Santa Fe Institute

CMM Centro de Modelamiento Matemático

INSTITUTO DE Sistemas Complejos DE VALPARAÍSO

Centro UC Cambio Global

Ecological challenges and opportunities

Pablo A. Marquet

Tara workshop, Valparíso, May 15-18, 2023

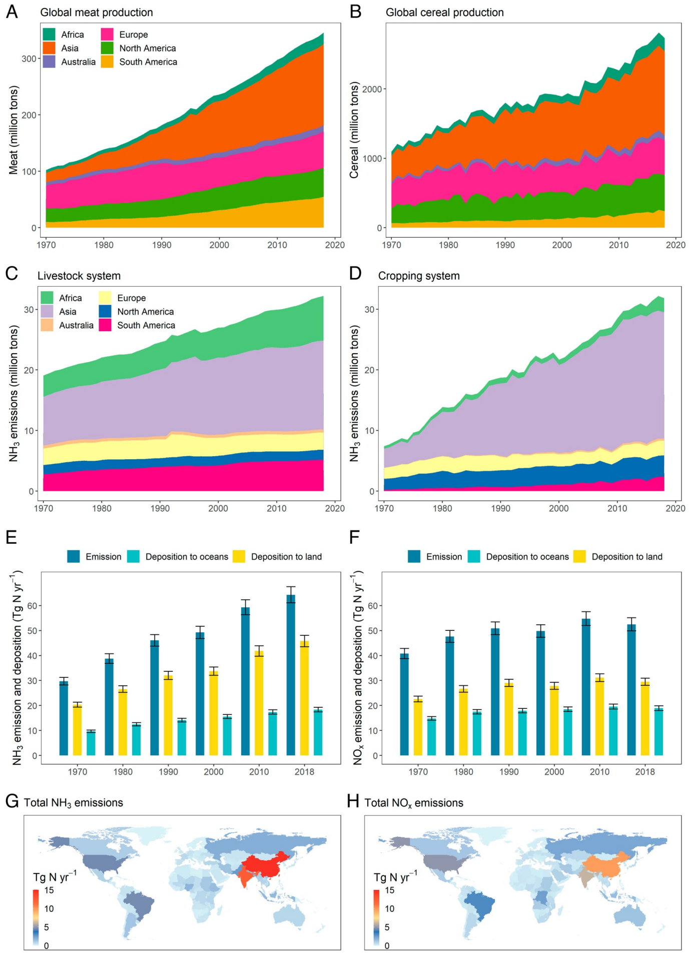
The most salient feature of life has been the stability of its bacterial mode from the beginning of the fossil record until today and, with little doubt, into all future time so long as the earth endures. This is truly the "age of bacteria"—as it was in the beginning is now and ever shall be.

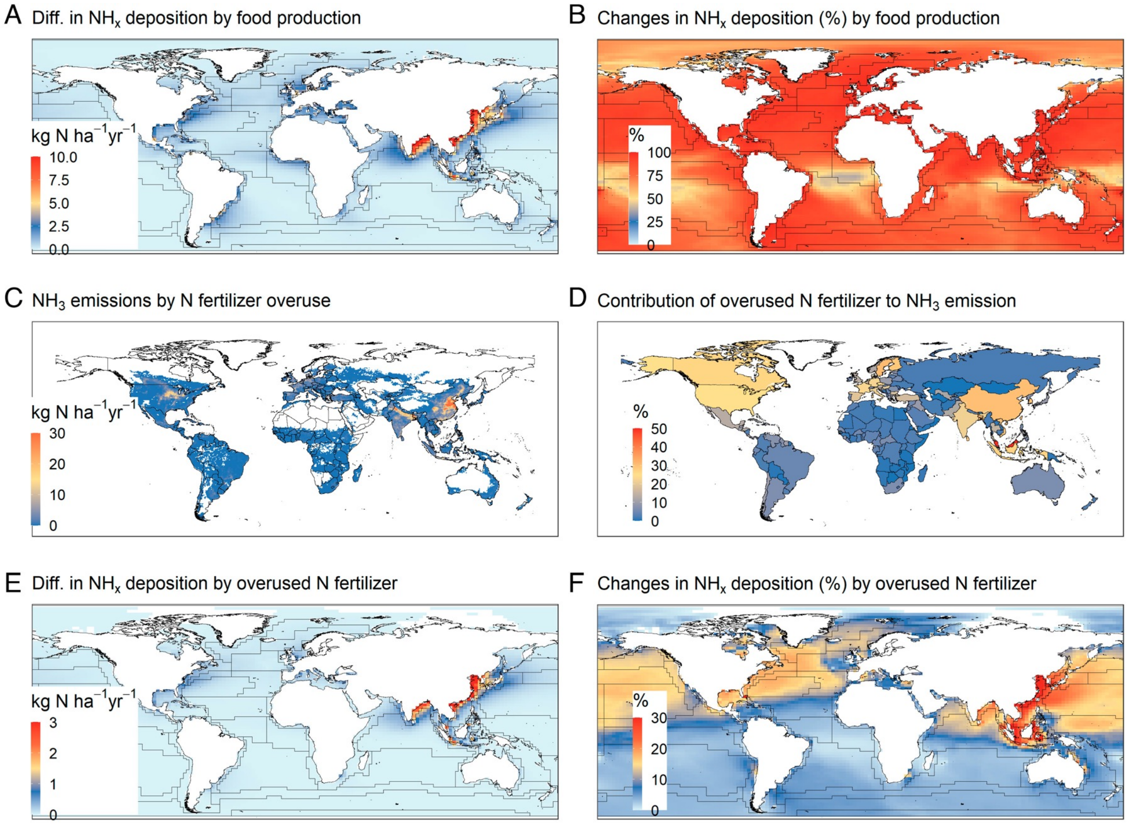
Stephen Jay Gould (1994)

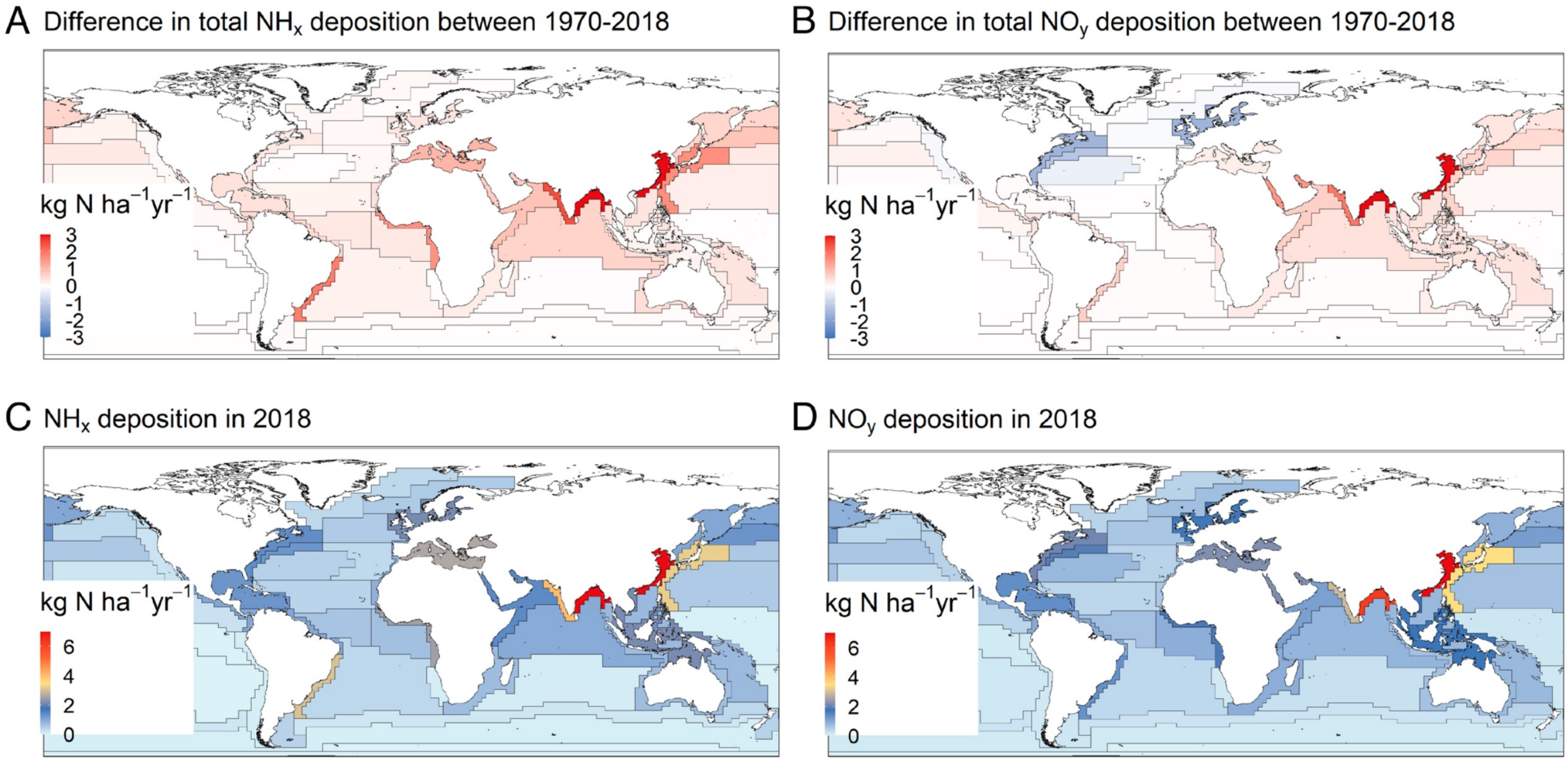
Border conditions…..

Nitrogen coming from the sky!!!

Ocean Nitrogen deposition







PNAS RESEARCH ARTICLE | SUSTAINABILITY SCIENCE

Modeling global oceanic nitrogen deposition from food systems and its mitigation potential by reducing overuse of fertilizers

Lei Liu[a,1], Wen Xu[b], Zhang Wen[b], Pu Liu[a], Hang Xu[a], Sheng Liu[a], Xiankai Lu[c], Buqing Zhong[c], Yixin Guo[d], Xiao Lu[e], Yuanhong Zhao[f], Xiuying Zhang[g], Songhan Wang[h], Peter M. Vitousek[i], and Xuejun Liu[b,1]

Edited by Stephen Carpenter, University of Wisconsin-Madison, Madison, WI; received January 9, 2023; accepted March 6, 2023

The Nitrogen cycle works different in polluted areas!!!

