Ecology: from the origin of life to the age of global change

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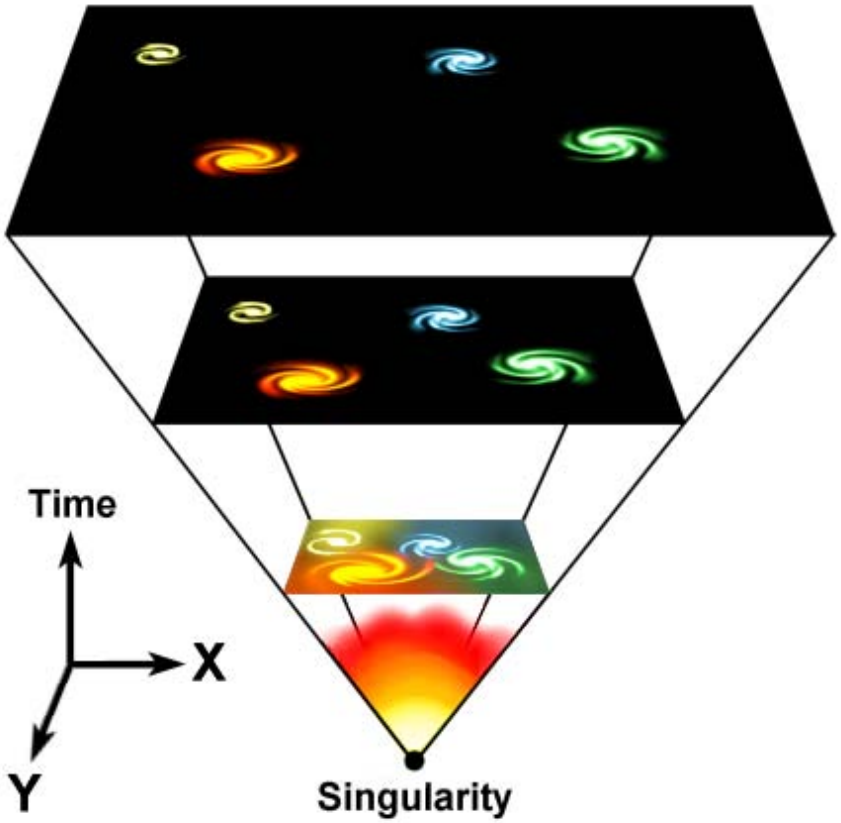
External Faculty The Santa Fe Institute

Part 1

- From the Big Bang (B^2) to the Big Biotic Bang (B^3)

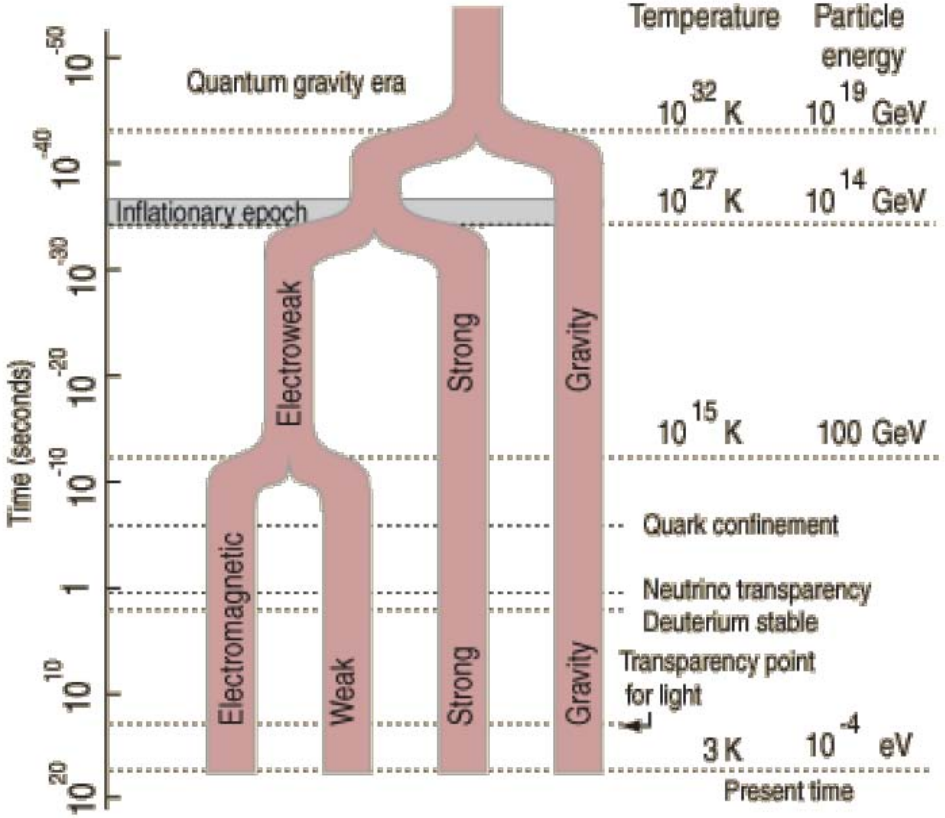
BIG BANG

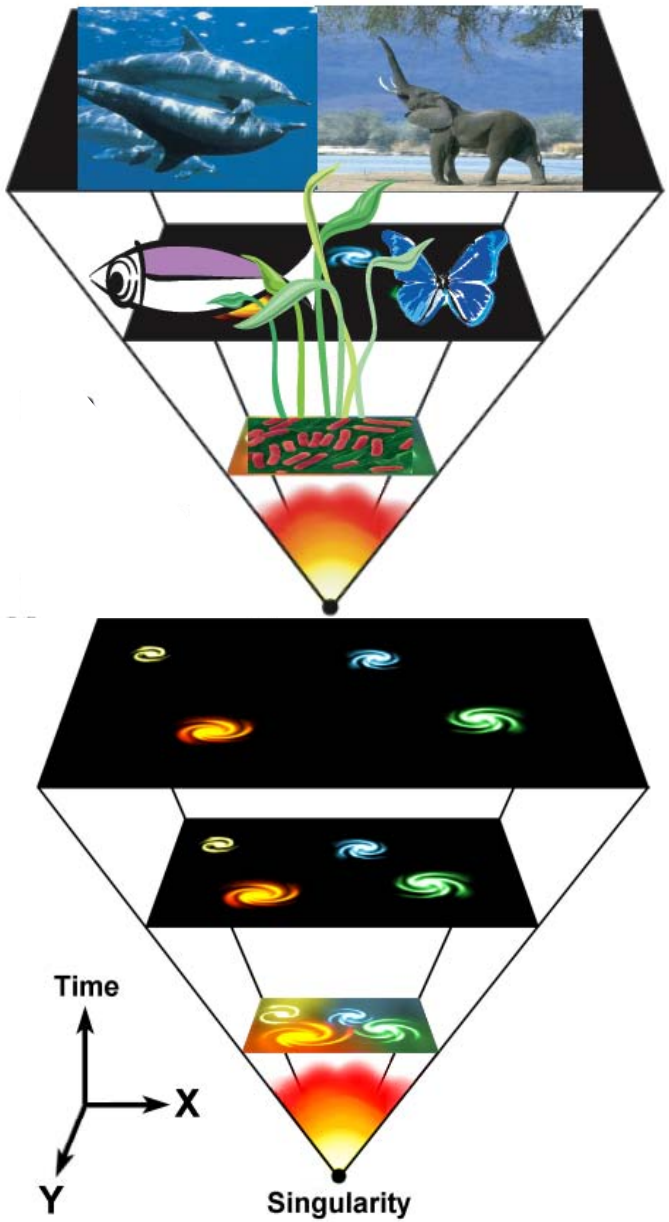


(From http://en.wikipedia.org/)

14-15 x 10^9 yrs

Standard Model





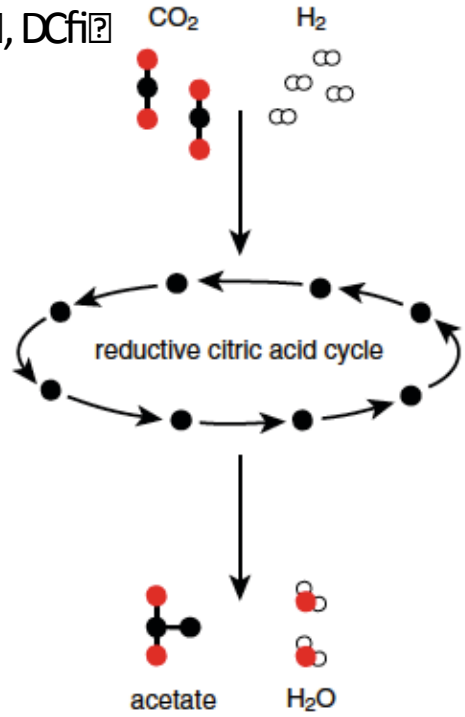
The Big Biotic Bang

3.5-4 x 10^9 yr

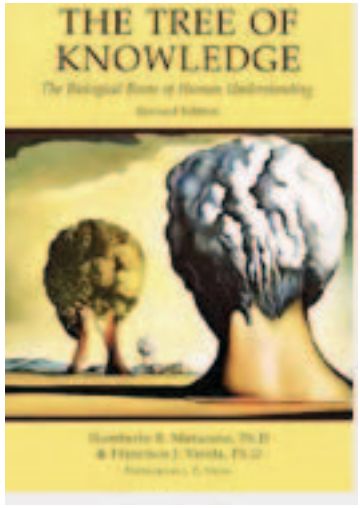
Dr. Albert Szent-Gyorgyi
Nobel Prize Laureate
Hungary (1893-1986)

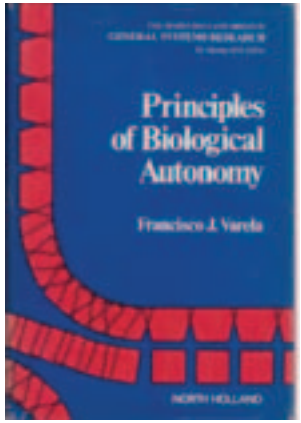
"Treating humans
without the concept
of energy is treating
dead matter."


Robinson Professor of
Biology & Natural Philosophy
Krasnow Institute
Harold Morowitz


CO_2
H_2
reductive citric acid cycle
acetate
H_2O


AUTOPOIESIS
AND
COGNITION
kluwer
the language of science


THE TREE OF
KNOWLEDGE


Principles
of Biological
Autonomy
Francisco J. Varela

While structure can change, organization is invariant

The minimal invariant organization is autopoietic (self-producing)

It is a network of component production processes (synthesis and destruction) such that these components:

1. continually generate and make effective the network that produces them

2. make the system as distinguishable unity in the domain they exist.

Autonomy and closure

Autopoietic systems should be understood as organizationally and operationally closed systems. That is, composed of processes whose result are autonomous networks of component production that realize the network that produced them.

‘Organizational closure’ describes the self-referential (circular and recursive) network of Relations that defines the system as a unity.

Thus autonomous systems so defined neither operate through representation of an Independent world or reality nor impose an internal one. There is no ground inside or outside the autopoietic system.

Autopoietic systems operate through ENACTION or the act of co-determination or mutual specification (with its environment) of a domain that is brought into existence as a result of the interaction between the system and its environment through a history of structural couplings

Like phenomenology, the enactive approach thus emphasizes that the organism defines its own point of view on the world. (Thompson et al 2005)

Enaction: A history of structural coupling that brings forth a world.

“Finally, we saw that these various forms of groundlesness are really one: organism and environment enfold into each other and unfold from one another in the fundamental circularity that is life itself.” (Varela et al. 1991)

Exploring some consequences of autopoiesis and Enaction

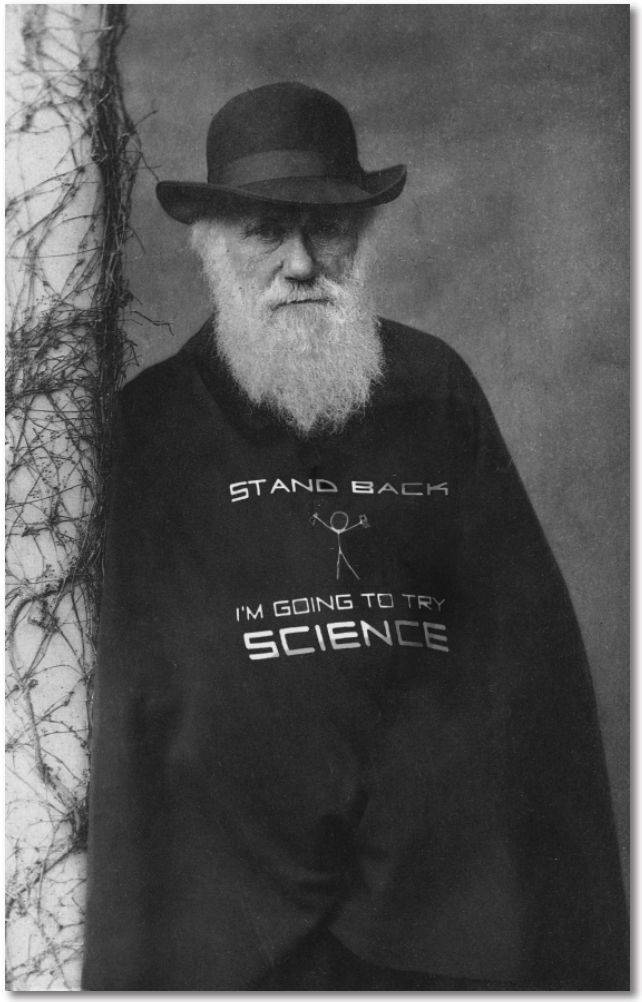
1. Reproduction is not required in a definition of life. It is a consequence of the physical realization or structure of the autopoietic system.

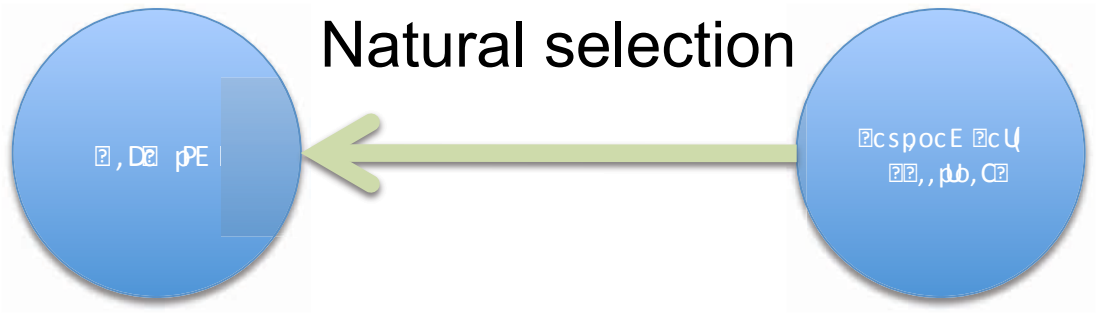
2. Operational closure and Enaction imply niche construction.

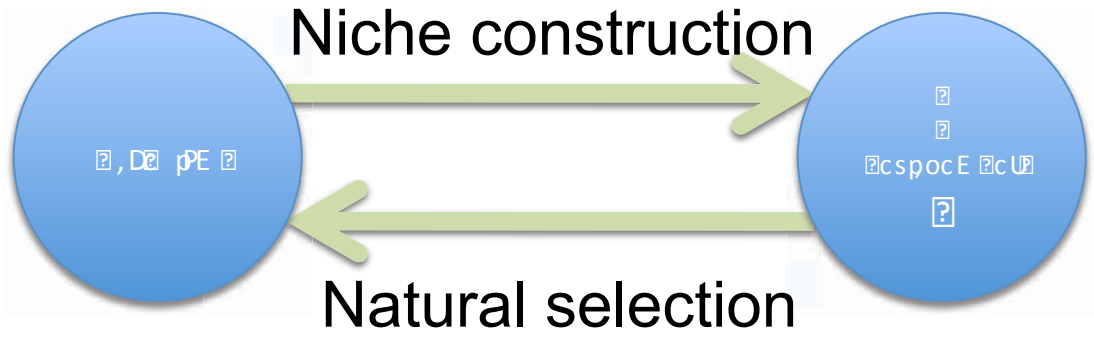
“It is, in general, not possible to understand the geographical and temporal distribution of species if the environment is characterized as a property of the physical region, rather than of the space defined by the activities of the organism itself.”

“...organisms not only determine what aspects of the outside world are relevant to them by peculiarities of their shape and metabolism but they actively construct, in the literal sense of the word, a world around themselves.”

Richard Lewontin (2000)


STAND BACK
I'M GOING TO TRY
SCIENCE


Natural selection


Niche construction
Natural selection

The emergence and maintenance of species diversity

"A primordial soup ecology perspective"

Theor Ecol (2012) 5:457–463
DOI 10.1007/s12080-011-0138-9

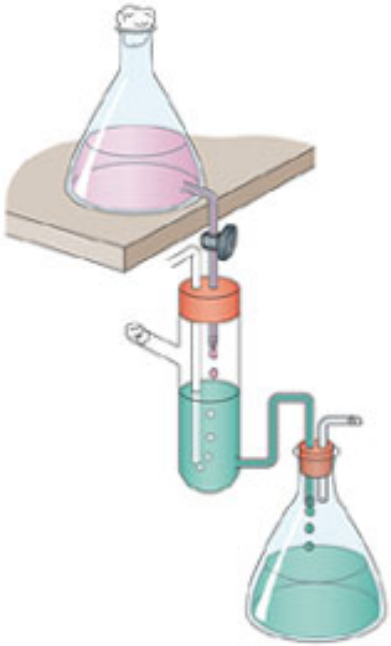
ORIGINAL PAPER

Diversity emerging: from competitive exclusion to neutral coexistence in ecosystems

