Optimal management of biodiversity preservation

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FIME-CREST, PARIS, 7 APRIL 2023

Outline of my presentation

- **INTRODUCTION**
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  - new topical research themes
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- **THE MODEL**
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  - optimal decision under uncertainty: the case of two species
  - adding an eco-system planner
  - discussion and main policy recommendations
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The economic case for protecting biodiversity

- Biodiversity is an **asset** which provides a crucially important flow of services

  - In life-support systems (e.g., green plants produce oxygen, bacteria clean water and fertilize soil): crucial activities for the maintainence of human life

  - Intrinsic value: a value in and of themselves independently of their anthropocentric value

  - Cultural and aesthetic value (they are part of the cultural identity and heritage)

- There is a significant gap between what we demand from nature and what it can supply. One way to close this gap is to treat nature as **an asset management problem**

- There is a great **uncertainty** about the value of certain types of biodiversity

There are costs to biodiversity loss whose magnitude we are highly uncertain, about others we currently know nothing; we have some ideas of the costs of conserving biodiversity, but more imprecise ideas about the benefits.

Hence «any formal cost-benefit analysis becomes challenging» (Heal, 2020)

Why biodiversity and nature-related risks matter

- While climate change continues to dominate the World Economic Forum's Global Risk Reports, biodiversity loss ranked in the top 5 risks by likelihood and impact since 2020.
- Research shows that deforestation and species loss made pandemic such as Covid19 more likely (Tollefson, 2020); reduced biodiversity and related ecosystem services could result in a decline in global GDP of $2.7 trillion annually by 2030 (World Bank- Johnson et al, 2020)
- 2022. COP15 of the UN Convention on Biological Diversity, Montreal («30x30» target)
- 2022. COP26, Glasgow, on Climate change & biodiversity
- 2023. World Economic Forum, Davos
- World Bank Report «Making the Economic Case for Nature» (2021) discusses the macroeconomic consequences of biodiversity. The framework paints a landscape of possible scenarios of interactions between ecosystem services and the economy up to 2030. The key driver of change is land use change
- The Taskforce on Nature-related Financial Disclosure (TNFD) aims at creating a framework to shift financial flows to «nature-positive» outcomes & innovative financial mechanisms

New topical themes

- Biodiversity and nature-related risks can have impacts on sovereign creditworthiness, default probability and cost of capital (Agarwala, Burke, Klusak, Kraemer & Volz, 2022)
- Rating agencies started recognizing the need to incorporate nature-related risks in their assessments (Fitch, 2021, Vanstone et al, 2021). Moody's joined TNFD in a quest to enhance credit analysis to better reflect biodiversity
- With little fiscal space, governments must crowd-in private finance to stimulate sustainable & resilient investments (Flammer, Giroux, Heal, 2023). A growing interest in incorporating biodiversity in sustainability and nature linked bonds (markets for biodiversity-linked products, Volz, 2022).
- Still, how do we evaluate both their risks and environmental benefits?
- Economies with high dependence on ecosystem services face a choice: pay now, by investing in nature, or pay later through reduced fiscal space and higher borrowing costs.
- Do markets provide adequate incentives for the preservation of biodiversity? Can we fully rely on the market to manage biodiversity?

