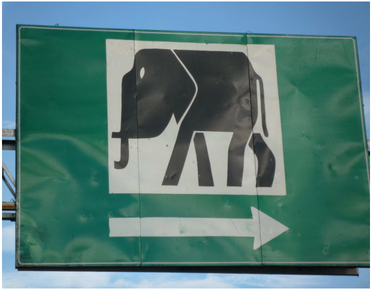
To What Extent Can Ecosystem Services Motivate Protecting Biodiversity? Insight from a Bioeconomic Perspective

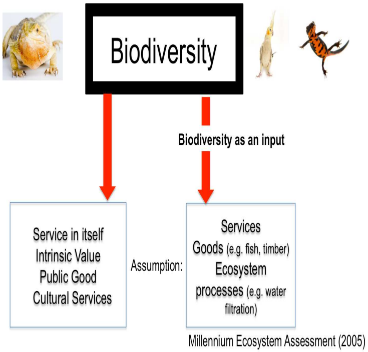
Michel De Lara
Cermics, École des Ponts ParisTech
and
Christopher Costello, Laura Dee, Steve Gaines
Bren School, UC Santa Barbara, USA

Labex Corail, Nouméa, 28 August 2019

Protecting biodiversity comes at a cost



Why care about biodiversity?



- The Millennium Ecosystem Assessment considers biodiversity to have both
  - intrinsic value (existence value)
  - functional value (some species contribute to other goods and services that benefit society beyond the existence value)
- We take the standpoint to consider only the functional value to assess the consequences of only protecting species to secure the provisioning of ecosystem services

We witness interest in protecting biodiversity for the services it provides society

- The Nature Conservancy revised mission statement to focus on ecosystem services
- The Intergovernmental Platform on Biodiversity and Ecosystem Services was established in 2012

There is an underlying assumption that optimizing ecosystem services will result in protection of biodiversity

Question: is this true?

We propose insight from a bioeconomic perspective

To make a long story short . . .

We claim that stochastic control offers insight to gauge optimal levels of biodiversity protection for ecosystem services delivery

Issues.

- Biodiversity is declining: critical species may disappear, affecting ecosystem services
- But critical species are unknown
- Protection of a species pool is costly
- Question: when is protecting optimal?

Methods.

- Bioeconomic stochastic optimal control formalization
- Dynamic programming resolution

Answers.

- Existence of a pivotal threshold for the number of species in a pool, below which protecting is optimal
- Dependence of this threshold on economic data
- Extension to multiple ecosystem services

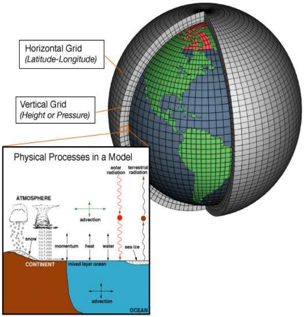
Outline of the presentation

Problem statement: costly protecting a declining pool of species

Protection is optimal only below a bioeconomic pool threshold

Extensions

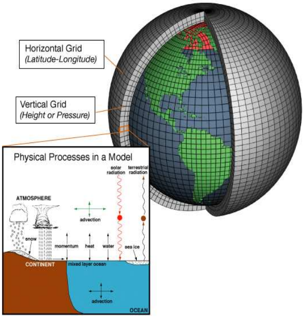
We distinguish two polar classes of models: knowledge models *versus* decision models



Knowledge models:
$1/1\ 000\ 000 \rightarrow 1/1\ 000 \rightarrow 1/1$
maps

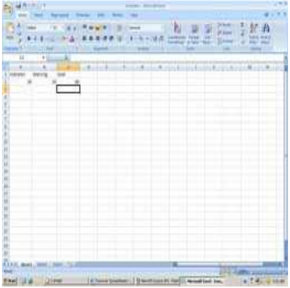
Office of Oceanic and Atmospheric Research (OAR) climate model

We distinguish two polar classes of models: knowledge models *versus* decision models



