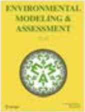
Mathematics for Scenarios of Biodiversity

Luc Doyen

Sustainability in the Digital Age,
Resilience facing Global Changes
Montreal, May 2019



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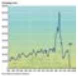
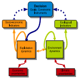
Mathematics for Scenarios of Biodiversity and Ecosystem Services

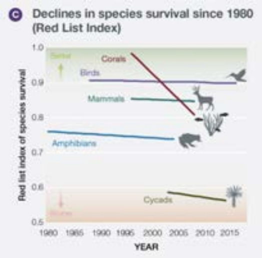
Authors Authors and affiliations

Luc Doyen





Biodiversity and ecosystems under pressure



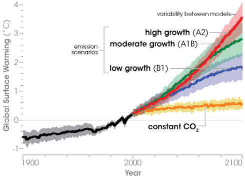
- Global changes in ecosystems
- Ecological vulnerabilities
- Economic vulnerabilities

$\Longrightarrow$ Management of bio-economic risks

The need for bio-economic scenarios

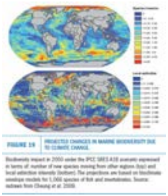
From

ipcc

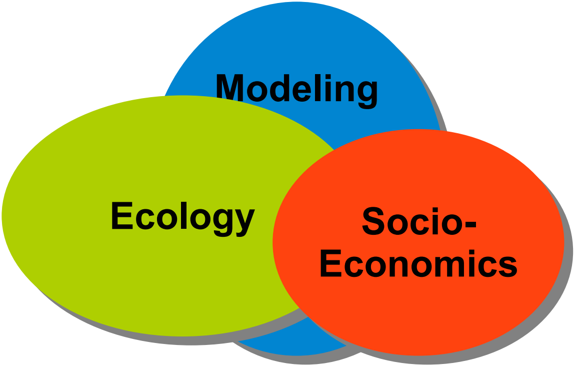


To

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services

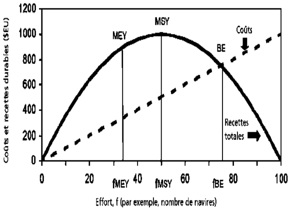


The need for bio-economic modeling



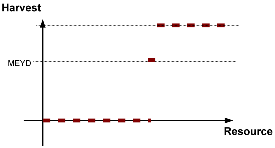
Important models

Equilibria
Gordon-Schaefer, 1954



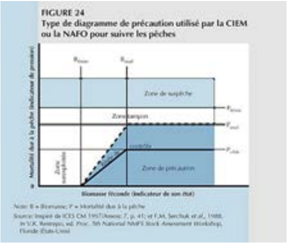
MSY $\longleftrightarrow$ MEY

Intertemporal Optimality
Clark, 1976



- Optimal closure
- Optimal extinction

Precautionary approach
ICES-CIEM



Renewable Resource Dynamics

In discrete time

$$x(t+1) = f(x(t)) - h(t)$$

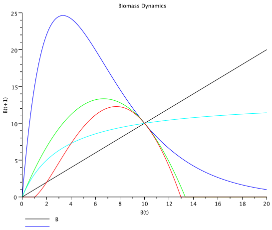
where

- $x(t)$ biomass or abundance
- $h(t)$ catches at time t

Examples of f :

Logistic,

$$f(x) = x + rx(1 - \frac{x}{k})$$



Ricker, Beverton-Holt, Gomperz

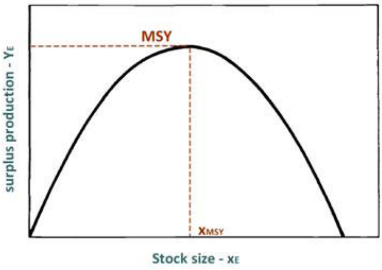
- Equilibrium :

$$x = f(x) - h$$

$\longrightarrow$ Sustainable yield
$\sigma(x) = f(x) - x$

- Example Logistic :

