Tragedy of Open Ecosystems

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Motivations

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The Tragedy of Open Ecosystems

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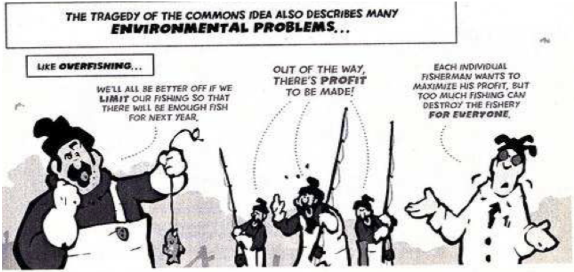
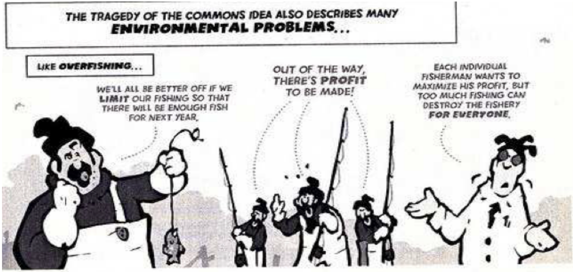
Motivations



- **Tragedy of the Commons** : Open-access detrimental
- **Game theory** : Levhari and Mirman (1980)
- But **single** stocks (Bailey et al, 2010)
- Exceptions : two-species : Fischer & Mirman (1992, 1996)

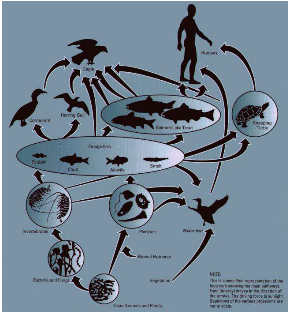
Objectives



Goals of the paper :

- Extension to larger ecosystem
- Gains in terms of biodiversity ?
- Promote models of intermediate complexity

Ecological model



Multi-species Gompertz dynamics in discrete time

$$x_i(t+1) = x_i(t) \exp\left(r_i + \sum_{j=1}^{n} s_{ij} \log\left(x_j(t)\right) \right)$$

with

- $x_i(t)$ stock of species $i = 1, \ldots, n$
- r_i intrinsic growth rate
- s_{ij} interspecies relationship
- $-1 \leq s_{ij} \leq 0$

Economic model

- Harvest $h_{ai}(t)$ of agents $a = 1, \ldots, A$:

$$x_i(t+1) = \left(x_i(t) - \sum_a h_{ai}(t) \right) \exp \left\{ r_i + \sum_{j=1}^{n} s_{ij} \log \left(x_j(t) - \sum_a h_{aj}(t) \right) \right\}$$

- Identical users : $a = 1, .., A$
- One-period utility function

$$U\left(h_{a1}, \ldots, h_{an}\right) = \sum_{i=1}^{n} u_i \log\left(h_{ai}\right),$$

Non-cooperative vs cooperative maximization

Non-cooperative

For each agent $a = 1, .., A$

$$\max_{h_{a.}(.)} \sum_{t=0}^{\infty} \rho^t U\left(h_{a1}(t) \ldots, h_{an}(t)\right),$$

Cooperative

$$\max_{h(.)} \sum_{t=0}^{\infty} \rho^t \left(\sum_{agents\ a} U\left(h_{a1}(t), \ldots, h_{an}(t)\right) \right.$$

with $0 < \rho < 1$ discount factor

Method : Dynamic programming + Nash solution

$$V_a(x) = \max_{h_{a.}} \left\{ u' \log(h_{a.}) + \rho V_a\left(G\left(x - h_{a.} - h_{-a.}\right)\right) \right\}.$$

Non-cooperative optimal harvest

Proposition

The noncooperative optimal catch for all species i is linear

$$h_i^{nc} = f_i^{nc} x_i \quad \text{with} \quad f_i^{nc} = \frac{Au_i}{Au_i + \rho\big((I+S)'w\big)_i}$$

with $w = \left(I - \rho\,(I+S)'\right)^{-1} u$
and assuming that w *well-defined and* $(I+S)'\,w > 0$.