Juan E. Keymer · Miguel A. Fuentes · Pablo A. Marquet

Types of microbial cultures

Chemostat



Serial transfer

Long-term

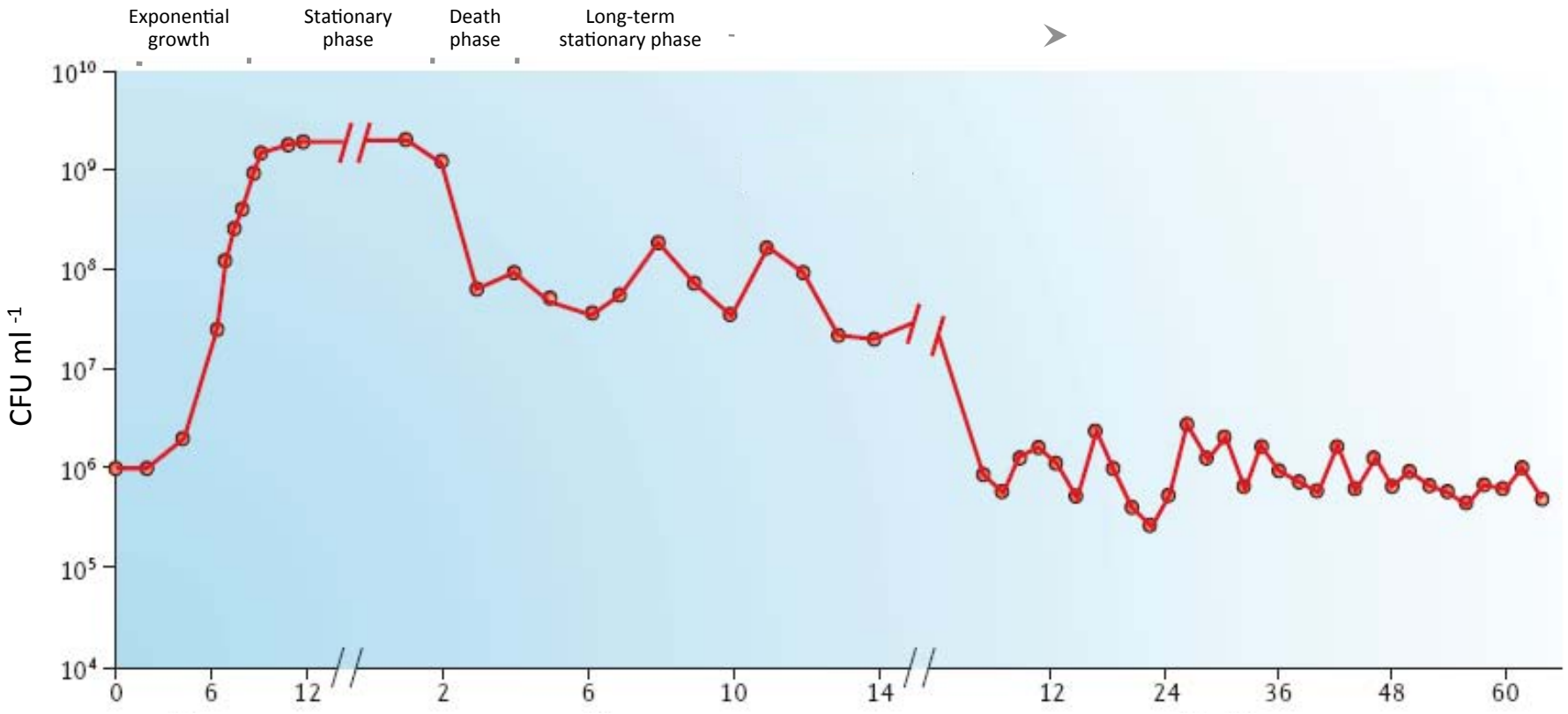
Genetic diversity

Resource competition

Modified from Stams, A. and Plugge, C. (2009) Electron transfer in syntrophic communities of anaerobic bacteria and archaea. Nature Reviews Microbiology

Roberto Kolter´s experiment

Growth phases in long-term cultures with prolonged starvation



CFU = colony-forming unit

Finkel, S.E. (2006) Long-term survival during stationary phase: evolution and the GASP phenotype. Nature Reviews Microbiology

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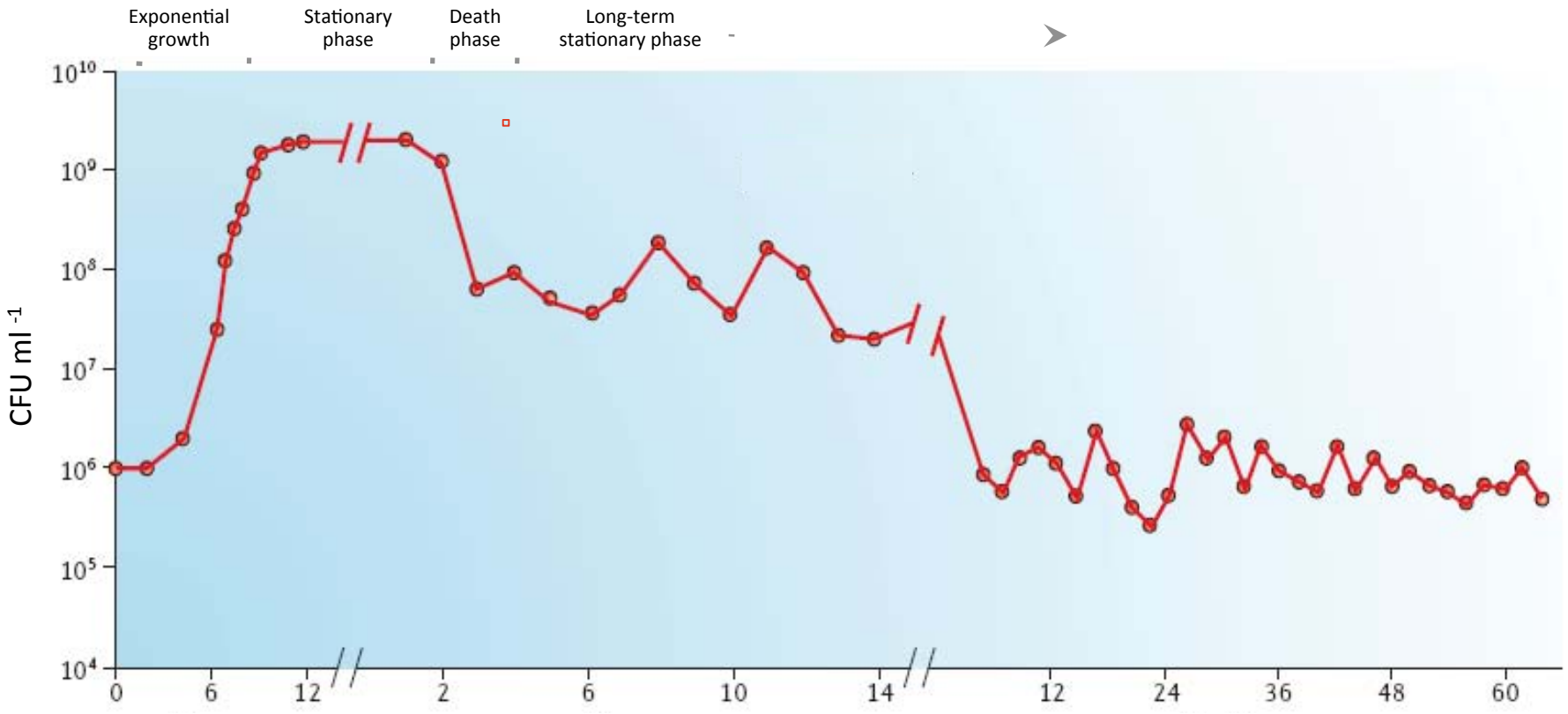

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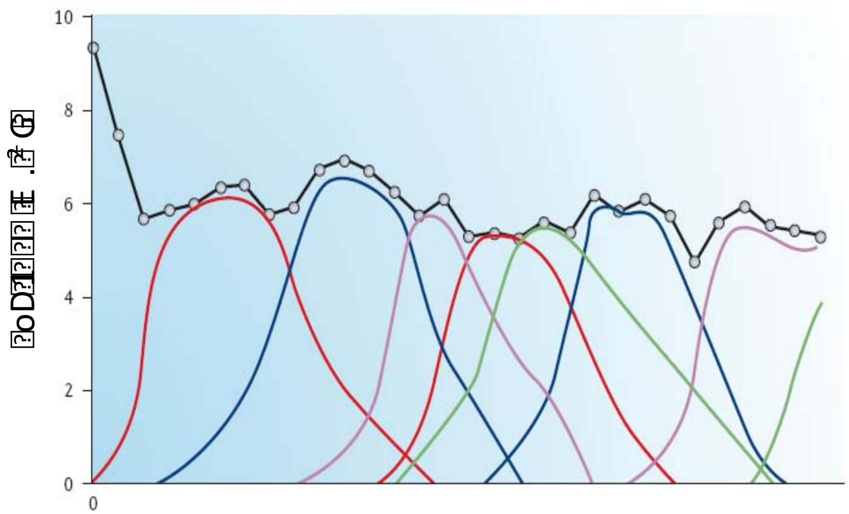
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8
6
4
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0
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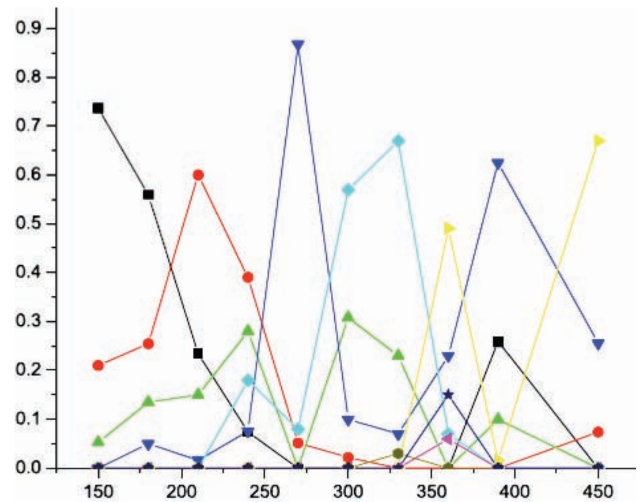
0.9
0.8
0.7
0.6
0.5
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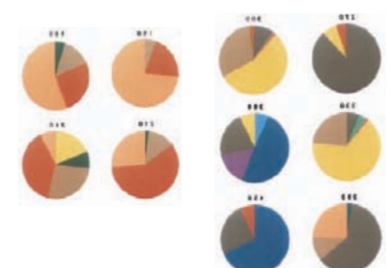
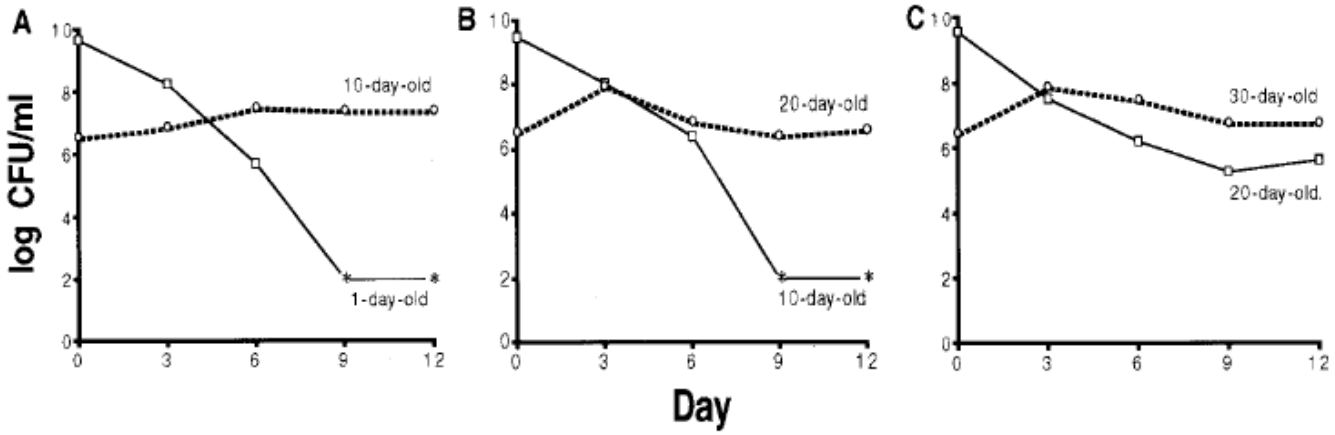
0.1
0.0
150
200
250
300
350
400
450



Progressively older mutants outcompete younger ones



The model

$$\frac{d}{dt}\phi = r\phi(1-\phi) \quad (1)$$

$$r(\omega) = f\omega - m. \quad (2)$$

$$\frac{d}{dt}\omega = S - C \quad (3)$$

$$S \equiv \lambda(1-\omega) \quad (4)$$

$$C \equiv \epsilon\phi\omega f \quad (5)$$

Phi= Biomass

f = fecundity

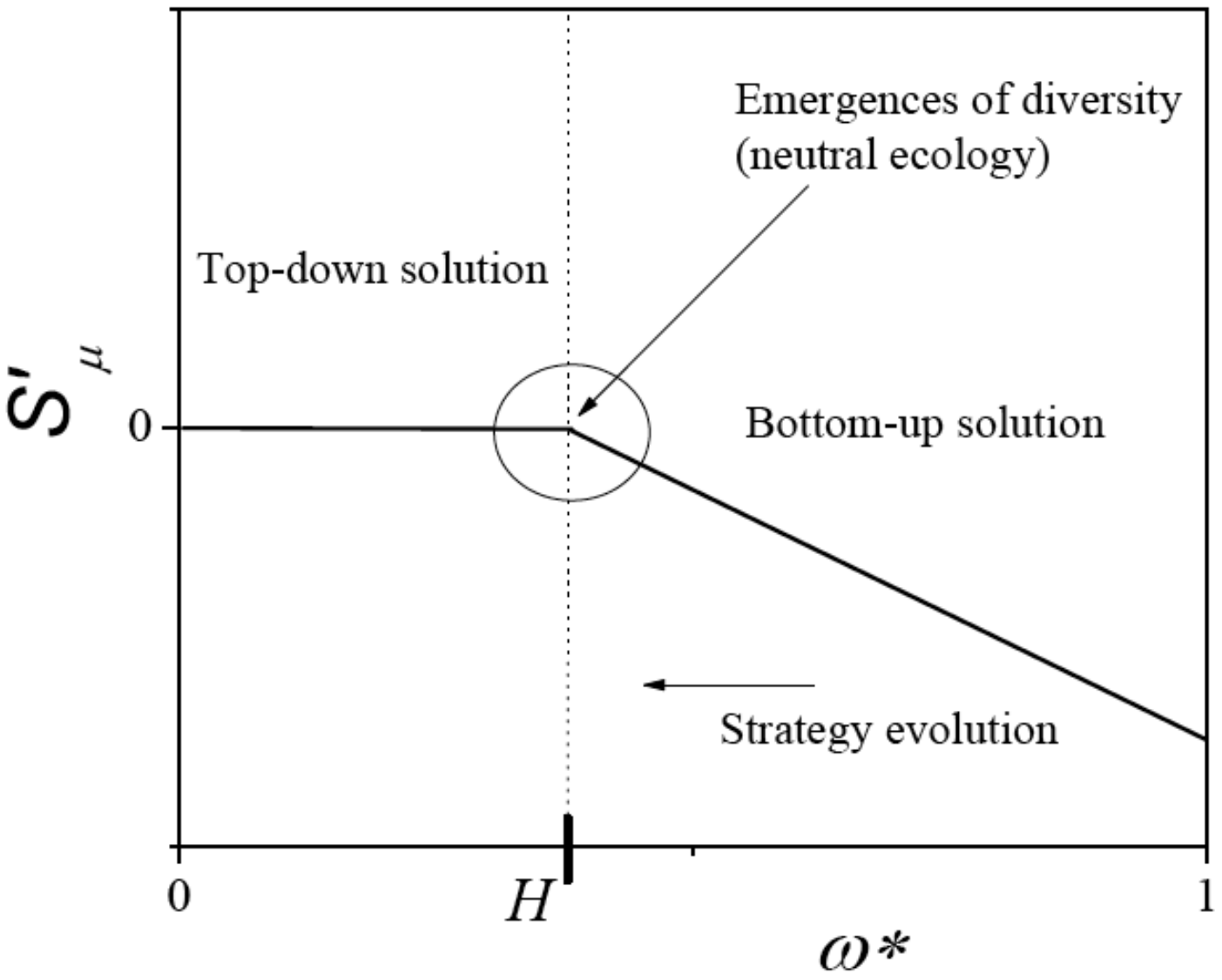
m= mortality

w = Available resources

e= Conversion efficiency of resources into biomass

$$S \equiv S_{\omega_r^*}(\omega_\mu^*) \equiv \frac{1}{\phi_\mu}\,\frac{d}{d\tau}\bigg|_{\phi_r=\hat{\phi}_r;\phi_\mu\to 0}\phi_\mu = (\omega_r^* - \omega_\mu^*)(1-\hat{\phi}_r).$$

Adaptive Dynamics



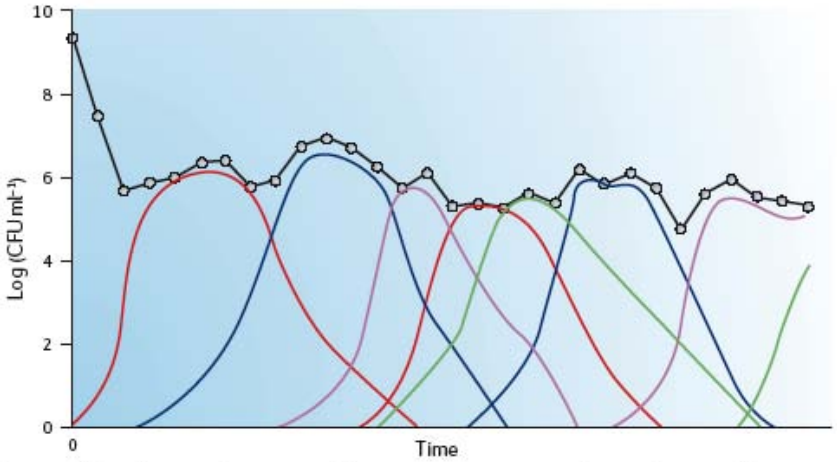
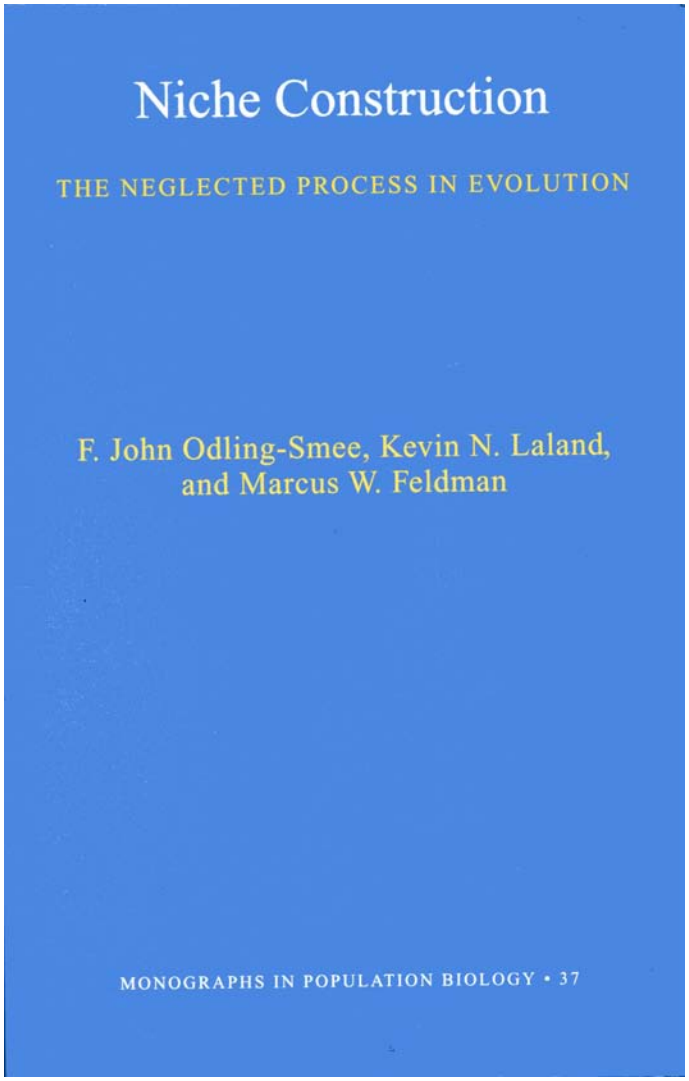
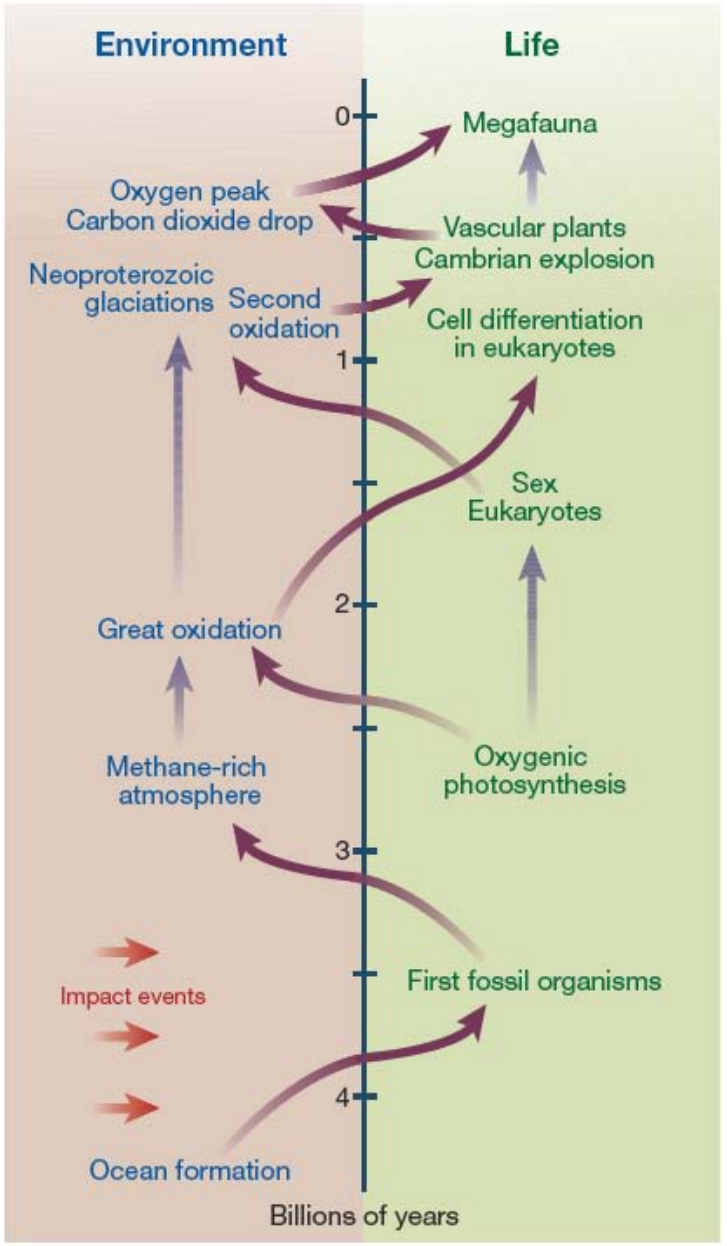


