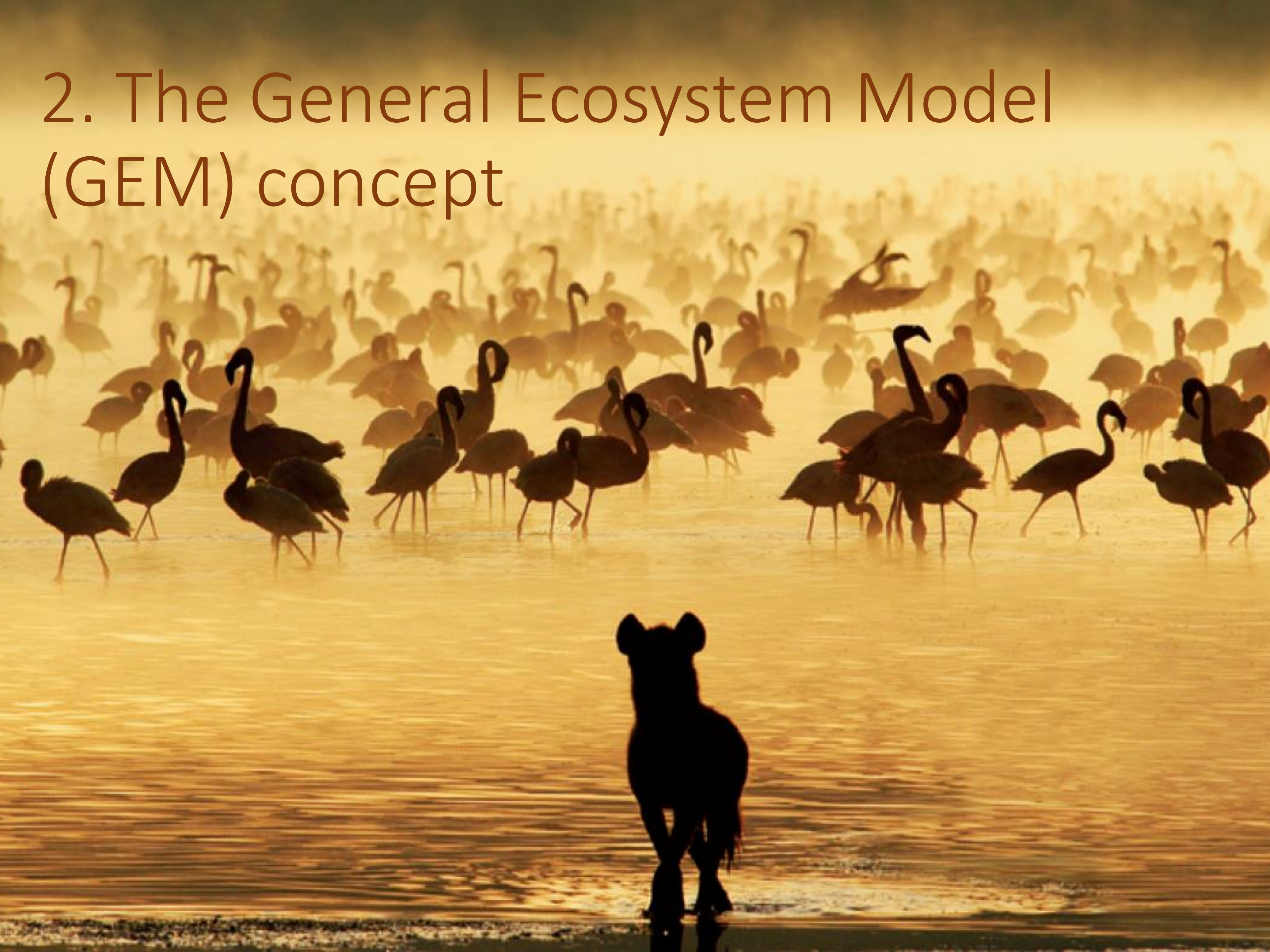
Ian L. Boyd

Predicting the dynamics of real ecosystems—or even of components of these ecosystems—will remain beyond the reach of even the best ecosystem models for the foreseeable future

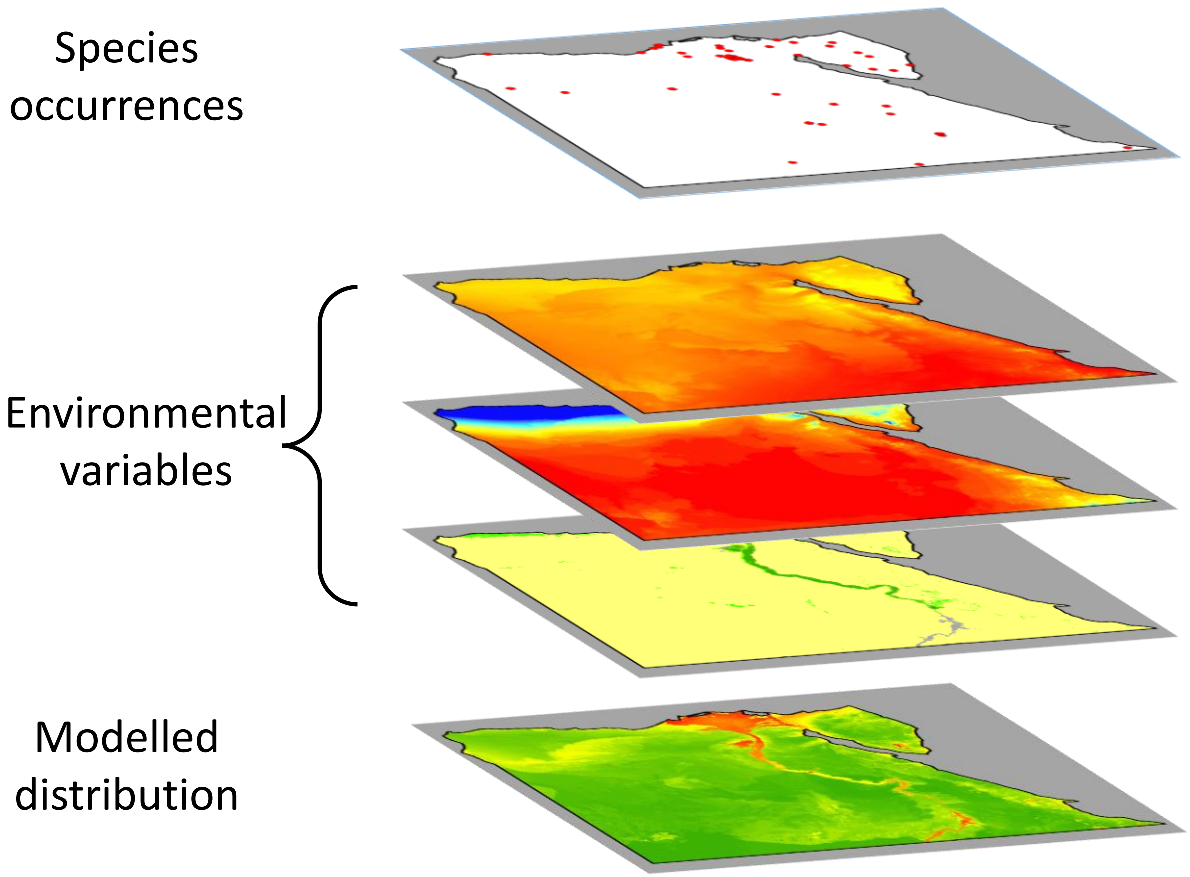
Boyd (2012) Science


Do ecologists get overwhelmed by complexity
in a way that physicists do not?
… because we can see butterflies, but not atoms?

2. The General Ecosystem Model (GEM) concept



Most models for ecology are correlative

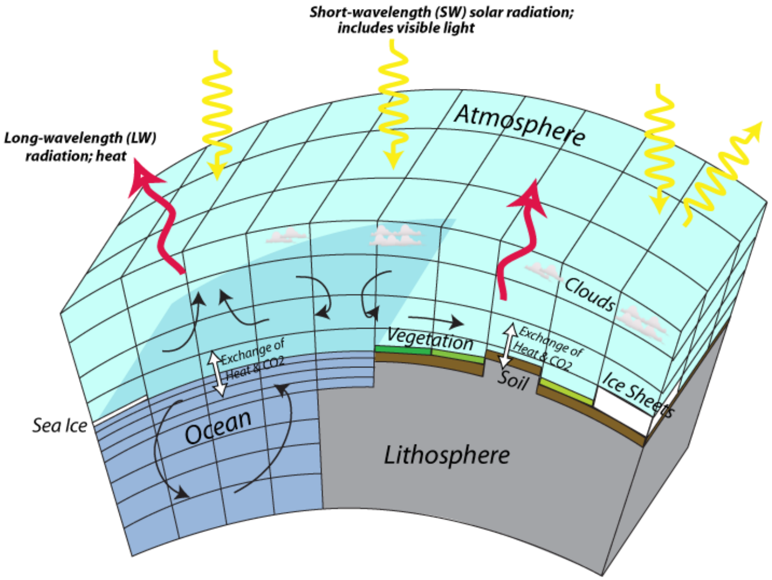


- Model patterns
- Extrapolate beyond the data to predict at new conditions
- Assumes constancy of processes

Process-based models

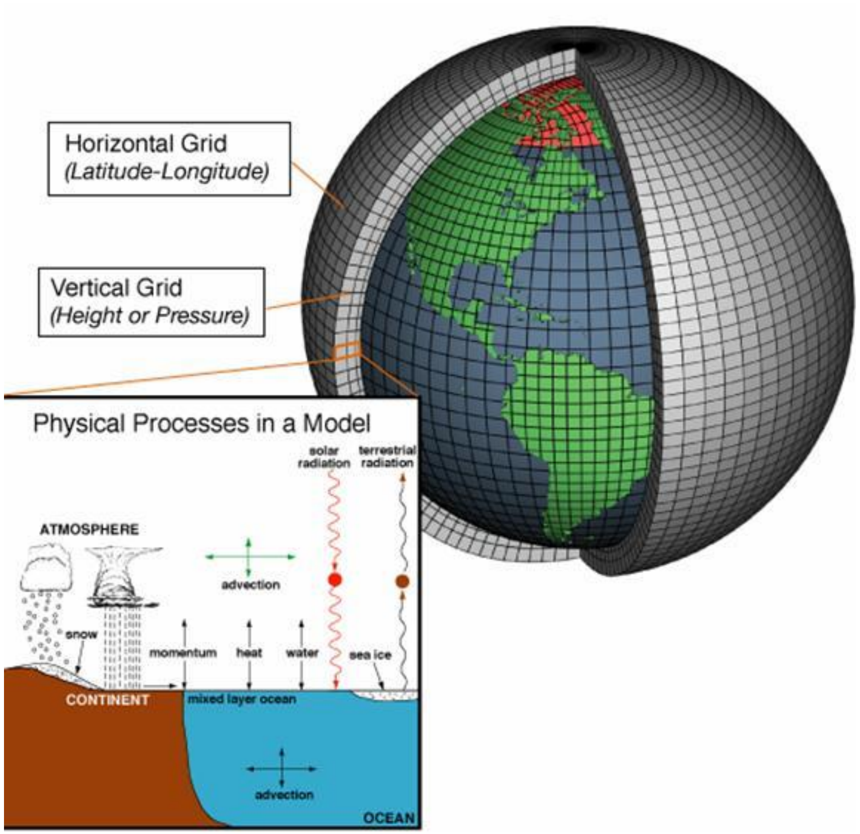
- Model underlying mechanisms (e.g. formation of clouds, hydrological cycle)

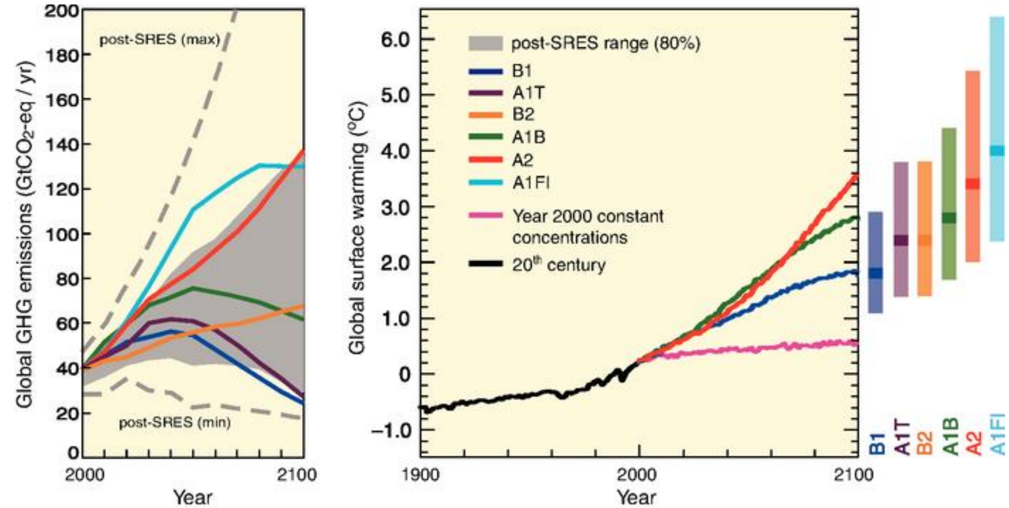
- Allows prediction to novel conditions & unexpected outcomes



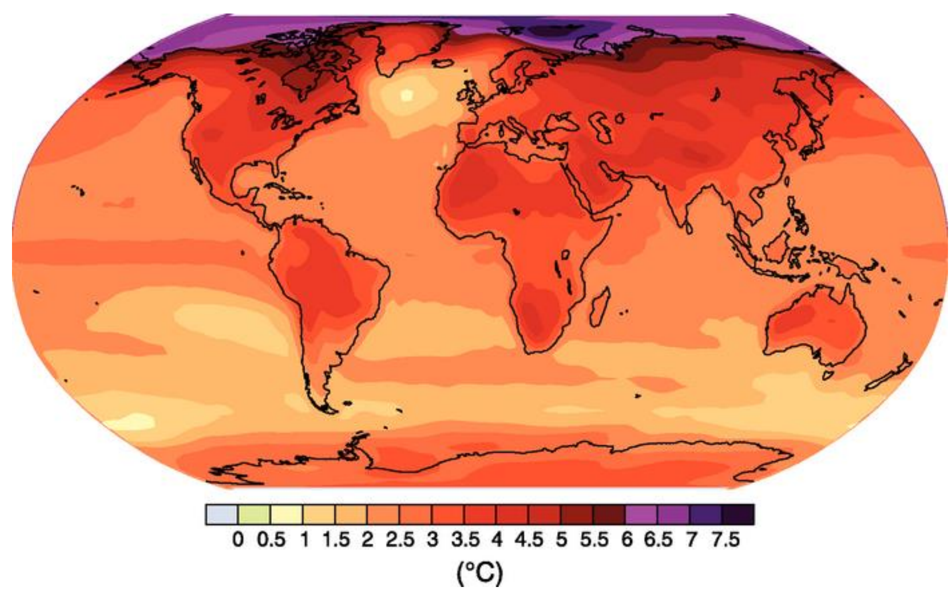
- As mechanistic understanding improves, so does model

General circulation models (GCMs)





IPCC, Fourth Assessment Report, 2007



The challenge

- Can we model the biosphere via fundamental ecological processes?
- Land and sea?
- Can we forecast changes in biodiversity and ecosystem stability/function?

I.e. can we create a general (global) ecosystem model?

What we can learn from the GCM experience

- Start simple
- Initial models will be crude
- Substantial oversimplifications…
- …but a foundation to build upon & engage a community

3. The Madingley model

Modelling philosophy

Balanced consideration of all trophic levels

Transparent

Open

Reproducible

Emergence

How?

Ecology, 85(7), 2004, pp. 1771–1789

TOWARD A METABOLIC THEORY OF ECOLOGY

JAMES H. BROWN,[1,2,4]
with JAMES F. GILLOOLY,[1] ANDREW P. ALLEN,[1] VAN M. SAVAGE,[2,3] AND GEOFFREY B. WEST[2,3]

OPEN ACCESS Freely available online PLoS one

The Probabilistic Niche Model Reveals the Niche Structure and Role of Body Size in a Complex Food Web

Richard J. Willia

The Functional Response of Predators to Prey Density and its Role in Mimicry and Population Regulation*

By C. S. HOLLING

The Madingley model

Key ecological problem (1)

- We haven't described the majority of species (85-91% undescribed)
- Want to include all taxa in a model
- How do we resolve this inconsistency?

OPEN ACCESS Freely available online PLOS BIOLOGY

How Many Species Are There on Earth and in the Ocean?

