An introduction to ecological modelling

3. (More) Complex Models of Ecological Systems

Lecture outline

Simpler systems-level models of ecosystems

Vegetation/plant-community models

Ocean ecosystem models

General ecosystem models

Relatively simple system-level models: coral reefs

Complex, interconnected dynamics

Not ethical to experiment with the effects of environmental change

Simple system-level model of coral reef dynamics

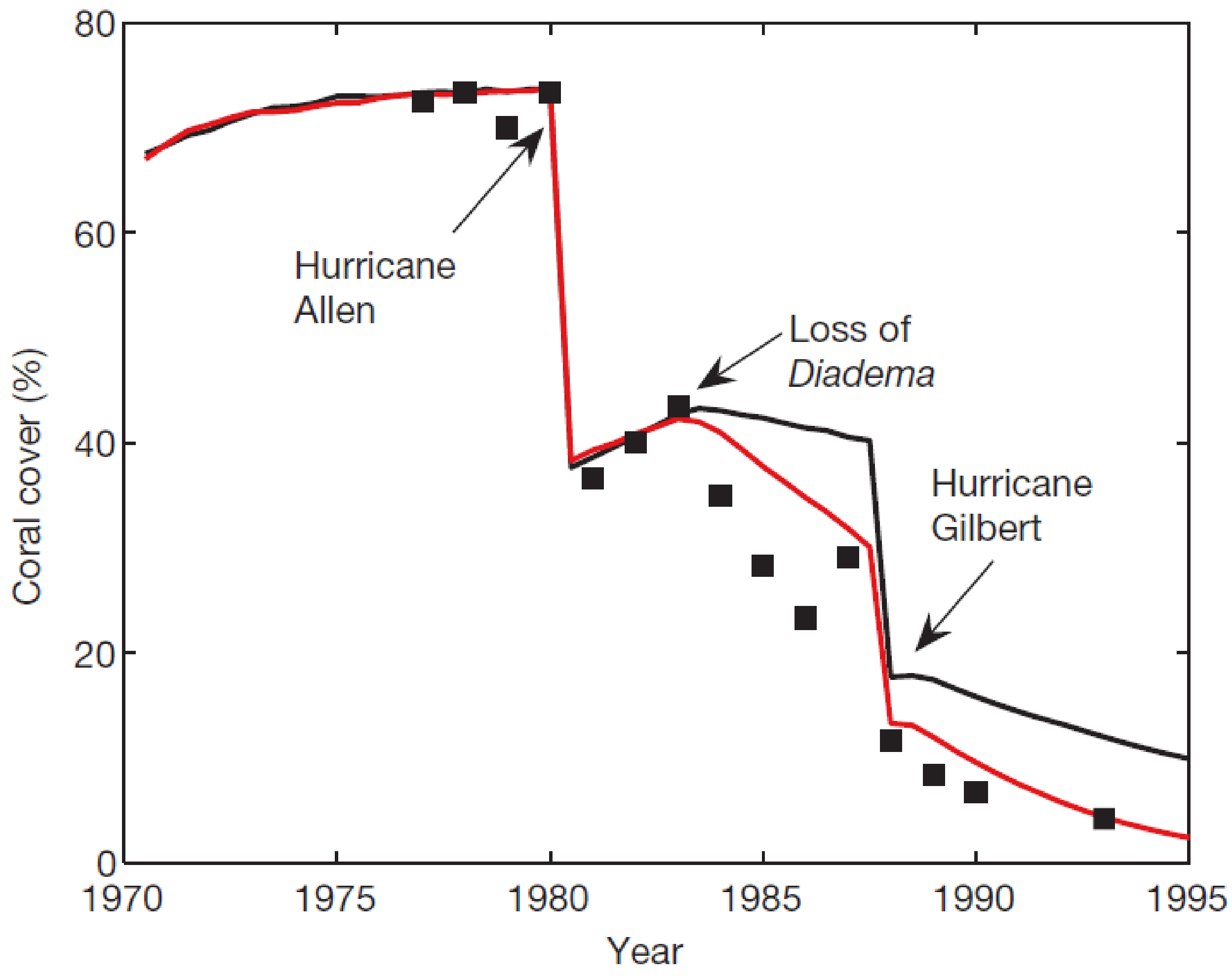
Model of cover of coral and algae

Processes (coral): recruitment, growth, reproduction, and competition (with corals and algae)

Processes (algae): colonization and growth

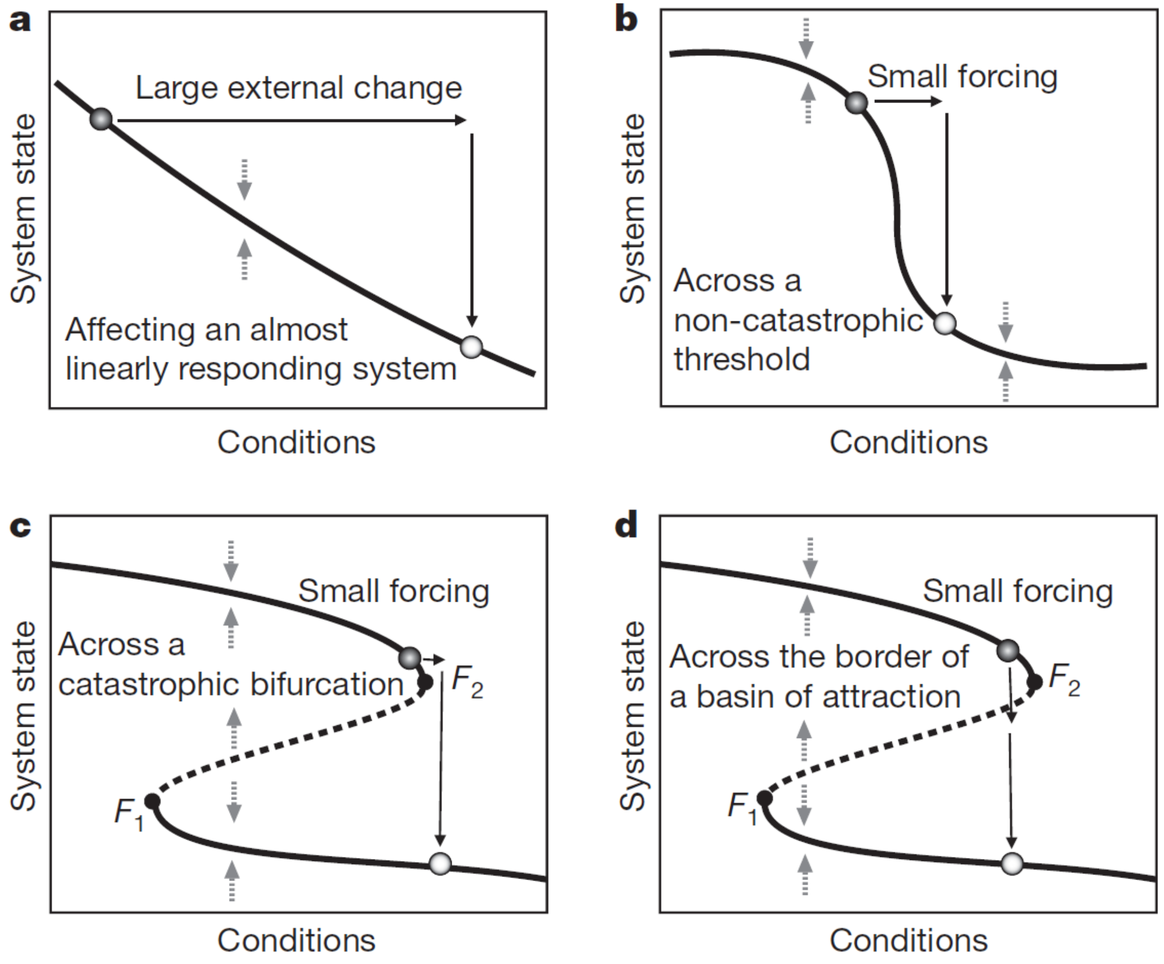
Processes (other): grazing by fish, fishing by humans

Model matches observed change in coral cover well



Mumby et al. (2007). *Nature* **450**: 98-101

Ecosystem regime shifts

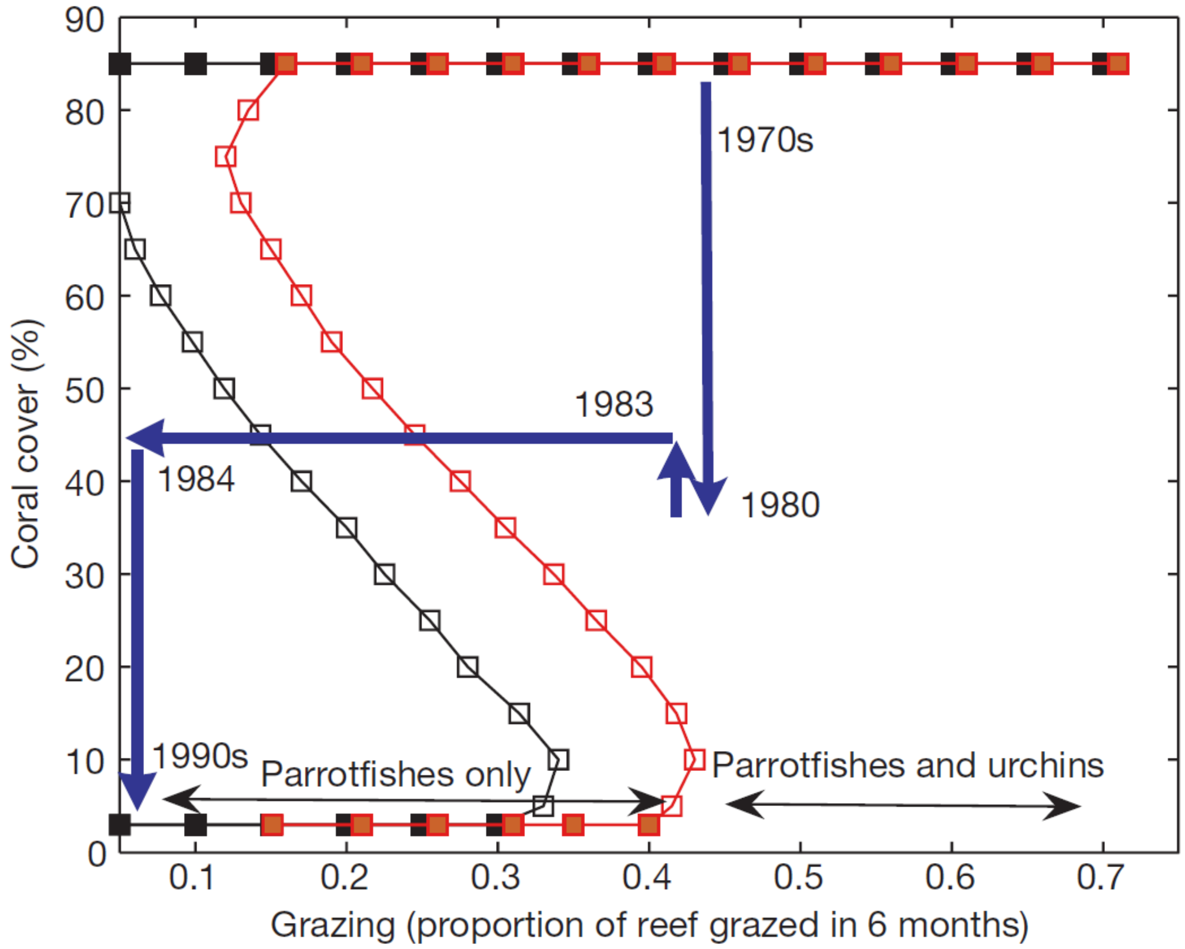


If conditions change beyond a certain point, ecosystems can abruptly shift to a new state

Reversing the conditions might not be enough to cause the ecosystem state to revert ('hysteresis')

Scheffer et al. (2009). *Nature* **461**: 53-59

Simple system-level model of coral reef dynamics



Mumby et al. (2007). *Nature* **450**: 98-101

System has unstable equilibria (open squares)

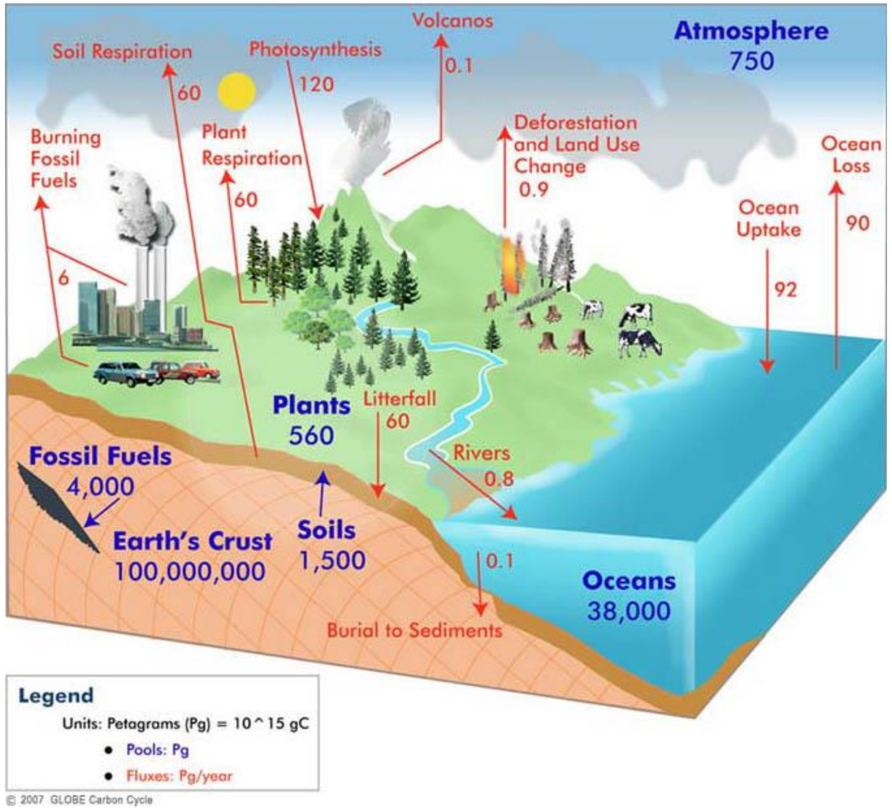
Grazing reduced after loss of urchins

Makes system less resilient to disturbance (e.g. by hurricanes)

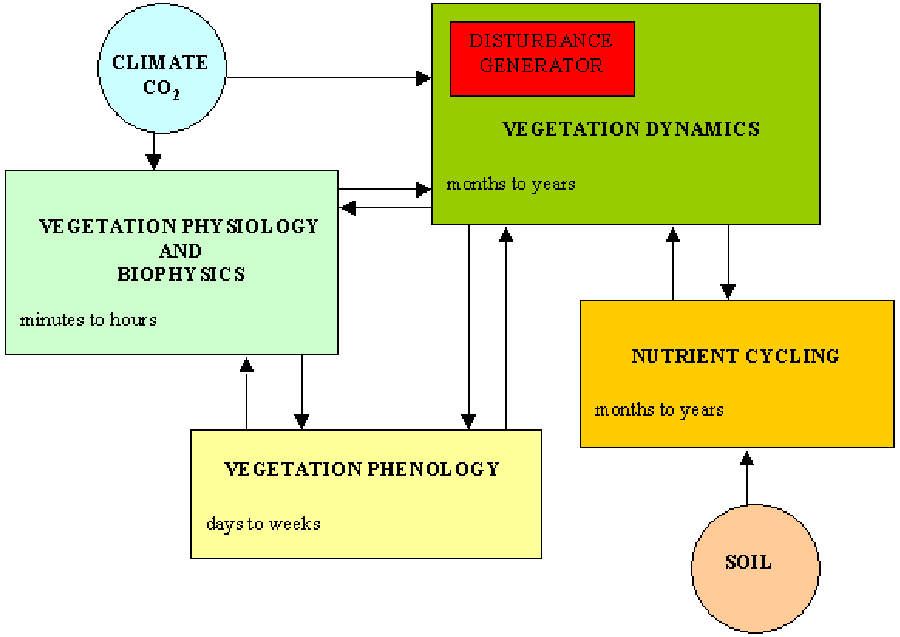
Switch to stable algal-dominated state more likely