Cooperative harvest

Remark : non cooperative with $A = 1$

Proposition

Same assumptions. The cooperative harvest for all species i is linear :

$$h_i^c = f_i^c x_i \quad \textit{with} \quad f_i^c = \frac{u_i}{u_i + \rho\left(\left(I+S\right)' w\right)_i}$$

Proposition

The non cooperative catch rate is larger than the cooperative mortality catch rate for all species i :

$$\textit{number of agents} \quad A > 1 \implies f_i^{nc} > f_i^{c}$$

Sketch of the proof

- Control : harvest rate $f_{ai}(t) = \frac{h_{ai}(t)}{x_i(t)}$
- A linear problem with $y(t) = \log(x(t))$

$$y(t+1) = r + (I+S)\log(1 - f(t)) + (I+S)\,y(t)$$

- Form of the value function $V_a(y) = \upsilon_a + w'y$
- Optimality conditions

$$\frac{u_i}{f_{ai}} = \frac{\rho\left((I+S)'\,w\right)_{ai}}{1 - f_{ai} - f_{(-a)i}} \Leftrightarrow f_{ai}^{nc} = \frac{u_i}{Au_i + \rho\left((I+S)'\,w\right)_{ai}}.$$

How cooperation promotes biodiversity with many agents

- Many agents $\approx A \to +\infty$
- Extinction in the non cooperative case :

$$\lim_{A\to+\infty} f_i^{nc}(t) = \lim_{A\to+\infty} \frac{Au_i}{Au_i + \rho\left((I+S)'\,w\right)_i} = 1$$

- Biodiversity metrics : Species Richness $SR(x) = \sum_i 1_{\mathbb{R}_+^*}(x_j)$

Proposition

When numerous agents cooperate, the ecosystem is more diverse

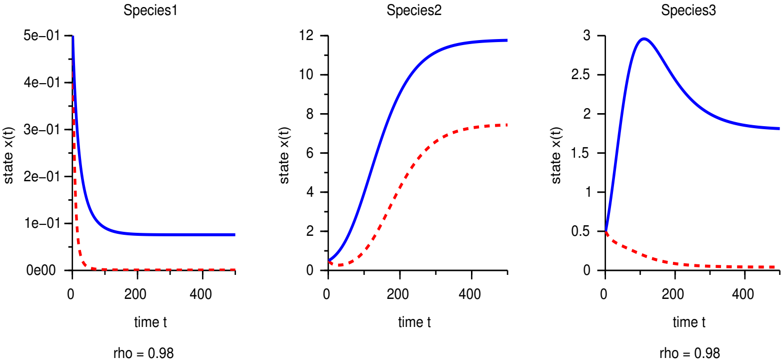
$$SR\left(\lim_{A\to+\infty} x^c(t)\right) > SR\left(\lim_{A\to+\infty} x^{nc}(t)\right)$$

Biodiversity gains of cooperation with few agents

$$r = \begin{pmatrix} -0.0026 \\ 0.0392 \\ 0.0644 \end{pmatrix} \quad S = \begin{pmatrix} -0.0218 & 0.0005 & 0.0001 \\ -0.0143 & -0.0153 & 0.0003 \\ -0.0003 & -0.0085 & -0.0161 \end{pmatrix} \quad u = \begin{pmatrix} 3 \\ 2 \\ 1 \end{pmatrix}$$

$$\rho = 0.98,$$

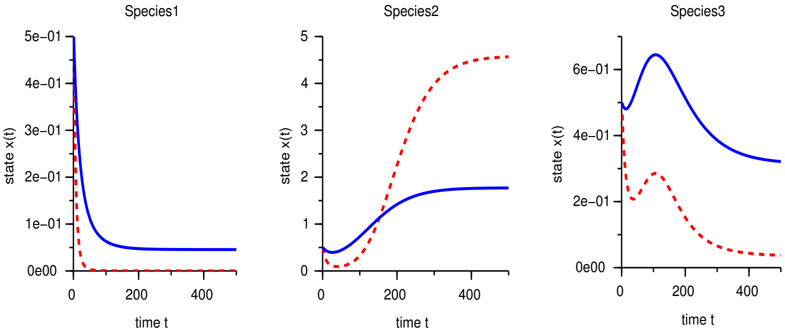
harvest fractions (%)	Species 1	Species 2	Species 3
cooperative f^c	5.45	3.91	3.52
non cooperative f^{nc} $m = 3$	14.79	10.88	9.87



But Gains of NON cooperation with few agents

$$r = \begin{pmatrix} -0.00002 \\ 0.00018 \\ 0.00027 \end{pmatrix} \quad S = \begin{pmatrix} -0.01902 & 0.00072 & 0.00030 \\ -0.01819 & -0.01766 & 0.00054 \\ -0.00757 & -0.01364 & -0.01254 \end{pmatrix} \quad u = \begin{pmatrix} 3 \\ 2 \\ 1 \end{pmatrix}$$

