# Evolutionary Games and Sustainable Fisheries Management

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## Motivation

Our is goal is to understand social-ecological dynamics of fisheries and to study the role of insitutions and individuals

- In 2016, approximately 30 percent of the world's fisheries were classified as depleted or overexploited [2]
  - Additional 58 percent of global were deemed fully exploited [2]
- How can sustainable management of fisheries be obtained in the presence of global population growth?
- Further, fisheries serve as a tractable model problem to understand management of common-pool resources
  - Models can provide insights into problems of climate cooperation or management of scarce water resources

## Baseline Fisheries Model

- Gordon-Schafer model for fish resource dynamics [3]
- Fish population $R(t)$ undergoes background logistic growth and is harvested by fishers
- Dynamics given by $\frac{dR}{dt} = rR(1-\frac{R}{k}) - qER$
  - where $E$ is cumulative extraction effort of fishers, $q$ is fisher catch probability, $r$ and $k$ are fish exponential growth rate and carrying-capacity
- For fixed $E$, fish equilibria are $R = 0$ and $R = \frac{k(r-qE)}{r}$

## Tragedy of the Commons

- $n$ fishers, fisher $i$ exerts extraction effort $e_i$
- Fishing payoff is $\pi(e_i) = (pqR(t) - w)e_i$
  - $w$ is per-unit cost of extraction effort
  - $p$ is price per fish
  - Because $R(t)$ is decreasing in cumulative effort $E$, fisher payoff is negatively impacted by extraction effort by other fishers
- If fish resource is in equilibrium (fish resources equilibrate quickly relative to fisher strategic dynamics), fisher payoff becomes $\pi_i^{eq} = \left(\frac{pgk(r-qE)}{r} - w\right)e_i$

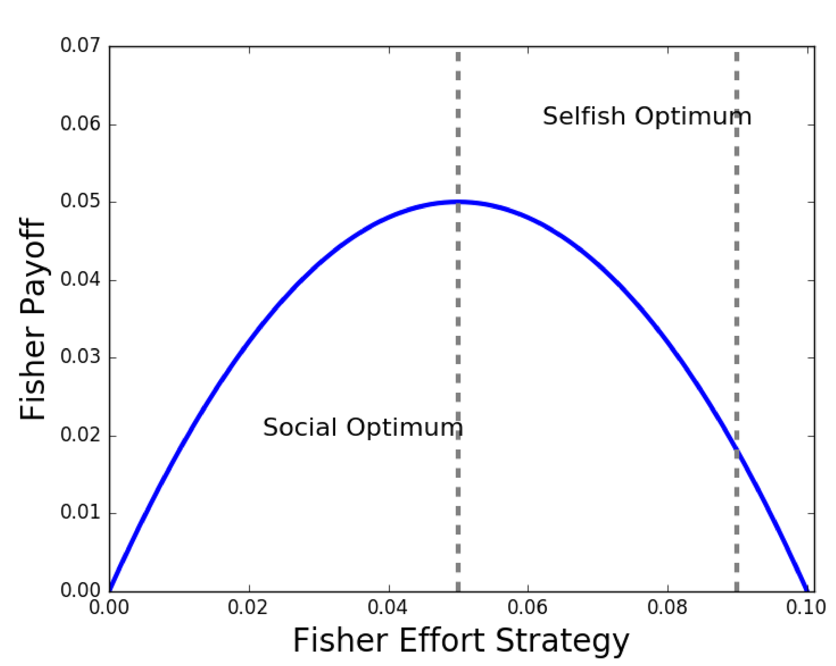


Figure 1: Illustration of Tragedy of the Commons for fisheries. Blue curve displays fisher profit for symmetric choice of effort. Nash equilibrium outcome produces less profit and fewer fish than socially optimal outcome.