Camilo Mora[1,2*], Derek P. Tittensor[1,3,4], Sina Adl[1], Alastair G. B. Simpson[1], Boris Worm[1]

1 Department of Biology, Dalhousie University, Halifax, Nova Scotia, Canada, 2 Department of Geography, University of Hawaii, Honolulu, Hawaii, United States of America, 3 United Nations Environment Programme World Conservation Monitoring Centre, Cambridge, United Kingdom, 4 Microsoft Research, Cambridge, United Kingdom

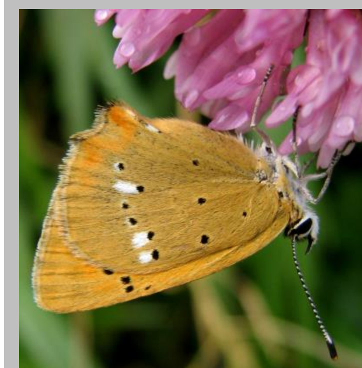
Model functional groups, not species

Herbivores

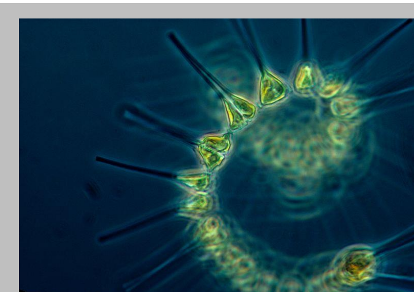
Carnivores

Omnivores

Ectotherm



Endotherm



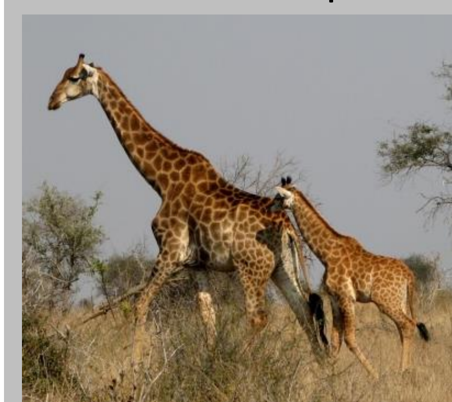
Autotrophs

Sessile

Mobile

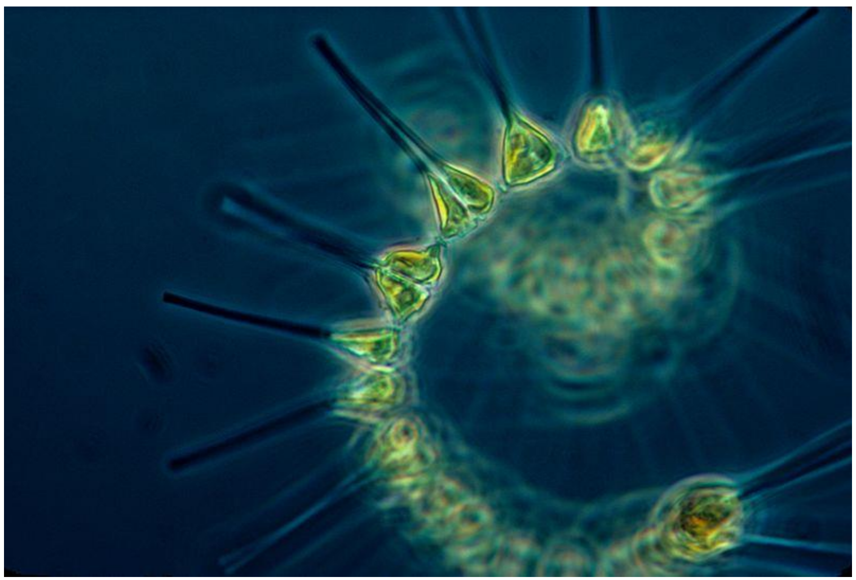
Semelparous

Iteroparous



Key ecological problem (2)

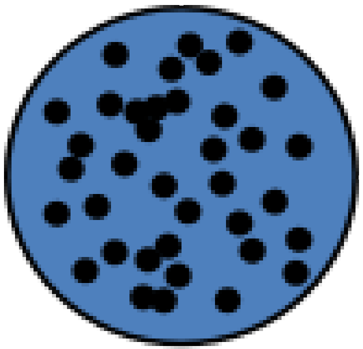
- Cannot model individuals separately



Millions per litre
(http://www.cefas.defra.gov.uk)

Up to c. 2500 per km^2
(Goodman, 1998, *Zoology*)

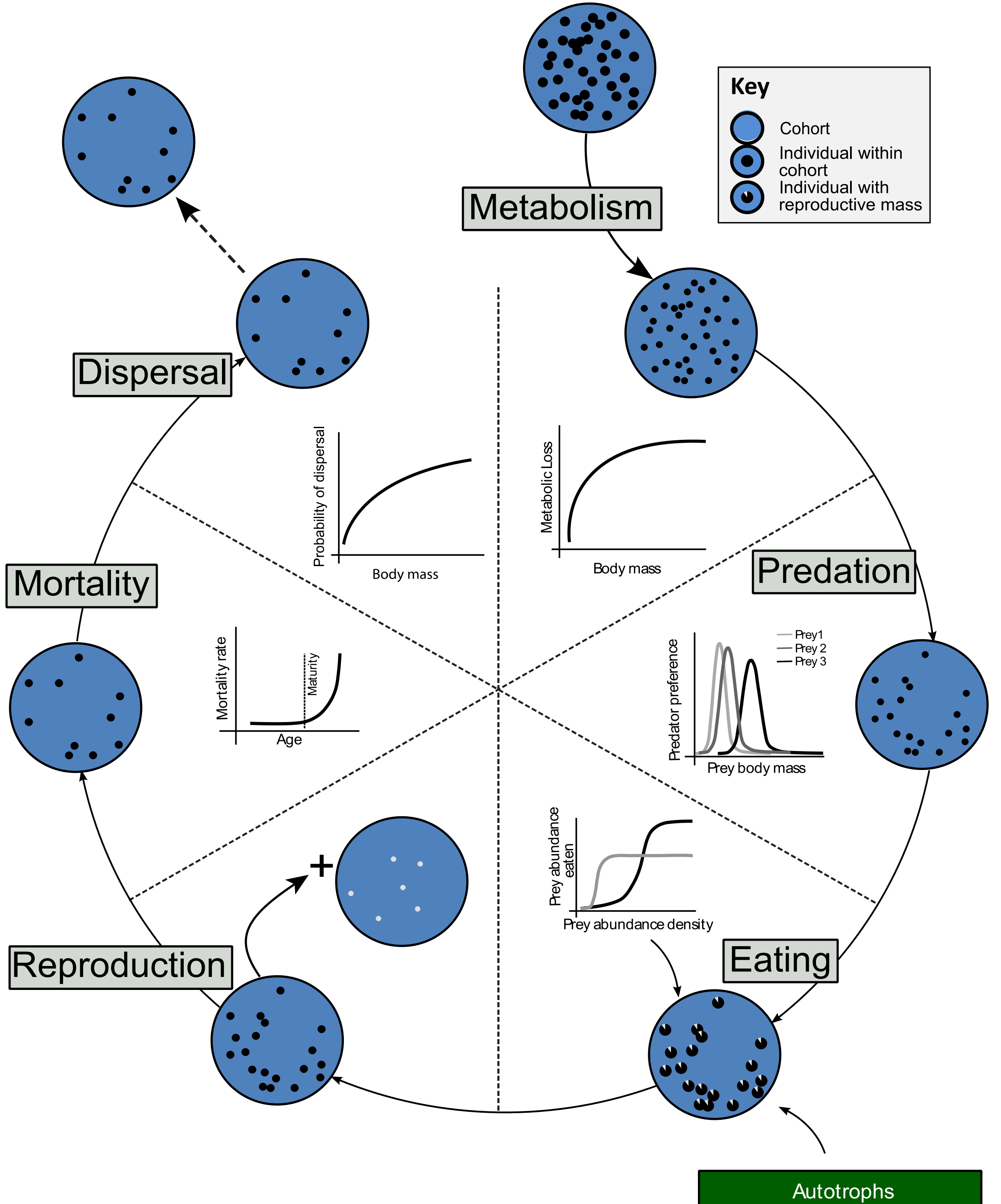
Individuals as (multispecies) cohorts



Functional traits:
Carnivorous, ectothermic, iteroparous, mobile

Num. individuals:	325
Individual mass:	2.6 kg
Age:	3.4 years
Juvenile mass:	0.01 kg
Adult mass:	4.3 kg
Optimal Prey body size:	12%

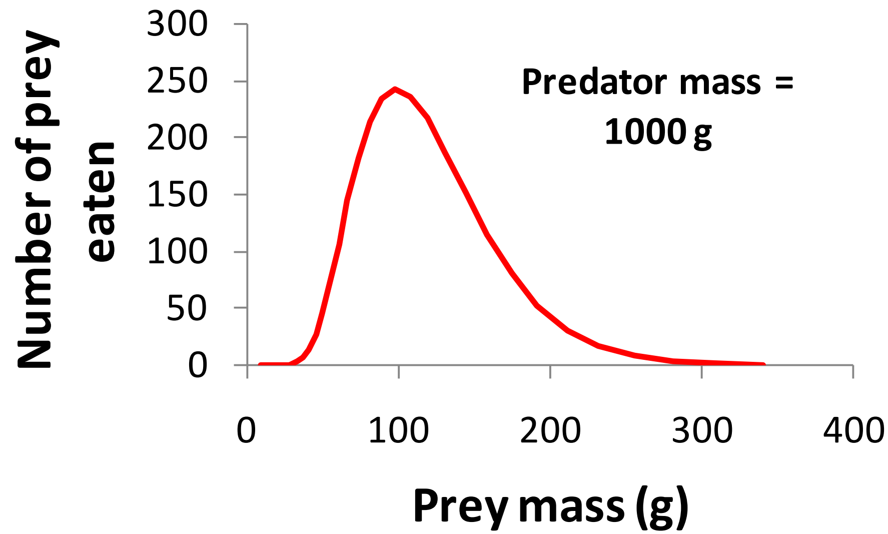
Dynamics

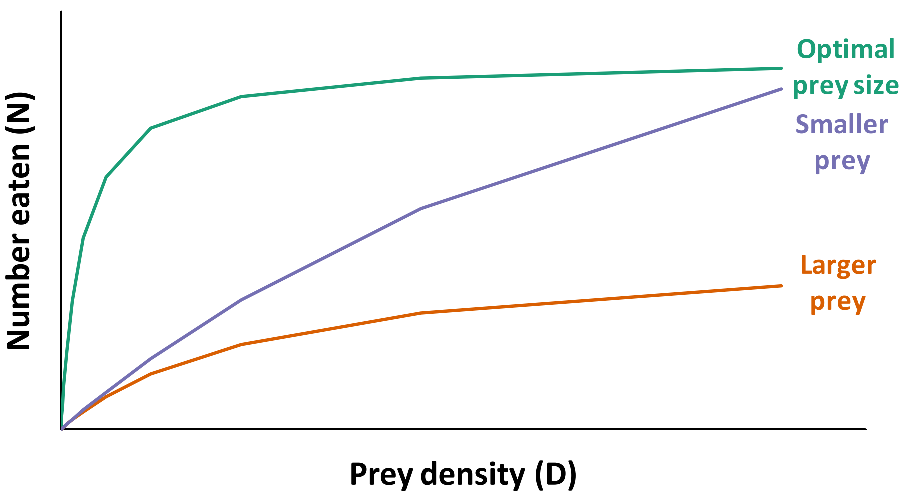


Harfoot *et al*. (PLoS Biology), 2014

Predation

Feeding niche

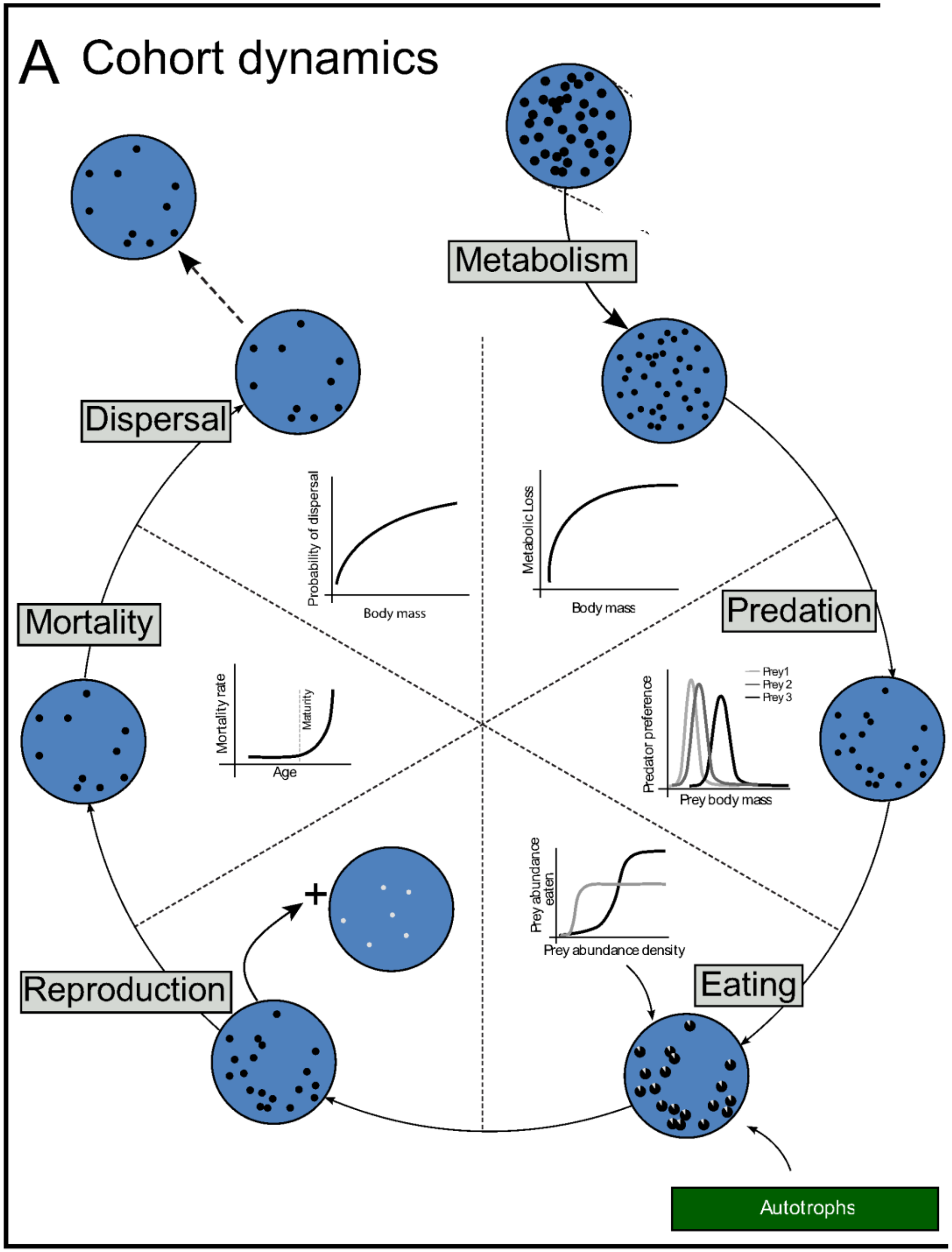




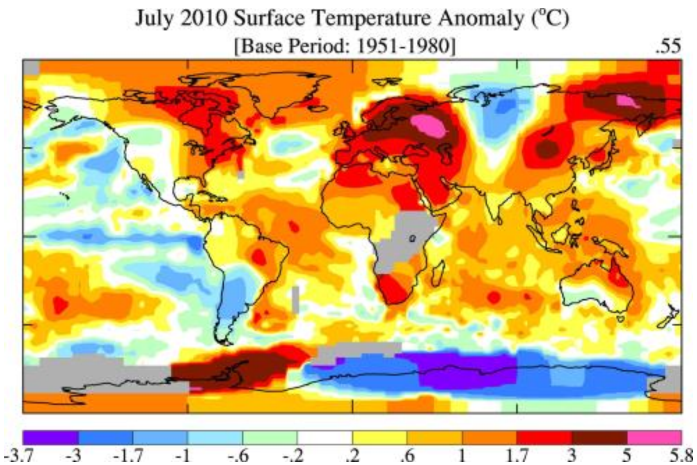
Also accounts for:

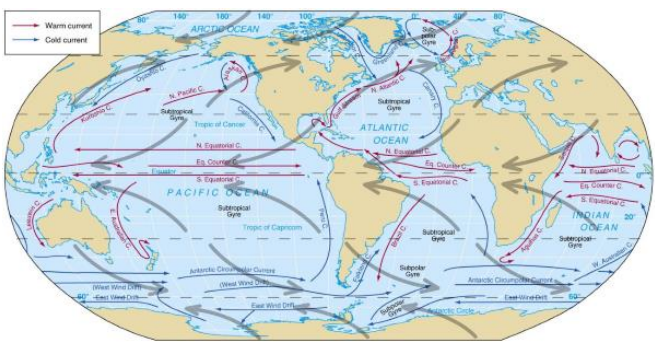
- Assimilation efficiency
- Time spent eating
- Emergent prey-switching