Knowledge models:
1/1 000 000 → 1/1 000 → 1/1
maps

Office of Oceanic and Atmospheric Research (OAR) climate model



Action/decision models:
economic models are fables designed to provide insight

William Nordhaus economic-climate model

Outline of the presentation

Problem statement: costly protecting a declining pool of species

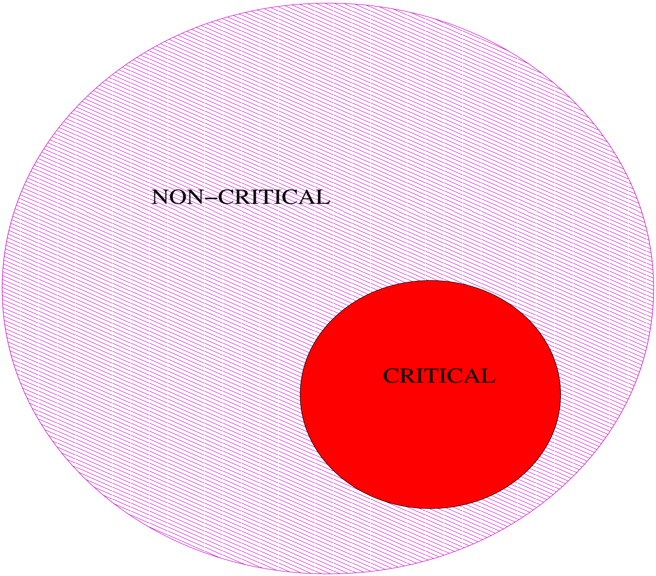
Protection is optimal only below a bioeconomic pool threshold

- Existence of a bioeconomic pivotal threshold
- Closed-form expression with k critical but unknown species

Extensions

- Extension to richer payoff functions
- Extension to multiple ecosystem services

(Unknown) critical and non-critical species



Protecting endangered species

A decision-maker (DM) manages, step by step, a pool of species where

- some are critical to provide an ecosystem service
- but the critical ones are unknown
- during a time period, one of the species — critical or not — will be lost, except if costly protection measures are taken

Framing the problem in mathematical clothes

Ecological data

- Time (steps) $t = 0, 1, \ldots$ runs from 0 to $+\infty$
- The pool of species is described by the number s of species
  - $\mathbb{N} = \{0, 1, 2, \ldots\}$ denotes the set of non-negative integers
  - $\mathbb{N}^* = \{1, 2, \ldots\}$ the set of positive integers
- If no protection measures are taken, during any time period $[t, t+1[$, one species is lost among the s in the pool
  - either a non-critical species with probability $p_{kc}(s)$ (kc for "keep critical")
  - or a critical species with probability $p_{lc}(s) = 1 - p_{kc}(s)$ (lc for "lose critical")
- The probability $p_{kc}(s)$ to lose one of the non-critical species increases with the size s of the pool:
  $s \in \mathbb{N}^* \mapsto p_{kc}(s) \in [0, 1] =$ is non-decreasing
  (like is $p_{kc}(s) = \frac{s-k}{s}$)

Framing the problem in mathematical clothes

Economic data

- Time (steps) $t = 0, 1, \ldots$ runs from 0 to $+\infty$
- The scalar discount factor δ, where $0 < \delta < 1$, measures the preference for the present/future
  - $\delta \approx 1$: future
  - $\delta \approx 0$: present
- The scalar $c > 0$ is the cost of protection during a time period $[t, t+1[$
- The scalar $v > 0$, where $v > c$, is the ecosystem services value provided by the pool when it contains *all* critical species

Protect or not protect?

At each time $t = 0, 1, \ldots$, when managing a pool of s species, the DM makes one of the following two decisions $d \in \{\mathtt{P}, \mathtt{NP}\}$

- either protects the pool $(d = \mathtt{P})$, at cost c,
  - and obtains the sure ecosystem service of value $v > c$ during the period $[t, t+1[$
- or does not protect the pool $(d = \mathtt{NP})$, and loses
  - either one of the non-critical species (with probability $p_{kc}(s)$) and obtains the ecosystem service of value v during the period $[t, t+1[$
  - or one of the critical species (with probability $1 - p_{kc}(s)$) and obtains nothing forever on

The DM maximizes the mean intertemporal payoff

- The mean instantaneous payoff is

$$U(d,s) = \begin{cases} v - c & \text{if } d = \mathtt{P} \\ p_{kc}(s)v & \text{if } d = \mathtt{NP} \end{cases}$$

- The DM maximizes the mean intertemporal payoff

$$\sum_{t=0}^{+\infty} \delta^t U(d_t, s_t)$$

First, we consider two polar decision rules

- If you protect all the the time, you obtain

$$\sum_{t=0}^{+\infty} \delta^t (v - c) = \frac{v - c}{1 - \delta} \quad (= \vartheta)$$

