Robust Management of a Harvested Ecosystem Model

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Introduction

The sustainable management of natural resources must deal with several technical issues:

- Conflicting objectives: balancing the risk of resource collapse versus the risk of forgone economic benefits.
- Taking into account the complexity of fisheries dynamics.
  ⇒ Calling for moving toward an ecosystemic approach of fisheries management (WSSD, Johannesburg, 2002).
- Accounting for various sources of uncertainty:
  - Stock estimation status.
  - Dynamics of ecosystems.
  - Disturbances: climatic hazard, technical progress, etc.

Motivation

Emphasizing the importance of taking into account disturbances likely to affect the dynamics of an ecosystem when designing a management strategy.

- A management strategy is the rule governing the practise of a regulatory instrument.
  Ex: Setting the yearly harvest as a fixed fraction of the exploited biomass.
- **Approach**: comparing the set of sustainable initial states (viability kernel) given by a deterministic strategy to that driven by strategies integrating uncertainty.
- **Case-study**: the hake-anchovy couple in the Peruvian up-welling ecosystem.

The Viability Theory

- Seeks the set of states, for which there exist controls, satisfying the dynamics of a system, and constraints, describing given objectives, at the same time (J. P. Aubin, 1991).
- Identifies a decisions sequence capable of maintaining the system viable. Decisions (controls) are computed by use of a dynamic programming equation.
- All constraints must be satisfied at all dates.
  The approach can be softened by accepting constraint violations with low probability in the stochastic case.

Generic ecosystem model

- We consider a two-dimensional state model

$$\begin{cases} y(t+1) = y(t)R_y\big(y(t), z(t)\big)\big(1 - v(t)\big) \\ z(t+1) = z(t)R_z\big(y(t), z(t)\big)\big(1 - w(t)\big) \end{cases}$$

- state vector (y, z) represents biomasses,
- control vector (v, w) is fishing effort of each species, each lying in $[0, 1]$
- R_y and R_z are annual growth factors.
- catches are $vyR_y(y, z)$ and $wzR_z(y)$ (measured in biomass)

The Viability Kernel

- The viability kernel is the set of initial states $y(t_0), z(t_0)$ from which there exists, for $t = t_0, \dots, T$, controls $v(t), w(t)$ producing a trajectory $y(t), z(t)$ such that *a priori* conflicting requirements

- preservation (minimal biomass thresholds):

  $y(t) \geq y^\flat$, $z(t) \geq z^\flat$

- economic/social requirements (minimal catch thresholds):

  $$v(t)y(t)R_y(y(t), z(t)) \geq Y^\flat,$$
  $$w(t)z(t)R_z(y(t), z(t)) \geq Z^\flat$$

  are satisfied for $t = t_0, \dots, T$.

The Viability Kernel

- If the thresholds $y^\flat$, $z^\flat$, $Y^\flat$,$Z^\flat$ are such that the following expressions are satisfied

$$y^\flat R_y\big(y^\flat, z^\flat\big) - Y^\flat \geq y^\flat \quad \text{and} \quad z^\flat R_z\big(y^\flat, z^\flat\big) - Z^\flat \geq z^\flat$$

- the viability kernel is

$$\mathbb{V}(t_0) = \Big\{ \ (y, z) \mid y \geq y^\flat, z \geq z^\flat, \\ yR_y\big(y, z\big) - Y^\flat \geq y^\flat, zR_z\big(y, z\big) - Z^\flat \geq z^\flat \Big\}$$

The Peruvian hake-anchovy system

- Fitted by a discrete-time Lotka-Volterra system with density-dependence (IMARPE):

$$y(t+1) = y(t)\overbrace{\left(R - \frac{R}{\kappa}y(t) - \alpha z(t)\right)}^{R_y\left(y(t),z(t)\right)}\left(1 - v(t)\right)$$

$$z(t+1) = z(t)\underbrace{\left(L + \beta y(t)\right)}_{R_z\left(y(t),z(t)\right)}\left(1 - w(t)\right)$$

  - y prey biomass: anchovy
  - z predator biomass: hake

- The associated viability kernel

$$\mathbb{V}(t_0) = \left\{\ (y,z) \mid y \geq y^\flat, z^\flat \leq z \leq \frac{1}{\alpha}[R - \frac{R}{\kappa}y - \frac{y^\flat + Y^\flat}{y}]\ \right\}.$$

The Viability Kernel

The annual objectives and calibration were set by IMARPE (taller internacional sobre la anchoveta peruana), based on data from 1971 to 1981:

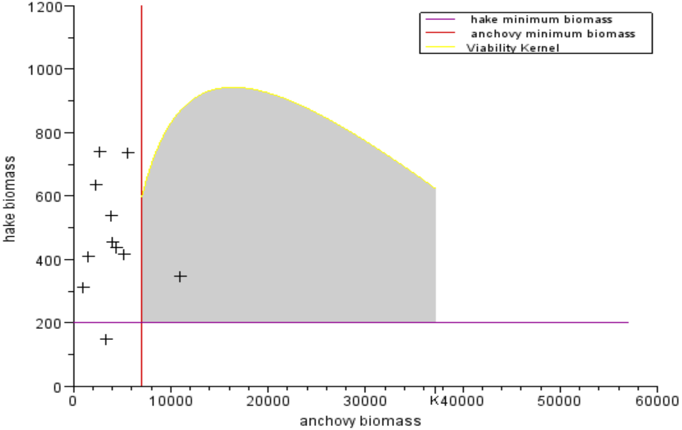

Figure: Viability Kernel for minimal biomass thresholds $y^\flat = 7000$ kt (Anchovy) and $z^\flat = 200$ kt (hake), and the minimal catches thresholds $Y^\flat = 2000$ kt (Anchovy) and $Z^\flat = 5$ kt (hake)