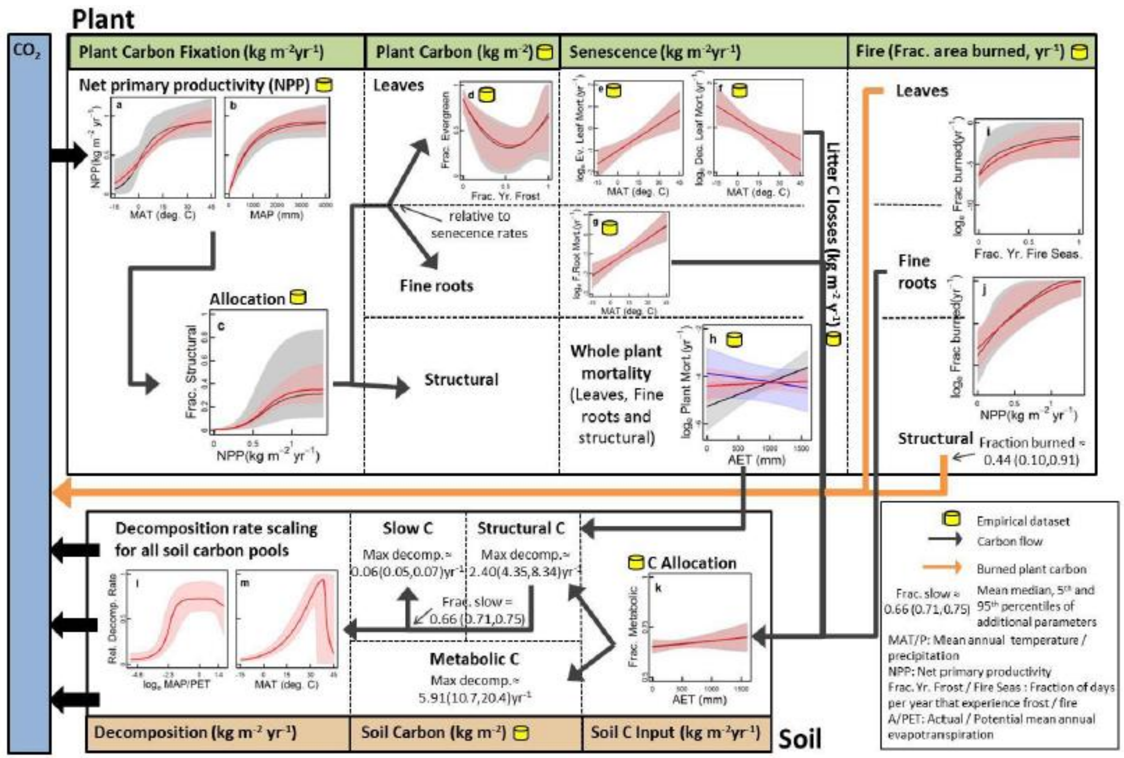
Brose et al. (2005), Ecology ; Williams & Purves (2011), Ecology

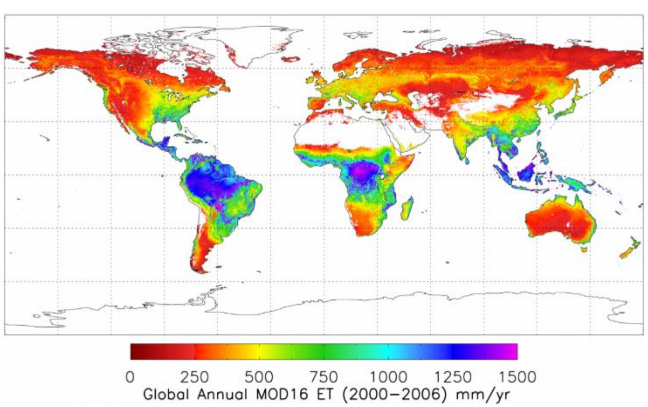


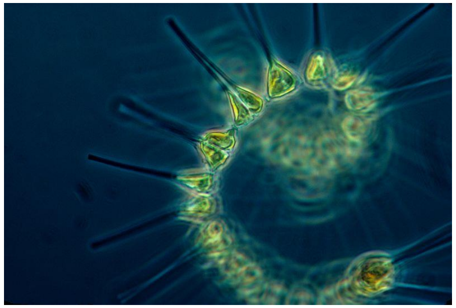
A Cohort dynamics
Metabolism
Dispersal
Predation
Mortality
Reproduction
Eating
Autotrophs
Probability of dispersal
Body mass
Metabolic Loss
Body mass
Mortality rate
Maturity
Age
Predator preference
Prey body mass
Prey1
Prey 2
Prey 3
Prey abundance eaten
Prey abundance density
+

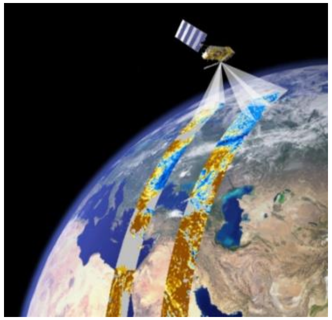

July 2010 Surface Temperature Anomaly (°C)
[Base Period: 1951-1980]
.55
-3.7 -3 -1.7 -1 -.6 -.2 .2 .6 1 1.7 3 5 5.8


Warm current
Cold current
ARCTIC OCEAN
ATLANTIC OCEAN
PACIFIC OCEAN
INDIAN OCEAN
Tropic of Cancer
Equator
Tropic of Capricorn


Plant
CO_2
Plant Carbon Fixation (kg m^{-2}yr^{-1})
Plant Carbon (kg m^{-2})
Senescence (kg m^{-2}yr^{-1})
Fire (Frac. area burned, yr^{-1})
Net primary productivity (NPP)
Leaves
relative to senecence rates
Fine roots
Allocation
Structural
Whole plant mortality (Leaves, Fine roots and structural)
Litter C losses (kg m^{-2} y^{-1})
Leaves
Fine roots
Structural
Fraction burned ≈ 0.44 (0.10,0.91)
Decomposition rate scaling for all soil carbon pools
Slow C
Max decomp.≈ 0.06(0.05,0.07)yr^{-1}
Structural C
Max decomp.≈ 2.40(4.35,8.34)yr^{-1}
Frac. slow = 0.66 (0.71,0.75)
Metabolic C
Max decomp.≈ 5.91(10.7,20.4)yr^{-1}
C Allocation
Frac. slow ≈ 0.66 (0.71,0.75)
Decomposition (kg m^{-2} yr^{-1})
Soil Carbon (kg m^{-2})
Soil C Input (kg m^{-2}yr^{-1})
Soil
Empirical dataset
Carbon flow
Burned plant carbon
Mean median, 5th and 95th percentiles of additional parameters
MAT/P: Mean annual temperature / precipitation
NPP: Net primary productivity
Frac. Yr. Frost / Fire Seas : Fraction of days per year that experience frost / fire
A/PET: Actual / Potential mean annual evapotranspiration

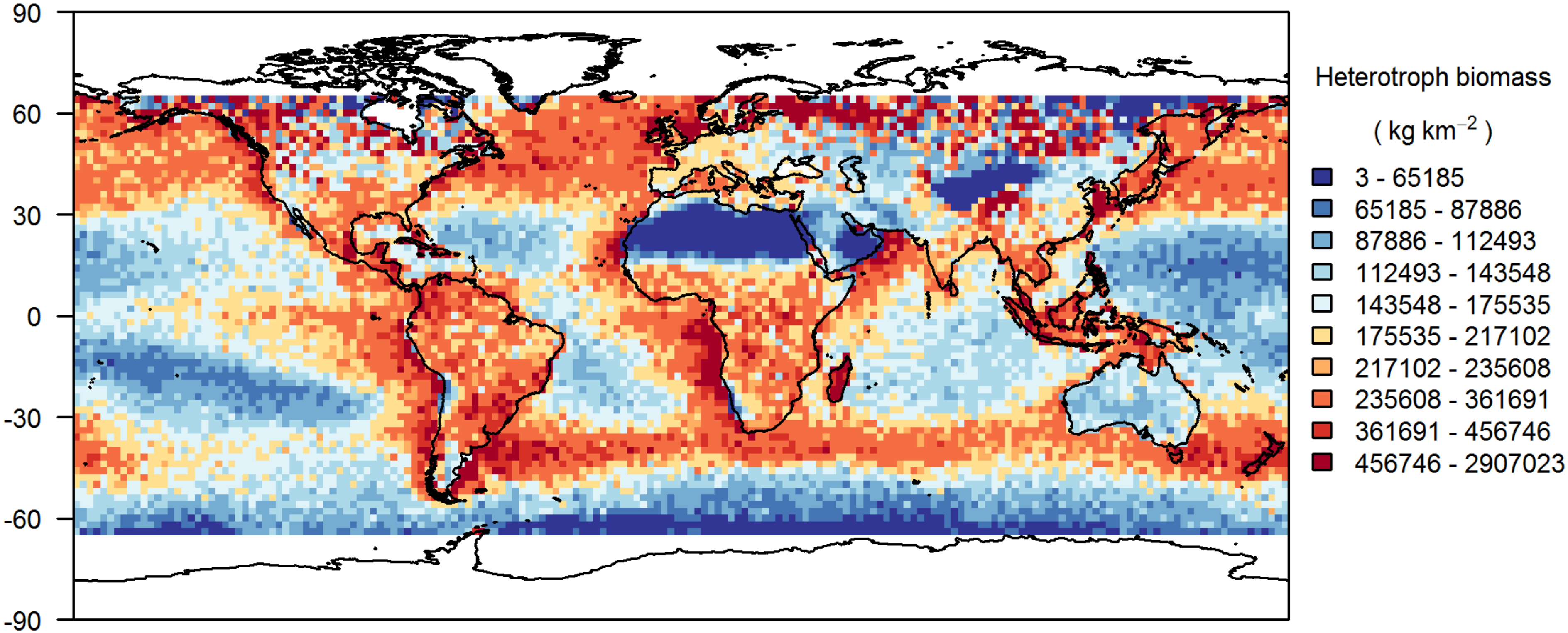

0 250 500 750 1000 1250 1500
Global Annual MOD16 ET (2000–2006) mm/yr





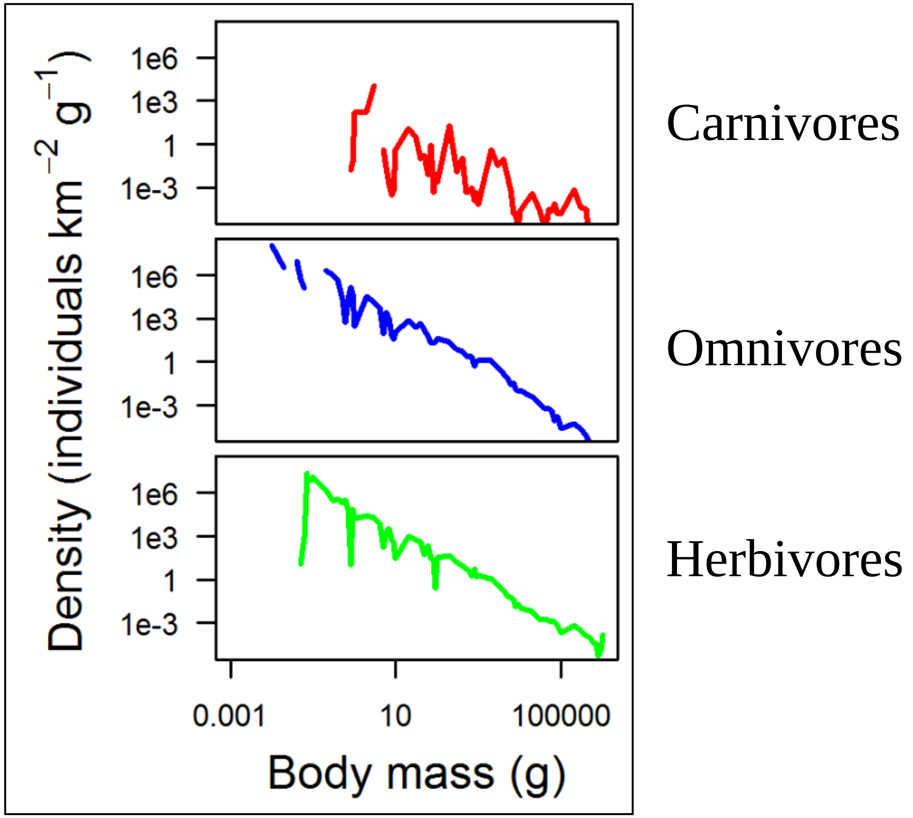
Seed the model with equal biomass everywhere