Figure 3 | **Population dynamics of long-term stationary-phase cultures.** After death phase, as cells continue to incubate under long-term stationary-phase conditions, the apparent number of colony-forming units (CFU) per ml remains relatively stable. However, these cultures are not static. There is a dynamic equilibrium between newly created growth advantage in stationary phase (GASP) mutants and less competitive cells. The birth rates and death rates within the population are balanced. Each coloured line represents a different GASP mutant that appears during long-term incubation. The black line represents the total population density.



The co-evolutionary ladder…



Earth's co-evolutionary ladder, as built so far…

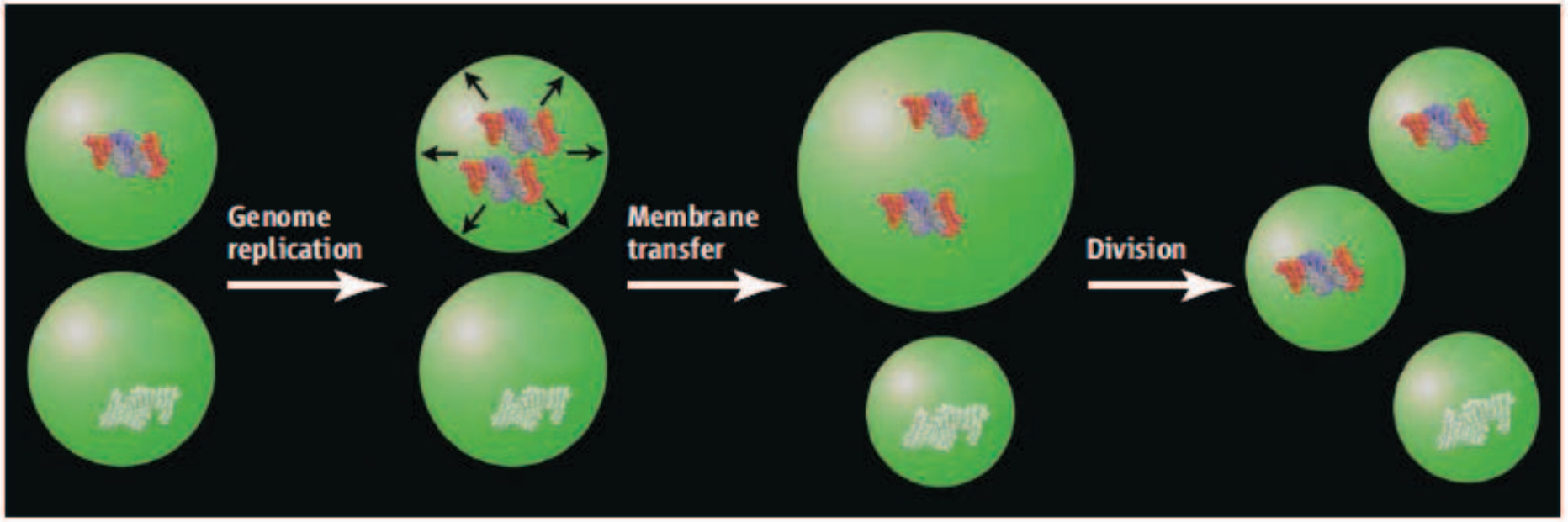
Lenton_et_al_2004, Nature 431:913

Exploring some consequences of autopoiesis and enaction

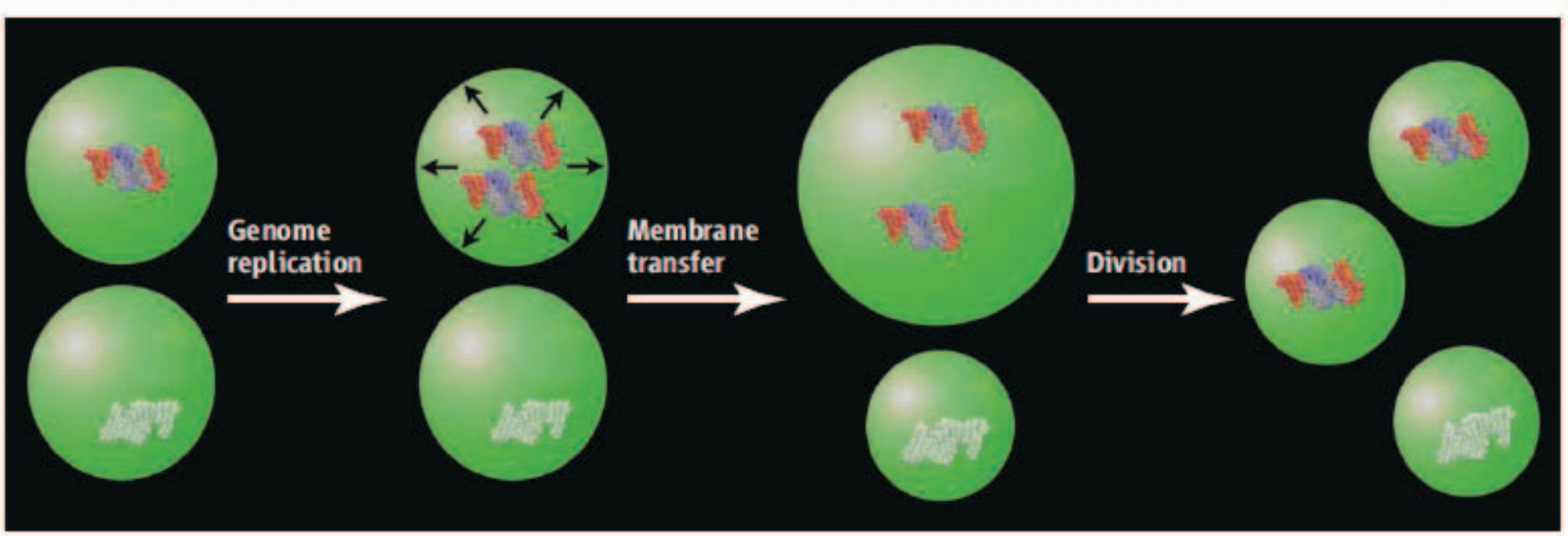
Reproduction is not required in a definition of life. It is a consequence of the physical realization or structure of the autopoietic system.

The Emergence of Competition Between Model Protocells

Irene A. Chen,[1,2] Richard W. Roberts,[3] Jack W. Szostak[1]*



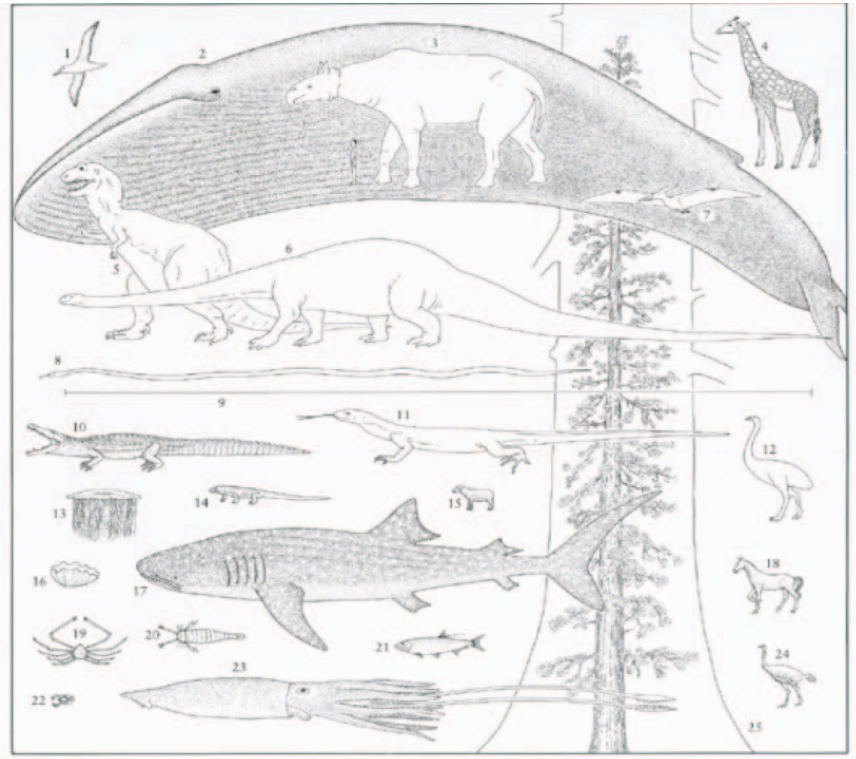
The emergence of cellular behavior. Competition emerges as protocells containing replicating genomes steal membrane from protocells containing inactive molecules.

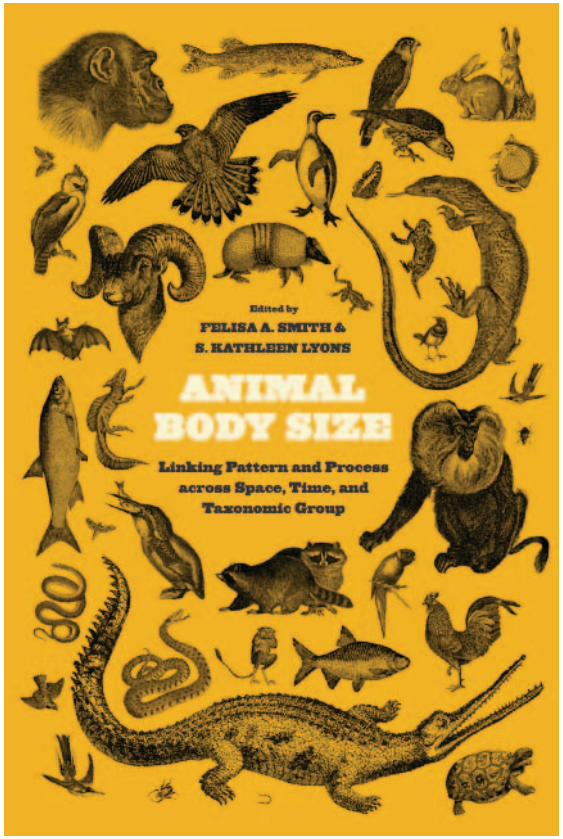


The emergence of cellular behavior. Competition emerges as protocells containing replicating genomes steal membrane from protocells containing inactive molecules.

Metabolic theory of ecology

•A large part of the diversity of living systems is related to diversity of the size of the system itself





What is this?

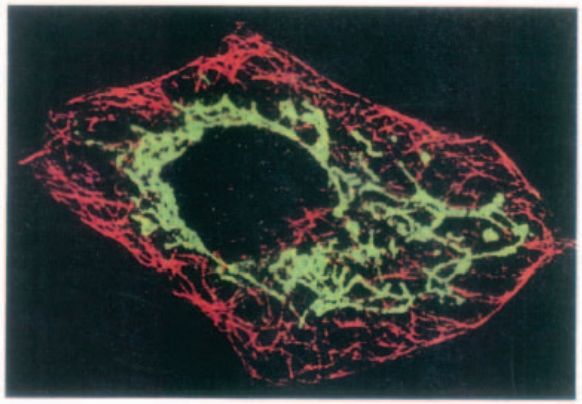


Fig. 1. Mitochondrial network in a mammalian fibroblast. A COS-7 cell labeled to visualize mitochondria (green) and microtubules (red) was analyzed by indirect immunofluorescence confocal microscopy. Mitochondria were labeled with antibodies to the β subunit of the F_1-ATPase and a rhodamine-conjugated secondary antibody. Microtubules were labeled with antibody to tubulin and a fluorescein-conjugated secondary antibody. Pseudocolor was added to the digitized image. Scale: 1 cm = 10 μm.

From M. P. Yaffe, *Science,* **283,** 1493 (1999).

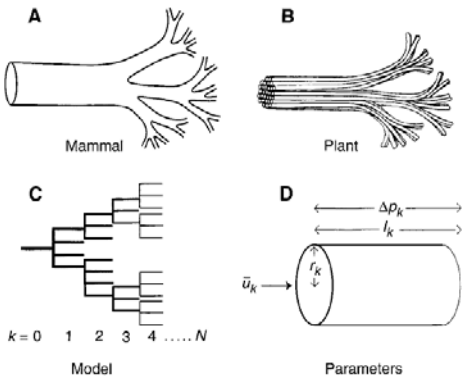
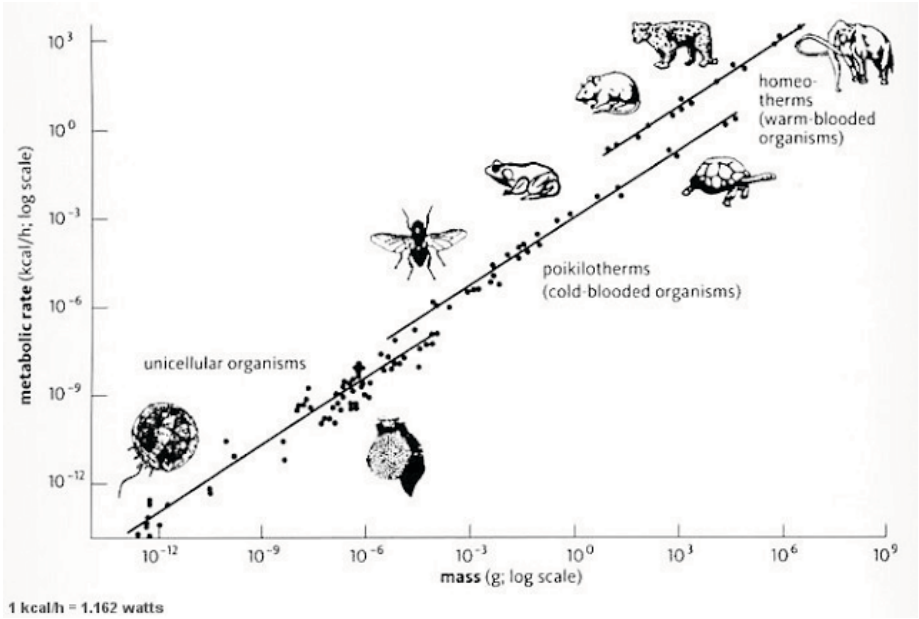
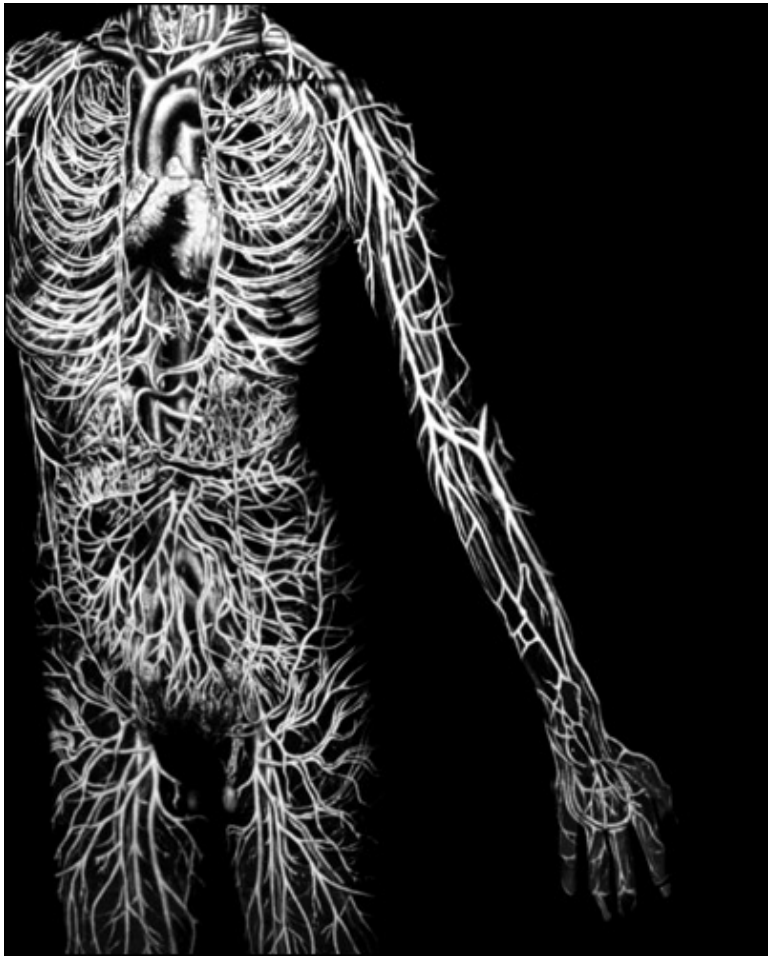


Fig. 1. Diagrammatic examples of segments of biological distribution networks: (**A**) mammalian circulatory and respiratory systems composed of branching tubes; (**B**) plant vessel-bundle vascular system composed of diverging vessel elements; (**C**) topological representation of such networks, where k specifies the order of the level, beginning with the aorta ($k = 0$) and ending with the capillary ($k = N$); and (**D**) parameters of a typical tube at the kth level.

