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

Shahid Naeem
Columbia University
Nutrients ($C_0$)

Plants ($C_1$)

Microbes ($C_2$)

$\frac{dP}{dt} = r_1 \frac{C_0}{(k + C_0)}$

$\frac{dM}{dt} = \delta M$

\[
\frac{dC_1}{dt} = r_1 \frac{C_0}{k_1 + C_0} C_1 - d_p C_1 \\
\frac{dC_2}{dt} = d_p C_1 - d_M C_2 \\
\frac{dC_0}{dt} = d_M C_2 - C_1 r_1 \frac{C_0}{k_1 + C_0}
\]
What happens if $r_1$ increases?
At high values of $r$ (plant growth), what would happen?

A. Plants win

B. Microbes win

C. Nutrients win

D. Tie between plants and microbes
Biological Diversity

Zavaleta

...
Biodiversity loss and its impact on humanity

Ecosystem function
(resource capture, biomass production, decomposition, nutrient recycling)

Biological diversity
(variation in genes, species, functional traits)

Link functions to services
Expand our focus
Improve predictions
Biodiversity loss and its impact on humanity

Table 1 | Balance of evidence linking biodiversity to ecosystem services

<table>
<thead>
<tr>
<th>Category of service</th>
<th>Measure of service provision</th>
<th>Source</th>
<th>Study type</th>
<th>N</th>
<th>Relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Provisioning</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crops</td>
<td>Crop yield</td>
<td>Plants</td>
<td>Genetic</td>
<td>DS</td>
<td>Exp</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Species</td>
<td>DS</td>
<td>Exp</td>
</tr>
<tr>
<td>Fisheries</td>
<td>Stability of fisheries yield</td>
<td>Fish</td>
<td>Species</td>
<td>PS</td>
<td>Obs</td>
</tr>
<tr>
<td>Wood</td>
<td>Wood production</td>
<td>Plants</td>
<td>Species</td>
<td>DS</td>
<td>Exp</td>
</tr>
<tr>
<td>Fodder</td>
<td>Fodder yield</td>
<td>Plants</td>
<td>Species</td>
<td>DS</td>
<td>Exp</td>
</tr>
<tr>
<td><strong>Regulating</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biocontrol</td>
<td>Control of herbivorous pests (bottom-up effect of plant diversity)</td>
<td>Plants</td>
<td>Species</td>
<td>DS*</td>
<td>Obs</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Plant</td>
<td>DS*</td>
<td>Exp</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Species</td>
<td>DS*</td>
<td>Exp</td>
</tr>
<tr>
<td></td>
<td>Control of herbivorous pests (top-down effect of natural enemy diversity)</td>
<td>Natural enemies</td>
<td>Species/ttait</td>
<td>DS*</td>
<td>Exp/Obs</td>
</tr>
<tr>
<td>Resistance to plant invasion</td>
<td>Plants</td>
<td>Species</td>
<td>DS</td>
<td>Exp</td>
<td>120</td>
</tr>
<tr>
<td>Disease prevalence (on plants)</td>
<td>Plants</td>
<td>Species</td>
<td>DS</td>
<td>Exp</td>
<td>107</td>
</tr>
<tr>
<td>Disease prevalence (on animals)</td>
<td>Multiple</td>
<td>Species</td>
<td>DS</td>
<td>Exp/Obs</td>
<td>45</td>
</tr>
<tr>
<td>Climate</td>
<td>Primary production</td>
<td>Plants</td>
<td>Species</td>
<td>DS</td>
<td>Exp</td>
</tr>
<tr>
<td></td>
<td>Carbon sequestration</td>
<td>Plants</td>
<td>Species</td>
<td>DS</td>
<td>Exp</td>
</tr>
<tr>
<td></td>
<td>Carbon storage</td>
<td>Plants</td>
<td>Species/traits</td>
<td>PS</td>
<td>Obs</td>
</tr>
<tr>
<td>Soil</td>
<td>Soil nutrient mineralization</td>
<td>Plants</td>
<td>Species</td>
<td>DS</td>
<td>Exp</td>
</tr>
<tr>
<td></td>
<td>Soil organic matter</td>
<td>Plants</td>
<td>Species</td>
<td>DS</td>
<td>Exp</td>
</tr>
<tr>
<td>Water</td>
<td>Freshwater purification</td>
<td>Multiple</td>
<td>Genetic/species</td>
<td>PS</td>
<td>Exp</td>
</tr>
<tr>
<td>Pollination</td>
<td>Pollination</td>
<td>Insects</td>
<td>Species</td>
<td>PS</td>
<td>Obs</td>
</tr>
</tbody>
</table>
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 vs. Biodiversity