"mesopredator release" hypothesis `CrooksSoule:1999`



rho = 0.98 rho = 0.98

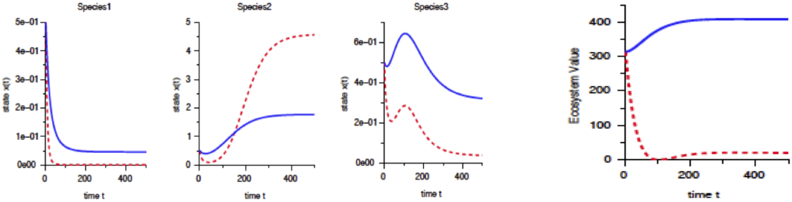
Gains for the ecosystem in every case

$$\mathrm{Ecos}(x) = w' \log(x) = \sum_j w_j \log(x_j)$$

Proposition

Assume that $(I + S')' \, w > 0$. *The cooperative ecosystem is larger than the noncooperative ecosystem at every time t*

$$\mathrm{Ecos}(x^c(t)) \geq \mathrm{Ecos}(x^{nc}(t))$$



Contribution value of species

- A marginal value : $w = \frac{\partial V}{\partial y}(y)$
- $w \geq u \geq 0$
- Example : $w \approx \begin{pmatrix} 54 & 51 & 28 \end{pmatrix}'$
- 2 species : The marginal prices

$$w_1 = \frac{u_1\left(1-\rho\left(1+s_{22}\right)\right)+\rho s_{21} u_2}{\Delta}, \qquad w_2 = \frac{u_2\left(1-\rho\left(1+s_{11}\right)\right)+\rho s_{12} u_1}{\Delta}$$

where $\Delta = det(I - \rho(I + S'))$

Account for interactions and species without direct utility ! !

Gains at equilibrium in every case

At equilibrium

$$x_* = \exp\left(-S^{-1}\left(r + (I+S)\log\left(1-F\right)\right)\right)$$

Idea :

$$\log(x_*^c) - \log(x_*^{nc}) = -(I+S^{-1})\log\left(\frac{1-F^c}{1-F^{nc}}\right)$$

Define the ecosystem value

$$\mathrm{E}(x) = \exp\left(-(1\ldots1)(I+S^{-1})^{-1}\log(x)\right)$$

Proposition

At equilibrium the cooperative ecosystem performs better

$$\mathrm{E}(x_*^c) \geq \mathrm{E}(x_*^{nc})$$

Looks like a trophic index (Pauly)

Example 2D predator-prey : $S = \begin{pmatrix} 0 & s_1 \\ s_2(< 0) & 0 \end{pmatrix}$

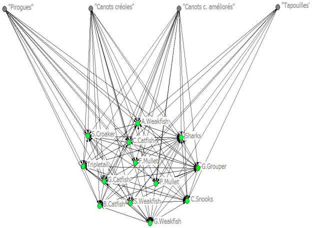
$$-(1 \ \ 1)(I + S^{-1})^{-1} \approx \frac{1}{\Delta}(-s_2 - 1 \quad - s_1 - 1)$$

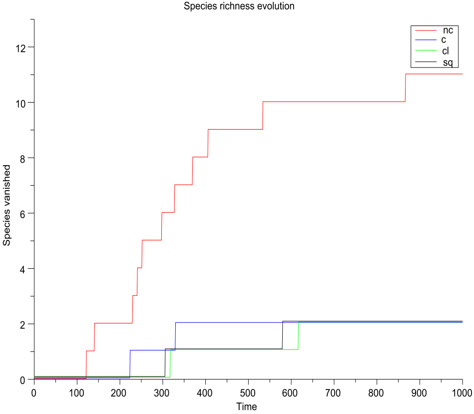
Put more weight on the predators ! ! !

French Guiana

Cissé et al., Environmental Development Economics, 2013

Cissé et al., Ecological Economics, 2015





Conclusion and perspectives

- Tragedy of the ‘commons’ revisited for many species
- Clear gains of cooperation in terms of pressure
- Clear gains of cooperation in terms of biodiversity when high number of players
- When few players, more ambiguous
- Contribution value of every species to ecosystem services
- Interest of models of intermediate complexity models MICE