What emerges: global



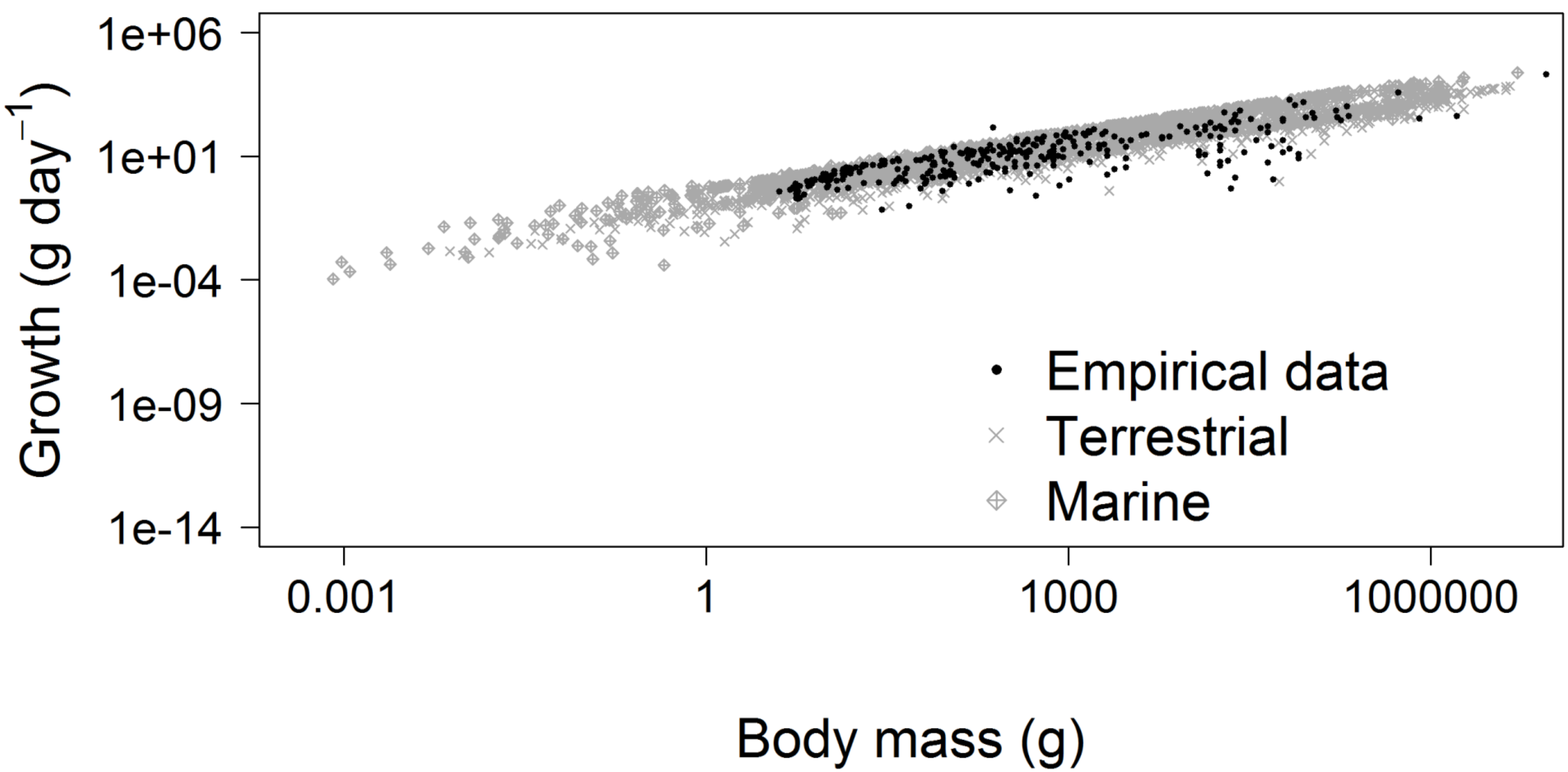
Harfoot *et al*. (PLoS Biology), 2014

Produces community-level metrics



Harfoot *et al.*
(PLoS Biology), 2014

Captures some properties at organismal level very well



Harfoot et al. (2014). *PLoS Biology*

4. What can GEMs do?

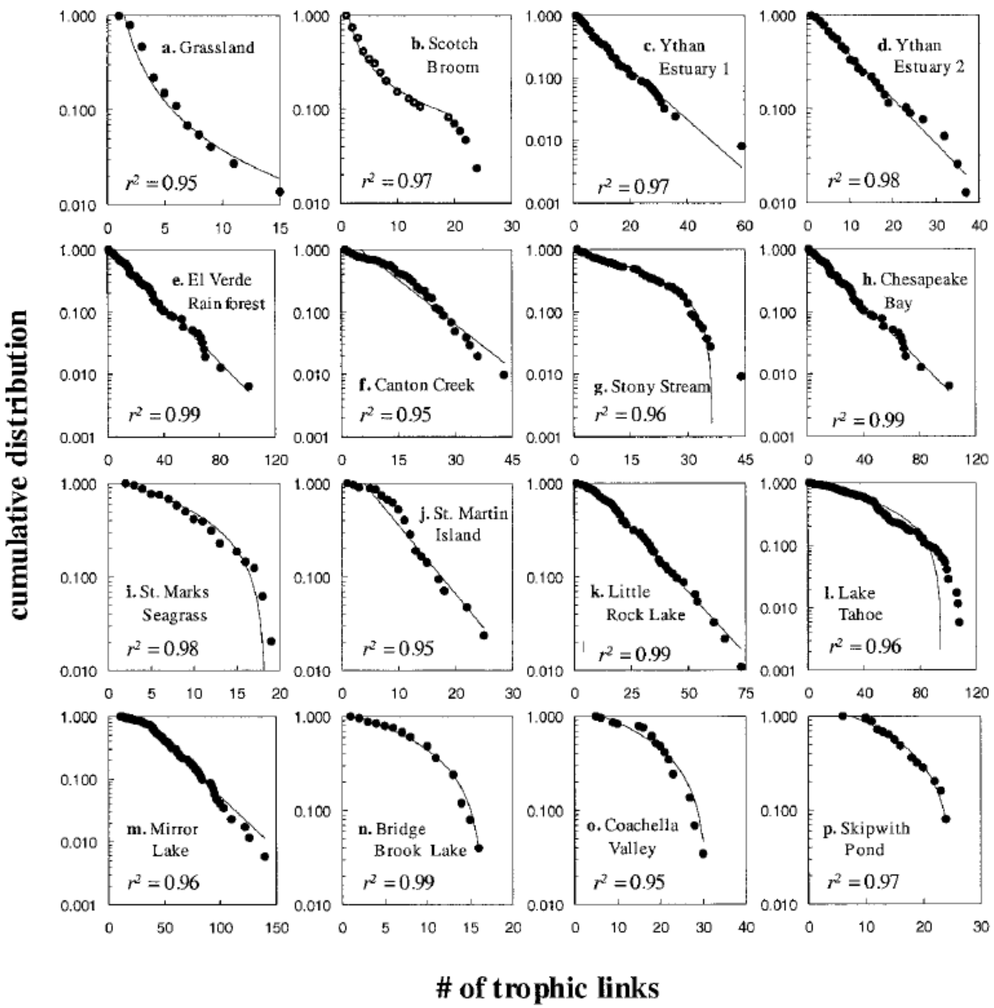
Model structure and emergence

- Madingley produces emergent behaviour at multiple ecological scales:

  - Individual (e.g. reproductive success)
  - Population (e.g. dynamics)
  - Community (e.g. food-web & trophic structure)
  - Ecosystem (e.g. energy & material flows)
  - Macroecological (e.g. latitudinal gradients)

Food web sampling

'Connectance'



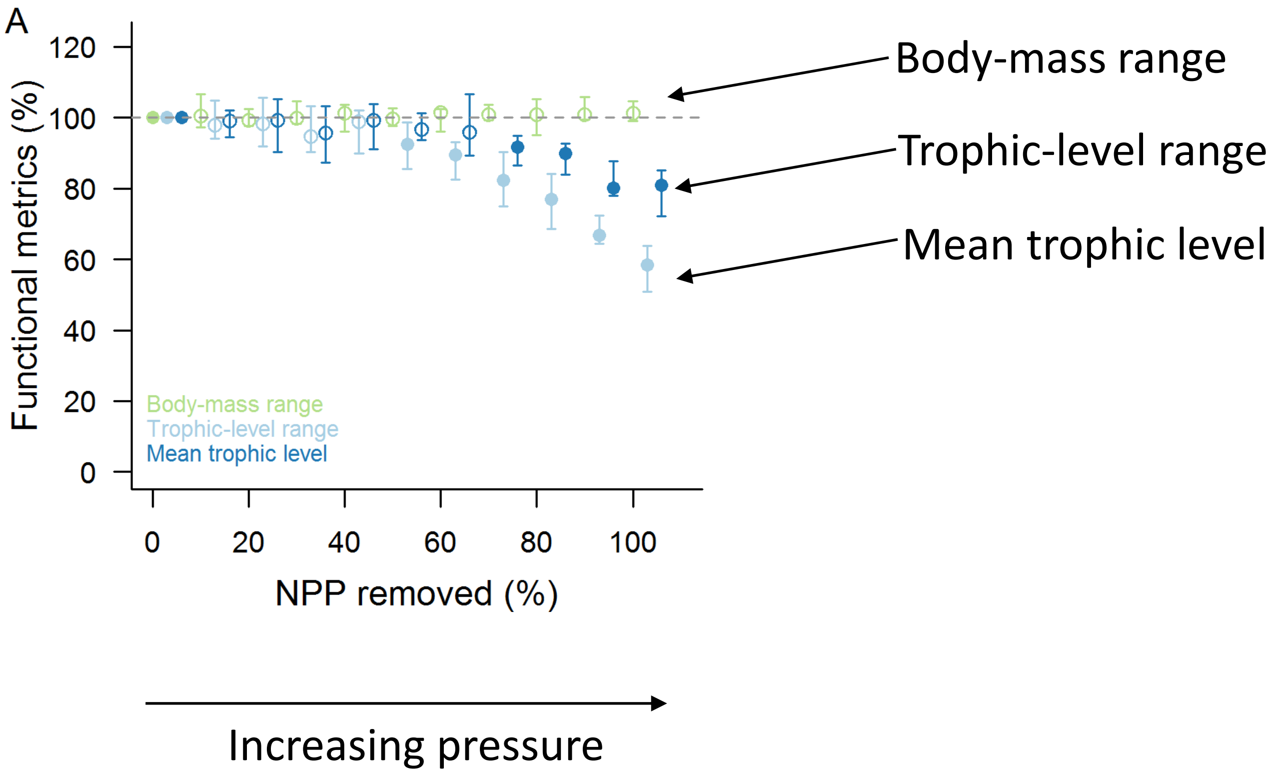
Compare empirical data to
'virtual gut sampling'
in Madingley

Dunne et al, PNAS, 2002

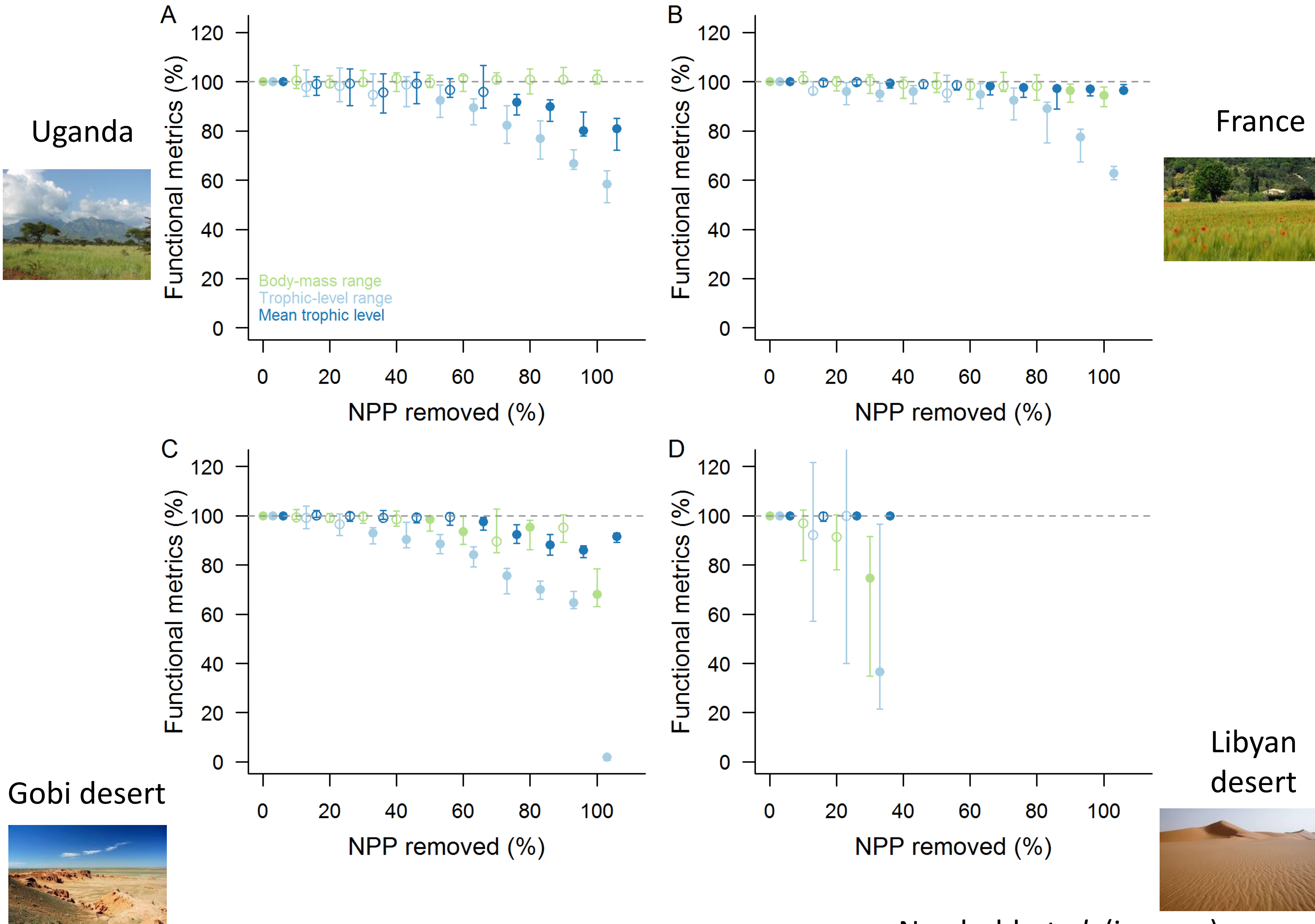
Perturbations & ecological collapse

- Thresholds
- Sudden state-changes and trophic cascades
- Resilience
- Recovery?

Uganda

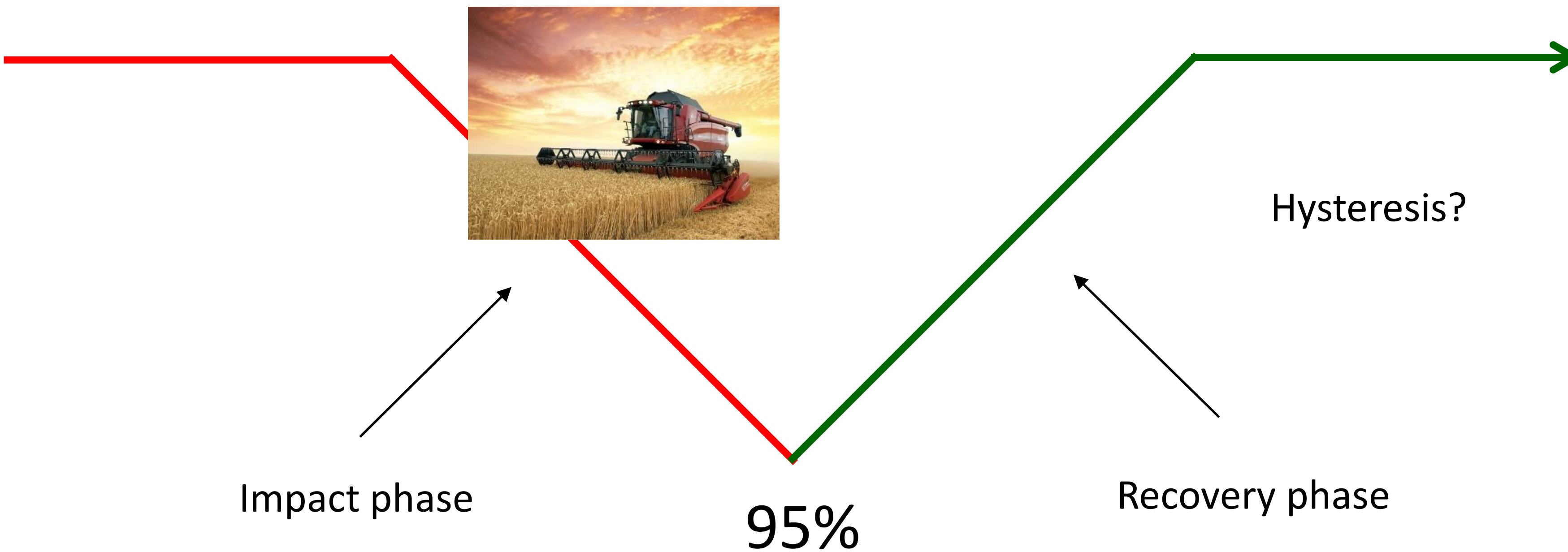


Newbold *et al.* (in prep).



Newbold *et al.* (in prep).

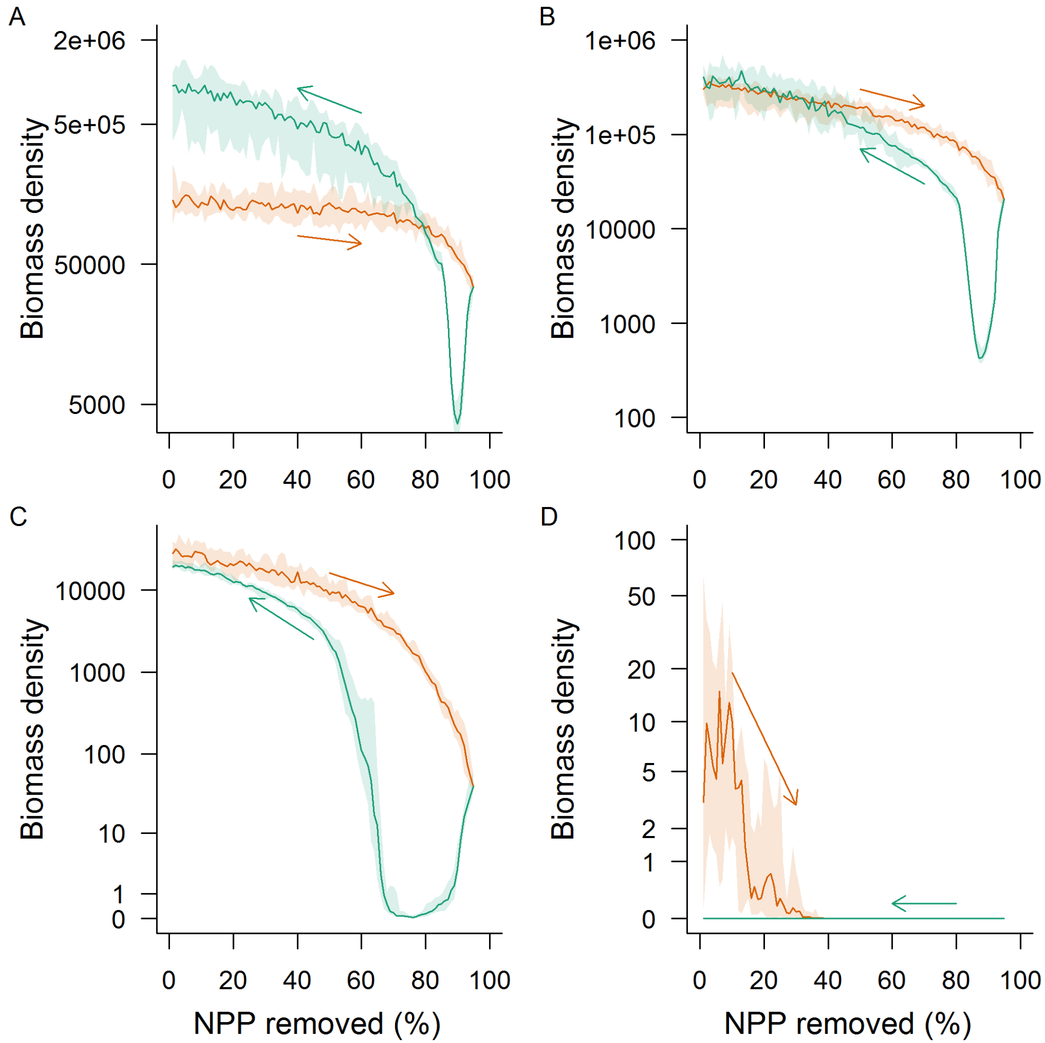
Do recovering ecosystems return to the pre-impact state?