$$\sigma(x) = rx(1 - \frac{x}{k})$$



MSY vs MEY

- MSY : Optimal catches at equilibrium

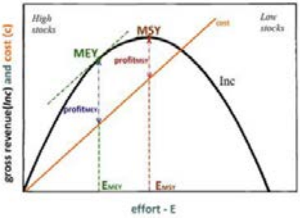
$$\max_{x} \sigma(x)$$

Logistic : $x_{\mathrm{MSY}} = \frac{k}{2}$

- MEY : Optimal rent at equilibrium

$$\max_{x, h=\sigma(x)} \pi(x, h)$$

where $\pi(x, h) = ph - c\frac{h}{qx}$
p price, c costs of effort
Logistic : $x_{\mathrm{MEY}} = \frac{k}{2} + \frac{c}{2pq}$



Bio-economic synergies

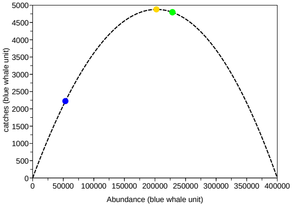
A discounted MEY

The optimal control problem

$$\max_{h(0),h(1),\ldots} \sum_{t=0}^{\infty} (1+r_f)^{-t} \pi(x(t), h(t))$$

The long term equilibrium x_ρ (Conrad-Clark, 1987)

$$r_f = \sigma_x(x_\rho) + \frac{\pi_x}{\pi_h}.$$



Particular cases :

- $r_f = 0$: $x_\rho \Longrightarrow x_{\mathrm{MEY}}$
- $r_f = \infty$: $x_\rho \Longrightarrow x_{\mathrm{OA}}$

Where extinction is optimal (Clark 1990)

Let us consider the illustrative case where

- Logistic dynamics
- rent is of the form $\pi_x = 0$

Result : Then if $r \leq r_f$ then extinction is optimal $x_\rho \leq 0$.

More general conditions in `Grafton et al. (2010)`

New bio-economic challenges

- How to operationalize the ecosystem approach ?
- How to operationalize sustainability ?
- How to operationalize resilience ?
- Which gouvernance for bio-economic public policies ?

ELSEVIER

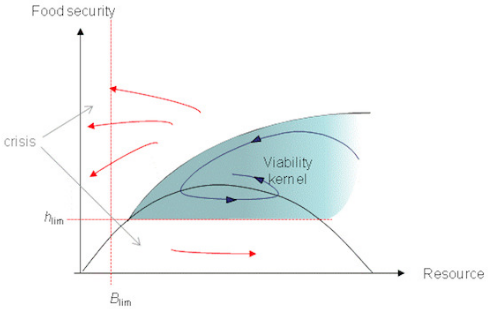
Ecological Economics

Volume 145, March 2018, Pages 346-367

A Survey of Applications of Viability Theory to the Sustainable Exploitation of Renewable Resources ☆

Aïchouche Oubraham, Georges Zaccour

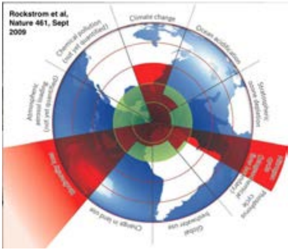
Safety of dynamic systems through constraints over time



Links with many approaches

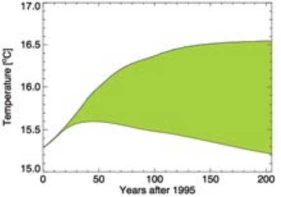
Doyen et al., Ecological Economics, 2019

SOS

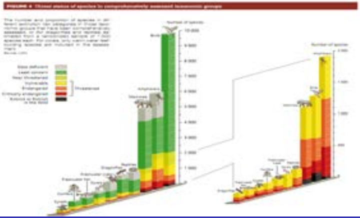


Minimal Sustainable Whinge

TWA



PVA



The mathematical formulation of viability

- Uncertain controlled dynamics :

$$\begin{cases} x_i(t+1) &= F_i(x(t), a(t), \omega(t)), \\ x(0) &= x_0 \end{cases}$$

where

- $x(t) \in \mathbb{R}^n$ the state at time t
- $a(t) \in \mathbb{R}^p$ the control at time t
- $\omega(t) \in \mathbb{R}^q$ the uncertainty at time t