- Singularity
- Redundancy
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

\[ F_{low} = \int_{B=x}^{x'} E_{\text{max}} - \frac{E_{\text{max}} B_{I}^{c_{\text{low}}}}{B_{\text{min}} + B_{I}^{c_{\text{low}}}} dB_{I} \]
Variance in Functioning (in the absence of subsidies!)
Above-ground Biomass

Species richness

Mean $\log_{10}(\text{Production})$

Variance $\log_{10}(\text{Production})$

Above-ground Biomass

Species richness

Mean $\log_{10}(\text{Production})$

Variance $\log_{10}(\text{Production})$
Biodiversity loss and carbon storage in the BCI Forest Dynamics Plot

Daniel E. Bunker¹, Fabrice De Clerck², Robert K. Colwell³, Ivette Perfecto⁴, Oliver Phillips⁵, Mahesh Sankaran⁶ and Shahid Naeem¹

1. Department of Ecology, Evolution and Environmental Biology, Columbia University
2. Earth Institute, Columbia University
3. Department of Ecology and Evolutionary Biology, University of Connecticut
4. School of Natural Resources and Environment, University of Michigan
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
Current ecosystem property / service
Standing crop / C storage
Variability (Standing crop / C storage)

Extinction

Future ecosystem
Future ecosystem property / service
Standing crop / C storage
Variability (Standing crop / C storage)

Compensatory growth
(Basal area restored)
High wood-density species lost first

Species richness

Raw data

Mean and CV relative to random extinction

Mean and CV of Carbon

Mg C ha$^{-1}$
Large-statured species lost first

Species richness

Raw data

Mean and CV

Mean and CV relative to random extinction

Species richness
Biological Diversity
What do we mean?

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

Dan F. B. Flynn, Nicholas Mirotchnick, Meha Jain, Matthew I. Palmer, and Shahid Naeem

Department of Ecology, Evolution, and Environmental Biology, Columbia University, 1200 Amsterdam Avenue, Schermerhorn Extension, New York, New York 10027 USA

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 were also analyzed using species abundance.
Biological Diversity: What do We Mean?

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

<table>
<thead>
<tr>
<th>Predictor</th>
<th>$R^2$</th>
<th>$w_i$</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>All plots</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$PD$</td>
<td>0.196</td>
<td>0.989</td>
<td>1074</td>
</tr>
<tr>
<td>$FD[N$, height, N-fixation]</td>
<td>0.181</td>
<td>$4.8 \times 10^{-5}$</td>
<td></td>
</tr>
<tr>
<td>$PD + FD[N$, height, N-fixation]</td>
<td>0.197</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>$S$</td>
<td>0.177</td>
<td>$5.5 \times 10^{-6}$</td>
<td></td>
</tr>
<tr>
<td>FGR</td>
<td>0.170</td>
<td>$7.5 \times 10^{-9}$</td>
<td></td>
</tr>
<tr>
<td>No legumes</td>
<td></td>
<td></td>
<td>506</td>
</tr>
<tr>
<td>$PD$</td>
<td>0.105</td>
<td>0.48</td>
<td></td>
</tr>
<tr>
<td>$FD[N$, height]</td>
<td>0.096</td>
<td>0.146</td>
<td></td>
</tr>
<tr>
<td>$PD + FD[N$, height]</td>
<td>0.107</td>
<td>0.064</td>
<td></td>
</tr>
<tr>
<td>$S$</td>
<td>0.097</td>
<td>0.043</td>
<td></td>
</tr>
<tr>
<td>FGR</td>
<td>0.074</td>
<td>$3.3 \times 10^{-6}$</td>
<td></td>
</tr>
<tr>
<td>Fertilized plots</td>
<td></td>
<td></td>
<td>212</td>
</tr>
<tr>
<td>$PD$</td>
<td>0.186</td>
<td>0.117</td>
<td></td>
</tr>
<tr>
<td>$FD[height$, N-fixation]</td>
<td>0.172</td>
<td>0.216</td>
<td></td>
</tr>
<tr>
<td>$PD + FD[height$, N-fixation]</td>
<td>0.188</td>
<td>0.024</td>
<td></td>
</tr>
<tr>
<td>$S$</td>
<td>0.161</td>
<td>0.002</td>
<td></td>
</tr>
<tr>
<td>FGR</td>
<td>0.123</td>
<td>$6.7 \times 10^{-5}$</td>
<td></td>
</tr>
<tr>
<td>Using PD from molecular phylogeny (110 species)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Using PD from angiosperm supertree (121 species)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Predictor</th>
<th>$R^2$</th>
<th>$w_i$</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>All plots</td>
<td></td>
<td></td>
<td>1419</td>
</tr>
<tr>
<td>$PD$</td>
<td>0.223</td>
<td>0.002</td>
<td></td>
</tr>
<tr>
<td>$FD[N$, height, N-fixation]</td>
<td>0.223</td>
<td>0.907</td>
<td></td>
</tr>
<tr>
<td>$PD + FD[N$, height, N-fixation]</td>
<td>0.229</td>
<td>0.003</td>
<td></td>
</tr>
<tr>
<td>$S$</td>
<td>0.204</td>
<td>$2.3 \times 10^{-8}$</td>
<td></td>
</tr>
<tr>
<td>FGR</td>
<td>0.187</td>
<td>$2.4 \times 10^{-16}$</td>
<td></td>
</tr>
<tr>
<td>No legumes</td>
<td></td>
<td></td>
<td>636</td>
</tr>
<tr>
<td>$PD$</td>
<td>0.123</td>
<td>$2.7 \times 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>$FD[N$, height, SRL]</td>
<td>0.120</td>
<td>0.495</td>
<td></td>
</tr>
<tr>
<td>$PD + FD[N$, height, SRL]</td>
<td>0.125</td>
<td>$3.8 \times 10^{-5}$</td>
<td></td>
</tr>
<tr>
<td>$S$</td>
<td>0.110</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>FGR</td>
<td>0.078</td>
<td>$4.8 \times 10^{-9}$</td>
<td></td>
</tr>
<tr>
<td>Fertilized plots</td>
<td></td>
<td></td>
<td>302</td>
</tr>
<tr>
<td>$PD$</td>
<td>0.220</td>
<td>0.002</td>
<td></td>
</tr>
<tr>
<td>$FD[height$, N-fixation]</td>
<td>0.221</td>
<td>0.606</td>
<td></td>
</tr>
<tr>
<td>$PD + FD[height$, N-fixation]</td>
<td>0.233</td>
<td>$2.8 \times 10^{-6}$</td>
<td></td>
</tr>
<tr>
<td>$S$</td>
<td>0.204</td>
<td>$2.6 \times 10^{-7}$</td>
<td></td>
</tr>
<tr>
<td>FGR</td>
<td>0.198</td>
<td>$3.5 \times 10^{-10}$</td>
<td></td>
</tr>
</tbody>
</table>
But aren’t FD, PD, and S all correlated?
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 ($\chi^2 = 3.37, \text{df} = 1, P = 0.067$). 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