## Strategic Framework

- Probability density $f(e)$ over extraction strategies (large population size $N$)
- Fisher profit given by $\pi_e^f = (b-w)e - ce^2 - (N-1)ce \int_0^{e_{max}} f(e')de'$ where $b$ and $c$ are quantities derived from fish resource model.
- Social institution with ability to reward or punish fishers based on level of effort
- Fisher utility given by sum of profit and effect of institutional incentives $U_e^f = \pi_e^f + I(e, f(\cdot), u)$, where $u$ is institutional policy.
  - Institutional incentives can be further subdivided into rewards $I^R(e, f(e), u)$ and penalties $I^P(e, f(e), u)$.
- Fishers use social learning to updae strategies
- Strategic dynamics governed by continuous-strategy replicator dynamics

$$\frac{\partial f(e,t)}{\partial t} = \frac{s}{2}\int_{e_{min}}^{e_{max}} f(e)f(e')\left[U(e) - U(e')\right]de'$$

- Change in mean extraction level given by

$$\frac{d\langle e\rangle}{dt} = \frac{s}{2}\int_{e_{min}}^{e_{max}}\int_{e_{min}}^{e_{max}} ef(e)f(e')\left[U(e) - U(e')\right]de'de$$

## Impact of Rewards / Penalties

- Provide reward of $\frac{\alpha\delta}{F(\hat{e}_R)}$ to all individuals satisfying $e < \hat{e}_R$
- Payoffs from rewarding are given by piecewise function

$$I^R(e, f(e)) = \begin{cases} \frac{\alpha\delta}{F(\hat{e}_R)} & : e < \hat{e}_R \\ 0 & : e > \hat{e}_R \end{cases}$$

- The contribution of rewards to the change in average extraction level is

$$D^R(\hat{e}_R) := \int_{e_{min}}^{e_{max}}\int_{e_{min}}^{e_{max}} ef(e)f(e')\left[I^R(e,\cdot) - I^R(e',\cdot)\right]de'de$$

- Using uniformity of institutional rewards,

$$D^R(\hat{e}_R) = \frac{\delta s}{2}\left(\frac{1}{F(\hat{e}_R)}\int_{e_{min}}^{\hat{e}_R} ef(e)de - \langle e\rangle\right)$$

- $D^R(\hat{e}_R)$ decreases as $\hat{e}_R \downarrow e_{min}$
- Similarly, contribution of penalties to change in average extraction level given by

$$D^P(\hat{e}_P) = \frac{\delta s}{2}\left(\langle e\rangle - \frac{1}{1-F(\hat{e}_P)}\int_{\hat{e}_P}^{e_{max}} ef(e)de\right)$$

and $D^P(\hat{e}_P)$ decreases as $\hat{e}_P \uparrow e_{max}$.
- Choosing $\hat{e}_R$ and $\hat{e_P}$ to minimize $D^R(\hat{e}_R)$ and $D^P(\hat{e}_P)$ facilitates decrease of $\langle e\rangle$.

## "First Carrot, Then Stick"

Main conclusions about uniform rewarding scheme: (i) institution is best able to decrease average extraction level $< e >$ by either focusing all resources on rewarding or on punishing; (ii) rewards (penalties) most effective when concentrated on most (least) efficient extractors; (iii) can characterize conditions under which it is best to focus on rewarding ($\langle e\rangle > \frac{e_{max}+e_{min}}{2}$) or on punishing ($\langle e\rangle < \frac{e_{max}+e_{min}}{2}$) based on how extraction levels are concentrated near relatively higher or lower levels of extraction.

## Role of Social Institution

- Social institution with fixed budget $\delta$
- Institution picks fraction $\alpha$ of budget to allocate towards rewarding efficient extractors
- Complementary $1-\alpha$ fraction of budget allocated to punishing overfishers
- Uniform incentives: all rewarded (punished) individuals receive same reward (penalty)
  - Reward buget divided equally amongst rewarded individuals
- Set threshold strategies $\hat{e}_R$ for rewards (i.e. reward only individuals with strategy $e \leq \hat{e}_R$) and $\hat{e}_P$ for punishment (i.e. punish only individuals with strategy $e \geq \hat{e}_P$ )
- Can also consider non-uniform incentives, with reward $r(e)$ for fisher with effort $e$. For general utility-to-updating function $g[U(e) - U(e')]$, can use calculus of variations to derive Euler-Lagrange integral equation of the form

$$\int_{\underline{e}}^{\overline{e}} f(e')\left\{(e-e')g'\left[s(U(e) - U(e'))\right] - \lambda\right\}de' = 0$$

## Carrot or Stick? [1]

- For given allocation $\alpha$ between rewards and penalties we have

$$\frac{d\langle e\rangle}{dt} = \Pi_f^{\Delta} + \alpha D^R(\hat{e}_R, f) + (1-\alpha)D^P(\hat{e}_P, f)$$