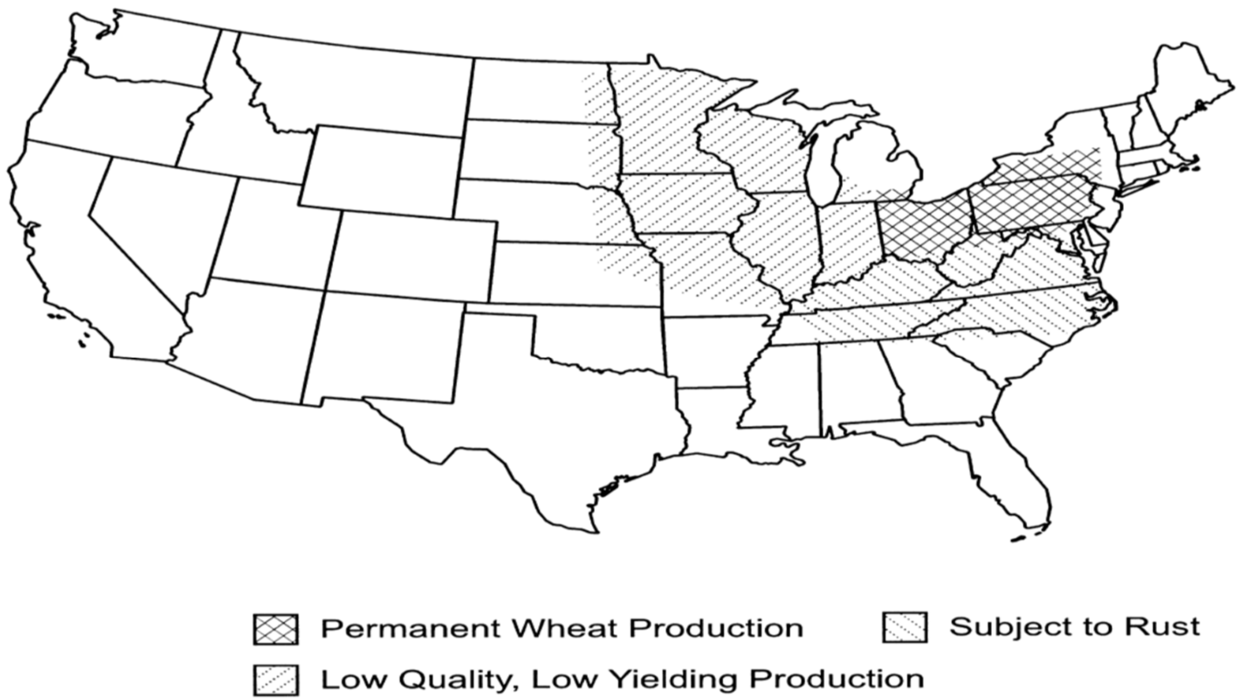
Climate Change and Biodiversity

WWF (2022) portrays an alarming picture of global biodiversity: the population of species have decreased an average of 68% more than forecasted earlier by WWF (2016), according to the Living Planet Index (a «code red» alert for humanity)

Studies have shown that an important driver is climate change (Brook et al, 2008, Guo et al, 2017…). Thomas et al (2004) already showed that climate change could result in the extinction of more than a million of terrestrial species in the next 50 years.

According to Tol (2009), *climate change is the mother of all externalities* and has a deep impact on biodiversity not only through changes in temperature and precipitation, and its increasing magnitude and frequency of extreme events such as floods, cyclones, droughts, but also the ways that climate change might affect ocean acidification, land use and nutrients, and also the prolification of invasive alien species into the new habitat.

Wheat production in 1858
(Olmstead and Rhode, 2011; Pindyck, 2022)



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The value of biodiversity

- **The economic value of biodiversity**
- ... derives from the value of the final goods and services it produces, which depend on the types of species that ecosytems contain, their substitutability or complementarity in the functioning of ecological systems, and on the way that such functioning is affected by resource use.
- ... differs depending on geographical location, income, scientific development, spiritual and cultural perception of intact ecosystems.
- Higher levels of biodiversity are often associated with enhanced ecosystem stability and resilience.
- Biodiversity is also associated with numerous economic benefits. Brock and Xepapadeas (2003) value biodiversity in terms of the value of characteristics or services that an ecosystem provides or enhances, when optimally managed.

The Model:
Optimal management of species

The value v_i of species i follows $dv_i/v_i = m_i dt + \sigma_i dW_t^{(i)}$

$W_t^{(i)}$ Wiener processes, $E[dW_t^{(1)} dW_t^{(2)}] = \rho dt.$

Cost of maintaining species i is $k_i v_i$, with $0 \leq k_i < 1.$

A fixed cost, H (e.g. cost for acquiring farmland to instal a plantation).

Optimal decision between

- conserving and exploiting **only** species i:

the cumulated expected return is:

$$E_t[\int_t^\infty e^{-r(\tau-t)}[(1-k_i)v_i(\tau) - H]d\tau = \frac{(1-k_i)v_i(t)}{r-m_i} - \frac{H}{r}$$

- grow many species (*biodiversity preservation*), exploit the most valuable species, but keep other species for future opportunities.

