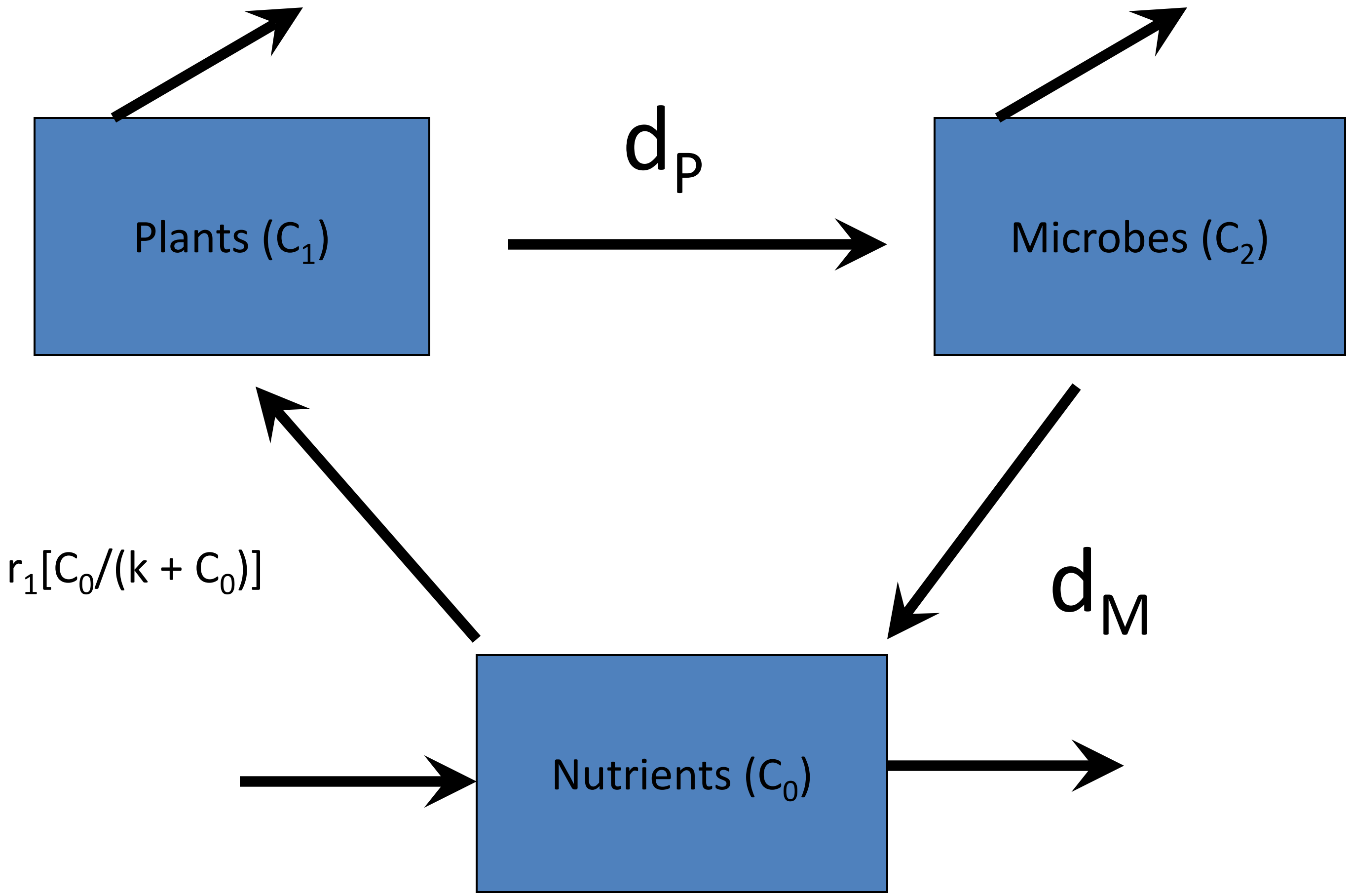
Dimensions of Biodiversity: The ecosystem consequence of agro-biodiversity loss.

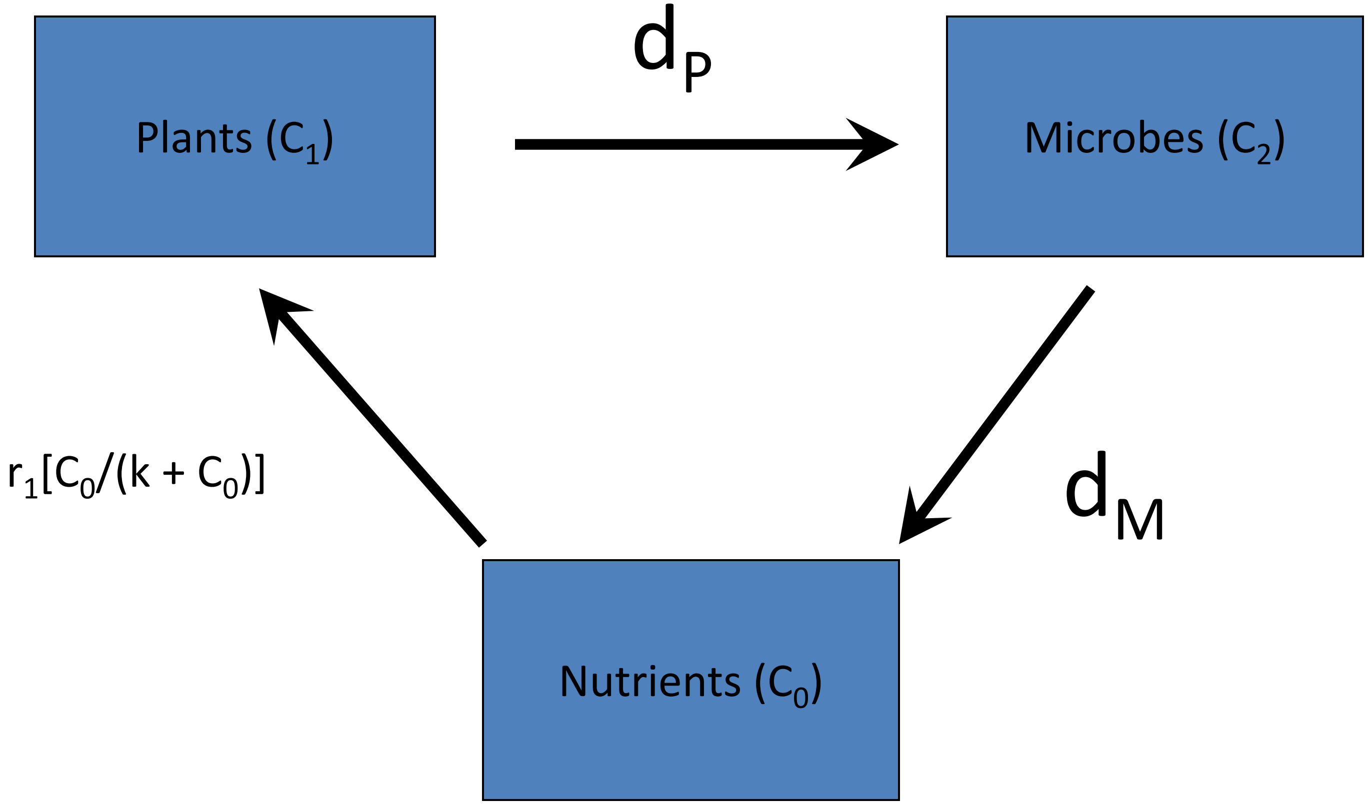
Shahid Naeem
Columbia University

DeAngelis type model



DeAngelis, D. L. (1992) Dynamics of nutrient cycling and food webs.

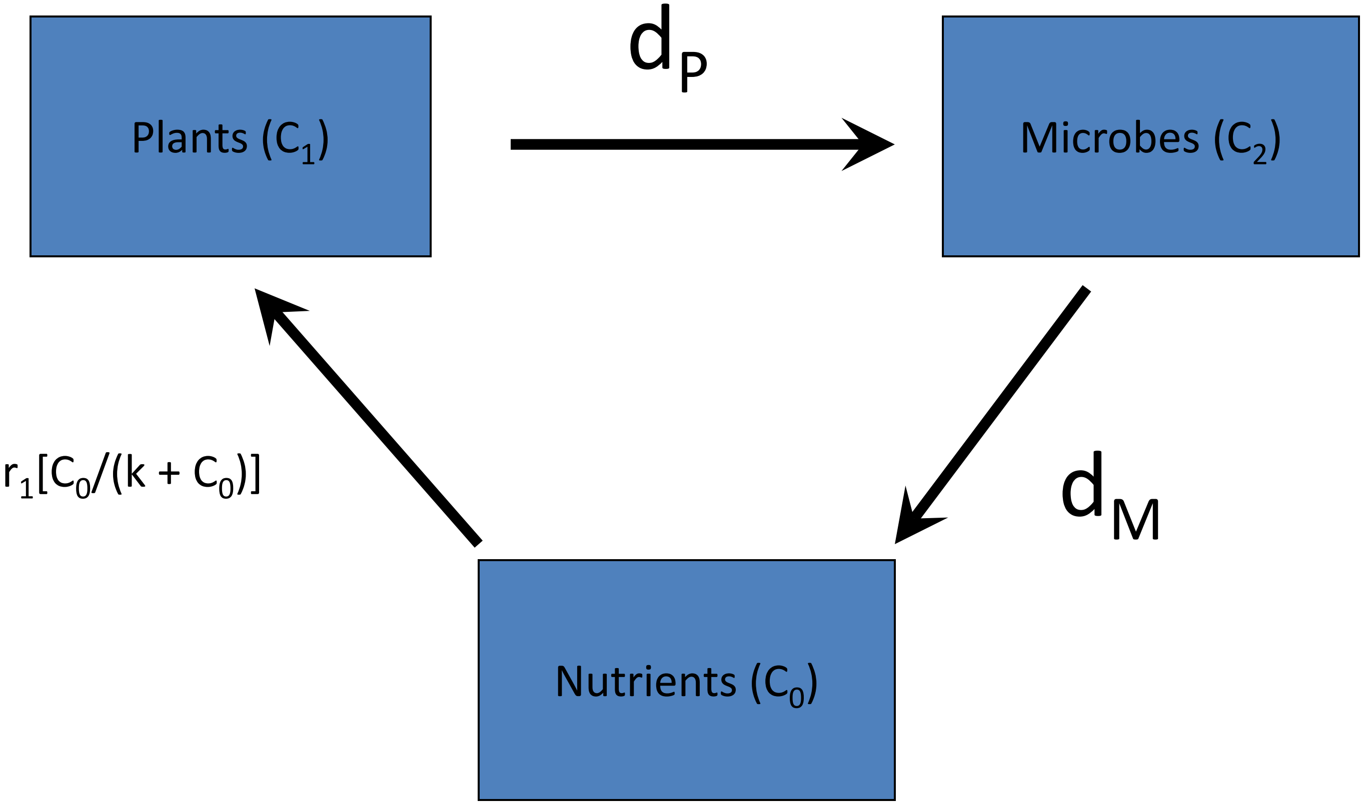
DeAngelis type model (grossly simplified!)



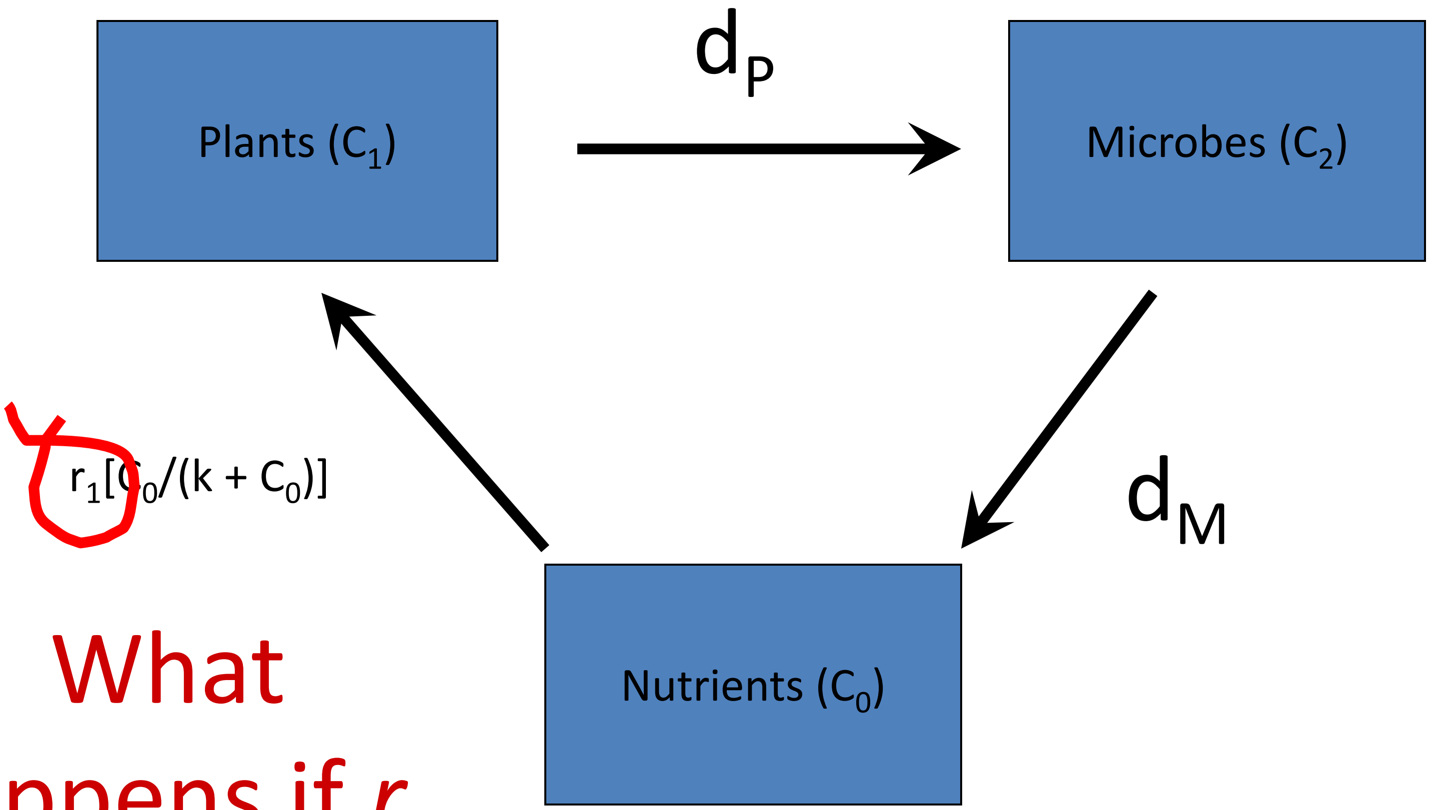
DeAngelis, D. L. (1992) Dynamics of nutrient cycling and food webs.

$$\frac{dC_1}{dt} = r_1 \frac{C_0}{k_1 + C_0} C_1 - d_p C_1$$

$$\frac{dC_2}{dt} = d_p C_1 - d_M C_2$$



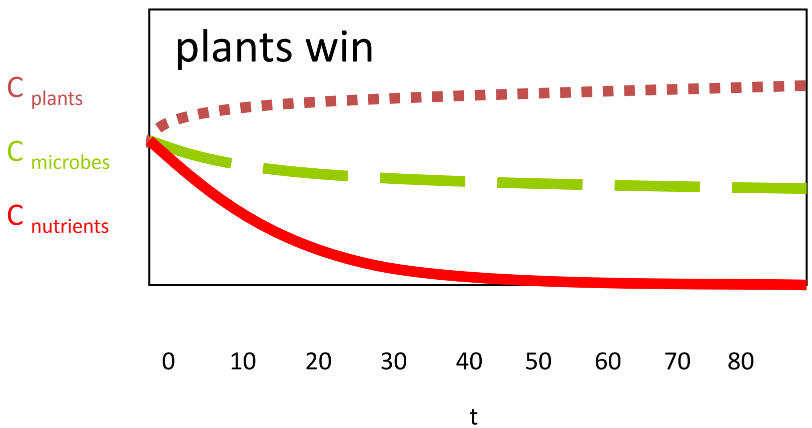
$$\frac{dC_0}{dt} = d_M C_2 - C_1 r_1 \frac{C_0}{k_1 + C_0}$$



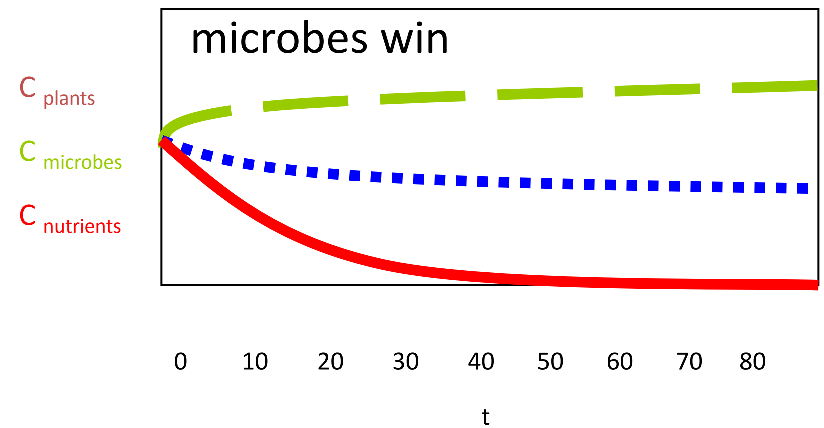
What happens if r_1 increases?