Published: 24 January 2002

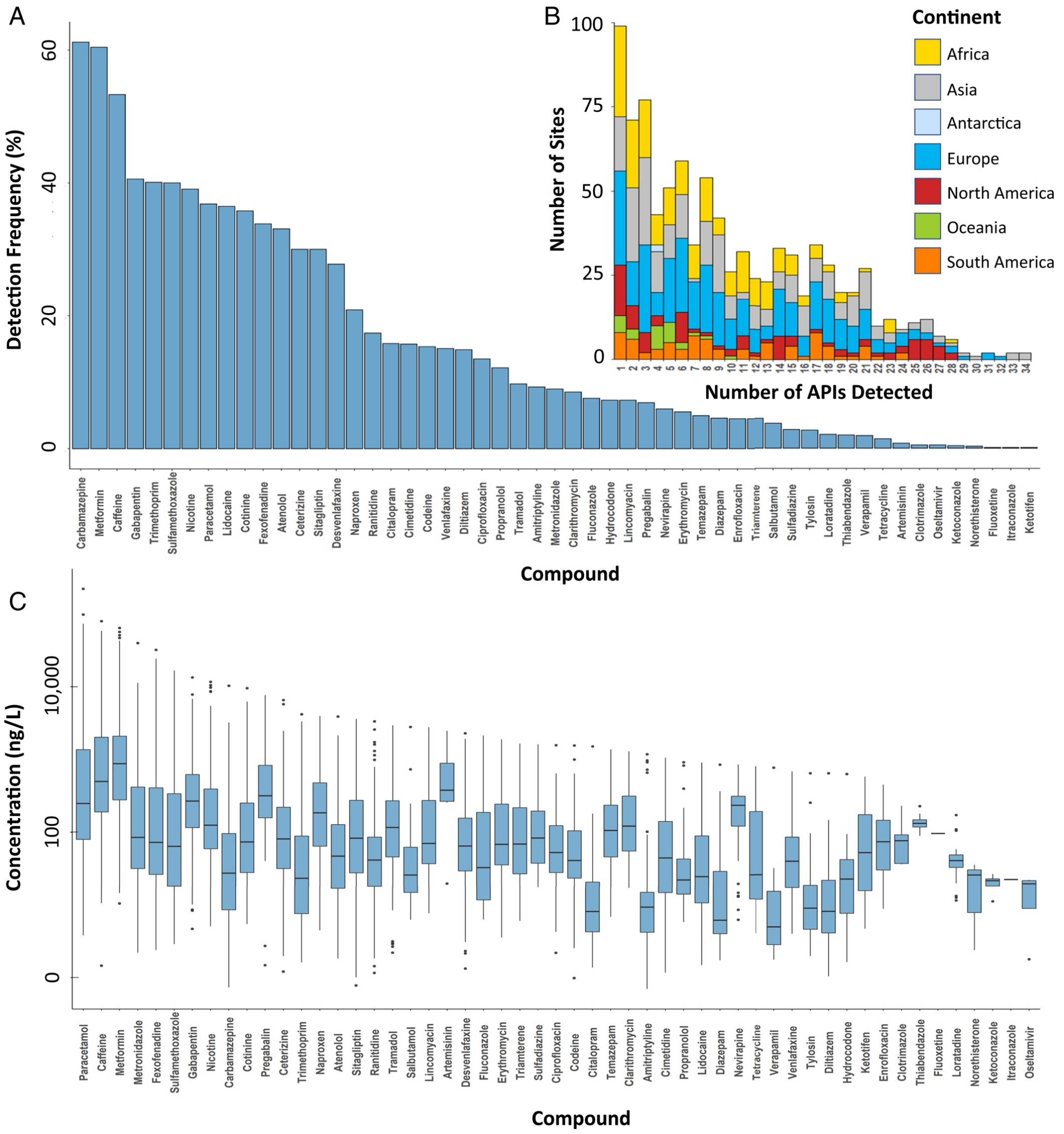
Nitrogen loss from unpolluted South American forests mainly via dissolved organic compounds

Steven S. Perakis & Lars O. Hedin

S@$%... coming from rivers

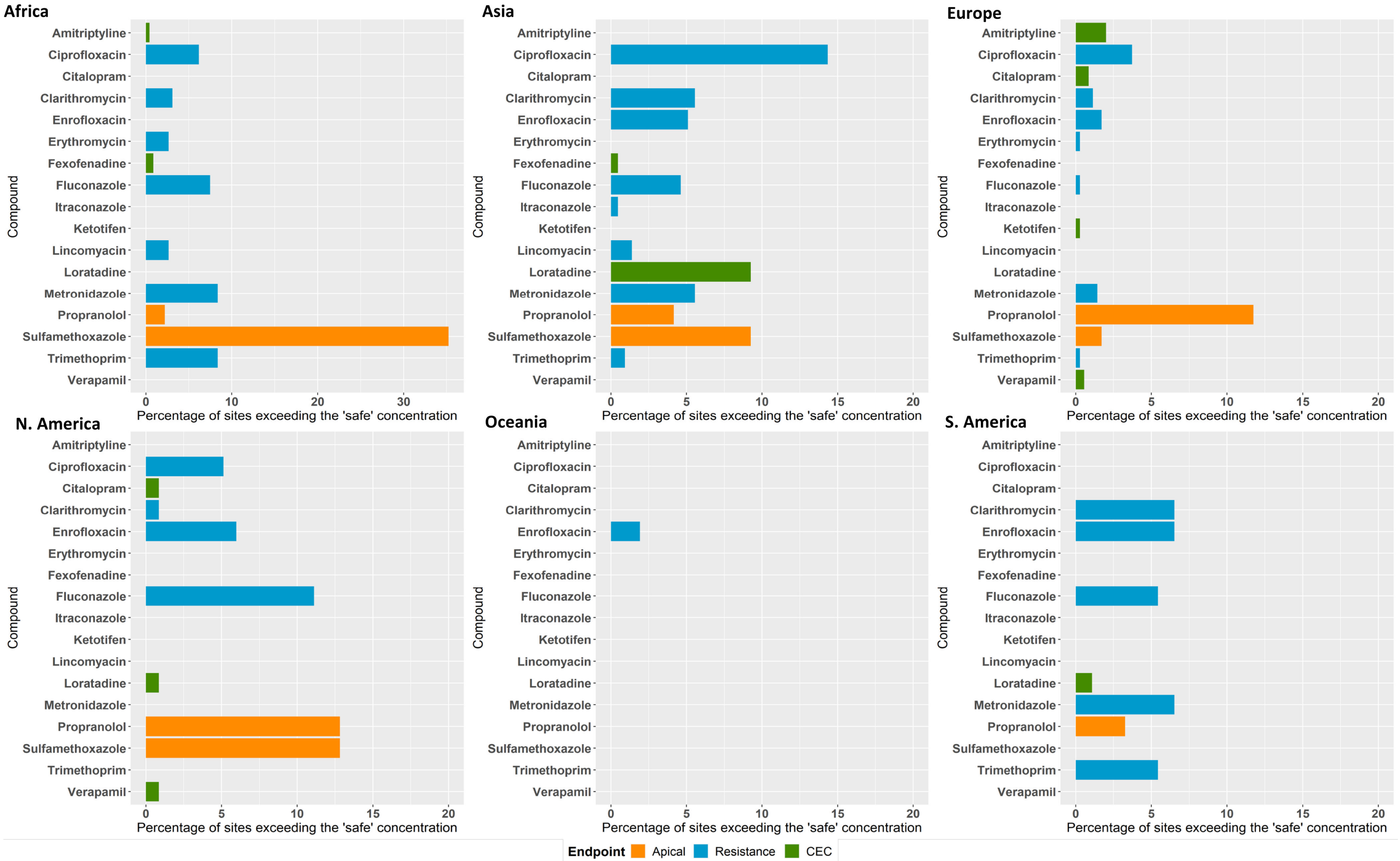
Pharmaceutical pollution of the world's rivers

John L. Wilkinson[a,1], Alistair B. A. Boxall[a], Dana W. Kolpin[b], Kenneth M. Y. Leung[c], Racliffe W. S. Lai[c],

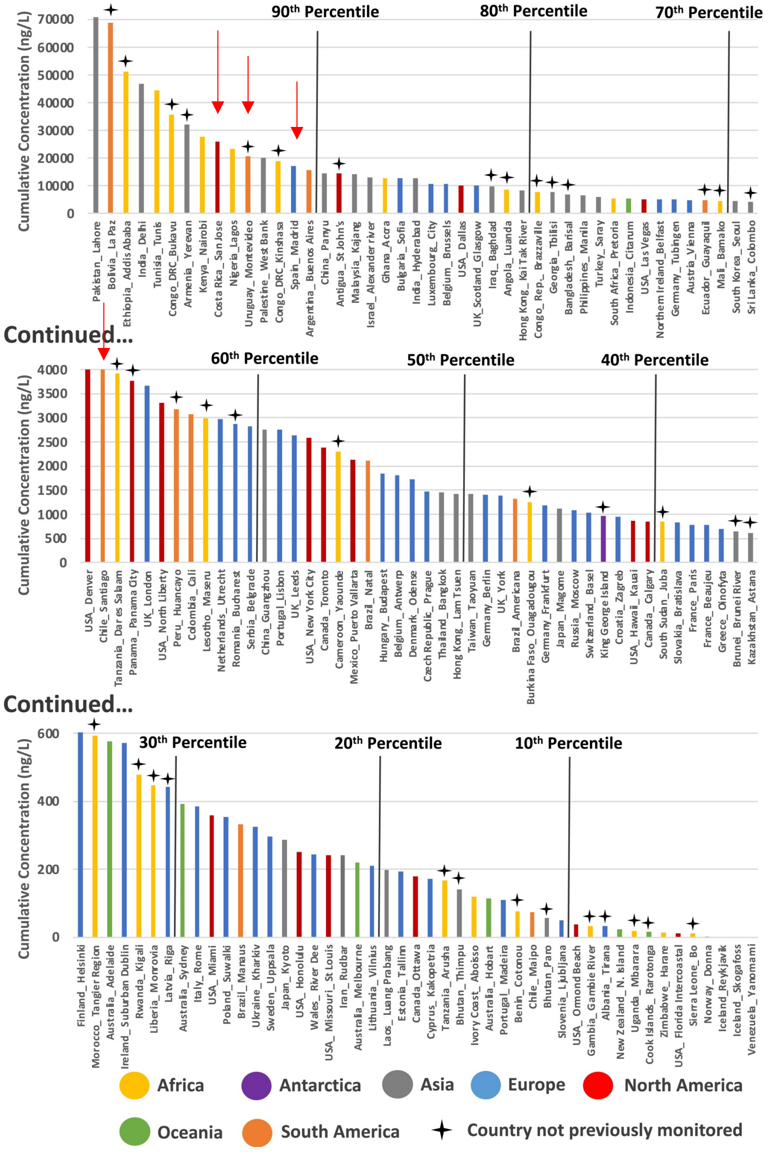


Glossary:

API = Active Pharmaceutical Ingredients



CEC= Critical Environmental Concentrations


Cumulative Concentration (ng/L)
70000
60000
50000
40000
30000
20000
10000
0
90th Percentile
80th Percentile
70th Percentile
Pakistan_ Lahore
Bolivia_ La Paz
Ethiopia_ Addis Ababa
India_ Delhi
Tunisia_ Tunis
Congo_DRC_Bukavu
Armenia_ Yerevan
Kenya_ Nairobi
Costa Rica_ San Jose
Nigeria_Lagos
Uruguay_ Montevideo
Palestine_ West Bank
Congo_DRC_Kinshasa
Spain_ Madrid
Argentina_ Buenos Aires
China_ Panyu
Antigua_ St John's
Malaysia_ Kajang
Israel_ Alexander river
Ghana_Accra
Bulgaria_ Sofia
India_ Hyderabad
Luxembourg_ City
Belgium_ Brussels
USA_ Dallas
UK_Scotland_Glasgow
Iraq_ Baghdad
Angola_ Luanda
Hong Kong_ Kai Tak River
Congo_ Rep._ Brazzaville
Georgia_ Tbilisi
Bangladesh_ Barisal
Philippines_ Manila
Turkey_ Saray
South Africa_ Pretoria
Indonesia_ Citarum
USA_ Las Vegas
Northern Ireland_Belfast
Germany_ Tubingen
Austria_ Vienna
Ecuador_ Guayaquil
Mali_ Bamako
South Korea_ Seoul
Sri Lanka_ Colombo
Continued...
Cumulative Concentration (ng/L)
4000
3500
3000
2500
2000
1500
1000
500
0
60th Percentile
50th Percentile
40th Percentile
USA_ Denver
Chile_ Santiago
Tanzania_ Dar es Salaam
Panama_ Panama City
UK_ London
USA_ North Liberty
Peru_ Huancayo
Colombia_ Cali
Lesotho_ Maseru
Netherlands_ Utrecht
Romania_ Bucharest
Serbia_ Belgrade
China_ Guangzhou
Portugal_Lisbon
UK_ Leeds
USA_ New York City
Canada_ Toronto
Cameroon_ Yaounde
Mexico_ Puerto Vallarta
Brazil_ Natal
Hungary_ Budapest
Belgium_ Antwerp
Denmark_ Odense
Czech Republic_ Prague
Thailand_ Bangkok
Hong Kong_ Lam Tsuen
Taiwan_ Taoyuan
Germany_ Berlin
UK_ York
Brazil_ Americana
Burkina Faso_ Ouagadougou
Germany_ Frankfurt
Japan_ Magome
Russia_ Moscow
Switzerland_ Basel
King George Island
Croatia_ Zagreb
USA_ Hawaii_ Kauai
Canada_ Calgary
South Sudan_ Juba
Slovakia_ Bratislava
France_ Paris
France_ Beaujeu
Greece_ Oinofyta
Brunei_ Brunei River
Kazakhstan_ Astana
Continued...
Cumulative Concentration (ng/L)
600
400
200
0
30th Percentile
20th Percentile
10th Percentile
Finland_ Helsinki
Morocco_ Tangier Region
Australia_ Adelaide
Ireland_ Suburban Dublin
Rwanda_ Kigali
Liberia_ Monrovia
Latvia_ Riga
Australia_ Sydney
Italy_ Rome
USA_ Miami
Poland_ Suwalki
Brazil_ Manaus
Ukraine_ Kharkiv
Sweden_ Uppsala
Japan_ Kyoto
USA_ Honolulu
Wales_ River Dee
USA_ Missouri_ St Louis
Iran_ Rudbar
Australia_ Melbourne
Lithuania_ Vilnius
Laos_ Luang Prabang
Estonia_ Tallinn
Canada_ Ottawa
Cyprus_ Kakopetria
Tanzania_ Arusha
Bhutan_ Thimpu
Ivory Coast_ Abobo
Australia_ Hobart
Portugal_ Madeira
Benin_ Cotonou
Chile_ Maipo
Bhutan_ Paro
Slovenia_ Ljubljana
USA_ Ormond Beach
Gambia_ Gambie River
Albania_ Tirana
New Zealand_ N. Island
Uganda_ Mbarara
Cook Islands_ Rarotonga
Zimbabwe_ Harare
USA_ Florida Intercoastal
Sierra Leone_ Bo
Norway_ Donna
Iceland_ Reykjavik
Iceland_ Skogafoss
Venezuela_ Yanomami
● Africa
● Antarctica
● Asia
● Europe
● North America
● Oceania
● South America
✦ Country not previously monitored

Ecology, 69(2), 1988, pp. 508–515

THE INDETERMINACY OF ECOLOGICAL INTERACTIONS AS PERCEIVED THROUGH PERTURBATION EXPERIMENTS[1]

PETER YODZIS

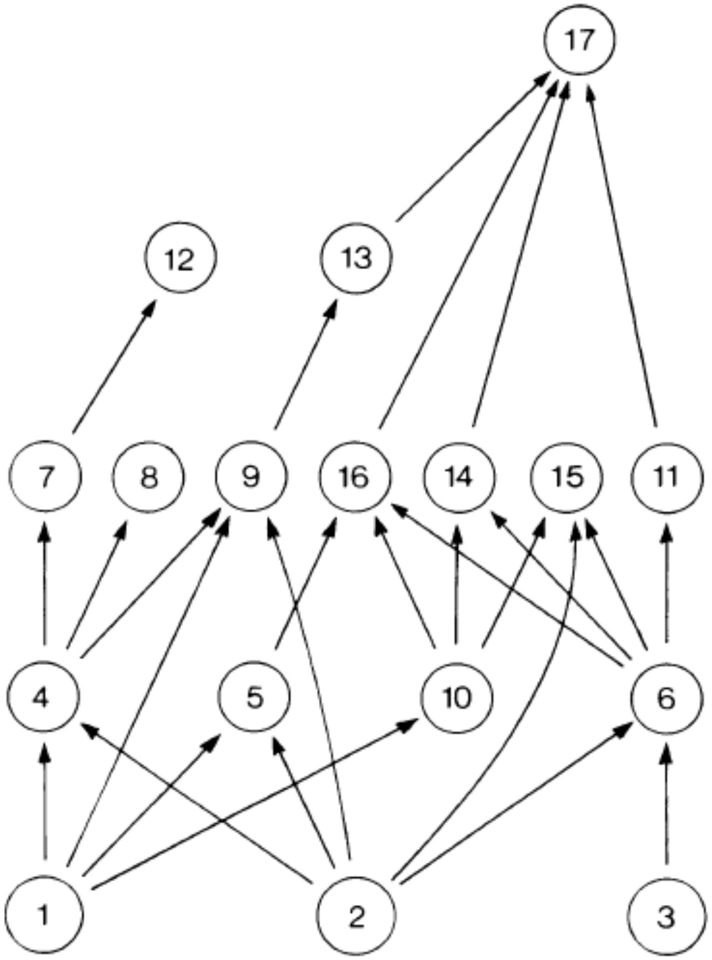


FIG. 1. Food web for Narragansett Bay, Rhode Island. Each vertex (circle) represents a species, and an arrow from vertex *i* to vertex *j* means that species *j* comsumes species *i*.