The case of two species






In Italy: 58000 animal species, over 6700 plants

In the subregion $v_1 \geq v_2$ one has $\max_{i=1,2} v_i = v_1$. Then F satisfies

$$\mathcal{L}F(v_1, v_2) + (1 - k_1)v_1 - k_2 v_2 - H = 0 \tag{1}$$

where $\mathcal{L} = \frac{1}{2}[\sigma_1^2 v_1^2 \partial^2_{v_1} + \sigma_2^2 v_2^2 \partial^2_{v_2} + 2\rho\sigma_1\sigma_2 v_1 v_2 \partial^2_{v_1 v_2}] + m_1 v_1 \partial_{v_1} + m_2 v_2 \partial_{v_2} - r$.

A particular solution to equation (1) is $\frac{(1-k_1)v_1}{r-m_1} - \frac{k_2 v_2}{r-m_2} - \frac{H}{r}$. The homogeneous part of equation (1) can be solved through the usual dimension reduction obtained by introducing a new variable $x = v_1/v_2$. If we search for a solution of the form $v_2 g(x)$, then g should solve the differential equation:

$\frac{S^2}{2} x^2 g"(x) + (m_1 - m_2)x g'(x) + (m_2 - r)g(x) = 0.$

where $S^2 = \sigma_1^2 + \sigma_2^2 - 2\rho\sigma_1\sigma_2$. If $g(x) = x^\beta$ then β should solve

$$\frac{S^2}{2}\beta^2 + (m_1 - m_2 - \frac{S^2}{2})\beta + m_2 - r = 0 \tag{2}$$

Let $\beta_\pm$ denote the two roots of equation (2). Note that in view of the assumption $m_i < r$, $i = 1, 2$, we have: $\beta_- < 0 < 1 < \beta_+$. Therefore

$F(v_1, v_2) = A_+(\frac{v_1}{v_2})^{\beta_+} v_2 + A_-(\frac{v_1}{v_2})^{\beta_-} v_2 + \frac{(1-k_1)v_1}{r-m_1} - \frac{k_2 v_2}{r-m_2} - \frac{H}{r}$ for $v_1 \geq v_2$

where A_+ are arbitrary constants.

Optimal decision under uncertainty

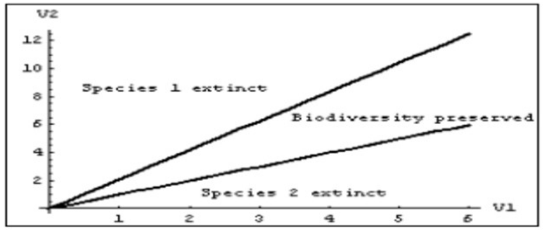
The lines separating the set of values (v_1, v_2) where both species are preserved from the regions where one species is abandoned are of the form $v_2 = z^* v_1$ (for abandoning species 2) and $v_2 = \widehat{z} v_1$ (for abandoning species 1), where z^* and $\widehat{z}$ are computed by solving the system

$$\begin{cases} \frac{(1-\beta_-)k_1}{r-m_1} \widehat{z}^{\beta_+-1} + \frac{k_2\beta_-}{r-m_2} z^{*\beta_+} = \frac{\beta_-}{r-m_2} + \frac{1-\beta_-}{r-m_1} \\ \frac{(\beta_+-1)k_1}{r-m_1} \widehat{z}^{\beta_--1} - \frac{k_2\beta_+}{r-m_2} z^{*\beta_-} = \frac{-\beta_+}{r-m_2} + \frac{\beta_+-1}{r-m_1} \end{cases}$$

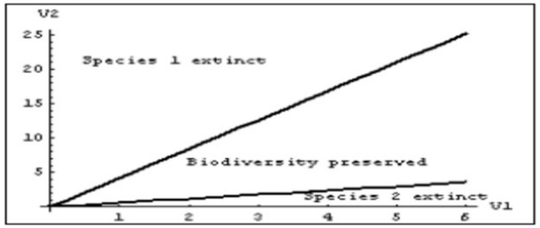
Proposition (cont'd)