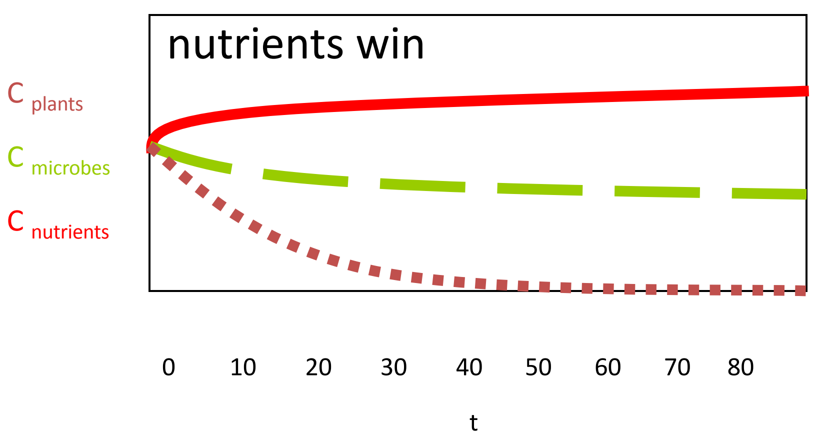
At high values of *r* (plant growth), what would happen?

A

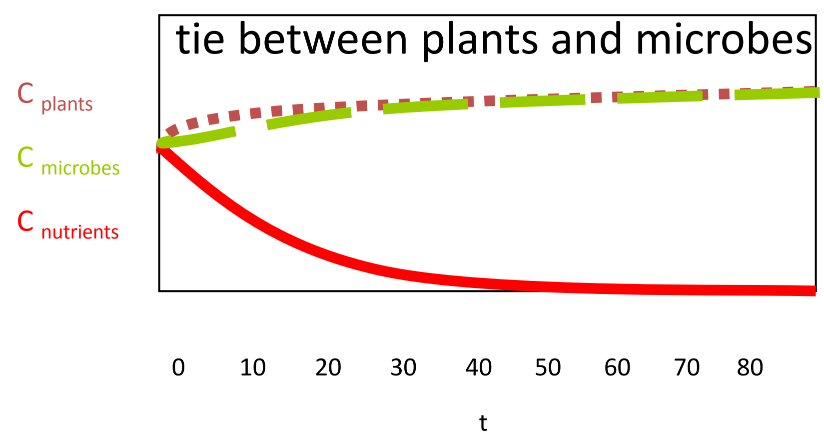


B

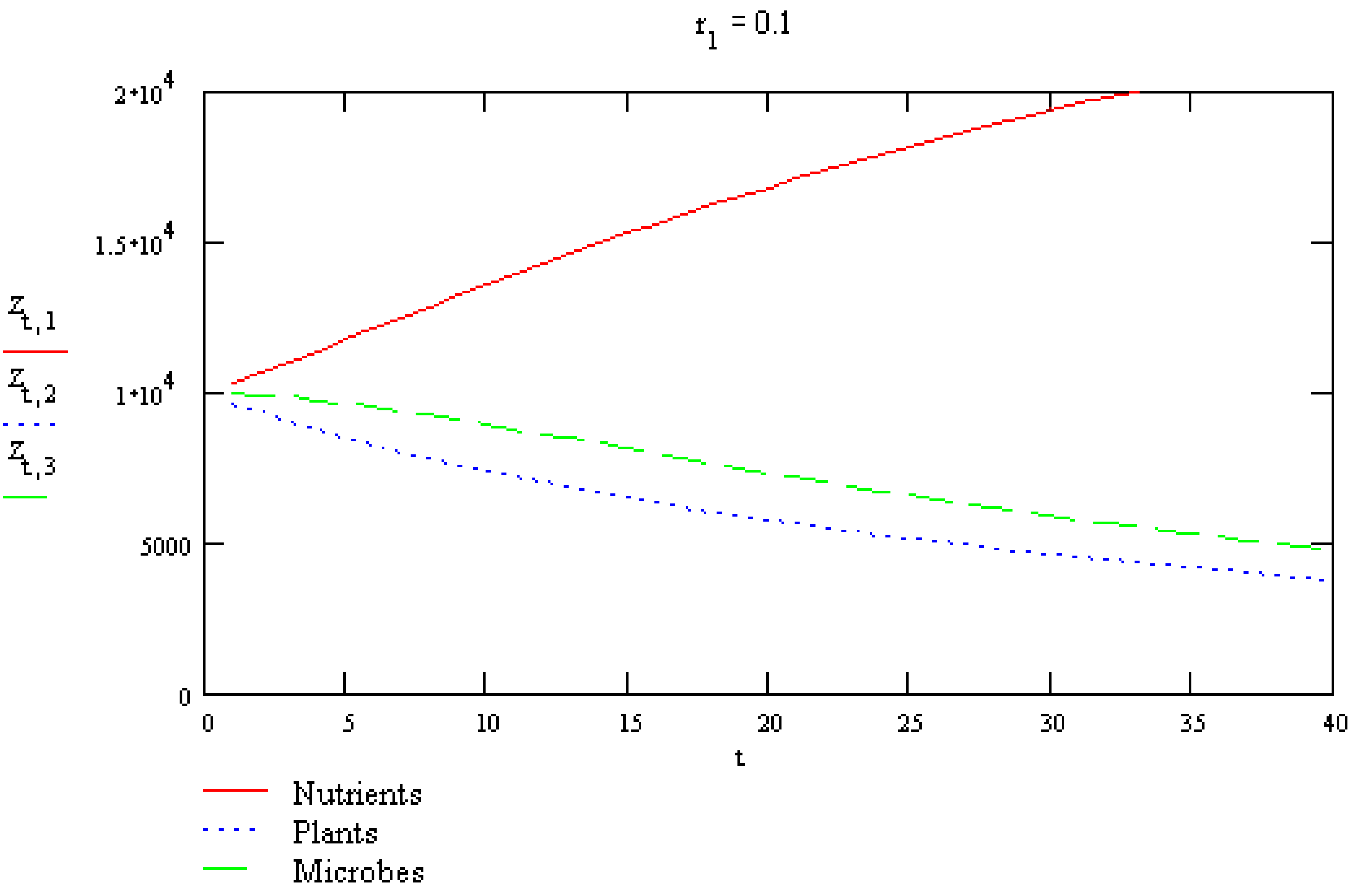




C



D



$r_1 = 0.1$
$2 \cdot 10^4$
$1.5 \cdot 10^4$
$1 \cdot 10^4$
5000
0
$Z_{t,1}$
$Z_{t,2}$
$Z_{t,3}$
0
5
10
15
20
25
30
35
40
t
Nutrients
Plants
Microbes

organic compounds) and material (nutrients, wa- ground and in the soil (16), that changes in plant ample, the relative abundance of grassland species

Science AAAS

Biological Diversity
nction

Zavaleta[3]

onomic, phylogenetic, genetic, and functional diversity
al resources, modification of habitats and climate, and

experiment, low-diversity plots (four plant species) produced lower interaction diversity among the 427 resident arthropod species than did high-diversity plots (16 plant species) (12). Taken to the extreme, the next step might seem to require conducting an experiment that examines the effects of taxonomic, functional, phylogenetic, genetic, spatial, temporal, landscape, and interaction diversity (all the dimensions we list in Box 1) to explain multiple ecosystem functions.

But such an additive progression—in which biodiversity and ecosystem function research

ngolia fluctuates with precipitation et overall primary production of the ss variable where diversity is high ly, wild salmon populations in indi- aries at Bristol Bay, Alaska, fluctuate , but total production of salmon bio- h the whole system is much more). In these and other studies, it is the arity of species' responses to envi- eterogeneity that allows increased ability. Greater biodiversity can also ater species turnover and compensa- s environments change, lowering sys- y (23–25). These effects are variously atistical averaging, biological insur- ortfolio effect [see (26) for a review]. acts of biodiversity change on eco- tion are clearly far richer than our cus on predominantly monotrophic, nal, monodimensional biodiversity vealed. Such studies generally lacked al structure inherent to ecosystems, creasingly realize is key to their func-

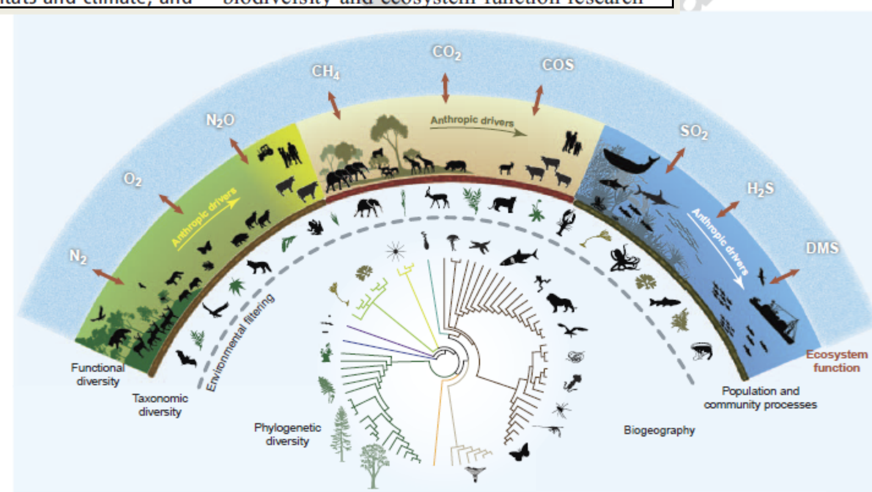


Fig. 1. Biodiversity and ecosystem functioning in an age of extinction. The phylogenetic tree of life, currently populated by about 10 million species, ranges from microscopic to enormous multicellular organisms, of which only a few representative phyla and divisions are shown as icons at the tips of the branches. Where species from the global phylogenetic pool are found is largely determined by environmental filters, represented here as a barrier with pores (dashed arch). Here we show only phylogenetic and taxonomic diversity, but biogeography, population processes, biotic interactions, metagenomic and intragenomic variation, and functional traits contribute to different dimensions of biodiversity (Box 1) that characterize the biota of each ecosystem. Three representative ecosystems are illustrated: a forested ecosystem (left arch), savanna ecosystem (center arch), and marine ecosystem (right arch). Microorganisms are represented by soils and sediments, illustrated as a dark band at the base of each arch. Each ecosystem contributes to ecosystem functioning, shown here primarily as biogeochemical processes (chemical exchanges between the atmosphere and biosphere shown in the outermost arch). Widespread extinction attributable to anthropic drivers (human transformations of ecosystems going from left to right in each arch) lead to biotic impoverishment (reductions in local biodiversity) and biotic homogenization (increasing dominance by domestic species). For clarity, the complexity of biogeochemical pathways and interaction networks (Figs. 2 and 3) is not shown.

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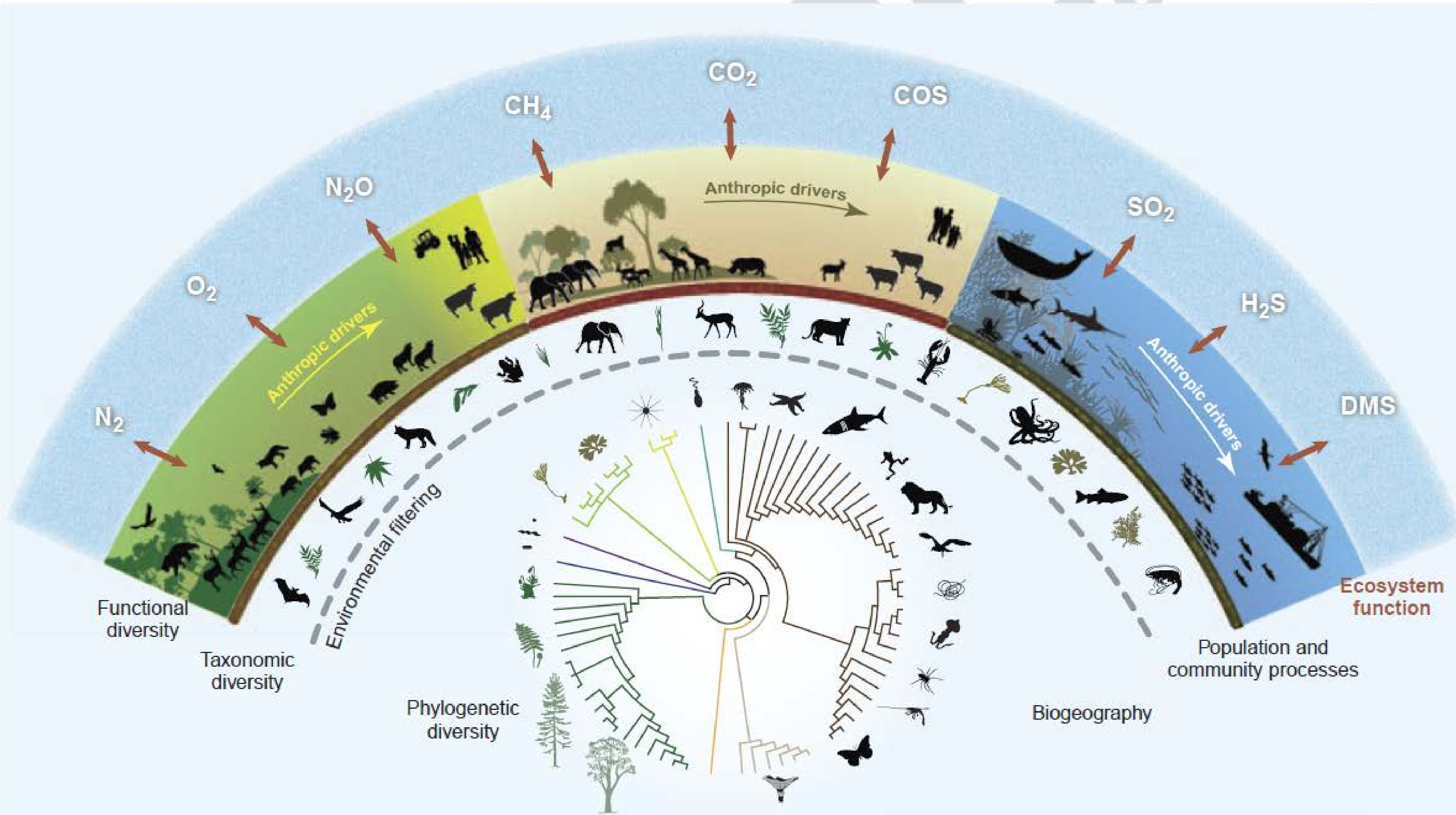


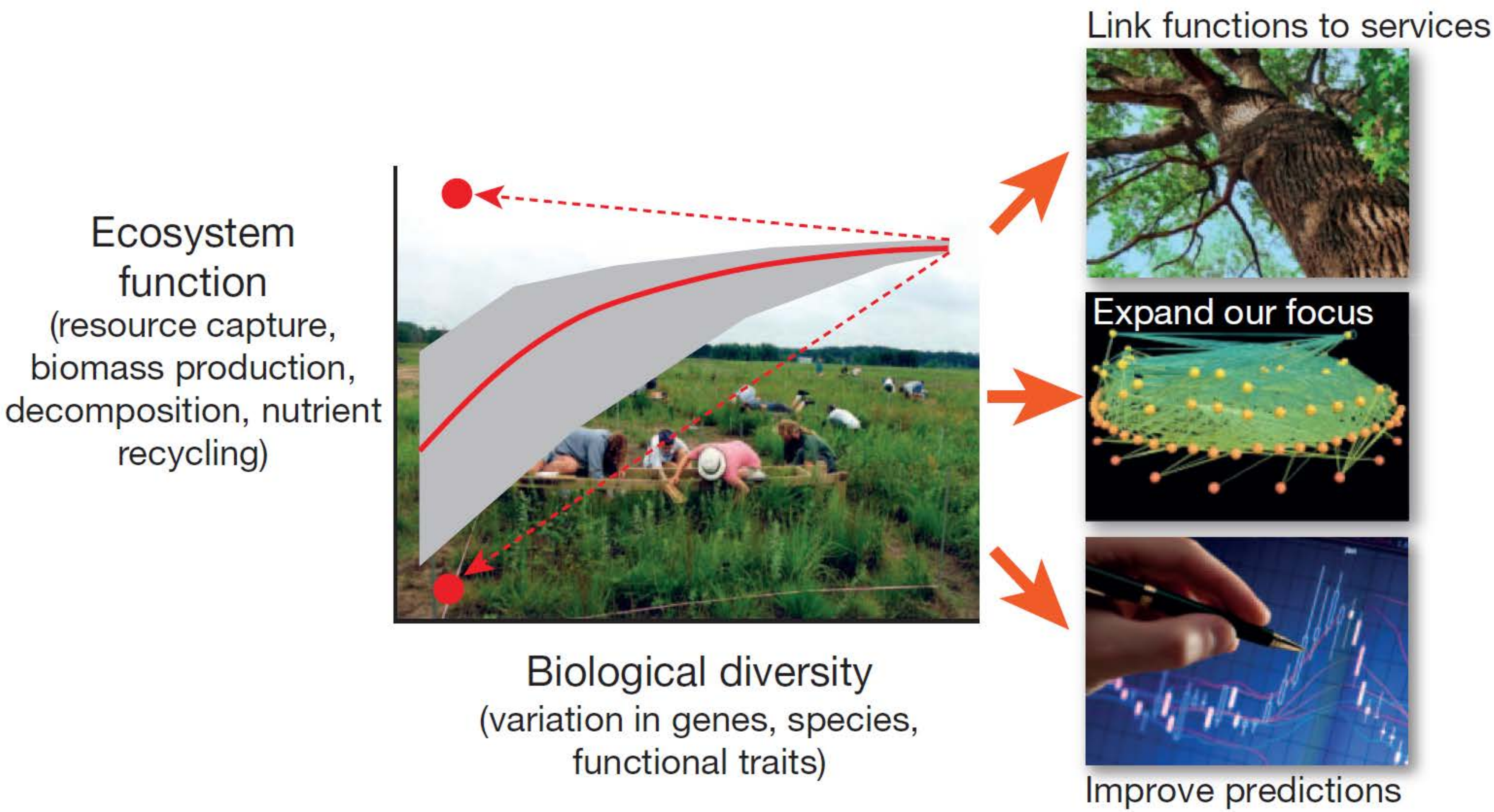
N_2
O_2
N_2O
CH_4
CO_2
COS
SO_2
H_2S
DMS
Anthropic drivers
Anthropic drivers
Anthropic drivers
Environmental filtering
Functional diversity
Taxonomic diversity
Phylogenetic diversity
Biogeography
Population and community processes
Ecosystem function

