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Dynamic economic analysis on invasive species management: Some policy implications of catchability ☆

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ABSTRACT

The problem of controlling invasive species has emerged as a global issue. In response to invasive species threats, governments often propose eradication. This article challenges the eradication view by studying optimal strategies for controlling invasive species in a simple dynamic model. The analysis mainly focuses on deriving policy implications of catchability in a situation where a series of controlling actions incurs operational costs that derive from the fact that catchability depends on the current stock size of invasive species. We analytically demonstrate that the optimal policy changes drastically, depending on the sensitivity of catchability in response to a change in the stock size, as well as on the initial stock. If the sensitivity of catchability is sufficiently high, the constant escapement policy with some interior target level is optimal. In contrast, if the sensitivity of catchability is sufficiently low, there could exist a threshold of the initial stock which differentiates the optimal action between immediate eradication and giving-up without any control. In the intermediate range, immediate eradication, giving-up without any control, or more complex policies may be optimal. Numerical analysis is employed to present economic intuitions and insights in both analytically tractable and intractable cases.

1. Introduction

An international conference, '*Turning the tide of biological invasion: Eradication of invasive species*,' sponsored by the World Conservation Union (IUCN), was held in 2001. This event represents increasing salience regarding decision-makings on whether or not to aim at eradication of invasive species in a globalized world and calls for more attention on this public issue. In the conference proceedings, many researchers claimed that although eradication is the best goal among several policy options, it cannot easily be concluded as a 'desirable goal' in reality due to various reasons (see, e.g., Refs. [6,37]).

Many factors that affect success or failure of eradication have already been well documented (see, e.g., Refs. [1,22,37]). Among them are economic factors that are concerned with operational costs for controlling invasive species and are summarized in the following quotation: 'Killing the first 99% of a target population can cost less than eliminating the last 1%.' More precisely, the operational cost of removing one unit of invasive species may escalate as the existing population decreases. In the case of killing the last 1–10% of the population, catchability often decreases very rapidly as the existing stock of invasive species declines. Focusing on such a escalating cost structure and the nature of catchability, this paper studies the optimal decision rule for the removal of invasive species, including whether or not to eradicate, through using a simple dynamic model.[1]

To the best of our knowledge, only a few papers examine optimal strategies for removing invasive species in an economic dynamic model in which the objective of a social planner is to

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[1] This study focuses on the case in which the operational cost of removing one unit of invasive species is non-decreasing as the population decreases. In general, the cost structure is highly dependent on which method or technology is employed for removal operations. Consequently, there may be the case that an escalating cost structure does not hold. For example, the sterile insect technique is the one with which the cost does not escalate, or may even decrease as the population gets smaller (see, e.g., Refs. [14,9]).

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minimize the long-term social cost.[2] Olson and Roy [24] theoretically develop a discrete-time dynamic model under a stochastic invasion growth and study the optimal policy of eradication under the assumption that the cost of removal operations is independent of the stock size. This assumption is also employed in the work of Eiswerth and Johnson [10], which develops a continuous-time optimal control model but does not analyze the eradication decision. Their analysis focuses mainly on the long-run equilibrium outcomes. Olson and Roy [26] is the only previous work that incorporates the cost function into a dynamic model that depends on current stock size.[3] They examine the long-run dynamic behavior of an optimally controlled invasion and show a wide variety of possible results under very general settings.

A new feature of our invasive species control problem is that the aforementioned nature of an escalating cost structure is explicitly captured as stock-dependent catchability in a discrete-time dynamic model. Based on this specification, some theoretical arguments on concrete policy implications in relation to the stock-dependent catchability are derived from the optimal removal strategies.[4] The catchability focus is motivated by the fact that catchability can be identified from empirical procedures or simple regression when stock estimates and CPUE are available as data. The characterization of optimal removal strategies with respect to catchability can assist managerial decision-making related to invasive species problems.

In our cost function specification, the more rapidly catchability decreases with a reduction in the population, the more the cost for removal operations rises. More precisely, such a property can be captured by the sensitivity of the operational cost of removing one unit of invasive species. That is, 'the sensitivity of catchability,' in response to a decline in the population size. The model building block, in terms of catchability, is not new in the economics of fishery. By providing justification in the context of general renewable resource management, Reed [30] and Clark [4] state that catchability increases in the stock size when the catch per unit of effort increases with population abundance. In other words, as the stock size of invasive species decreases, the removal operation per unit of effort becomes less effective.