Proof. $F(v_1, v_2)$ for $v_1 \geq v_2$ is matched with $\frac{(1-k_1)v_1}{r-m_1} - \frac{H}{r}$ on the line $v_2 = z^* v_1$ along with their derivatives ∂_{v_1} and ∂_{v_2}. Three equations are obtained, but one of them is redundant. Similarly, $F(v_1, v_2)$ for $v_1 \leq v_2$ is matched with $\frac{(1-k_2)v_2}{r-m_2} - \frac{H}{r}$ on the line $v_2 = \widehat{z} v_1$ along with the derivatives. In total, four equations are obtained where the unknowns are $A_{\pm}$, z^* and $\widehat{z}$. Solving for $A_{\pm}$ in terms of the remaining unknowns, we are left with the two equations (3) for the unknowns z^* and $\widehat{z}$. Note that the condition $\frac{\beta_+ - 1}{\beta_+} \frac{r-m_2}{r-m_1} < \frac{1-k_2}{1-k_1} < \frac{\beta_- - 1}{\beta_-} \frac{r-m_2}{r-m_1}$ is necessary for $z^* \leq 1$ and $\widehat{z} \geq 1$.

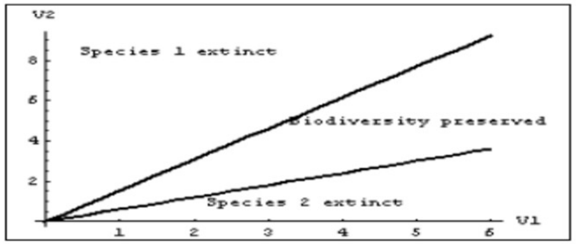
Sensitivity analysis



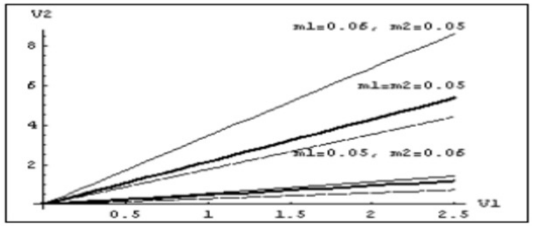
Base case ($\rho = 0.5$)



Base case ($\rho = -0.5$)

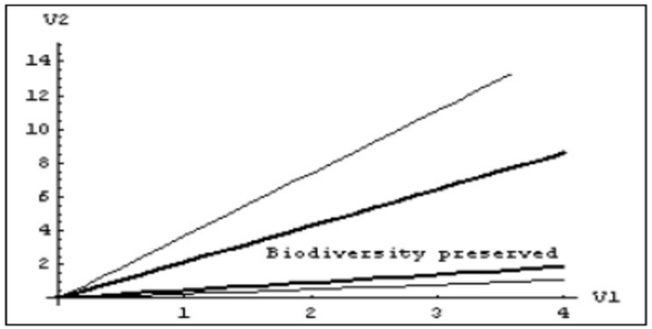


k_2 reduced (compare to Fig.1)



Varying m_i

Effect of volatility



Solid line: $\sigma_1 = 20\%$; thin line $\sigma_1 = 30\%$

Introducing Ambiguity

Distorted Brownian motions in the presence of ambiguity.

The theory is based on Choquet's capacities (non-additive unit measures used to represent beliefs). The key parameter is c, a

proxy for decision-makers' attitudes towards ambiguity:

$\mathbf{0 < c < 0.5}$ ambiguity aversion,

$\mathbf{0.5 < c < 1}$ ambiguity-seeking,

$\boxed{\mathbf{c = 0.5}}$ absence of ambiguity.

‘Deep’ Uncertainty & Ambiguity

“Embracing deep or radical uncertainty therefore calls for an “epistemological break” to shift from a management of risks approach to one that seeks to assure the resilience of complex systems in the face of such uncertainty”

(*The Green Swan: Central banking and financial stability in the age of climate change*, Bolton, Desprez, Pereira da Silva, Samama, Svatzman, 2020)

from a management perspective, deep uncertainty and aversion to ambiguity are important concepts in ecologicaleconomic systems. Levin and Xepapadeas (2021) list major gaps in global and national monitoring systems: the lack of inventory of species; definitional ambiguities that may lead to confusing results; and lack of theories to anticipate how humans will respond to changing conditions. Therefore, ‘efficient management should be based on a recognition that there are deep uncertainties and that people have preferences that are averse to deep uncertainty, or ambiguity’ (page 367).

How to model ambiguity

To model uncertainty, we refer to

- *capacities* (instead of additive probabilities) to weight likelihood of events
- *discounted Choquet integrals* to compute payoffs value.