REVIEW

doi:10.1038/nature11148

Biodiversity loss and its impact on humanity

Bradley J. Cardinale[1], J. Emmett Duffy[2], Andrew Gonzalez[3], David U. Hooper[4], Charles Perrings[5], Patrick Venail[1], Anita Narwani[1], Georgina M. Mace[6], David Tilman[7], David A. Wardle[8], Ann P. Kinzig[5], Gretchen C. Daily[9], Michel Loreau[10], James B. Grace[11], Anne Larigauderie[12], Diane S. Srivastava[13] & Shahid Naeem[14]



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Biodiversity loss and its impact on humanity

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The most unique feature of Earth is the exist
Approximately 9 million types of plants, anin
Two decades ago, at the first Earth Summit,
were dismantling the Earth's ecosystems, eli
observation led to the question of how such l
their ability to provide society with the goods

7 June 2012

Table 1 | Balance of evidence linking biodiversity to ecosystem services

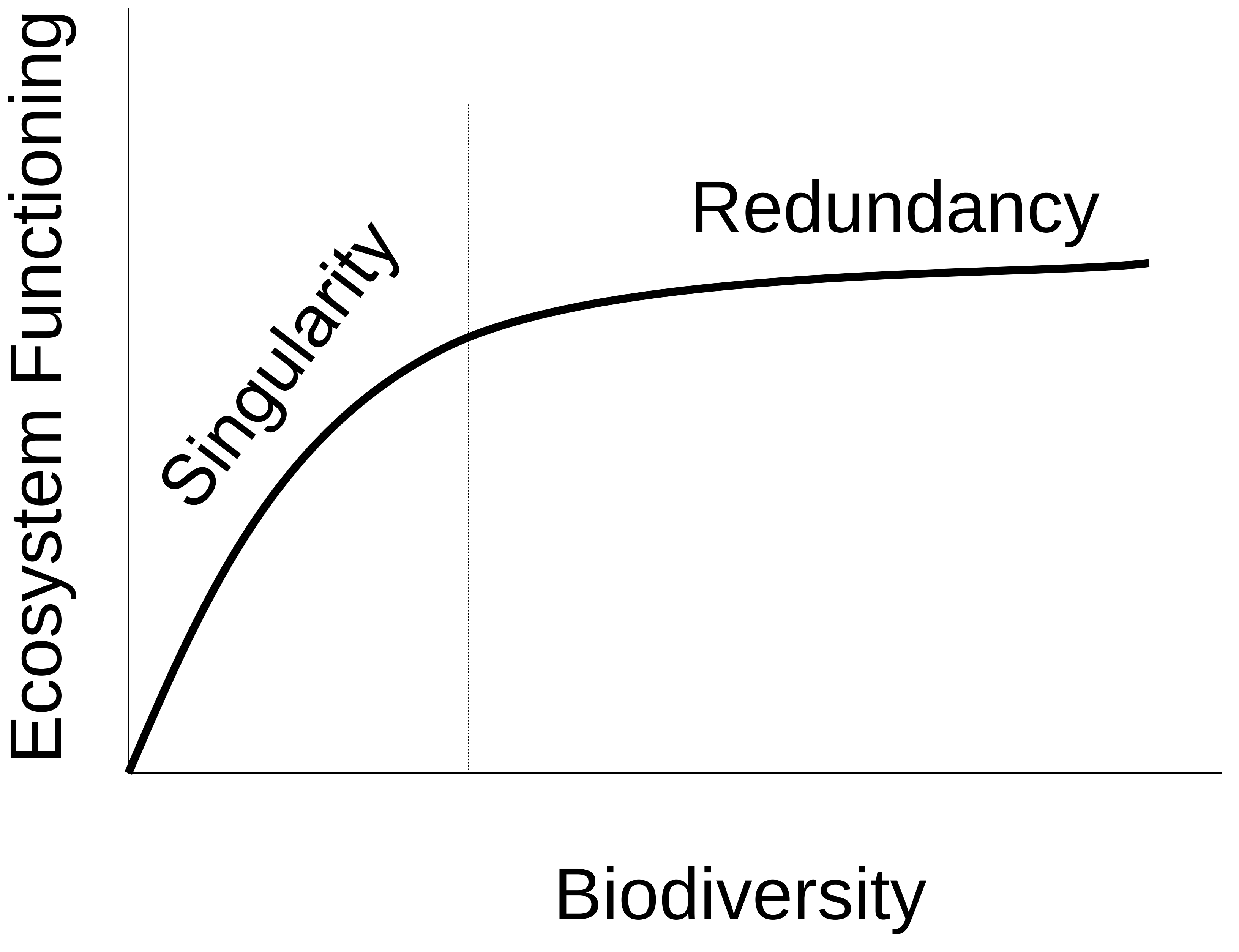
Category of service	Measure of service provision	SPU	Diversity level	Source	Study type	*N*	Relationship: Predicted	Relationship: Actual
Provisioning								
Crops	Crop yield	Plants	Genetic	DS	Exp	575	↗ (green)	↗ (green)
			Species	DS	Exp	100	↗ (yellow)	↗↘ (yellow)
Fisheries	Stability of fisheries yield	Fish	Species	PS	Obs	8	↗ (green)	↗ (green)
Wood	Wood production	Plants	Species	DS	Exp	53	↗ (green)	↗ (green)
Fodder	Fodder yield	Plants	Species	DS	Exp	271	↗ (green)	↗ (green)
Regulating								
Biocontrol	Control of herbivorous pests (bottom-up effect of plant diversity)	Plants	Species	DS*	Obs	40	↘ (green)	↘ (green)
		Plants	Species	DS†	Exp	100	↘ (green)	↘ (green)
		Plants	Species	DS‡	Exp	287	↘ (yellow)	↗↘ (yellow)
		Plants	Species	DS§	Exp	100	↘ (red)	0
	Control of herbivorous pests (top-down effect of natural enemy diversity)	Natural enemies	Species/trait	DS*	Obs	18	↘ (green)	↘ (green)
		Natural enemies	Species	DS†	Exp/Obs	266	↘ (green)	↘ (green)
		Natural enemies	Species	DS‡	Exp	38	↘ (yellow)	↗↘ (yellow)
	Resistance to plant invasion	Plants	Species	DS	Exp	120	↗ (green)	↗ (green)
	Disease prevalence (on plants)	Plants	Species	DS	Exp	107	↘ (green)	↘ (green)
	Disease prevalence (on animals)	Multiple	Species	DS	Exp/Obs	45	↘ (yellow)	↗↘ (yellow)
Climate	Primary production	Plants	Species	DS	Exp	7	↗ (red)	0
	Carbon sequestration	Plants	Species	DS	Exp	479	↗ (green)	↗ (green)
	Carbon storage	Plants	Species/trait	PS	Obs	33	↗ (yellow)	↗↘ (yellow)
Soil	Soil nutrient mineralization	Plants	Species	DS	Exp	103	↗ (green)	↗ (green)
	Soil organic matter	Plants	Species	DS	Exp	85	↗ (green)	↗ (green)
Water	Freshwater purification	Multiple	Genetic/species	PS	Exp	8	↗ (red)	0
Pollination	Pollination	Insects	Species	PS	Obs	7	↗ (yellow)	↗↘ (yellow)

Diversity begets stability

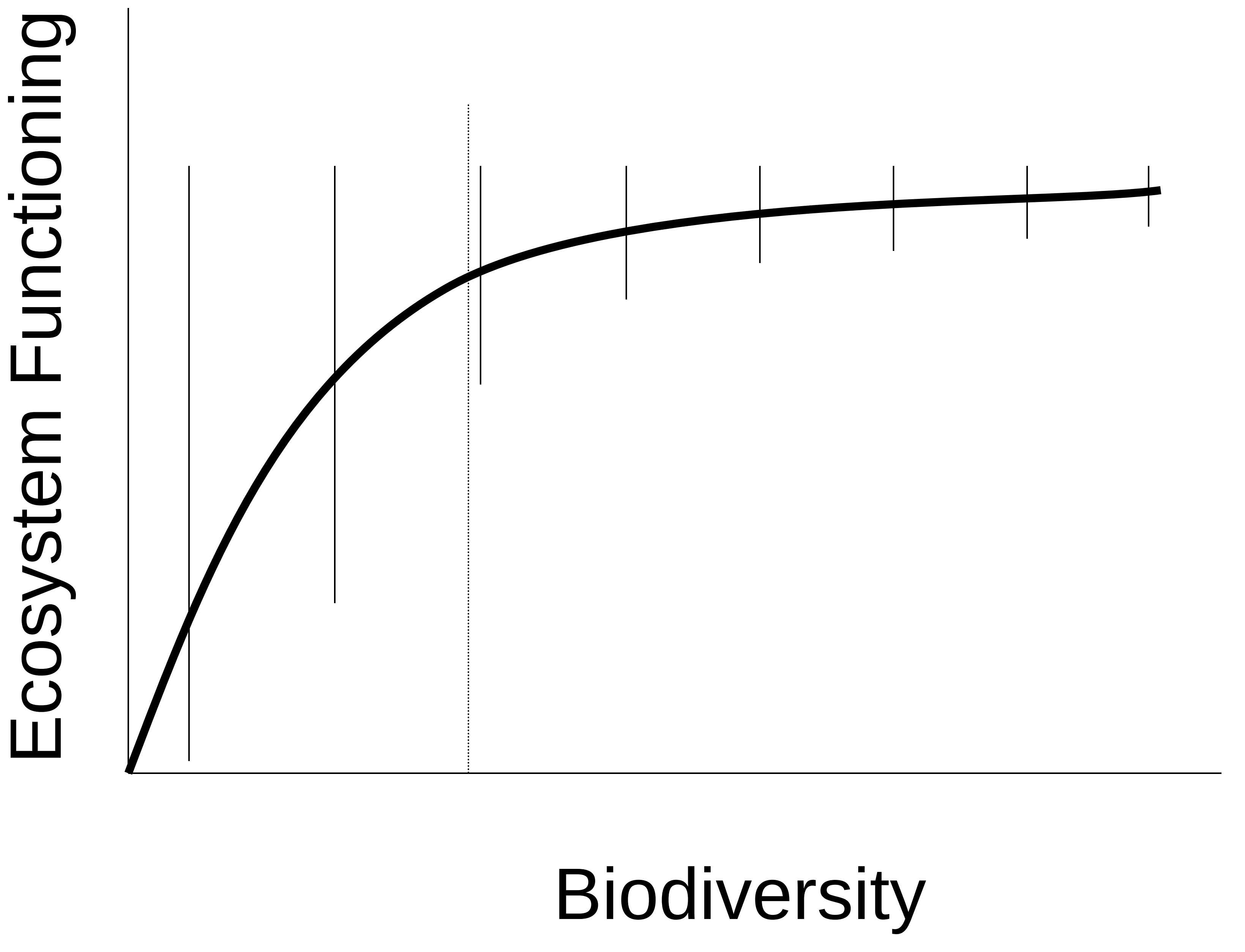
- **Over-yielding** enhances stability when mean biomass production increases with diversity more rapidly than its standard deviation.
- **Statistical averaging** occurs when random variation in the population abundances of different species reduces the variability of aggregate ecosystem variables.
- **Compensatory dynamics** are driven by competitive interactions and/or differential responses to environmental fluctuations among different life forms, both of which lead to asynchrony in their environmental responses

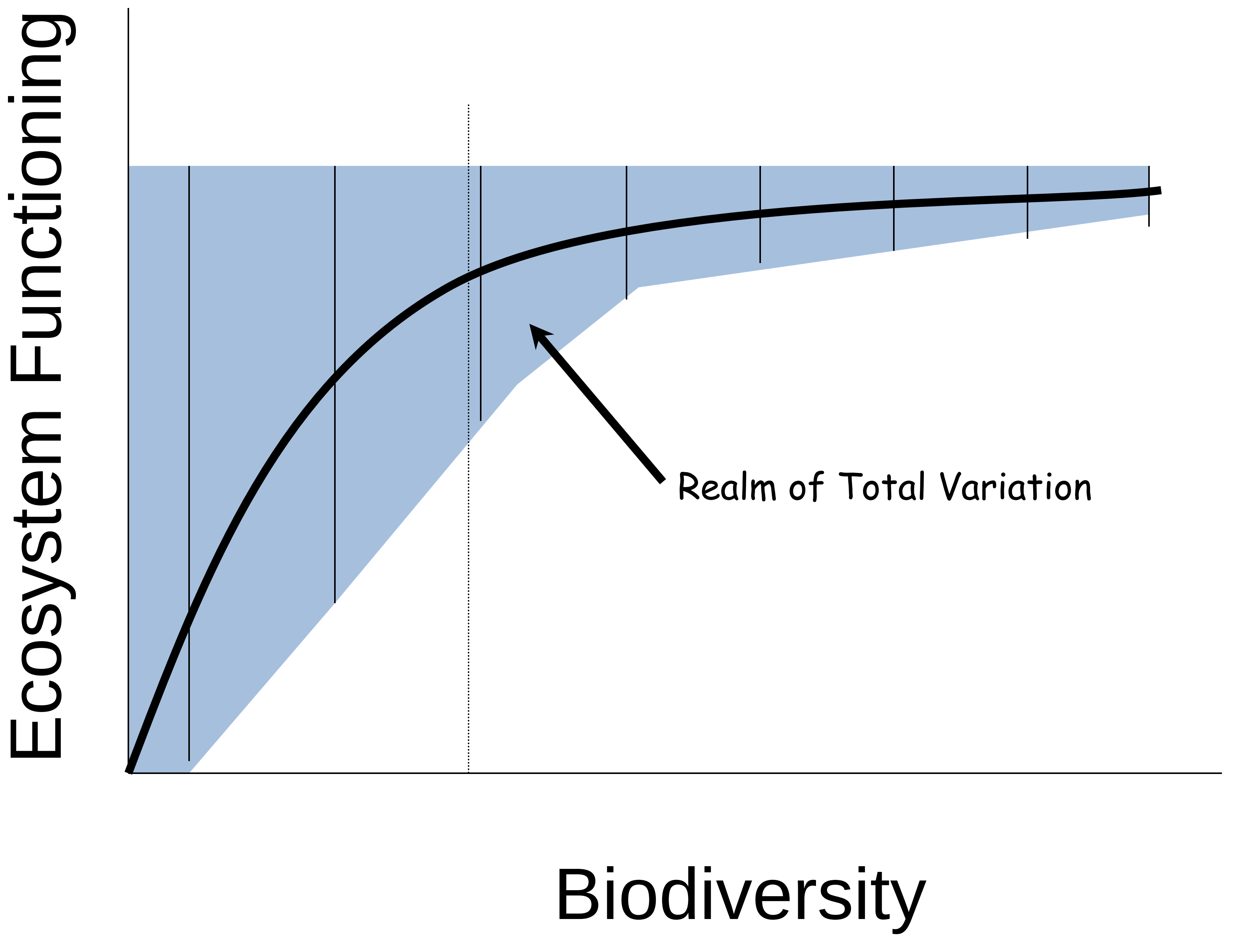
Resilience
Carpenter and Folke (2006) *TREE*