- If you never protect, you obtain

$$\sum_{t=0}^{s-1} \delta^t p_{kc}(s - t) v$$

- In between, lies the optimum

The Bellman function plays a major role to bring optimal strategies to light (1/2)

By definition, the so-called Bellman function

$$J(s) = \max_{(d_t)_{t=0,\dots,+\infty}} \sum_{t=0}^{+\infty} \delta^t U(d_t, s_t)$$

- is the best intertemporal mean payoff
- achieved over all possible streams $(d_t)_{t=0,\dots,+\infty}$ of decisions $d_t \in \{\mathtt{NP}, \mathtt{P}\}$
- where the number s_t of species in the pool at time t starts with $s_0 = s$ species at time $t = 0$ and then follows the dynamics

$$s_0 = s \text{ and } s_{t+1} = \begin{cases} s_t & \text{if } d_t = \mathtt{P} \\ s_t - 1 & \text{if } d_t = \mathtt{NP} \end{cases}$$

The Bellman equation plays a major role to bring optimal strategies to light (2/2)

- The Bellman function J is solution of the Bellman equation

$$
\begin{aligned}
J(0) =& 0 \\
J(s) =& \max \{ v - c + \delta J(s) ; p_{kc}(s) [v + \delta J(s-1)] \} \\
& \forall s = 1, 2, \ldots
\end{aligned}
$$

- The Bellman equation yields an optimal policy $\pi^\star : \mathbb{N} \to \{\mathtt{NP}, \mathtt{P}\}$, which yields optimal decisions

$$
d_t = \pi^\star(s_t)
$$

Our roadmap

Once the question has been framed in bioeconomic clothes

- Show the existence of a pivotal threshold
  for the number of species in a pool,
  below which protecting is optimal
- Provide analytical closed-form expressions for the threshold
- Extend to
  - smoother ecosystem service value functions
  - multiple ecosystem services

Outline of the presentation

Outline of the presentation

Problem statement: costly protecting a declining pool of species

Protection is optimal only below a bioeconomic pool threshold

- Existence of a bioeconomic pivotal threshold
- Closed-form expression with k critical but unknown species

Extensions

- Extension to richer payoff functions
- Extension to multiple ecosystem services

First, we turn the implicit Bellman equation into an explicit form

- The Bellman function $J(s)$ appears on both sides of the Bellman equation

$$J(s) = \max \{v - c + \delta J(s); p_{kc}(s)[v + \delta J(s-1)]\}$$

making it difficult to prove uniqueness and to analyze $J(s)$

- We set the mean intertemporal payoff of always protecting

$$\vartheta = \frac{v-c}{1-\delta} = \sum_{t=0}^{+\infty} \delta^t (v-c) > 0$$

Proposition

The Bellman equation is equivalent to $J(0) = 0$ *and*

$$J(s) = \max \{\vartheta; p_{kc}(s)[v + \delta J(s-1)]\} \ , \ \forall s \in \mathbb{N}^*$$

The Bellman function $J(s)$ *is non-decreasing in the number* s *of species in the pool*

The Bellman function J displays two regimes separated by a pivotal threshold (number $\overline{s}$ of species in the pool)

- With the convention that $\min \emptyset = +\infty$, let

$$\overline{s} = 1 \qquad \text{if } p_{kc}(1) \geq \vartheta/v$$

$$\overline{s} = \min\{s = 2, 3, \ldots \mid p_{kc}(s) \geq \frac{v - c}{v - \delta c}\} \qquad \text{if } p_{kc}(1) < \vartheta/v$$

- (More on $\overline{s}$ in the next slides)

Theorem

The Bellman function J is given by the following induction

$$J(s) = p_{kc}(s)[v + \delta J(s-1)] \,, \qquad \forall s = \overline{s}, \ldots$$

$$J(s) = \vartheta \,, \qquad \forall s = 1, \ldots, \overline{s} - 1$$

$$J(0) = 0$$

The optimal policy displays two regimes separated by a pivotal threshold for the number of species in the pool