As a result, the dynamics of the real option cash flows will be represented by a distorted Brownian motions (*Choquet-Brownian motions*) rather than by a standard geometric Brownian.

The recursive multi-prior model in Epstein and Schmeidler (2003) restricts the kind of ambiguity that one wants to address.

Capacities

(Schmeidler, 1989, Gilboa and Schmeidler, 1989, etc)

S≠∅ set of states;

A set of events

Capacity: a function v: $A \longrightarrow$ R s.t. :

(i) F subset of G implies v(F) ≤ v(G) (monotonicity);

(ii) *v(∅)=0* and *v(S)=1* (normalization).

It is convex if v(FUG)≥v(F)+v(G)-v(F∩G); it is concave if the reverse inequality holds. Probability distributions are special cases of capacities which are both concave and convex.

Expectations are defined as Choquet integrals

The decision weigths used in the Choquet integral will overweight high outcomes if the capacity is concave and low outcomes if it is convex (optimism, pessimism).

Choquet integral and ambiguity level

$$\int_S X dv = \sum_{i=1}^{n-1} [x_i - x_{i+1}] v(X \geq x_i) + x_n$$

In particular, if $X=x_1$ on E and $=x_2$ on S-E, where $x_1>x_2$, then

$$E(X)=x_1 v(E)+ x_2 (1-v(E))= x_1 v(E)+ x_2 v(S-E)+ x_2 \psi_v(E)$$

where $\psi_v(E)=1- v(E)-v(S-E)$ **ambiguity level** of the capacity v at an event E.
It is positive for convex capacities

The **bad outcome is 'over-weighted' by the ambiguity level** of the event under the capacity v

Dynamically consistent Choquet random walk

A binomial tree where, at each point in time t=0,1,...T, the uncertain states are $\{s_t^1, \ldots, s_t^{t+1}\} =: S_t$

Two possible successors of s_t at time t+1: $s_{t+1}^u \quad s_{t+1}^d$

The conditional capacities are: $v(s_{t+1}^u | s_t) = v(s_{t+1}^d | s_t) = c$

$$
\begin{tikzcd}
 & & s_2^1 & \cdots\cdots \\
 & s_1^1 \arrow[ur] \arrow[dr] & & \\
s_0^1 \arrow[ur] \arrow[dr] & & s_2^2 & \cdots\cdots \\
 & s_1^2 \arrow[ur] \arrow[dr] & & \\
 & & s_2^3 & \cdots\cdots
\end{tikzcd}
$$

Dynamically consistent Choquet random walk

.

$$\sum_{s_t \in S_t} \left[\sum_{s_\tau \in S_\tau} X_\tau(s_\tau) \Delta v(s_\tau | s_t) \right] \Delta v(s_t) = \sum_{s_\tau \in S_\tau} X_\tau(s_\tau) \Delta v(s_\tau)$$

In particular, if $B \subseteq S_{t+1}$ then

$$v(B) = (1-c) v(s_t | s_{t+1}^u \in B \wedge s_{t+1}^d \in B) + c v(s_t | s_{t+1}^u \in B \vee s_{t+1}^d \in B)$$

All the capacities at time t+1 are uniquely determined by capacities at time t. Going backward until date 1 (where the capacities are c, $0 < c < 1$) the set function v is completely defined. The dynamically consistent Choquet random walk is completely defined by a capacity v satisfying: $v(s_{t+1}^u | s_t) = v(s_{t+1}^d | s_t) = c$

In a DCCRW the capacity v is **convex** iff $c \leq 1/2$.

Moreover, it does not reduce to a probability iff $c \neq 1/2$.

Dynamically consistent Choquet random walk

The parameter c represents DM's ambiguity about the likelihood of the states to come:

$\upsilon(\emptyset \mid s_t) = 0$, $\upsilon(\{s_{t+1}(up), s_{t+1}(down)\} \mid s_t) = 1$, for any B, $\upsilon(B \mid s_t) = \upsilon(B \cap \{s_{t+1}(up), s_{t+1}(down)\} \mid s_t)$

- A DCCRW is defined by a unique capacity, $\upsilon(s_{t+1}(up), \mid s_t) = \upsilon(s_{t+1}(up), \mid s_t) = c$
- The Choquet expectation of the payoffs of a symmetric Choquet random walk is for any t, $E(X_t) = t(2c-1)$.
- **When the time interval converges to 0, the symmetric DCCRW converges towards a general Wiener process with mean m=2c-1 and variance =4c(1-c)**