Tomado de West et al. (1997)



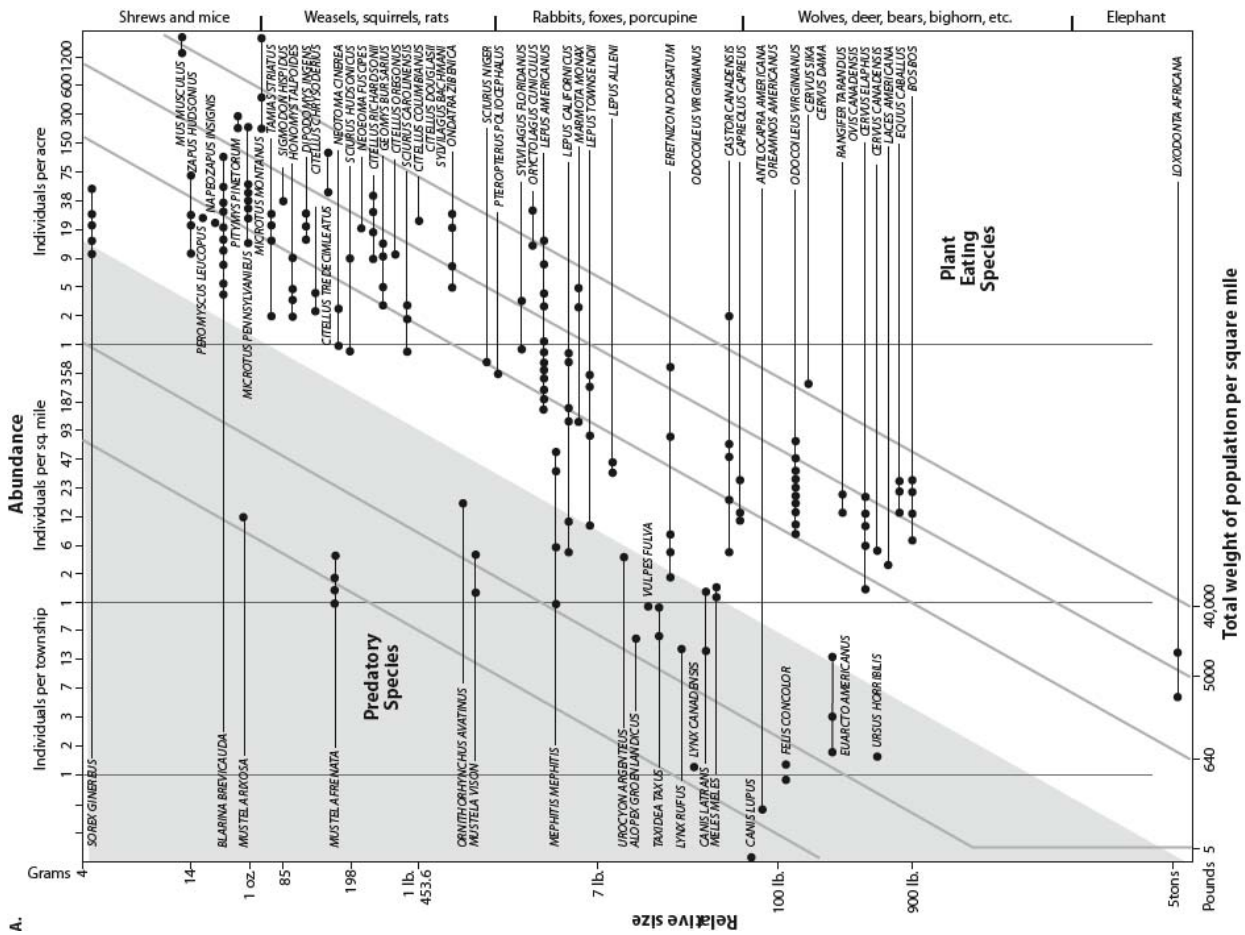


Metabolism

$$B = B_0 M^{3/4}$$

1. Brief History

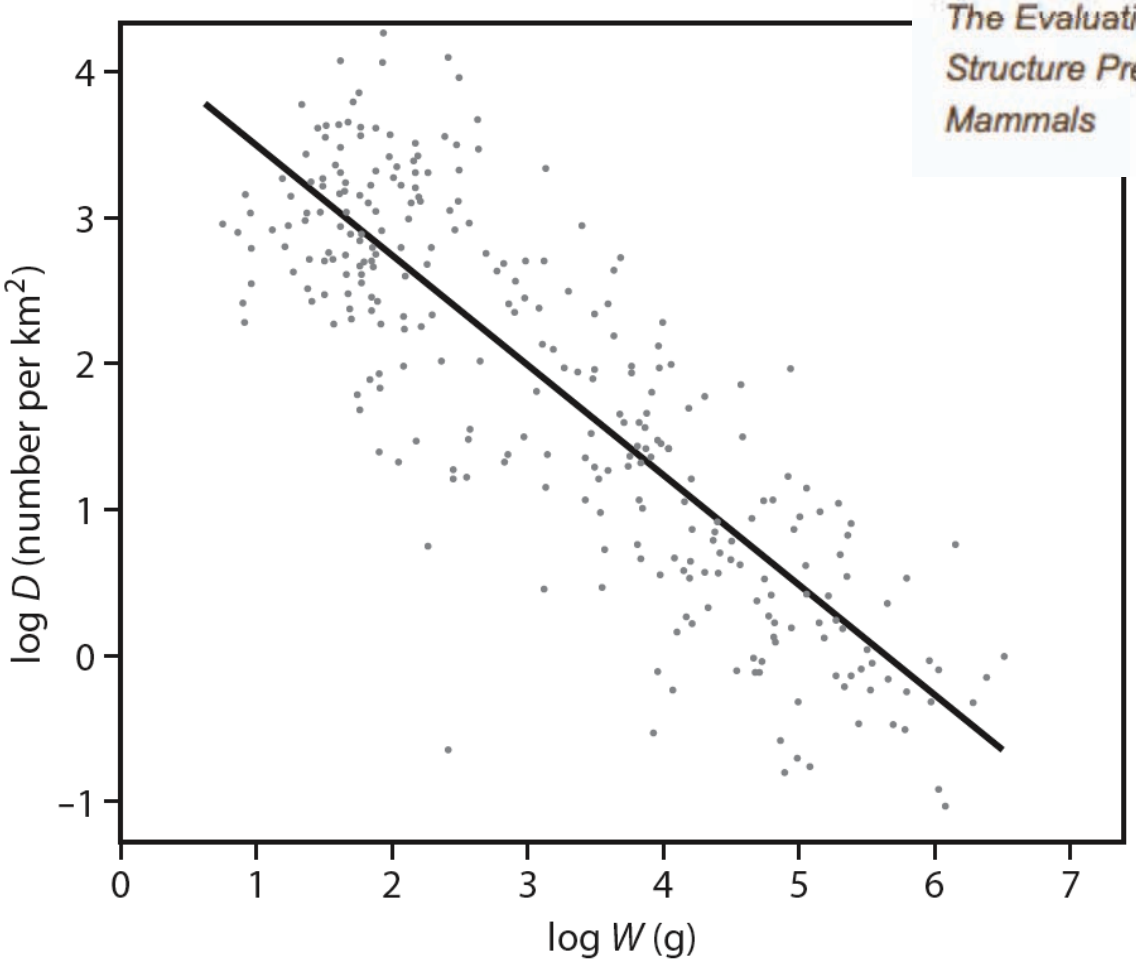
Mohr´s plot



Carl Mohr (1940)

John Damuth

Leigh Van Valen (advisor)
1982
The Evaluation of the Degree of Community Structure Preserved in Assemblages of Fossil Mammals



The maximum number of individuals that can be supported in an environment with an amount R of resources per unit area is predicted to be:

$$N_{max} \alpha R/B$$

which is equivalent to:

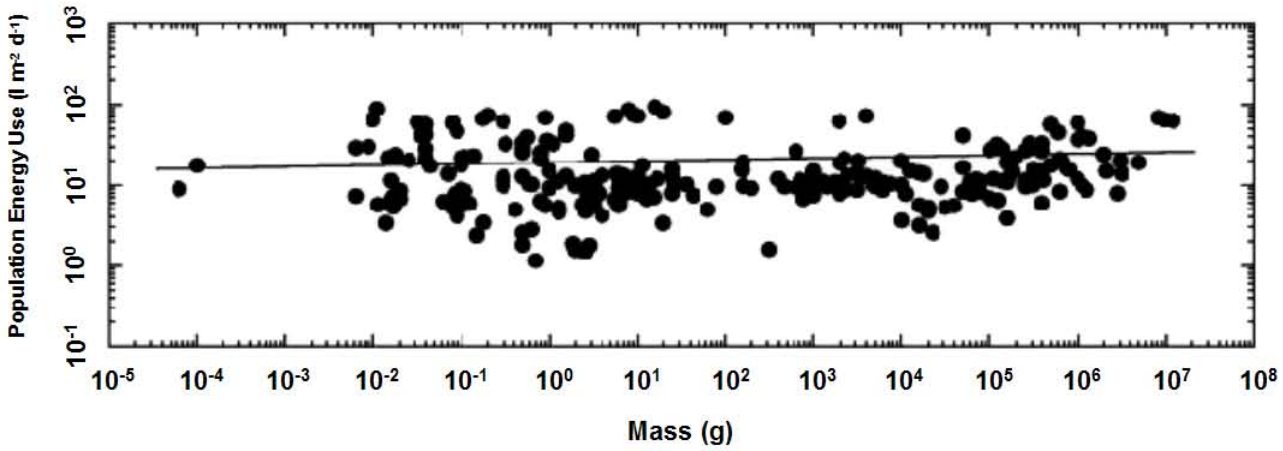
$$N = C_1 M^{-3/4}$$

Thus implying that, on average, species tend to use a similar amount of energy within ecosystems !!!!
This relationship was first identified by Van Valen (1976,1977) as a consequence of zero sum dynamics.

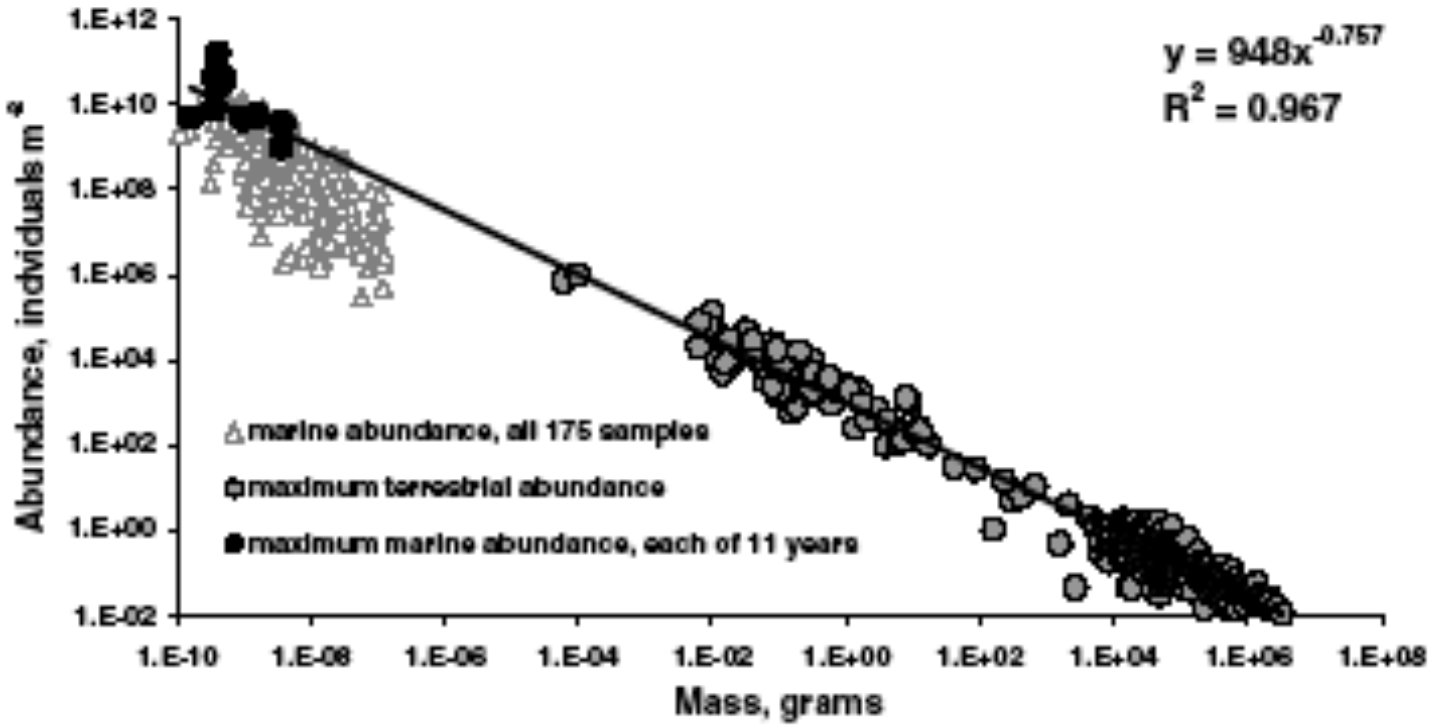
Since the total amount of energy used by a population (PEU) is the product of its local density (N) times the amount of energy required by each individual (B) it follows that:

$$PEU = B \times N \propto M^{3/4} \times M^{-3/4} \propto M^{0}$$

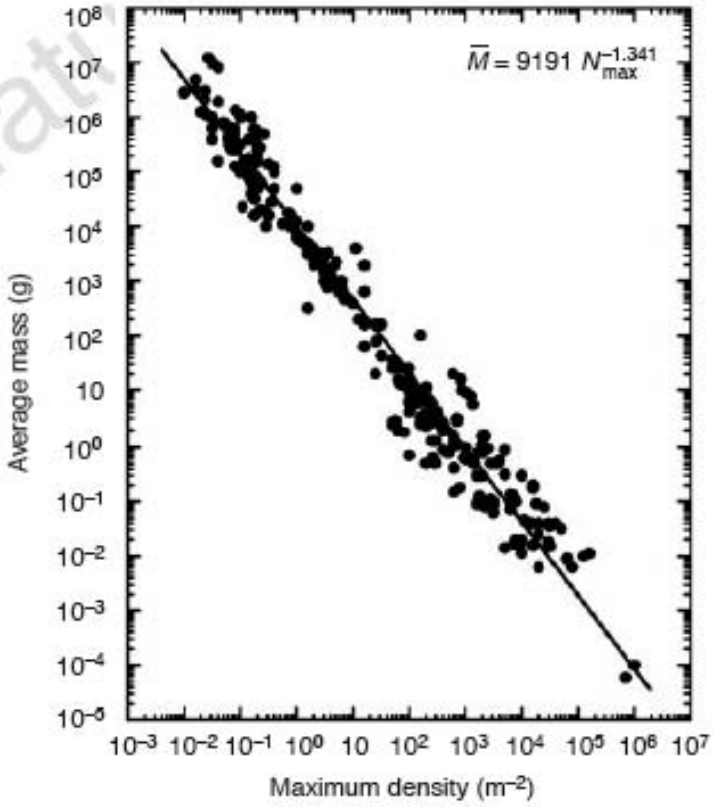
Thus implying that, on average, species tend to use a similar amount of energy within ecosystems !!!!
This relationship was first predicted by Van Valen (1976,1977) as a consequence of a zero sum game dynamics.



Enquist et al. (1998)



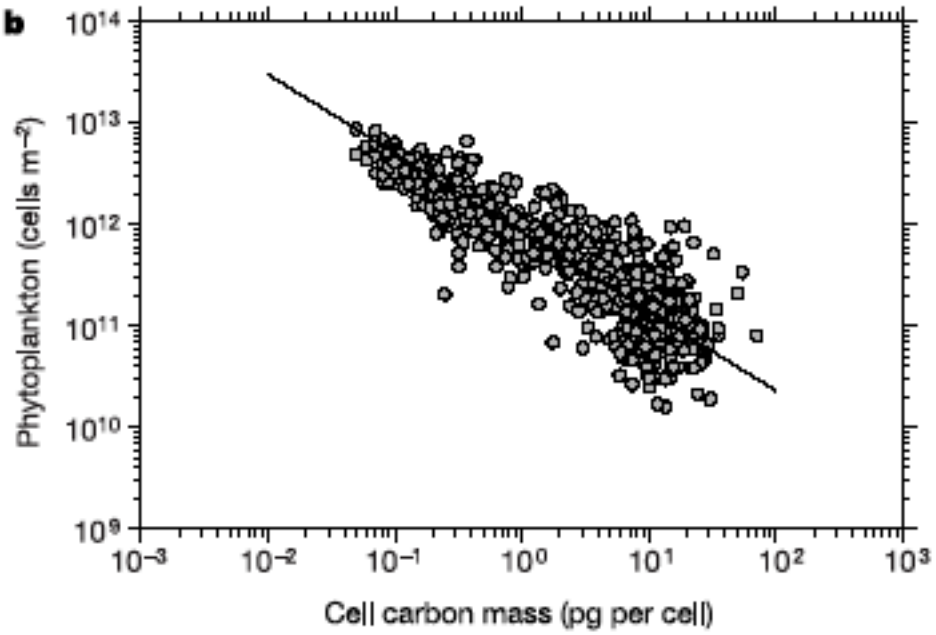
Belgrano et al (2002)



Allometric scaling of plant energetics and population density

Brian J. Enquist*, James H. Brown* & Geoffrey B. West†

NATURE | VOL 395 | 10 SEPTEMBER 1998



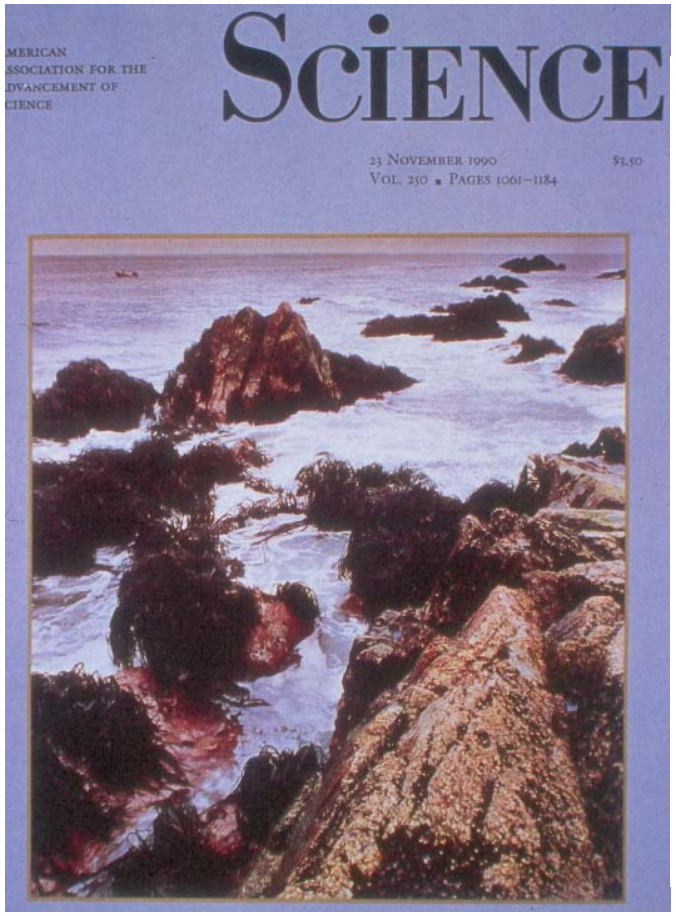
Macroecological patterns of phytoplankton in the northwestern North Atlantic Ocean