Accounting for uncertainty

(a) Anchovy (b) Hake

Figure: Observed and Simulated biomasses over 1971-1981

Ecosystem model with uncertainty

- In the stochastic approach the model becomes:

$$y(t+1) = y(t)\overbrace{\left(R - \frac{R}{\kappa}y(t) - \alpha z(t)\right)}^{R_y\left(y(t),z(t)\right)}\left(1 - v(t)\right) + \varepsilon_y(t)$$

$$z(t+1) = z(t)\underbrace{\left(L + \beta y(t)\right)}_{R_z\left(y(t),z(t)\right)}\left(1 - w(t)\right) + \varepsilon_z(t)$$

where $\varepsilon_y(t)$ and $\varepsilon_z(t)$ are additive disturbance terms.

- The targeted preservation and economic objectives are kept equal.

The uncertainties space S

- Defined by taking the difference between observed and simulated biomasses
  $\varepsilon_y(t) = y(t) - \hat{y}(t)$; $\varepsilon_z(t) = z(t) - \hat{z}(t)$.

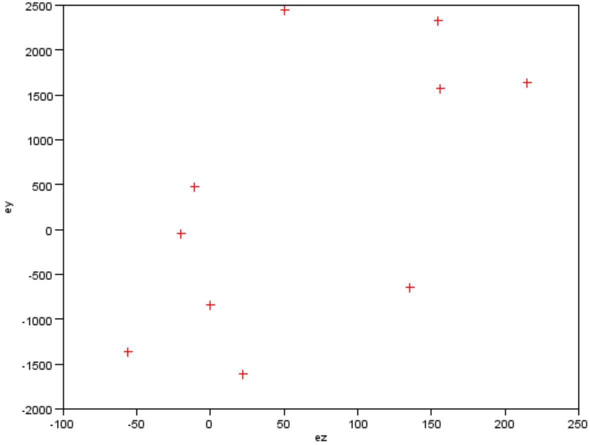

Figure: $(\varepsilon_y(t), \varepsilon_z(t))$ over 1971-1981

The Stochastic Viability approach

- $S = [\varepsilon_y^{min}, \varepsilon_y^{max}] \times [\varepsilon_z^{min}, \varepsilon_z^{max}]$
- An uncertainty scenario is $\big(\varepsilon_y(\cdot), \varepsilon_z(\cdot)\big) = ((\varepsilon_y(t_0), \varepsilon_z(t_0)), \ldots, (\varepsilon_y(T), \varepsilon_z(T)))$
- The set of uncertainty scenarios is $\Omega = S^{T-t_0+1}$.
- Ω is equipped with probability distribution.
- We adopt the uniform distribution law to simulate scenarios over S (of course results will be conditioned by this choice).

The Stochastic Viability approach

- The stochastic viability kernel of confidence level β is the set of initial states $y(t_0), z(t_0)$ from which there exists, for $t = t_0, \ldots, T$, controls $v(t), w(t)$ producing a trajectory $y(t), z(t)$ such that over all scenarios

- minimal biomass thresholds:

$$y(t) \geq y^\flat, z(t) \geq z^\flat$$

- minimal catch thresholds:

$$v(t)y(t)R_y(y(t), z(t)) \geq Y^\flat,$$
$$w(t)z(t)R_z(y(t), z(t)) \geq Z^\flat$$

are satisfied for $t = t_0, \ldots, T$ with a probability $\geq \beta$.

The Stochastic Viability Kernel

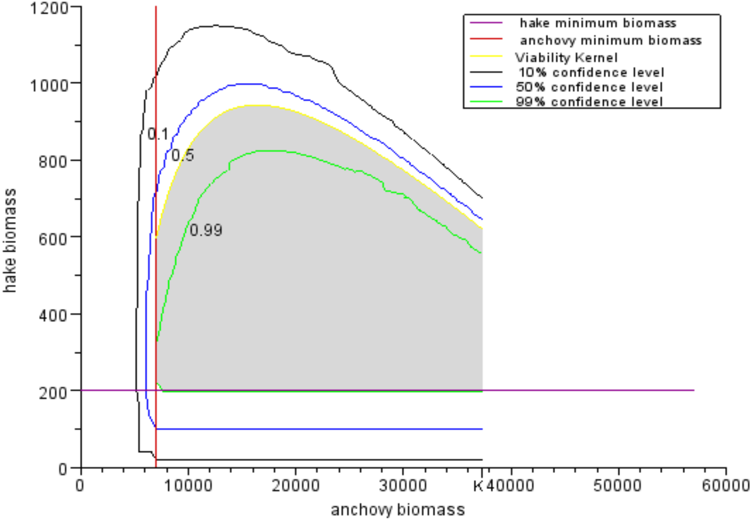

Figure: Viability Probability level curves

Conclusion

- There are no robust viability kernel (100% probability)
- The set of initial states included in the determinist viability kernel are viable with a probability of about 70%
- We have developed a tool capable of attaching to a potential initial state, a probability of achieving conflicting objectives
- For a given confidence level, the approach provides a corresponding control sequence