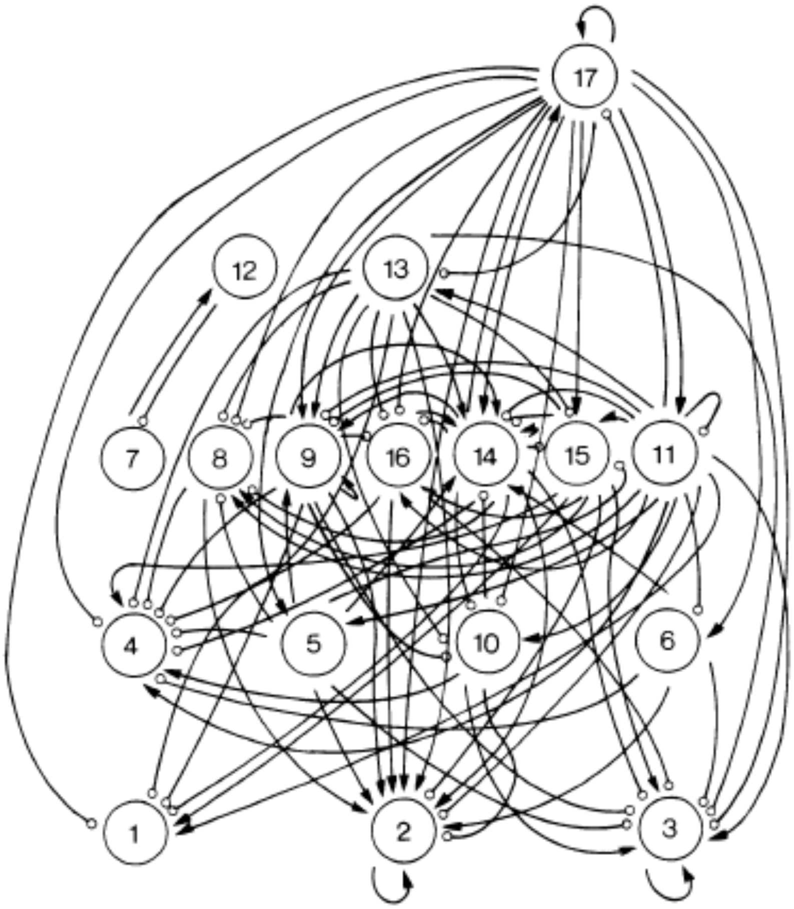


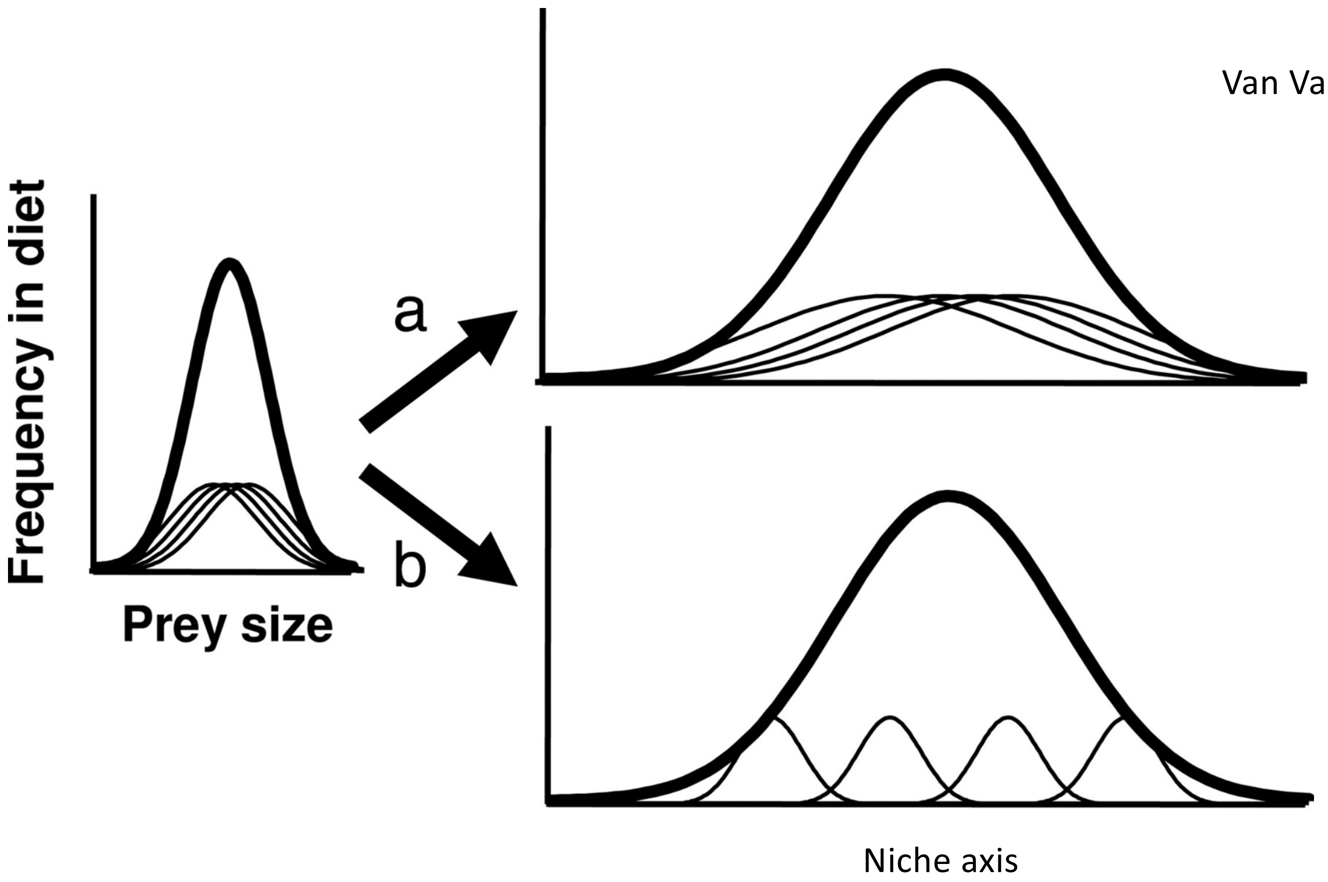
FIG. 4. Major effects on each species of the Narragansett Bay food web, obtained from another randomly generated plausible community matrix. Symbols here have the same meaning as in Fig. 2, except that here they are based on the inverse matrix A^{-1} rather than on the community matrix itself.

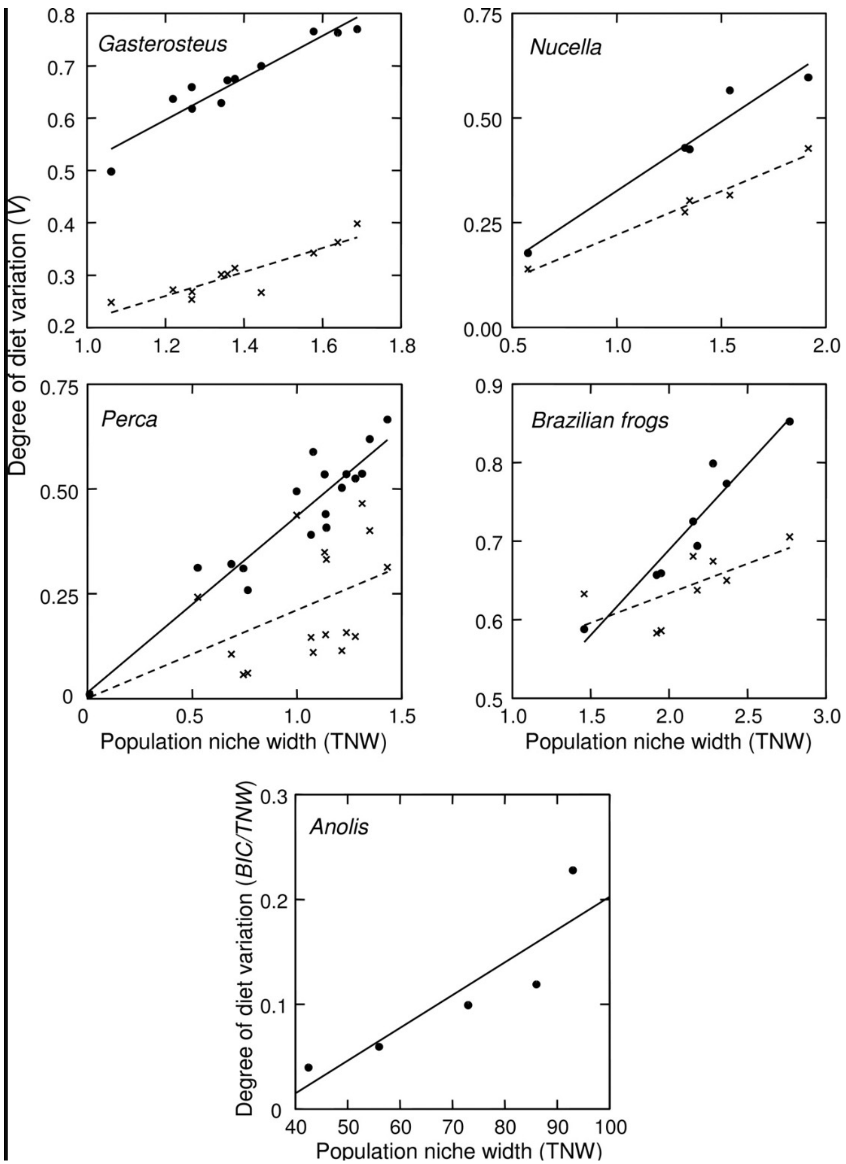
“*For those doing practical work with environmental impacts, it is of crucial importance to understand that short-term observations of environmental impacts that can be viewed as press perturbations are close to useless for estimating probable long-term impacts. Moreover, as the present study makes clear, predicting those long-term effects not only requires data on the strengths of many interactions in the system, it requires very accurate data on many interaction strengths. This is a daunting prospect indeed.*” (Yodzis 1988)

Niche complexity

Roughgarden theory of niche width

Van Valen’s Niche Variation Hypothesis




Gasterosteus
Nucella
Perca
Brazilian frogs
Anolis
Degree of diet variation (V)
Degree of diet variation (BIC/TNW)
Population niche width (TNW)
Population niche width (TNW)
Population niche width (TNW)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
1.0
1.2
1.4
1.6
1.8
0.75
0.50
0.25
0.00
0.5
1.0
1.5
2.0
0.75
0.50
0.25
0
0
0.5
1.0
1.5
0.9
0.8
0.7
0.6
0.5
1.0
1.5
2.0
2.5
3.0
0.3
0.2
0.1
0
40
50
60
70
80
90
100

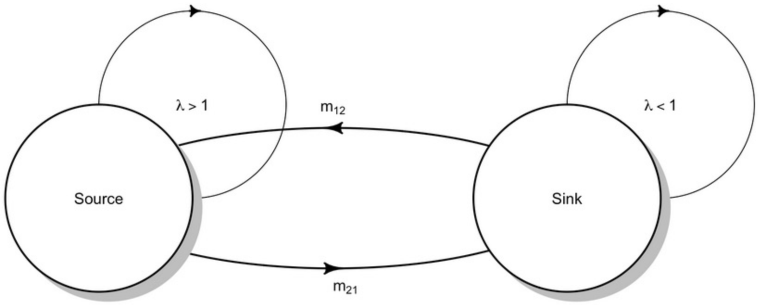
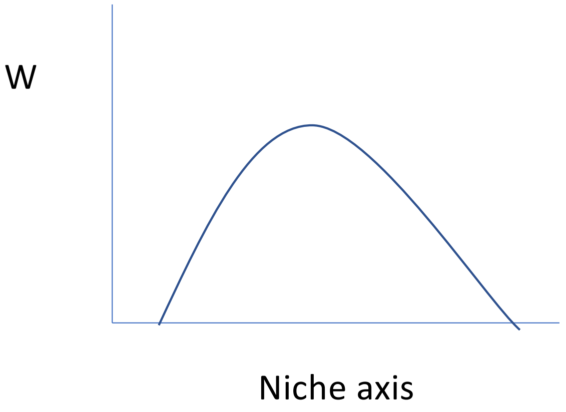
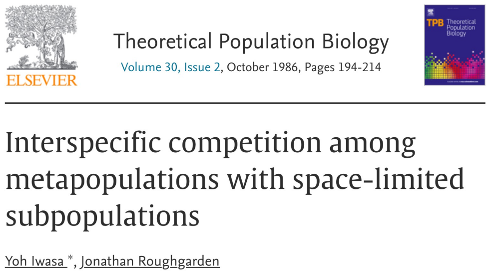


Figure 6.2: The simplest source-sink model, where $m_{21} > m_{12}$ so that net movement of individuals is from the source to the sink.





