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Effect of marine reserve establishment on non-cooperative fisheries management

Nao Takashina [a,*], Joung-Hun Lee [b], Hugh P. Possingham [c,d]

[a] Tropical Biosphere Research Center, University of the Ryukyus, 3422 Sesoko Motobu, Okinawa 905-0227, Japan
[b] Department of Biology, Kyushu University, 744, Motooka, Nishi-ku, Fukuoka 819-0395, Japan
[c] ARC Centre of Excellence for Environmental Decisions, School of Biological Sciences, The University of Queensland, St Lucia, QLD 4072, Australia
[d] The Nature Conservancy, 4245 North Fairfax Drive Suite 100, Arlington, VA 22203-1606, USA

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ABSTRACT

Introducing effective marine reserves is a critical issue in fisheries management and marine ecosystem conservation. In recent years, a number of marine reserves or no-take marine protected areas (MPAs) have been implemented worldwide, and some MPAs have shown ecological and economic benefits. However, consideration for coordinated competition between institutions, a central for successful resource management, is often omitted in research on effective MPA management. Given increasing discussions on implementing MPAs in the high seas, where international fisheries often exemplify the tragedy of the commons, understanding potential competition between institutions can affect MPA management. With this in mind, we aimed to gain generic insight into non-cooperative fisheries management with MPAs. Specifically, we explored the effect of MPA establishment on (1) competition strength between fishery institutions, (2) fish population abundance resulting from the competition, and (3) distribution of the gross fishery profit between institutions. To approach these questions, we developed a minimal model that accounts a non-cooperative behavior of fishery institutions and population dynamics under the MPAs management. We demonstrate that, given a small price-to-cost ratio, a prominent increase in fishery competition could occur as a result of introducing an MPA, leading to reductions in fisheries profits and fish population abundance, and greater unevenness in distribution of the gross fishery profit. Intensified fishery competition was typically observed in the case where the rate of population exchange between the fishing grounds and the MPA is not large, and the fraction of the MPA is intermediate, suggesting that regulation agreements will be required to coordinate the competitive harvesting.

1. Introduction

The introduction of effective marine reserves has been a critical consideration in fisheries management and marine ecosystem conservation (Pikitch et al., 2004). Marine reserves or no-take marine protected areas (MPAs) are increasingly being used globally, both within national jurisdictions and in the high seas, and the pace of its new enforcement has been accelerated (Leenhardt et al., 2013; Edgar et al., 2014; Lubchenco and Grorud-Colvert, 2015; Gill et al., 2017). This global trend has evoked a number of researches exploring the potential impact of MPAs establishment on marine ecosystems and a way to make MPAs management beneficial socially, economically, and ecologically (Baskett and Barnett, 2015; Fulton et al., 2015; Gill et al., 2017).

Coordinating competition between institutions or fishers is of central importance for successful fishery management (Hardin, 1968; Ostrom, 1990; Pomeroy and Berkes, 1997). Typically, fisheries that exploit highly migratory species that traverse multiple exclusive economic zones, and the high seas (~58% of the ocean) are more likely to overfish or deplete than those exploit exclusively (McWhinnie, 2009) and these fisheries often exemplify the 'tragedy of the commons' (White and Costello, 2014), a typical example of undesirable outcome of non-cooperative resource management. Also, illegal, unreported and unregulated (IUU) fishing has pervasively escalated in the past 20 years both within EEZ, and the high seas, and these lead to race to fish, overexploitations,

* Corresponding author at: Biodiversity and Biocomplexity Unit, Okinawa Institute Science and Technology Graduate University, Onna-son, Okinawa 904-0495, Japan.
E-mail address: nao-takashina@oist.jp (N. Takashina).

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and significant collateral damage to ecosystems (High Seas Task Force, 2006; Ostrom, 2008; Agnew et al., 2009). Given increased discussions concerning the high seas closure (Sumaila et al., 2007; Leenhardt et al., 2013; Lubchenco and Grorud-Colvert, 2015), further insight into the potential impacts of MPA establishment on non-cooperative management, which is likely to occur in the high seas, or fisheries targeting a species that traverses multiple EEZs, would be of critically importance to predict management outcomes and give management implications to reduce the risk of producing a 'tragedy of the commons'. Although with prevalence of the tragedy of commons in fisheries management, previous researches of MPA management typically focus on the case of sole-owner management, where competition does not occur (e.g., Neubert, 2003; Takashina et al., 2012; Kar and Ghosh, 2013; Takashina and Mougi, 2014; Ghosh et al., 2017). Limited research has been conducted on the strategic decision-making of fishers in the context of MPA management (Punt et al., 2010). Ruijs and Janmaat (2007) explored strategic MPA placement within a national boundary wherein two nations share the fishing resource through species migration. They found that 'the prisoner's dilemma' occurs in the absence of cooperation between countries. Sumaila (2002) simulated the economic rent over a 28-year-period of two non-cooperative management groups, using the specific example of the Northeast Atlantic cod fishery equipped with an age-structured two-patch model. With an assumption of one-directional fish migration from the MPA to the fishing grounds, the study concluded that economic rent is maximized when the size of the MPA is 50–70% of the concerned region, and the standing biomass peaks around this point. Kellner et al. (2007) showed MPA establishment causes high fishing pressure along its boundary, resulting in fishers' competitive behavior to maximize catch per unit effort, and it equalizes the population abundance across the area outside the MPA.