- Constraints :

$$I_k(x(t), a(t), \omega(t)) \geq I_k^{\lim}$$

Stochastic viability

Summers-Lygeros, Automatica, 2010

Doyen-DeLara, Systems Control Letters, 2010

- Maximal probability of viability

$$V(t_0, x_0) = \max_{a(.)\ \text{feedback}} \mathbb{P}\Big(\text{constraints satisfied} \quad t = t_0, \dots, T \Big)$$

- Viability kernels : level sets of V

$$\mathrm{Viab}_\beta = \{ x_0 \mid V(t_0, x_0) \geq \beta \}.$$

- A dynamic programming structure

$$\boxed{\text{V(t,x)}} \quad = \quad \max_a \mathbb{E}\left[\mathbf{1}_{constraints}(x, a) * \boxed{V\Big(t+1, F(x, a, \omega)\Big)} \right]$$

where $\mathbf{1}_{constraints}$ boolean function of constraints.

Maximin and viability

Doyen-Martinet, JEDC, 2012

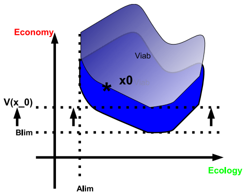
- Maximin   Rawls (1971), Solow (1974)

$$\max_{a(.)} \min_{t} I(x(t), a(t))$$

$$= \max\left(I_{lim},\ x_0 \in \mathrm{Viab}(I_{lim})\right)$$

where $\mathrm{Viab}(I_{lim})$ the viability kernel with

$$I(x(t), a(t)) \geq I_{lim}$$



- Maximin : extreme viability
- Intergenerational equity in viability
- Inverse viability : sustainable thresholds : Gajardo et al., 2019

Applications to fisheries

ELSEVIER

Ecological Economics
Volume 124, April 2016, Pages 69-75

Methodological and Ideological Options

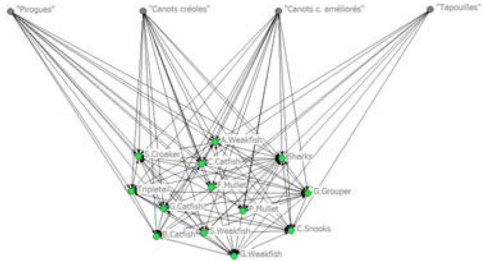
Economic viability and small-scale fisheries — A review

Anna Schuhbauer, U. Rashid Sumaila

A first example : Small scale fisheries in French Guiana

Cissé et al., Environmental Development Economics, 2013

Cissé et al., Ecological Economics, 2015



The bio-economic dynamic model

Cissé et al., Ecological Economics, 2015

A MICE model (14 species - 4 fleets)

$$x_i(t+1) = x_i(t)\Bigg(1 + r_i + \underbrace{\sum_{\text{species } j} s_{ij} x_j(t)}_{\textit{Trophic}} - \underbrace{\sum_{\text{fleets } f} q_{if}\, e_f(t)}_{\textit{Fishing}} \underbrace{+\epsilon_i(t)}_{\textit{Stochastic}}\Bigg)$$

where $\epsilon_i(t) \rightsquigarrow \mathcal{N}(0, \sigma_i)$

Calibration

Cissé et al., Ecological Economics, 2015

From data 2006-2010 :