Generally not

Uganda

France



Gobi desert

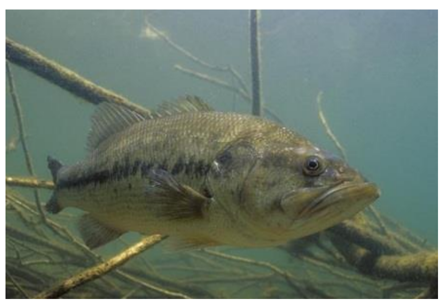
Libyan desert

Newbold *et al.* (in prep).

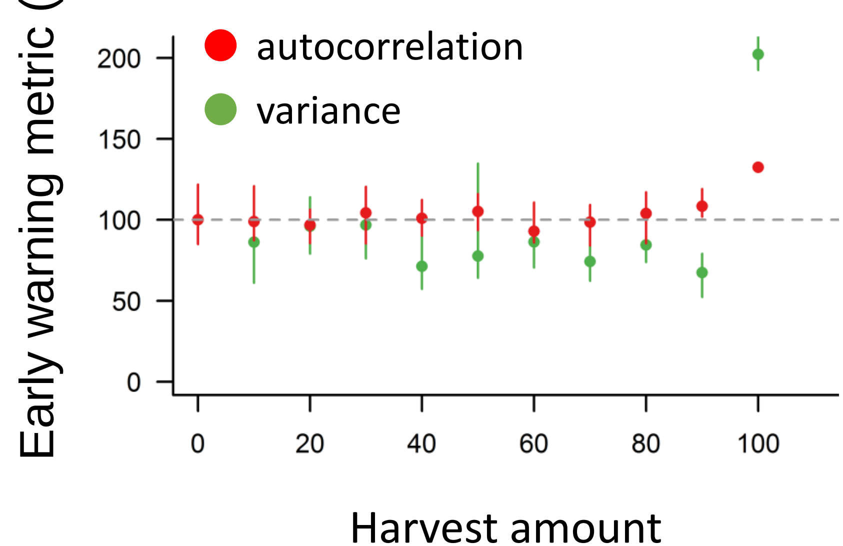
Early-warning signals of collapse

Early Warnings of Regime Shifts: A Whole-Ecosystem Experiment

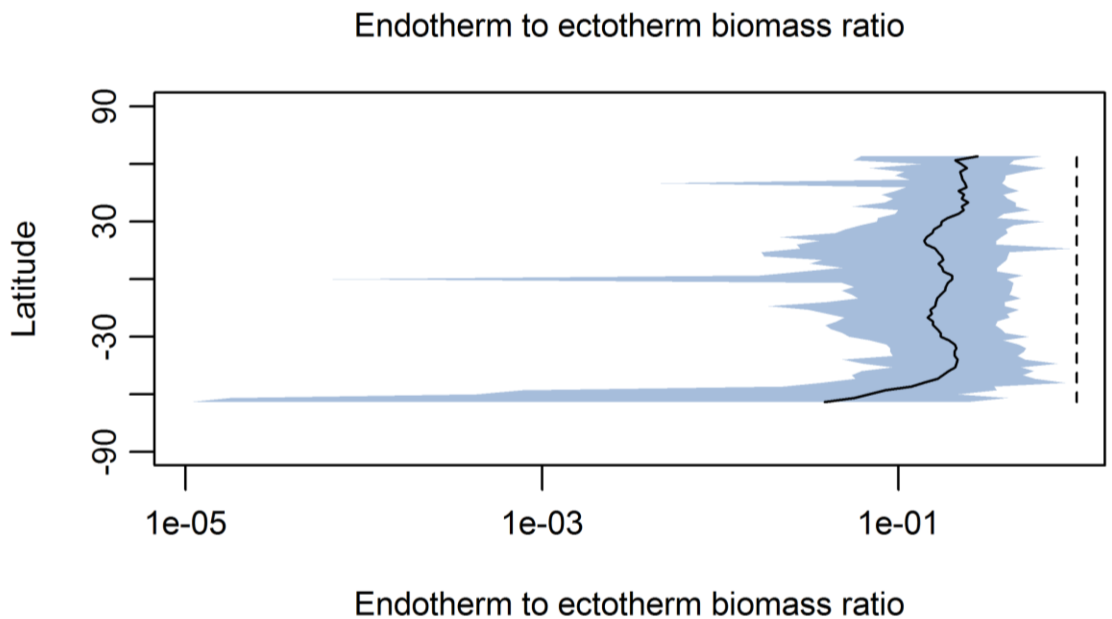
S. R. Carpenter,[1*] J. J. Cole,[2] M. L. Pace,[3] R. Batt,[1] W. A. Brock,[4] T. Cline,[1] J. Coloso,[3] J. R. Hodgson,[5] J. F. Kitchell,[1] D. A. Seekell,[3] L. Smith,[1] B. Weidel[1]



Unpubl.



Latitudinal ratio of endotherms to ectotherms



Marine

AP PHOTO/VENTURA COUNTY STAR/CHUCK KIRMAN

Past, present and future of ecosystems

- Project back to 1859 using GCM-ES model outputs
- Project forward under scenarios of future change (to 2100)
- Use the strengths of modelling approach (land and ocean, can produce novel metrics)
- Trade-offs (e.g. agriculture vs. fisheries)

1859
↓
2005
↓
2100

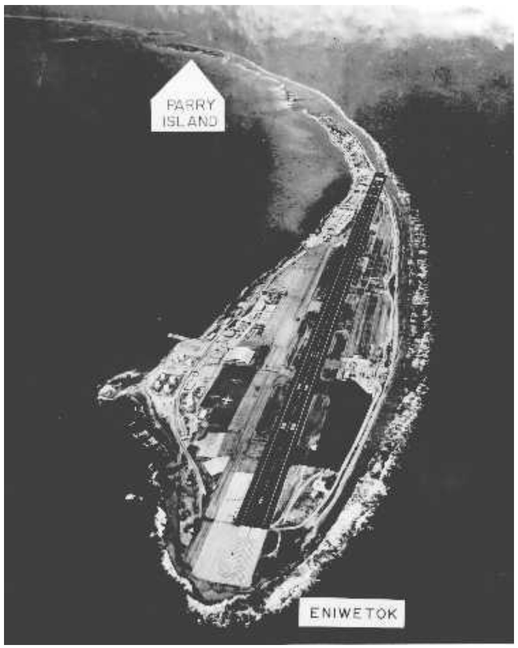
5. DNA barcoding & GEMs

Not much data with which to evaluate patterns

- Ecology -> generally small-scale observations & experiments

Sampling ecosystems from top to bottom

Eniwetok Atoll



TROPHIC STRUCTURE AND PRODUCTIVITY OF A WINDWARD CORAL REEF COMMUNITY ON ENIWETOK ATOLL[1]

HOWARD T. ODUM[2] and EUGENE P. ODUM[3]

Odum & Odum (1955)

Sampling ecosystems from top to bottom

- International Biological Program (IBP) 1964 - 1974

Fig. 15–14. Placement of a collection cage (biocenometer) for sampling 10 m^2. (Photo by Y. Gillon.)

Trawl surveys… close but not enough

Table 3.1. Shellfish and cephalopods to be recorded during surveys.

TSNCode	Common name	Scientific name	Recording	Measurement	Unit
Crustaceans					
98682	Golden crab	*Cancer bellanius*	Male/Female	Carapace width	mm below
98681	Edible crab	*Cancer pagurus*	Male/Female	Carapace width	mm below
98908	Deep-water red crab	*Geryon affinis*	Male/Female	Carapace width	mm below

ICES. 2012. Manual for the International Bottom Trawl Surveys. Series of ICES Survey Protocols. SISP 1-IBTS VIII. 68 pp

Can metabarcoding and eDNA help?

DNA barcoding and metabarcoding of standardized samples reveal patterns of marine benthic diversity

Matthieu Leray and Nancy Knowlton[1]

Leray & Knowlton (2015), PNAS

OPEN ACCESS Freely available online PLOS ONE

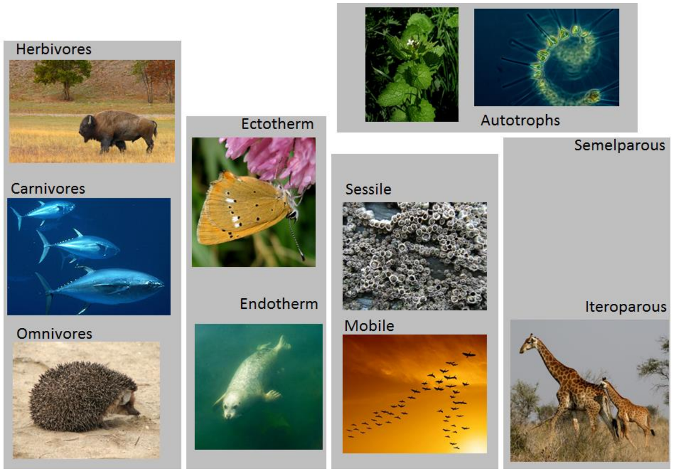
Detection of a Diverse Marine Fish Fauna Using Environmental DNA from Seawater Samples

Philip Francis Thomsen[1*9], Jos Kielgast[19], Lars Lønsmann Iversen[2], Peter Rask Møller[3], Morten Rasmussen[1], Eske Willerslev[1*]

Thomsen *et al*. (2012), PLoS One

In the shorter term….

- Identification of function from DNA
- Family level traits?



- Gut sampling -> dynamic food webs
- … IBP but with DNA barcoding technology?

Wishlist…

- Relative abundance of species / taxa
- Biomass of every functional group / trophic level
- Ecological function
- Flow rates of material through food web
- Sampling ecosystem from top to bottom
- Repeatedly
- Will next Friday work?

The future.....?

- Add automated eDNA samplers to acoustic or satellite tags?

Sustainable development goals

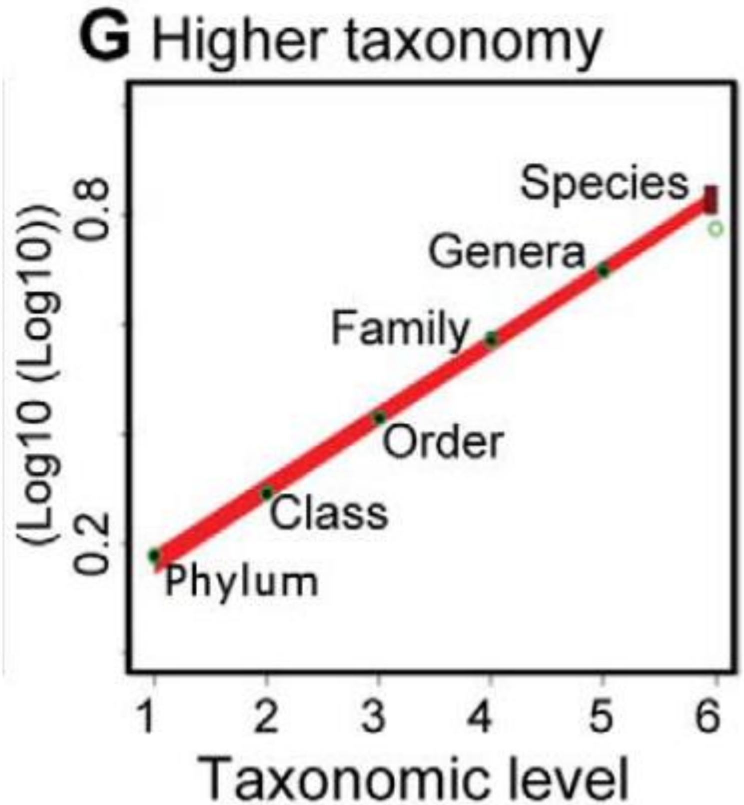
Planetary Biodiversity Mission

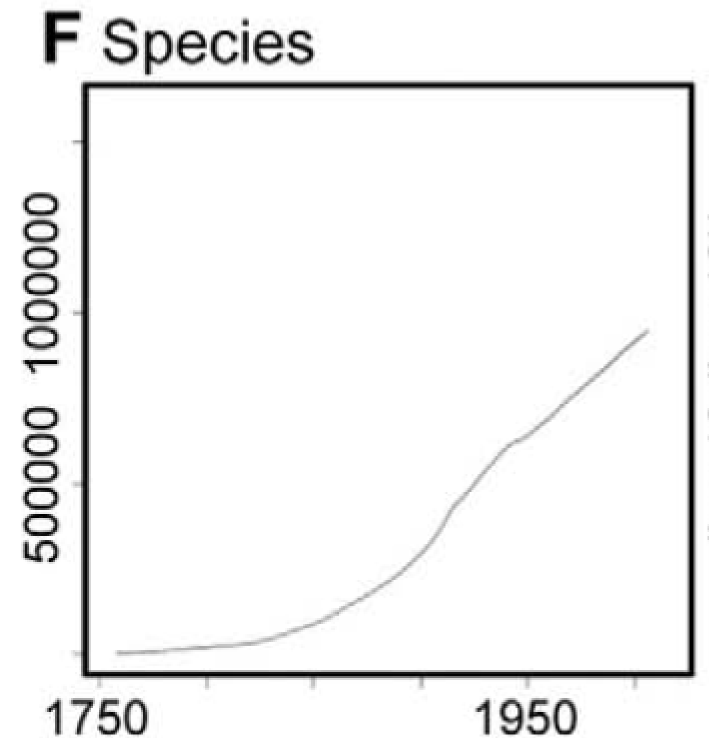
For humanity – and for life

Acknowledgements

Michael Harfoot, Tim Newbold
Drew Purves, Matthew Smith,
Phil Underwood
Microsoft Research Cambridge
Stephen Emmott and Jon Hutton

A ‘moving target’

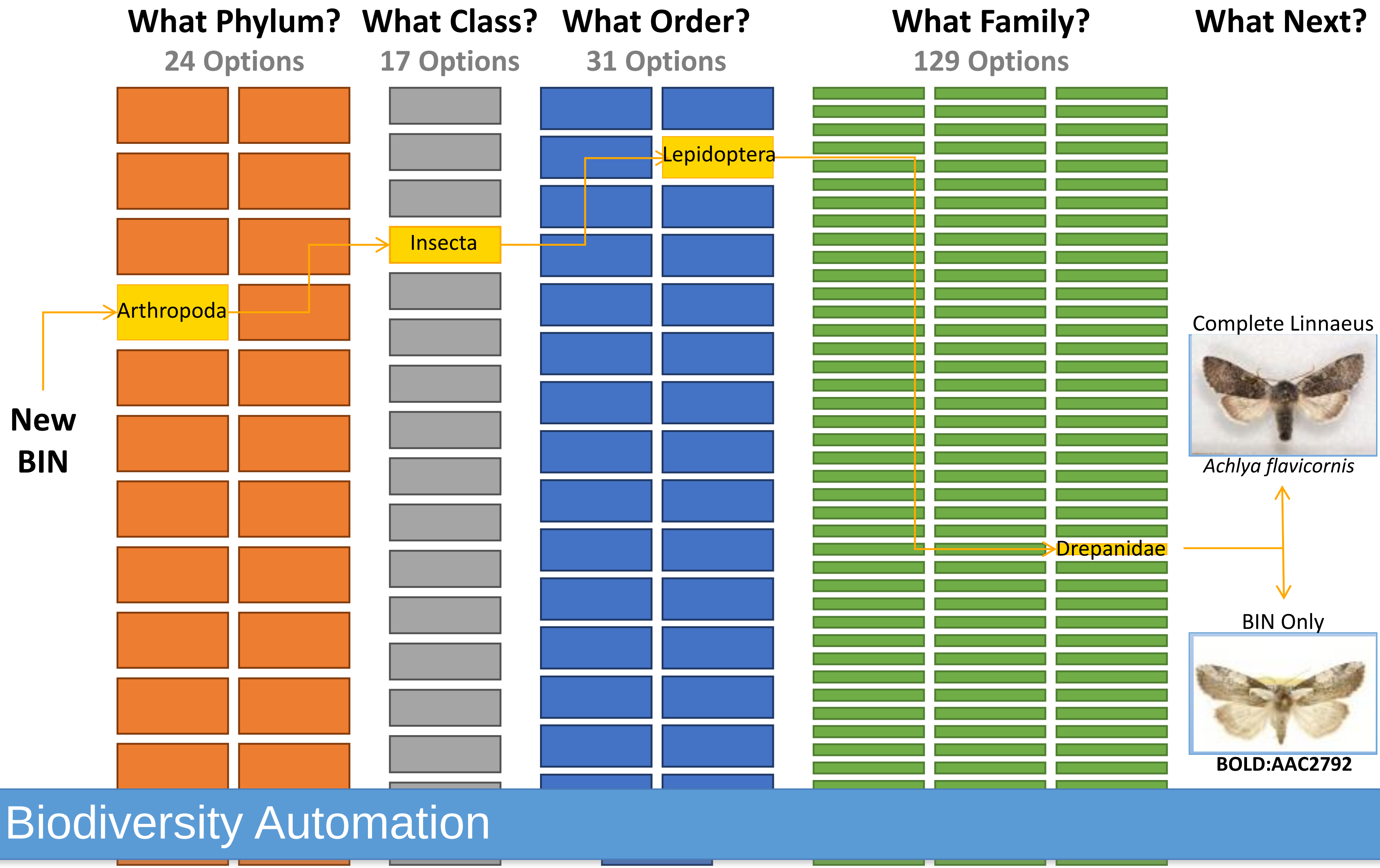




in Animalia fro

starting years sel

Automating Taxonomic Assignments



Probing Biodiversity with DNA Barcodes

1. **Are estimates of global number of animal species accurate?** MAYBE

2. **Has competition been the primary force in limiting the number of animal species?** **No**