, where $\Pi_f^{\Delta}$ is the impact of utility from fishing / fish sales on changing extraction effort.
- Because $D^R(\cdot)$ and $D^P(\cdot)$ do not depend on $\alpha$, we can minimize each of $D^R(\cdot)$ and $D^P(\cdot)$ as we would for any $\alpha$.
- Similar to two-strategy case, we can choose budget allocation depending on $D^R(\hat{e}_R^*, f)$ and $D^P(\hat{e}_P^*, f)$, (the minimizing thresholds $\hat{e}_R^*$ and $\hat{e}_P^*$), and see that optimal budget allocation is given by

$$\alpha^*(f(e,t)) = \begin{cases} 1 & : D^R(\hat{e}_R^*, f) > D^P(\hat{e}_P^*, f) \\ 0 & : D^R(\hat{e}_R^*, f) < D^P(\hat{e}_P^*, f) \\ c \in [0,1] & : D^R(\hat{e}_R^*, f) = D^P(\hat{e}_P^*, f) \end{cases}$$

## First Carrot, Then Stick

- Can classify when to reward or punish as follows

$$\alpha^*(f(e,t)) = \begin{cases} 1 & : \langle e\rangle > \frac{e_{\max}+e_{\min}}{2} \\ 0 & : \langle e\rangle < \frac{e_{\max}+e_{\min}}{2} \\ c \in [0,1] & : \langle e\rangle = \frac{e_{\max}+e_{\min}}{2} \end{cases}$$

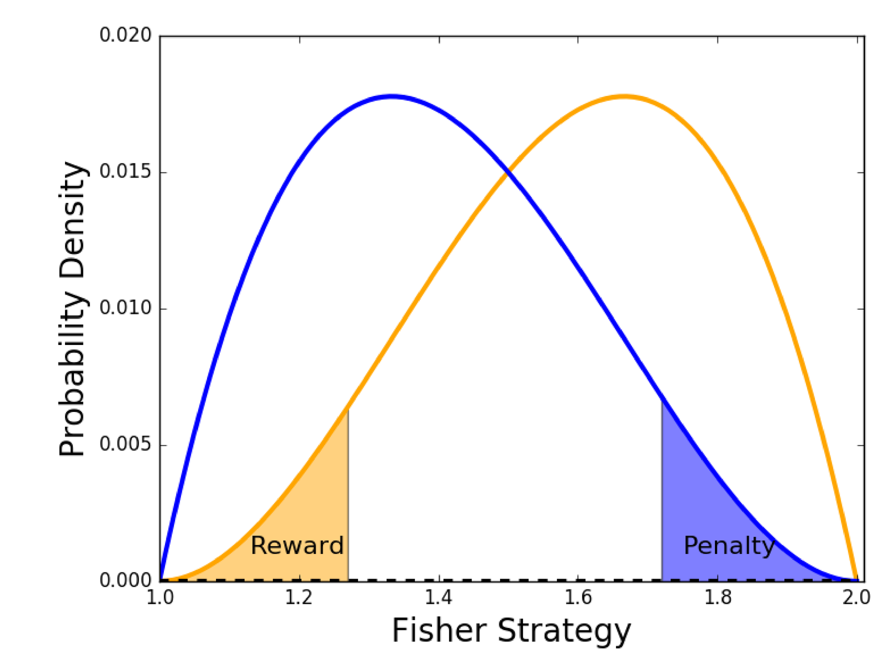


Figure 2: Illustration of "First Carrot, Then Stick" Idea: orange curve corresponds case where it is optimal to reward rare efficient extractions, blue curve to case where it is optimal to punish rare overextractor.

## Conclusion

- Examined model for the role of institutional rewards and penalties to influence strategies for extraction of a common-pool resource
- Found that "first carrot, then stick" scheme helps to initially encourage efficient extraction via rewards and to subsequently discourage overfishing via penalties.

## References

[1] Xiaojie Chen, Tatsuya Sasaki, Åke Brännström, and Ulf Dieckmann. First carrot, then stick: how the adaptive hybridization of incentives promotes cooperation. *Journal of the royal society interface*, 12(102):20140935, 2015.

[2] FAO. The state of world fisheries and aquaculture. , Food and Agriculture Organization, 2016.

[3] H Scott Gordon. The economic theory of a common-property resource: the fishery. *Journal of political economy*, 62(2):124–142, 1954.

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