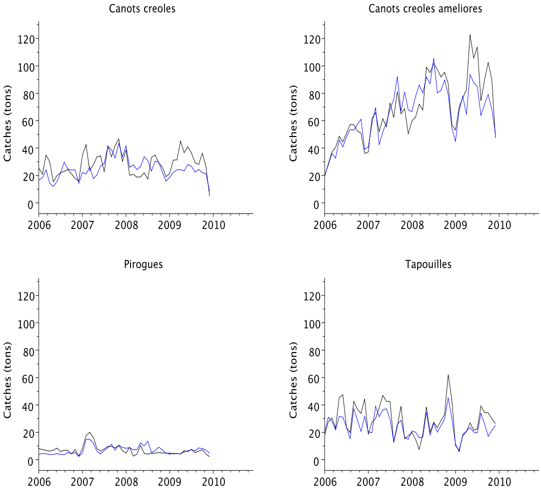
- catches + efforts

  $h_{if}(t) = q_{fi} e_f(t) x_i(t)$

  $e_f(t)$

We estimate

- Trophic matrix s_{ij}
- Catchability q_{fi}
- Initial biomass $x_i(2006)$



Ecoviability fishing scenarios at $T = 2050$

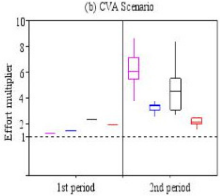
Identify fishing efforts $e_f(t)$ such that

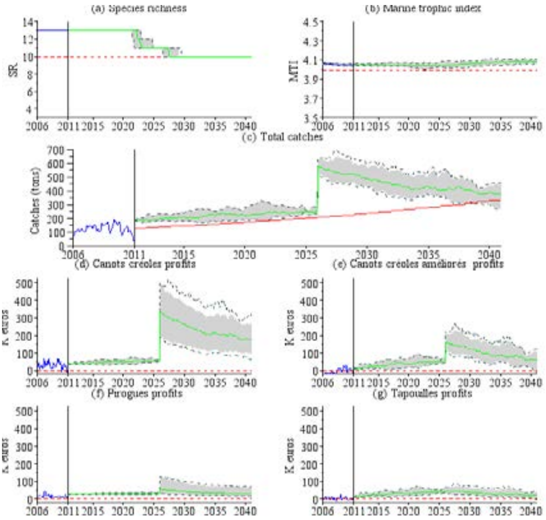
$$\left\{ \begin{array}{ll} \text{guaranteed biodiversity :} & \text{Species richness and MTI} \\ \text{guaranteed profitability :} & \pi_f(t) \geq 0, \ \ \forall \text{ fleet } f \\ \text{food supply} > \text{demand :} & H(t) \geq D_{2008}(1+d)^t \end{array} \right.$$

Stochastic approach

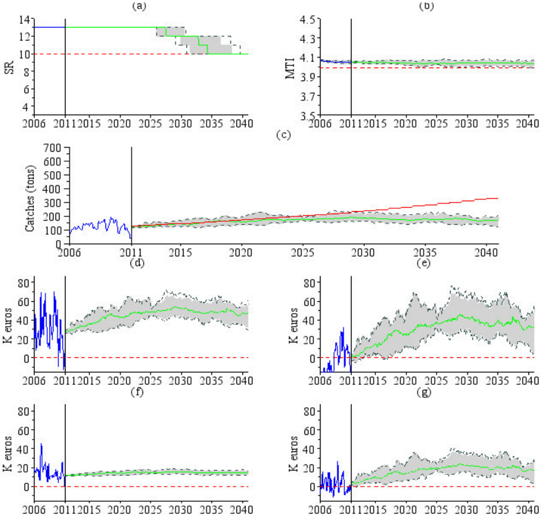
$$\max_{e_f(t_0),\, e_f(t_1,.)} \mathbb{P}\left(\text{ constraints satisfied for } t = 2011, .., T \right)$$

