The Economics of Biodiversity Loss

Stefano Giglio
Yale & NBER

Theresa Kuchler
NYU & NBER

Johannes Stroebel
NYU & NBER

Olivier Wang
NYU

Motivation

- Recent interest in understanding and managing the complex relationships between the **economy** and the **health of our planet**
- Much of the (econ and finance) focus in the last decades has been on **climate change**
- **Biodiversity** is a crucial – and understudied – planetary boundary, that has been rapidly deteriorating due to human action
    - The **ecosystem services** associated to it represent a fundamental factor of production: *"destroying nature means destroying the economy"* (ECB, 2023).
- **This paper:** We take a first step in modeling the **dynamics of biodiversity loss** and their two-way interactions with the economy.

This paper

- We propose a flexible specification for how species and their diversity interact to produce **ecosystem services**
  - Captures main features documented in the ecology literature
- Introduce ecosystem services in the economic production function
- Model the effects of **human activity**, and especially land use, on the dynamics of biodiversity
- Derive qualitative predictions and test implications using asset prices
- **Key idea:** Nature is not just one "natural capital", but **complex interactions of species** that jointly produce ecosystem services that are fundamental for life and economic activity $\rightarrow$ analogous to supply chains, input-output networks in economics
- *Implications for policy design:* Biodiversity Offsets, Pigovian Taxes, Biodiversity Risk Assessments in Financial System

What is Biodiversity?

- Biodiversity refers to the variety of life on earth – of genes, of species, of ecosystems
    - In this paper, we focus on **diversity of species**
    - Plays a crucial role in supporting economic activity by providing **ecosystem services**
- Provisioning services
    - Direct role in agricultural production (food, timber)
    - Raw materials and genetic information useful for pharmaceutical R&D
- Regulating and supporting services
    - Pollination, provision of clean air and water, carbon sequestration, pest regulation, natural hazard regulation (e.g., pandemics)
- These functions are **complementary** with each other: a decline in the availability of one function cannot be compensated by other functions

Modeling Biodiversity and Ecosystem Services

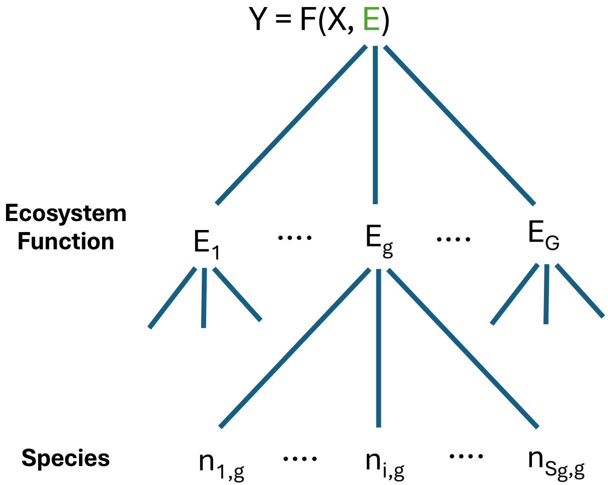
- We begin from the aggregate production function:

$$Y = F(\mathrm{X}, E)$$

  with E being ecosystem services and X all other factors of production.

- Rather than focusing on E as an aggregated "natural capital" factor, we disaggregate it into its ecological elements using a **hierarchical model**:
  - "Functional groups" g that include different species fulfilling similar primary ecosystem functions (e.g., pollination)
  - Diversity and abundance of species *within* each functional group

Modeling Biodiversity and Ecosystem Services



$$E = \left[\sum_{g=1}^{G} a_g E_g^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}}$$

$$\sigma < 1$$

$$E_g = \left[\sum_{i=1}^{S_g} n_{i,g}^{\frac{\epsilon_g-1}{\epsilon_g}} \right]^{\frac{\epsilon_g}{\epsilon_g-1}}$$

$$1 < \epsilon_g < \infty$$

Interaction of species within a function g

Two key roles of biodiversity in provision of ecosystem services:

1. Biodiversity-productivity relationship:
   - Productivity is an increasing and concave function of biodiversity
   - Due to "niche differentiation": *If species use different resources, or the same resources but at different times or different points in space, more of the total available resources are expected to be used by the community* $\rightarrow$ generates love of variety as in international trade.
2. Biodiversity-stability relationship:
   - Greater resilience to human and environmental stresses
   - *As some species do worse, others do better because of different environmental tolerances or competitive release. In this sense, redundancy of functional effect traits acts as* ***insurance*** *in carrying out ecological processes.*