Given deficiencies in previous studies, we aimed to gain generic insight into non-cooperative management with MPAs, and particularly (1) the effect of MPA establishment on strength of the competition behavior, (2) changes in population abundance as a result of the competition, and (3) distribution of the gross fishery profit between the fishery institutions. To address these issues, we developed a simple spatially-explicit model to account for non-cooperative behavior of fishery institutions and the population dynamics under the MPA management, and compare the management outcome with its sole-owner counterparts; the most common assumption of optimal fishing without competition. The model is a two-patch extension of the Schaefer model (Schaefer, 1954): one patch represents the fishing grounds, wherein non-cooperative management takes place, and the other patch is an MPA, wherein no fishing activity occurs. We demonstrate that given a small price-to-cost ratio, a prominent increase in competition between institutions will occur owing to implementing the MPA, likely leading to well below fishery profit and population abundance than the sole-owner management, and greater unevenness in distribution of the gross fishery profit. Intensive competition would typically be observed when the population exchange rate between the fishing ground and the MPA is not large, and intermediate fractions of the MPA exist, suggesting that regulations will be required to coordinate competitive harvesting. Notably, it has repeatedly reported that, with these conditions, implementing MPAs can improve fishery profits as well as population abundance and reproductive capacity. However, our findings suggest that a careful implementation is needed under these conditions, since our results shows intensive competitions would occur in non-cooperative management, leading to well below benefit of MPAs management and population size compared to sole-owner management.

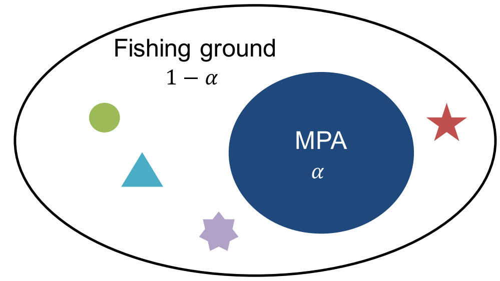

Fig. 1. Schematic description of non-cooperative fisheries management with MPA establishment. Each symbol in the fishing grounds represents a different institution, whereby each institution makes a rational decision in terms of maximizing its own fisheries profit; $1-\alpha$ and α, respectively, are the fractions of the fishing grounds and the MPA.

2. Methods

2.1. Non-spatial model for non-cooperative fisheries management

Here, we describe a model of non-cooperative fisheries management (hereafter, non-cooperative management) that accounts for the population dynamics of a target species and the spatial structure of the region concerned. We extend the Schaefer model (Schaefer, 1954), which has been widely used in investigations of game-theoretic approaches to fisheries management (e.g., Mesterton-Gibbons, 1993; Kaitala and Lindroos, 2007), to a two-patch model so as to quantify the spatial effect on non-cooperative management (Fig. 1). The similar, spatially generalized Schaefer model was investigated in Takashina and Mougi (2015). Given a species' maximum growth rate per unit time r, carrying capacity K, catchability q_i, and the fishing effort of institution i per unit time e_i, the dynamics of population abundance x in the Schaefer model with n-institution fisheries is described as follows:

$$\frac{dx}{dt} = rx\left(1-\frac{x}{K}\right) - \sum_{i}^{n} q_i e_i x. \tag{1}$$

Following Clark (1990), given the price per unit of abundance harvested p_i and the cost per unit fishing effort of institution i, c_i, the equilibrium fisheries profit of institution i is

$$\pi_i = (p_i q_i x^* - c_i)e_i \tag{2}$$

where x^* is the equilibrium population abundance. To quantify the efficiency of fishery institution i, Mesterton-Gibbons (1993) defined the efficiency parameter as $b_i := c_i/(Kp_iq_i)$. By setting the value of the efficiency parameter properly, we can discuss, for example, the effect of improving fishing technology, which may lower the cost per unit fishing effort.

2.2. Model with two-patch extension for non-cooperative management

A spatially explicit model of non-cooperative management is highly complex, and hence is not feasible for deriving analytical results except in certain extreme situations, such as where a species has an extremely high migration rate m. To make the discussion clearer here, we restricted ourselves to the simplest possible situation. Namely, we considered a two-institution two-patch extension of the Schaefer model, where one patch represents open fishing grounds and the other patch represents an MPA (Fig. 1), and the two patches are connected by a simple manner of fish movement or migration. However, to check the sensitivity of our minimal assumptions, more complex situations, such as n-institution man-