Theorem

The optimal policy $\pi^\star : \mathbb{N} \to \{NP, P\}$ displays two regimes

- *when the species pool size s is so small that the probability $p_{lc}(s)$ to lose a critical species is high, that is, when $s \leq \overline{s} - 1$, or equivalently, $p_{lc}(s) > \overline{p}_{lc}$, it is optimal to protect the pool*
- *when the species pool size s is so large that the probability $p_{lc}(s)$ to lose a critical species is small, that is, when $s \geq \overline{s}$, or equivalently, $p_{lc}(s) \leq \overline{p}_{lc}$, it is optimal not to protect the pool*

More on the pivotal threshold $\overline{s}$ for the number of species in the pool

$$s \geq \overline{s} > 1 \iff \overbrace{p_{lc}(s) = 1 - p_{kc}(s)}^{\substack{\text{probability of losing} \\ \text{a critical species}}} \leq \overbrace{\overline{p}_{lc} = \frac{c - \delta c}{v - \delta c}}^{\text{critical probability}}$$

$$\text{do not protect} \iff \underbrace{p_{lc}(s)}_{\text{ecological quantity}} \leq \underbrace{\frac{c - \delta c}{v - \delta c}}_{\text{economic based quantity}}$$

Sensitivity analysis

	ecosystem service low	ecosystem service high
myopic	low protection	
farsighted		high protection

- If the value v of the ecosystem service is relatively low (slightly above the cost c of protection), or if the discount factor δ is low (preference for the present), then
  - the critical probability $\overline{p}_{lc}$ is high
  - the pivotal threshold $\overline{s}$ is low
- If the value v of the ecosystem service is relatively high (well above the cost c of protection), or if the discount factor δ is high (preference for the future), then
  - the critical probability $\overline{p}_{lc}$ is low
  - the pivotal threshold $\overline{s}$ is high

The myopic protects less than the farsighted

- When $\overline{s} = 1$, this means that a single species is possibly critical with so small a probability (less than $1 - \vartheta/v$), that it is better not to protect
- When $\overline{s} \geq 2$, then $\overline{p}_{lc}(v - \delta c) = \underbrace{v - c}_{\text{immediate payoff of protecting}}$
- The farsighted DM starts to protect at a size $\overline{s}$ such that

$$p_{kc}(\overline{s})(v - \delta c) \geq v - c > p_{kc}(\overline{s} - 1)(v - c)$$

whereas the myopic DM starts to protect at a size $\underline{s}$ such that

$$p_{kc}(\underline{s})v \geq v - c > p_{kc}(\underline{s} - 1)v$$

so that, since protection is costly ($c > 0$),
the myopic protects less than the farsighted

$$\underline{s} \leq \overline{s}$$

Outline of the presentation

Problem statement: costly protecting a declining pool of species

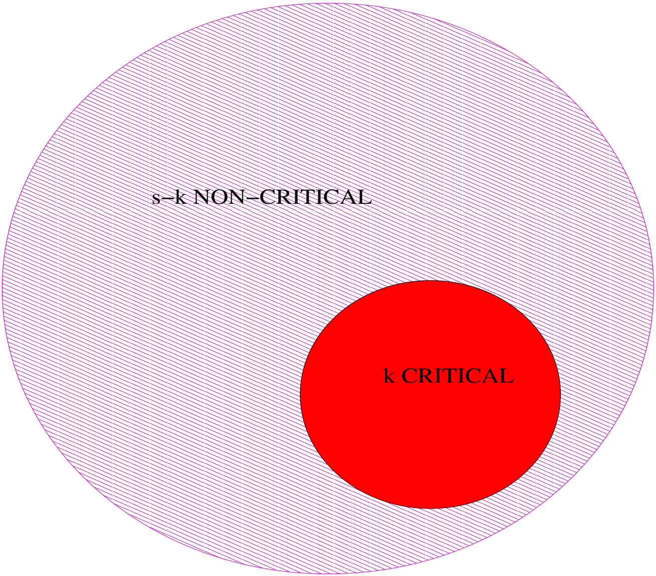
Protection is optimal only below a bioeconomic pool threshold

- Existence of a bioeconomic pivotal threshold
- Closed-form expression with k critical but unknown species

Extensions

- Extension to richer payoff functions
- Extension to multiple ecosystem services

The number k of (unknown) critical species is kwown



Here, we suppose known the *number k* of critical species

- Let $k \in \mathbb{N}^*$ denote the number of species that are critical to provide the ecosystem service
- When not protecting a pool of s species, the probability to lose one of the k critical species is

$$\begin{cases} p_{lc}(s) = 1 & \forall s = 1, \ldots, k \\ p_{lc}(s) = k/s & \forall s = k+1, \ldots \end{cases}$$