Interaction of species within a function g

- S_g unique species providing function g (e.g., pollination)
- $n_{i,g}$ abundance of species i
- Production of function g:

$$E_g = \left[\sum_{i=1}^{S_g} n_{i,g}^{\frac{\epsilon_g - 1}{\epsilon_g}} \right]^{\frac{\epsilon_g}{\epsilon_g - 1}}$$

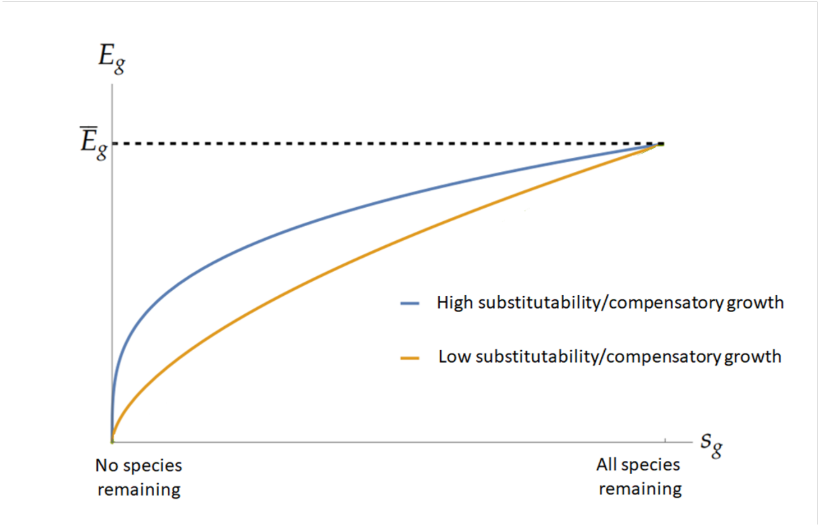
- **Within each function species are highly, but not perfectly, substitutable**:

$$1 < \epsilon_g < \infty.$$

- We also directly model **compensatory growth**: when one species disappears, others partially compensate

What is Biodiversity Loss?

- When species in a function g are lost, ecosystem services E_g are reduced.
- This relation is concave, as more biodiversity gives additional stability



Complementarity Across Functions

- Synergies (complementarities) between functions
- OECD: *the loss or decline in any single ecosystem service, stemming from [. . .] reduction in the stock of biodiversity, is likely to reduce the productivity of other ecosystem services*

$$E = \left[\sum_{g=1}^{G} a_g E_g^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}} . \tag{1}$$

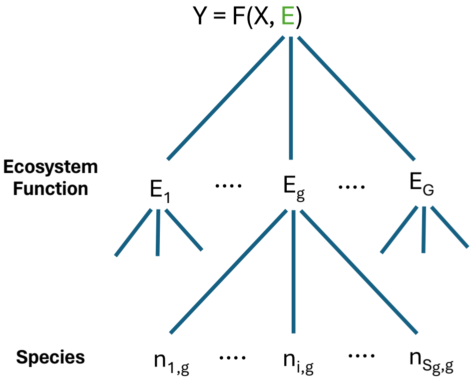
with

$$\sigma < 1.$$

- Ex: Sutter and Albrecht (2016) find "*strong synergistic effects of insect pollination and pest control on yield quantity and quality. Their joint effect increased yield by 23% [...], while their single contributions were 7% and 6%, respectively.*"
$\rightarrow$ corresponds to $\sigma \approx 0.1$

How Biodiversity Losses affects Ecosystem Services

- This "bottom-up" construction allows us to study how shocks to biodiversity, S_g, affect function-level services E_g and ultimately total services E.



$$E = \left[\sum_{g=1}^{G} a_g E_g^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}}$$

$$\sigma < 1$$

$$E_g = \left[\sum_{i=1}^{S_g} n_{i,g}^{\frac{\epsilon_g-1}{\epsilon_g}} \right]^{\frac{\epsilon_g}{\epsilon_g-1}}$$

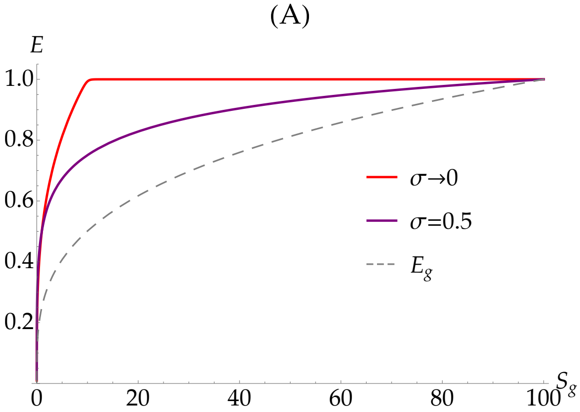
$$1 < \epsilon_g < \infty$$

- We review three main insights from our theoretical results.