3. **Are most species old?`** **Yes**

Ecopath with Ecosim

No fish is an island

National Research FLAGSHIPS

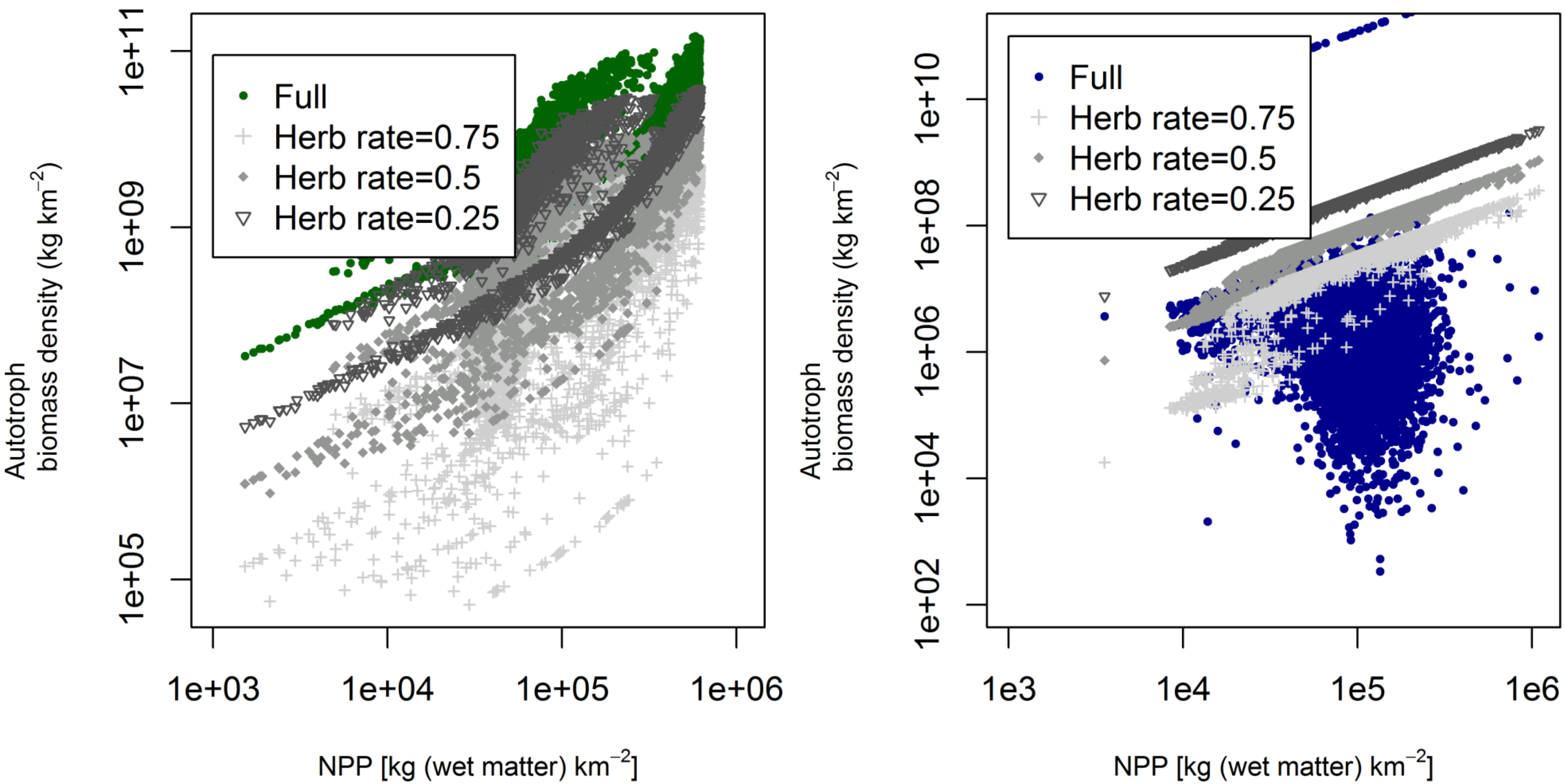
CSIRO

Atlantis - Ecosystem Model

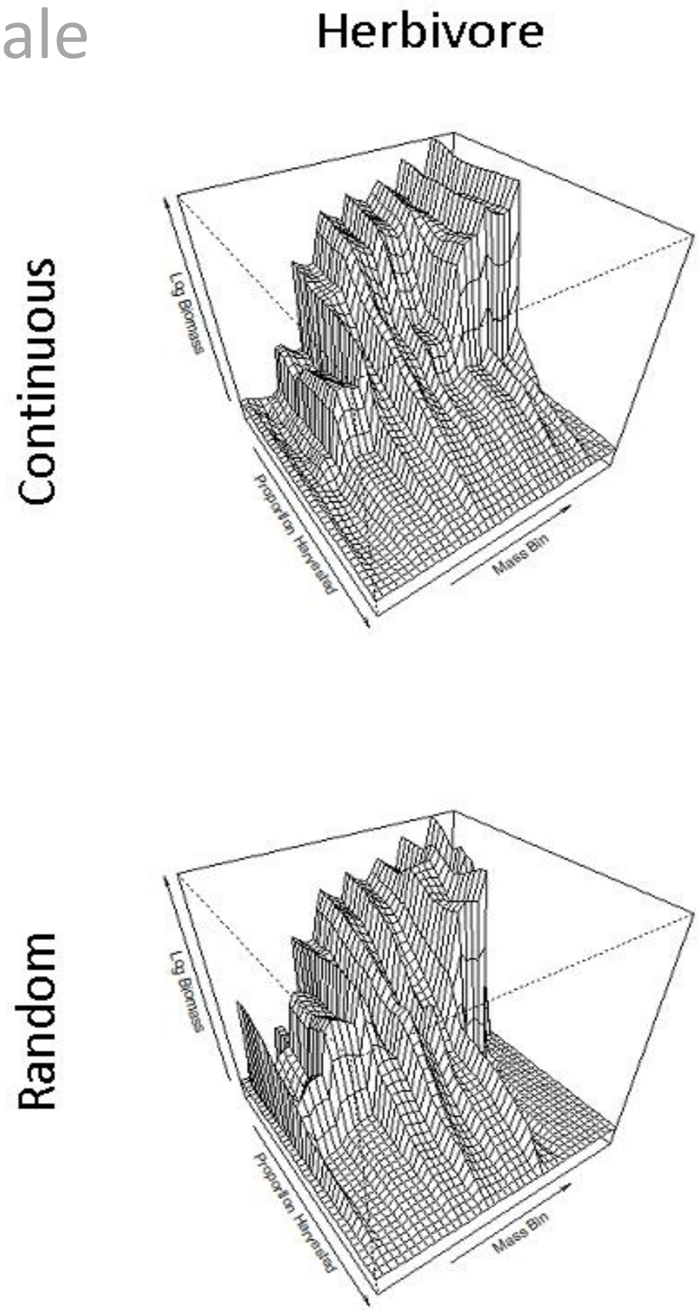
the darwin project

http://www.ecopath.org/
http://atlantis.cmar.csiro.au/
http://darwinproject.mit.edu/

Ecology in the Earth System



Community responses to small-scale fragmentation



Bartlett *et al.*, (*in prep.*)

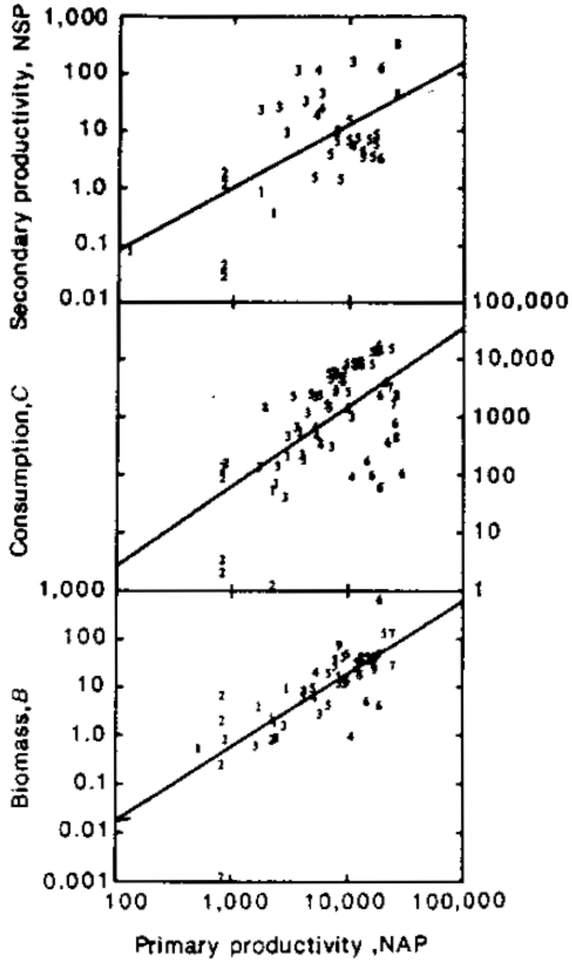
2.5 A diversion…

What separates GEMs from existing models?

- Global in scale, land and sea
- Focus on ecology/biodiversity
- Fully dynamic allowing for total ecosystem shifts
- Model entire ecosystems (~ all species)
- Ontogenetic changes (individuals, not mass pools)


Ecosystem-level patterns of primary productivity and herbivory in terrestrial habitats

S. J. McNaughton, M. Oesterheld, D. A. Frank & K. J. Williams

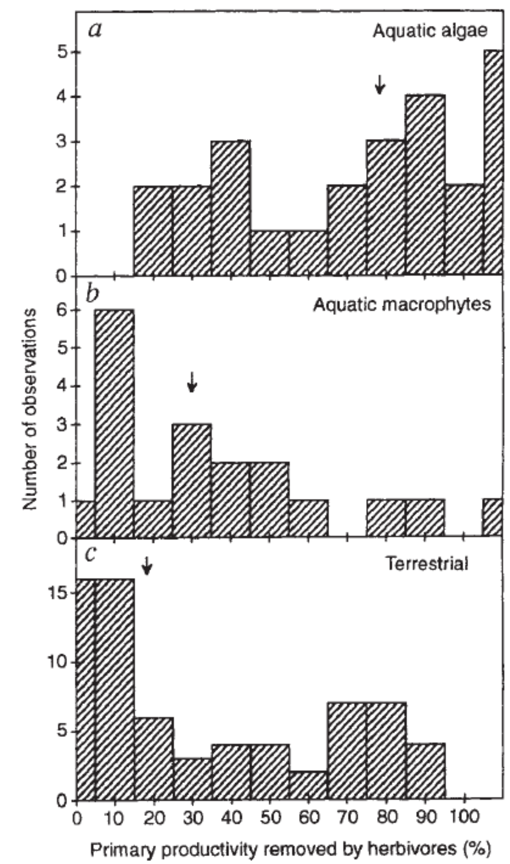


Nature, 1989

Magnitude and patterns of herbivory in aquatic and terrestrial ecosystems

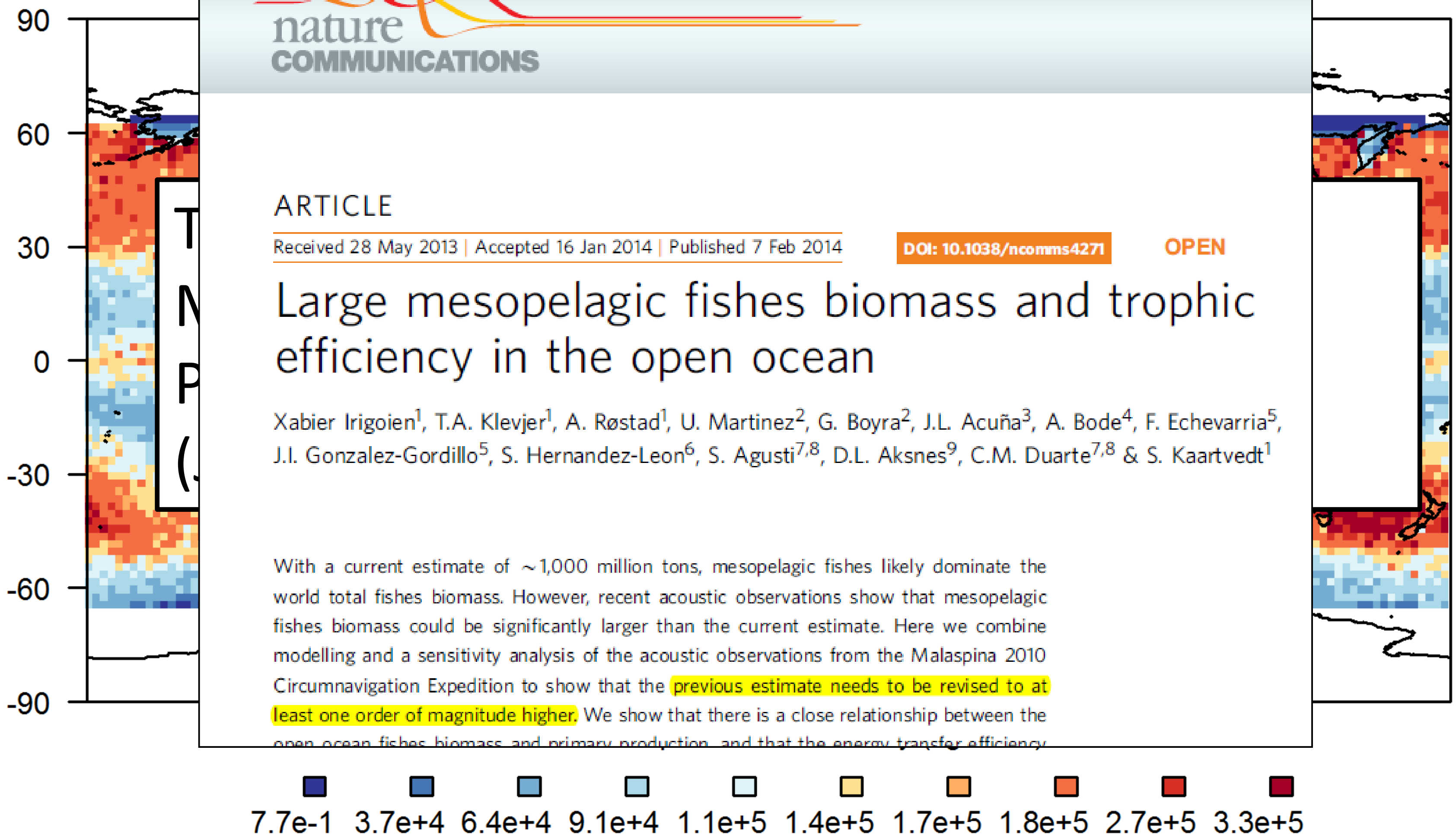
Hélène Cyr*†‡ & Michael L. Pace†

† Institute of Ecosystem Studies, Box AB, Millbrook, New York, 12545 USA
‡ Ecology Program, Rutgers University, Piscataway, New Jersey 08855-1059, USA



Nature, 1993

Not much data with which to evaluate biomass patterns at a global scale



nature COMMUNICATIONS

ARTICLE

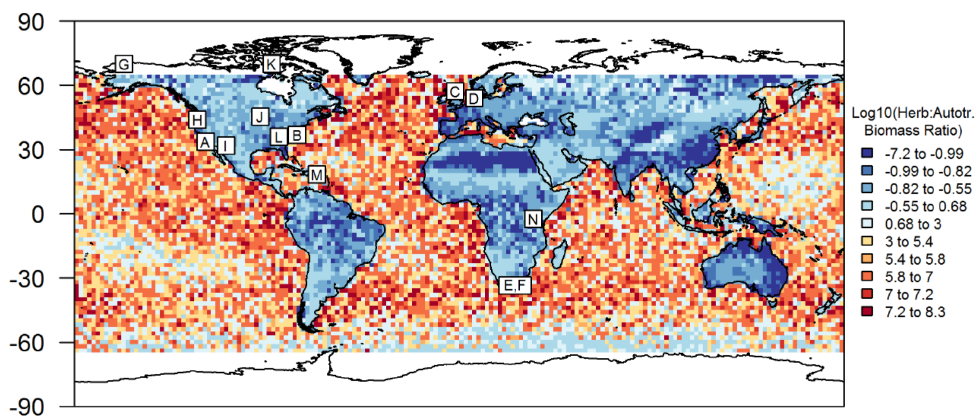
Received 28 May 2013 | Accepted 16 Jan 2014 | Published 7 Feb 2014 DOI: 10.1038/ncomms4271 OPEN