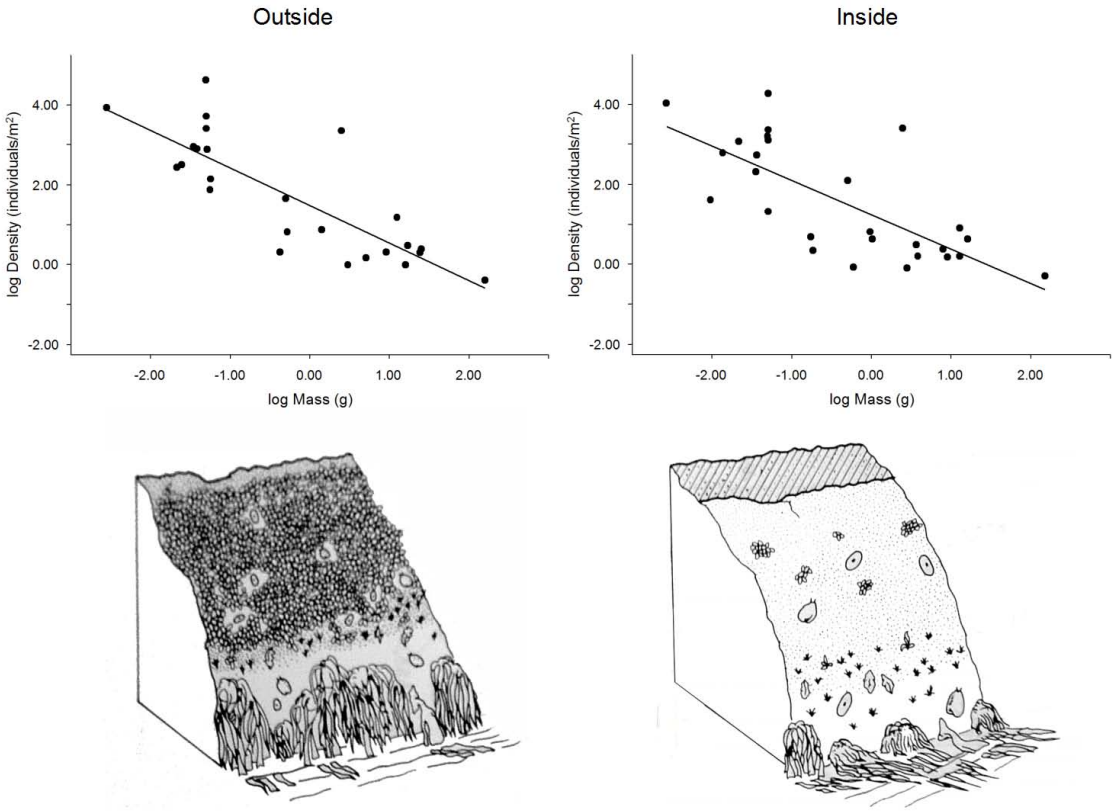
W. K. W. Li

NATURE | VOL 419 | 12 SEPTEMBER 2002 |

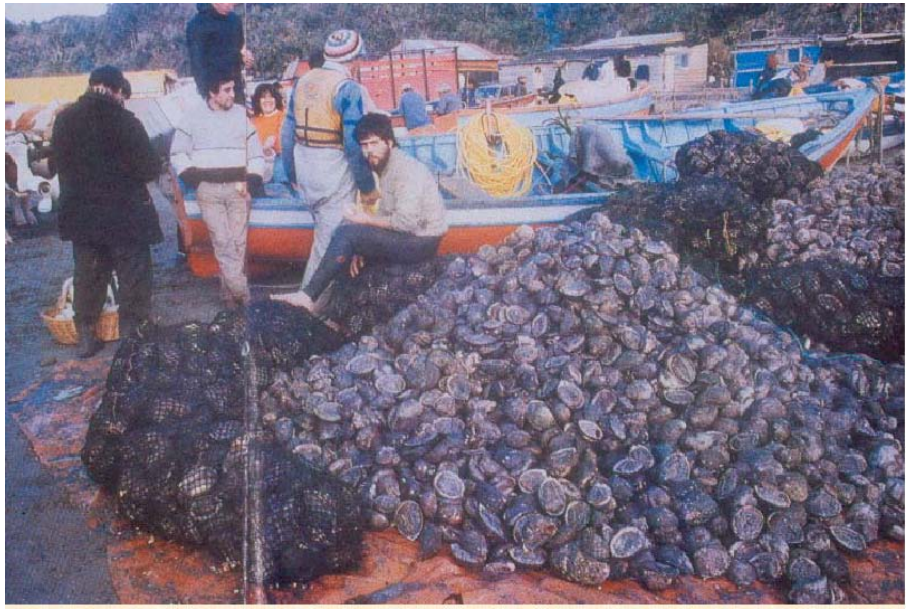
There are several remarkable aspects to this scaling relationship:

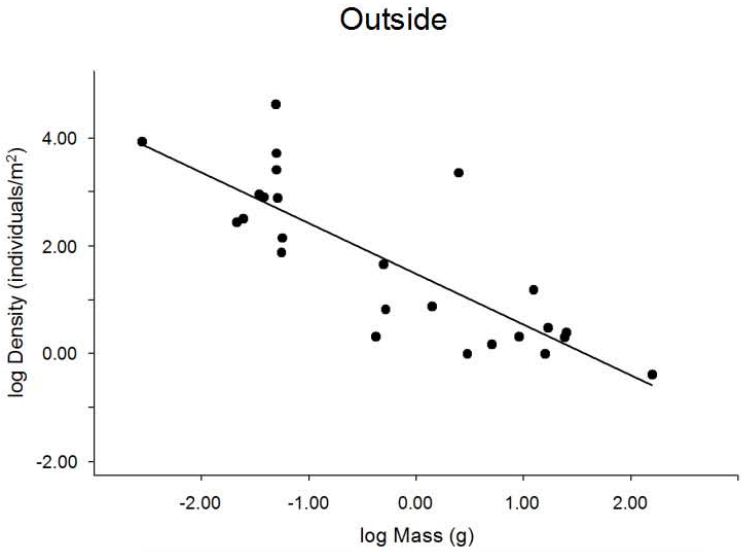
- It is invariant across time and space.

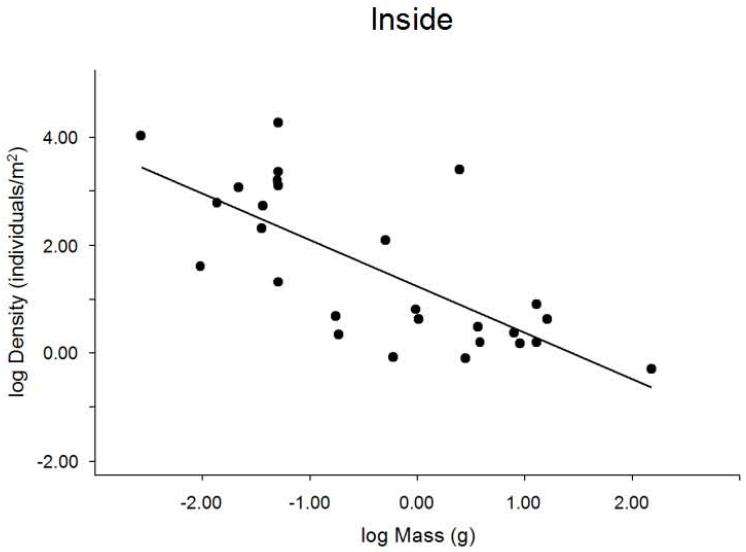


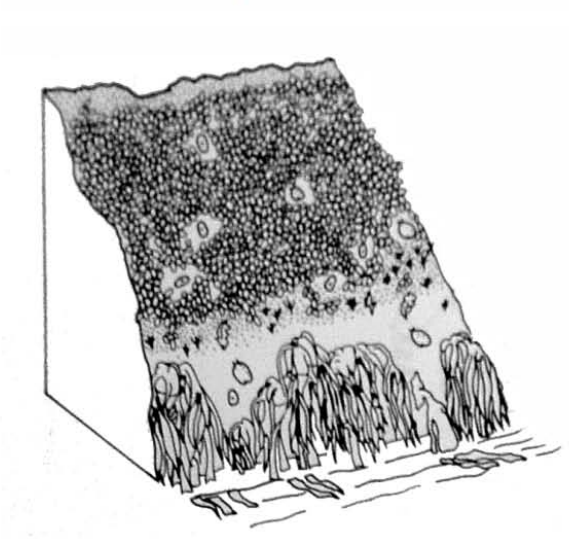


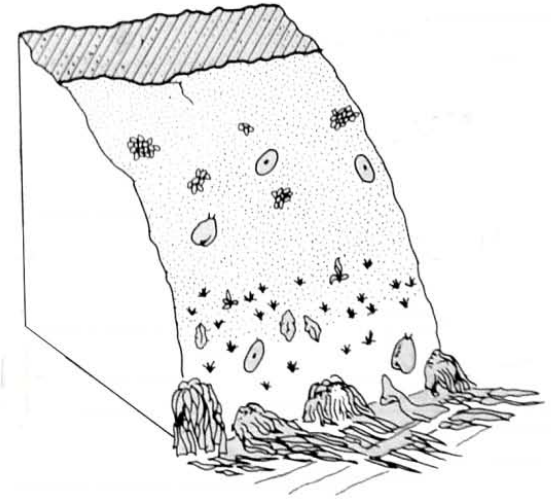
Marquet, Navarrete & Castilla (1990)



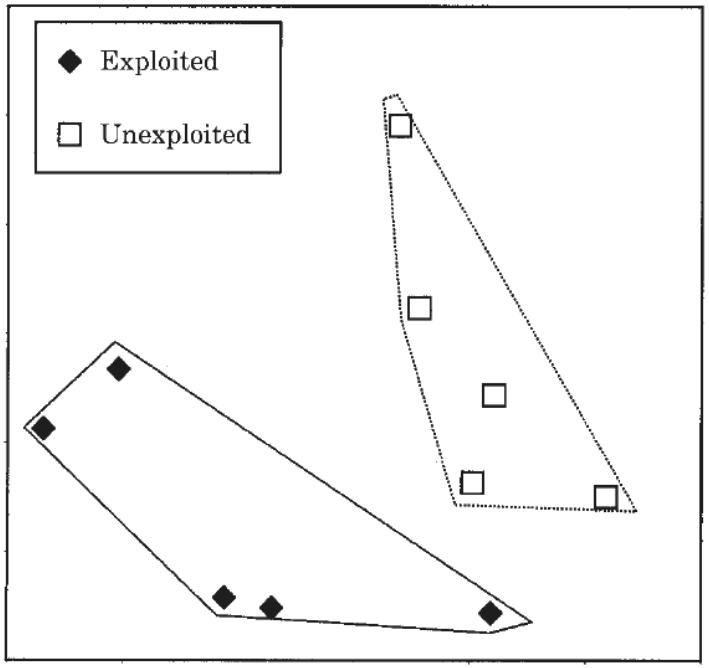


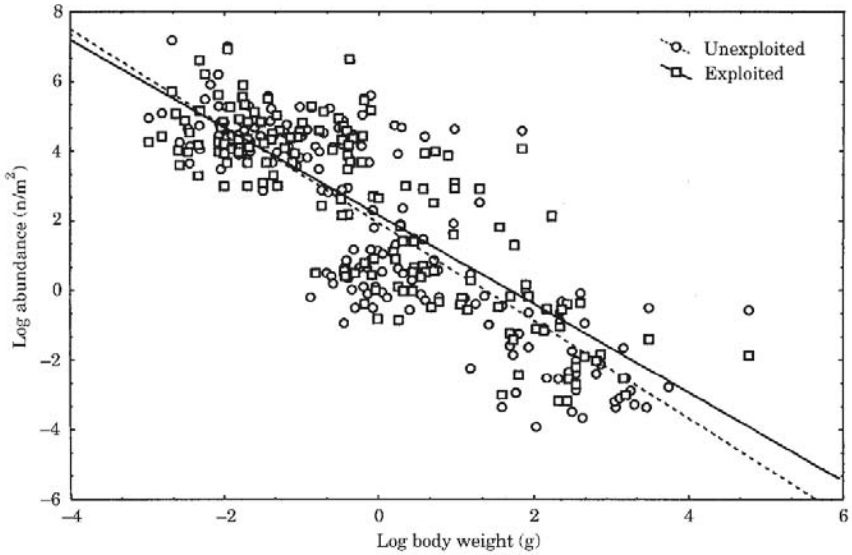






Marquet, Navarrete & Castilla (1990)





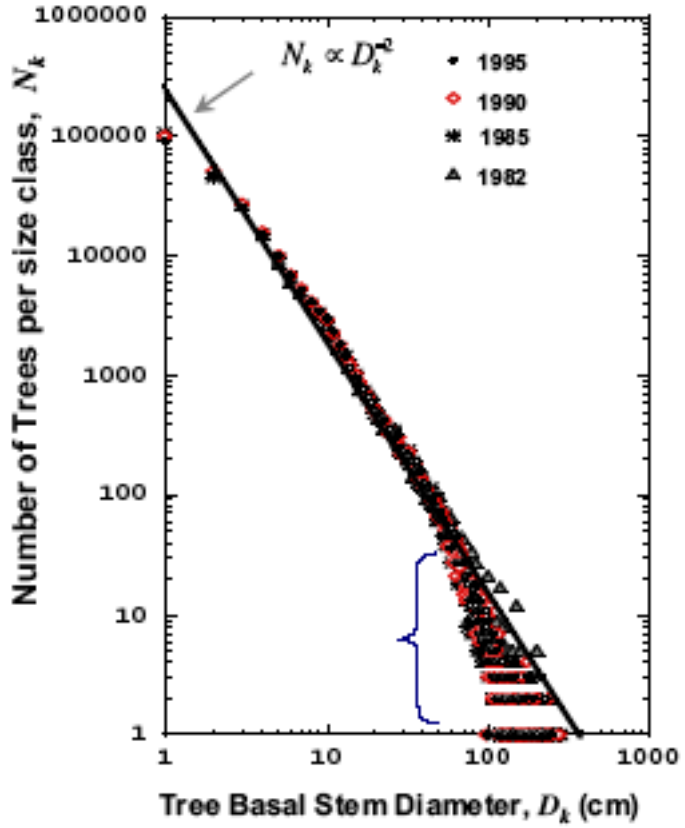
ICES Journal of Marine Science, 59: 1237–1247. 2002
doi:10.1006/jmsc.2002.1287, available online at http://www.idealibrary.com on IDEAL®

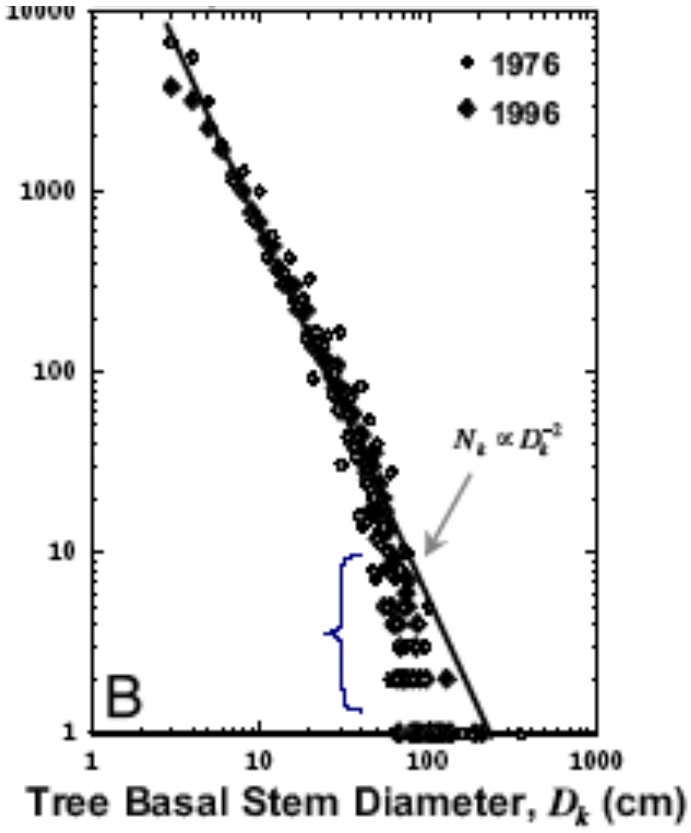
The community structure of a tropical intertidal mudflat under human exploitation

W. F. de Boer and H. H. T. Prins

BCI

San Emilio (Guanacaste, Costa Rica)