Result 1: Double concavity in $S_g \to E_g \to E$

- Recall that $S_g \to E_g$ is concave due to the relation between species within functions
  - Intuition: due to the dynamics between species, losses are more easily absorbed when the system is biodiversity-rich
- The relation $E_g \to E$ amplifies this concavity (complementarity across functions)
  - Intuition: When functions are complementary, losses are more damaging if they occur in more constrained functions
  - So the losses make a function g more constrained and amplify further losses
  - As an extreme, consider the Leontief case [losses in non-constrained functions have no immediate effect on E]

Result 1: Double concavity in $S_g \to E_g \to E$



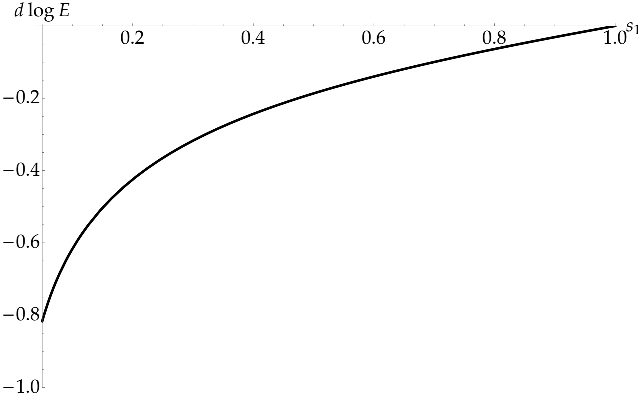
Result 2: The importance of *keystone species*

- When the number of species in a function declines, the remaining species are more likely to become *keystone species*, because they don't have a functional replacement
    - *[A keystone species is a] species whose impact on its community or ecosystem is large, and disproportionately large relative to its abundance.* (Power et al. 1996)
    - Example: Frank and Sudarshan (2023), 4% increase in mortality due to collapse of vulture population in India
    - Frank (2024), increases in infant mortality following increased use of pesticides, in turn due to loss in bat population
- **Corollary**: the effects of biodiversity losses are context-dependent: it is not just a matter of **how many** species are lost, but **which ones**
    - *Ecosystem response to extinction or invasion in the real world will be determined at least as much by which species and functional traits are lost and remain behind as by how many species are lost* (Hooper et al. 2015)

Result 3: Fragility and Exposure to Biodiversity Shocks

- Previous results focused on shocks to biodiversity in a particular function, S_g
- In reality, shocks to biodiversity (natural or due to human activity) can affect many species and functions
- We characterize how an **arbitrary** (vector) shock to biodiversity across many functions, ds, affects ecosystem services starting from an arbitrary (vector) state s
- We formalize the concept of ecosystem fragility, as is the sensitivity of the ecosystem to a **common** shock ds
  - Summary statistic for the exposure of the ecosystem to future shocks

Result 3: Fragility and Exposure to Biodiversity Shocks



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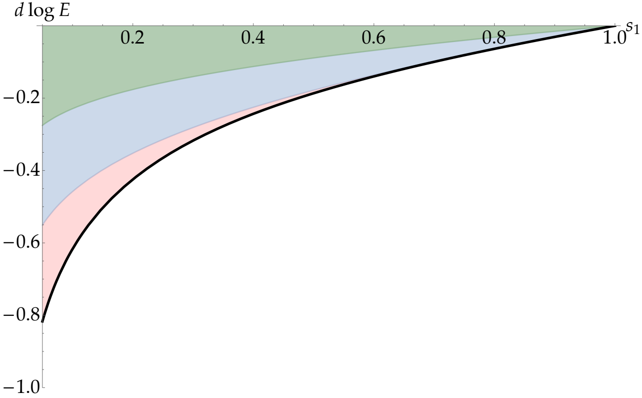


$$d \log E = \underbrace{\sum_{g=1}^{G} \omega_g \frac{\alpha_g}{s_g} ds_g}_{\Delta \text{ Community abundance}} + \underbrace{\sum_{g=1}^{G} \omega_g \frac{v_g}{s_g} ds_g}_{\Delta \text{ Niche differentiation}} + \underbrace{\text{Cov}\left[\gamma_g, \frac{\phi_g}{s_g} ds_g\right]}_{\Delta \text{ Across-function imbalances}}$$

