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# The Perverse Incentives of Strong Enforcement


Caren Rattray

Supervised by Michael Bode

Queensland University of Technology (QUT)



AMSI AUSTRALIAN MATHEMATICAL SCIENCES INSTITUTE

Australian Government Department of Education

# Abstract

Sea cucumbers are a valuable marine species caught in tropical oceans and exported to markets in South Asia and China. The National Fishing Authorities in Papua New Guinea can choose to allow or prohibit the exportation of sea cucumbers, creating temporal closure. Although fishing mortality is not easily regulated, spatial closure in the form of Marine Protected Areas can be used by local authorities to prevent over-fishing. The optimal spatial conservation strategy of the local communities is dependent on the temporal conservation implemented by the authorities. Strong conservation enforcement – or increased temporal closure – has the unintended incentive to resource users towards reduction in spatial closure. In this project, numerical simulation is used to simulate a two-patch population with and without temporal closure, and the optimal Marine Protected Area to maximise the Net Present Value is determined numerically. Further, the process is repeated for an array of temporal closure configurations. The effects of adjustments in the parameter values is examined and interpreted. A comparison to enforced superannuation is used to simplify comprehension of the relationship between temporal and spatial closures.

# Introduction

## Background

### Behavioural background

Well-intentioned policies can create perverse incentives, encouraging communities to react adversely which undermines the good work intended by the policy. Strong enforcement by governments is a common discouragement to resource users towards environmental conservation measures.

### Ecological Background

Sea cucumbers or sandfish (species in the class Holothuroidea) are easily caught, readily preserved and transported. They are a traditional delicacy in south east Asia, purported to cure arthritis, impotence, frequent urination and cancer. Modern studies have found them to be low in fat, high in protein, and a healthy source of vitamins, minerals and antioxidants, with antimicrobial properties. (Kubala, 2018)

The limited supply and purported health benefits of sea cucumbers has made them valuable on the market in south east Asia. Due to their commercial value, sea cucumbers are an important and highly valuable fish stock across the tropical coastal oceans. Many coastal communities in Papua New Guinea (PNG) catch and trade a wide variety of sea cucumber species, primarily to markets in south Asia and China. Alongside trochus and shark fin, these fisheries are a critical source of income for the local communities, and one of their few means of accessing the cash economy.

# Papua New Guinea fisheries management

There are two hierarchical levels of management in Papua New Guinea which regulate the Sea Cucumber exportation industry. At the superior level, the National Fisheries Authority (NFA) regulates export of sea cucumbers overseas. Their authority in this case is primarily limited to a binary decision – that is, to either allow or prohibit international trade of the commodity. This closure in time, known as temporal closure, is detrimental to the community’s economy. The volatile income temporal closure creates forces many community members to budget wisely or face bankruptcy.

A more economically stable option for conservation is spatial closure – consistent closure of a percentage of the total coastline – enforced by the local communities themselves. Including a Marine Protected Area (MPA) established by the local communities protects sea cucumber populations from overfishing and localised extinction. The local community’s primary goal is to maximise total profits from the exportation of sandfish, with a greater emphasis on immediate profit.

The NFA and local authorities operate independently, and local authorities have no control over the decision-making of the NFA. The NFA wish to encourage the local authorities to create larger MPAs.

# Objectives

Local fisheries wish to determine a division of their coastline into MPAs and fished areas in order to maximise profit. Their decision is impeded by the uncertainty surrounding the NFA's closure of exportation. Although this closure allows recovery of the population, the inclusion of this uncertainty is expected to encourage the coastal fisheries to decrease the optimal size of the MPA.

In this project, a model was constructed to simulate the sea cucumber population within the fishing area and reserve. The profit from exportation was quantified using Net Present Value (NPV) for a range of MPA percentages, as well as different length and frequency of temporal closure. This allowed the effects of temporal closure on the decision of spatial closure to be examined.

Rather than parameterise the model to a particular species and location, the qualitative insights of this project are applicable to conservation of other marine species, particularly those with sedentary adults. Generalisations of our conclusions can be applied to other instances of strong environmental protection policies, such as logging and hunting on private property as opposed to creation of national parks. Game theory has been used to demonstrate how public trusts will optimally choose to conserve less if the government chooses to conserve more, especially in non spatial-dependant models (Albers, Ando, Batz. 2006). Due to time constraints on research, the situation with sea cucumbers in PNG was concentrated on.

## Statement of Authorship

The workload was divided as follows:

- Caren Rattray assisted in the derivation of the population model, developed the code in MATLAB, produced the mathematical results, reported and interpreted the results, and wrote this report.
- Michael Bode derived the population model, supervised the work, and proofread this report.

# Construction of the Model

To build a dynamic population model, spatial and temporal closures were considered. A two-patch time series captured the growth and immigration of populations between the reserve and fishing grounds. Intermittent closure of the fishery was simulated by setting the fishing mortality rate to zero.