Despite the fact that the cost function, based on catchability, seems to help the practitioners' decision-making related to invasive species management, no previous work has analyzed this issue. Given this research gap, the goal and contribution of this paper are to find policy implications in relation to catchability by answering the following question: how does the sensitivity of catchability in response to a change in invasive species stock affects optimal decision-making?

A deterministic dynamic model is developed, although uncertainty such as measurement error or environmental variability is present in reality (see, e.g., Refs. [33,35]). This is due to the fact that even under deterministic settings, a wide variety of policy implications are obtained, and complex situations arise, which cannot be seen in the other fields of renewable resource management. Our view is that an analysis within a deterministic dynamic framework can provide a benchmark and be extended to a model under uncertainty for the purpose of comparison.

Our results show that the optimal policy changes drastically, depending not only on the initial stock of invasive species but also on the sensitivity of catchability in response to a change in invasive species stock. More importantly, the sensitivity of catchability is confirmed as a key for determining the type of optimal policy. A series of optimal policies is derived as follows. The constant escapement policy with some interior target level is optimal if the sensitivity of catchability is sufficiently large. In contrast, if the sensitivity of catchability is sufficiently low, there could exist a threshold of the initial stock which differentiates the optimal action between immediate eradication and giving-up without any control.[5] In the intermediate range, immediate eradication, giving-up without any control, or more complex policies might be optimal. These intermediate cases are analytically intractable to be characterized in general. Thus, we employ numerical analysis on such cases to illustrate the optimal policy and to provide economic intuitions of our results and further insights.

The novelty of this study is that our model shows concrete conditions of catchability under which each of policies, i.e., eradication, non-eradication, or constant escapement policies, should be optimally adopted. Our analysis reveals how optimal strategies change with the sensitivity of catchability (the degree of stock-dependence) in a simple form. In contrast, Olson and Roy [26] do not focus on how optimal policies are affected by the degree of stock-dependence in the removal cost. We are successful in connecting the conditions of optimal policies into catchability in an empirically estimable way since the sensitivity of catchability is identifiable from field data of stock and CPUE, which most management agencies collect as an informative source of decision-making. Furthermore, we believe that this paper is the first to derive the conditions related to the invasive species management under which (1) the constant escapement rule with some interior target level is optimal, and (2) the emergence of a Skiba point. The Skiba point differentiates optimal actions between immediate eradication and giving-up without any control with regard to stock-dependent catchability.

Although our model is similar in structure to Olson and Roy [26], our analysis method is closer to the standard bio-economic literature [3,30,4]. Specifically, 'sensitivity of catchability' and the corresponding cost structure are based on bio-economic concerns. Thus, a set of novel results derived in this paper can be compared with those of the bio-economic models. In a class of standard harvesting models, Clark [3] is the pioneering work that analyzes the optimal extinction of animals. Reed [30] derives the most general results for conditions under which a constant escapement policy with some interior target escapement is optimal. While the standard bio-economic models assume that the social planner maximizes long-term profits, the objective in our model is to minimize long-run social costs which consist of removal costs and damages related to invasive species management. This distinction in the objective between this and theirs gives rise to the sharp contrast of the conditions for optimal eradication as well as

[2] There are many studies which examine the invasive species problem with a different focus from this paper such as prevention of invasive species' introduction, spatial issues in the spread of invasive species population, and human interactions and competition with native species. With respect to the prevention of invasive species, Olson and Roy [25], Kaiser and Roumasset [16] and Kim et al. [17] suggest an integrated model which considers both prevention and control of invasive species. With regard to the spatial issue, Potapov and Lewis [27] and Potapov et al. [28] examine the spatial control problems via meta-population models. Finally, Settle et al. [36] consider the feedback link between human choices and ecosystem. Although there is much previous research, none of these studies examine how optimal removal strategies change with respect to the stock-dependent catchability. This is the focus of this paper.

[3] As an example of related studies, Nyarko and Olson [23] study optimal policy within the context of a stochastic growth model with stock-dependent rewards.

[4] Fresard and Boncoeur [12] and Kaiser and Roumasset [16] explicitly adopt the same type of functions to consider the stock-dependent catchability in the invasive species problem. Fresard and Boncoeur [12] examine the fishery problem of present value profit maximization with the continuous-time model of two species between native and invasive species, while Kaiser and Roumasset [16] develop an integrated model that considers both prevention and removal control within a single model. However, their focus is more on the application, and both of them do not theoretically characterize how optimal removal strategies change with the catchability.

[5] In some cases, there exists a threshold of the initial invasive species stock which differentiates long-run behaviors of stock dynamics by optimal programs. Such a threshold is generally called a Skiba point, which is typically discussed in relation to non-convexity [38].