The importance of understanding vegetation dynamics

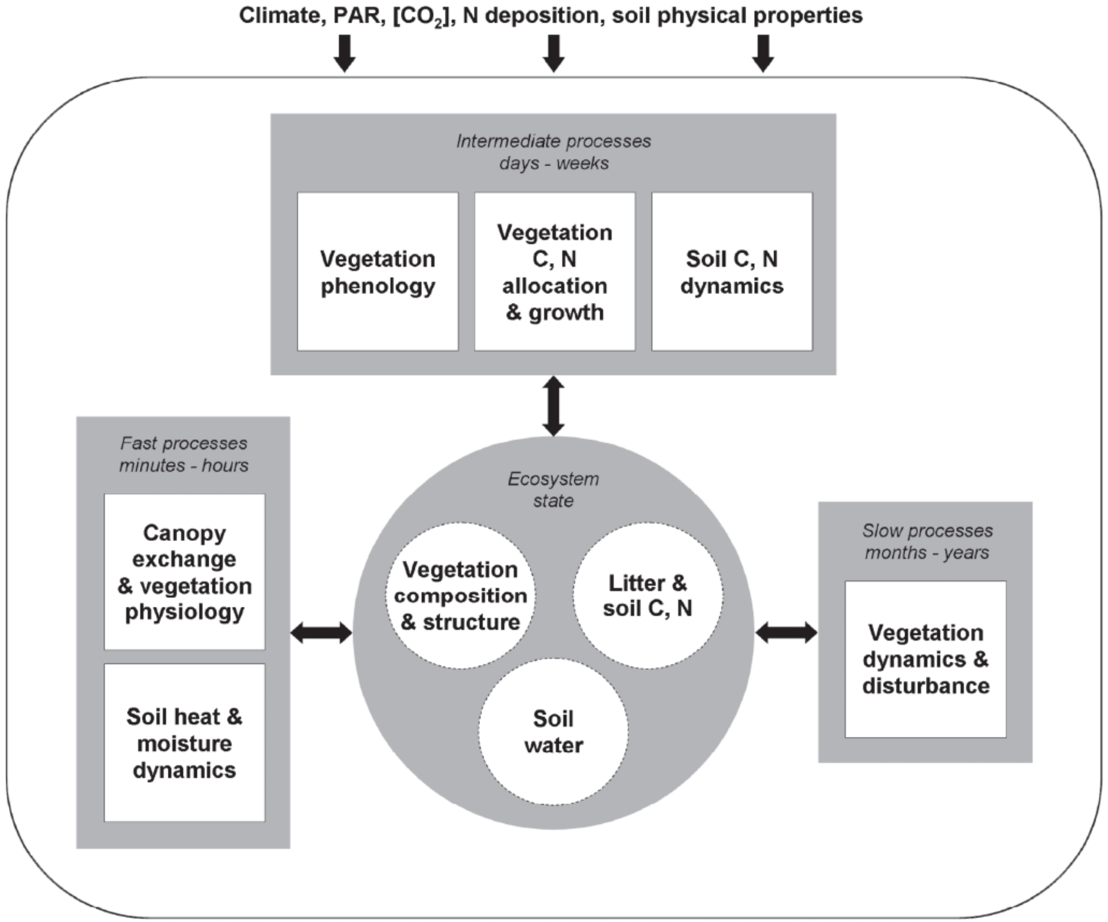
Vegetation plays an important role in the global carbon cycle



Dynamic Global Vegetation Models (DGVMs) are useful to understand and predict changes



Dynamic Global Vegetation Models



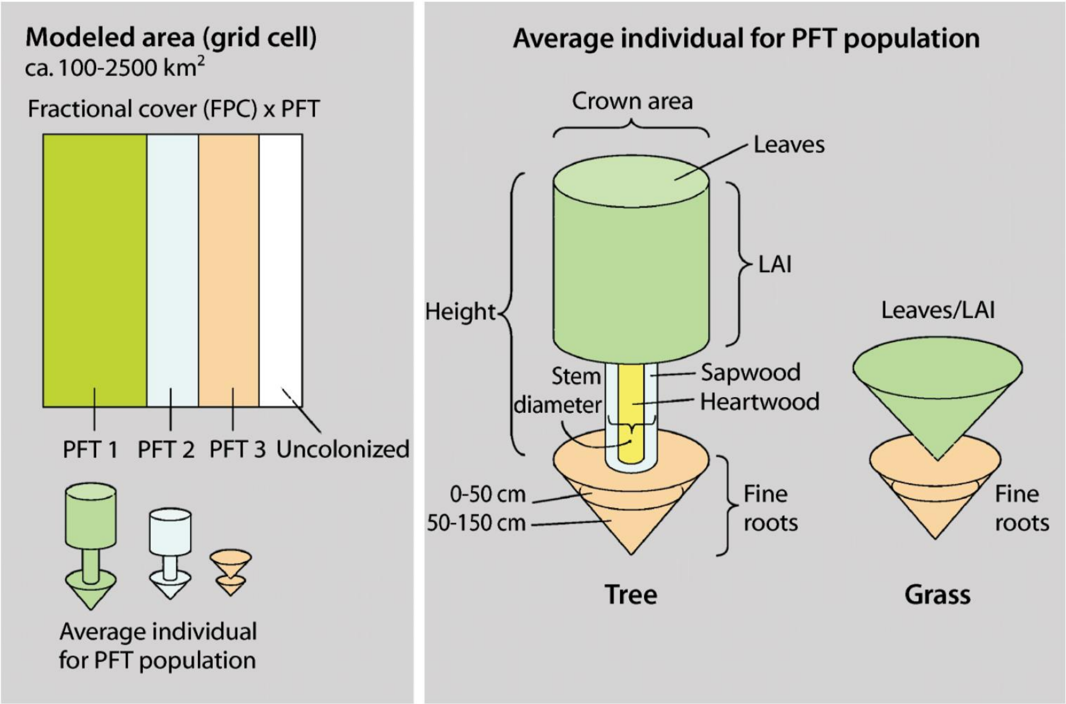
Prentice et al. (2007). In *Terrestrial Ecosystems in a Changing World*. Springer

Four main process types: plant geography, plant physiology and biochemistry, vegetation dynamics, and biophysics

Increasingly capturing human disturbances

Generally capture only fractional cover of Plant Functional Types (PFTs), but sometimes also age/size structure

Dynamic Global Vegetation Models



All plants classified into small number (10+) functional types, characterized in terms of the average individual

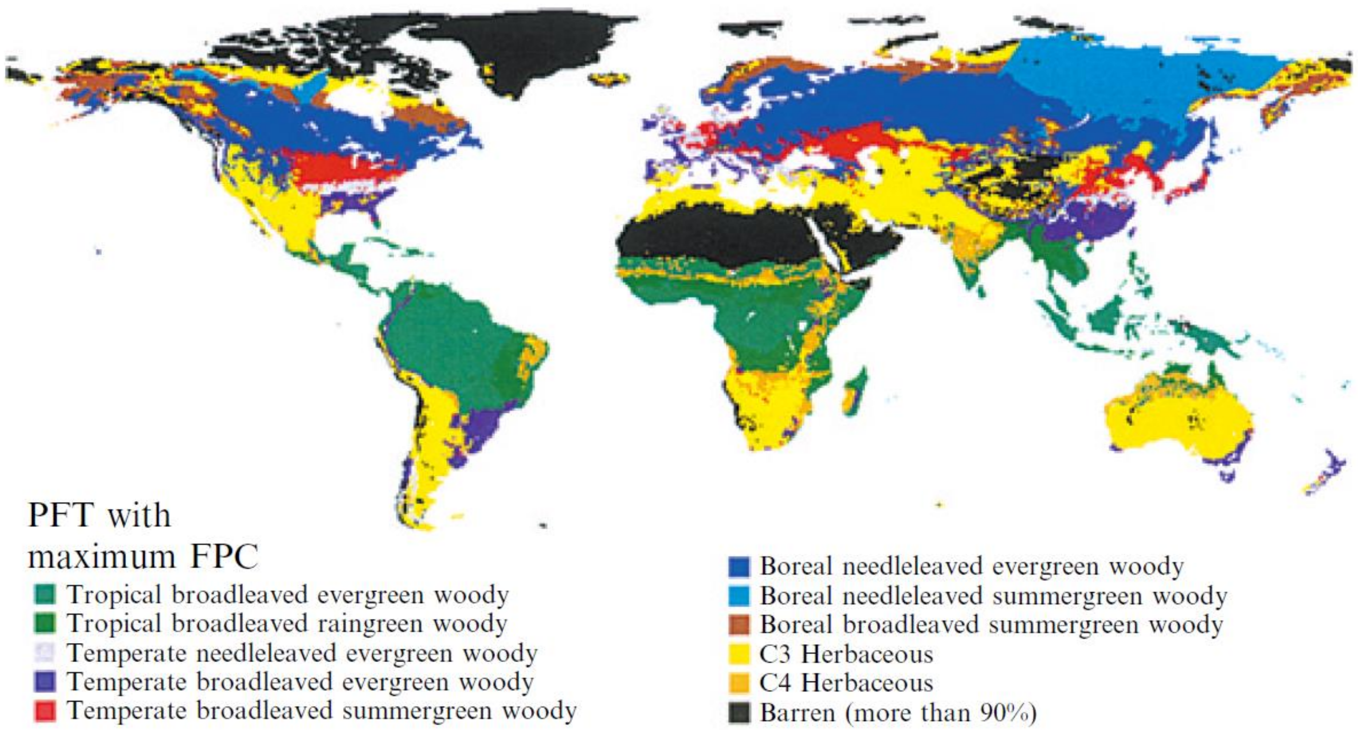
PFT
Tropical broad-leaved evergreen (TrBE)
Tropical broad-leaved raingreen (TrBR)
Temperate needle-leaved evergreen (TeNE)
Temperate broad-leaved evergreen (TeBE)
Temperate broad-leaved summergreen (TeBS)
Boreal needle-leaved evergreen (BoNE)
Boreal needle-leaved summergreen (BoNS)
Boreal broad-leaved summergreen (BoBS)
Temperate herbaceous (TeH)
Tropical herbaceous (TrH)

Prentice et al. (2007). In *Terrestrial Ecosystem in a Changing World*.

Sitch et al. (2003). *Global Change Biology* **9**: 161-185.

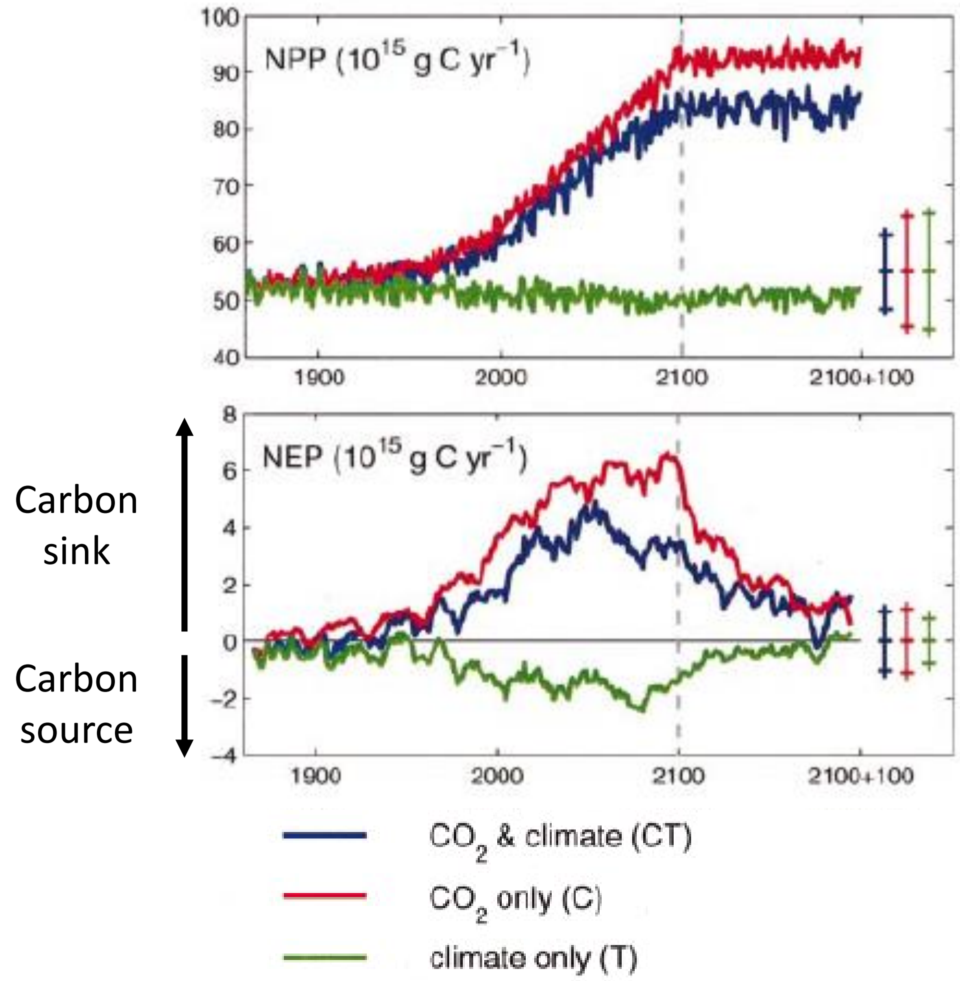
Coarse coverage of PFTs is captured well

Lund-Potsdam-Jena (LPJ) DGVM estimation of dominant plant functional types:



Sitch et al. (2003). *Global Change Biology* **9**: 161-185.

Applications of Dynamic Global Vegetation Models: Climate change



6 DGVMs

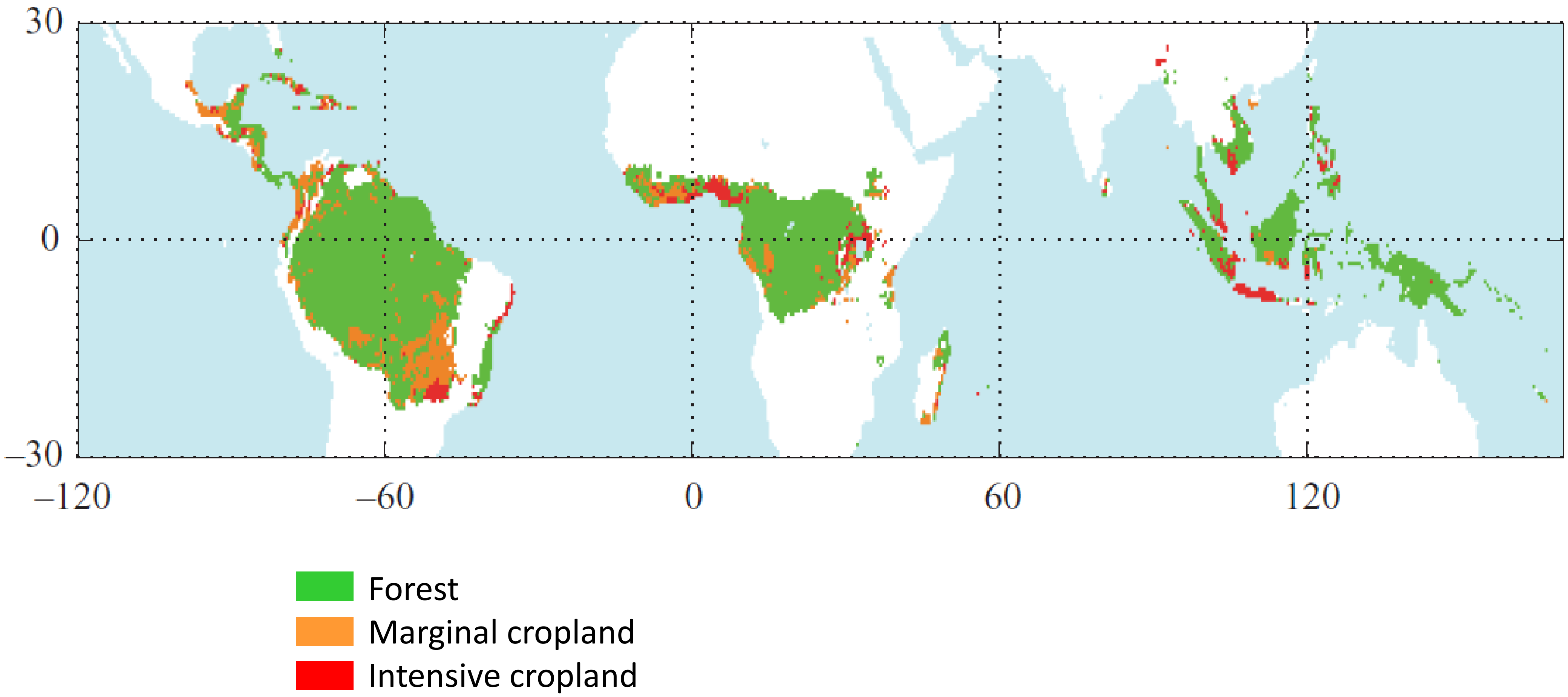
Predicted under change in climate, CO_2 concentration, or both

Increased CO_2 concentration predicted to increase carbon sink potential

Offset by climate change: effect of CO_2 asymptotes, but effect of temperature on respiration continues

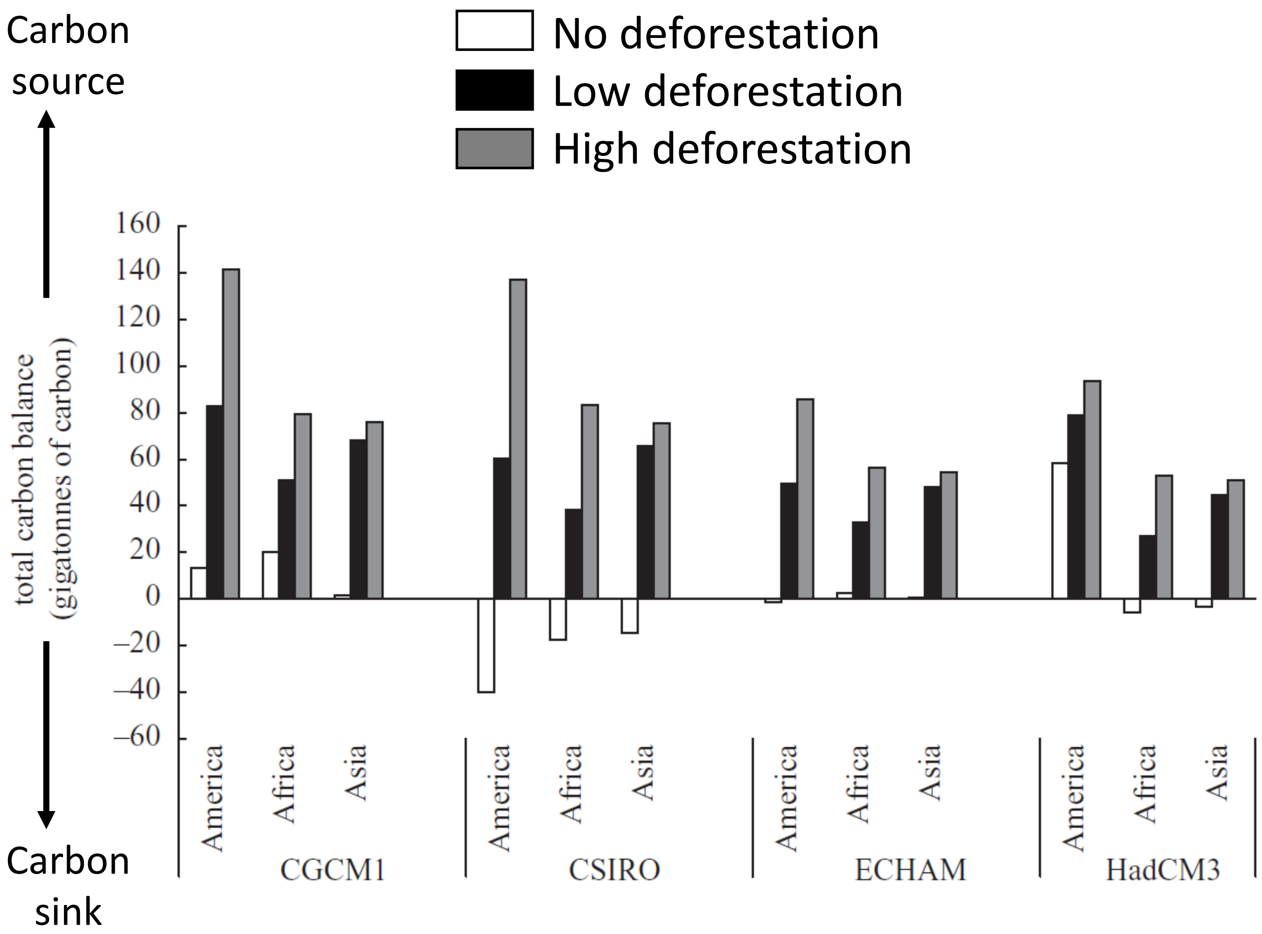
Cramer et al. (2001). *Global Change Biology* **7**: 357-373.