  (see Kast, Lapied, Roubaud, EM, 2013)

- **When c < 1/2 both the mean and variance are lower than in the probabilistic model, because ambiguity aversion yields lower weights on the ups and downs.**

Species values follow a Choquet Brownian motion

The actual underlying dynamic process is a standard Wiener process and ambiguity leads to a distortion in the perception of this process:

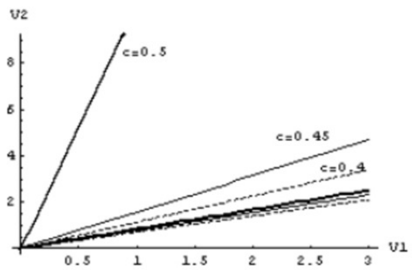
$$dv_i/v_i = (m_i + \sigma_i(2c-1))dt + s\sigma_i dW_t^{(i)}$$

Mean = 2c-1

Variance= 4c(1-c)

Both drift and volatility are smaller: with ambiguity aversion mass is shifted to the «worst case» outcome.

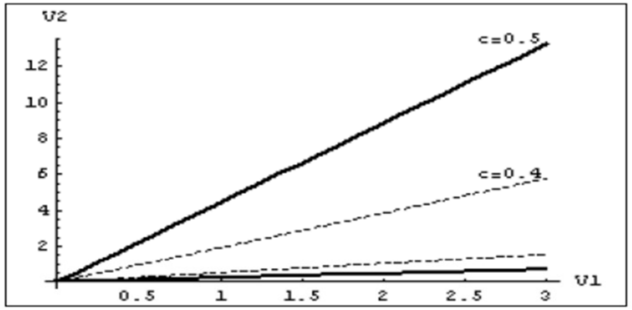
The case of Ambiguity



The introduction of ambiguity dramatically shrinks the scope for preserving both species. Here perfectly correlated Wiener processes, $\sigma_1 >> \sigma_2$ and equal costs: the zone for keeping alive species 1 is strongly reduced when ambiguity is introduced in favour of the less risky species.

Ambiguity and 'calculated' risk work in opposite directions!

The case of Ambiguity



Here independent Wiener processes, symmetric parameters, ambiguity interacts with correlation. (See Roubaud, Lapied, Kast (2017). Modelling under ambiguity with two correlated Choquet-Brownian motions).

Adding an Ecosystem Planner

- Ecosystem or landscape planner whose main consideration is the total value of species, including the non-use values of social importance...
- Harvesting rules (see Brock and Xepapadeas, 2002).
- $h_i \in [0, 1]$ = proportion of the biomass of the i^{th} species which is harvested.
- The producer receives a compensation for growing the non-harvested mass, f.e. the unit cost k_i is reduced by a unit subsidy s_i, $i = 1, 2$.
- In our model the total value achieved by the landscape planner reaches its peak in the central region where both species are preserved.

The total net present value becomes:

$$\frac{1-k_2}{r-m_2}v_2 - \frac{H}{r} \quad \text{if } v_2 > \widehat{z}_{h_1,s_1}v_1;$$

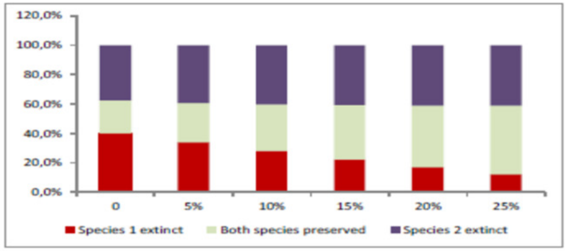
$$\left\{(1-\beta_-)\widehat{z}_{h_1,s_1}^{\beta_+-1}\left(\frac{v_1}{v_2}\right)^{\beta_+-1} + (\beta_+-1)\widehat{z}_{h_1,s_1}^{\beta_--1}\left(\frac{v_1}{v_2}\right)^{\beta_--1}\right\}\frac{k_1h_1v_1}{(r-m_1)(\beta_+-\beta_-)} + \frac{(1-k_1)v_1}{(r-m_1)} + \frac{(1-k_2)v_2}{(r-m_2)} - \frac{H}{r} \quad \text{if } v_1h_1 \leq v_2 \leq \widehat{z}_{h_1,s_1}v_1;$$