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

Brenda B. Lin¹,²*, Dan F.B. Flynn²†, Daniel E. Bunker²†, María Uriarte² and Shahid Naeem²
Functional (Bio-) Capacity: Functional Trait Volume (FTV): Convex Hull

(a) Contraction

(b) Expansion

(c) Shifting centroid

(d) Displacement

Native hull

Agricultural 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 = \( f(\text{genotypic richness, functional diversity}) \)

• Stability = reliability = ecosystem function variability across treatments.
Eisenhauer et al. 2012

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

(a) Varied resource experiment

- Bacterial genotypic richness
- Bacterial functional diversity
- Stability of community productivity

(b) Varied invader experiment

- Bacterial genotypic richness
- Bacterial functional diversity
- Stability of community productivity
Ecosystem Reliability

Serial dependency

Parallel redundancy
\[ R_1(t) := e^{-\lambda_1 t} \quad (\lambda_1 = 0.1) \]

\[ R_2(t) := R_1(t)^N \quad \text{serial dependency} \quad (N = 10 \text{ components}) \]

\[ R_3(t) := 1 - (1 - R_1(t))^N \quad \text{parallel redundant} \quad (N = 10 \text{ components, fully redundant}) \]

\[ R_{ls}(t) := 2 \cdot e^{-\lambda_2 t} + e^{-2 \lambda_1 t} - 2 \cdot e^{-(\lambda + \lambda_2) t} \]

Load sharing for a 2 component system

\[ (\lambda_1 = 0.1, \lambda_2 = 2 \times \lambda_1, \lambda_3 = 0.2 \times \lambda_1) \]

\[ R_{ls2}(t) := 2 \cdot e^{-\lambda_3 t} + e^{-2 \lambda_1 t} - 2 \cdot e^{-(\lambda + \lambda_3) t} \]

\[ R_{mN}(t) := 1 - \sum_{n = (N - m + 1)}^{N} \left( \frac{N!}{(N-n)! \cdot n!} \right) \cdot (1 - R_1(t))^n \cdot R_1(t)^{N-n} \quad m/N \text{ parallel} \quad (m = 3) \]
Ecosystem Services: Time line

Natural  Slash & Burn  Degraded  Rehabilitation  Intensive

Bonaaso, Ghana
Ikram, Nigeria
Sauri, Kenya
Ruhira, Uganda
Koraro, Ethiopia

Time and population density

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