Applications of Dynamic Global Vegetation Models: Climate change and deforestation



Cramer et al. (2004). *Philosophical Transactions of the Royal Society, Series B* **359**: 331-343.

Applications of Dynamic Global Vegetation Models: Climate change and deforestation



One DGVM (LPJ)

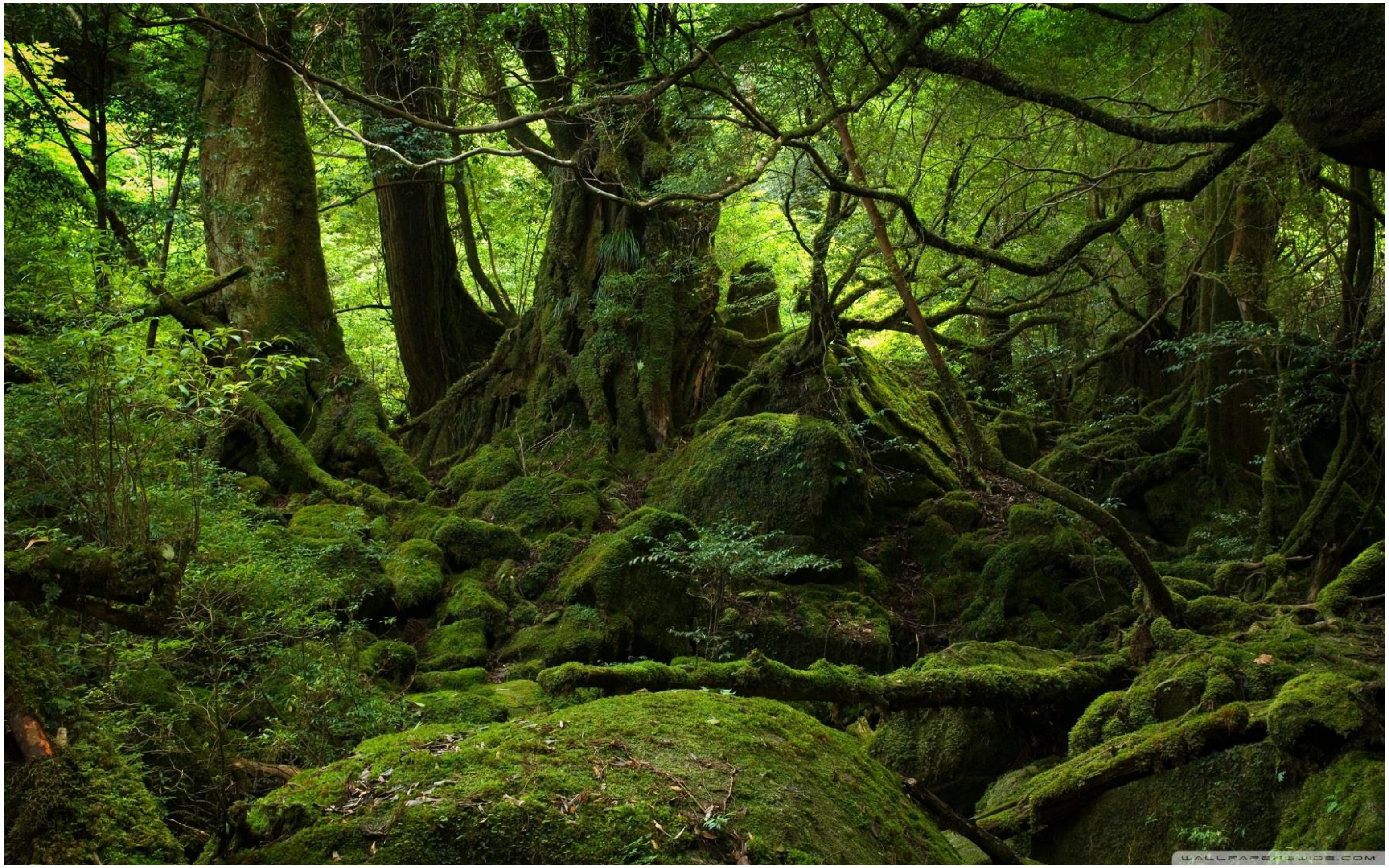
Predicted vegetation and carbon balance of tropical forest

No, low and high deforestation scenarios

Carbon source over 21st Century under most scenarios, especially with deforestation

Cramer et al. (2004). *Philosophical Transactions of the Royal Society, Series B* **359**: 331-343.

Plant communities are composed of individuals with large variation



Individual-based vegetation models: aDGVM

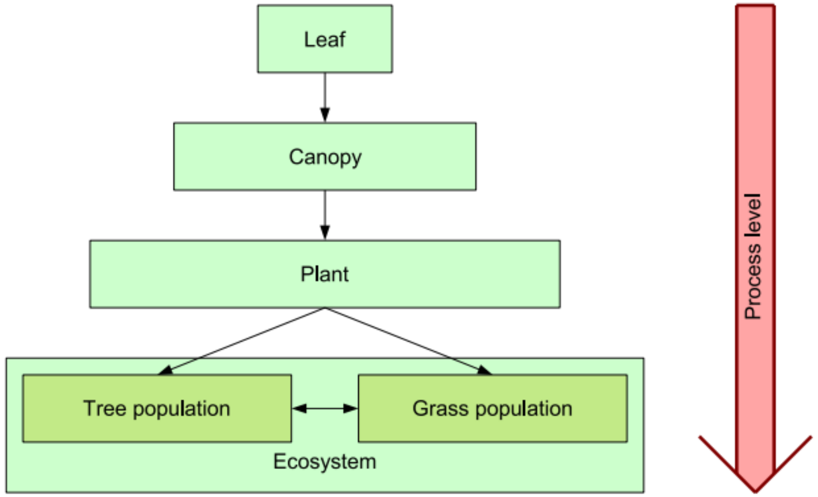
Adaptive Dynamic Global Vegetation Model (aDGVM)

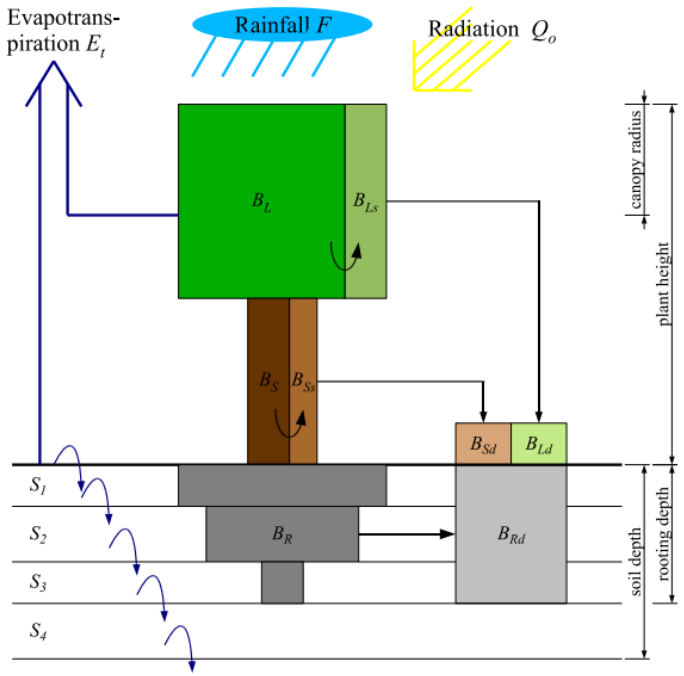
Leaf photosynthesis →

Canopy photosynthesis, respiration and conductance →

Plant growth, allometry, competition, reproduction and mortality

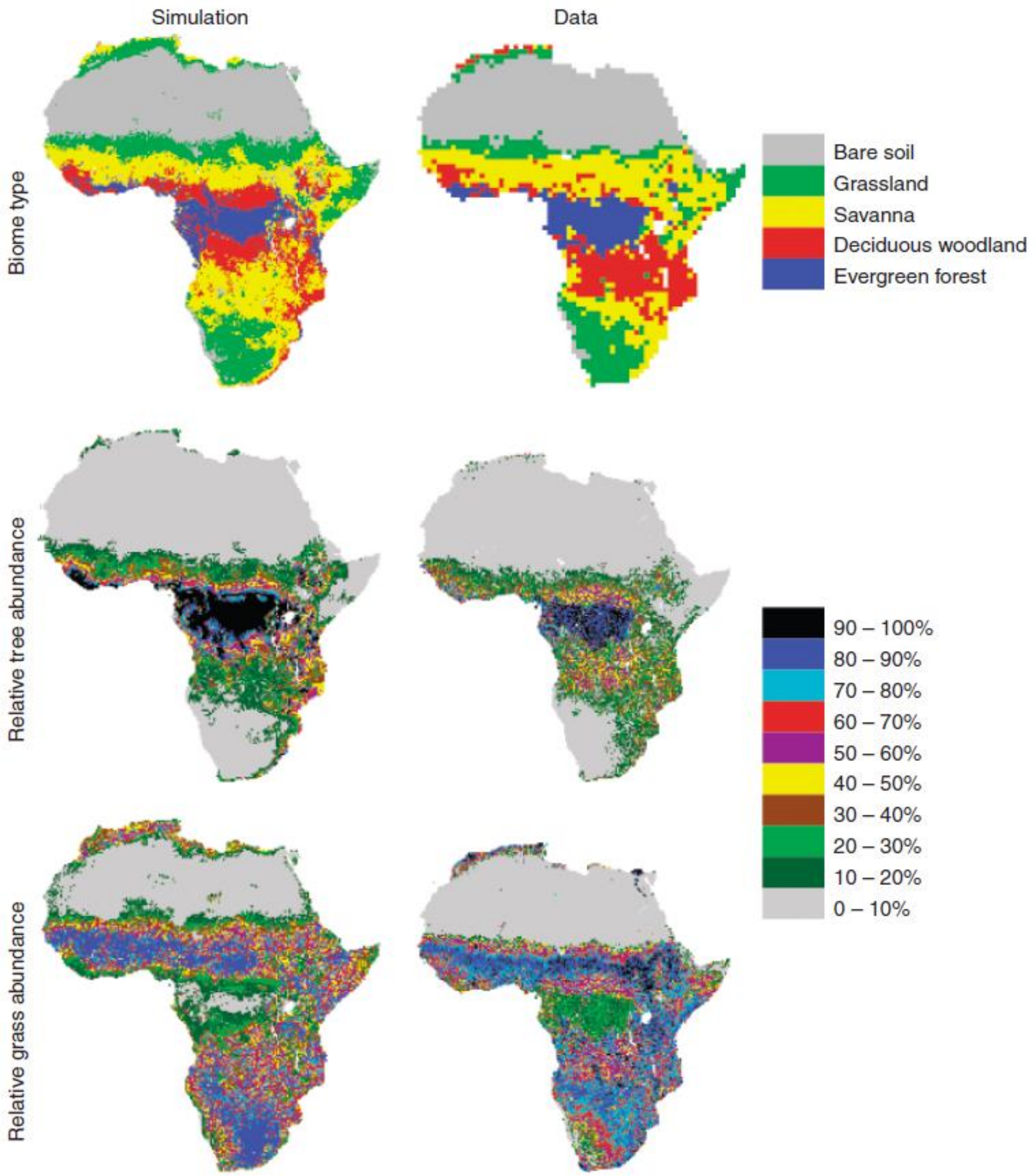
Representative 1-ha stands, scaled up to ⅓°





Scheiter & Higgins (2009). *Global Change Biology* **15**: 2224-2246

Individual-based vegetation models: aDGVM



Fits observed data fairly well

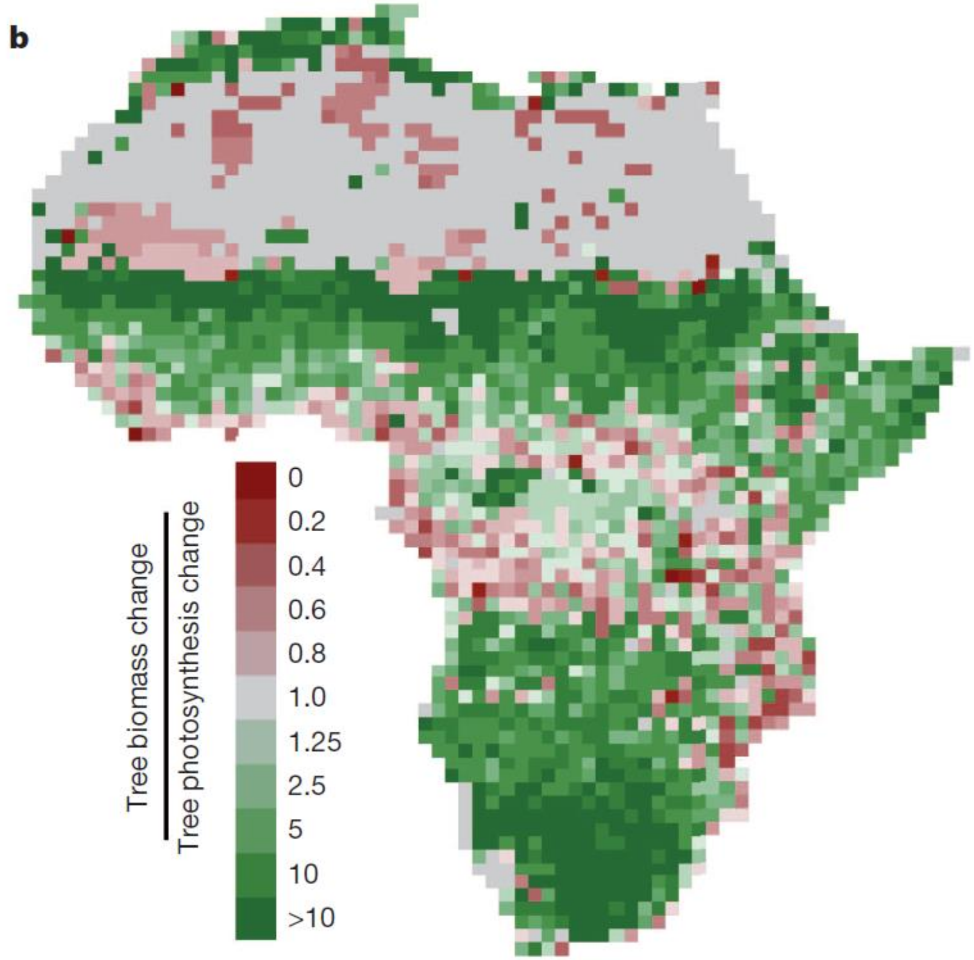
Fit generally better than models based on coverage of plant functional types

Scheiter & Higgins (2009). *Global Change Biology* **15**: 2224-2246

Applications of individual-based vegetation models: climate change

Predicted vegetation shifts from desert to grassland, grassland to savanna/woodland, and savanna to forest