- We provide an explicit, closed-form expression for the pivotal threshold $\overline{s}$ for the number of species in a pool, below which protecting is optimal

We display a closed-form expression for the pivotal threshold $\overline{s}$

Proposition

The pivotal threshold $\overline{s}$ is the unique integer $\overline{s} \geq k+1$ such that

$$\overline{s} \geq k/\overline{p}_{lc} > \overline{s} - 1$$

$$\overline{s} = \underbrace{\lceil k/\overline{p}_{lc} \rceil}_{\text{ceiling integer}}$$

The number of species to protect is proportional to the number k of critical species

The number $\overline{s}$ of species to protect

$$\overline{s} \approx \frac{k}{\overline{p}_{lc}} = \underbrace{k}_{\text{ecological quantity}} \Big/ \underbrace{\frac{c - \delta c}{v - \delta c}}_{\text{economic based quantity}}$$

is (approximately)

- proportional to the number k of critical species,
- with $1/\overline{p}_{lc} = \frac{v-\delta c}{c-\delta c}$ as a multiplier

Sensitivity analysis

	ecosystem service low	ecosystem service high
myopic	protect $\overline{s} \approx k$ species	
farsighted		protect $\overline{s} >> k$ species

- If $v \approx c$, the value provided by the ecosystem is little above the cost of protection, or if the discount factor δ is low (preference for the present), then $\overline{p}_{lc} \approx 1$ and $\overline{s} \approx k$: do not protect more than about the number k of critical species
- If $v >> c$, the value provided by the ecosystem is well above the cost of protection, or if the discount factor δ is high (preference for the future), then $\overline{p}_{lc} \approx 0$ and $\overline{s}$ is very large: protect a large number of species

When value exceeds costs enough, the DM should protect the whole pool for all times

We define the ratio of value to costs

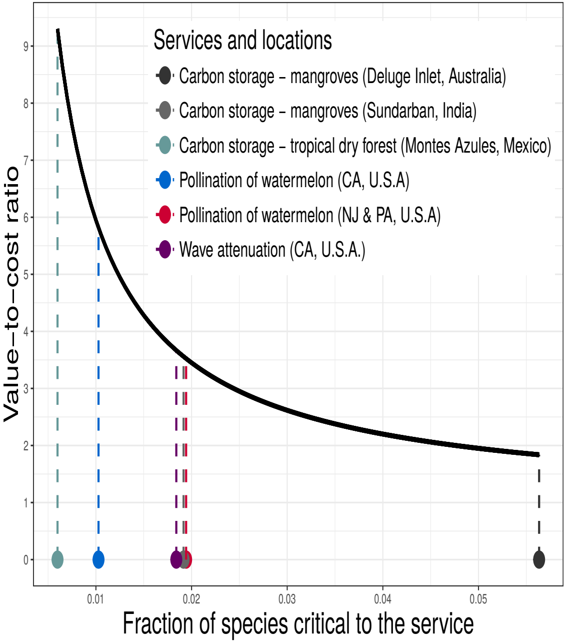
$$\beta = \frac{v}{c}$$

Proposition

Protecting for all times all the $s_0 > k$ species initially present is optimal when the ratio $\beta = v/c$ of value to costs exceeds

$$\beta^*(s_0) = \delta + \frac{(1-\delta)s_0}{k}$$

$$\text{protect forever} \iff \frac{v}{c} > \underbrace{\delta + \frac{(1-\delta)s_0}{k}}_{\substack{\text{decreases with} \\ \text{the discount factor } \delta}}$$


Services and locations
Carbon storage – mangroves (Deluge Inlet, Australia)
Carbon storage – mangroves (Sundarban, India)
Carbon storage – tropical dry forest (Montes Azules, Mexico)
Pollination of watermelon (CA, U.S.A)
Pollination of watermelon (NJ & PA, U.S.A)
Wave attenuation (CA, U.S.A.)
Value–to–cost ratio
0
1
2
3
4
5
6
7
8
9
0.01
0.02
0.03
0.04
0.05
Fraction of species critical to the service

Outline of the presentation

Problem statement: costly protecting a declining pool of species

Protection is optimal only below a bioeconomic pool threshold

- Existence of a bioeconomic pivotal threshold
- Closed-form expression with k critical but unknown species