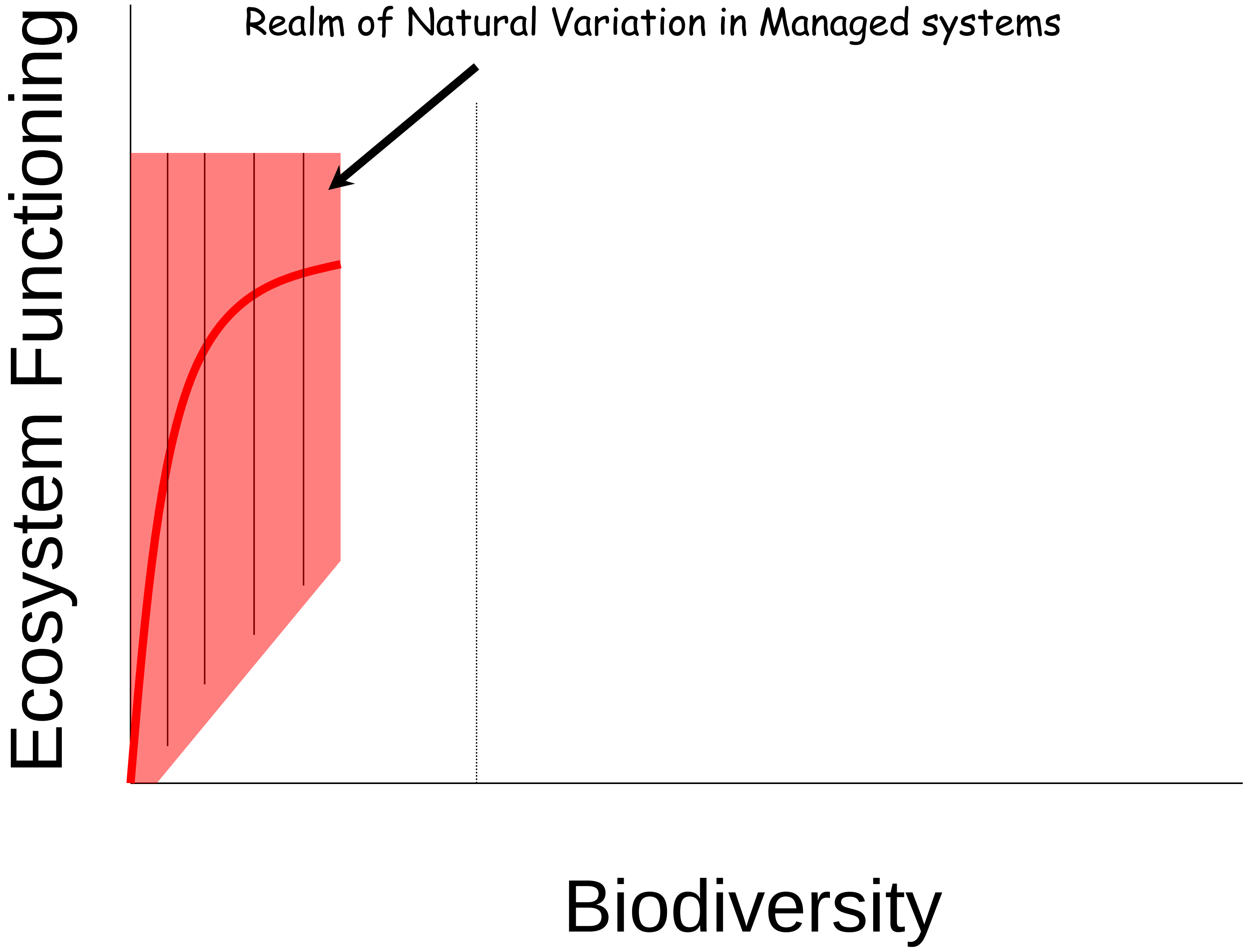
- magnitude of exogenous change or disturbance that a system can experience without undergoing a regime shift under specified conditions, functions or processes;
- the degree to which the system can organize itself (versus lack of organization, or organization forced by external factors) and
- the degree to which the system can build and increase the capacity for learning and adaptation

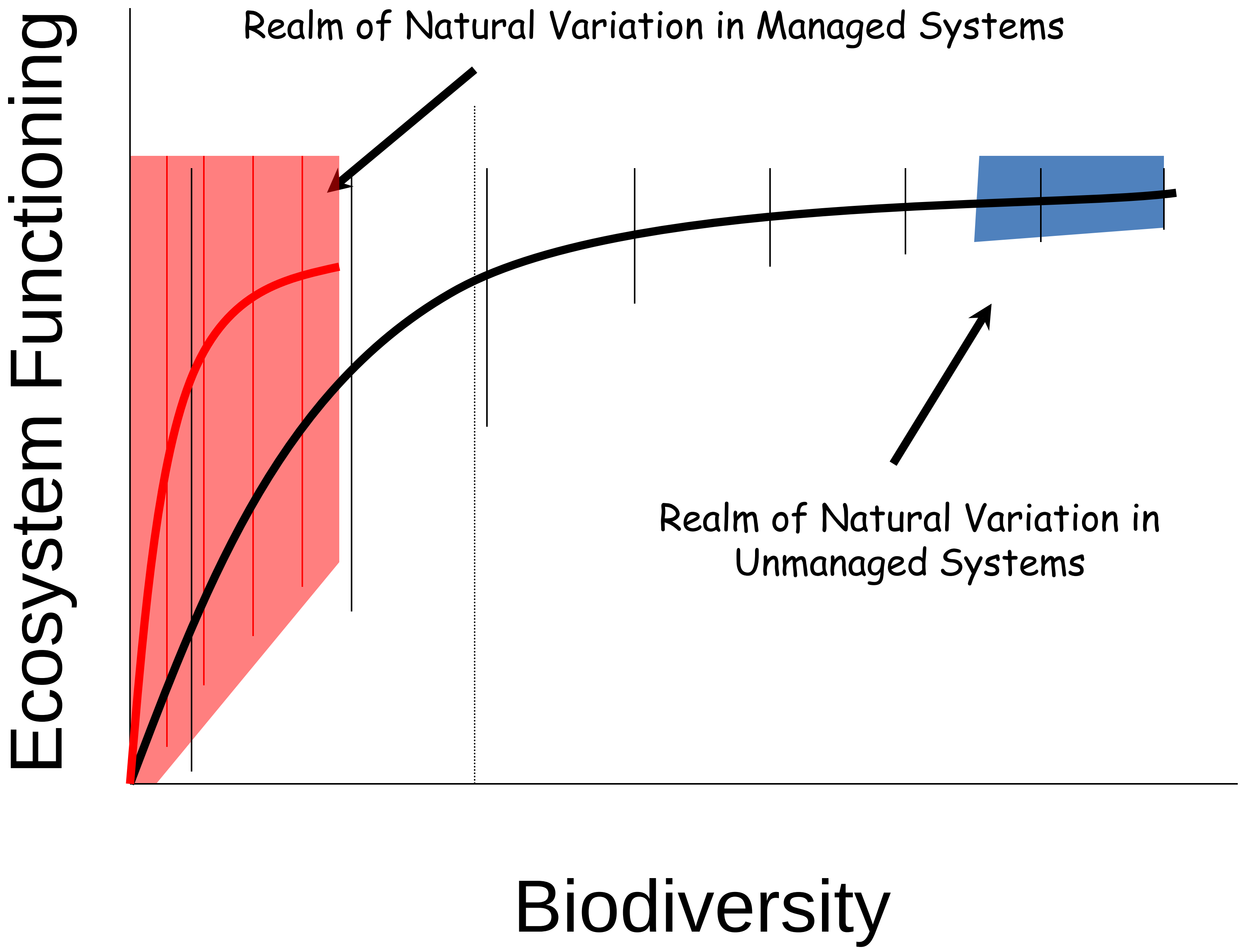


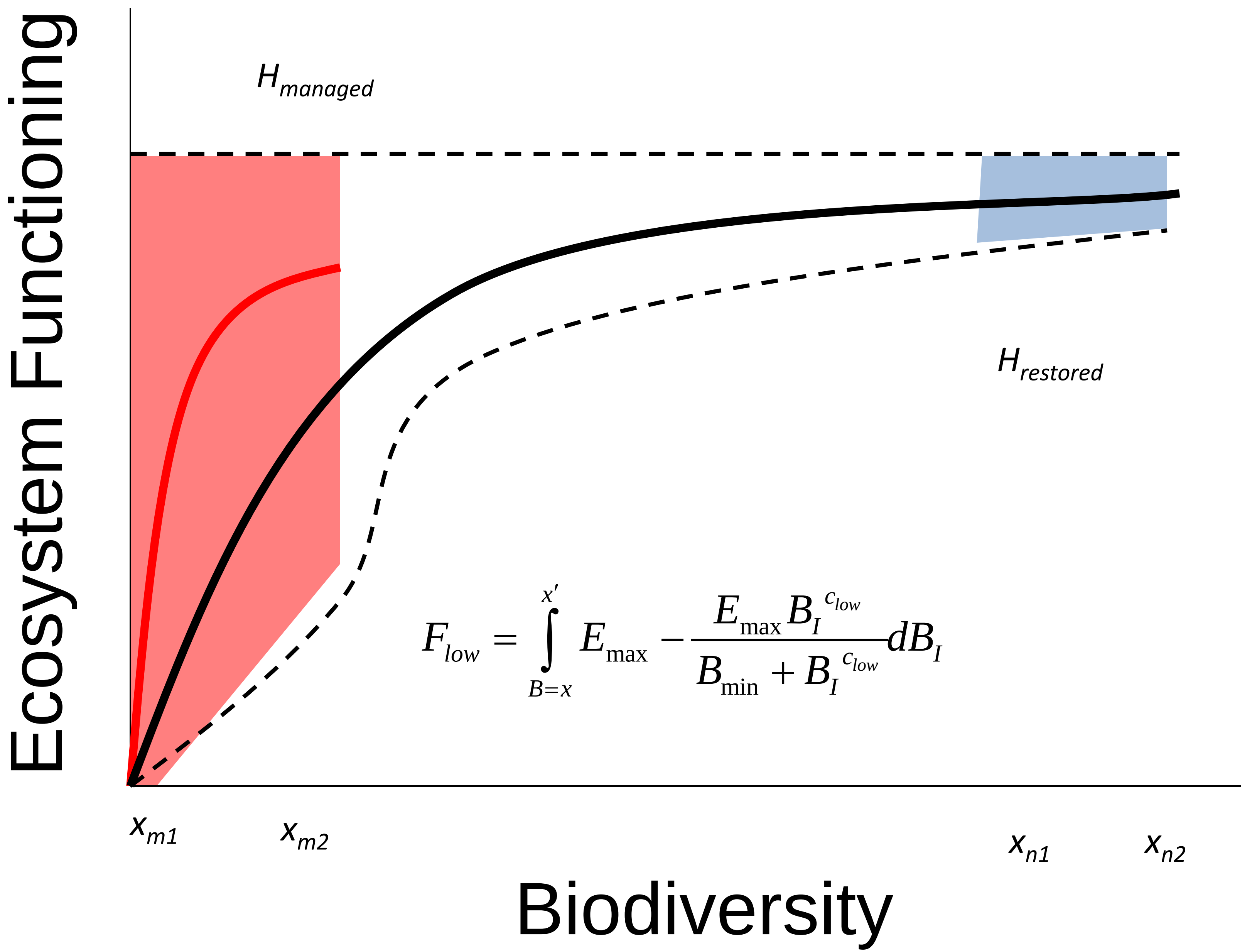
Ecosystem Functioning
Singularity
Redundancy
Biodiversity


Ecosystem Functioning
Biodiversity

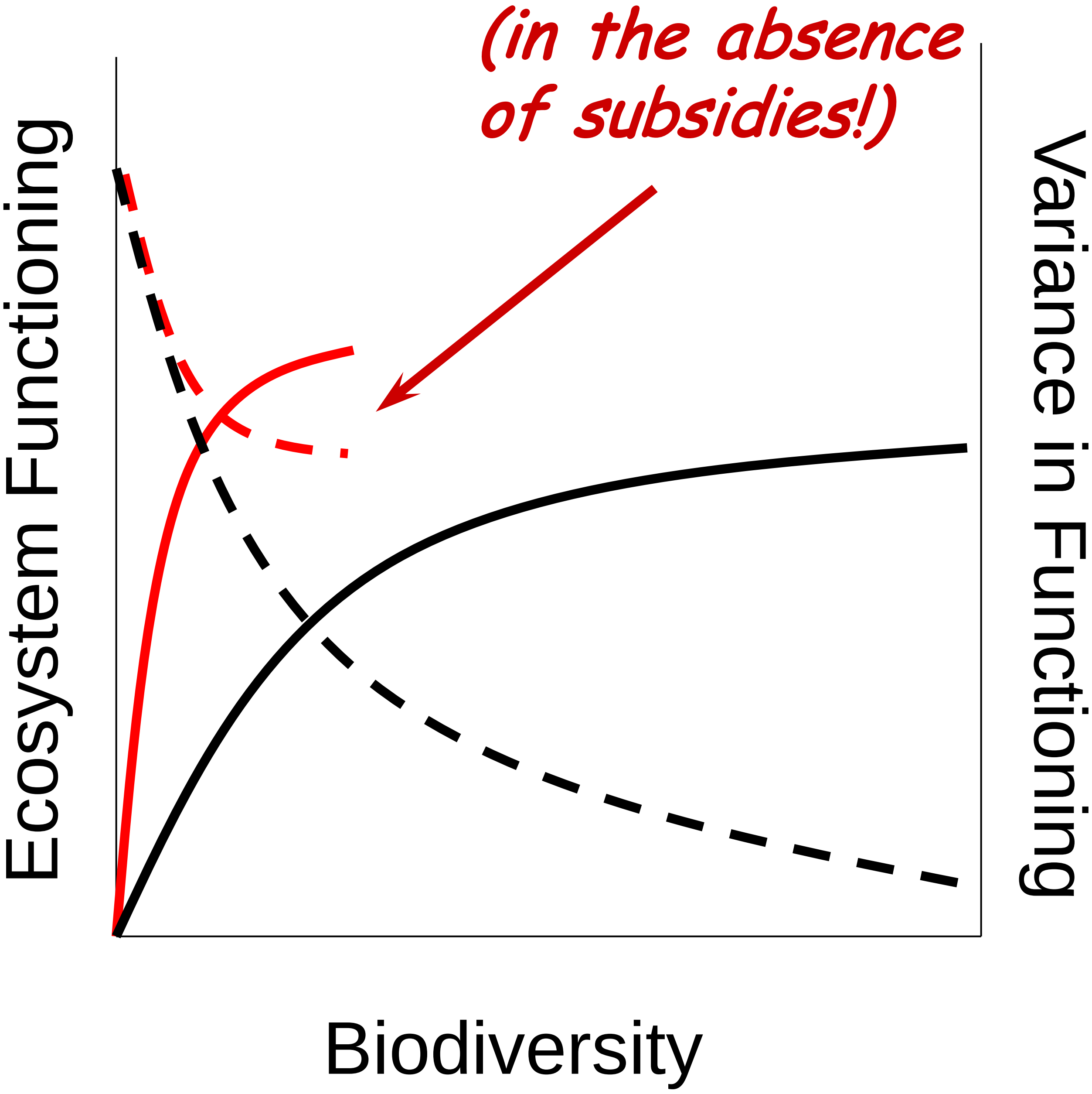

Ecosystem Functioning
Realm of Total Variation
Biodiversity


Realm of Natural Variation in Managed systems
Ecosystem Functioning
Biodiversity

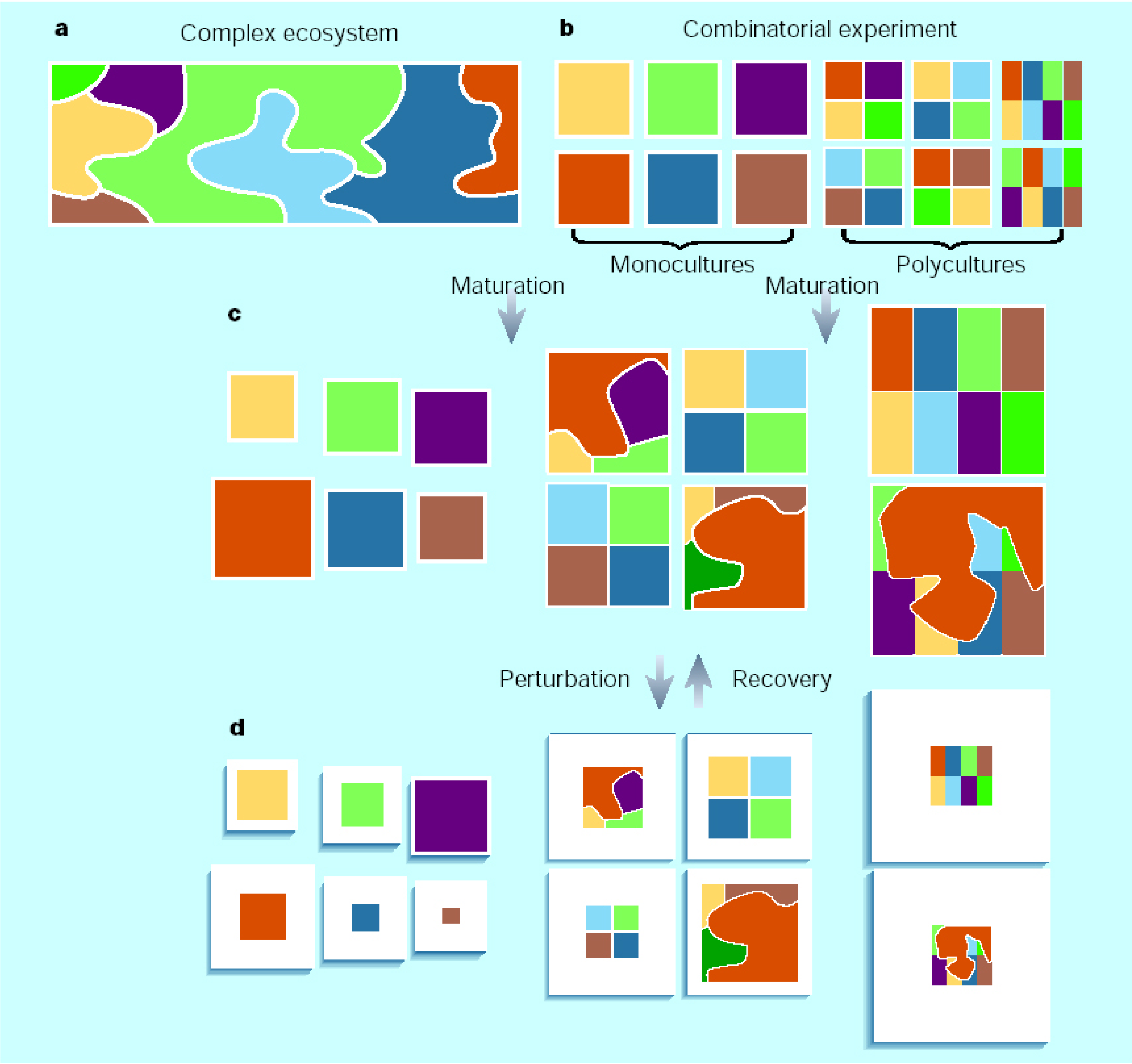

Realm of Natural Variation in Managed Systems
Realm of Natural Variation in Unmanaged Systems
Ecosystem Functioning
Biodiversity