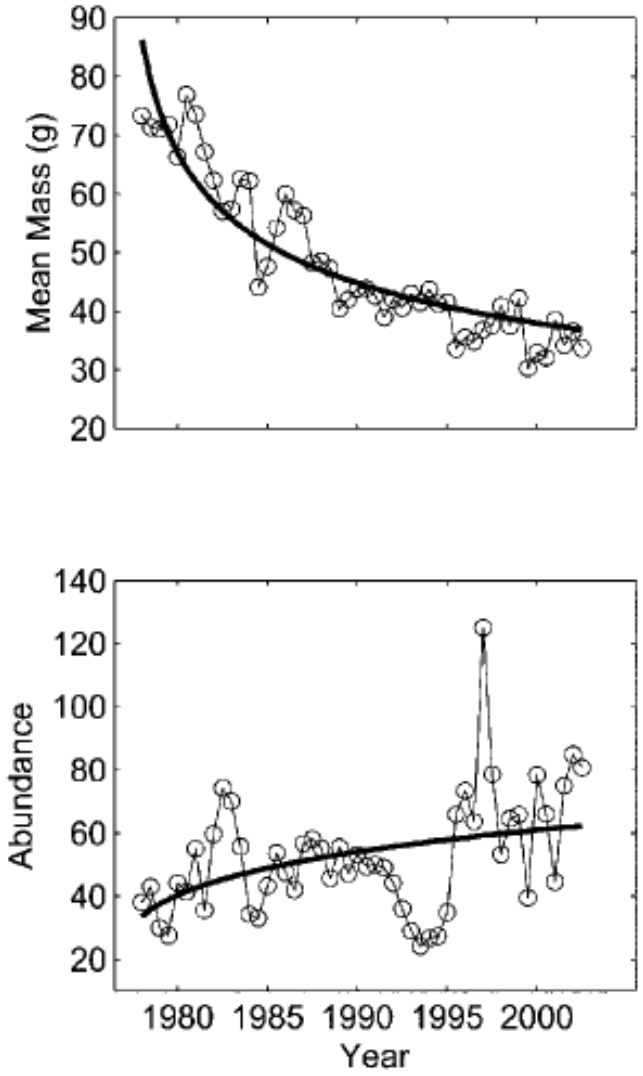


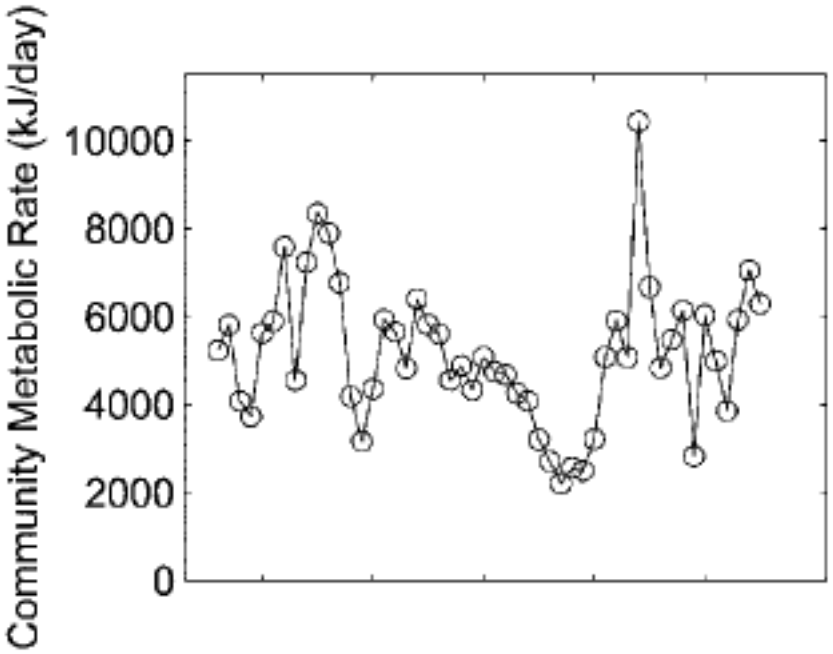


Enquist et al. 2009

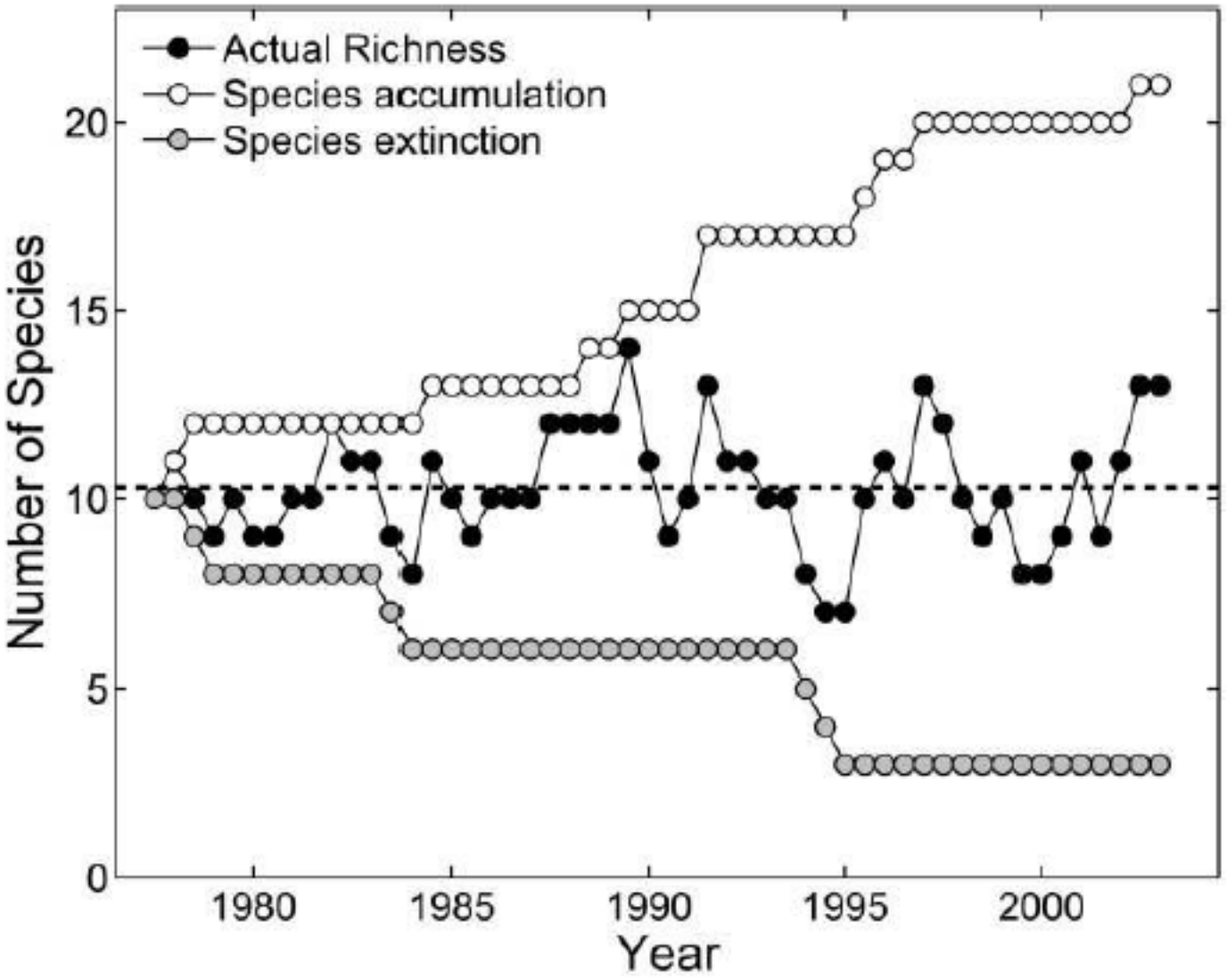
1978-2002

Total energy use is invariant in time (energetic constraint)





White et al. 2004

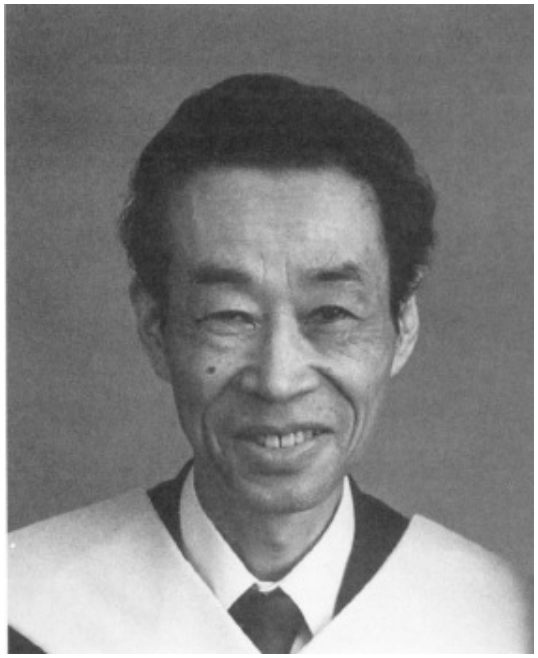


Ernest et al. 2008

The zero-sum Red queen hypothesis entails the existence of interacting assemblages wherein the amount of energy captured by one species is balanced by equal losses of some other members of the assemblage.

Neutral Theory of Biodiversity

Stephen P. Hubbell (1942-



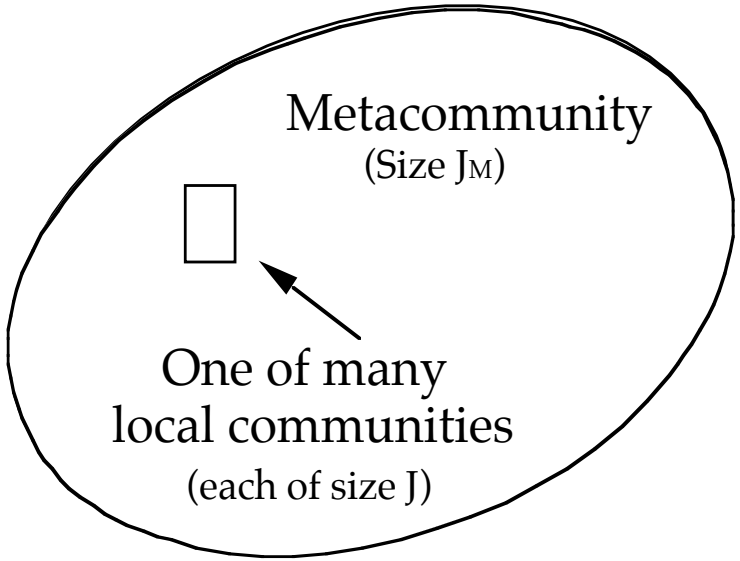
Motoo Kimura (1924-1994)

The Unified Neutral Theory of BIODIVERSITY AND BIOGEOGRAPHY

STEPHEN P. HUBBELL

MONOGRAPHS IN POPULATION BIOLOGY • 32

Classic Neutral Theory in a nutshell



J = Local community size

J_M = Metacommunity size

m = migration rate

ν = speciation rate

$$\frac{dp_{n,k}(t)}{dt} = p_{n+1,k}(t)d_{n+1,k} + p_{n-1,k}(t)b_{n-1,k} - p_{n,k}(t)(b_{n,k} + d_{n,k}) \quad (1)$$

which leads to the steady-state or equilibrium solution, denoted by P:

$$P_{n,k} = P_{0,k}\prod_{i=0}^{n-1}\frac{b_{i,k}}{d_{i+1,k}} \quad (2)$$

Assumptions:

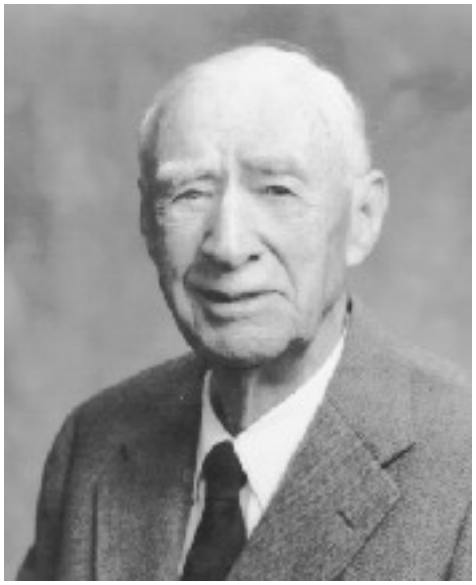
i) The species are assumed to be demographically identical, i.e. $b_{n,k} = b_n$ and $d_{n,k} = d_n$.
ii) Density independent case, i.e. $b_n = b * n$ and $d_n = d * n$ $(n > 0)$

$$< \Phi_n >= \theta \frac{x^n}{n}$$

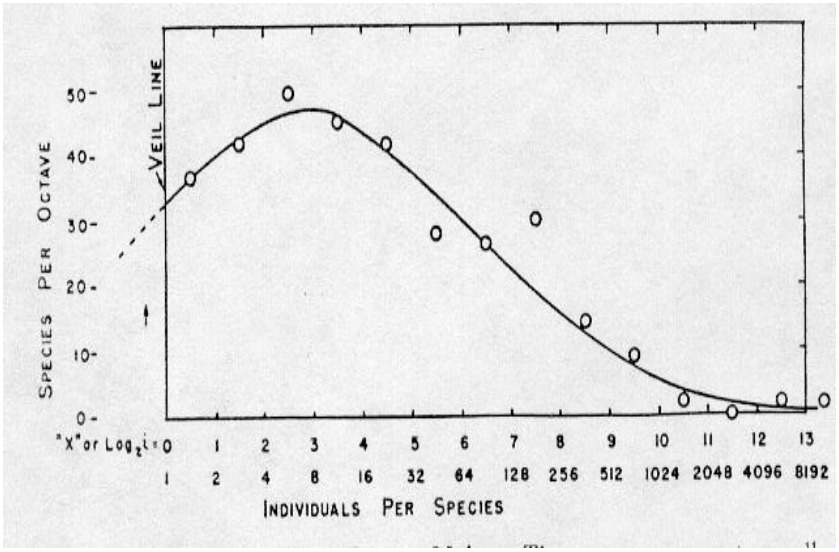
where $x = b/d$ and $\theta = SP_0\nu/d$ biodiversity parameter.

$$\langle \phi_n \rangle = \theta \frac{J!}{n!(J-n)!} \frac{\Gamma(\gamma)}{\Gamma(J+\gamma)} \int_0^{\gamma} \frac{\Gamma(n+y)}{\Gamma(1+y)} \frac{\Gamma(J-n+\gamma-y)}{\Gamma(\gamma-y)} \exp(-y\theta/\gamma) dy \tag{7}$$

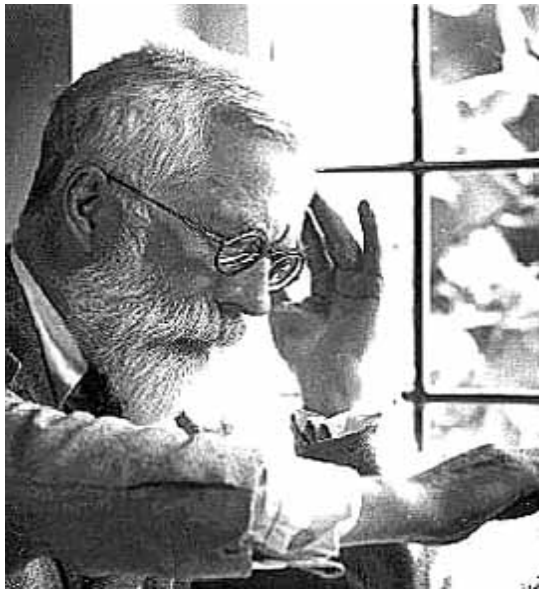
Frank William Preston (1889-1989)



Born in Leicester, England, on May 14, 1896.



Sir Ronald Aylmer Fisher (1890-1962)



Born in London, England, on February 17 Feb, 1890.

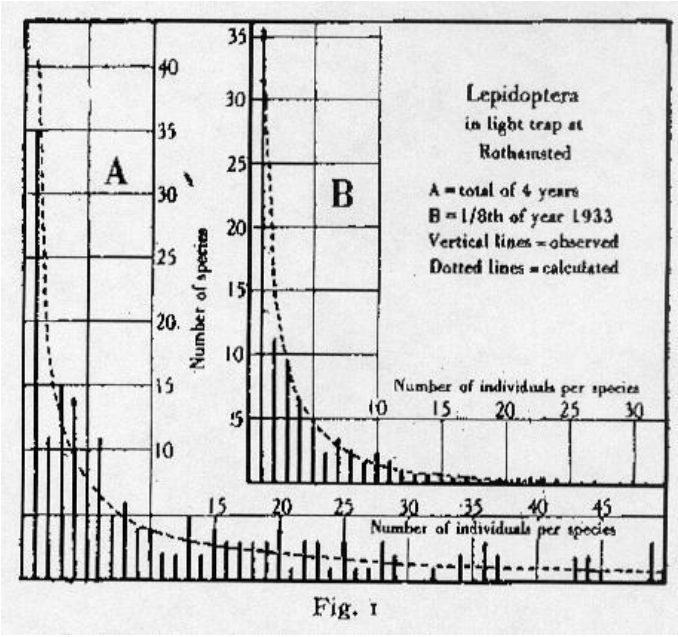
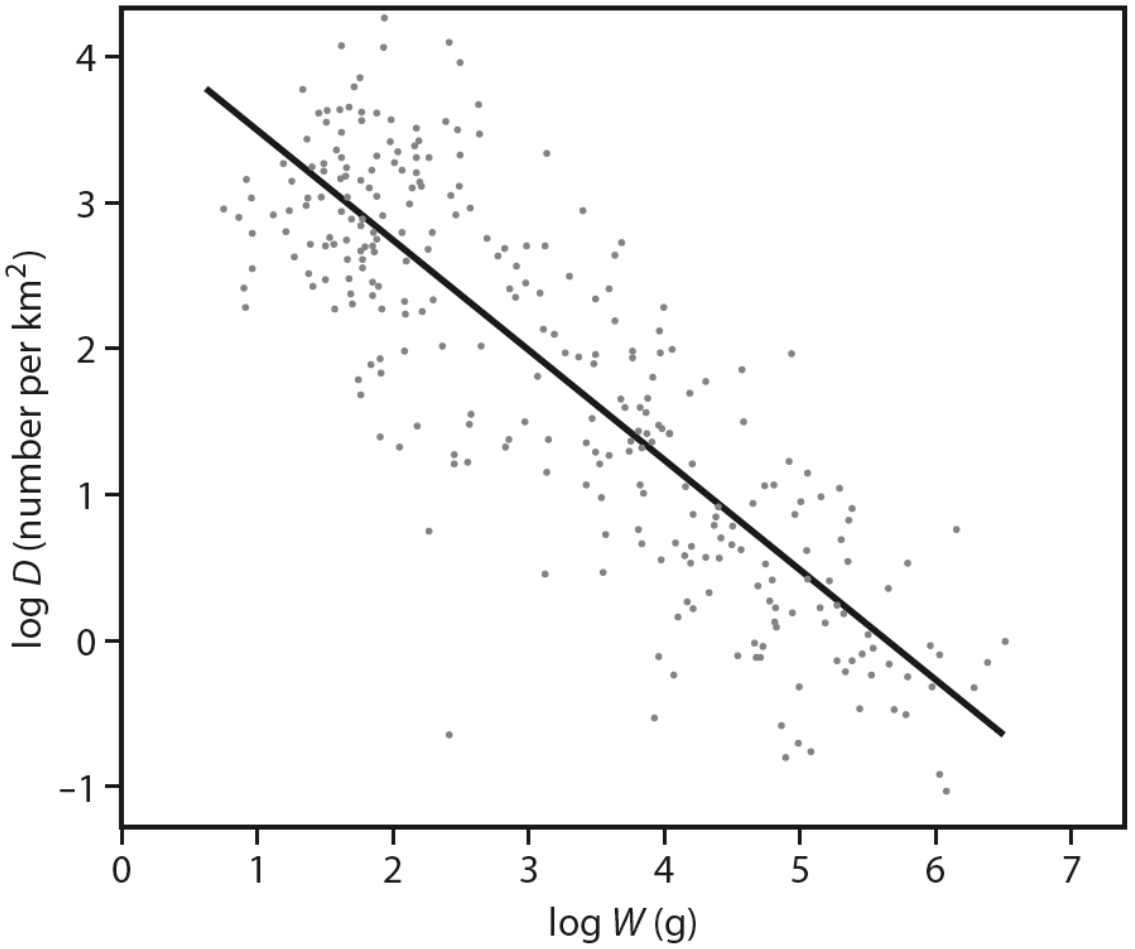
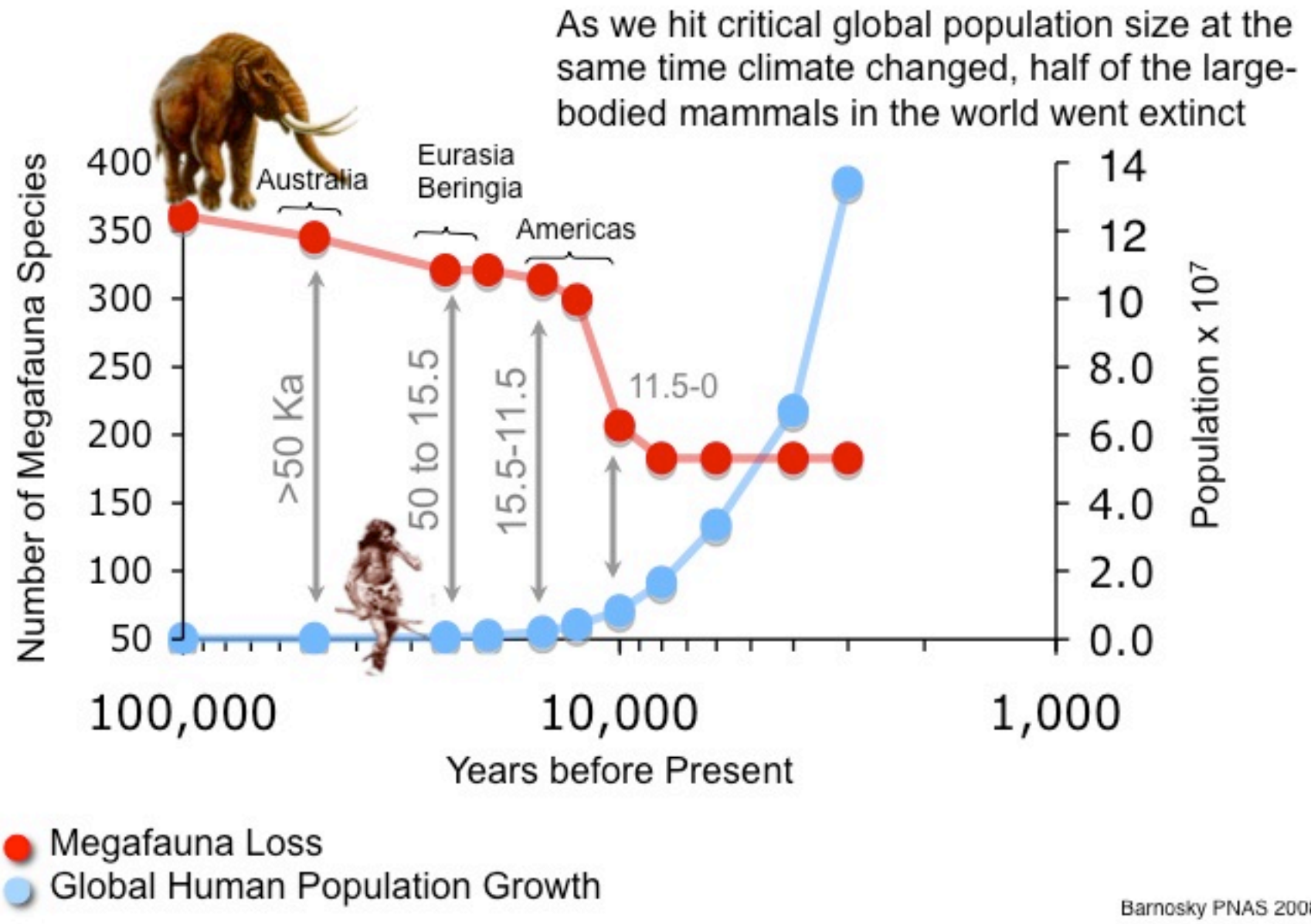