ELSEVIER

Theoretical Population Biology
Volume 30, Issue 2, October 1986, Pages 194-214

Interspecific competition among metapopulations with space-limited subpopulations

Yoh Iwasa *, Jonathan Roughgarden

https://hankstevens.github.io/Primer-of-Ecology/meta.html

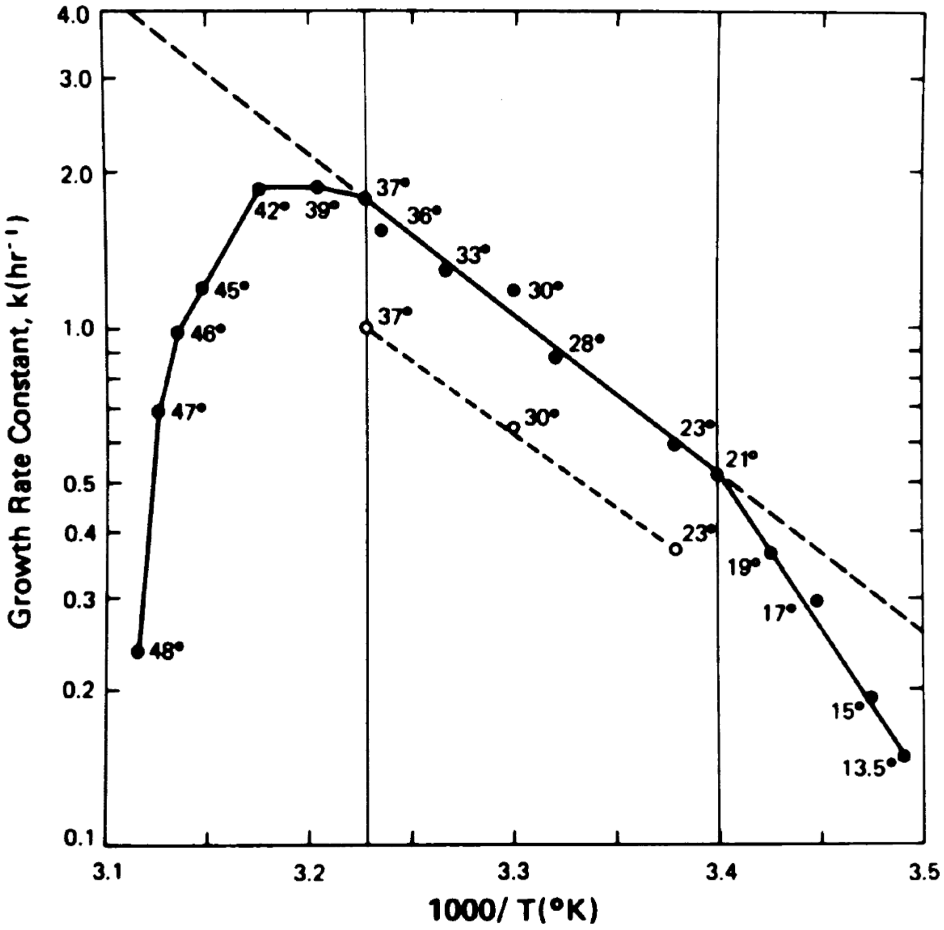
Niche

Colwell and Fuentes (1975)

Columbarium

Colwell and Fuentes (1975)

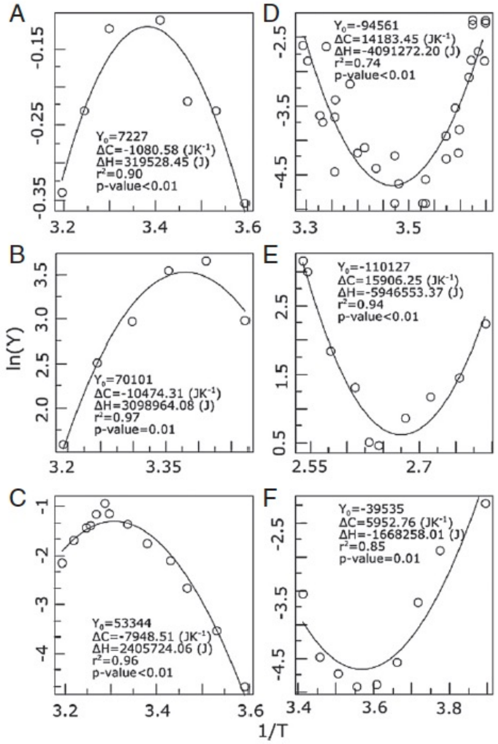
Temperature



Growth rate of E. coli

$K = ae^{-e/KT}$

Herendeen et al



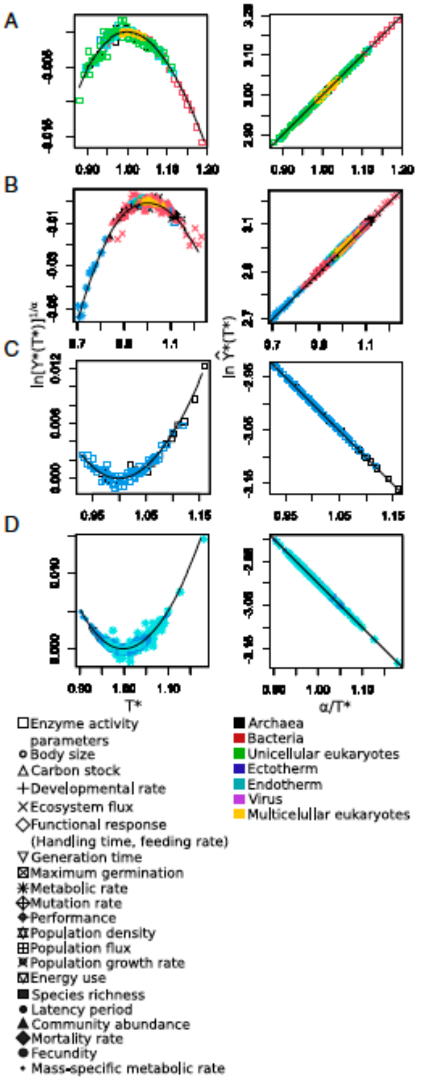
The Eyring–Evans–Polanyi (EEP) transition state theory (TST)

$$k = \frac{k_B}{h} T e^{\Delta S / R} e^{-\Delta H / RT}.$$

PNAS RESEARCH ARTICLE | ECOLOGY

A general theory for temperature dependence in biology

José Ignacio Arroyo[a,b,1,2], Beatriz Díez[c,d,e], Christopher P. Kempes[b], Geoffrey B. West[b], and Pablo A. Marquet[a,b,f,g,h,I,2]



$$Y(T) \approx Y_0 \left(\frac{1}{T}\right)^{\frac{-\overline{\Delta C}}{R} - \alpha} e^{\frac{-\overline{\Delta H}}{RT}}.$$

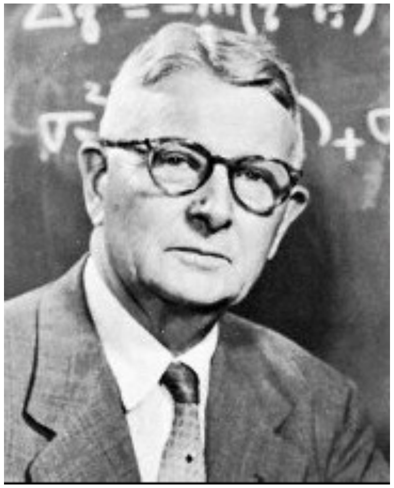
$$Y^{*1/a} = T^* e^{1/T^* - 1}$$

$$\hat{Y}^*(T^*) \equiv (e/T^*)^a \, Y^*(T^*) = e^{a/T^*}$$

Arroyo et al. (2022) PNAS

General patterns

Diffusion processes



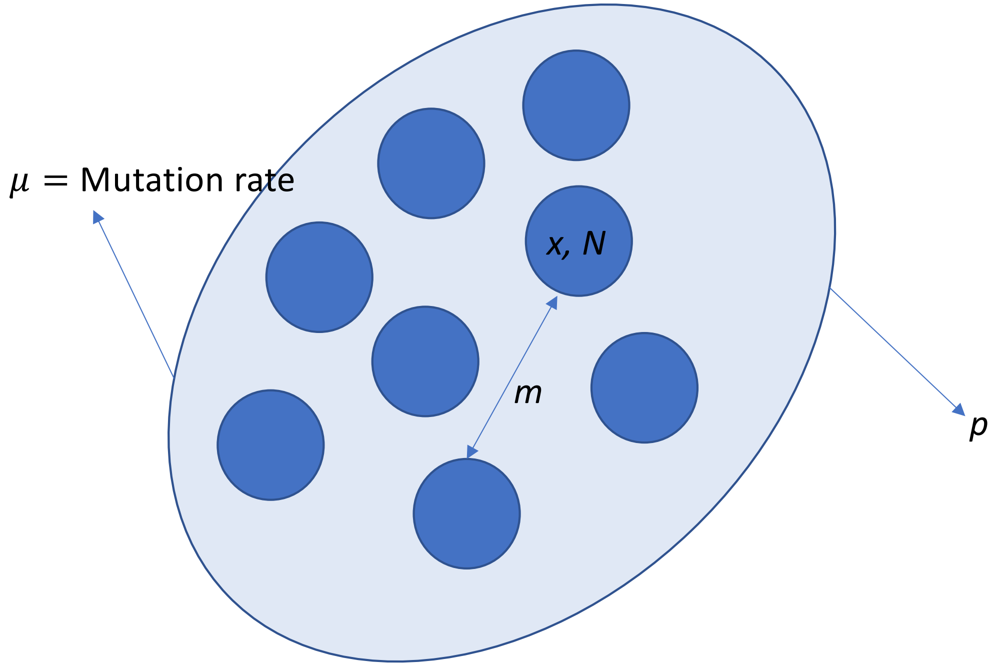
Sewall Wright

Andrey Kolmogorov

Ronald Fisher

- The frequency of genes in a structured population

$$\rho_\infty(x) = \frac{\Gamma(4Nm)}{\Gamma(4Nmp)\Gamma(4Nmq)} x^{4Nmq-1}(1-x)^{4Nmp-1}.$$



x = Frequency of a given allele in a local population

N= Effective population size

m = Proportion of migrating individuals among population each generation.

p= Frequency of a given allele in the total population

Kolmogorov (1935) Dokl. Akad. Nauk SSSR 3 (1935), 129-132.