To reproduce the annual spawning and fishing dynamics, a discrete recurrence formula was implemented.

Expecting profit in the distant future is less valuable than immediate profit, thus the economic principle of Net Present Value (NPV) was used in calculating profit from resource exportation. This allows the preference of immediate and long-term profit to be quantified in an analytical way.

# Definitions

The population dynamics of the sandfish *Holothuria scabra* was described using a two-patch model. Patch F represents the fished portion $1-\varphi$ of the total area $A$, and patch $P$ represents the no-take MPA which occupies the remaining proportion $\varphi$. Let $N_F(t)$ denote the abundance of *H. scabra* at time $t$ in the fished area, and $N_P(t)$ denote the abundance of sea cucumbers in the MPA, where $t$ is measured in years.

Sandfish reproduce by spawning. The eggs and sperm are released into the ocean and dispersed by the current. Migration of sea cucumbers between patches is described solely by the area of the patches. The percentage of offspring from sandfish within the MPA which remain in the MPA was assumed to be $\phi$. Respectively, $(1-\phi)$ migrate to the fishing area, and conversely for offspring originating from the fishing area.

We assume that each year, a constant percentage of the population $m_n$ will die from natural causes. In patch $F$, a fraction $m_p$ is removed due to fishing each year. The rate of fishing is not easily regulated for sea cucumbers and was assumed to be constant and high.

In simple biological models, $k$ would represent the carrying capacity of the population, and $r$ the birth-death ratio. However, as mortality is dependent on fishing, it has been extracted separately from the equation. Let $r$ denote the rate of reproduction in population, and $k$ signify the maximum abundance of the entire coastline.

# The bioeconomic model

With these definitions, the yearly catch is simply the fishing area population multiplied by the fishing mortality rate. The population in the MPA at time $t+1$ may be described by:

$$N_P(t+1) = N_P(t)(1-m_n) + rN_P(t)\left(1-\frac{N_P(t)}{\varphi k}\right)\varphi + rN_F(t)\left(1-\frac{N_F(t)}{(1-\varphi)k}\right)\varphi$$

And the population in the fished patch $F$ may be described by

$$N_F(t+1) = N_F(t)(1-m_n)(1-m_p) + rN_P(t)\left(1-\frac{N_P(t)}{\varphi k}\right)(1-\varphi) + rN_F(t)\left(1-\frac{N_F(t)}{(1-\varphi)k}\right)(1-\varphi)$$

Let $\pi_t$ denote the revenue at time $t$ and $\rho$ denote the market price of sandfish. Value of delayed profit is reduced using discount rate $d$ in a time value of money formula. The expected revenue is given by

$$\pi = \rho m_p \sum_{t=1}^{\infty} N_f(t)(1-d)^t$$

The optimal area of fishing reserve is the one which maximises the time-discounted profit.

# Discussion

## Optimal $\phi$ to Maximise Profit

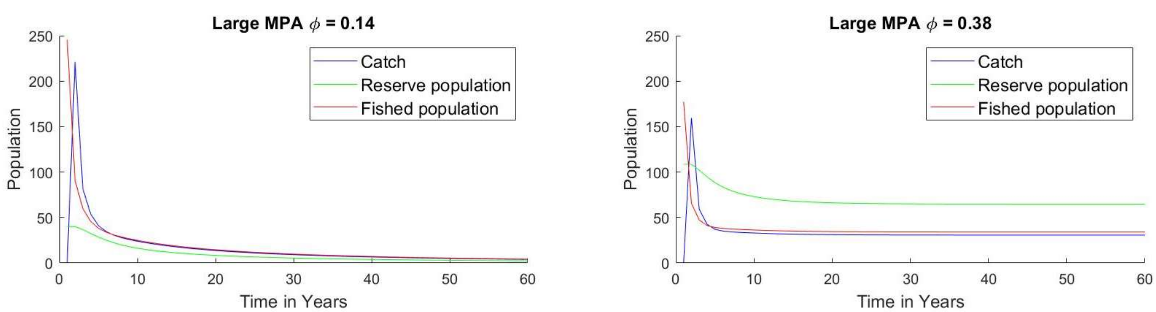


Figure 1: Population within the MPA and fishery, as well as the yearly catch over time with constant fishing. Parameters m_n = 0.3, m_p = 0.9, r = 0.7, k = 500

In all simulations, the population begins in an unfished state, where the population density has reached carrying capacity. From an unfished population, increasing fishery size proportionately increases the initial catch. Consequently, with constant fishing, increasing the size of the fishery results in less repopulation from the reserve, causing the equilibrium catch to be less. For a consistently open fishing ground, the optimal $\phi$ depends on the relative value placed on immediate profit over long term stability.