$$\left\{-\beta_- z_{h_1,s_1}^{*\beta_+}\left(\frac{v_1}{v_2}\right)^{\beta_+} + \beta_+ z_{h_1,s_1}^{*\beta_-}\left(\frac{v_1}{v_2}\right)^{\beta_-}\right\}\frac{k_2v_2}{(r-m_2)(\beta_+-\beta_-)} + \frac{(1-k_1)v_1}{(r-m_1)} + \frac{(1-k_2)v_2}{(r-m_2)} - \frac{H}{r} \quad \text{if } z_{h_1,s_1}^{*}v_1 \leq v_2 \leq v_1h_1;$$

$$\frac{1-k_1}{r-m_1}v_1 - \frac{H}{r} \quad \text{if } v_2 < z_{h_1,s_1}^{*}v_1.$$

Ecosystem planner

Case where the planner's policy is applied only to species 1.

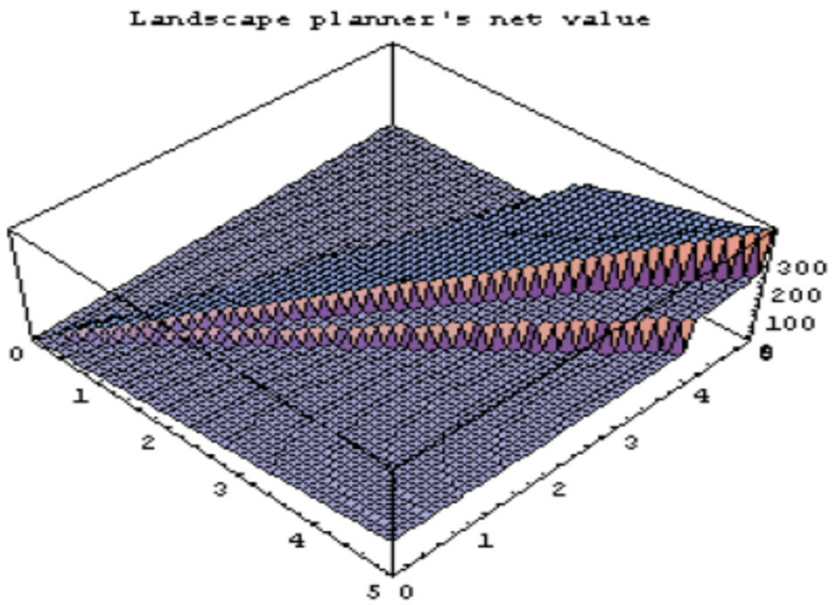


$h_1 = 90\%$ with several subsidy rates

For comparison: when $h_1 = 1$ and $s_1 = 0$ (no special policy activated) the area of extinction of species 1 is 31% of all possible states.

Ambiguity offsets the subsidy policy: if $c = 0.4$, a subsidy $s_1 = 20\%$ reduces the likelihood of eliminating species 1 only by 2.4% and $s_1 = 25\%$ by 6%. Perceived ambiguity has a disruptive effect on the policy and expenditures of ecosystem planners.

Social value of growing two species



Conclusions & policy recommediations

- Calculated risk creates a scope for biodiversity preservation as the availability of different species provides flexibility in case of consumers' shifts in taste and habits and increases resilience to negative externalities (pests, diseases, climate change, etc.)
- Ambiguity has a deterring influence on biodiversity development.
- A successful safeguard plan should remove ambiguity (avoid abrupt changes in policy measures, complicated and vexhatious cross-compliance rules, lack of clear and prioritized objectives and should instead increase transparency in the development and monitoring process).

Conclusions & policy recommendations

- A **two-tier policy** wrt investments and conservation. One policy tier would target the investors and their investment and production policies, under base-line expectations or obligations regarding conservation efforts. The other policy tier would target conservation efforts financed through public subsidies, without any specific expectations or obligations regarding the economic viability of the investment and production decisions involved. The main consideration of this tier would be safeguarding biodiversity and working towards sustainability.

Further steps…

- A Jump-diffusion process
- Multi-dimensional case (more than 2 species)
- Modelling climate change into the stochastic process
- Further combinations of financial mechanisms (e.g. Payments for Ecosystem services (PES))