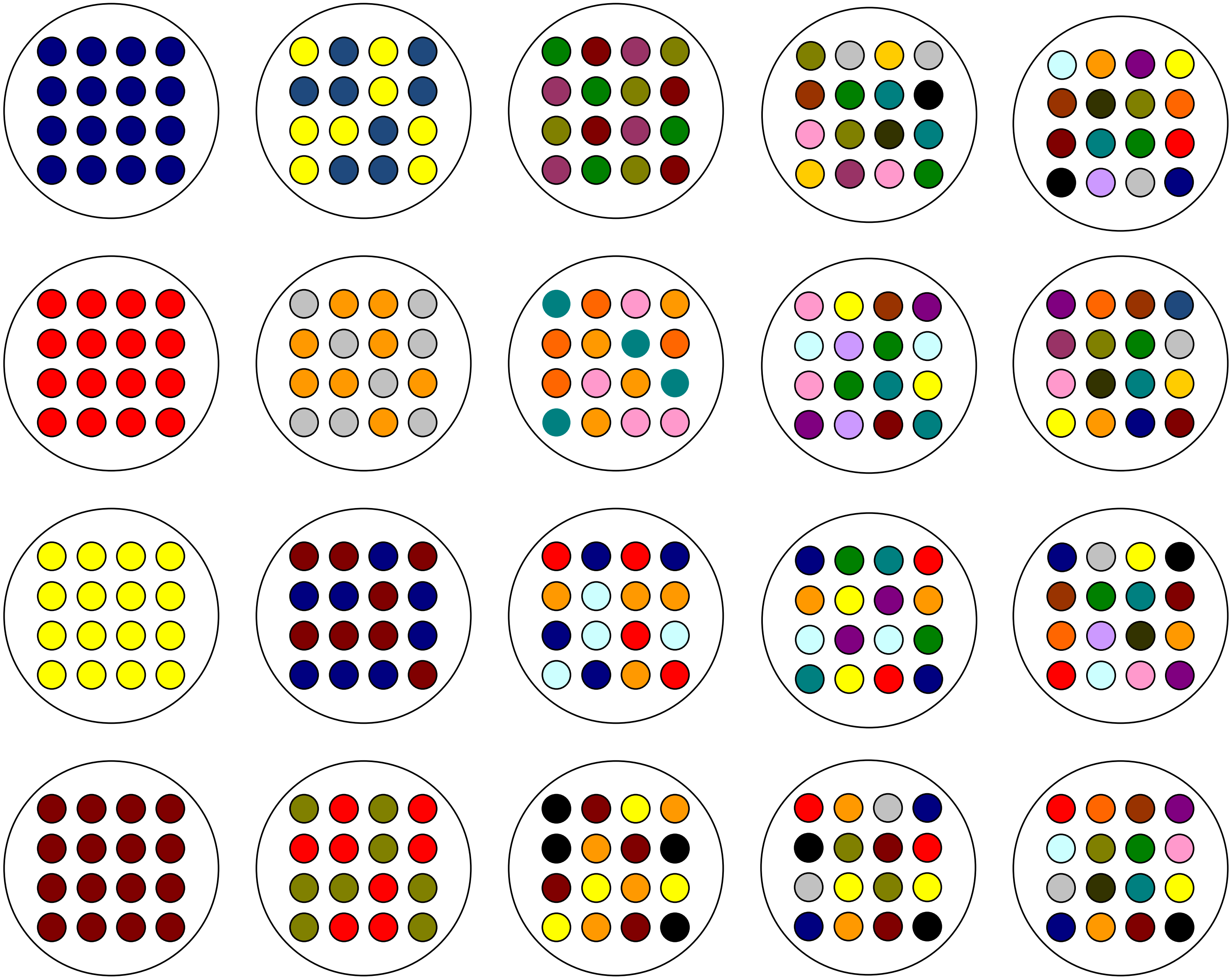
Ecosystem Functioning
$H_{managed}$
$H_{restored}$
$$F_{low} = \int_{B=x}^{x'} E_{max} - \frac{E_{max} B_I^{c_{low}}}{B_{min} + B_I^{c_{low}}} dB_I$$
x_{m1}
x_{m2}
x_{n1}
x_{n2}
Biodiversity



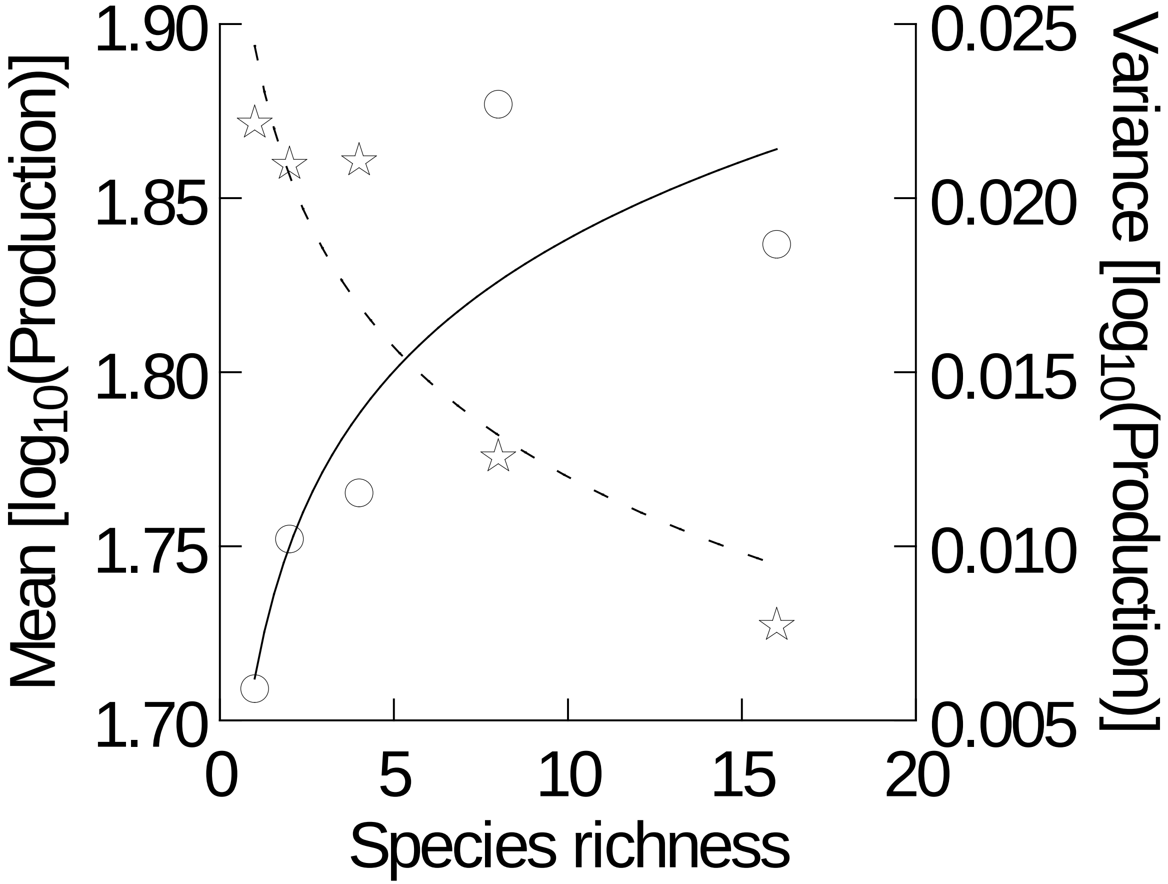
(in the absence
of subsidies!)
Ecosystem Functioning
Variance in Functioning
Biodiversity



Naeem, S. 2002. Nature 416:23-24



Above-ground Biomass



Biodiversity loss and carbon storage in the BCI Forest Dynamics Plot

Daniel E. Bunker[1], Fabrice De Clerck[2], Robert K. Colwell[3], Ivette Perfecto[4], Oliver Phillips[5], Mahesh Sankaran[6] and Shahid Naeem[1]

1. Department of Ecology, Evolution and Environmental Biology, Columbia University
2. Earth Institute, Columbia University
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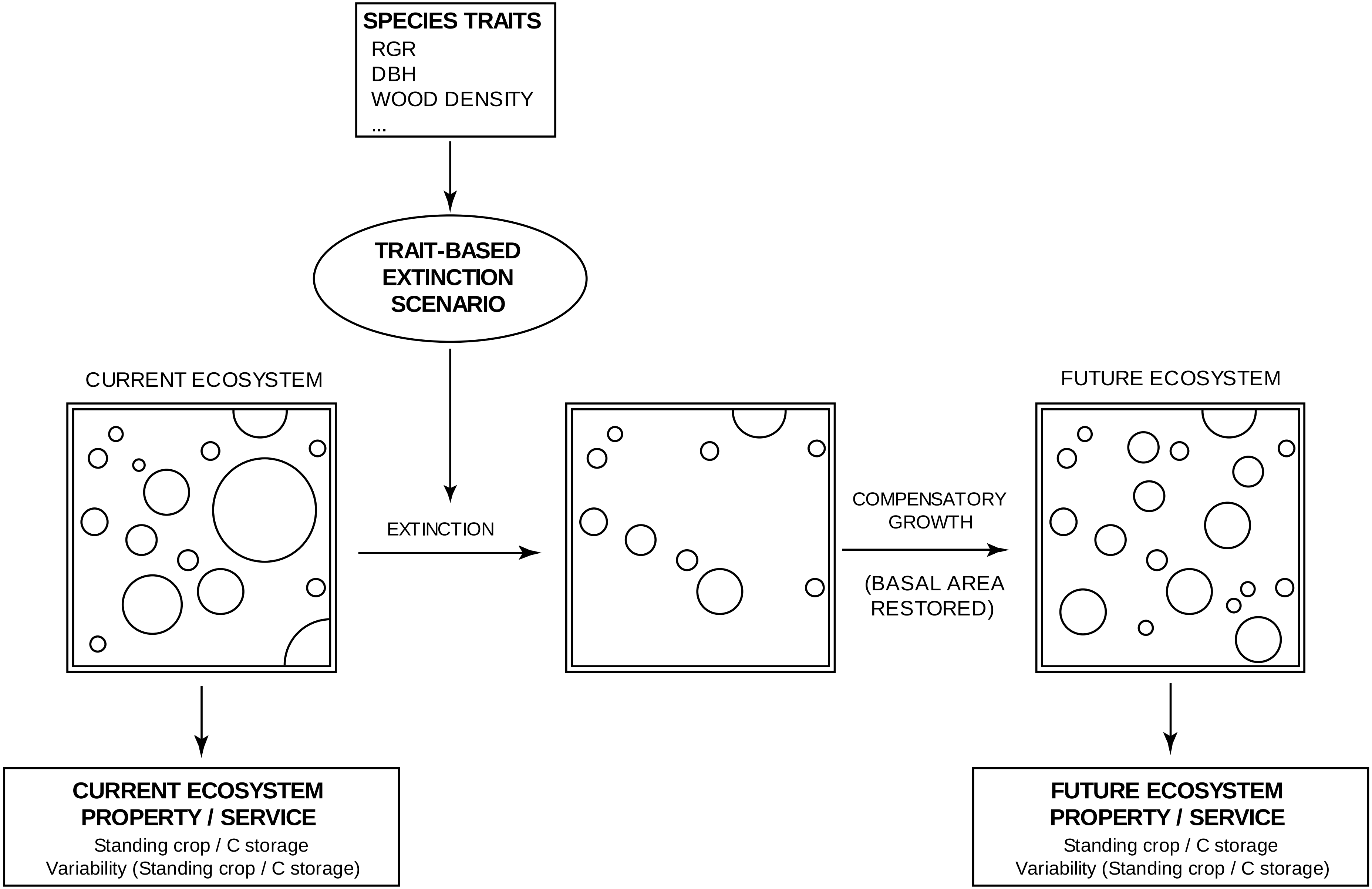
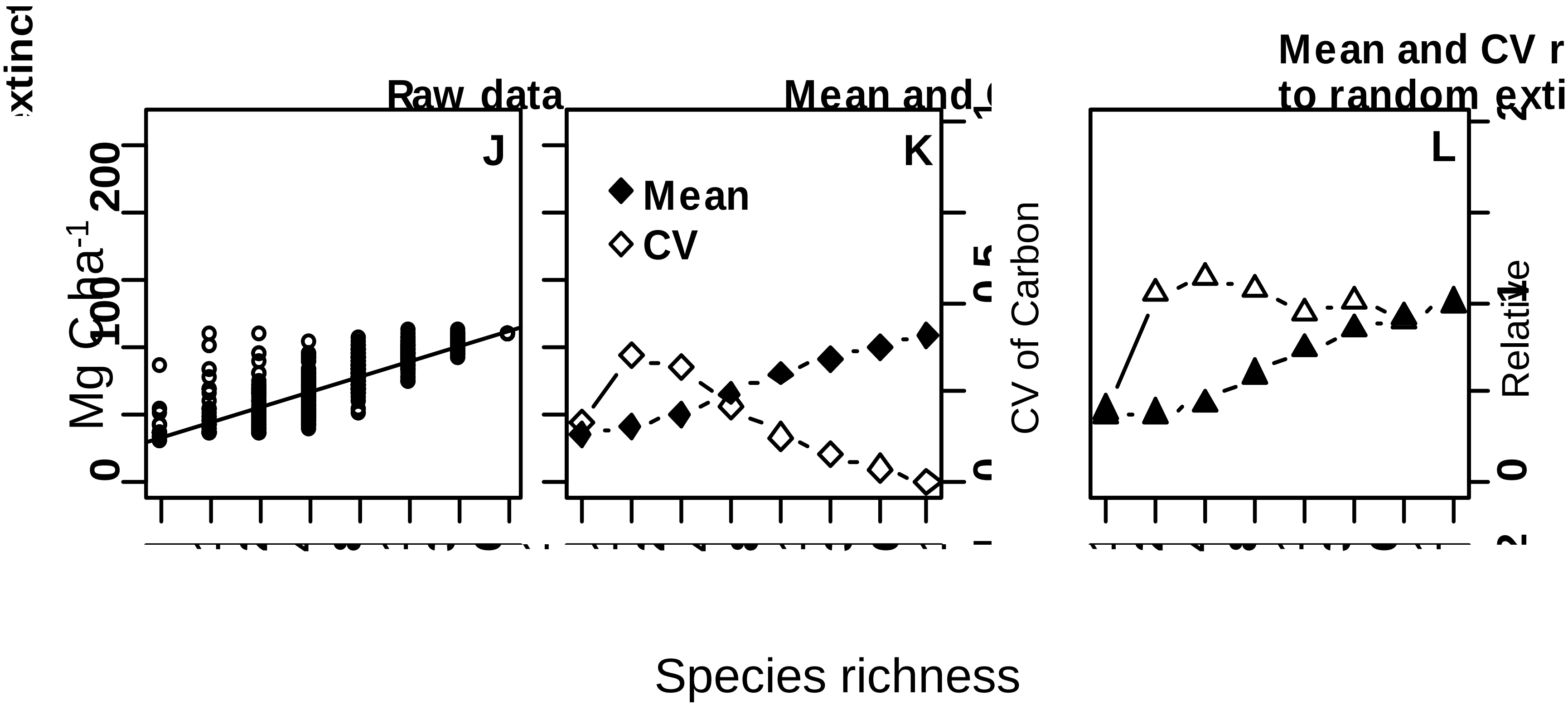
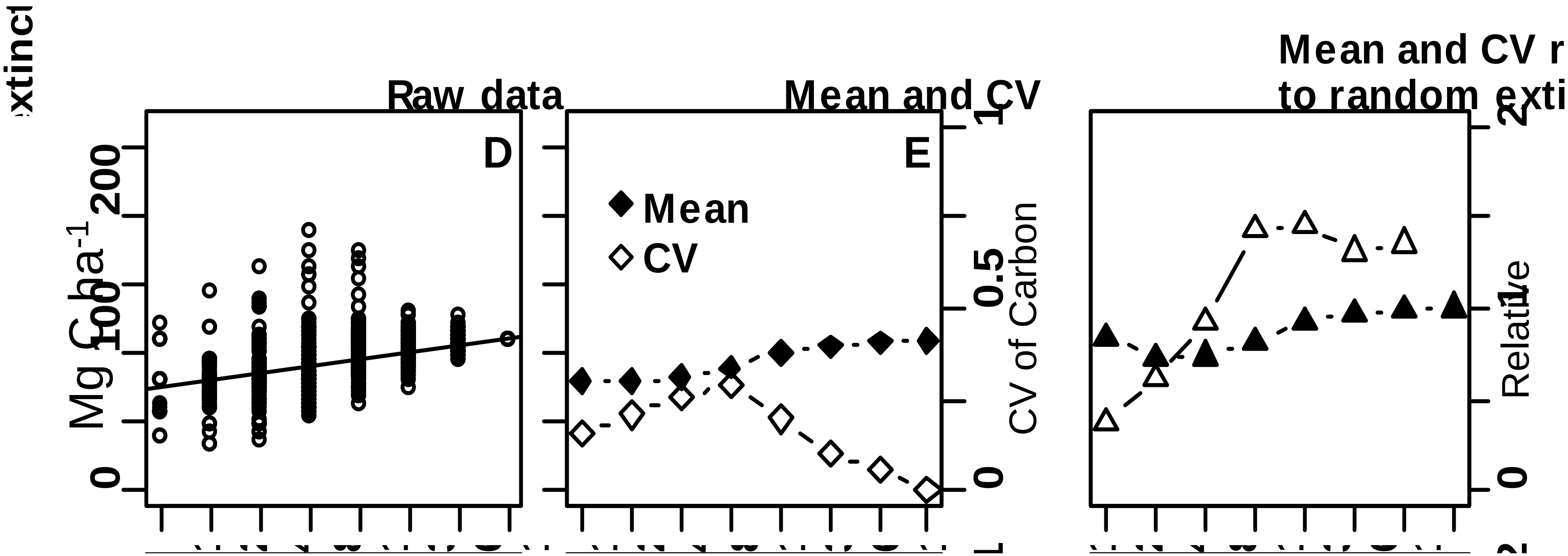
5. Earth and Biosphere Institute, School of Geography, University of Leeds
6. Natural Resource Ecology Laboratory, Colorado State University


SPECIES TRAITS
RGR
DBH
WOOD DENSITY
...
TRAIT-BASED EXTINCTION SCENARIO
CURRENT ECOSYSTEM
EXTINCTION
COMPENSATORY GROWTH
(BASAL AREA RESTORED)
FUTURE ECOSYSTEM
CURRENT ECOSYSTEM PROPERTY / SERVICE
Standing crop / C storage
Variability (Standing crop / C storage)
FUTURE ECOSYSTEM PROPERTY / SERVICE
Standing crop / C storage
Variability (Standing crop / C storage)

High wood-density species lost first



Large-statured species lost first



Species richness

Biological Diversity
What do we mean?