Large population of ***N*** individuals consisting of ***s*** partial populations with ***n*** individuals each (*N=sn*)

Each generation ***k*** individuals disperse randomly across the partial populations.

$\bar{p}$ = gene frequency in the large population

p = gen frequency in a local population

Δp =change in the frequency of p over one generation

$q = 1 - p$

Following Wright and Fisher:

$$M(p) = E(\Delta p) = \frac{k}{n}(\bar{p} - p) \qquad Var(p) = E(\Delta p)^2 = \frac{pq}{2n}$$

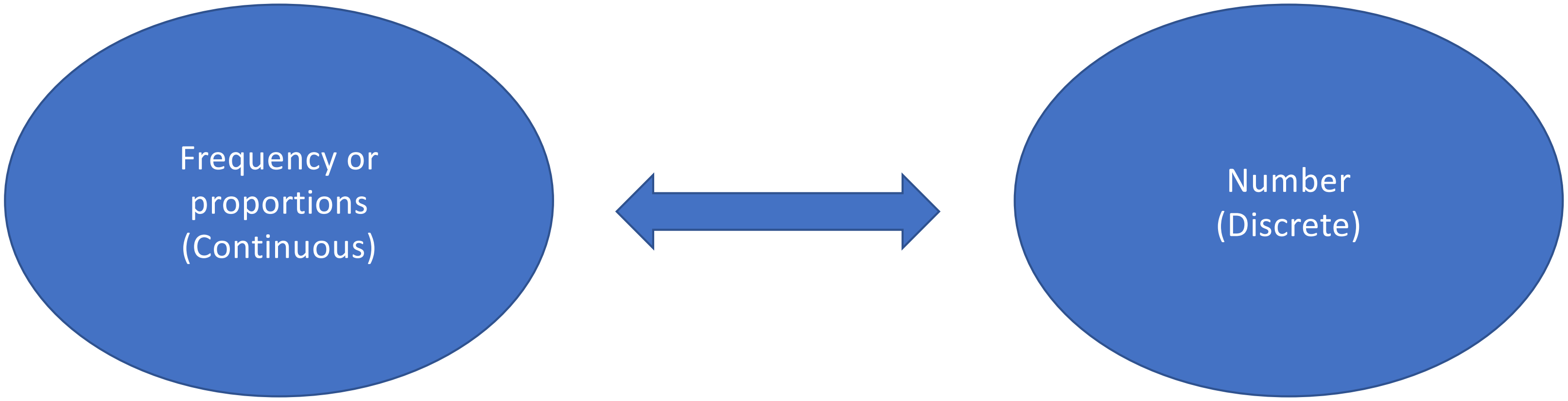
"Since *s* is large, the variation of the total concentration $\bar{p}$ will proceed much more slowly than those of the partial concentrations *p*. Therefore, $\bar{p}$ can temporarily be taken constant. The concentrations *p* in partial populations deviate from $\bar{p}$ in either direction. After sufficiently long time the fluctuations of *p* around $\bar{p}$ result in a certain stationary probability distribution for the concentrations *p*." (Kolmogorov 1935)

This stationary distribution satisfies the Kolmogorov forward or Fokker-Planck equation:

$$\frac{1}{2}\frac{\partial^2}{\partial p^2}(\mathrm{Var(p)\mu}) - \frac{\partial}{\partial x}(M(p)\mu) = 0$$

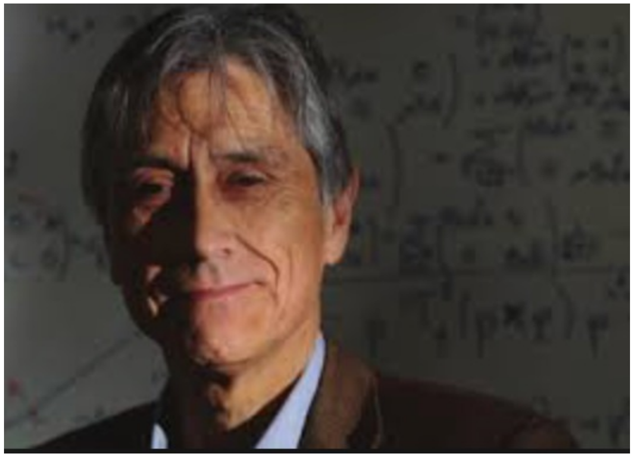
Whose solution $\mu(p)$ is:

$$\mu(p) = \frac{1}{\mathrm{B}(4k\bar{p}, 4k\bar{q})}\, p^{4k\bar{p}-1} q^{4k\bar{q}-1}$$

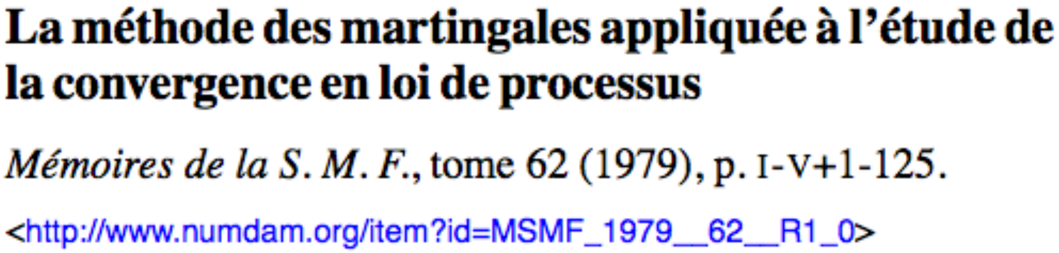


Frequency or proportions (Continuous)

Number (Discrete)



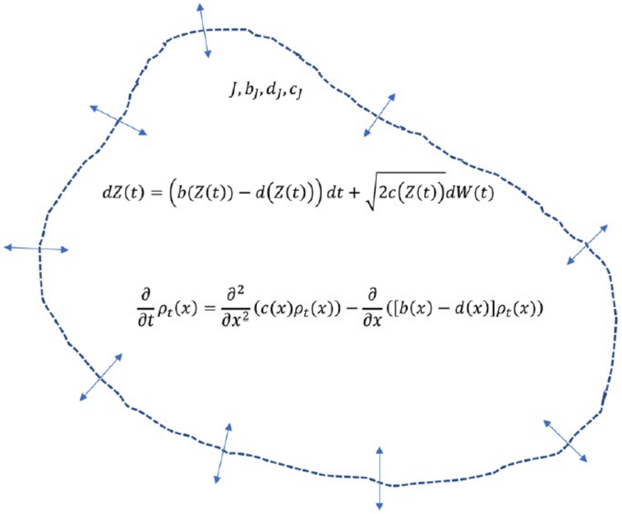
Prof. Rolando Rebolledo



La méthode des martingales appliquée à l'étude de la convergence en loi de processus

Mémoires de la S. M. F., tome 62 (1979), p. I-V+1-125.

<http://www.numdam.org/item?id=MSMF_1979__62__R1_0>

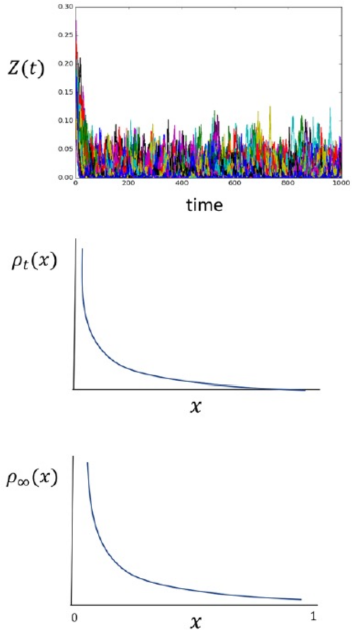


J, b_J, d_J, c_J

$$dZ(t) = \big(b(Z(t)) - d\big(Z(t)\big)\big)\,dt + \sqrt{2c\big(Z(t)\big)}dW(t)$$

$$\frac{\partial}{\partial t}\rho_t(x) = \frac{\partial^2}{\partial x^2}(c(x)\rho_t(x)) - \frac{\partial}{\partial x}([b(x) - d(x)]\rho_t(x))$$

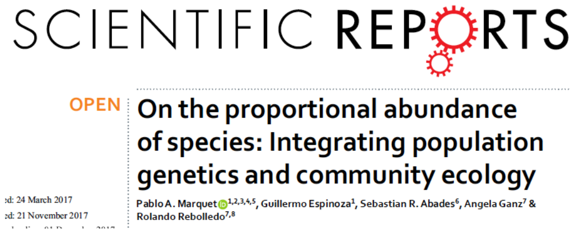
$$\rho_\infty(x) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)+\Gamma(\beta)}x^{\alpha-1}(1-x)^{\beta-1}$$



$$B_J(n) = b_J(n) + c_J(n)$$

$$D_J(n) = d_J(n) + c_J(n).$$

$$\begin{aligned} b(x) &= b_0 + b_1 x \\ d(x) &= d_0 + d_1 x \\ c(x) &= \gamma x(1-x), \end{aligned}$$



SCIENTIFIC REPORTS

OPEN

On the proportional abundance of species: Integrating population genetics and community ecology

Pablo A. Marquet[1,2,3,4,5], Guillermo Espinoza[1], Sebastian R. Abades[6], Angela Ganz[7] & Rolando Rebolledo[7,8]

ed: 24 March 2017
ed: 21 November 2017

$$\rho_{\infty}(x) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)+\Gamma(\beta)} x^{\alpha-1}(1-x)^{\beta-1}$$

The Proportional Species Abundance Distribution (PSAD)