Eco-viability strategy EVA





Status Quo strategy



SEAVIEW Network

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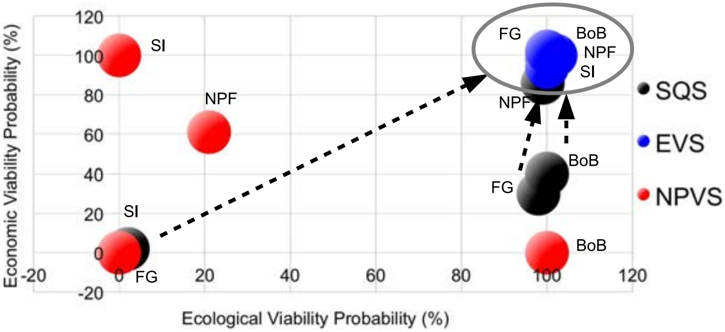
Scenario, fishEry, ecologicAl-economic modelling and VIability nEtWork (SEAVIEW)

Funded Project Information

Call: Scenarios of Biodiversity and Ecosystem Services
Lead PI: Luc Doyen, CNRS, Pessac
Partners: Olivier Thebaud, IFREMER, Plouzane
L. Richard Little, CSIRO, Hobart
Martin Quaas, University of Kiel, Kiel
Astrid Jarre, University of Cape Town, Cape Town
Leo Duta, CSIRO, Dutton Park
Debora Martins de Freitas, Technological Institute of Aeronautics, Santos
Fabian Blanchard, IFREMER, Cayenne
Claire Armstrong, University of Tromsø, Tromsø
Felipe Gusmao, Federal University of Sao Paulo, Santos
Sponsored by: ANR, CSIRO, DFG, FAPESP, NRF, RCN

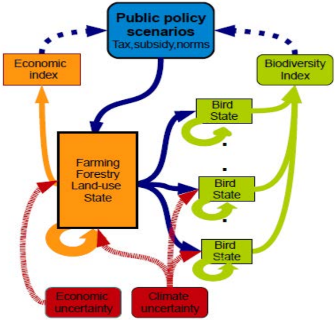
Doyen et al., Fish and Fisheries, 2017

FG : French Guiana ; NPF : Australian Northern Prawn ;
SI : Solomon Islands ; BoB : Bay of Biscay

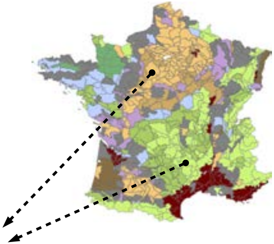


Ay et al., Climatic Change, 2014; Mouysset et al., Ecological Economics, 201

A MICE model



Databases 2001-2009



At SAR scale

(small agricultural region)

620 regions

13 land-uses

+ gross margins

35

bird species

An example of bird community dynamics

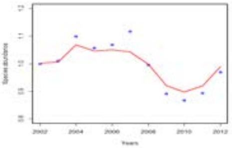
Mouysset et al., Env. Mod. Ass., 2016

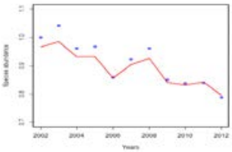
Mouysset et al., Ecological Economics, 2011

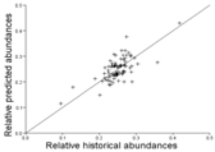
Mouysset et al., Ecological Indicators, 2012

Land-uses –> Habitat quality –> Carrying capacity of species

$$\underbrace{\frac{x_i(t+1)}{x_i(t)}}_{\text{abundance growth of species } i} = \frac{1+r_i}{1+r_i\dfrac{x_i(t)}{k_i(t)}} \quad \text{with} \quad k_i(t) = a_{i,0} + \sum_{\text{land-use } u} a_{i,u}. \underbrace{A_u(t)}_{\text{area of landuse } u}$$







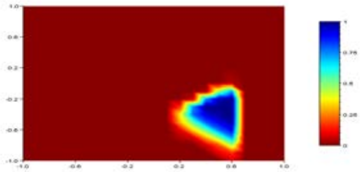
Ecoviability approach

Mouysset et al., Conservation Biology, 2014

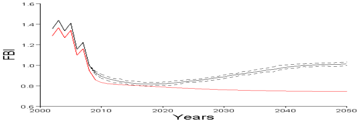
Bio-economic constraints :