Ecology, 92(8), 2011, pp. 1573–1581

Functional and phylogenetic diversity as predictors of biodiversity–ecosystem-function relationships

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Abstract. How closely does variability in ecologically important traits reflect evolutionary divergence? The use of phylogenetic diversity (PD) to predict biodiversity effects on ecosystem functioning, and more generally the use of phylogenetic information in community ecology, depends in part on the answer to this question. However, comparisons of the predictive power of phylogenetic diversity and functional diversity (FD) have not been conducted across a range of experiments. To address how phylogenetic diversity and functional trait variation control biodiversity effects on biomass production, we summarized the results of 29 grassland plant experiments where both the phylogeny of plant species used in the experiments is well described and where extensive trait data are available. Functional trait variation was only partially related to phylogenetic distances between species, and the resulting FD values therefore correlate only partially with PD. Despite these differences, FD and PD predicted biodiversity effects across all experiments with similar strength, including in subsets that

Biological Diversity: What do We Mean?

What is the best predictor of ecosystem function? S, FD, or PD?

Table 2. Model comparison results of linear mixed models predicting the log response ratio of biomass production for all plots, including with and without legumes and fertilized experimental plots.

Using PD from molecular phylogeny (110 species)				Using PD from angiosperm supertree (121 species)			
Predictor	R^2	w_i	n	Predictor	R^2	w_i	n
All plots			1074	All plots			1419
PD	**0.196**	**0.989**		PD	0.223	0.002	
FD[N, height, N-fixation]	0.181	4.8×10^{-5}		**FD[N, height, N-fixation]**	**0.223**	**0.907**	
PD + FD[N, height, N-fixation]	0.197	0.01		PD + FD[N, height, N-fixation]	0.229	0.003	
S	0.177	5.5×10^{-6}		*S*	0.204	2.3×10^{-8}	
FGR	0.170	7.5×10^{-9}		FGR	0.187	2.4×10^{-16}	
No legumes			506	No legumes			636
PD	**0.105**	**0.48**		PD	0.123	2.7×10^{-4}	
FD[N, height]	0.096	0.146		**FD[N, height, SRL]**	**0.120**	**0.495**	
PD + FD[N, height]	0.107	0.064		PD + FD[N, height, SRL]	0.125	3.8×10^{-5}	
S	0.097	0.043		*S*	0.110	0.001	
FGR	0.074	3.3×10^{-6}		FGR	0.078	4.8×10^{-9}	
Fertilized plots			212	Fertilized plots			302
PD	0.186	0.117		PD	0.220	0.002	
FD[height, N-fixation]	**0.172**	**0.216**		**FD[height, N-fixation]**	**0.221**	**0.606**	
PD + FD[height, N-fixation]	0.188	0.024		PD + FD[N, height, N-fixation]	0.233	2.8×10^{-6}	
S	0.161	0.002		*S*	0.204	2.6×10^{-7}	
FGR	0.123	6.7×10^{-5}		FGR	0.198	3.5×10^{-10}	

But aren't FD, PD, and S all correlated?

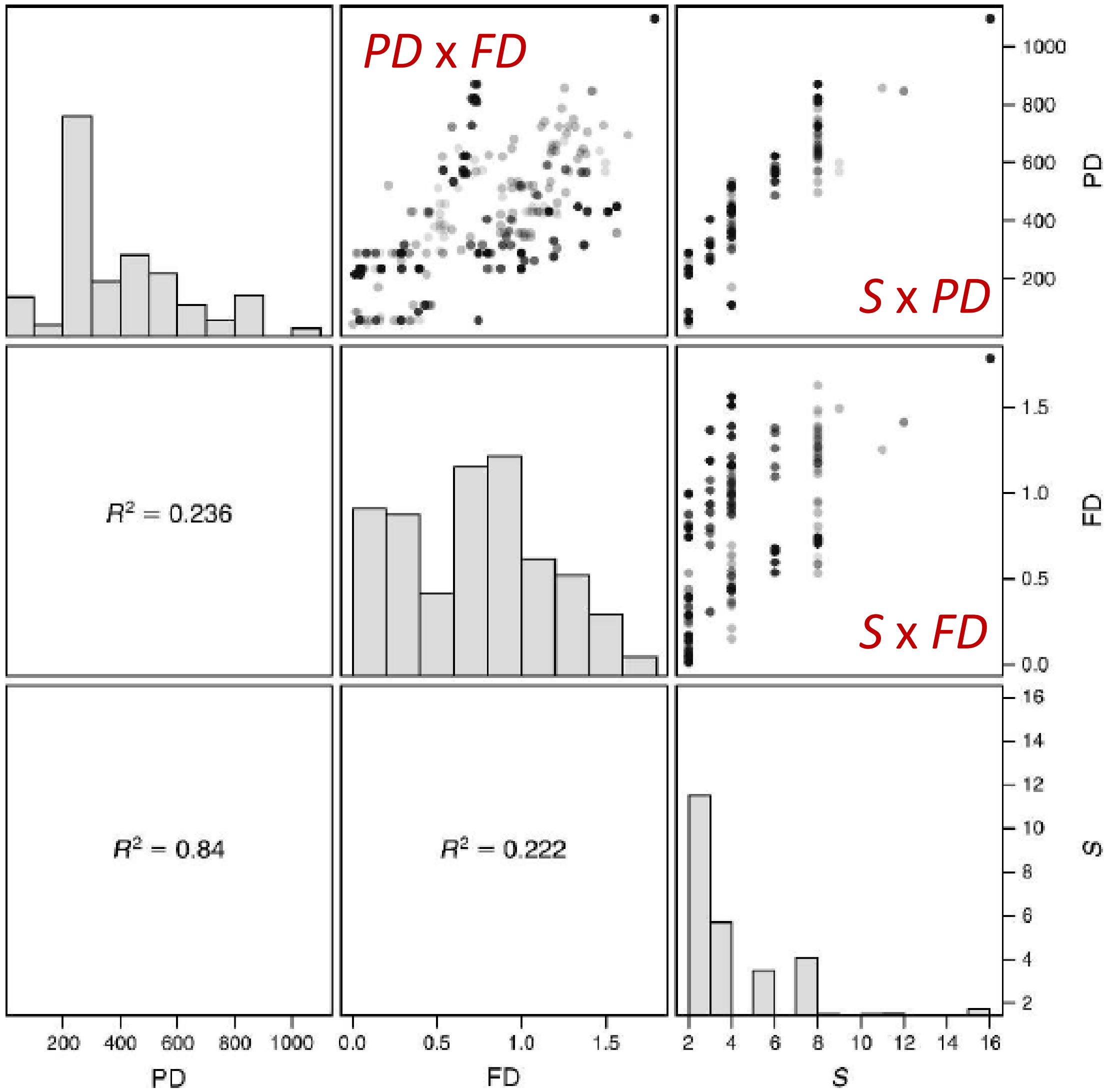


FIG. 2. Relationships between the three continuous measures of biodiversity used in this study. Axes for scatter plots are in units of diversity for each measure. Histograms are shown in the diagonal, with R^2 values shown in the bottom panels. PD and FD values shown are the same as in Fig. 1.

What is the right dimension of biodiversity?

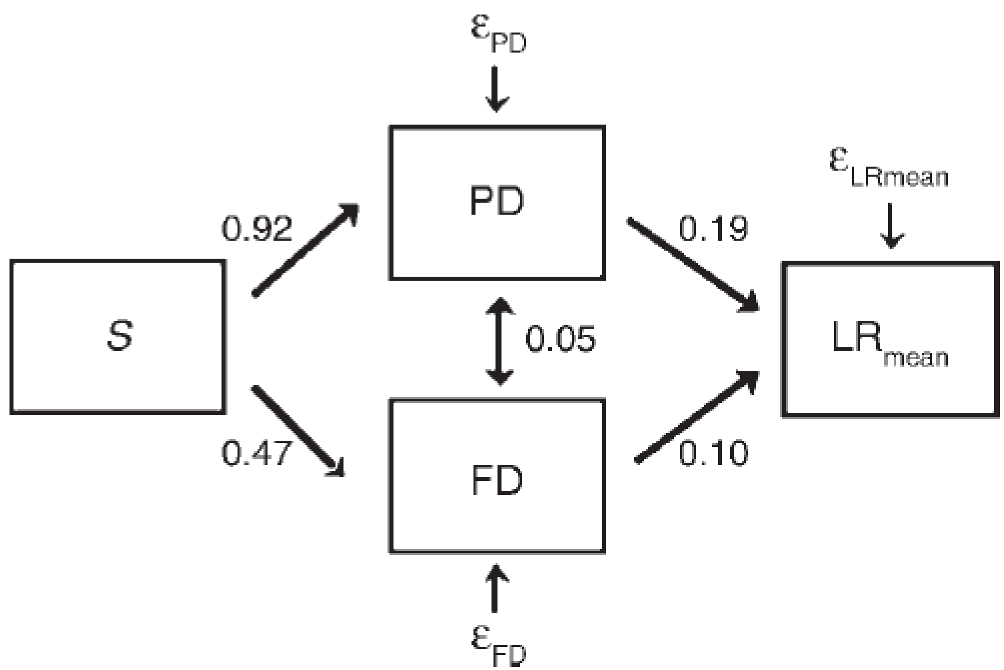


FIG. 3. Best-fit structural equation model combining S, FD, and PD calculated from the molecular phylogeny, across all plots ($\chi^2 = 3.37$, df = 1, $P = 0.067$). The model shown, M8, includes a correlation between FD and PD. Model M3, the best model for three subsets of the data, excludes this correlation (see Table 3). Values give the standardized coefficients for the relationship between "upstream" and "downstream" variables; all coefficients are significant. Epsilons represent the error term for downstream variables. See the Appendix for the full set of models.

A. Biological Capacity

Journal of Applied Ecology

British Ecological Socie

Journal of Applied Ecology doi: 10.1111/j.1365-2664.2010.0194

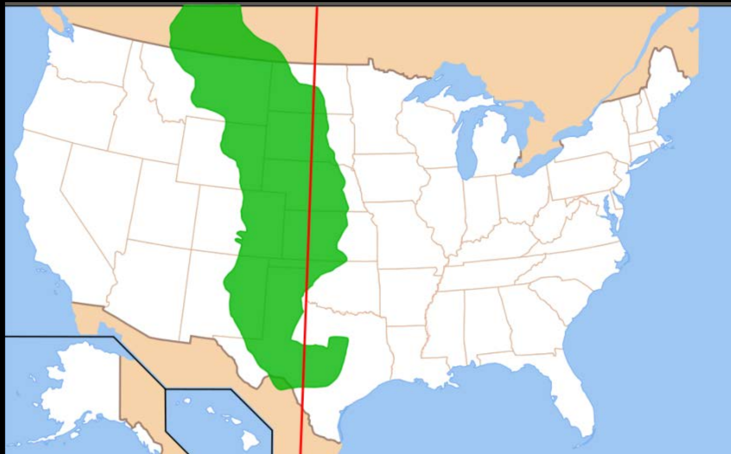
The effect of agricultural diversity and crop choice on functional capacity change in grassland conversions

Brenda B. Lin[1,2]*‡, Dan F.B. Flynn[2]‡, Daniel E. Bunker[2]†, María Uriarte[2] and Shahid Naeem[2]