Result 3: Fragility

- The decomposition above gives us the general sensitivity of E to arbitrary vector shocks ds.
- If the shock is uniform (common) across functions, then it can be summarized into one number, **fragility** (μ_g is *criticality* of function):

$$\mathcal{F}(s) = \sum_{g=1}^{G} \mu_g \frac{\phi_g}{s_g} \tag{2}$$

- We then have:

$$d \log E = \mathcal{F}(s) ds \tag{3}$$

- And if we have a uniformly distributed idiosyncratic shock with mean $\bar{dz}$, then:

$$\mathbb{E}\left[d \log E | s\right] = \mathcal{F}(s) \bar{dz}.$$

Additional Implications

1. The large recent biodiversity loss has not led to large-scale decline in output. Why?
   - Effects of losses in high-abundance functions may be small
   - Because of the concavity, the economic effect can be small while *fragility* increases
   - Higher future risks, especially if future damages in more critical species

Additional Implications

2. Biodiversity Offsets:
    - Because of heterogeneity and complementarity, the compensatory value of conservation efforts is highly ecosystem-and species-dependent
    - Biodiversity losses in one location/function/species are not the same (and not substitutable for) losses in another
    - Much harder to calculate than carbon offsets (1 ton of carbon is the same everywhere)
3. Risk:
    - The framework can be used to assess the risk exposures of economies and financial systems (once mapped to the data)

Biodiversity and the Economy

- So far we have studied the aggregation of species and biodiversity into ecosystem services
- Here we describe how human activity affects biodiversity, and then study jointly the dynamics of the economy and the biodiversity
- We build our model on two insights from the ecology literature
    1. "Strong sustainability": difficult or impossible to substitute for natural capital with produced capital ($\xi < 1$)
    2. Biodiversity losses arise from human activities that yield a production benefit, most importantly land use ($u \in [0, 1]$)

$$F(K, E, uL) = \left(\left[K^{\theta}(uL)^{1-\theta}\right]^{\frac{\xi-1}{\xi}} + E^{\frac{\xi-1}{\xi}} \right)^{\frac{\xi}{\xi-1}}$$

The dynamics of biodiversity

- We specify a 2-period intertemporal model:

$$\log(C_0) + \beta \log(C_1)$$

  where

$$\begin{aligned} C_0 &= F(K_0, uL, E_0) - K_1, \\ C_1 &= F(K_1, \bar{u}L, E_1(u)). \end{aligned}$$

- Both K_1 and u are chosen at time 0

The dynamics of biodiversity

- Finally, we model how land use u affects biodiversity
- We assume that land use u directly multiplies biomass by $1 - u$
- Also, land use directly affects biodiversity:

$$s_{g,1}(u) = s_{g,0} - \mathcal{L}(s_{g,0}, u). \tag{4}$$

- "*The smaller the population size of a particular species, the more likely it is to go extinct locally, due to random—stochastic—fluctuations*" (Cleland 2011)

The dynamics of biodiversity

Note that this resembles a standard problem of use of an exhaustible resource, but important differences:

1. Heterogeneity in effect across species (that depend on the initial configuration of s_g). Cannot easily disentangle the effects of u for loss of different species ("targeted" land use)
2. Biodiversity loss affects *flow* of ecosystem services, that directly enter production for a very long time.
3. Potentially very nonlinear loss function $\mathcal{L}$. Particularly interesting is the cross-derivative $\frac{\partial^2 \mathcal{L}}{\partial u \partial s_{g,0}}$, that can capture potential tipping points and selection.
    - E.g., a negative cross-derivative means that land use becomes more destructive for the remaining biodiversity as species losses accumulate over time (tipping points)
    - Positive cross-derivative can capture selection effects (weakest species are lost first)

Model solution and Insights

- First-order condition with respect to u (or conservation $1-u$):

$$1-u=\Lambda\,\frac{\partial \log E_1}{\partial \log(1-u)},$$

where Λ is the relative cost of depleting future ecosystems relative to the current benefits.

Model solution and Insights

- If loss is linear in u, the term in square brackets reduces to the **fragility** we derived above, and we get:

$$1 - u = \min \left\{ 1, \frac{\Lambda}{1 - \Lambda \delta \mathcal{F}(s_1)} \right\}$$

- Optimal conservation increases with Λ, patience, and **fragility**

- Additional implication: complementarity between physical and natural capital $\Rightarrow$ capital-rich countries, with a higher K_0, should invest more in biodiversity preservation.
  - They can save more out of their current output, and have higher future physical capital K_1.
  - In the future, natural capital will be the relatively scarcer factor of production so conservation of natural capital has a higher return and should optimally be higher.

Fragility

$$1 - u = \min\left\{1, \frac{\Lambda}{1 - \Lambda\delta\mathcal{F}(s_1)}\right\}$$

- Recall that fragility is a measure of the current imbalance between functions.