Fig. 1

Part 2

- From the Big Biotic Bang (B^3) to the age of global change


log D (number per km²)
log W (g)
0
1
2
3
4
5
6
7
−1
0
1
2
3
4


As we hit critical global population size at the same time climate changed, half of the large-bodied mammals in the world went extinct
Number of Megafauna Species
400
350
300
250
200
150
100
50
Australia
Eurasia
Beringia
Americas
>50 Ka
50 to 15.5
15.5-11.5
11.5-0
14
12
10
8.0
6.0
4.0
2.0
0.0
Population x 10^7
100,000
10,000
1,000
Years before Present
Megafauna Loss
Global Human Population Growth
Barnosky PNAS 2008]

Barnosky (2008)

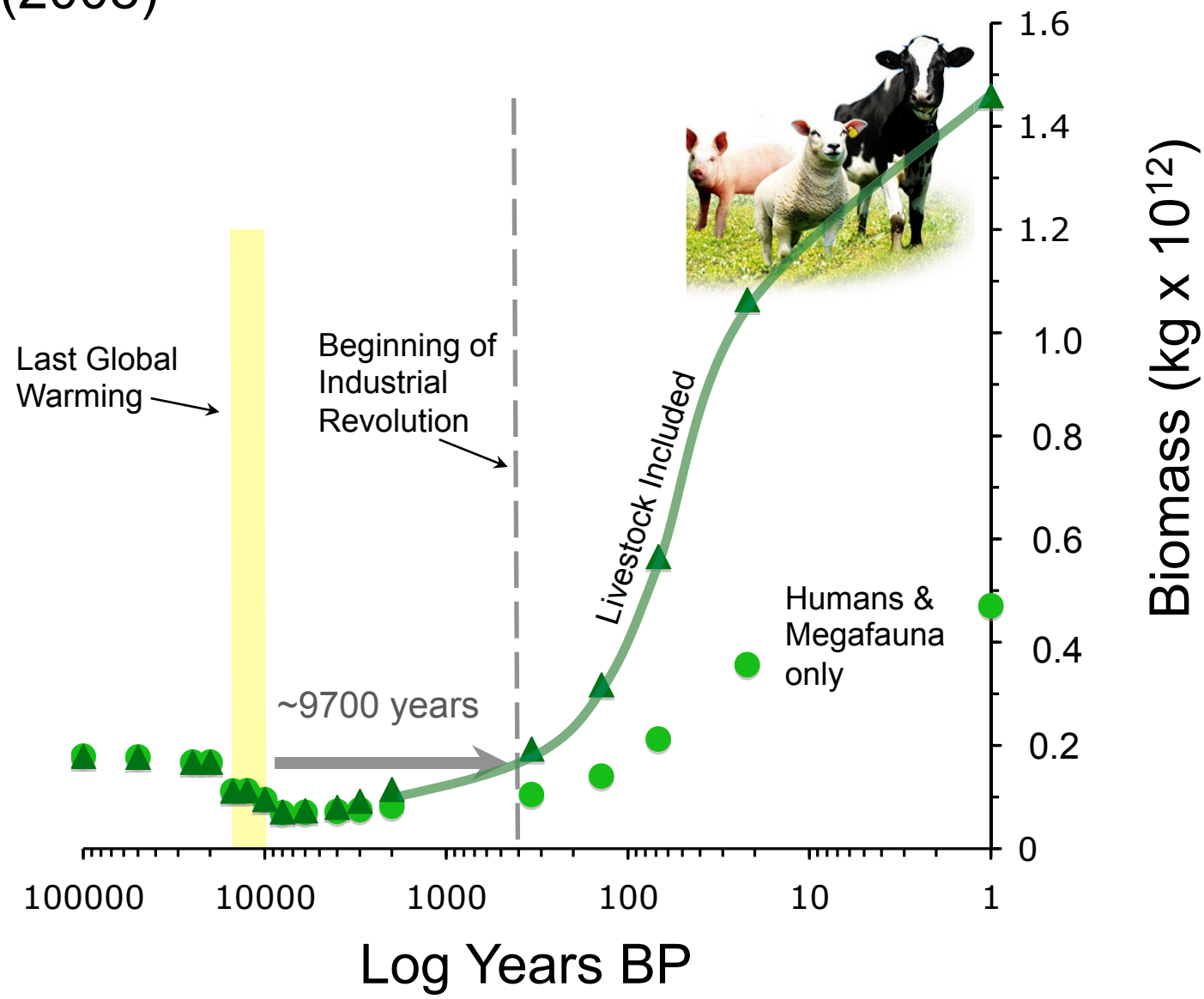
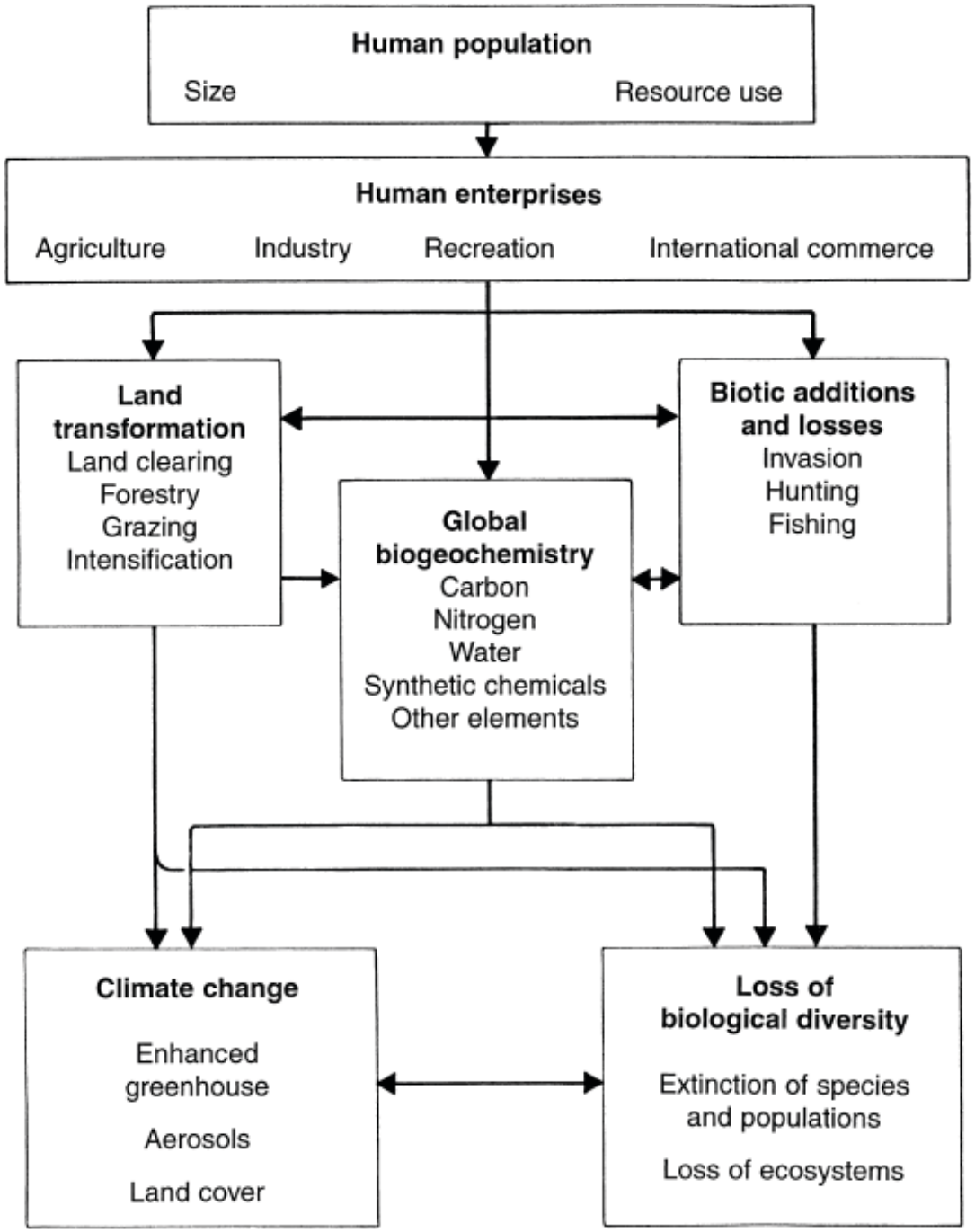
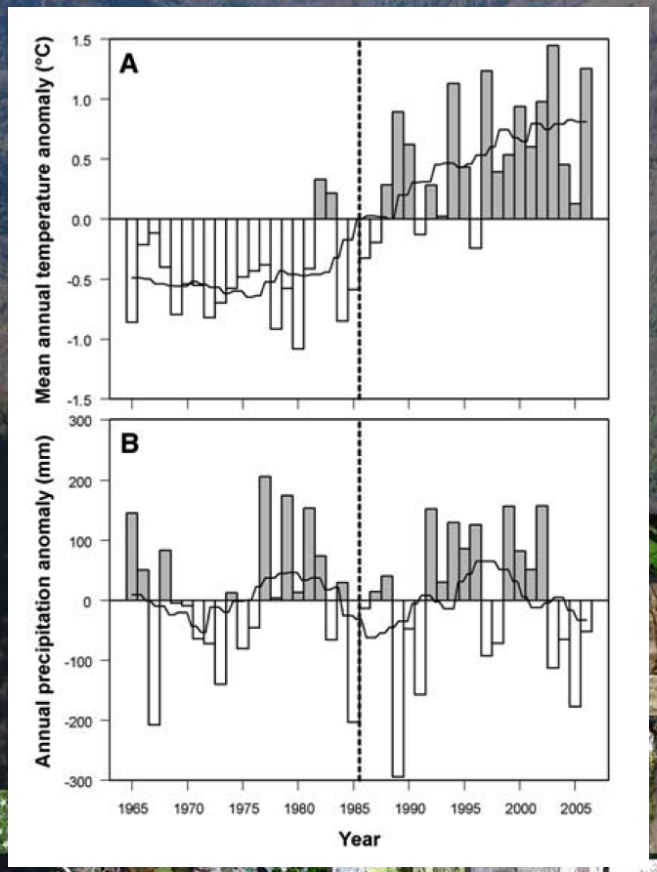
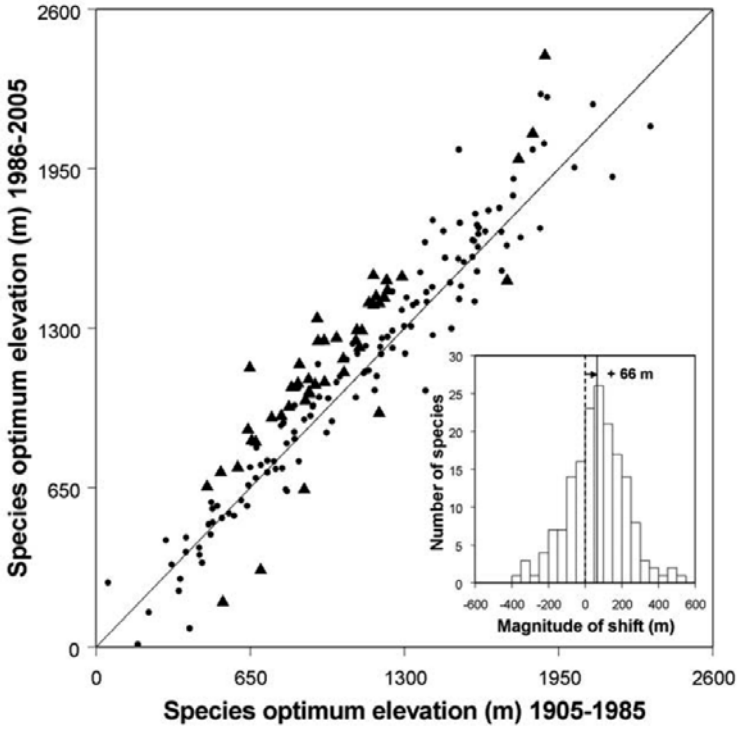


Fig. 1. A conceptual model illustrating humanity's direct and indirect effects on the Earth system [modified from (*56*)].



Movement of the altitudinal range of plants in Europe





Lenoir et al (2008)

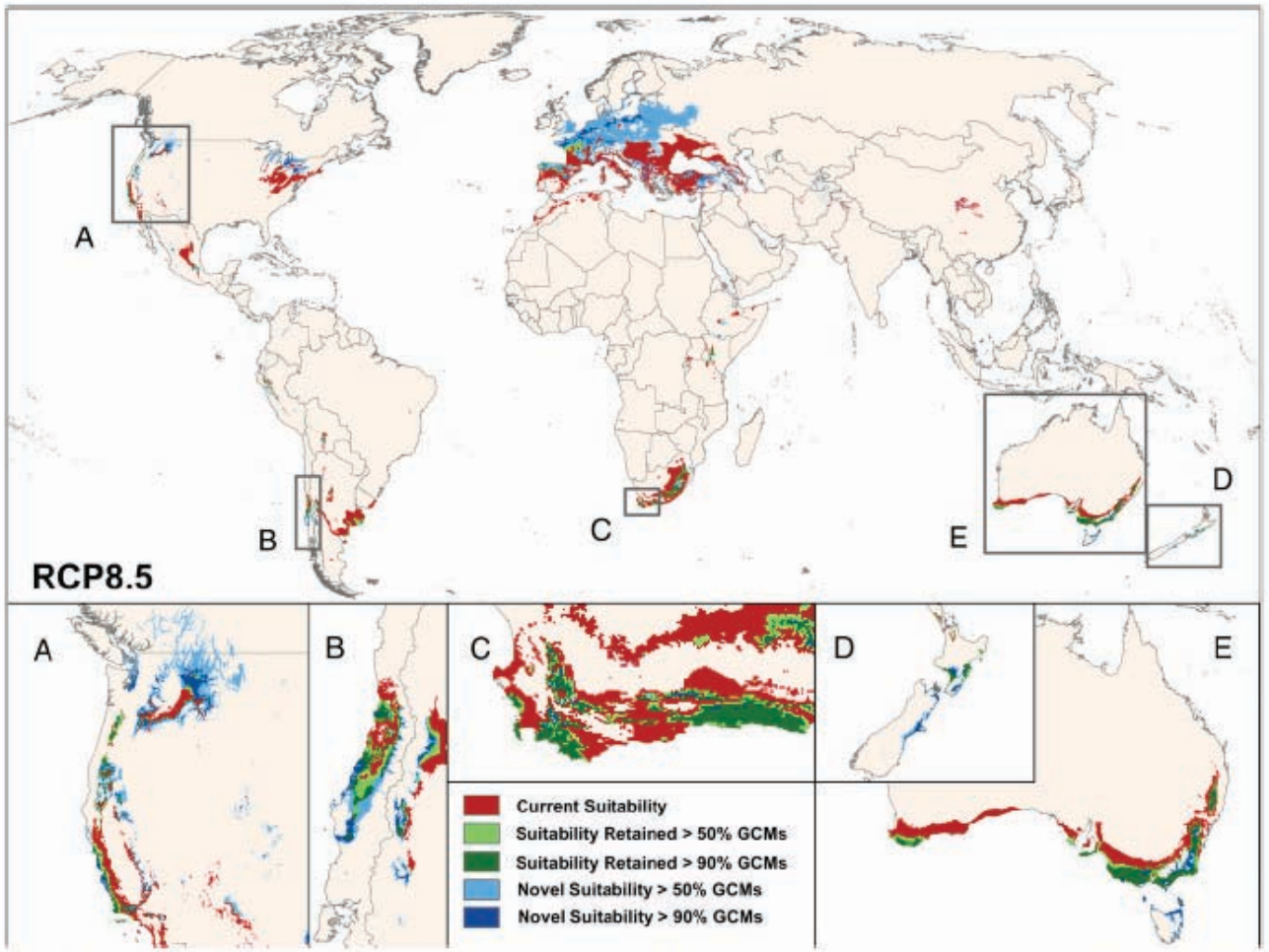
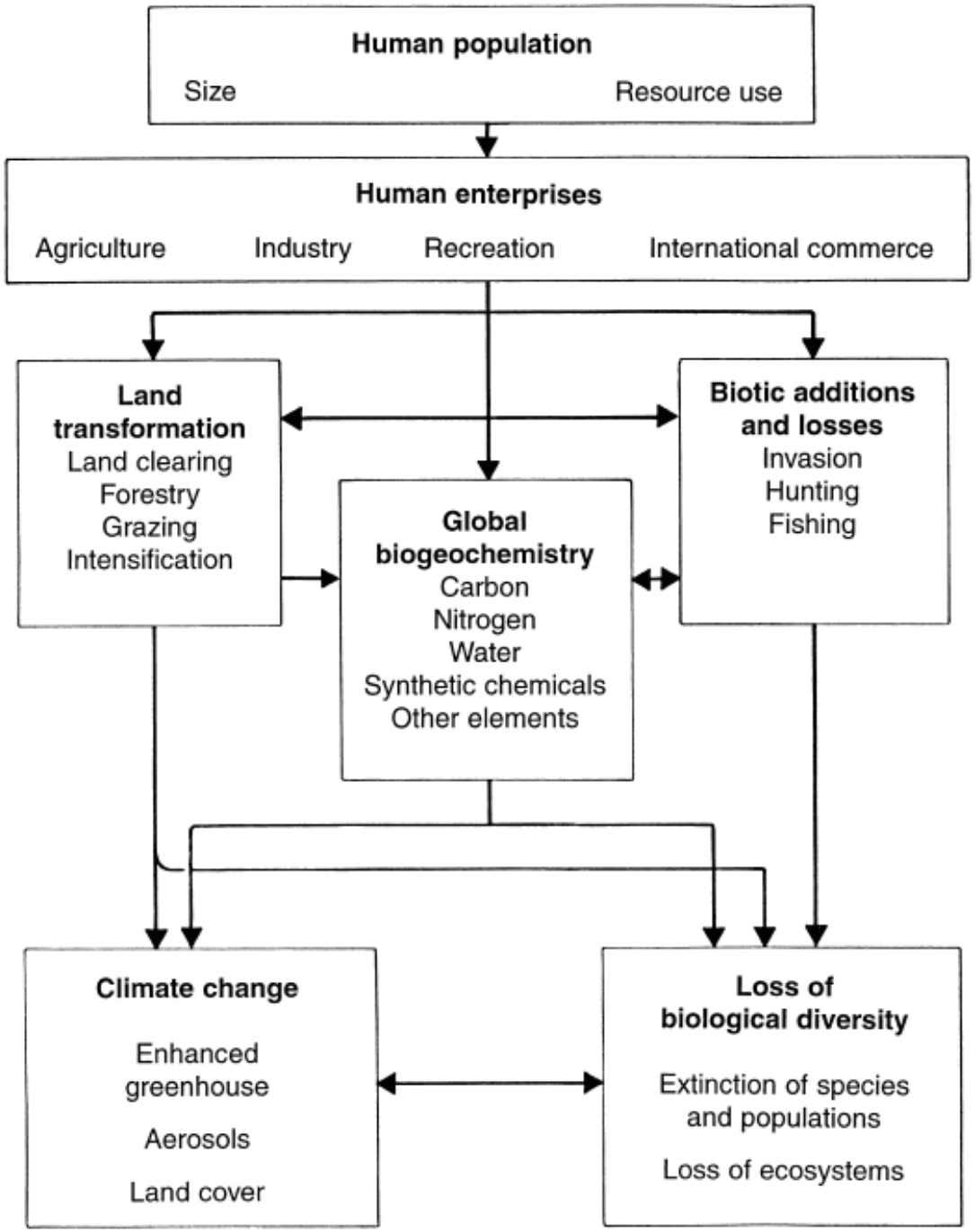