GREAT PLAINS PRAIRIE

THIRD IN A SERIES

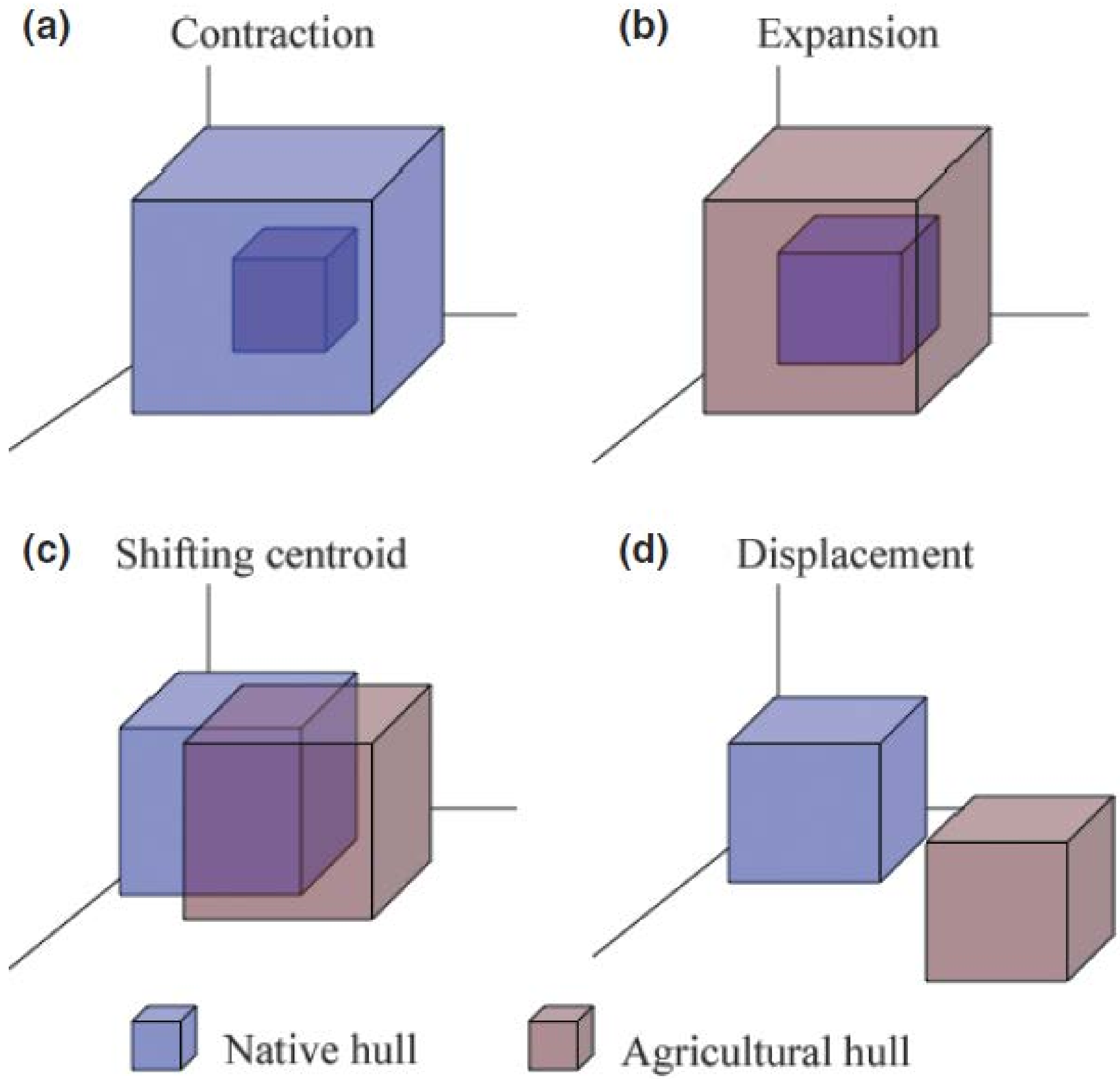
N A T U R E   O F   A M E R I C A



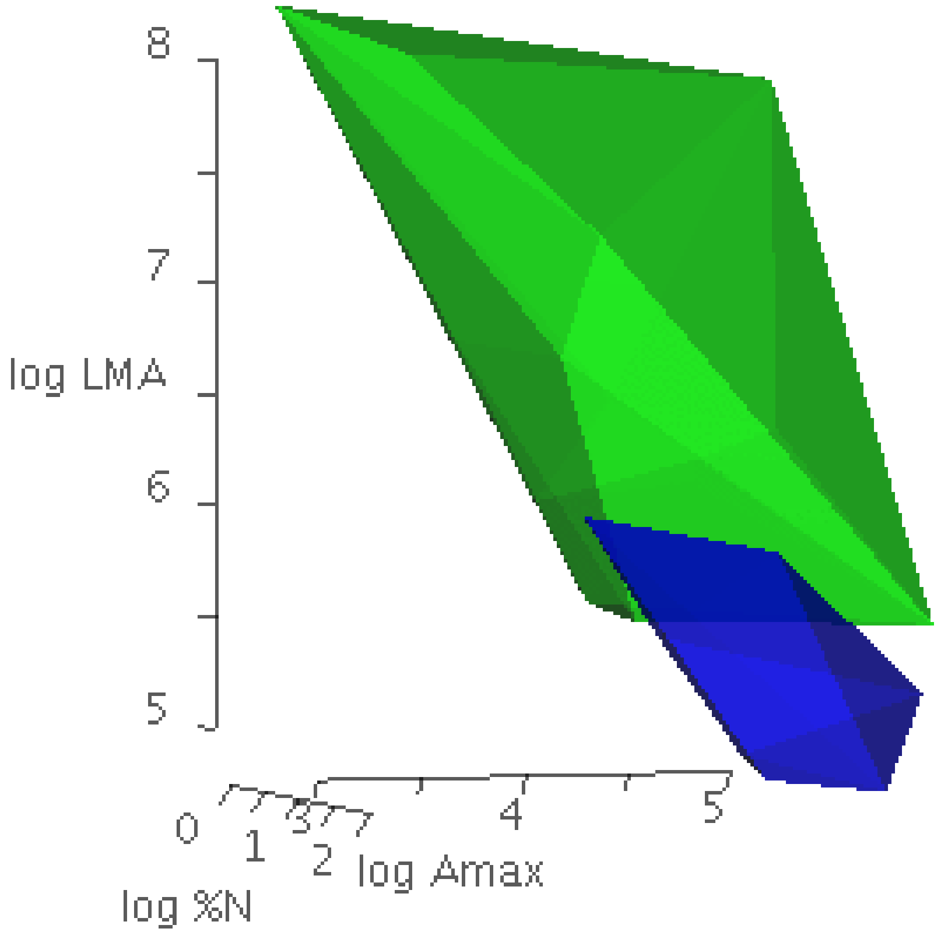
Edenic

Human-dominated

Functional (Bio-) Capacity: Functional Trait Volume (FTV): Convex Hull



All Natives vs. All Agricultural Plants



Lin et al. 2010

Eisenhauer *et al.* 2012

- "Microorganisms represent the functional backbone of virtually any ecosystem, and it is essential to understand their response under changing abiotic and biotic conditions."
- Stability of microbial productivity = f(genotypic richness, functional diversity)
- Stability = reliability = ecosystem function variability across treatments.

Eisenhauer *et al.* 2012

- 8 *Pseudomonas fluorescens* strains.
- Microbial productivity = OD_{600}
- Varied resources
- Varied invasion by *Seratia liquefaciens or Pseudomonas putida*
- Reliability = 1/CV
- Functional diversity = 5 carbon sources they could use

Eisenhauer *et al.* 2012

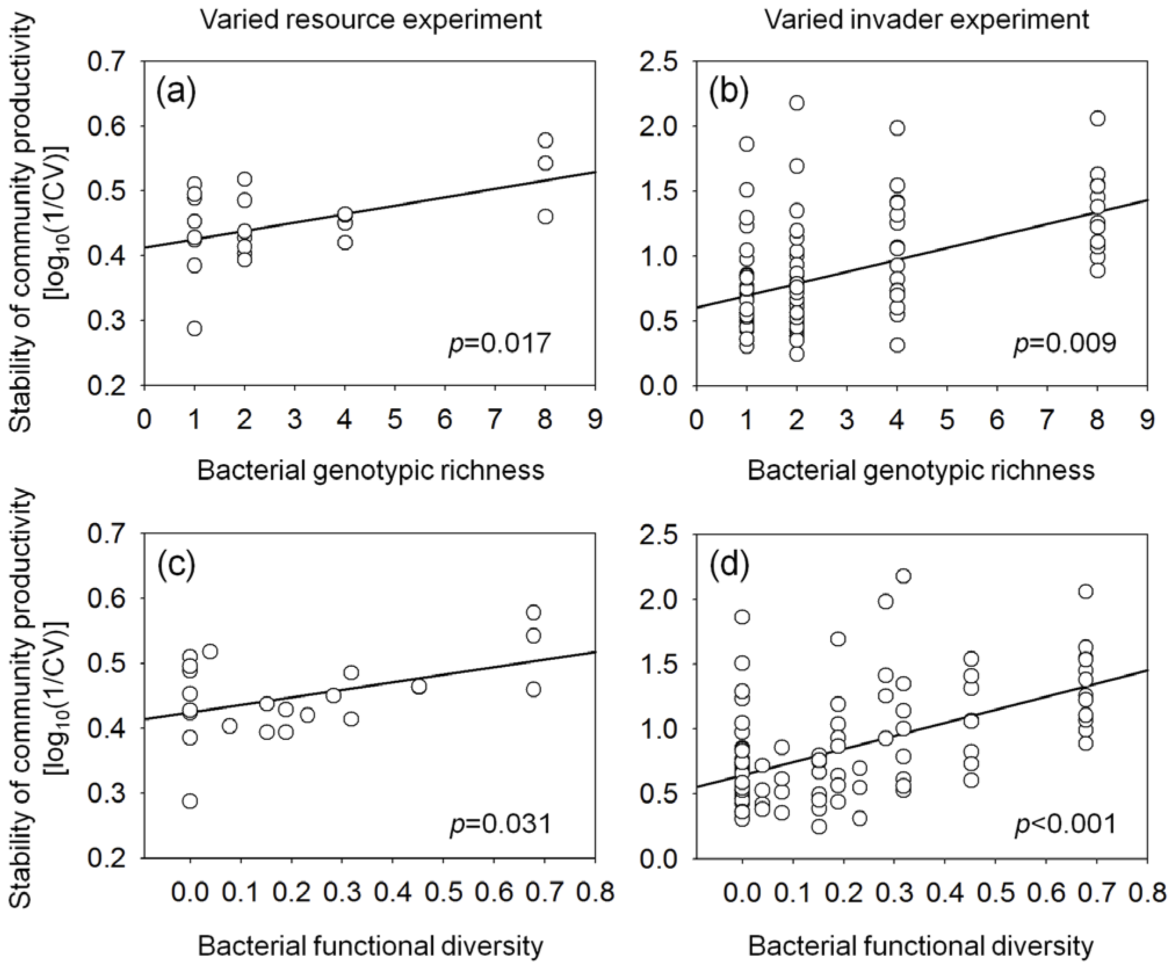
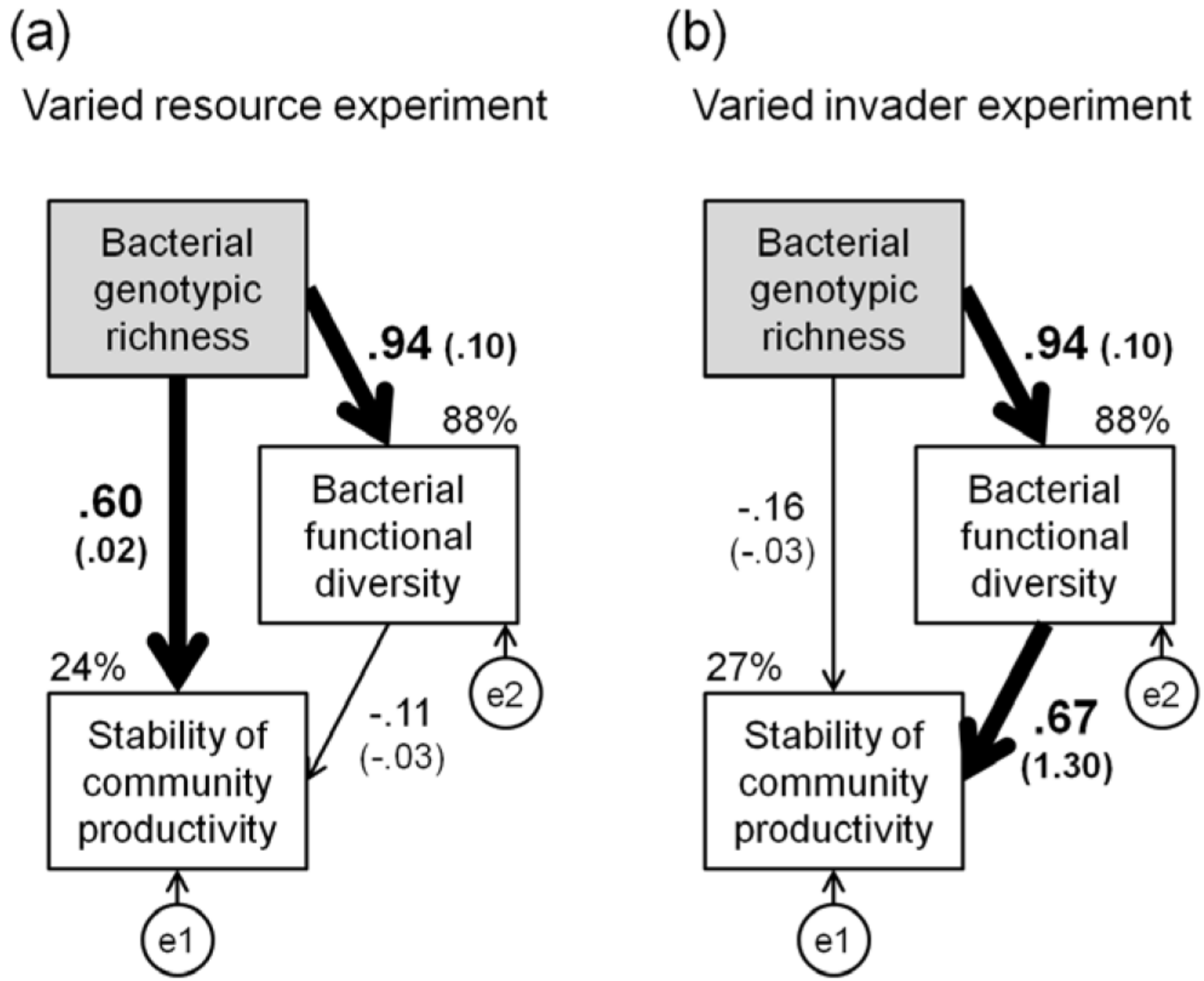


Figure 1. Stability of community productivity as affected by bacterial genotypic and functional diversity. Effects of bacterial genotypic (a, b) and functional diversity (c, d) on the stability of community productivity in varied resource environments (1/coefficient of variation of 14 resource treatments) (a, c) and invader treatments (no invader, *Pseudomonas putida* and *Serratia liquefaciens* as model invaders) (b, d). Each circle represents the stability of productivity of a given bacterial community in varied abiotic (a, c) or biotic environments (b, d).

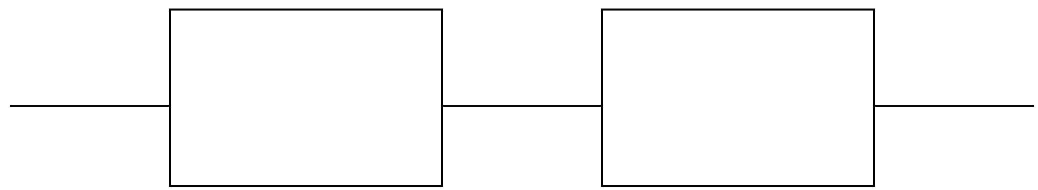
doi:10.1371/journal.pone.0034517.g001

Eisenhauer *et al.* 2012

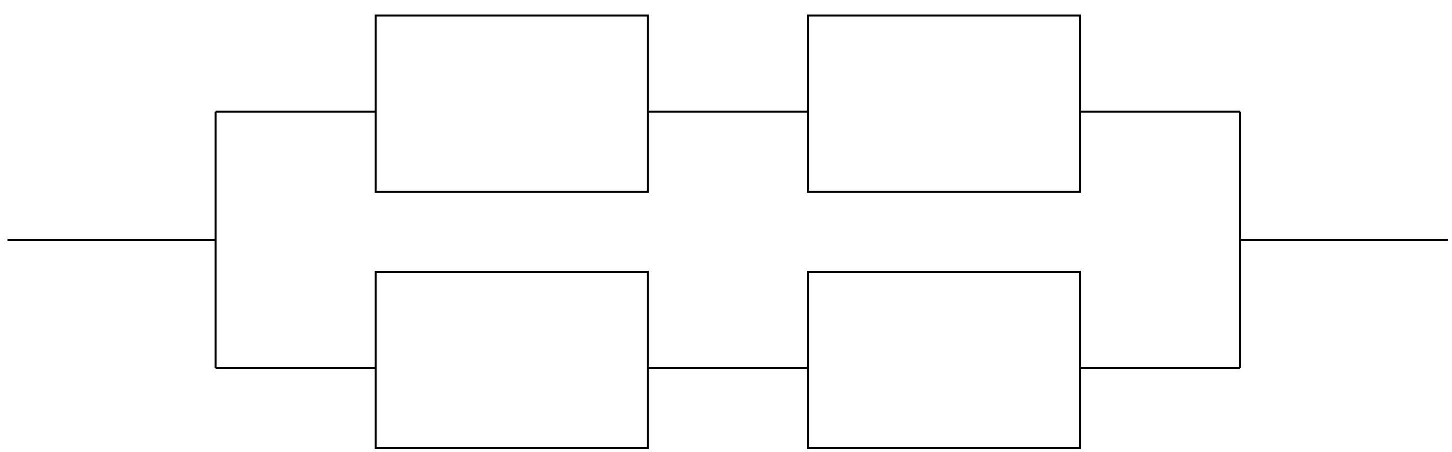


Ecosystem Reliability

Serial dependency



Parallel redundancy



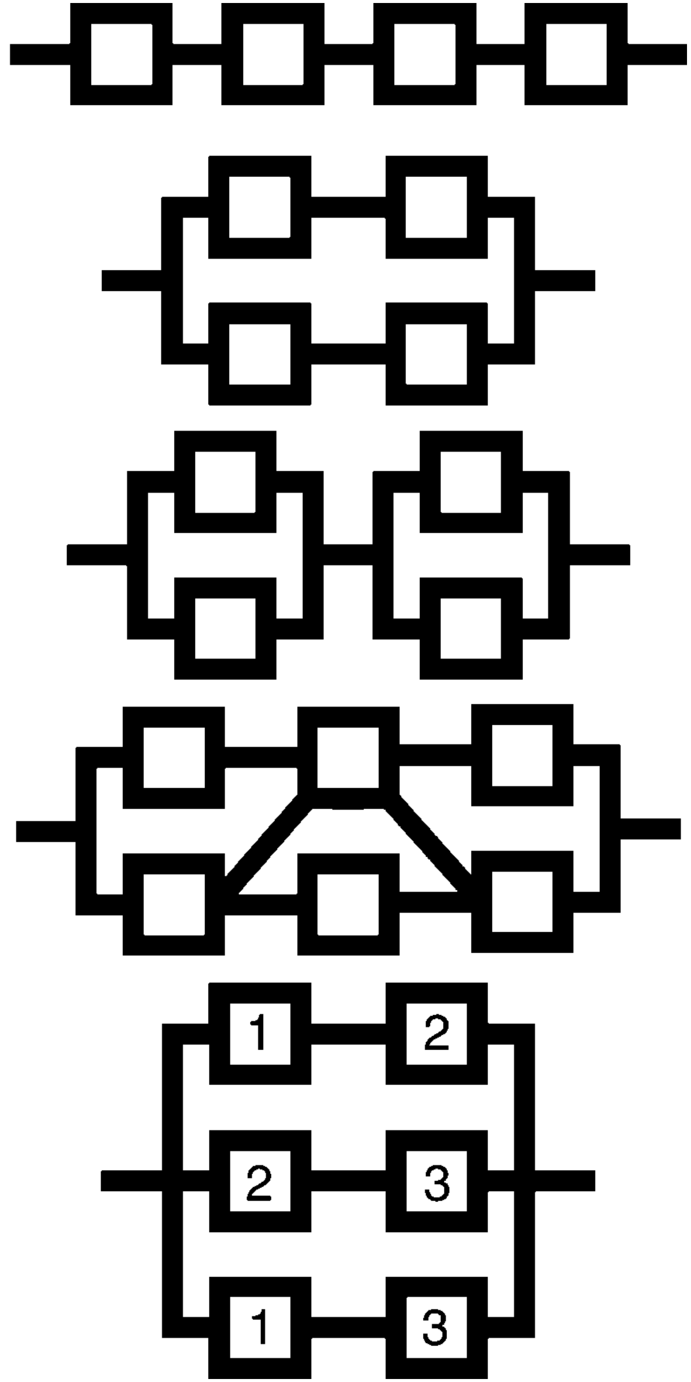
SERIAL

PARALLEL REDUNDANCY (high level)

PARALLEL REDUNDANCY (low level)