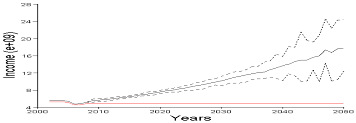
$$
\begin{array}{rcl}
FBI(t) & \geq & a * FBI^{SQ}(t) \\
CTI(t) & \geq & a * CTI^{SQ}(t) \\
CSI(t) & \geq & a * CSI^{SQ}(t) \\
Inc(t) & \geq & a * Inc^{SQ}(t) \\
\textsc{Budget}(t) & \leq & \textsc{Budget}(t_0)
\end{array}
$$

2050

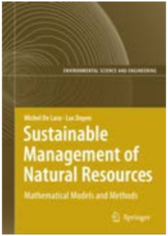


Viability probability





Some references



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Resilience

Earth's Future

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From resistance to transformation: a generic metric of resilience through viability

Christophe Béné, Luc Doyen

Resilience a concept to **be less vulnerable to shocks**

- **Successful :**
  ...in Rugby

SPORT | Rugby

Rugby: Hansen praises All Blacks' resilience

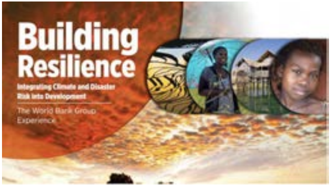
10 Nov, 2013 3:22pm

3 minutes to read

France's Brice Dulin is tackled by New Zealand's All Blacks players during their international rugby match at the Stade de France stadium in Saint Denis. Photo / AP

Resilience a concept to **be less vulnerable to shocks**

- **Successful** : FAO, EU, World Bank, ...
- **Successful in sciences :**
  psychology (Glantz & Johnson, 1996)
  engineering sciences (Grimm and Wissel, 1997),
  ecology (Holling, 1973 ; Gunderson - Folke, 2005)
  economics (Derisen et al, 2011)



However

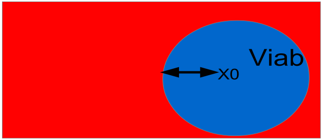
- Generic metrics across disciplines ?
- Bad resilience
- Resilience with respect to what ?

1. **Viability probability** $\approx$ reliability
2. **Magnitude of acceptable shocks**

Béné & Doyen, Earth's Future, 2018

distance to non viable zone :

$$\min_{x \notin \mathrm{Viab}} \|x_0 - x\|$$



3. **Recovery after a shock** :

Doyen-StPierre, 1997 ; Martin, 2006 ; Deffuant Gilbert, 2011; Rougé et al. 2013, Hardy et al, 2016

Minimal time of crisis

$$\min_{a(.)} \sum_{t=t_0}^{T} \mathbf{1}_{X \setminus \mathrm{Constraints}}(x(t), a(t))$$

Renewable resource management example

Renewable stock $x(t)$ harvested at rate $e(t)$

$$x(t+1) \quad = \quad f(x(t)) - qe(t)x(t)$$

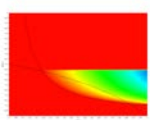
Change in the decision $e(t)$

$$e(t+1) = e(t) + u(t) \text{ with } |u(t)| \leq \frac{1}{\theta}$$

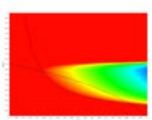
Profitability constraint and threshold :

$$\pi(x(t), e(t)) = pqe(t)x(t) - ce(t) \geq \pi^{\lim}$$

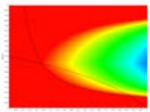
Béné & Doyen, Earth's Future, 2018



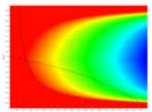
(a) Resistance
$q = 1,\ \pi^{\lim} = 0.1,\ \theta = +\infty$



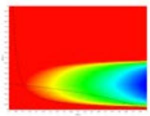
(b) Coping
$q = 1,\ \pi^{\lim} = 0.1,\ \theta = 10$