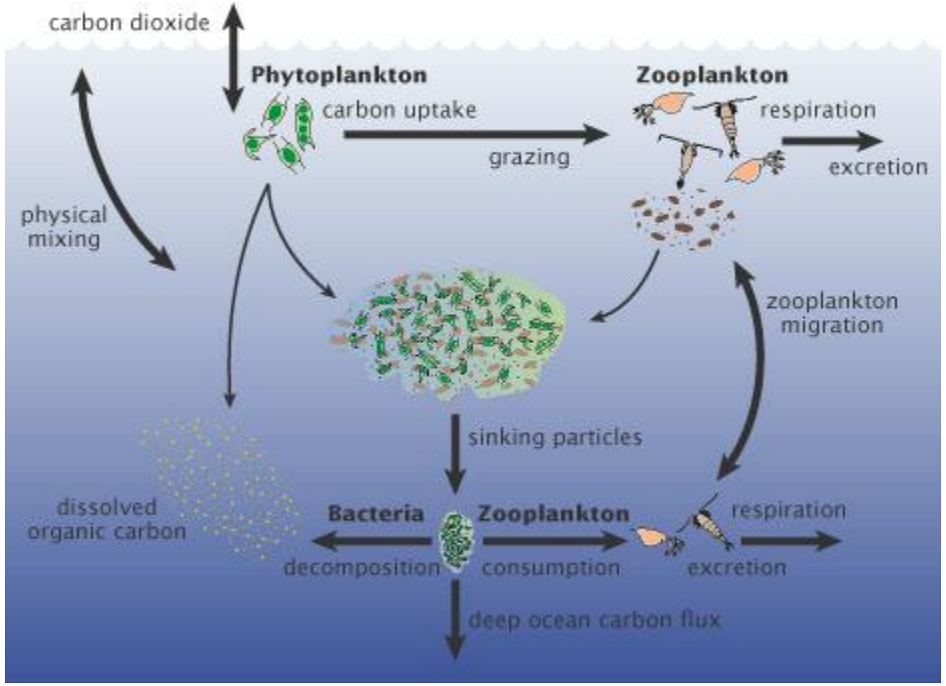
Probability of a given state depended on historical conditions (hysteresis)



Higgins & Scheiter (2012). *Nature* **488**: 209-212

Ocean ecosystem models: more developed than on land

Understanding contribution of primary producers to the carbon cycle and climate



Managing fisheries

NPZ(D) Models: Nutrient-Phytoplankton-Zooplankton(-Detritus)

(Relatively) simple formulation

Captures photosynthesis and phytoplankton growth, grazing of phytoplankton by zooplankton, mortality and vertical movement

$$\frac{dN}{dt} = \omega P + gZ + \frac{(1-f)cP^2 Z}{K+P^2} - \frac{\alpha(L_d, M_d, P)PN}{j+N} - (N - N_d)\zeta_N(M_d)/M_d,$$

$$\frac{dP}{dt} = \frac{\alpha(L_d, M_d, P)PN}{j+N} - \omega P - \frac{cP^2 Z}{K+P^2} - P\zeta_P(M_d)/M_d,$$

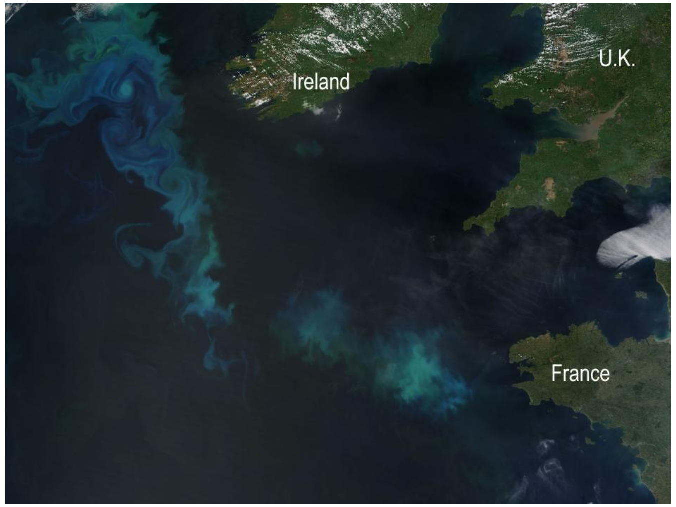
$$\frac{dZ}{dt} = \frac{fcP^2 Z}{K+P^2} - gZ - Z\zeta_Z(M_d)/M_d,$$

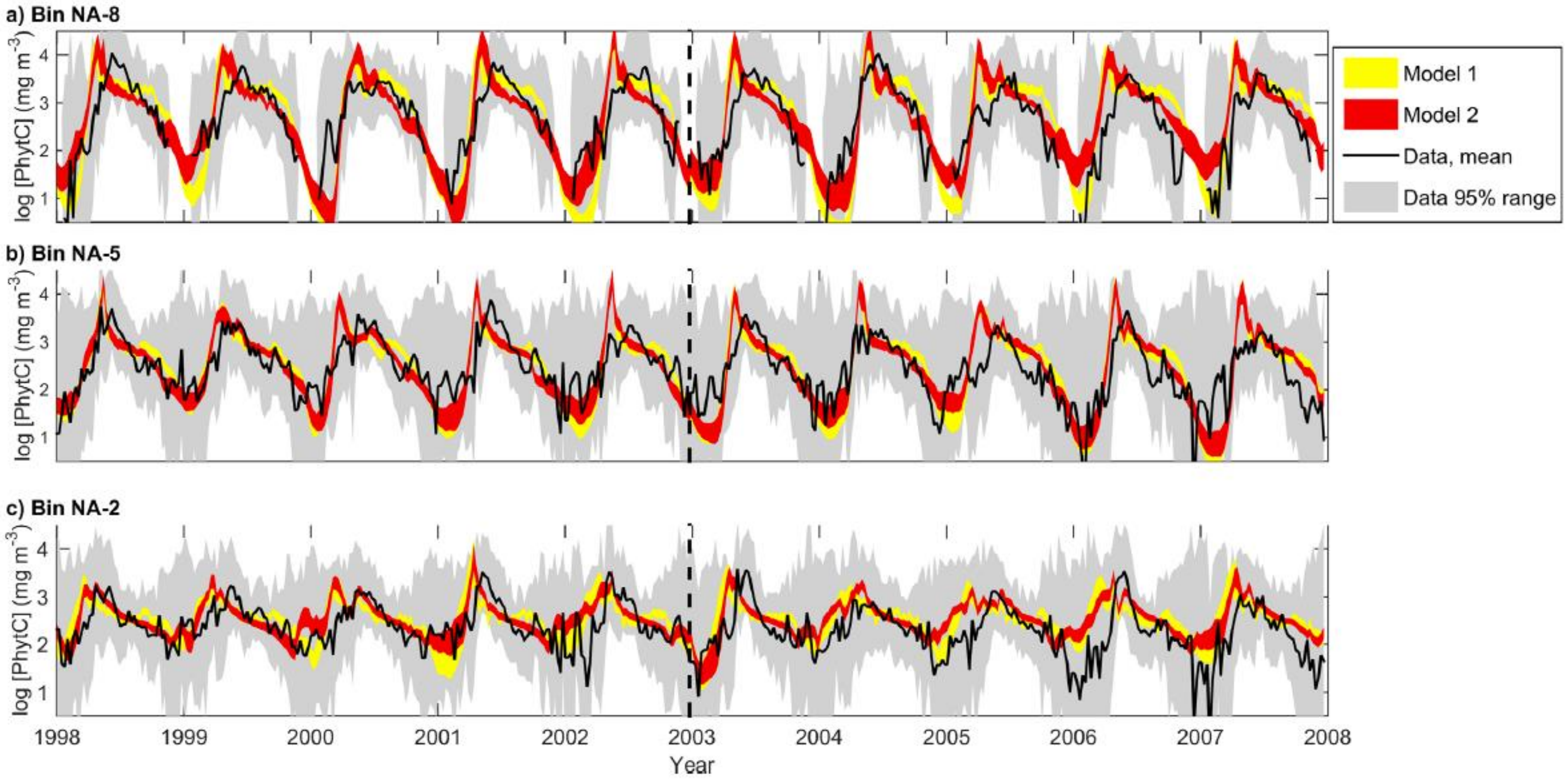
Textual Definition	Symbol
Nitrate uptake half saturation	j
Phytoplankton background mortality rate	ω
Grazing half saturation	K
Maximum grazing rate	c
Grazing efficiency	f
Zooplankton background mortality rate	g
Maximum photosynthetic rate (supporting information Text S1)	Q
Lowlight photosynthetic slope (supporting information Text S1)	s
Light attenuation by water (supporting information Text S1)	k
Light attenuation by phytoplankton (supporting information Text S1)	l
Nitrate diffusion rate	m_N
Phytoplankton diffusion rate out of mixed layer	m_P
Nitrate conc. below the mixed layer	N_d

Smith et al. (2015). *J Geophysical Research: Oceans* **120**: 7067-7090

Can capture well observed phytoplankton concentrations

North Atlantic phytoplankton bloom





Smith et al. (2015). *J Geophysical Research: Oceans* **120**: 7067-7090

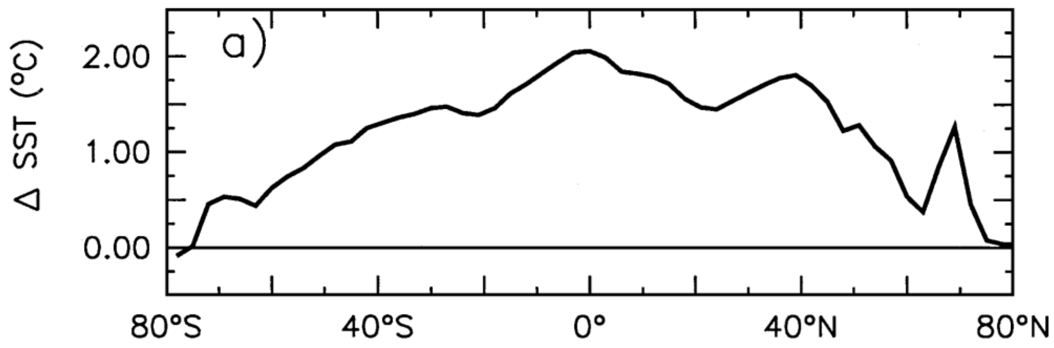
Application of NPZ models: climate change

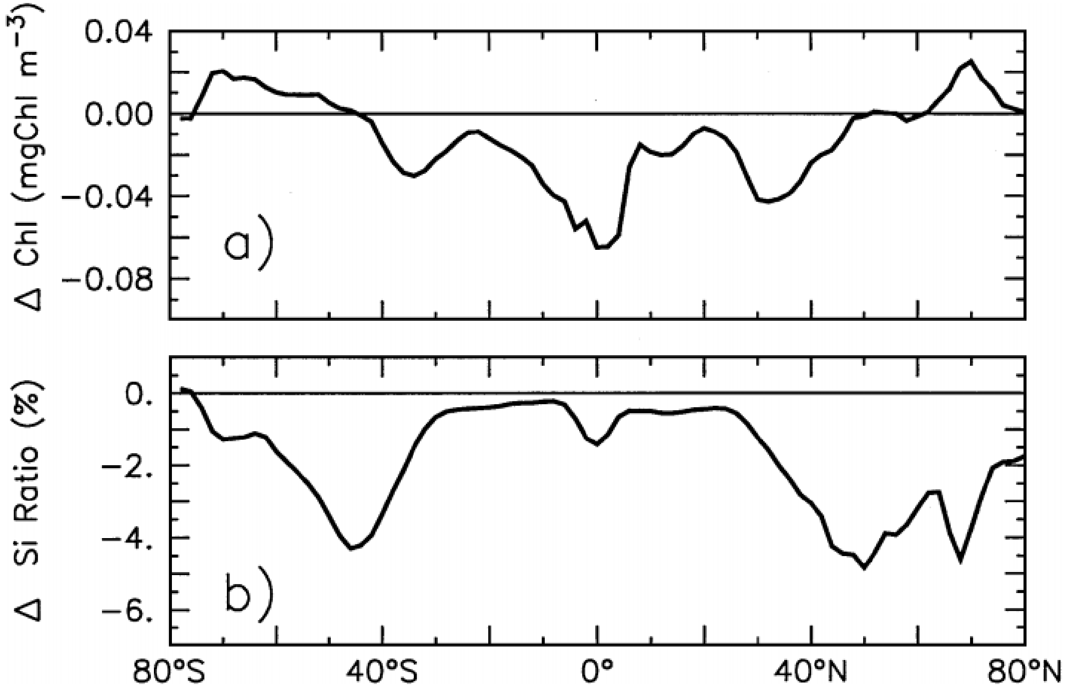
Predicted effects of doubling of pre-industrial CO_2

Increase in Sea Surface Temperature at most latitudes

Overall decline (9%) in primary productivity, but increases at some latitudes

Decrease in representation of siliceous phytoplankton





Bopp et al. (2003). *Tellus B* **55**: 11-22.

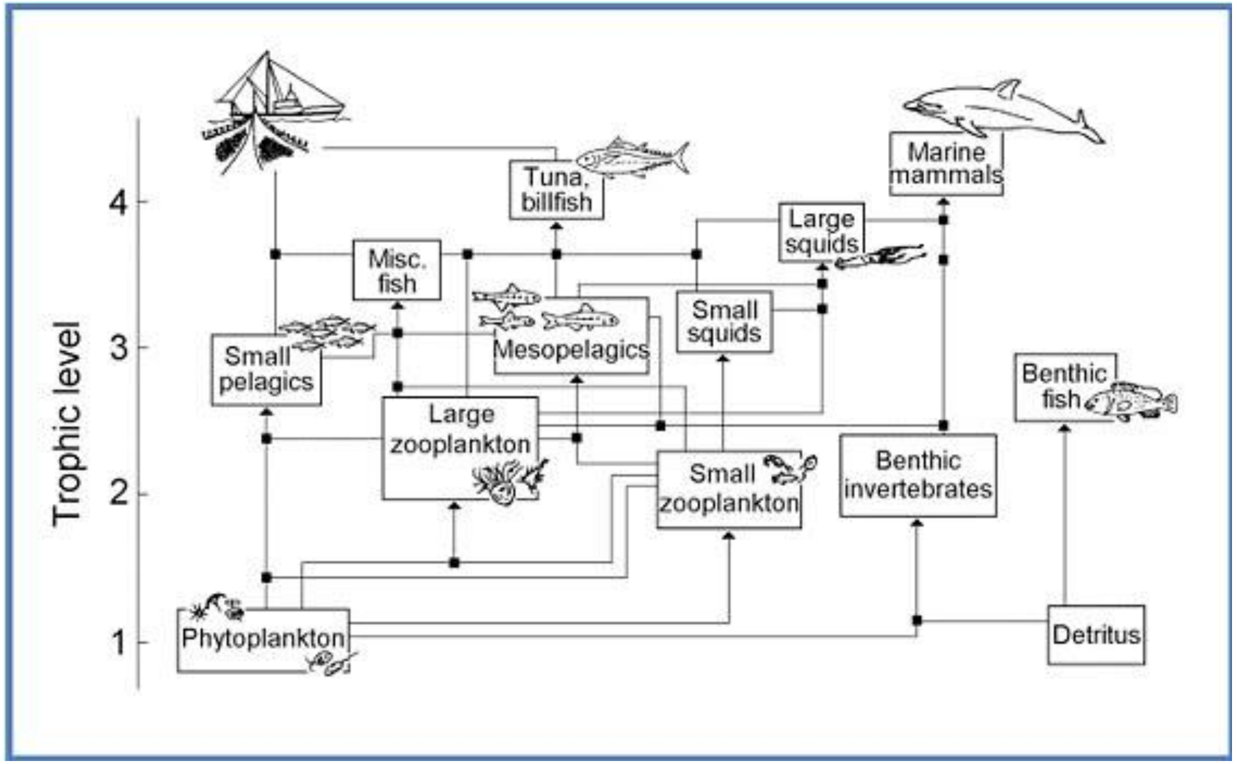
Summarized in Richardson (2008). *ICES J Marine Science* **65**: 279-295.