LINKED REDUNDANCY

m/k REDUNDANCY



$$R1(t) := e^{-\lambda \cdot t}$$ (λ1 = 0.1)

$$R2(t) := R1(t)^{N}$$ serial dependency (N = 10 components)

$$R3(t) := 1 - (1 - R1(t))^{N}$$ parallel redundant (N = 10 components, fully redundant)

$$Rls(t) := 2 \cdot e^{-\lambda 2 \cdot t} + e^{-2 \cdot \lambda \cdot t} - 2 \cdot e^{-(\lambda + \lambda 2) \cdot t}$$

$$Rls2(t) := 2 \cdot e^{-\lambda 3 \cdot t} + e^{-2 \cdot \lambda \cdot t} - 2 \cdot e^{-(\lambda + \lambda 3) \cdot t}$$

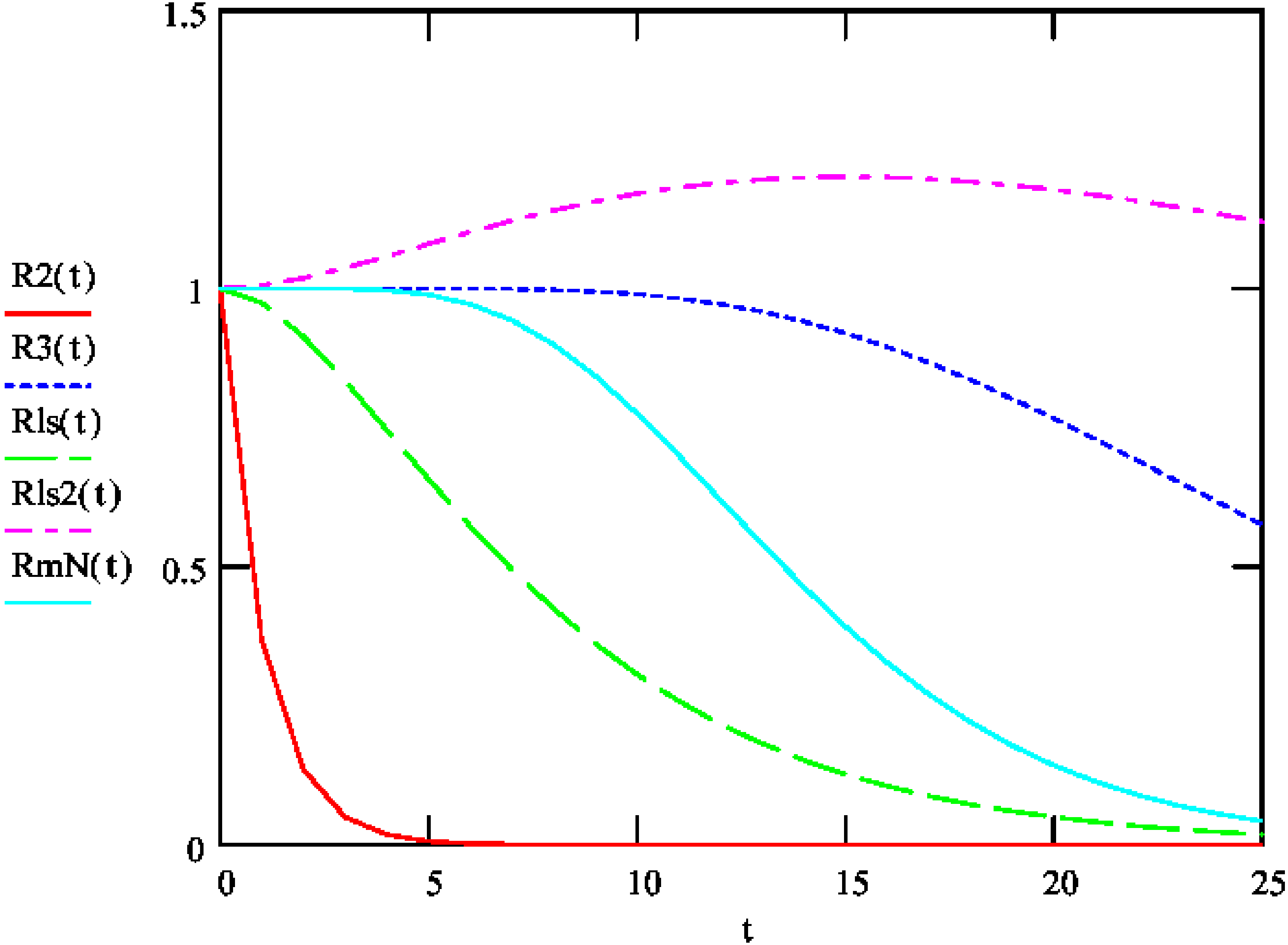
Load sharing for a 2 component system

(λ1 = 0.1, λ2 = 2 x λ1 , λ3 = 0.2 x λ1)

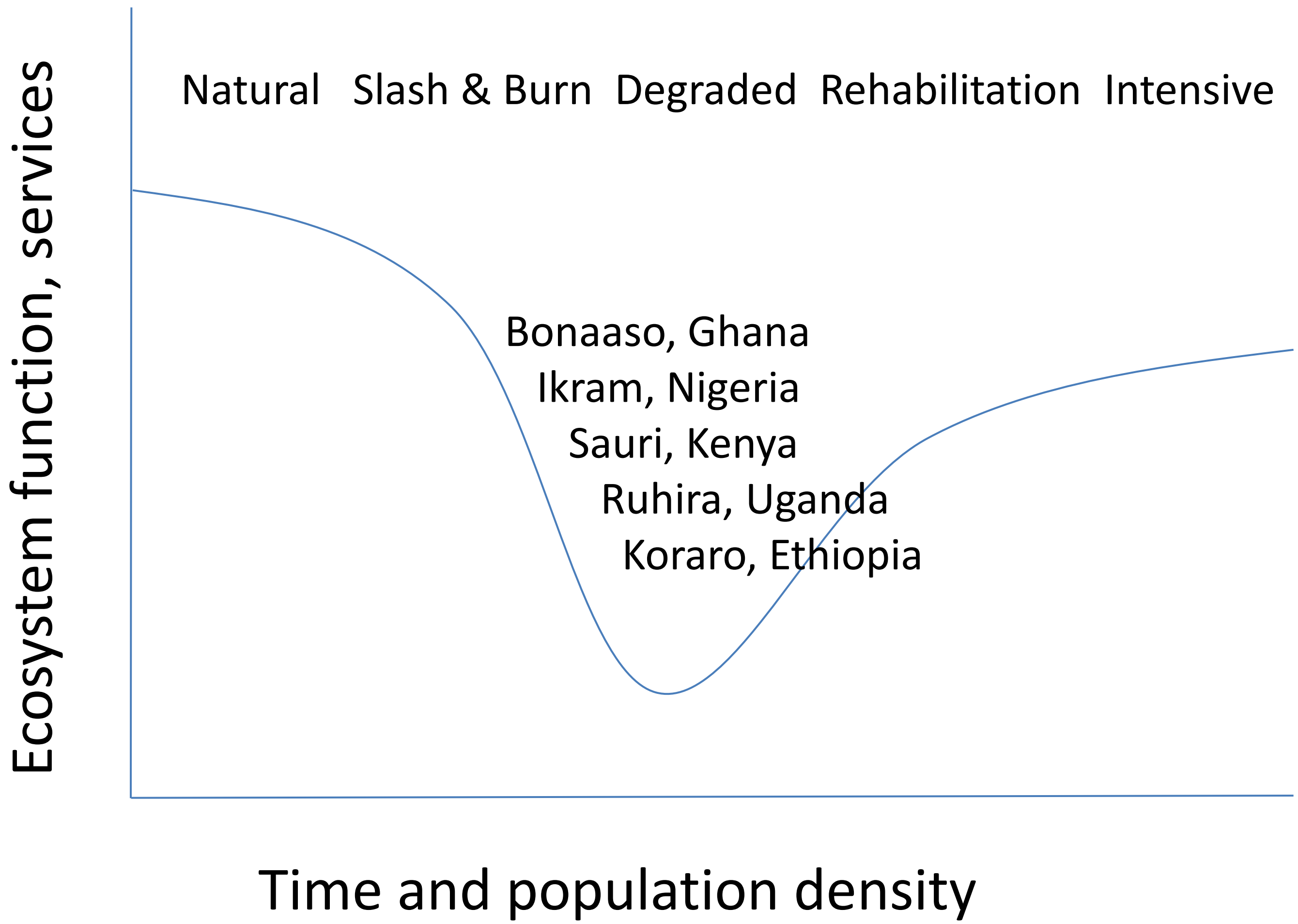
$$RmN(t) := 1 - \sum_{n = (N - m + 1)}^{N} \left(\frac{N!}{(N - n)! \cdot n!} \right) \cdot (1 - R1(t))^{n} \cdot R1(t)^{N - n}$$

m/N parallel

(*m* = 3)

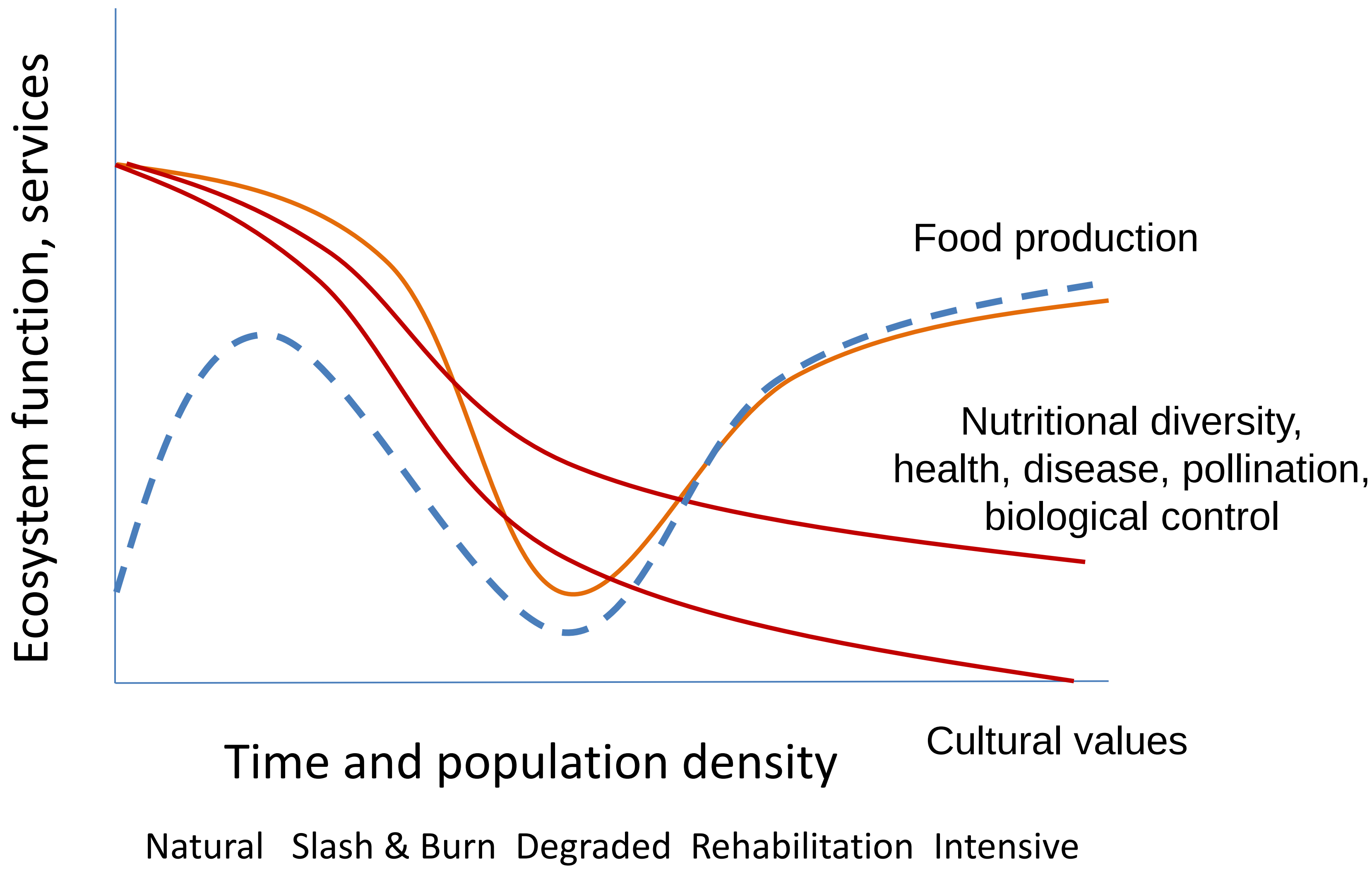

1.5
1
0.5
0
0
5
10
15
20
25
t
R2(t)
R3(t)
Rls(t)
Rls2(t)
RmN(t)

Ecosystem Services: Time line

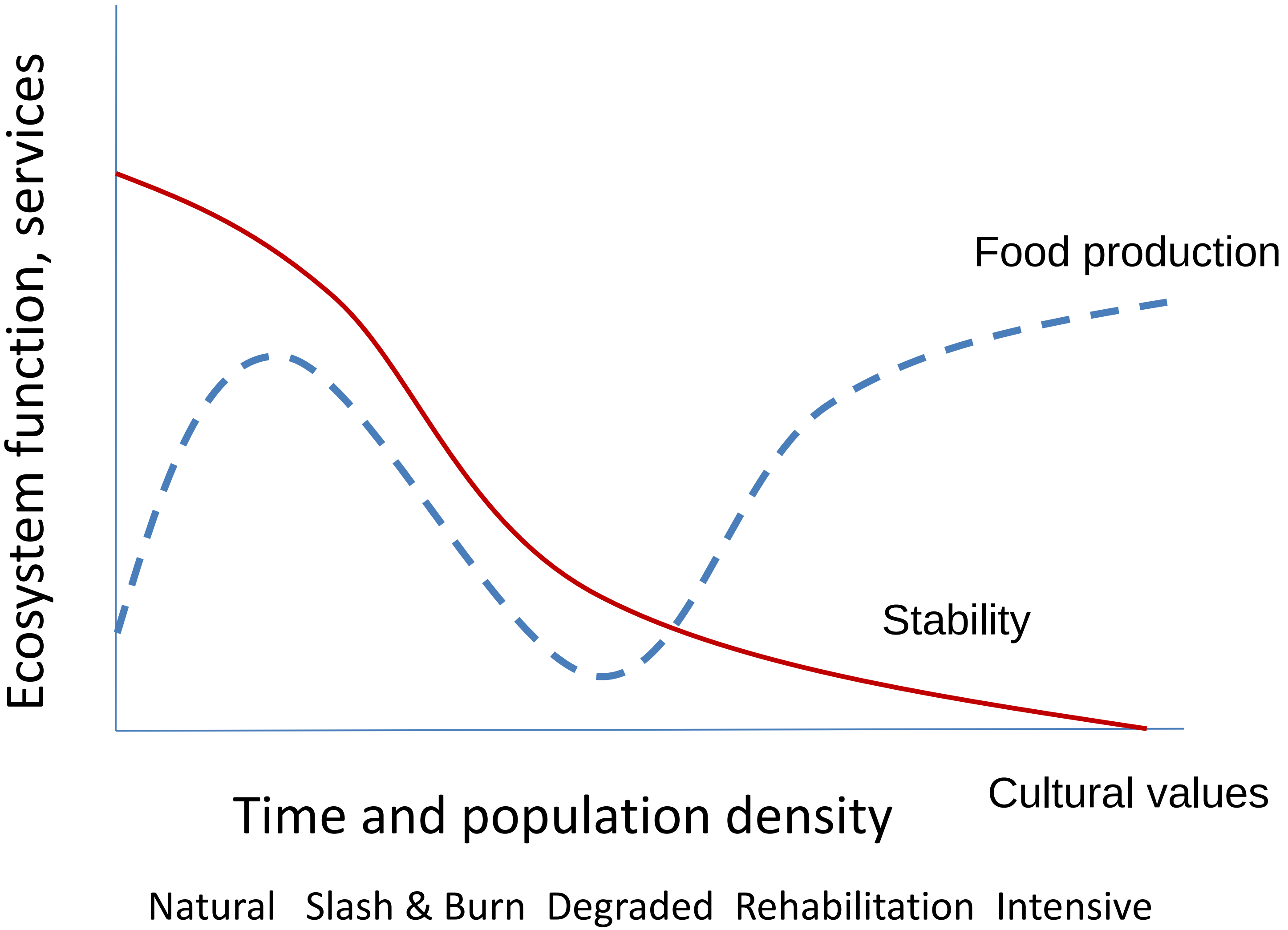


Natural   Slash & Burn Degraded Rehabilitation Intensive

Or does the bundle or basket of ecosystem services follow this trajectory?



Or does the bundle or basket of ecosystem services follow this trajectory?



Summary

- Biodiversity begets stability (lower variability)
  - Over-yielding (mean increases faster than variance)
  - Statistical averaging (portfolio effect)
  - Compensatory dynamics (insurance)
- BEF experiments critical, yet not done with agriculture – can we extrapolate?
- Biodiversity has many dimensions
  - They all correlate
  - They have different effects on resilience
  - We need to assemble universally accessible databases for taxonomy, phylogeny, and traits
- Reliability is important for interconnected systems (soil invertebrate/microbial communities)
- Resilience has multiple meanings
  - Ecological resilience – short return time
  - Holling-type resilience – resisting regime shifts, reorganization, structural failure