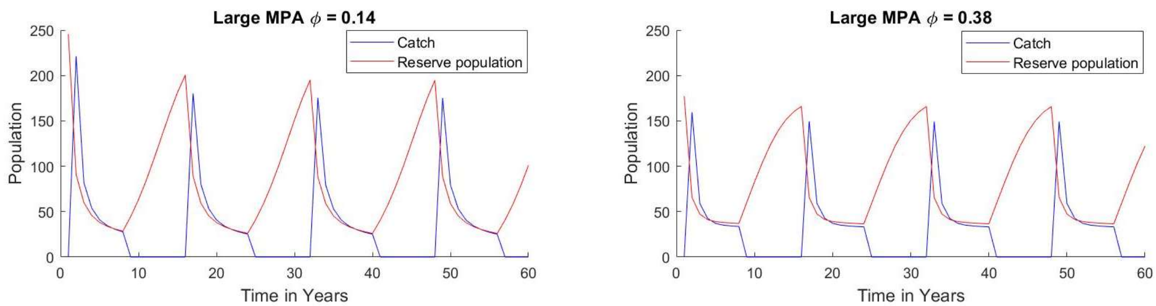


Figure 2: Population within the fishery, as well as the catch over time with intermittent closure. Parameters m_n = 0.3, m_p = 0.9, r = 0.7, k = 500, open 8 years, closed 8 years.

With constant fishing, a large MPA is less profitable initially and more profitable in the long-term. However, when closure occurs, the long-term benefits of large MPAs are negated, and greater reopening catches from larger fishing areas are desired. These details are explored further in later sections of the report.

For each value of $\phi$, the recurrence formulas were run, the profit formula was applied, and the resulting profit was plotted against MPA size.

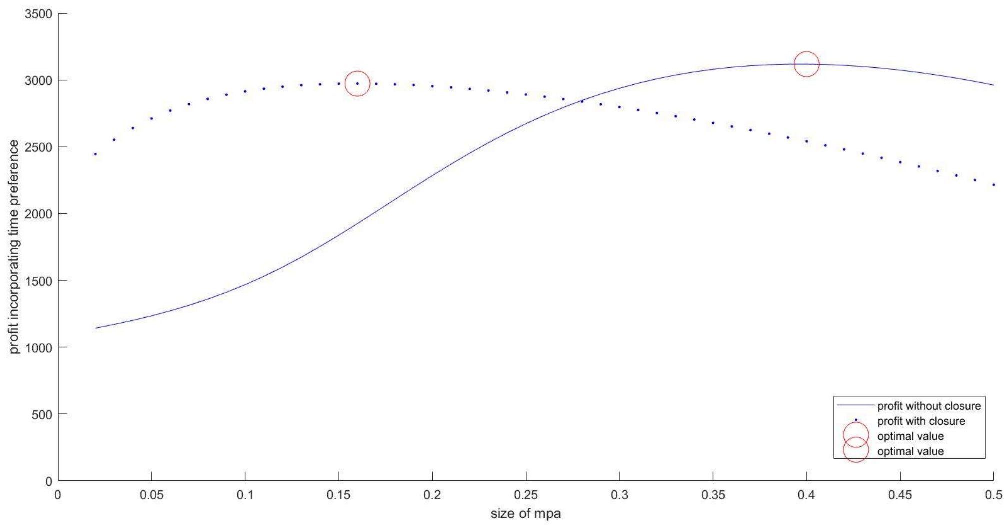


Figure 3: NPV from sea cucumber exportation for a range of $\phi$ values, both with and without closure. The maximum profit values are circled in red. Parameters m_n = 0.3, m_p = 0.9, r = 0.7, k = 500, p = 2, d = 0.01, open 8 years, closed 8 years.

# Sensitivity analysis

For theoretical models, the values assigned to parameters are not as important as the effect they cause on the outcome variable. Sensitivity analysis reveals that the optimal $\phi$ or MPA size increases with the length of open seasons, rate of fishing, time discounting rate and the rate of natural mortality, but decreases with length of closure and growth rate.

Increased time discounting rate indicates a greater preference towards long-term profit. Larger MPAs produce greater catches in the long-term, hence increasing the time discounting rate will increase the optimal MPA size.

Increasing the fishing mortality rate makes the population more vulnerable to overfishing and localised extinction. To counteract increased fishing, enlarging the fishing reserve will increase the emigration from the reserve. Hence, a larger MPA size is optimal.

Increasing the growth rate or decreasing the natural mortality rate will have the same effect on the optimal $\phi$ value. If the population can recover rapidly from overfishing, benefits from temporal closure are increased and reliance on a reserve to avoid extinction is diminished, resulting in smaller MPAs being more profitable.

The effect of adjustments in spatial closure durations is of keen importance to the analysis. As such, the relationship was explored in detail.