Large mesopelagic fishes biomass and trophic efficiency in the open ocean

Xabier Irigoien[1], T.A. Klevjer[1], A. Røstad[1], U. Martinez[2], G. Boyra[2], J.L. Acuña[3], A. Bode[4], F. Echevarria[5], J.I. Gonzalez-Gordillo[5], S. Hernandez-Leon[6], S. Agusti[7,8], D.L. Aksnes[9], C.M. Duarte[7,8] & S. Kaartvedt[1]

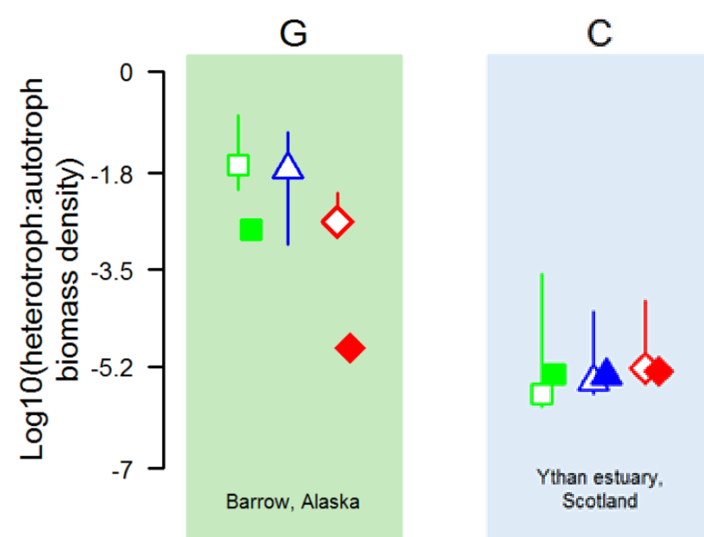
With a current estimate of ~1,000 million tons, mesopelagic fishes likely dominate the world total fishes biomass. However, recent acoustic observations show that mesopelagic fishes biomass could be significantly larger than the current estimate. Here we combine modelling and a sensitivity analysis of the acoustic observations from the Malaspina 2010 Circumnavigation Expedition to show that the previous estimate needs to be revised to at least one order of magnitude higher. We show that there is a close relationship between the open ocean fishes biomass and primary production, and that the energy transfer efficiency

Not much data with which to evaluate patterns



Biomass ratios
(solid = data, white = model)

- Herbivore : autotroph
- Omnivore : autotroph
- Carnivore : autotroph

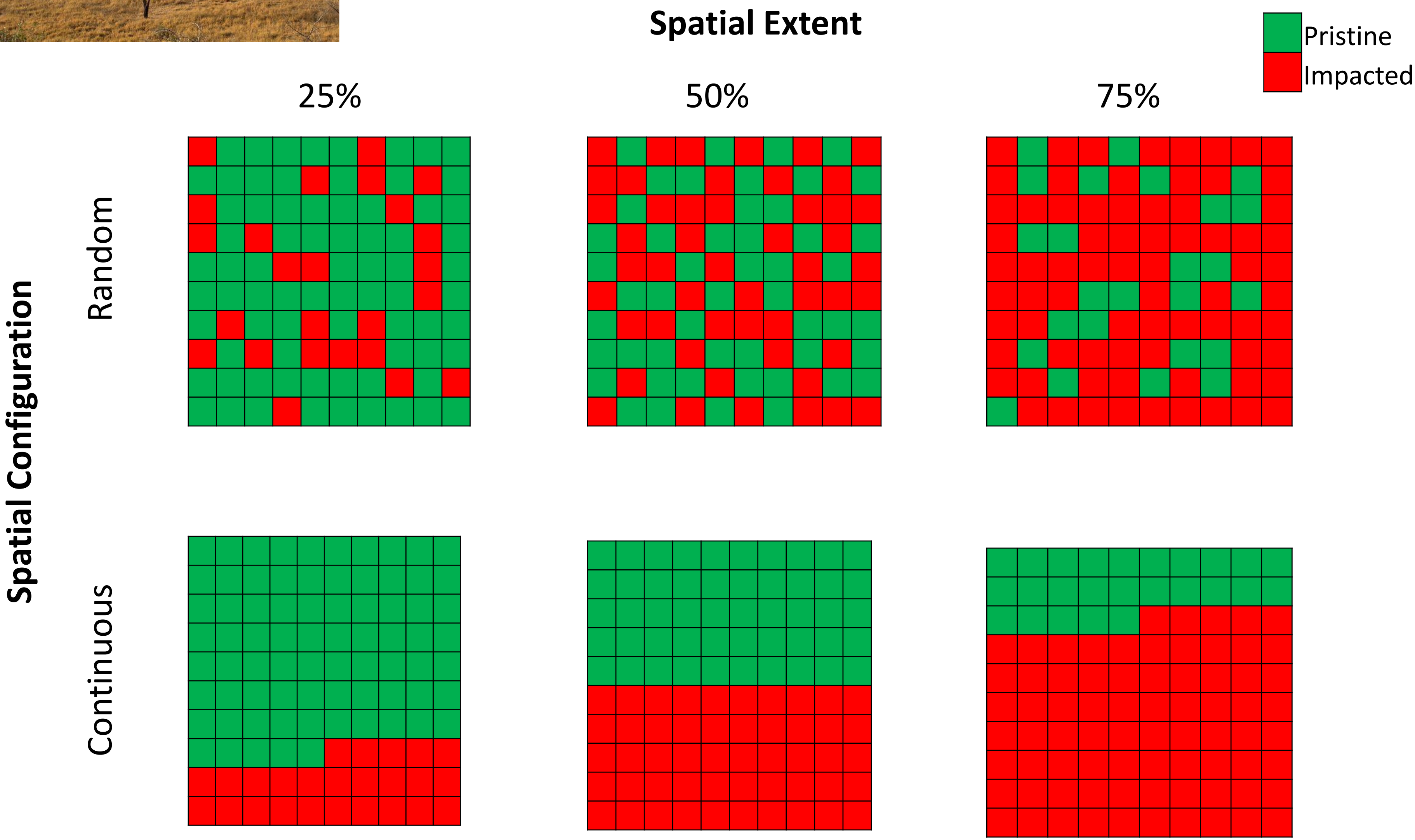


Marine developments

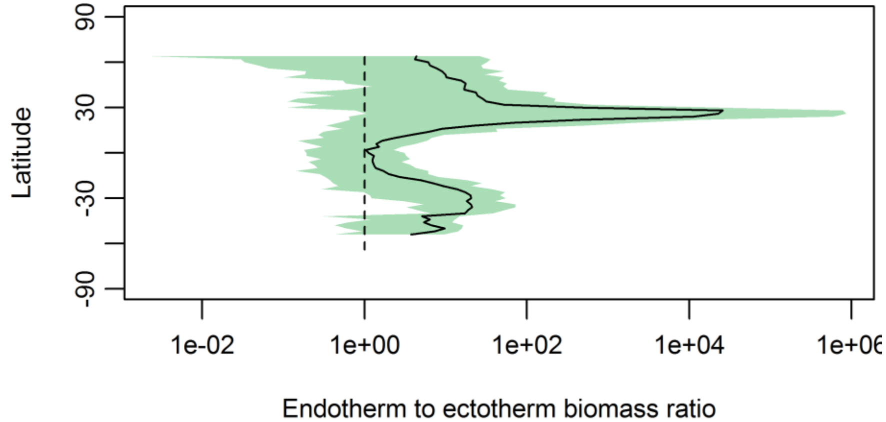
…including

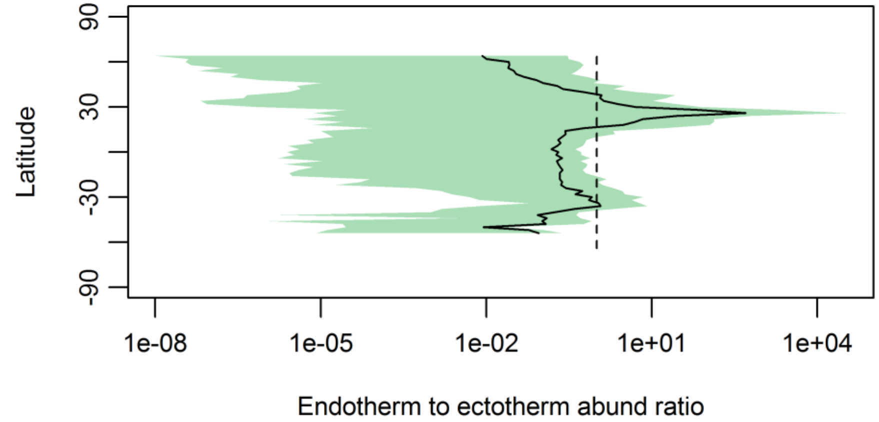
- 2.5D / fully 3D marine model
- Migration & learned dispersal
- More finely resolved functional groups
- Habitat -> coral reefs, mangroves, seagrass beds
- MPAs
- Aquaculture
- Fully coupled NPZD model
- Bayesian MCMC constaint of parameters

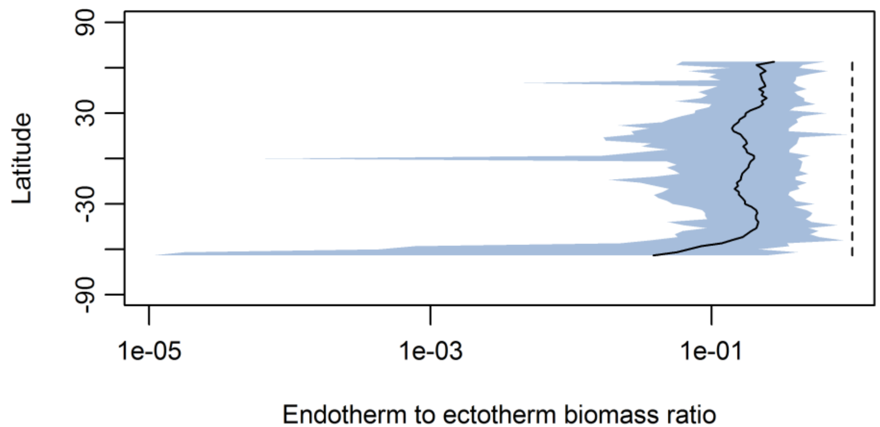
Community responses to small-scale fragmentation