Ecopath with Ecosim

Ecopath: biomass stocks and trophic flows

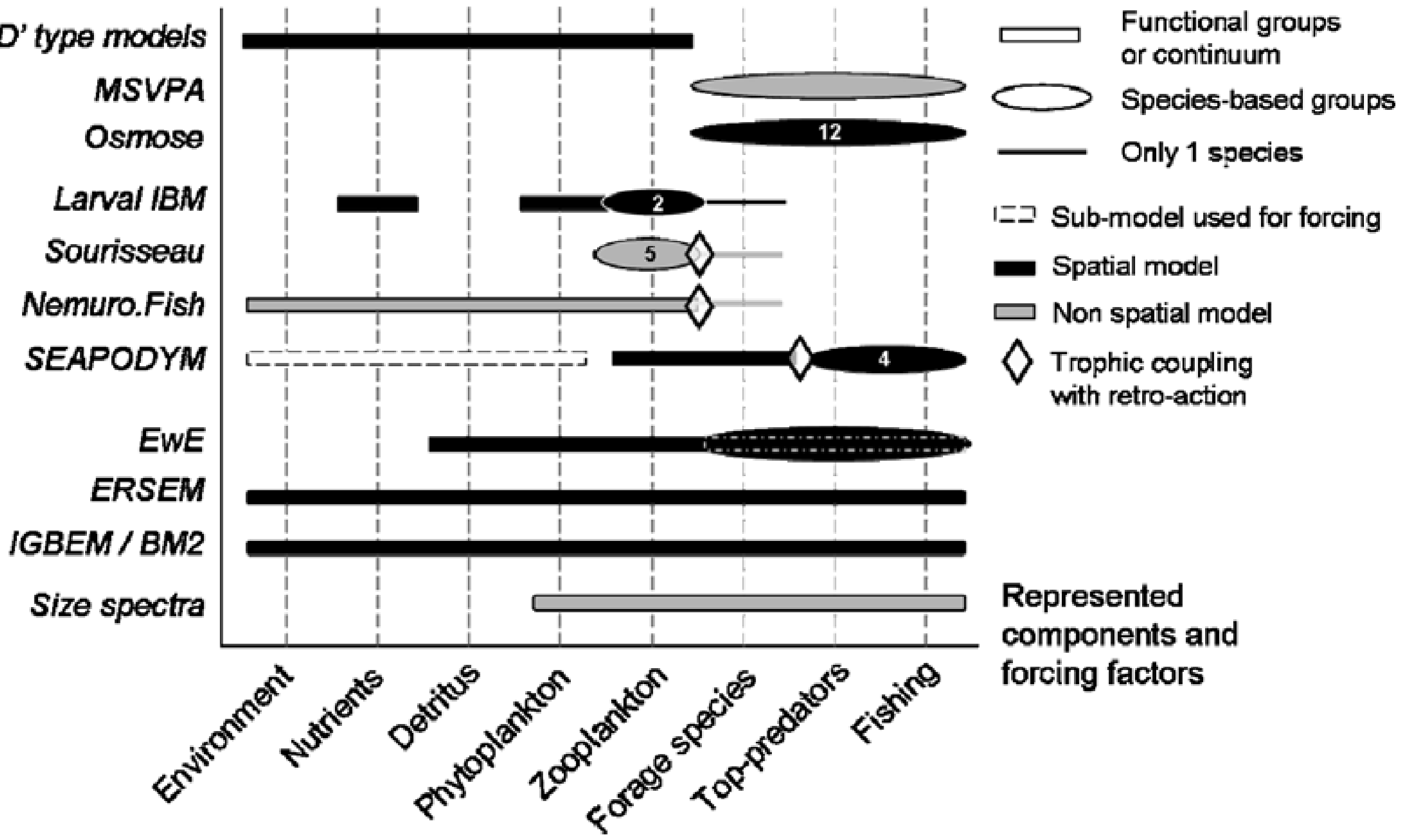
Ecosim: coupled differential equations to simulate dynamics

Ecospace: spatial representation, including dispersal/migration



Christensen & Walters (2004). *Ecological Modelling* **172**: 109-139

Many marine models only capture parts of the whole system

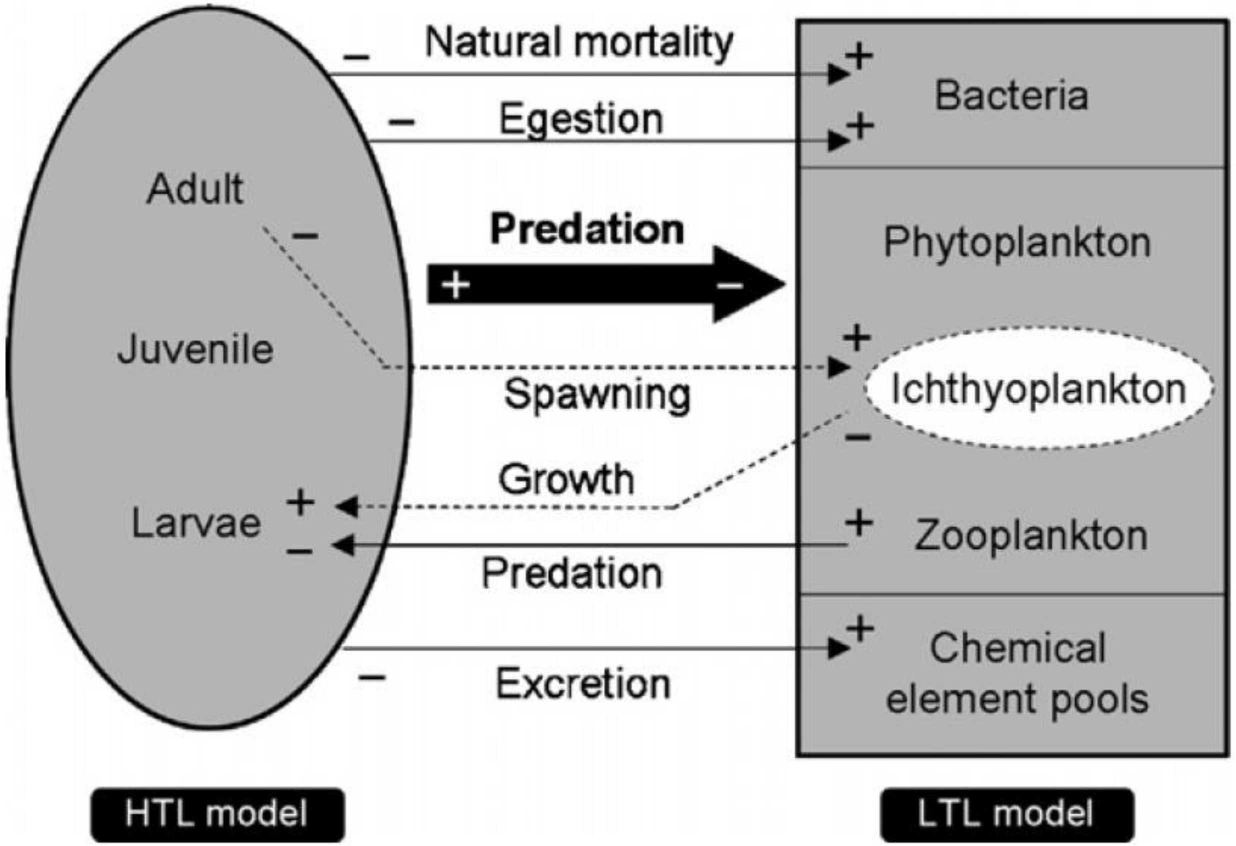


Travers et al. (2007). *Progress in Oceanography* **75**: 751-770

Many marine models only capture parts of the whole system

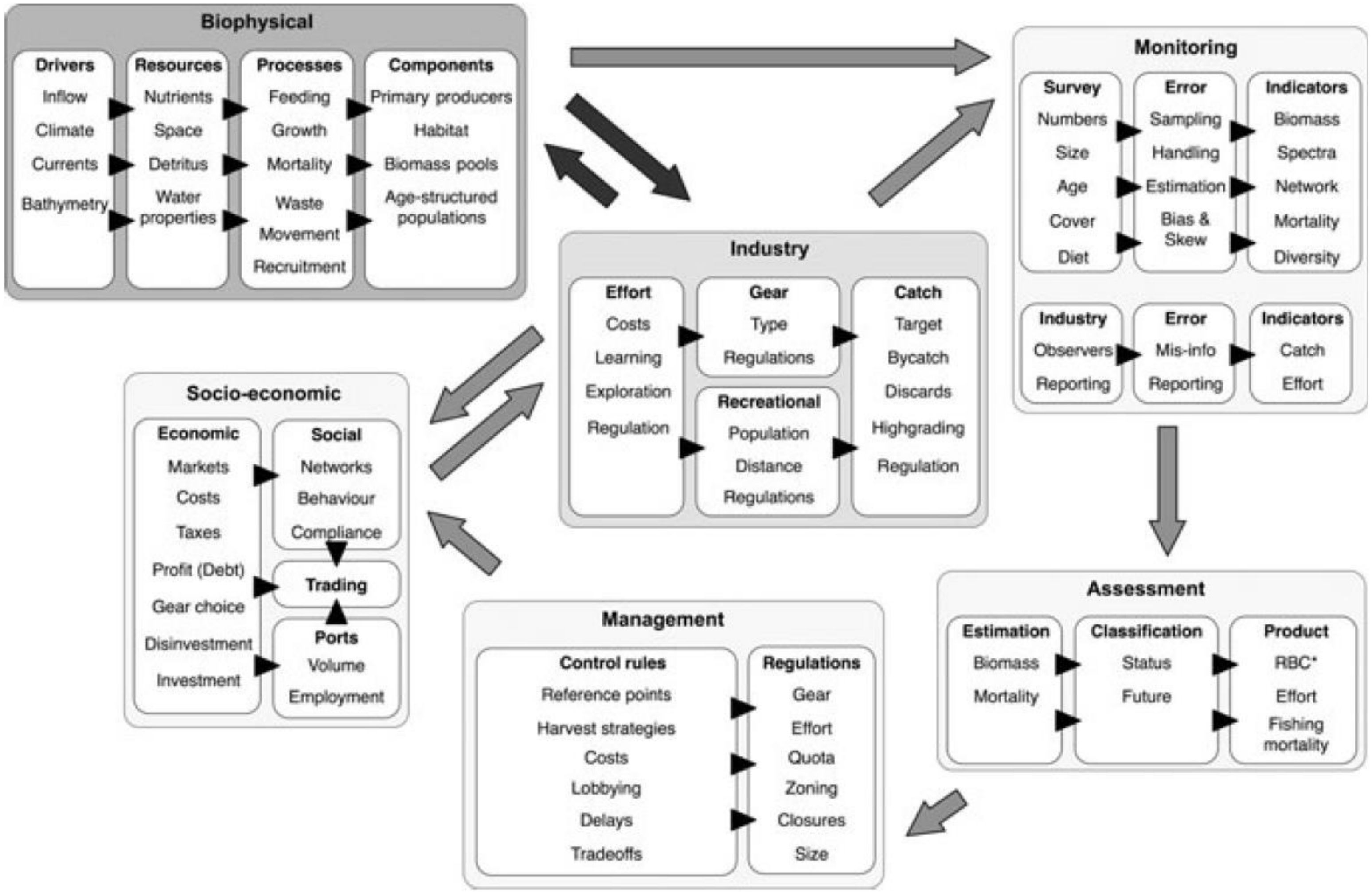
There exist some coupled models of low and high trophic levels

There is an increasing trend toward developing full ‘end-to-end’ ecosystem models



Travers et al. (2007). *Progress in Oceanography* **75**: 751-770

Atlantis: an end-to-end ecosystem model



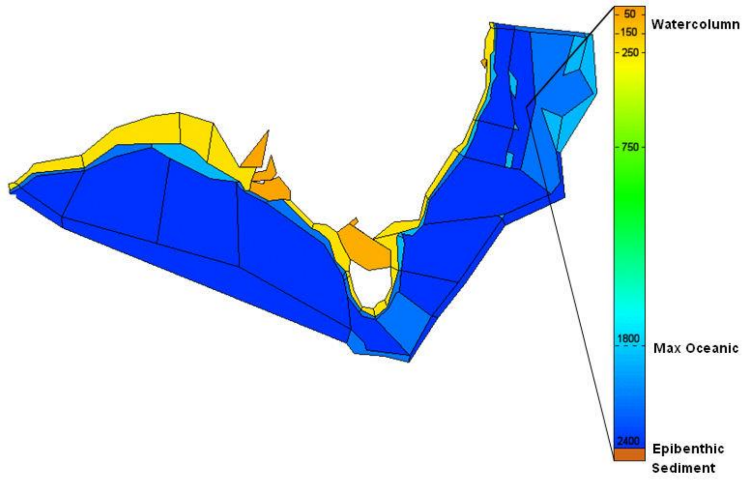
Fulton et al. (2011). *Fish & Fisheries* **12**: 171-188

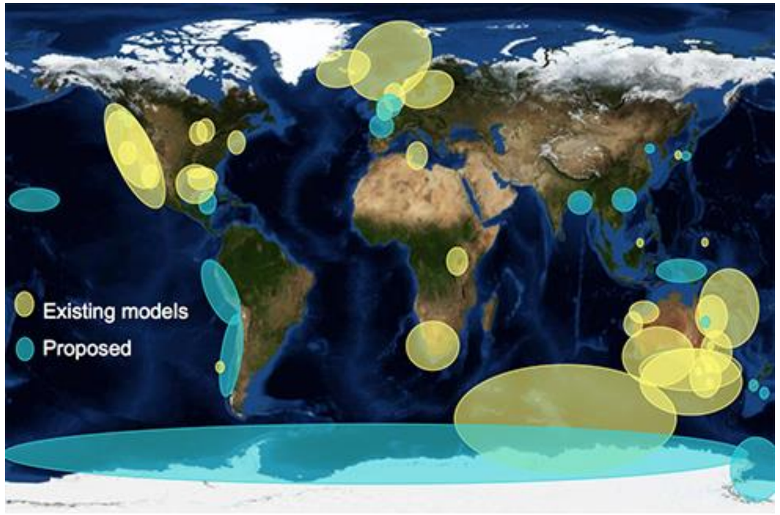
Atlantis: an end-to-end ecosystem model

Biophysical model spatially resolved into 3D, unequal-sized polygons

Ecological processes: consumption, production, movement and migration, predation, recruitment, habitat dependency and mortality

Human effects simulated as agents in the model





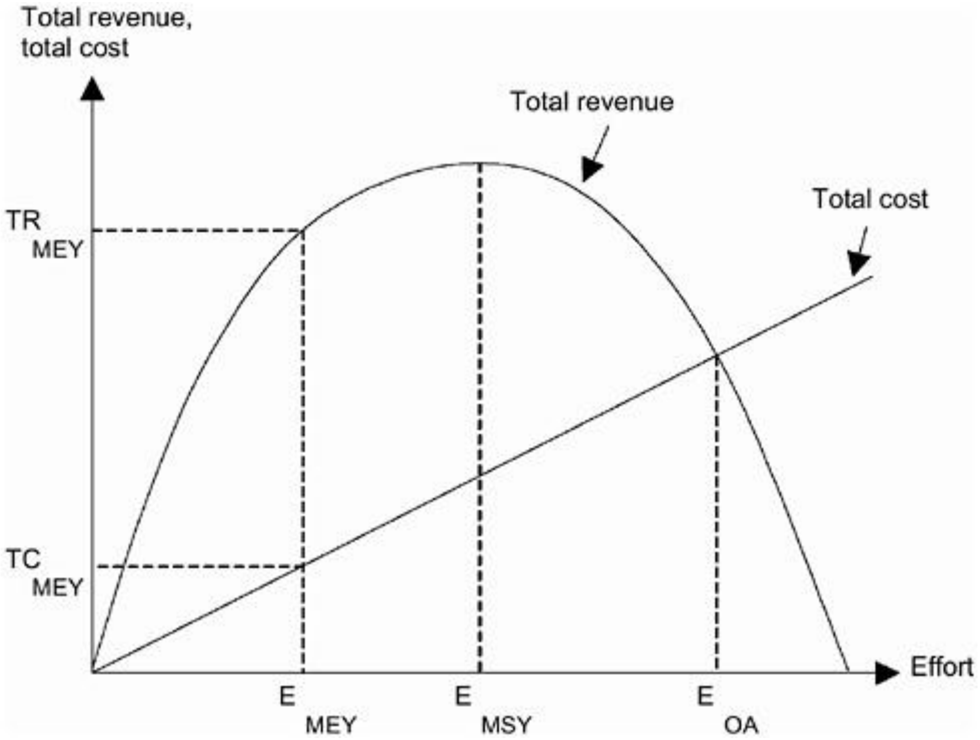
Fulton et al. (2011). *Fish & Fisheries* **12**: 171-188

Applications of marine ecosystem models: fisheries management

Maximum sustainable yield

Has been dismissed several times over the years

But still has resonance



From Townsend & Wilson (1987). An economic view of the tragedy of the commons. In *The Question of the Commons: the Culture and Ecology of Communal Resources*

Applications of marine ecosystem models: fisheries management

Fisheries management is often based on single-species assessments (e.g. using population models)