# Optimal $\phi$ as a function of closure time

The code was modified to incorporate different opening and closing lengths. The simulated fishery was open for *i* years, then closed for *j* years and reopened. For each percentage of coastline, the yearly catch and temporal profit was calculated. The percentage of coastline which resulted in the greatest profit was recorded in the *(i, j)* element of a matrix. This matrix is colour-coded in Figure 4.

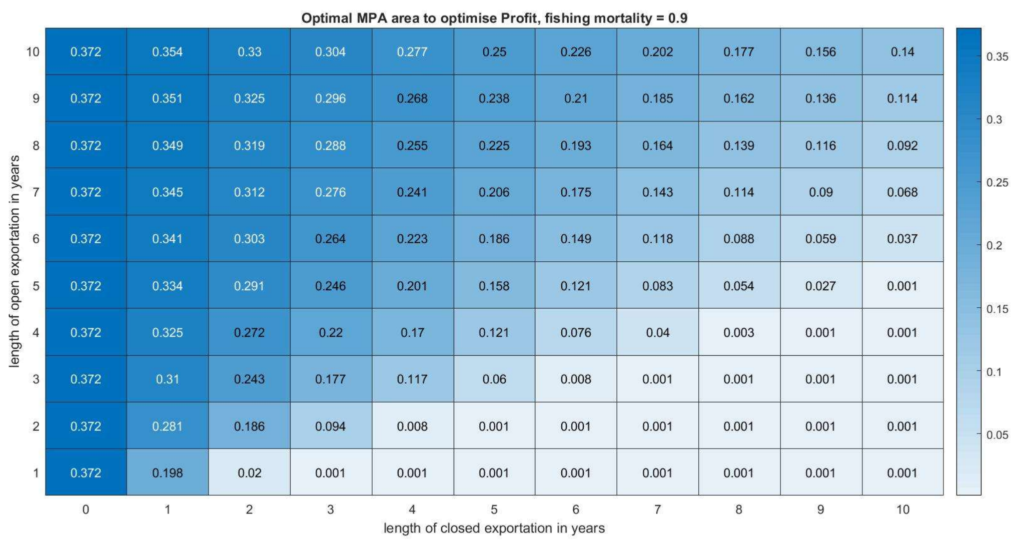


Figure 4: The percentage of coastline reserved as MPA which maximises the NPV for ranges of opening and closing years, calculated to three decimal places. Parameters m_n = 0.3, m_p = 0.9, r = 0.7, k = 500, p = 2, d = 0.01

The values in the matrix decrease from the top left corner, which confirms that MPA size decreases with closing length and increases with decreased frequency of closure.

To illustrate the effects of strong enforcement on the behaviour of fisheries, an analogy is beneficial. Let us consider a consumer with a weekly savings goal of \$100 a week towards their retirement. If the government enacted policies forcing \$90 of their earnings into superannuation, the consumer would offset the enforced savings with a reduction of \$90 to their voluntary savings, resulting in no increase in their total savings. However, If the value of the forced savings is more than their planned savings contributions, they will be unable to make additional contributions, and the result will be a decreased weekly consumption or increased accruement of debt. (Connolly, 2004)

In a fished system, for a given set of ecological parameters, there exists an optimal conservation effort, that maximises the community's NPV. Conservation effort can be achieved with either spatial or temporal closure. This is because temporal closure can be equated to spatial closure, where the coastline is totally reserved. The coastal community will try to maximise their NPV by achieving the optimal conservation effort, a combination of enforced temporal closure and voluntary spatial closure.

If the conservation forced by temporal closure is less than the optimal conservation desired by the local authorities, the community will offset the compulsory conservation by a reduction in spatial closure. If the temporal closure is greater than optimal, the local authorities will avoid the creation of MPAs entirely and profit will be decreased.

In the upper triangular region of figure 4, the communities' voluntary conservation is reduced as the closure-over-fishing ratio is increased. The creation of an MPA is no longer profitable once this ratio becomes large.

# Conclusion

According to our simulations, for the NFA to maximise the size of the MPA created by the local authorities, they should avoid closing exportation, and offset closures by extended periods of fishing. Proper implementation of these results will not only increase the yearly catch and stabilise the local economy, but also stabilise the sea cucumber's annual population, which supports prevention of extinction due to climate change or natural disasters.

Enforcing strong environmental protection has the perverse incentive of reduction in natural resource user's voluntary protection of resources, as evidenced by the described situation in Papua New Guinea. This generalised statement can be adapted to other circumstances where government policies adversely affect natural resource user's conservation efforts.

# Further research

Some extensions to this project to consider for future research would include considering the effect of probability of the NFA initiating temporal closure being dependant on the current population, rather than fixed. Comparison of data gathered in Papua New Guinea and other areas with consistently open exportation is necessary to determine whether the results theorised by this report are observed in reality.

# References

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