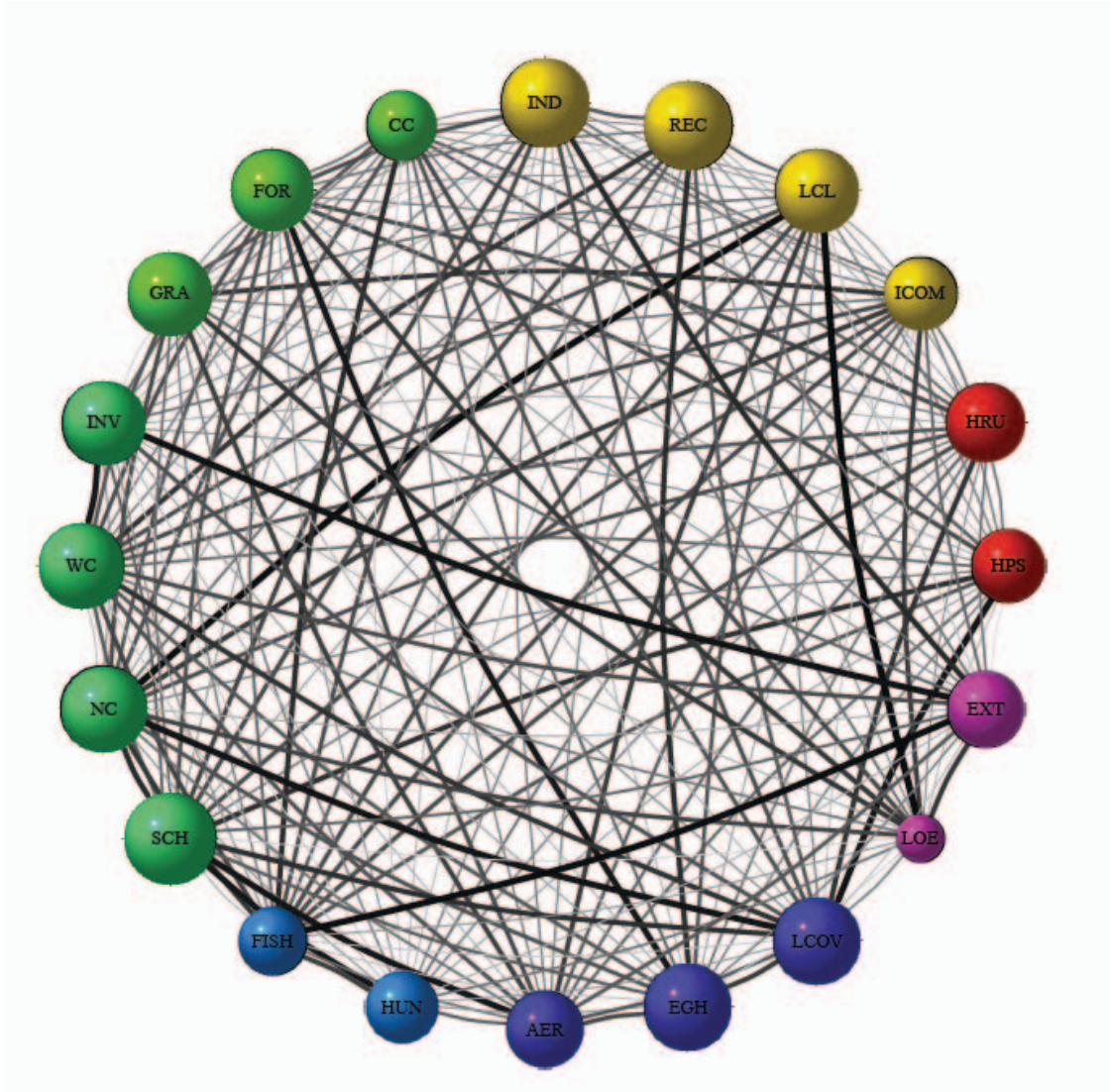
Fig. 1. Global change in viticulture suitability RCP 8.5. Change in viticulture suitability is shown between current (1961–2000) and 2050 (2041–2060) time periods, showing agreement among a 17-GCM ensemble. Areas with current suitability that decreases by midcentury are indicated in red (>50% GCM agreement). Areas with current suitability that is retained are indicated in light green (>50% GCM agreement) and dark green (>90% GCM agreement), whereas areas not suitable in the current time period but suitable in the future are shown in light blue (>50% GCM agreement) and dark blue (>90% GCM agreement). *Insets:* Greater detail for major wine-growing regions: California/western North America (*A*), Chile (*B*), Cape of South Africa (*C*), New Zealand (*D*),

Climate change, wine, and conservation

Lee Hannah[a,b,1], Patrick R. Roehrdanz[b], Makihiko Ikegami[b], Anderson V. Shepard[b,2], M. Rebecca Shaw[c], Gary Tabor[d], Lu Zhi[e], Pablo A. Marquet[f,g,h,i], and Robert J. Hijmans[j]

Fig. 1. A conceptual model illustrating humanity's direct and indirect effects on the Earth system [modified from (*56*)].




IND
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FISH
LCOV
HUN
AER
EGH

REVIEW

doi:10.1038/nature11018

Approaching a state shift in Earth's biosphere

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Localized ecological systems are known to shift abruptly and irreversibly from one state to another when they are forced across critical thresholds. Here we review evidence that the global ecosystem as a whole can react in the same way and is approaching a planetary-scale critical transition as a result of human influence. The plausibility of a planetary-scale 'tipping point' highlights the need to improve biological forecasting by detecting early warning signs of critical transitions on global as well as local scales, and by detecting feedbacks that promote such transitions. It is also necessary to address root causes of how humans are forcing biological changes.

Humans now dominate Earth, changing it in ways that threaten its ability to sustain us and other species[1–3]. This realization has led to a growing interest in forecasting biological responses on all scales from local to global[4–7].

However, most biological forecasting now depends on projecting recent trends into the future assuming various environmental pressures[5], or on using species distribution models to predict how climatic changes may alter presently observed geographic ranges[8,9]. Present work recognizes that relying solely on such approaches will be insufficient to characterize fully the range of likely biological changes in the future, especially because complex interactions, feedbacks and their hard-to-predict effects are not taken into account[6,8–11].

Particularly important are recent demonstrations that 'critical transitions' caused by threshold effects are likely[12]. Critical transitions lead to state shifts, which abruptly override trends and produce unanticipated ic effects. Although most previous work on threshold-induced state has been theoretical or concerned with critical transitions in ed ecological systems over short time spans[12–14], planetary-scale transitions that operate over centuries or millennia have also ulated[3,12,15–18]. Here we summarize evidence that such planetary- l transitions have occurred previously in the biosphere, albeit d that humans are now forcing another such transition, with the ntial to transform Earth rapidly and irreversibly into a state unknown in human experience.

Two conclusions emerge. First, to minimize biological surprises that would adversely impact humanity, it is essential to improve biological forecasting by anticipating critical transitions that can emerge on a planetary scale and understanding how such global forcings cause local changes. Second, as was also concluded in previous work, to prevent a global-scale state shift, or at least to guide it as best we can, it will be necessary to address the root causes of human-driven global change and to improve our management of biodiversity and ecosystem services[3,15–17,19].

Basics of state shift theory

It is now well documented that biological systems on many scales can shift rapidly from an existing state to a radically different state[12]. Biological 'states' are neither steady nor in equilibrium; rather, they are characterized by a defined range of deviations from a mean condition over a prescribed period of time. The shift from one state to another can be caused by either a 'threshold' or 'sledgehammer' effect. State shifts resulting from threshold effects can be difficult to anticipate, because the critical threshold is reached as incremental changes accumulate and the threshold value generally is not known in advance. By contrast, a state shift caused by a sledgehammer effect—for example the clearing of a forest using a bulldozer—comes as no surprise. In both cases, the state shift is relatively abrupt and leads to new mean conditions outside the range of fluctuation evident in the previous state.

Threshold-induced state shifts, or critical transitions, can result from 'fold bifurcations' and can show hysteresis[12]. The net effect is that once a critical transition occurs, it is extremely difficult or even impossible for the system to return to its previous state. Critical transitions can also result from more complex bifurcations, which have a different character from fold bifurcations but which also lead to irreversible changes[20].

Recent theoretical work suggests that state shifts due to fold bifurcations are probably preceded by general phenomena that can be characterized mathematically: a deceleration in recovery from perturbations ('critical slowing down'), an increase in variance in the pattern of within-state fluctuations, an increase in autocorrelation between fluctuations, an increase in asymmetry of fluctuations and rapid back-and-forth shifts ('flickering') between states[12,14,18]. These phenomena can theoretically be

An international team of 22 biologists agree

Theoreticians Ecologists Paleontologists Population Biologists Modelers

Earth's life-support system

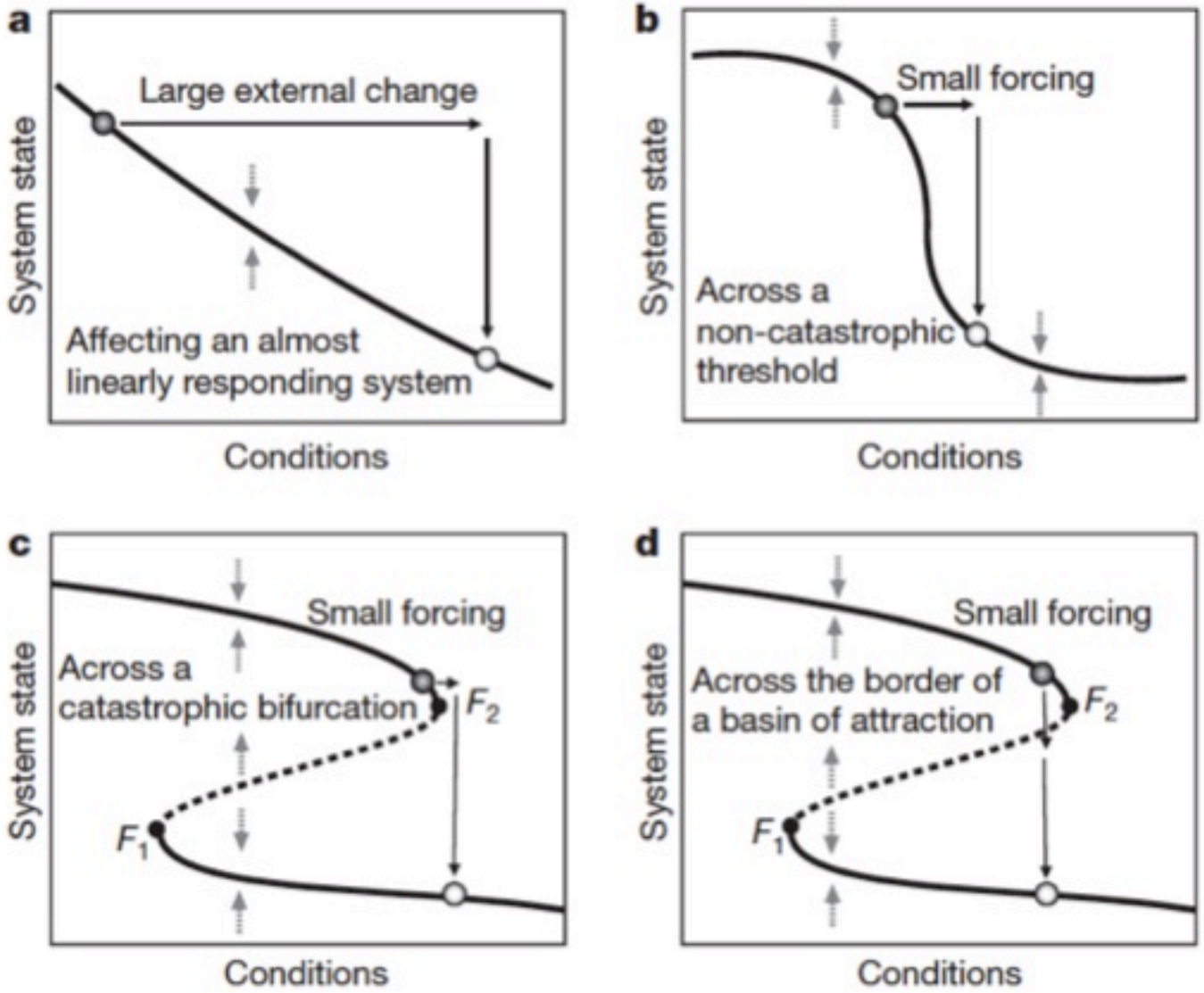
We are pushing the planet

Towards a Tipping Point

Illustration by Cheng (Lily Li) Stanford University

That will affect our lives

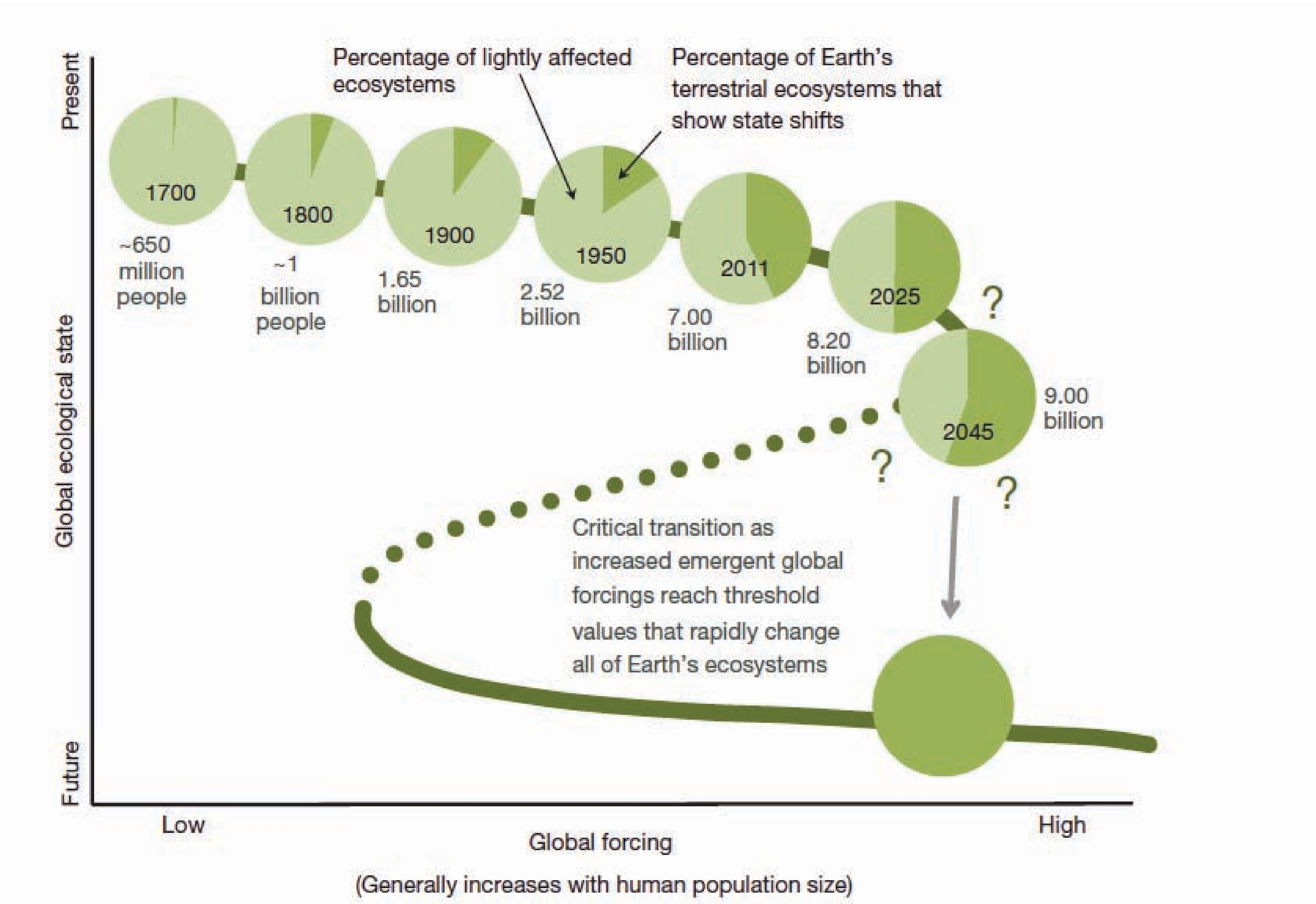
Tipping Points Mean Sudden Change



When a threshold is crossed, there's no going back.

The system moves to a new state.

Scheffer et al., 2009, Nature 461:53-59


Percentage of lightly affected ecosystems
Percentage of Earth's terrestrial ecosystems that show state shifts
1700
~650 million people
1800
~1 billion people
1900
1.65 billion
1950
2.52 billion
2011
7.00 billion
2025
8.20 billion
2045
9.00 billion
?
?
?
Critical transition as increased emergent global forcings reach threshold values that rapidly change all of Earth's ecosystems
Present
Global ecological state
Future
Low
High
Global forcing
(Generally increases with human population size)