Complex interactions might effect potential catches

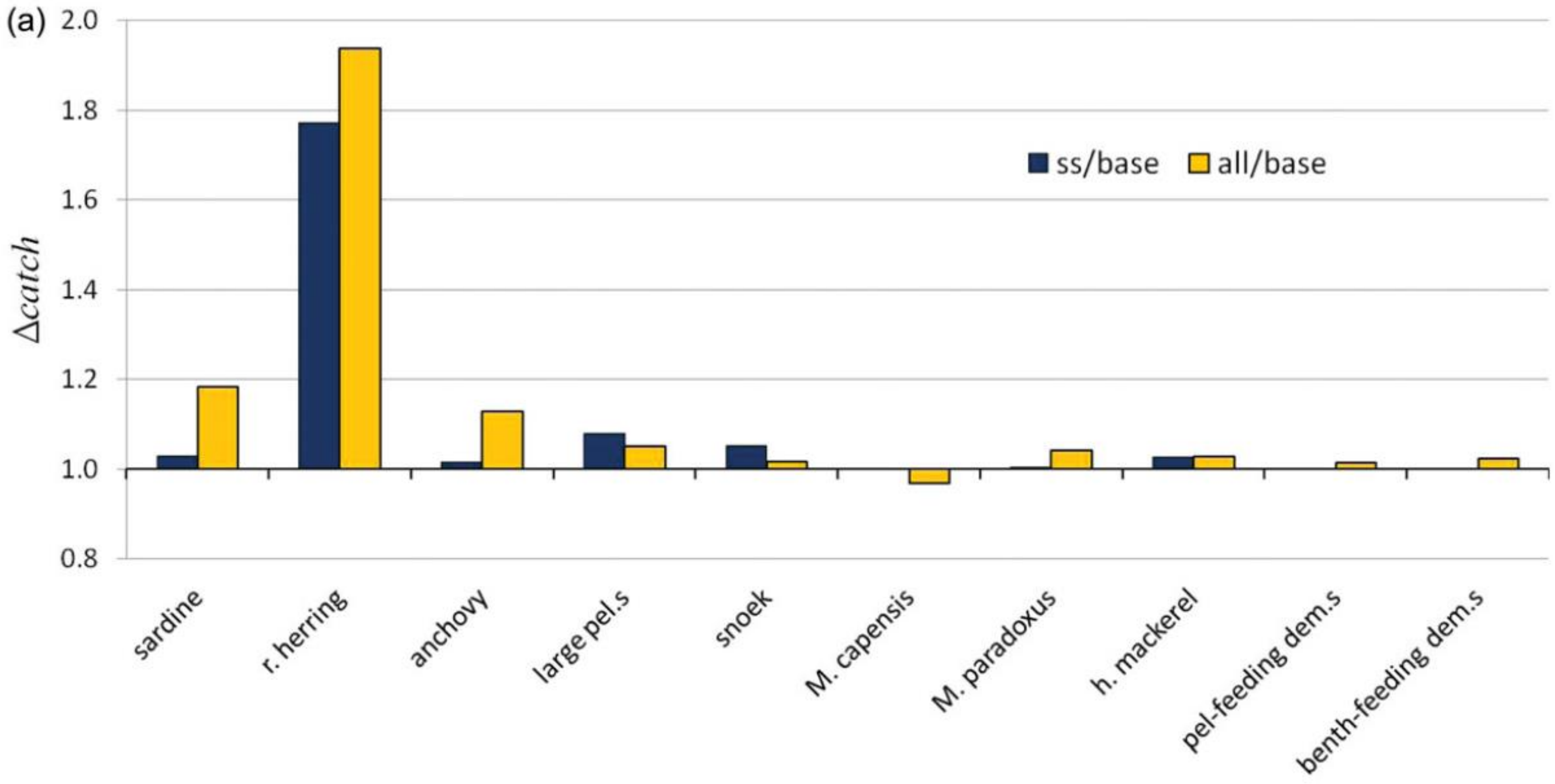
Ecosystem models can be used to assess multi-species maximum sustainable yields

Applications of marine ecosystem models: fisheries management

Fisheries 9% more productive using single-species assessment

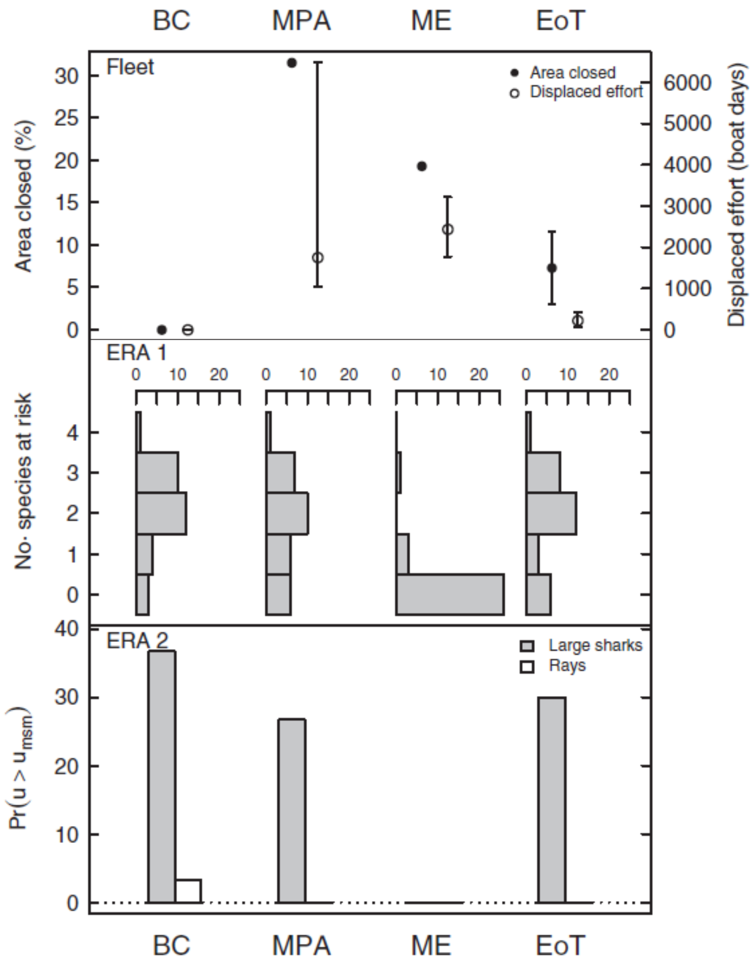
16% more productive with multi-species assessment

But benefits of multi-species assessments varied among species



Smith et al. (2015). *ICES J Marine Science* **72**: 275-283

Applications of marine ecosystem models: conservation strategies



Four scenarios: ‘business-as-usual’ (BC), marine protected areas (MPA), strategic attempt to reduce risk of particularly threatened groups (ME), and adaptive closures to reduce impacts on benthos (EoT)

Outcomes simulated using Ecopath with Ecosim

Targeting at-risk groups was most effective at conserving those groups

Dichmont et al. (2013). *J Applied Ecology* **50**: 1060-1070

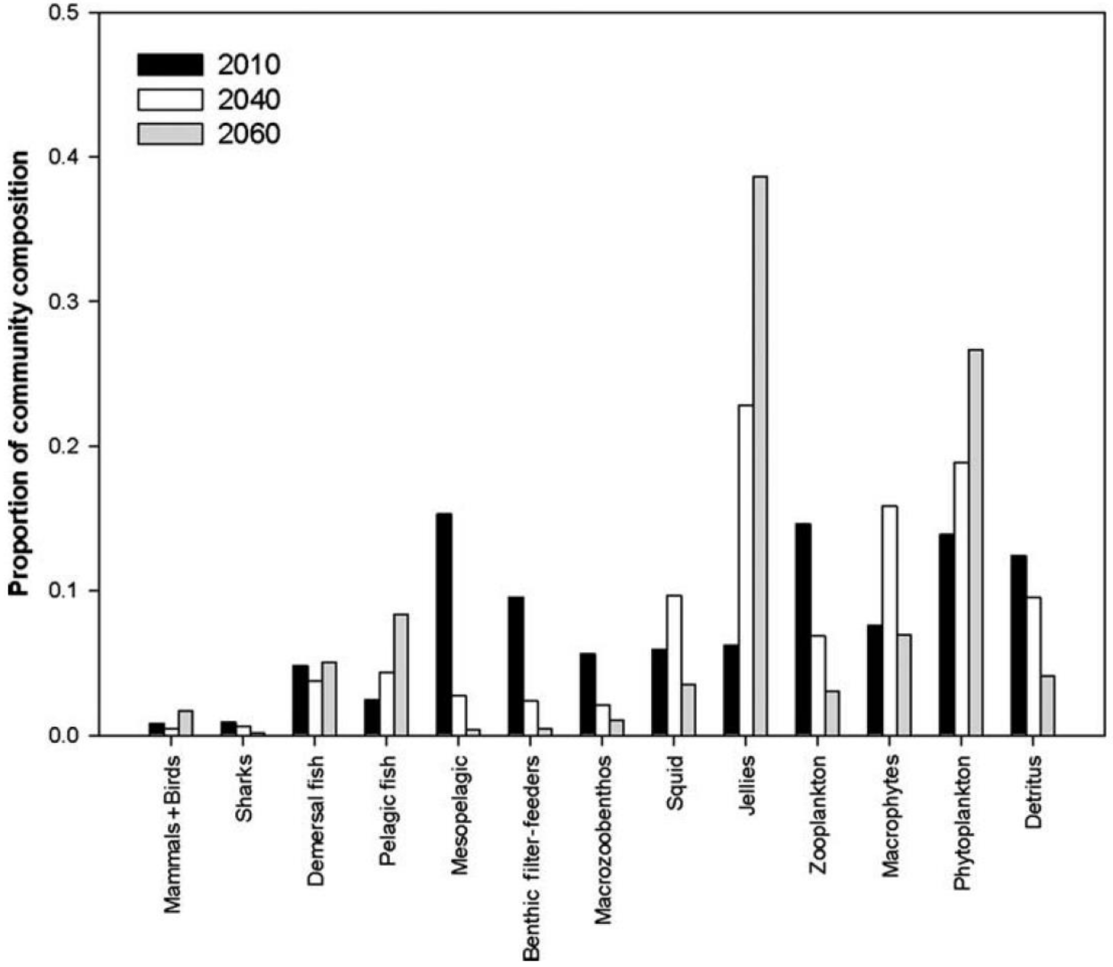
Applications of marine ecosystem models: climate change

3 modelling frameworks: Atlantis, Ecopath with Ecosim, InVitro

Models for 7 ecosystems

Climate and socio-economic projections under the SRES A2 scenario

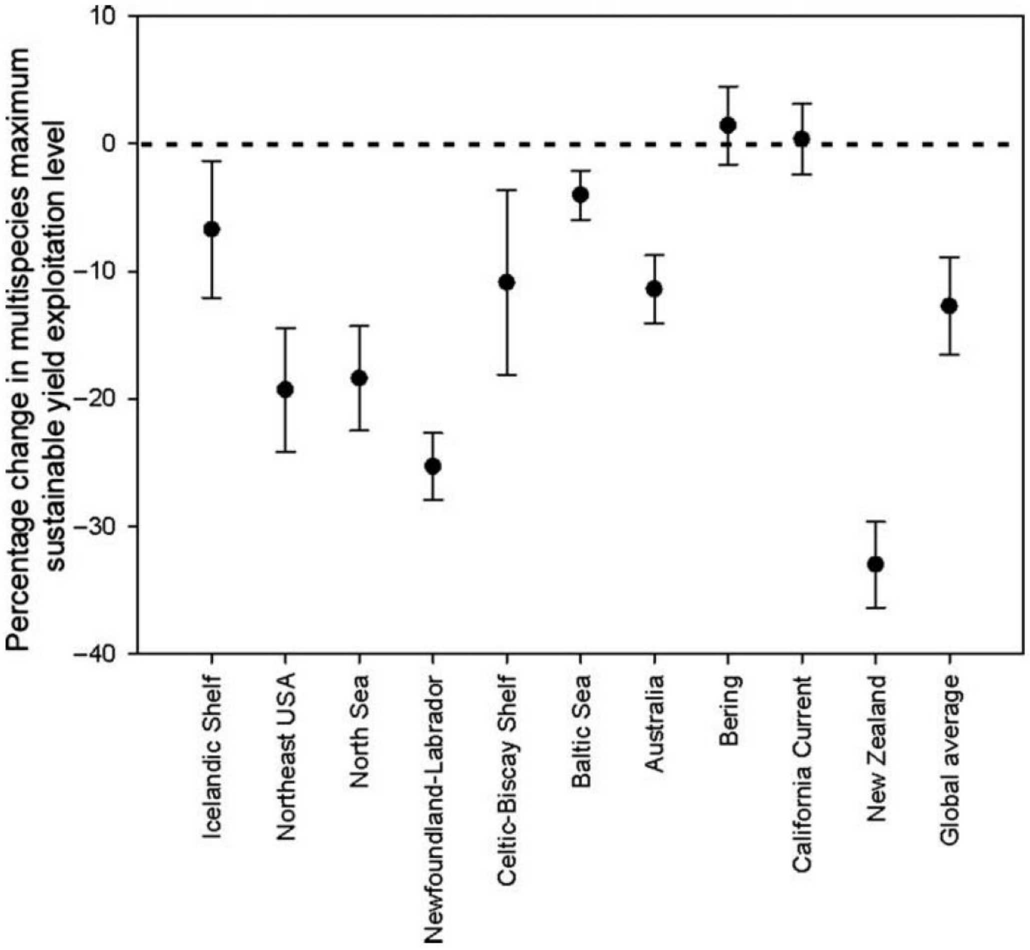
Some functional groups increased and some decreased → big changes in community composition



Fulton (2011). *ICES J Marine Science* **68**: 1329-1342

Applications of marine ecosystem models: climate change

Multi-species maximum sustainable yield declined in most regions



Fulton (2011). *ICES J Marine Science* **68**: 1329-1342

Can we model everything?

All realms: marine, terrestrial, freshwater

Common set of ecological processes

All major ecosystem components


COMMENT

COMMUNICATION Sally Rockey reflects on two years of blogging at the NIH p.298

ECOLOGY Zoological travelogue tracks rare species worldwide p.300

WOMEN Calls to root out sexism in journals, conferences and experiments p.305

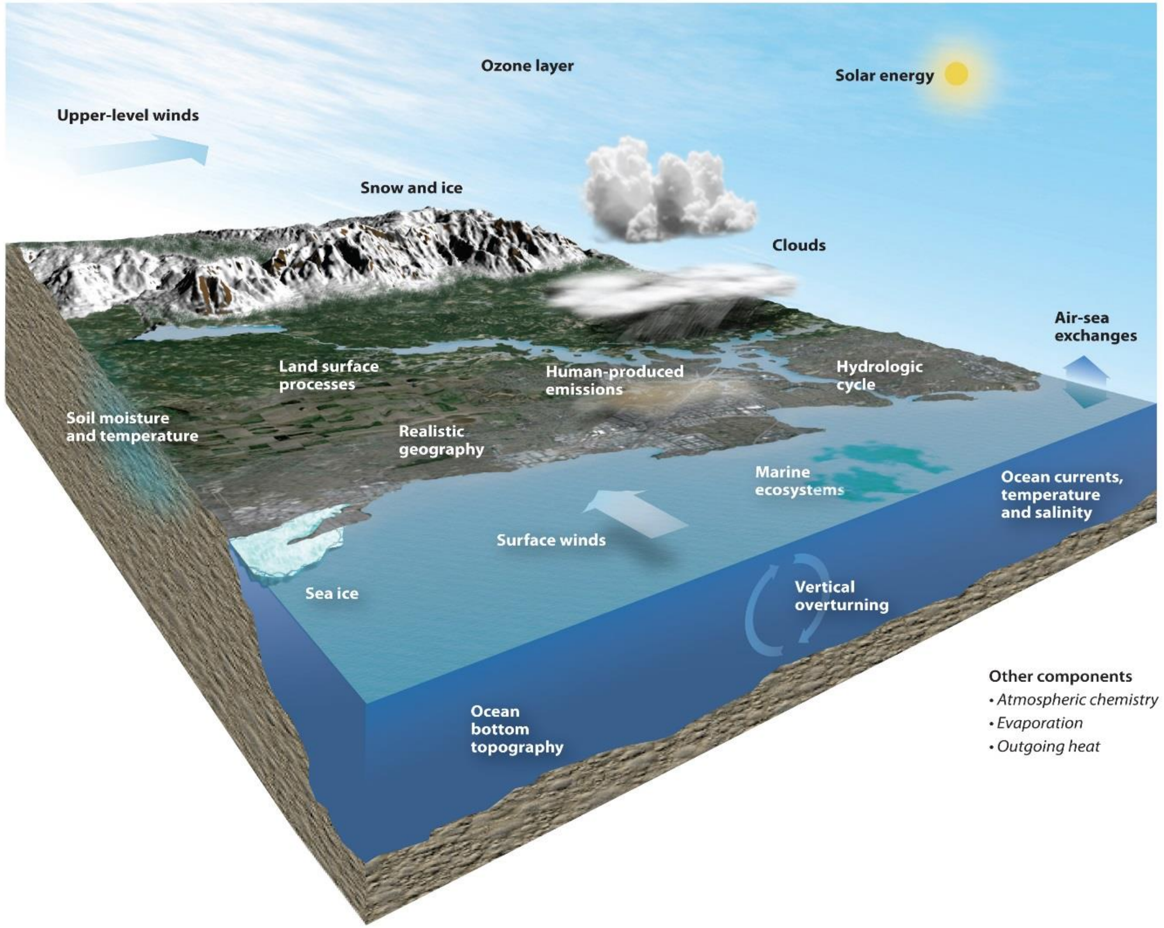
OBITUARY Rita Levi-Montalcini, nerve growth factor pioneer and science advocate p.306

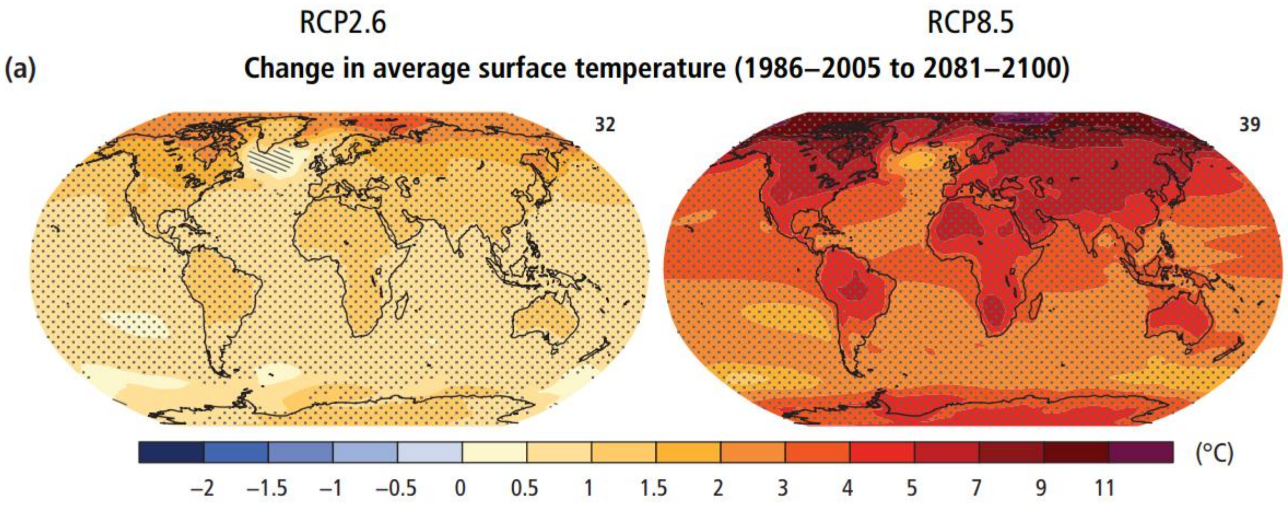
A hyena surveys a flock of flamingos in South Africa.