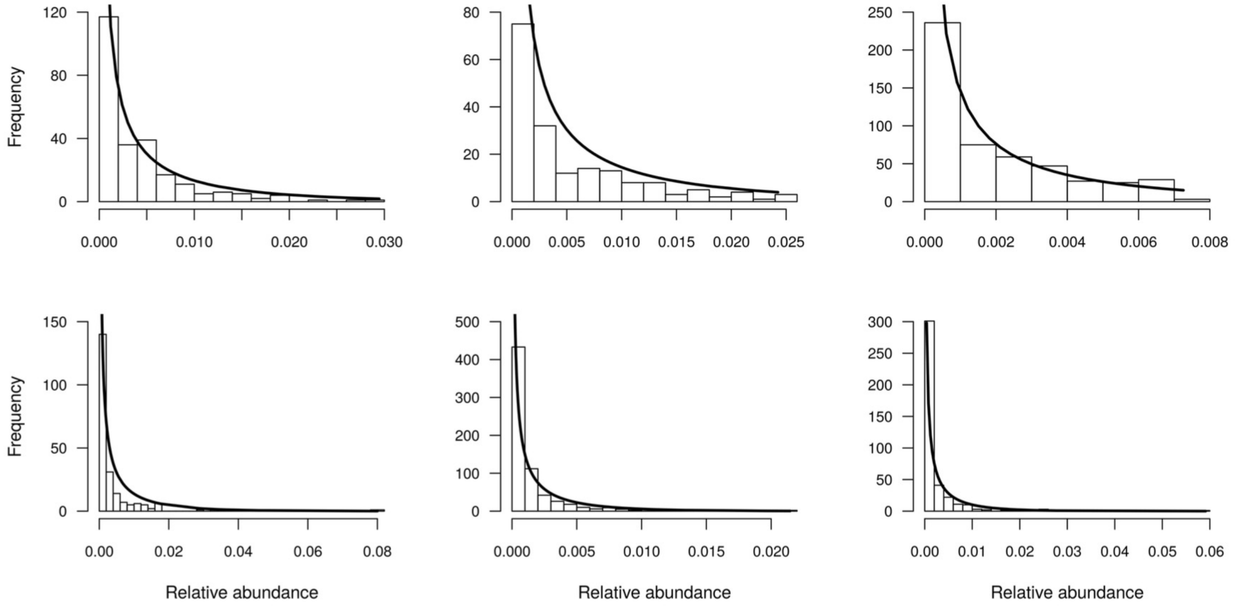
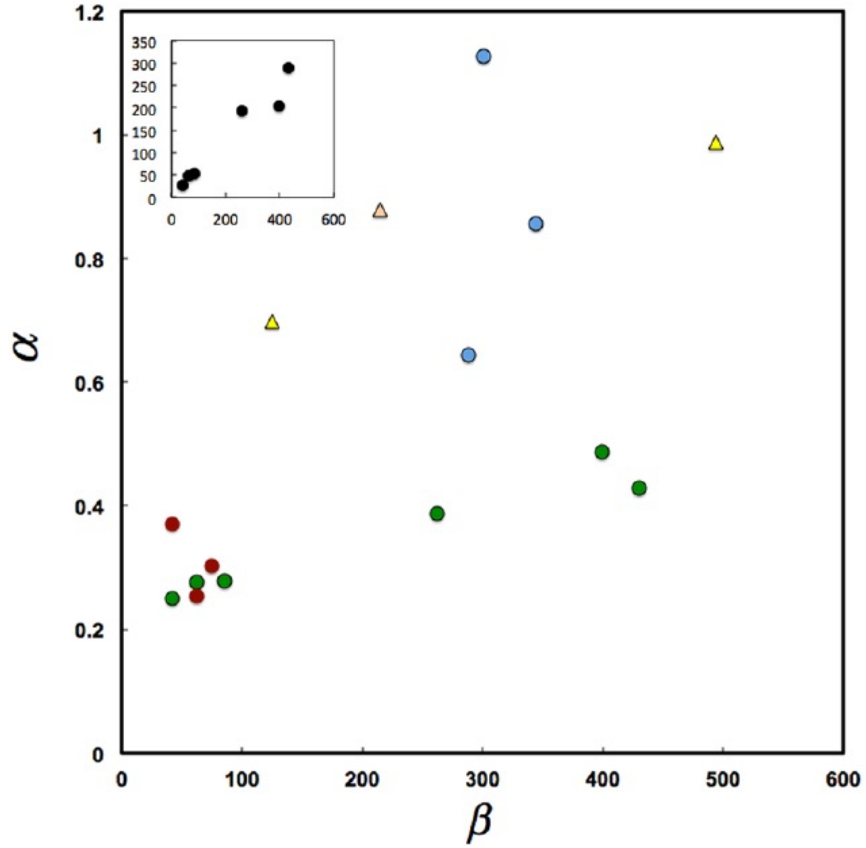


Figure 1. Fit of the Beta distribution to different animal and plant communities. First row, from left to right Amazon birds (community 10 in Table 1), Lepidoptera (12 in Table 1), butterflies (11 in Table 1), second row from left to right Tropical trees (6 in Table 1), Tropical trees (2 in Table 1) and Coral reefs (14 in Table 1)

$$\rho_\infty(x) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)+\Gamma(\beta)} x^{\alpha-1}(1-x)^{\beta-1}$$



● Marine communities

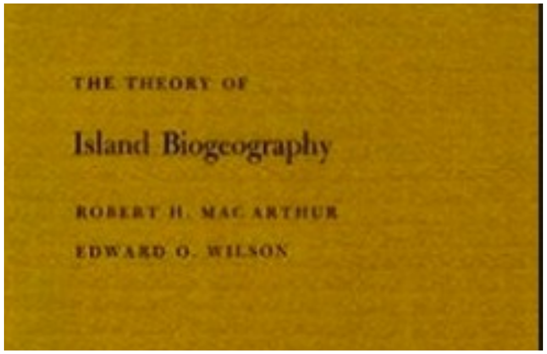
● Shrublands

● Tropical Forest

▲ Bird communities

$\alpha \sim$ Dispersal

$\beta \sim$ Speciation



THE THEORY OF

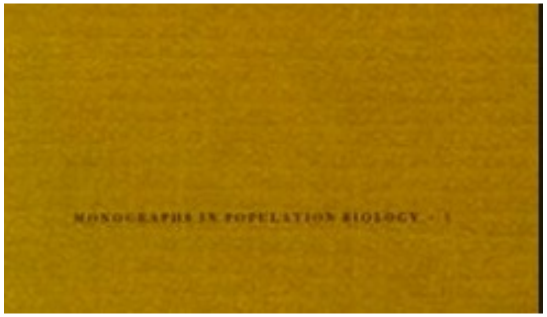
Island Biogeography

ROBERT H. MAC ARTHUR

EDWARD O. WILSON

$$\text{(3-4)}\quad \frac{dP_S(t)}{dt} = -(\lambda_S + \mu_S)P_S(t) + \lambda_{S-1}P_{S-1}(t) + \mu_{S+1}P_{S+1}(t).$$

$$Z(t) = Z(0) + \int_0^t \theta(Z(s))ds + \int_0^t \sigma(Z(s))dW_s,\ (t \geq 0).$$



MONOGRAPHS IN POPULATION BIOLOGY · 1

$$\rho_\infty(x) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)+\Gamma(\beta)} x^{\alpha-1}(1-x)^{\beta-1}$$

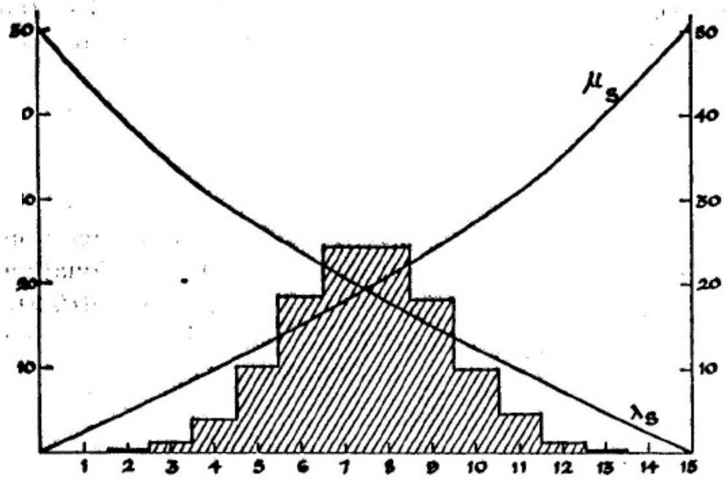
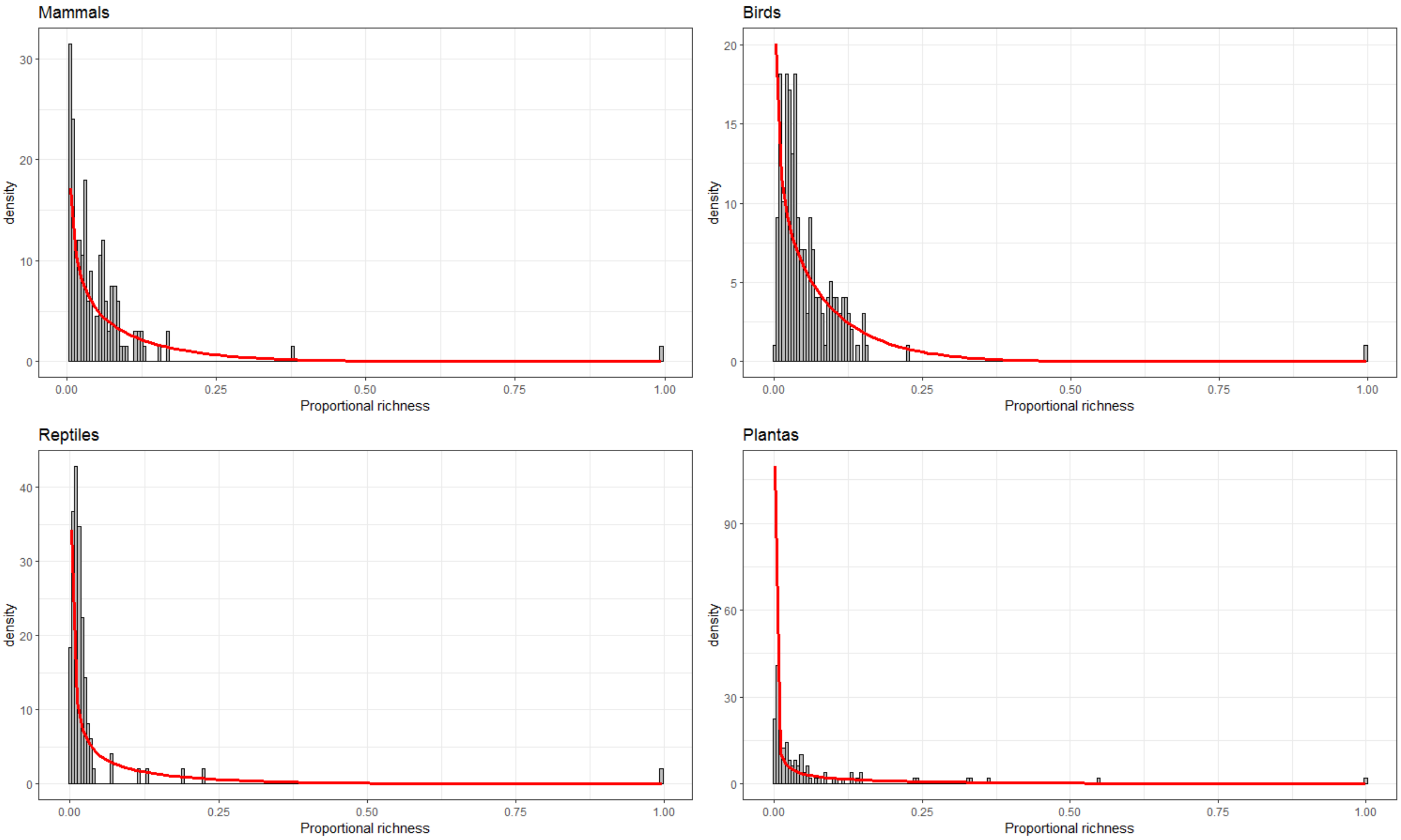