Extensions

- Extension to richer payoff functions
- Extension to multiple ecosystem services

Outline of the presentation

Smoothing the ecosystem service value with the number of critical species

- Suppose that, among the pool of s species, stand r critical species that provide the ecosystem service with value v_r where the family $\{v_r\}_{r\in\mathbb{N}}$ is such that

$$r \in \mathbb{N} \mapsto v_r \text{ is non-decreasing}$$
$$r \in \mathbb{N}^* \mapsto v_r - v_{r-1} \text{ is non-increasing}$$
$$v_r > c > 0 \ , \ \forall r \in \mathbb{N}$$

- Before, the ecosystem service value was more abrupt
  - $v_r = 0$, for all $r \leq k$
  - $v_r = v$, for all $r \geq k+1$

Probability of losing one of the critical species

- The quantity $p_r(s)$ represents the probability of losing one of the $s-r$ non-critical species in a pool of s species
- where family $\{p_r(s)\}_{0\leq r\leq s}$ in $[0,1]$ is such that

$$\begin{aligned} s \in \{r, r+1, \ldots\} &\mapsto p_r(s) \in [0,1] \text{ is non-decreasing} \\ r \in \{0, \ldots, s\} &\mapsto p_r(s) \in [0,1] \text{ is non-increasing} \\ p_r(r) &= 0 \end{aligned}$$

- A natural candidate is $p_r(s) = (s-r)/s$

Protect or not protect?

At each time $t = 0, 1, \ldots$, with a pool of s species, including r critical ones ($r \leq s$), the DM

- either protects the pool ($d = \mathtt{P}$), at cost c,
  - and obtains the sure ecosystem service of value $v_r > c$ during the period $[t, t+1[$
- or does not protect the pool ($d = \mathtt{NP}$), and loses
  - either one of the $s - r$ non-critical species, with probability $p_r(s)$, and obtains the ecosystem service of value v_r during the period $[t, t+1[$
  - or one of the r critical species, with probability $q_r(s) = 1 - p_r(s)$, and obtains the ecosystem service of value v_{r-1} during the period $[t, t+1[$

Unfortunately, we reap weaker results

The mean instantaneous payoff is

$$U_r(d,s) = \begin{cases} v_r - c & \text{if } d = \texttt{P} \\ p_r(s)v_r + q_r(s)v_{r-1} & \text{if } d = \texttt{NP} \end{cases}$$

Proposition

If the incremental loss of value is bounded above by

$$0 \leq v_r - v_{r-1} \leq (1-\delta)c \ , \ \ \forall r \in \mathbb{N}^*$$

then, for $s \geq r+1$, it is never optimal to protect
(except maybe at $s = r$)

Outline of the presentation

We consider multiple ecosystem services

- For the sake of simplicity, we consider two services, which can be
  - both available: $(1, 1)$
  - both unavailable: $(0, 0)$
  - partially available: $(1, 0)$ or $(0, 1)$
- We analyze the Bellman equation which involves a series of
  - ecosystem values: v_{11}, v_{10}, v_{01}, v_{00}
  - probability functions: p_{11}, p_{10}, p_{01}, p_{00}
  - Bellman functions: J_{11}, J_{10}, J_{01}, J_{00}

The Bellman equation displays an inductive form

Proposition

- *The Bellman function $J_{11}(s)$ is non-decreasing in the number s of species in the pool*
- *The Bellman equation is equivalent to*

$$J_{11}(s) = \max\{\vartheta_{ij}; \sum_{(i,j)\in\{0,1\}^2} p_{ij}(s)[v_{ij} + \delta J_{ij}(s-1)]\} \ ,$$

  for all $s \in \mathbb{N}^*$, and $J_{11}(0) = 0$
- *As a consequence, the solution $J_{11}(s)$ is unique*

The Bellman function J displays two regimes separated by a switching point

With the convention that $\min \emptyset = +\infty$, let

$$\overline{s}_{11} = \min\{s = 1, 2, \dots \mid \sum_{i,j} p_{ij}(s)[v_{ij} + \delta J_{ij}(s-1)] \geq \vartheta_{11}\}$$

The following result is less powerful than in the single service case, because the switching point $\overline{s}_{11}$ is not characterized from the data, but depends on the solution J_{11}