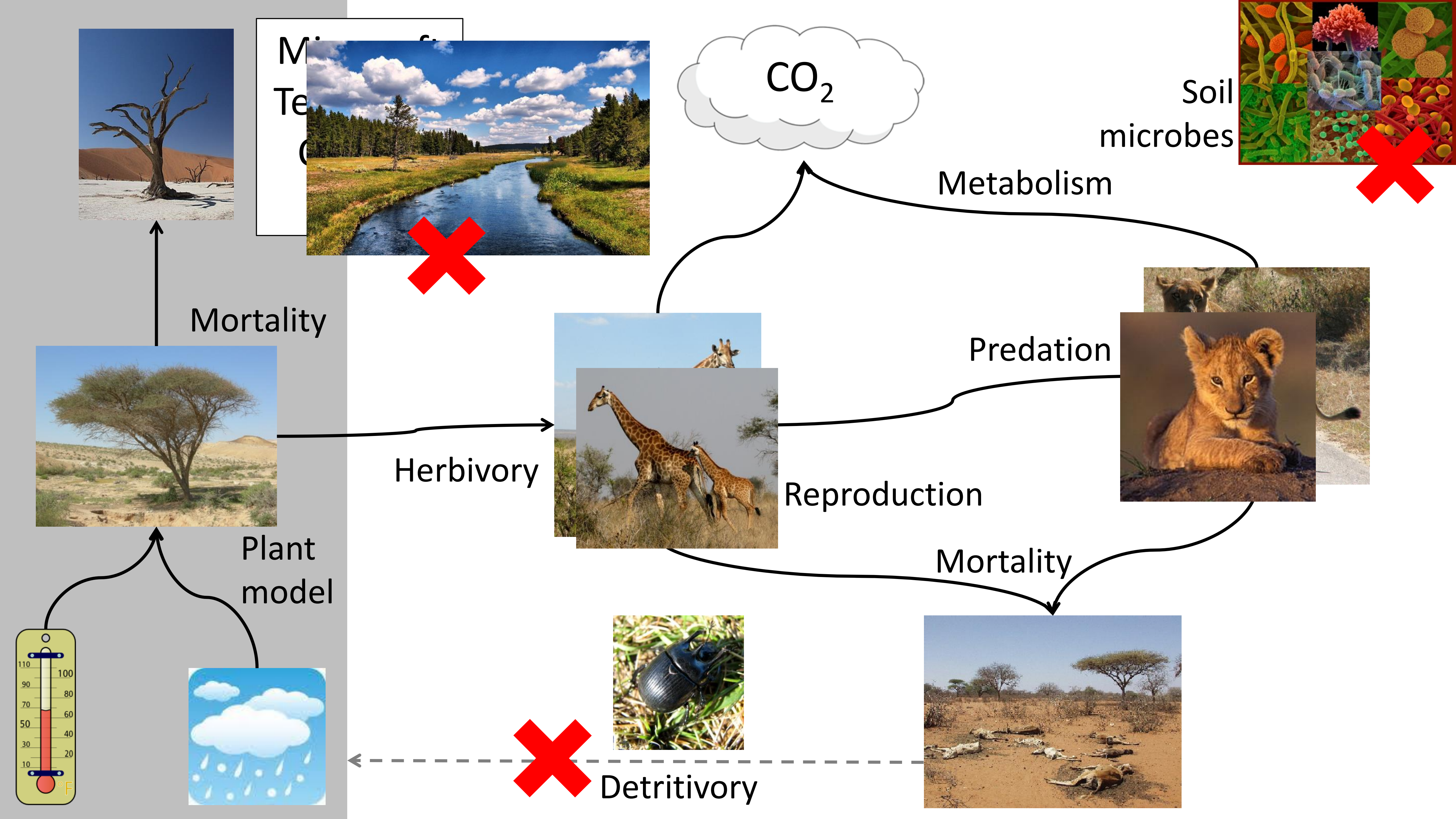
Time to model all life on Earth

Purves et al. (2013). *Nature* **493**: 295-297

Similar conceptually to global climate models

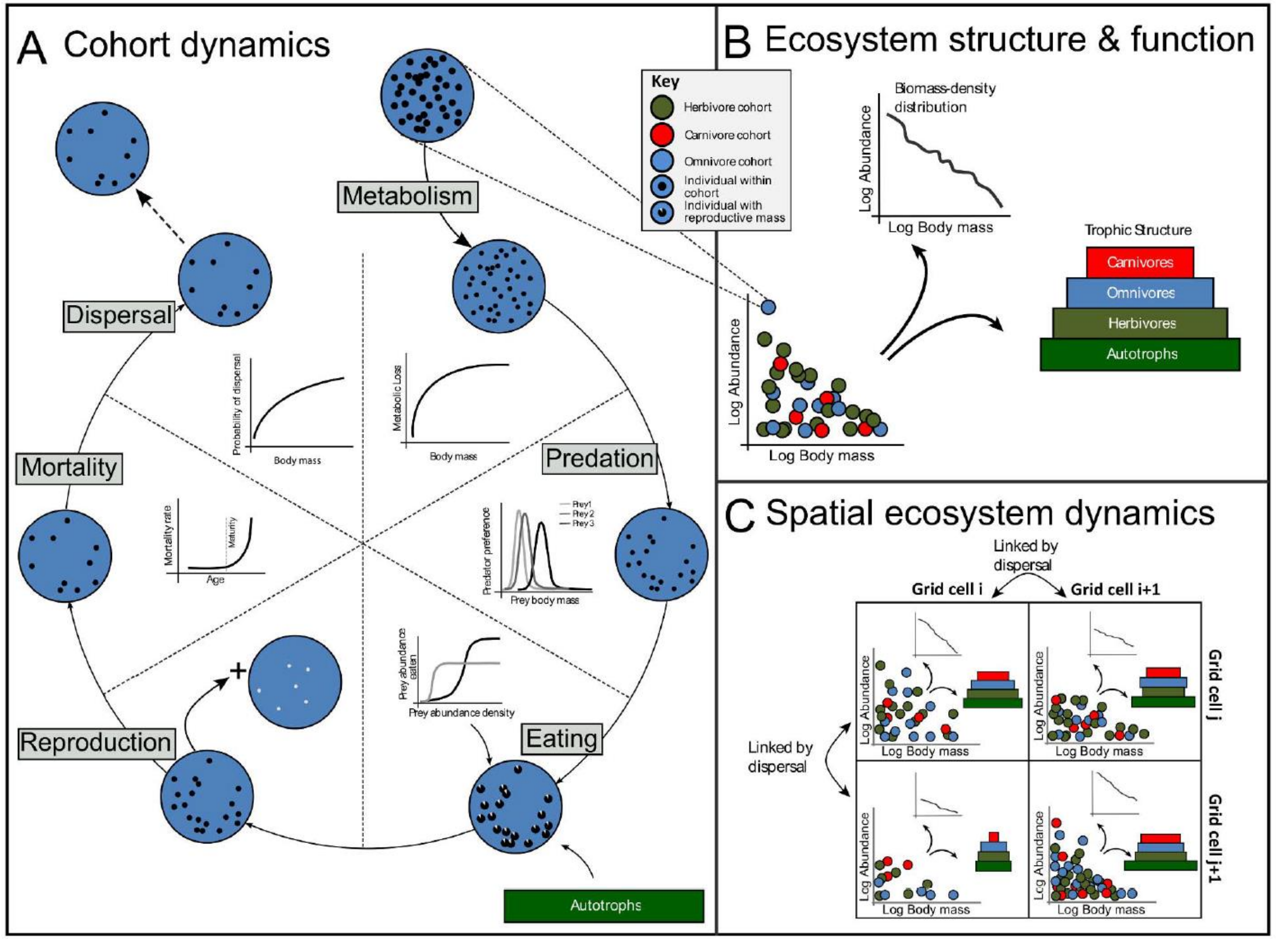






CO$_2$
Soil
microbes
Metabolism
Mortality
Predation
Herbivory
Reproduction
Plant
model
Mortality
Detritivory

Ecological processes operate on individual cohorts; predictions are made about emergent ecosystem structure



Harfoot et al. (2014). *PLoS Biology* **12**: e1001841

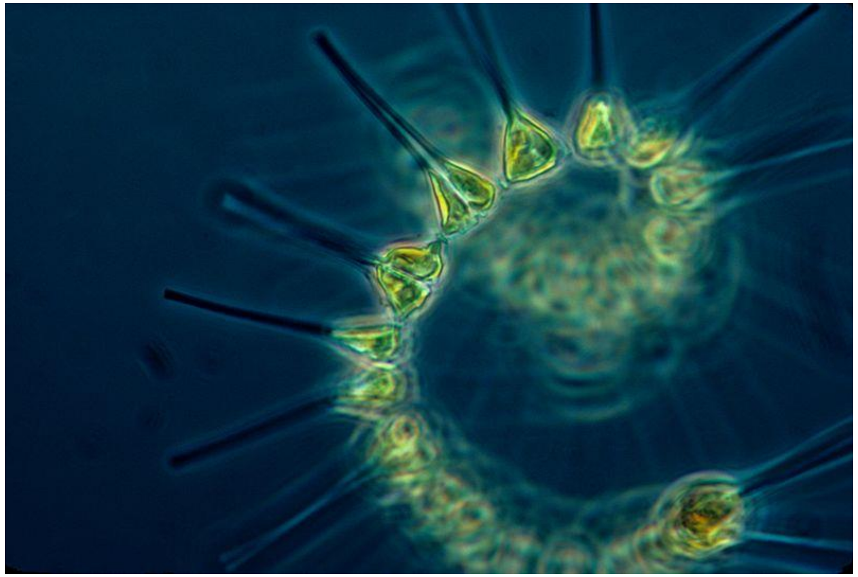
Represents functional groups not species

Herbivore
Ectotherm
Semelparous
Mobile
Terrestrial

Omnivore
Endotherm
Iteroparous
Mobile
Marine

Carnivore
Endotherm
Iteroparous
Mobile
Terrestrial

An individual-based model would be computationally intractable



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

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

Instead individuals are grouped into 'cohorts'

ID:	4520
Num. individuals:	1221
Individual mass:	450 kg
Age:	11.3 years
Functional group:	3

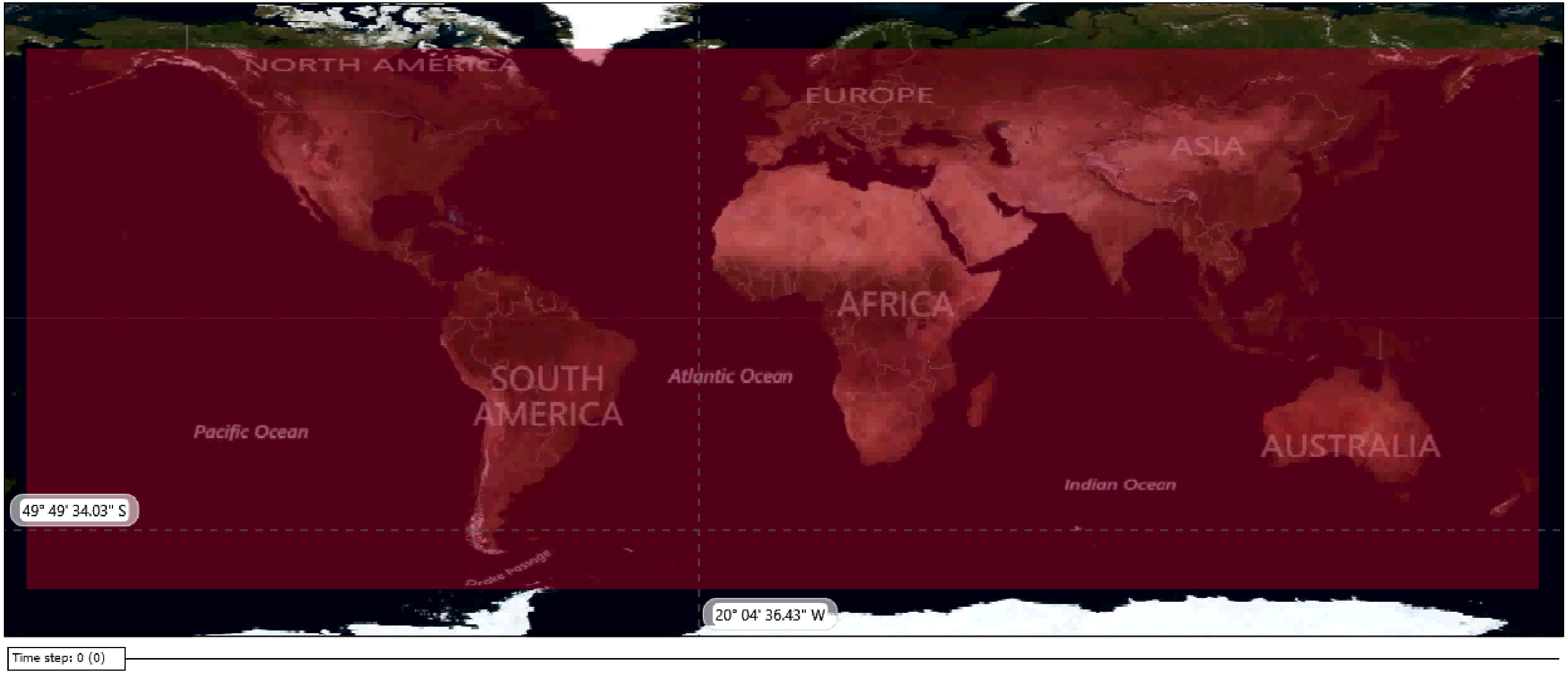
ID:	10,802
Num. individuals:	426
Individual mass:	5.6 kg
Age:	3.4 years
Functional group:	19

An individual-based model would be computationally intractable

Cohort-based model for a single ecosystem: ≈ 10 hours

Individual-based model: ≈ 47 billion years

Emergent biomass patterns

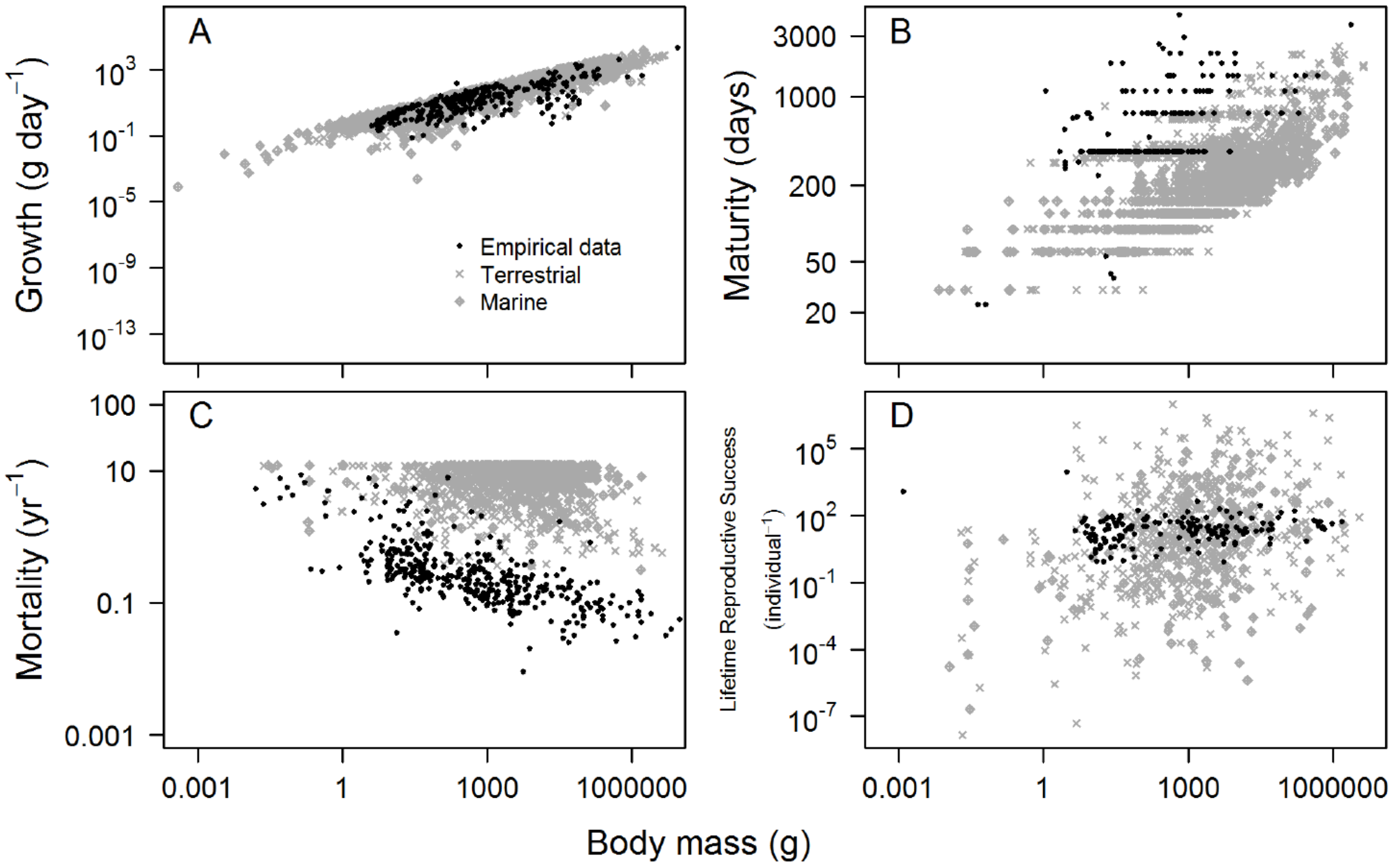


Based on data in Harfoot et al. (2014). *PLoS Biology* **12**: e1001841

Correspondence with empirical data: individual-level process rates

Empirical data on lifetime reproductive success are species averages, so much less variable than modelled cohorts