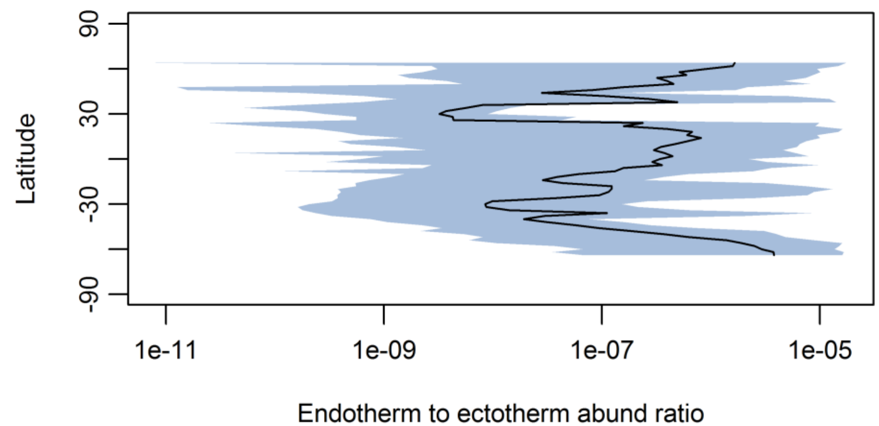


Latitudinal ratio of endotherms to ectotherms

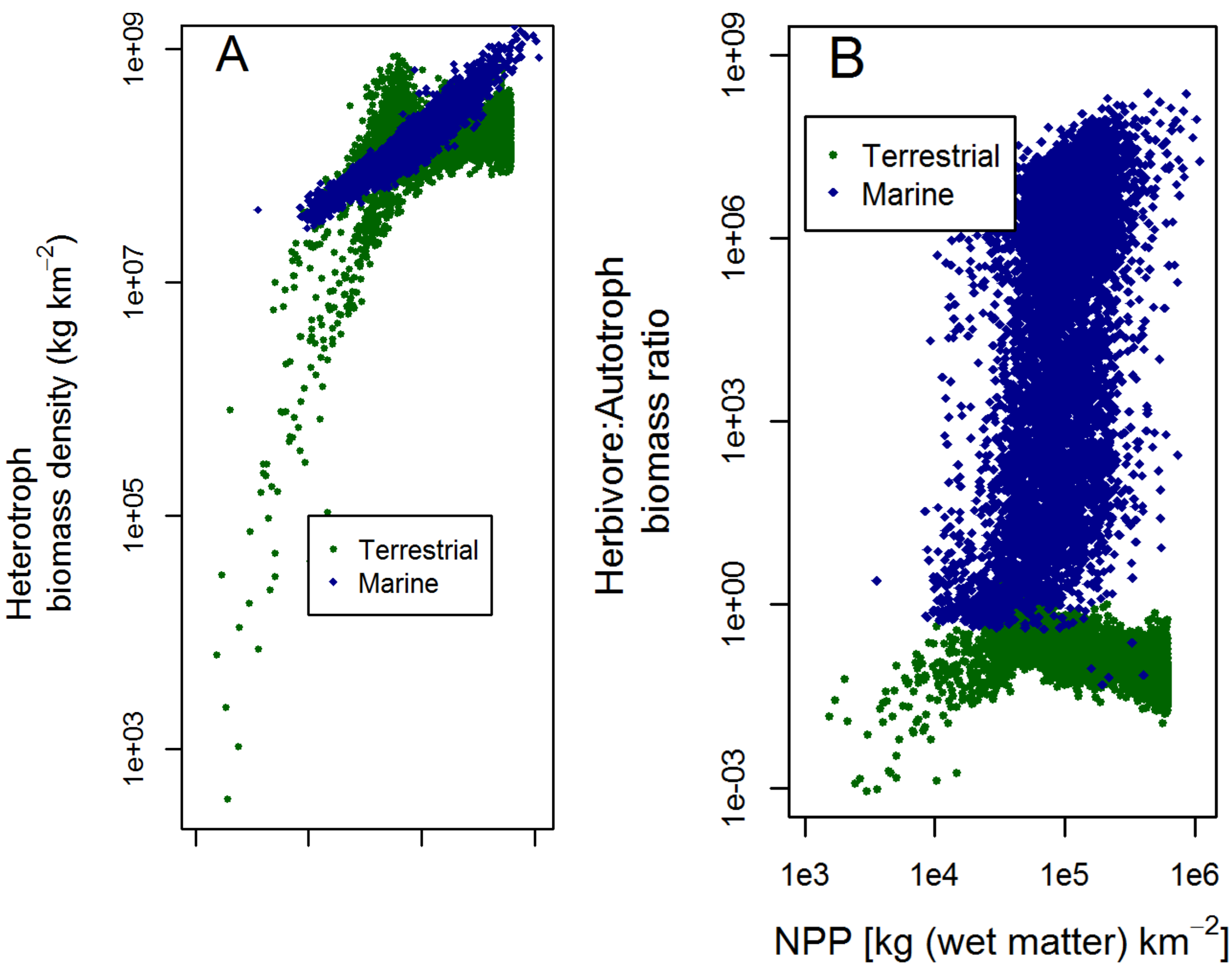




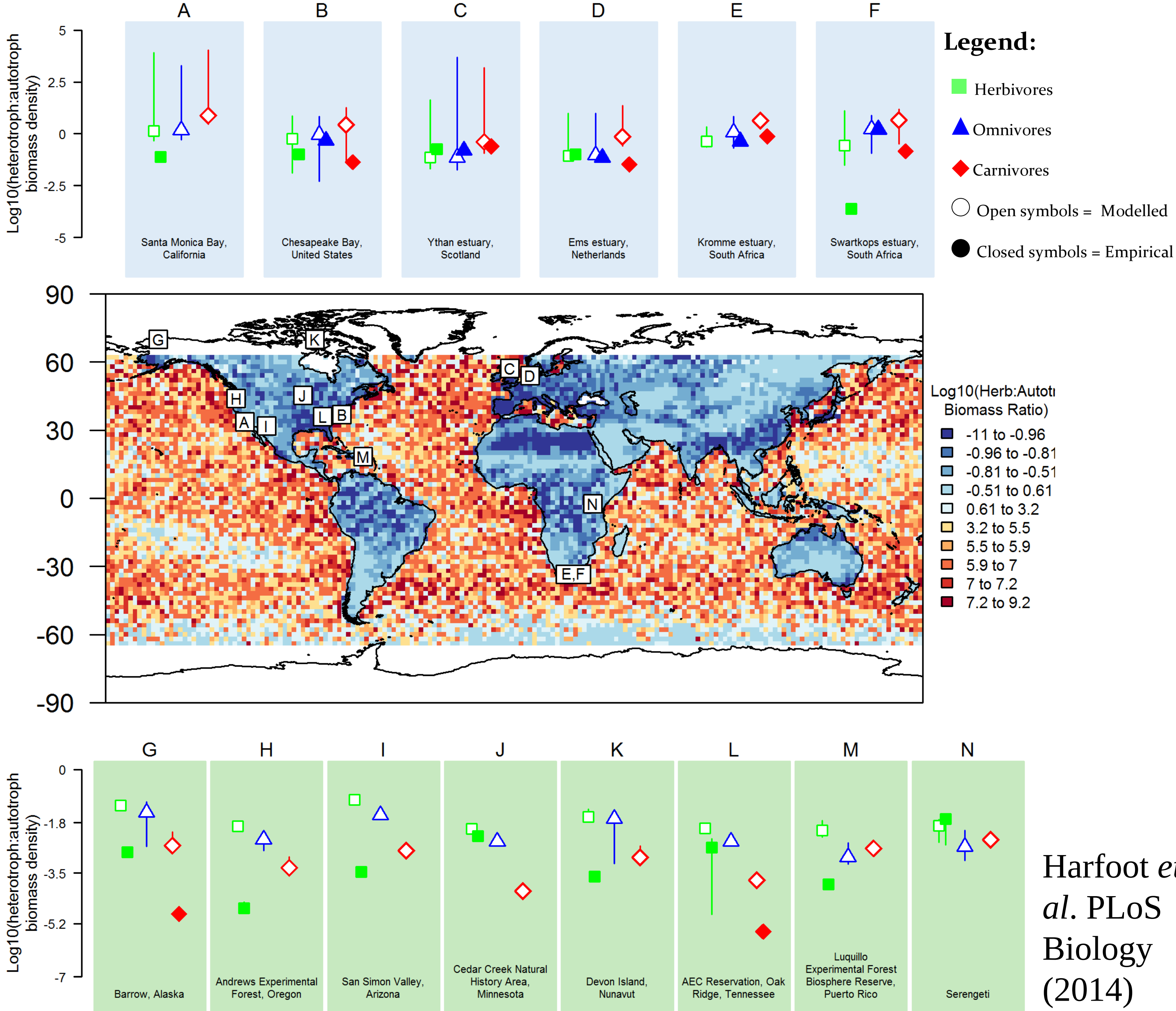




Ecology in the Earth System

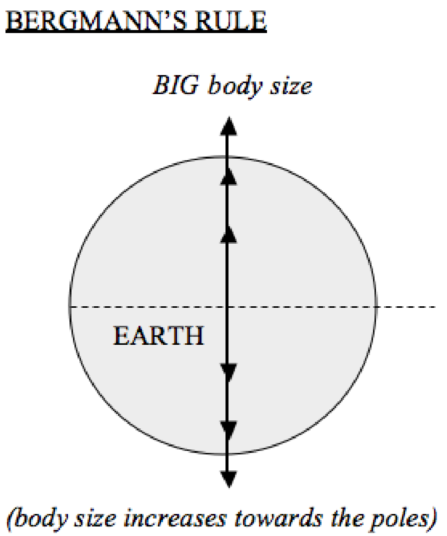


Community-level properties

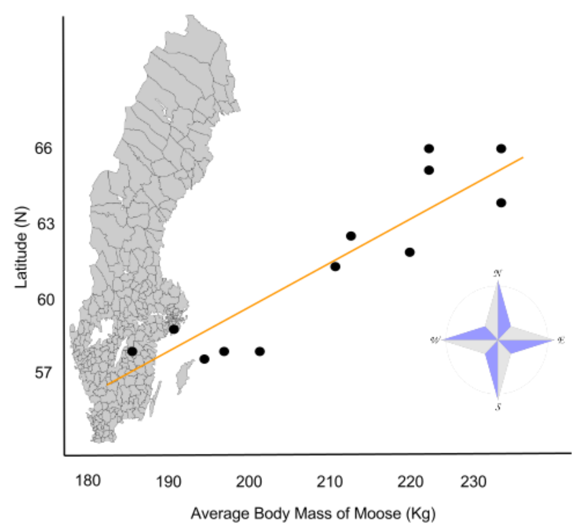


Harfoot *et al*. PLoS Biology (2014)

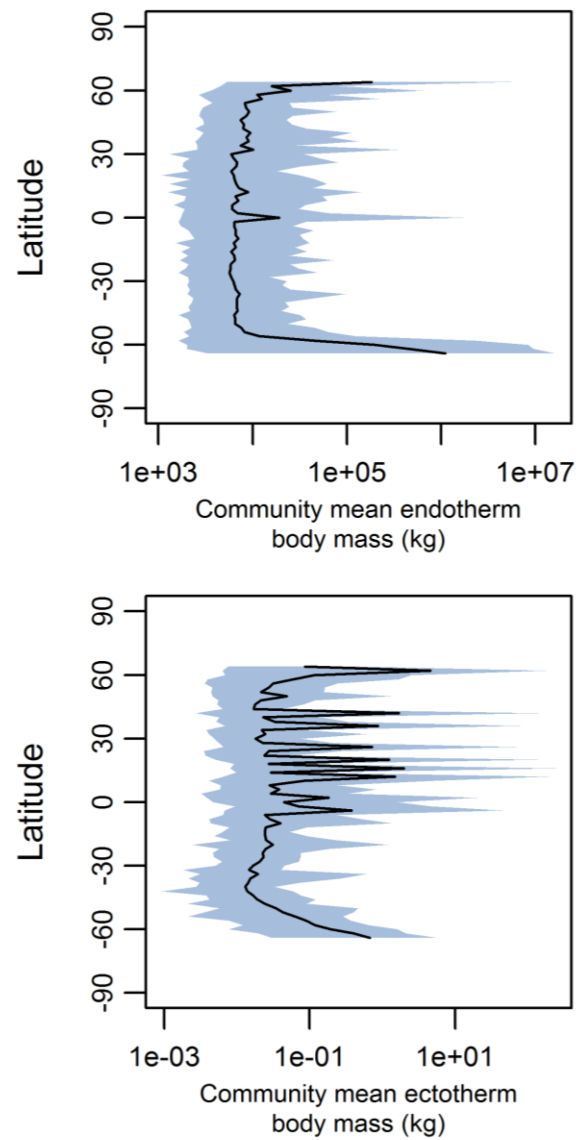
Testing ecological theories: e.g. Bergmann's rule



Håkan et al., Oecologia (1995)



Marine

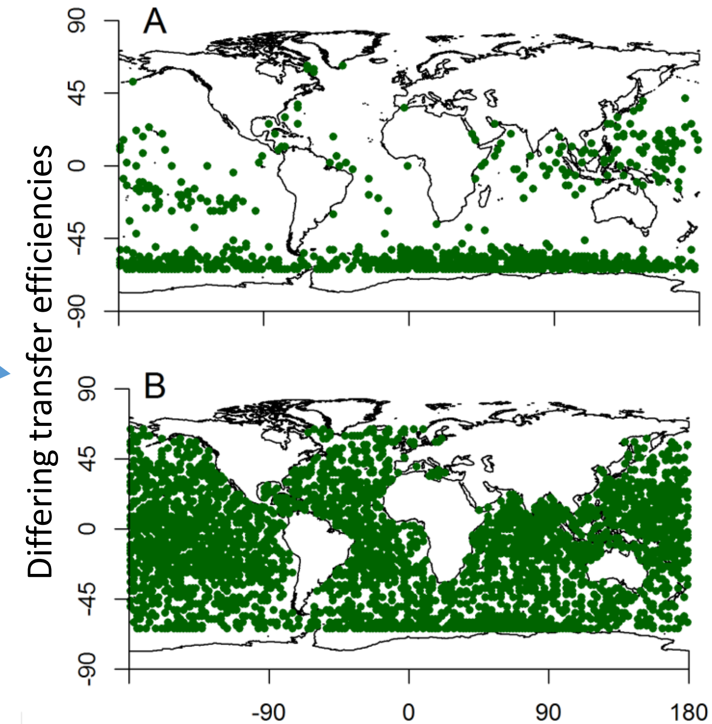


Abraham *et al.*, (*in prep.*)

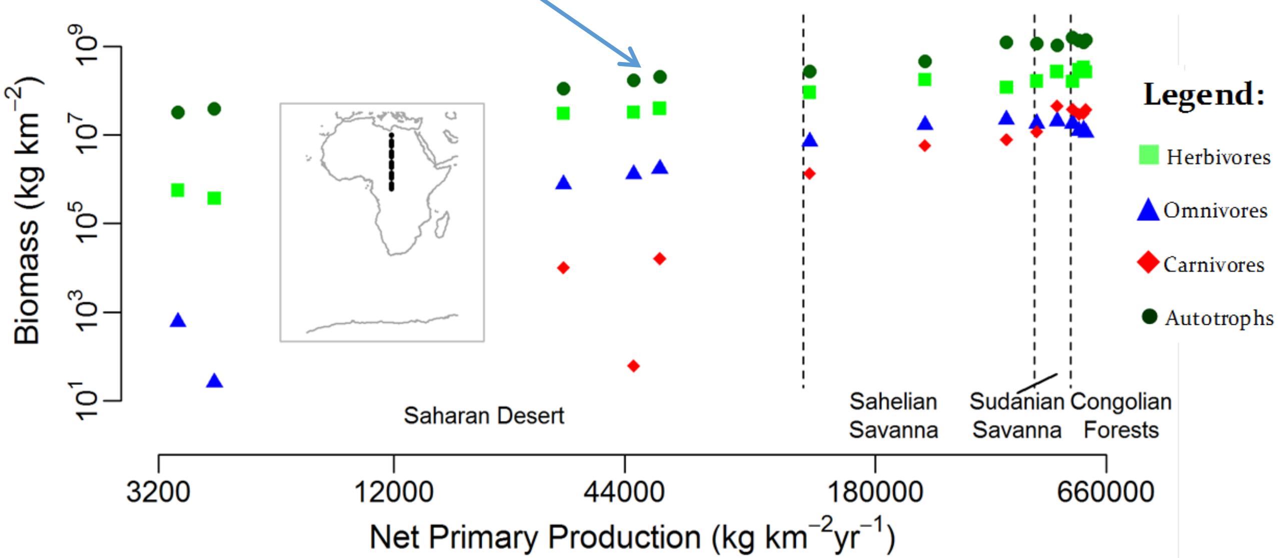
Investigation of ecological mechanism

E.g.

Inverted marine trophic biomass pyramids

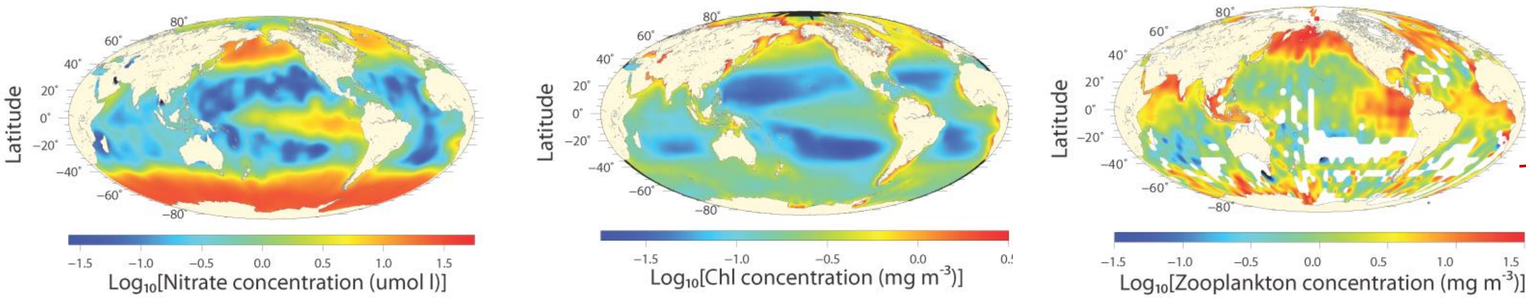


Trophic structure and productivity gradient



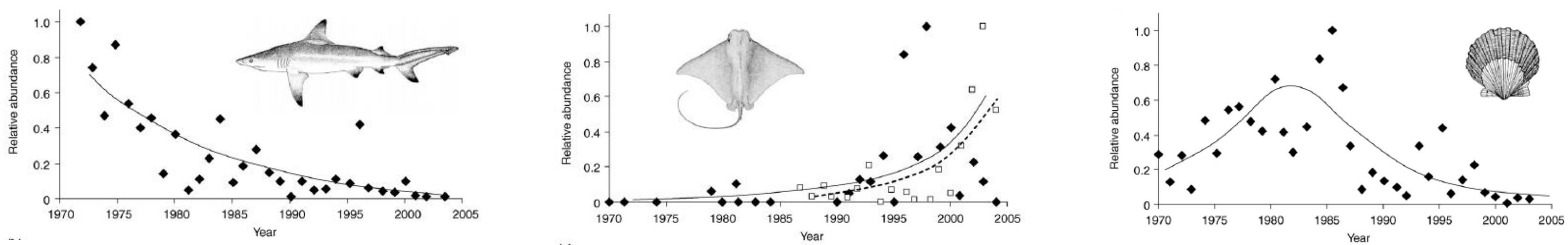
Trophic control

Resource control: Prey availability constrains abundance of predators
- *i.e.* carrying capacity



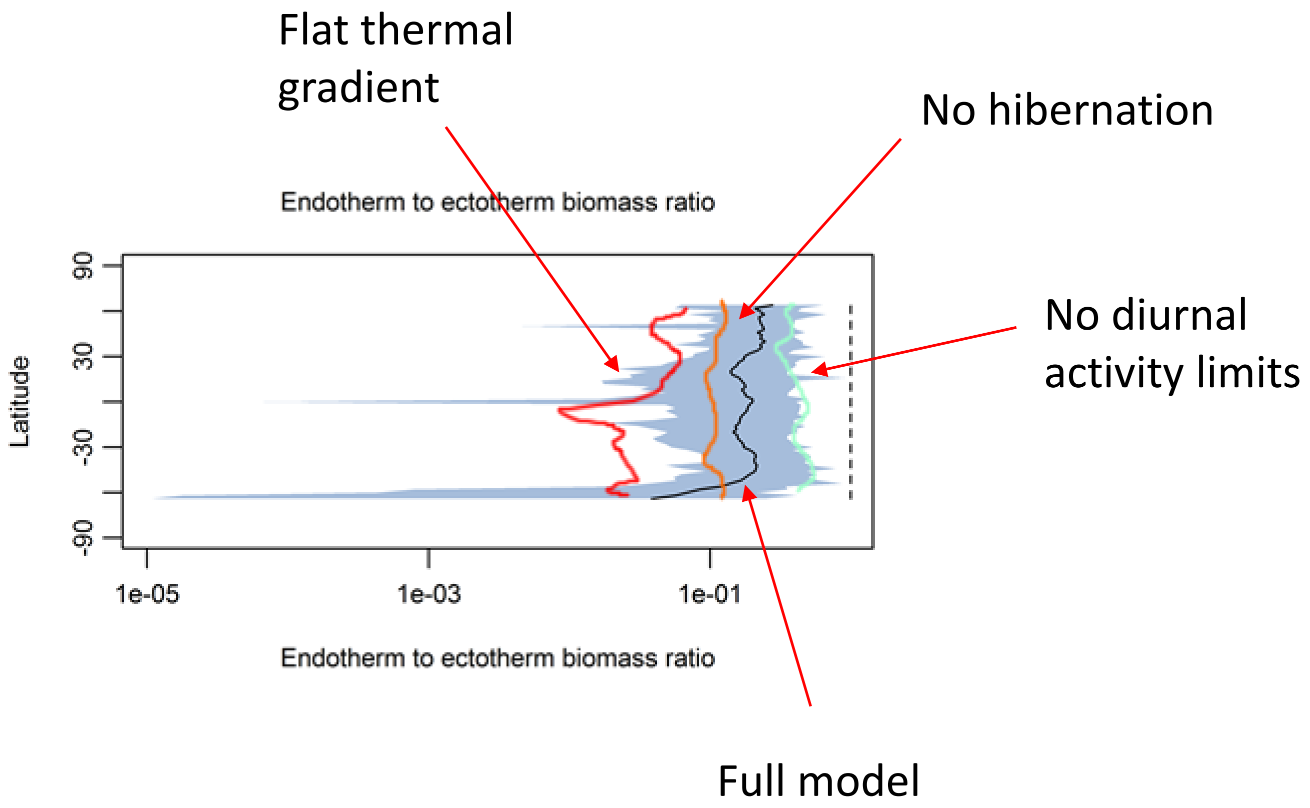
Fishes
Mammals
Catch

Consumer control: Predators suppress the abundance of prey
- *i.e.* trophic cascade



Boyce D.G. & Worm, B (2014) *submitted*; Heithaus, M.R. *et al.* (2008) *Trends Ecol. Evol.*; Myers, R.A. *et al.* (2007) *Science*

Isolate specific mechanisms



(Not real results – for illustration only)