Proposition

The solution J_{11} to the Bellman equation is given by the following induction

$$J_{11}(s) = \sum_{i,j} p_{ij}(s)[v_{ij} + \delta J_{ij}(s-1)] \; , \qquad \forall s = \overline{s}_{11}, \dots$$

$$J_{11}(s) = \vartheta_{11} \; , \qquad \forall s = 1, \dots, \overline{s}_{11} - 1$$

$$J_{11}(0) = 0$$

The optimal policy displays two regimes separated by a pivotal threshold for the number of species in the pool

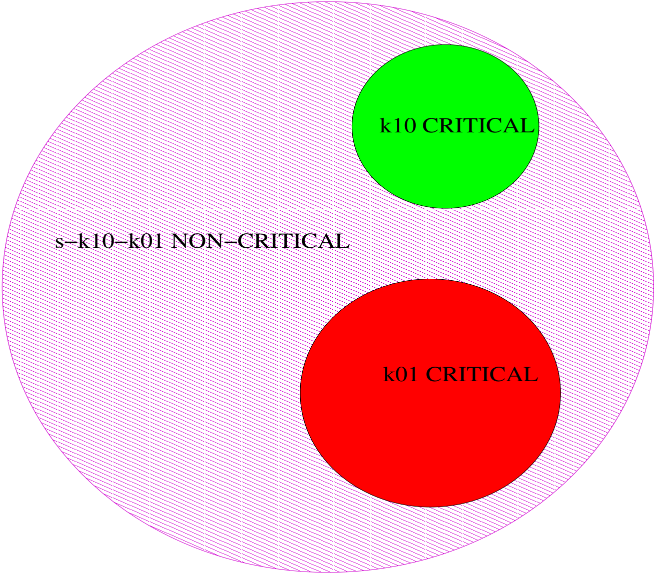
Proposition

The optimal policy $\pi^\star : \mathbb{N} \to \{NP, P\}$ displays two regimes

- *when the species pool is small, that is, when $s \leq \overline{s}_{11} - 1$, it is optimal to protect it*
- *when the species pool is large, that is, when $s \geq \overline{s}_{11}$, it is optimal not to protect it*

$$\overline{s}_{11} = \min\{s = 1, 2, \ldots \mid \sum_{i,j} p_{ij}(s)[v_{ij} + \delta J_{ij}(s-1)] \geq \vartheta_{11}\}$$

Critical and non-critical species



We consider two groups of critical species

Let k_{01} and k_{10} be two positive integers such that

$$p_{10}(s) = 0\ ,\ \ \forall s = 1, \ldots, k_{10} \text{ and}$$
$$p_{10}(s) = \frac{s - k_{10}}{s}\ ,\ \ \forall s = k_{10} + 1, \ldots$$

$$p_{01}(s) = 0\ ,\ \ \forall s = 1, \ldots, k_{01} \text{ and}$$
$$p_{01}(s) = \frac{s - k_{01}}{s}\ ,\ \ \forall s = k_{01} + 1, \ldots$$

$$p_{11}(s) = 0\ ,\ \ \forall s = 1, \ldots, k_{01} + k_{10} \text{ and}$$
$$p_{11}(s) = \frac{s - k_{01} - k_{10}}{s}\ ,\ \ \forall s = k_{01} + k_{10} + 1, \ldots$$

We display a condition ensuring that multiple services lead to more protection

Proposition

If two services make together better than the best of the two

$$v_{11} \geq \max\{v_{10}, v_{01}\}$$

then the size pool $\overline{s}_{11}$ *below which protecting is optimal in presence of two services is such that*

$$\overline{s}_{11} \geq \max\{\overline{s}_{10}, \overline{s}_{01}\}$$

Outline of the presentation

Problem statement: costly protecting a declining pool of species

Protection is optimal only below a bioeconomic pool threshold

- Existence of a bioeconomic pivotal threshold
- Closed-form expression with k critical but unknown species

Extensions

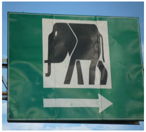
- Extension to richer payoff functions
- Extension to multiple ecosystem services

Conclusion

- We have provided a framework to explore conditions that hold for ecosystem services to provide and enhance economic incentives for biodiversity conservation in the face of uncertainty
- Managing for ecosystem services can, but does not universally, provide an economic incentive for protection of species
- Ecosystem service approaches
  may justify less protection of biodiversity
  than many suspect under a range of conditions

THANK YOU!



2018 Award
by
Ecological Society of America
for
Innovation in Sustainability Science