Mortality rates don’t match observed scaling with mass

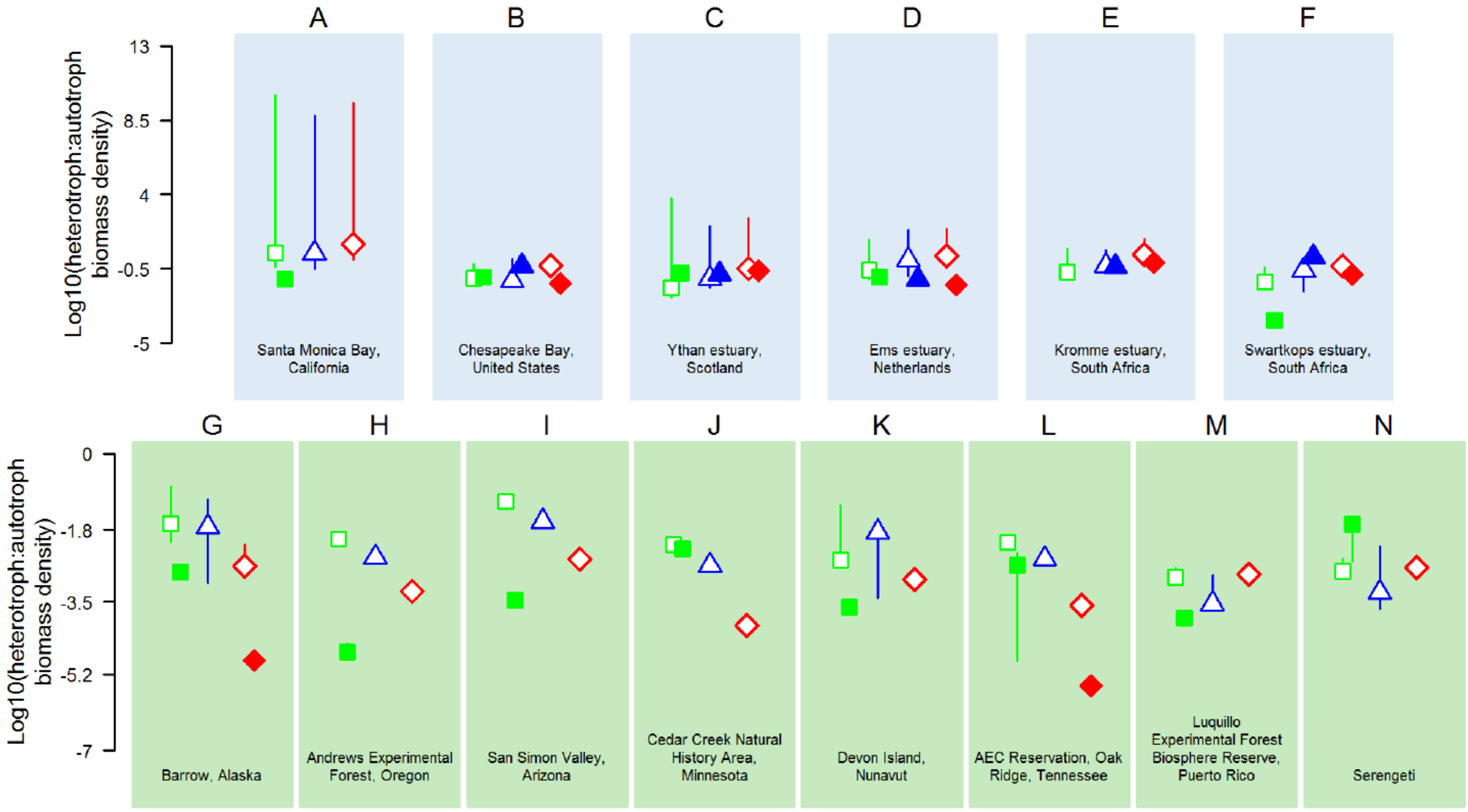


Harfoot et al. (2014). *PLoS Biology* **12**: e1001841

Correspondence with empirical data: individual-level process rates

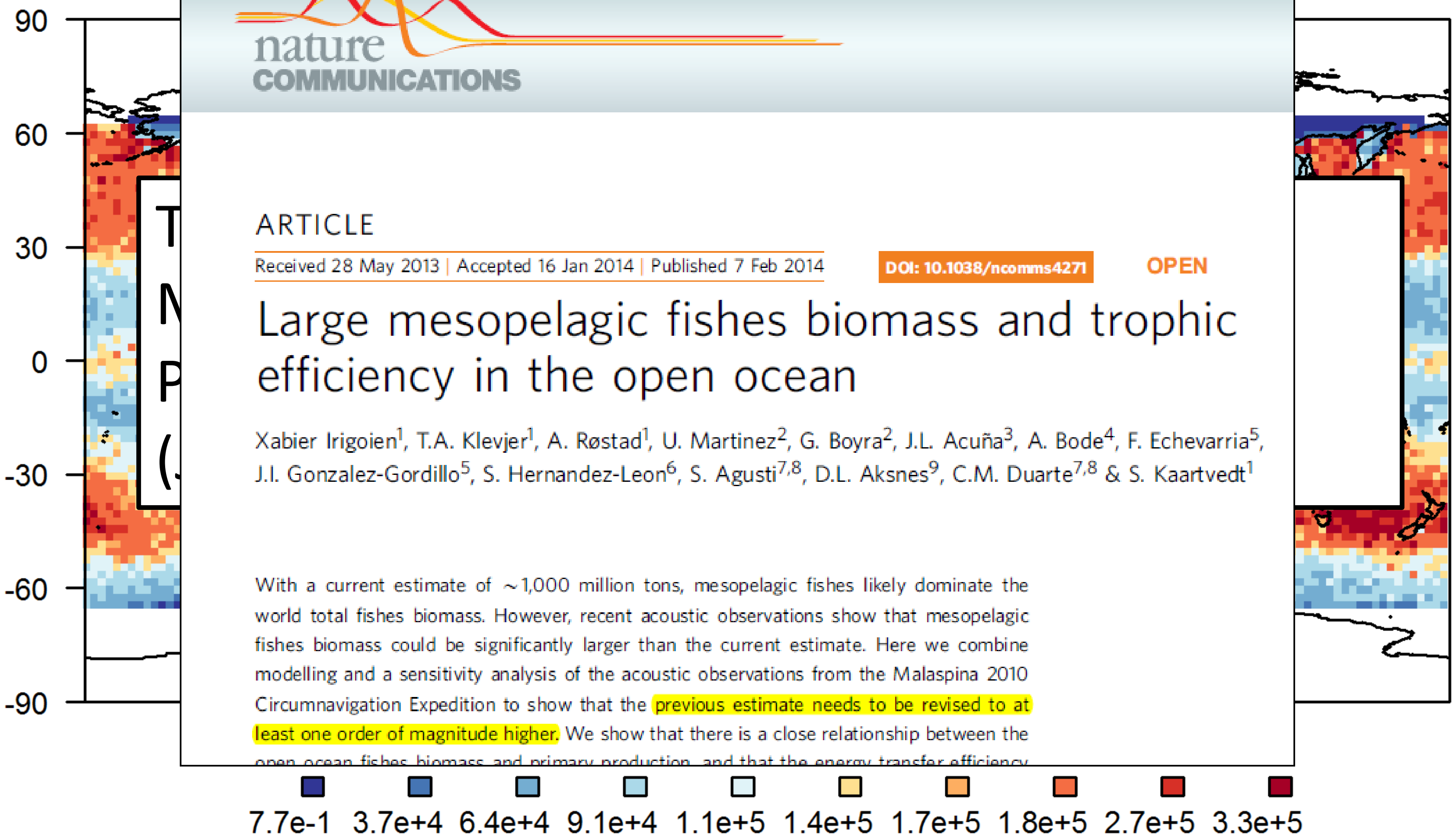
Match with empirical data generally good in marine systems

On land, better for grassland ecosystems than forests – vertical vegetation structure?



Harfoot et al. (2014). *PLoS Biology* **12**: e1001841

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

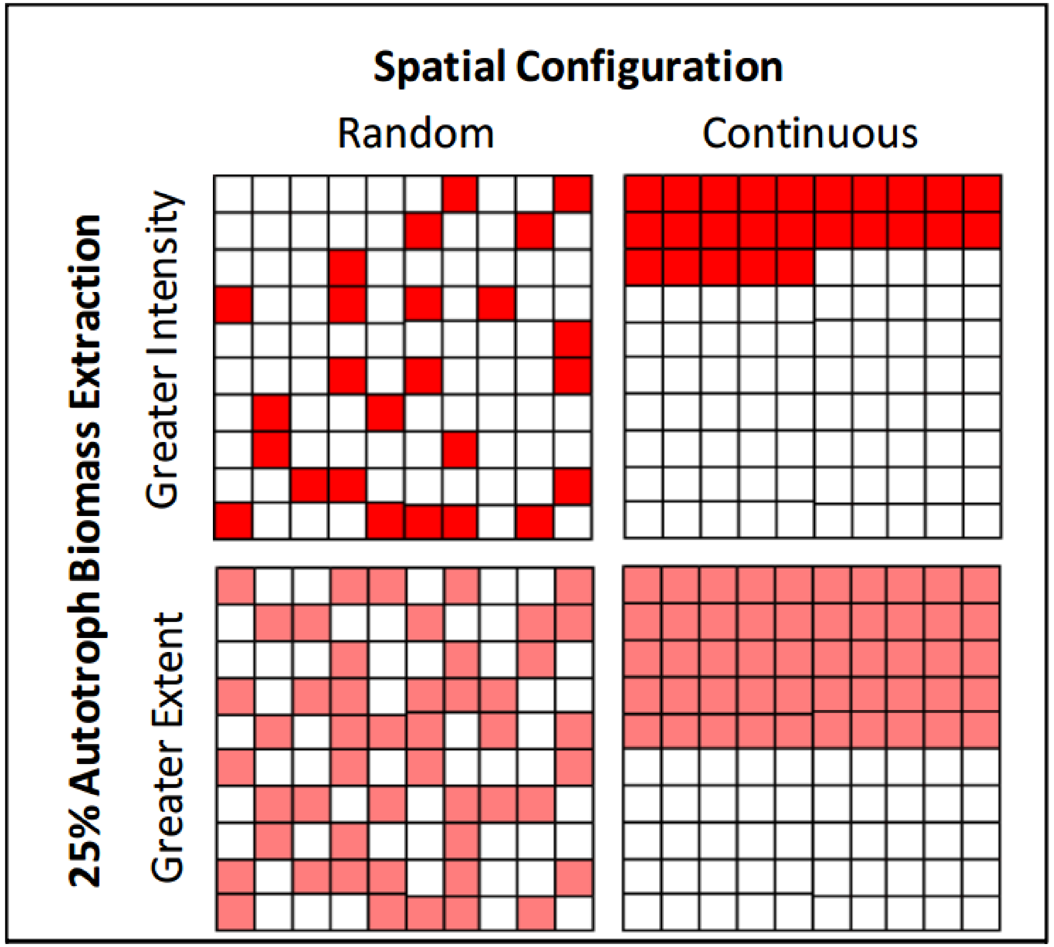
Large mesopelagic fishes biomass and trophic efficiency in the open ocean

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

Harfoot et al. (2014). *PLoS Biology* **12**: e1001841

Applications of general ecosystem models: effects of habitat fragmentation

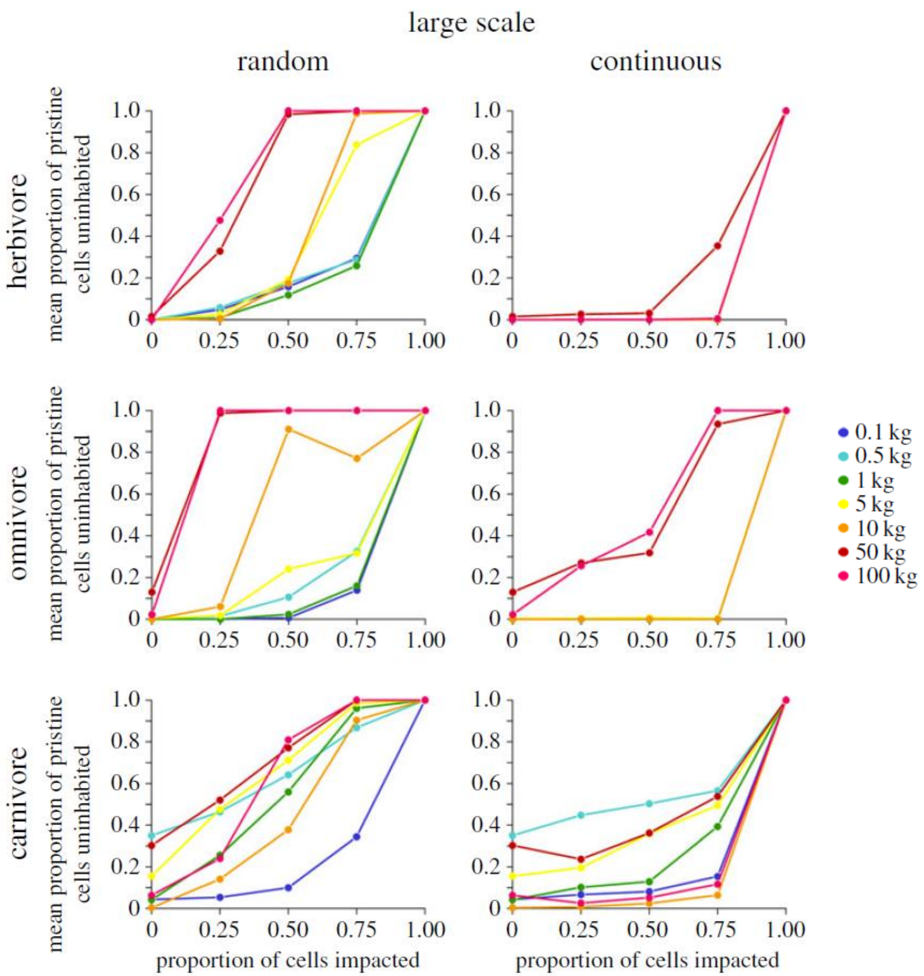


Plant biomass removed from Madingley-Model ecosystems in different extents, intensities and configurations

Simulated impacts on higher trophic levels, for organisms of different body mass

Bartlett et al. (2016). *Proceedings of the Royal Society, Series B* **283**: 20161027

Applications of general ecosystem models: effects of habitat fragmentation



Impacts depended on fragmentation scenario

Higher trophic levels and large organisms generally more likely to be lost

Losses generally greater under fragmented than continuous habitat loss

Bartlett et al. (2016). *Proceedings of the Royal Society, Series B* **283**: 20161027

Summary: complex ecosystem models

System-level models can capture the multiple interacting entities that make up ecological systems

Some outcomes of environmental change can be a product of the interactive nature of ecosystems

These interactive effects can lead to abrupt changes/tipping points

A challenge for systems-level model is obtaining enough information on all of the relevant processes

General summary

No model is perfect (not even close)

The right model depends on the questions being asked

No amount of model sophistication will correct for bad assumptions/data/model structure

It is important to constantly question the assumption of models and to confront models with empirical data

Reading list (I am not expecting you to read all of these!)

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Smith et al. (2015). An investigation into fisheries interaction effects using Atlantis. *ICES Journal of Marine Science* **72**: 275-283.

Reading list (I am not expecting you to read all of these!)

Smith et al. (2015). Inferred support for disturbance-recovery hypothesis of North Atlantic phytoplankton blooms. *J of Geophysical Research: Oceans* **120**: 7067-7090.

Travers et al. (2007). Towards end-to-end models for investigating the effects of climate and fishing in marine ecosystems. *Progress in Oceanography* **75**: 751-770.