Figure 19. A particular case of a predicted distribution of numbers of species on a family of island biotas all with identical extinction and immigration curves and all having had time to reach equilibrium. The histogram represents the number of islands with each number of resident species in an equilibrium situation. The species pool from which the biotas were assembled contained 15 species. If the immigration and extinction curves were straighter, the variance of equilibrial species numbers would be even greater; yet this large variance is still consistent with the equilibrial condition.

“In principle one could solve eq. 3-4….for our purpose is more useful to find the mean M(t) and the variance, var(t), of the number of species at time t. These can be estimated in nature by measuring the mean and variance in number of species of a series of islands of about the same distance and are and hence of the same λ and μ." pp.33-34


Mammals
density
30
20
10
0
0.00
0.25
0.50
0.75
1.00
Proportional richness
Birds
density
20
15
10
5
0
0.00
0.25
0.50
0.75
1.00
Proportional richness
Reptiles
density
40
30
20
10
0
0.00
0.25
0.50
0.75
1.00
Proportional richness
Plantas
density
90
60
30
0
0.00
0.25
0.50
0.75
1.00
Proportional richness

Some Sources of Stochasticity at Different Levels of Organization

Frequency of Gene families within Genomes	Frequency of genes within and among population	Frequency of individuals among species	Frequency of species Among communities
• Mutation	• Mutation	• Birth	• Speciation
• Lateral gene transfer	• Drift	• Death	• Extinction
• Gene duplication	• Migration	• Migration	• Migration
	• Loss		

Abundance of gene families within genomes

- Birth-death processes are applicable to understand genome evolution

- Driving processes are similar

Duplication

Mutation

Lateral gene transfer and retroviral infection

Plasmids

Gene extinction

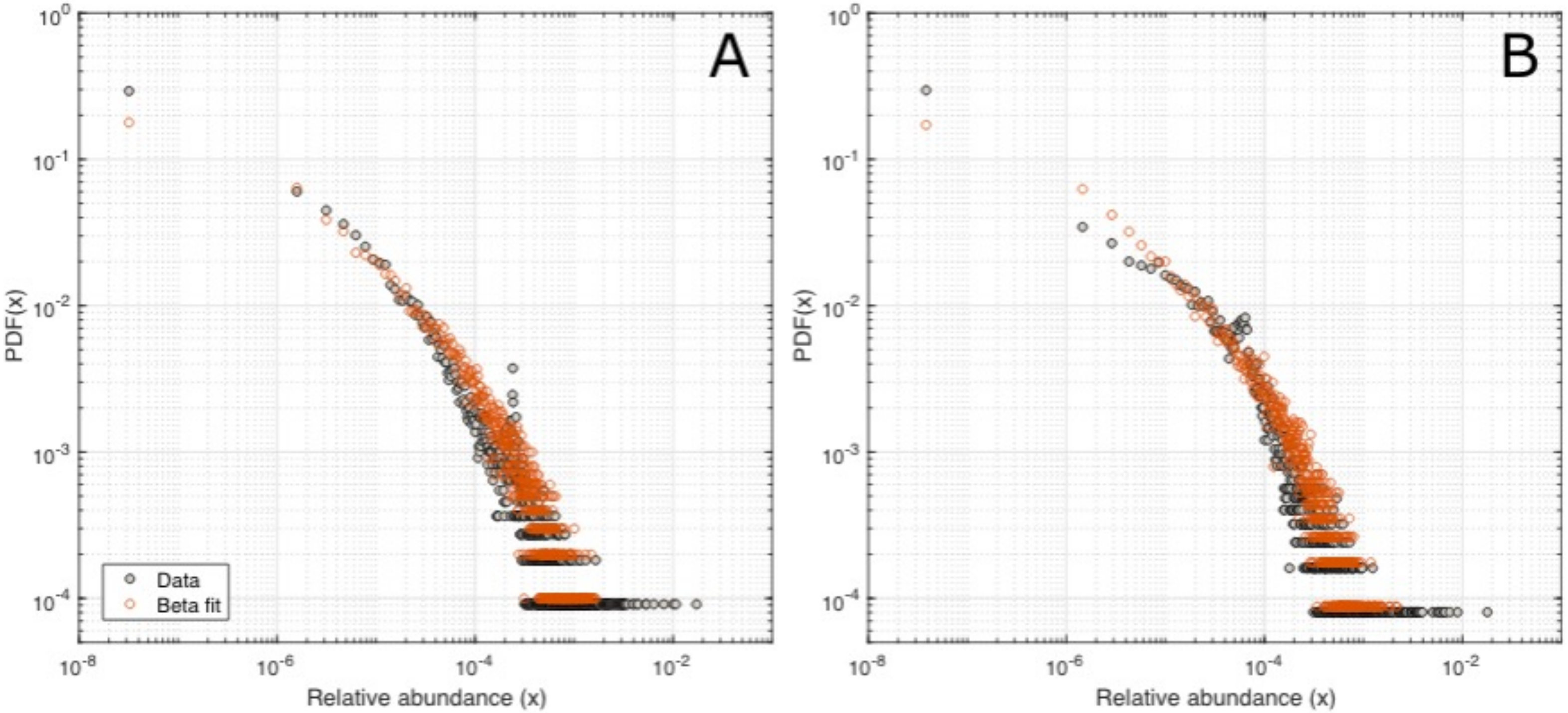


Figure 1. The relative abundance of protein families follows a Beta distribution. The relative abundance of protein families in bacteria and eukarya according to the Pfam classification. **A**. Data from 7,694 bacterial proteomes; 11,106 families; and 30,743,438 genes. Best fit beta distribution parameters: α=0.273 (0.264, 0.283), β=3,031.9 (2823.4, 3240.4). **B**. Data from 1,496 eukaryotic proteomes; 12,579 families; and 25,625,956 genes. Best fit beta distribution parameters: α=0.291 (0.281, 0.300), β=3,655.2 (3424.3, 3886.2).

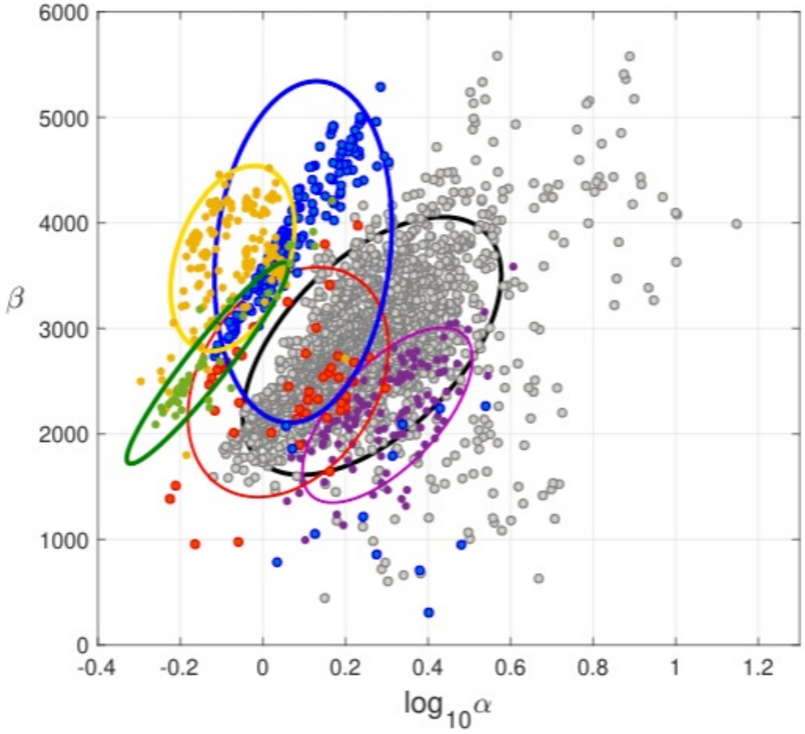


Figure 2. Shape parameters of Beta distributions arising from the relative abundance of gene families in genomes. Annotations of protein families (Pfam v32) in Uniprot reference proteomes (n=17,543). Reference proteomes include Archea (n=285, magenta), Bacteria (n=6,554, grey); unicellular eukarya (n=1,202, red); plants (n=, green); metazoa (n=, yellow); fungi (n=, blue). The total number of protein families classified by Pfam is 15,964.

Gracias