(c) Adaptive resilience
$q = 1,\ \pi^{\lim} = 0.1,\ \theta = 0$



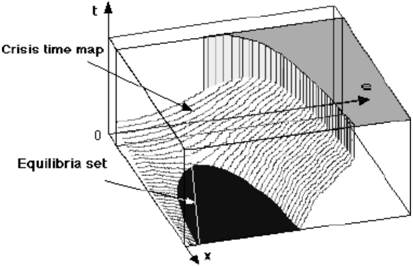
(d) Adaptive preference
$q = 1,\ \widetilde{\pi^{\lim}} = 0.05,\ \theta = 0$



(e) Transforming
$\widetilde{q} = 2,\ \pi^{\lim} = 0.05,\ \theta = 0$

Minimal time of crisis

Bene-Doyen, Ecological Economics, 2001



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pp 1–24

The Tragedy of Open Ecosystems

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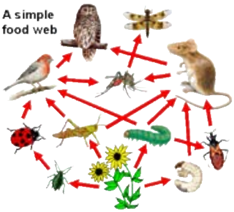
A MICE bio-economic model



Multi-species Gomperz Dynamics

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

Harvest $h_{if}(t)$ of agent $f = 1, \dots, n$ on species i :

$$x_i(t+1) = \left(x_i(t) - \sum_f h_{if}(t)\right)\exp\left\{ r_i + \sum_{j=1}^{m} s_{ij}\ln\left(x_j(t) - \sum_f h_{jk}(t)\right)\right\},$$

Non-cooperative vs cooperative maximization

Non-cooperative

For each agent $f = 1, .., n$

$$\max_{h_{f.}(.)} \sum_{t=0}^{\infty} \rho^t U\left(h_{f1}(t) \ldots, h_{fm}(t)\right),$$

Cooperative

$$\max_{h(.)} \sum_{t=0}^{\infty} \rho^t \left(\sum_{f=1}^{n} U\left(h_{f1}(t), \ldots, h_{fm}(t)\right) \right)$$

with $0 < \rho < 1$ discount factor

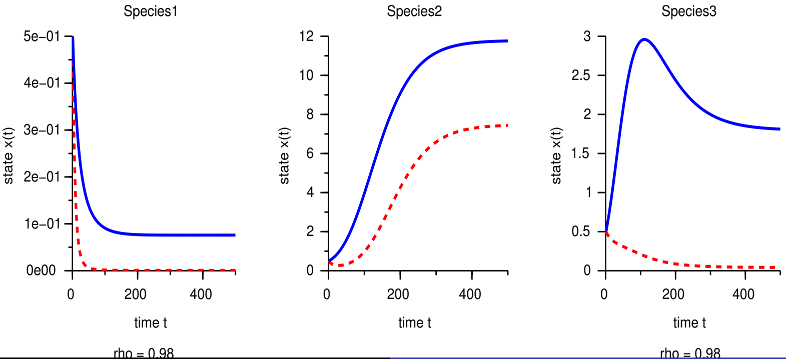
Analytical solutions using Dynamic Programming and Cournot-Nash optimum and Utility $U(h) = \sum_i a_i \log(h_i)$

Bio-economic gains of cooperation

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

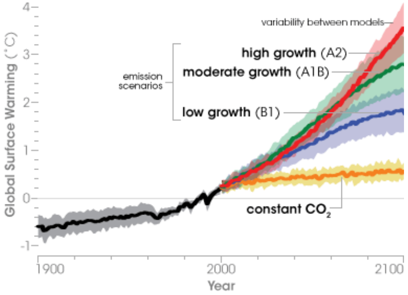
$$a = (3 \quad 2 \quad 1)', \ \rho = 0.98, \ n = 3$$

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



Integrate climate changes : Jean-Sauveur Ay

Sauveur-Jiguet-Leadley-Chakir-Doyen, climatic Change, 2014



http://dentafas.free.fr/SpecialistesAgricoles/

NPV strategy