  In the limit ($\sigma \to 0$) fragility is entirely determined by the *most critical function:*

$$\mathcal{F}(s) \to \frac{\phi}{\min_g s_g}.$$

- So in turn optimal conservation is determined by the **most critical** function

Evidence from Asset Prices

- An important result we obtained is that current biodiversity losses may not have an immediate effect on current output – but they should affect future output

- Asset prices, which are forward looking, should capture the potential damages from biodiversity

- Suppose we sort countries by their "biodiversity fragility"
  - Those countries with more fragile ecosystems should be more sensitive to bad news about biodiversity

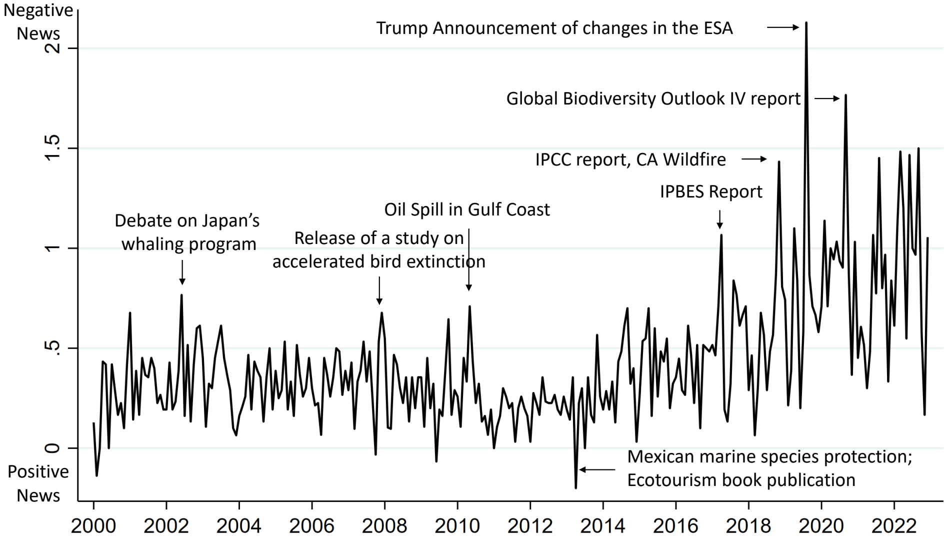
- We need to:
  1. Identify countries that are more exposed
  2. Identify bad news about biodiversity
  3. Check if a forward-looking measure of country risk responds to these news differentially as a function of country exposure

Measuring Aggregate Biodiversity Risk

NYT Biodiversity News Index:

- Use a dictionary-based approach to identify NYT articles that cover biodiversity risk (terms include "ecosystem", "deforestation", "habitat", etc.)
- Article sentiment: Bidirectional Encoder Representations from Transformers (BERT)
- Index: Number of negative biodiversity articles minus the number of positive biodiversity articles.

NYT-Biodiversity News Index



Note: Monthly NYT-Biodiversity News Index from 2000 to 2022, annotated with biodiversity-relevant news announcements. ESA: Endangered Species Act; IPBES: Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services; IPCC: Intergovernmental Panel on Climate Change.

Measuring country exposure

- "Environmental Performance Index", from the Yale Center for Environmental Law and Policy (EPI)
  - Measures degradation of biodiversity and fragility
- Share of natural capital in wealth (from World Bank data)
  - Extent to which biodiversity constraining factor in production

Measuring country exposure

- Ideally, we'd like to get as close as possible to the model-implied measure of "fragility" – reflecting imbalances in species loss
- Yale's Map of Life initiative (Species Habitat Index) collects detailed information about each species and the degradation of their habitats, using satellite data and direct observation
  - Covers 180 countries, 20 years
  - Many thousands of species, mostly vertebrates
- We aggregate them into groups

Results

Biodiversity News	0.434
	(1.664)
Biodiversity News * State of Biodiversity Score	-0.094***
	(0.028)
Biodiversity News * Natural Capital Share of Wealth	-0.083***
	(0.030)
Biodiversity News * Habitat SD	0.018*
	(0.010)
Biodiversity News * Habitat Average	-0.004
	(0.017)
Year * Tenor	x
Week * Tenor	x
Country * Tenor * Year	x
N	395,506
N excluding singleton observations	395,452
Unique countries	87
Sample period	2001-2022

Conclusion

- *Biodiversity finance* is a new field with many unanswered questions
- Here: first steps in modeling the interactions of biodiversity and the economy
    - Parallels the development of IAMs in climate economics and finance
- Much more research needed, on both the theoretical and empirical fronts