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Optimal invasive species management under multiple uncertainties ☆

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ABSTRACT

The management programs for invasive species have been proposed and implemented in many regions of the world. However, practitioners and scientists have not reached a consensus on how to control them yet. One reason is the presence of various uncertainties associated with the management. To give some guidance on this issue, we characterize the optimal strategy by developing a dynamic model of invasive species management under uncertainties. In particular, focusing on (i) growth uncertainty and (ii) measurement uncertainty, we identify how these uncertainties affect optimal strategies and value functions. Our results suggest that a rise in growth uncertainty causes the optimal strategy to involve more restrained removals and the corresponding value function to shift up. Furthermore, we also find that a rise in measurement uncertainty affects optimal policies in a highly complex manner, but their corresponding value functions generally shift down as measurement uncertainty rises. Overall, a rise in growth uncertainty can be beneficial, while a rise in measurement uncertainty brings about an adverse effect, which implies the potential gain of precisely identifying the current stock size of invasive species.

1. Introduction

The problems of controlling invasive species have been increasingly important, as every part of the world is intertwined each other in a globalized world and there is no way to perfectly prevent potential entries of invasive species in that environment (see, e.g., [17,18] for general discussions). What we can do best for this problem includes (i) to take countermeasure to prevent invasion and (ii) to manage an established invasive species as a consequence of post-invasion. Once an invasive species succeeds in invasion, serious social damage on indigenous ecosystem and agriculture can occur in many cases. The topic addressed in this paper is concerned with the latter: how to manage the established invasive species, especially focusing on the analysis of optimal strategies in a stochastic dynamic model.

Invasive species management in reality consists of several decision processes. The government authorities first determine whether to aim at eradication. When eradication is set as a goal, they must determine how to achieve it, i.e., eradication strategies. On the other hand, when the goal of eradication is abandoned or identified to be infeasible, they need to decide how to manage the invasive species. If controlling costs are not taken into account and eradication appears to be feasible, eradication would be the best option for a society. However, policies aiming at eradication are often judged to be impossible. This problem arises from "stock-dependent catchability."[1] The eradication cost is prohibitively expensive when catchability rapidly declines with the existing invasive species stock (see, e.g., [13,1,22]). In particular, there is an anecdote that killing the first 99% of a target population can cost less than eliminating the last 1%.

To make matters worse, there is another key factor that makes the management decision more complex. The invasive species management is typically subject to various stochasticity, such as "growth uncertainty" and "measurement uncertainty." In the field of resource economics, it is established that growth uncertainty does not generally affect the qualitative feature of optimal control strategies, especially when the current stock can accurately be measured [19]. However, in more realistic settings, the decision of management practices must be made in the informational absence of current states due to measurement uncertainty. Indeed, some papers claim that measurement uncertainty may fundamentally affect optimal strategies (see, e.g., [4,20,11]). Thus, it is important to analyze how measurement uncertainty affects optimal strategies.

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[1] The term of catchability refers to the proportion of the current stock that can be removed or harvested by one unit of effort [3].

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Real world cases that exemplify the above issues of invasive species problems include Fili mongoose (*Herpestes auropunctatus*) management on Amami island, Kagoshima, Japan (see [7] for the details). Thirty individuals of mongooses were initially introduced in the area by means of biological control for habu snake (*Trimeresurus flavoviridis*) in 1979, since there was a serious problem of the rapid increase in habu snake population, which caused a high risk in human life. However, the original aim could not be achieved at all. Instead, mongoose population has increased up to more than 5,000 individuals and has damaged agricultural productions as well as the unique indigenous ecosystem in that area. Given this circumstance, the Japanese government has organized a program for the eradication of mongooses since 1996. However, it is reported that the catchability depends highly on the existing mongoose population and catch per unit of effort declines due to the decrease in the population. Moreover, the difficulty in implementing the eradication program also comes from the fact that the management agency cannot obtain the accurate information about how mongoose population changes. Therefore, some researchers claim that the above two facts related to stock-dependent catchability and uncertainty significantly plague the mongoose management aiming at eradication.

Several previous research efforts examine the optimal control of invasive species in economic dynamic models in which the objective of a society is to minimize the long-run social cost. Olson and Roy [14] theoretically develop a discrete-time dynamic model under a stochastic invasion growth and study the optimal policy of eradication. Eiseworth and Johnson [5] develop a continuous-time optimal control model, and their focus is mainly on the long-run equilibrium outcomes without analysis on the decision of eradication. Moreover, Eisewerth and van Kooten [6] make the assumption that the current stock is inaccurately known and apply the fuzzy membership function in the invasive species controls. However, all of the above efforts employ the assumption that the cost of removal operations is independent of the current stock size. That is, their analyses neither consider the stock-dependent catchability, nor address when to eradicate in relation to it.

Olson and Roy [16] is a pioneering work that considers stock-dependent removal costs and derives the conditions under which eradication or non-eradication can be optimal in the deterministic setting. While their innovative model is built under general settings, they do not explicitly examine the implications of stock-dependent catchability. Thus, their analytical results may not directly be applied in real management practices. Kotani et al. [9] focus on analyzing policy implications of stock-dependent catchability by deriving the conditions for various optimal policies in the deterministic setting. More specifically, our previous work shows that if the sensitivity of catchability is sufficiently high, eradication policy is never optimal and in effect the constant escapement policy with some interior target level is optimal. In contrast, if the sensitivity of catchability is sufficiently small, eradication policy could be optimal and there may exist a threshold of the initial stock (called a Skiba point) which differentiates optimal actions between immediate eradication and giving-up without controls. If the sensitivity of catchability takes some intermediate values, more complex policies would be optimal.

Building upon [9], this paper derives optimal control strategies of the invasive species management in a stochastic environment. Of particular interest is a situation where managers make a decision on controls when the stock of invasive species fluctuate due to growth uncertainty, and also the current stock cannot be precisely identified due to measurement uncertainty. To the best of our knowledge, this paper is novel in the sense that the model considers both "stock-dependent catchability" and "multiple stochasticity" in the single framework of a bioeconomic model. With this unique model, we seek to clarify the impacts of uncertainties on invasive species management. To achieve this goal, we identify how the degrees of the two uncertainties affect optimal strategies and the corresponding value functions in two distinct scenarios of when (i) eradication and (ii) non-eradication are aimed in the management practices.

Our results suggest that an increase in growth uncertainty leads to the optimal strategies that removals should be more restrained. By doing so, the corresponding value functions shift up as the growth uncertainty increases. Furthermore, we also find that an increase in measurement uncertainty leads to complex impacts on the optimal strategies in the sense that any systematic pattern of the change in optimal strategies has not been found. However, a rise in measurement uncertainty generally shifts down their corresponding value functions. Overall, these results suggest that an increase in growth uncertainty can be beneficial when the control strategy is optimally adapted. On the other hand, a rise in measurement uncertainty brings about an adverse effect on the management, which implies an importance and potential gain of identifying a precise stock size of invasive species.

This paper is organized as follows. In the next section, we elaborate on the basic elements of the model. The section is followed by the analysis of a stochastic model with only growth uncertainty and presents how growth uncertainty affects the optimal strategy. Next, measurement uncertainty is incorporated into the model. We show how the interaction between growth and measurement uncertainties affects the optimal strategy. In the next section, we present how each of growth and measurement uncertainties affects the value functions of the optimal strategy or social welfare. The final section offers some discussions and conclusions.

2. The model

We consider an infinite-period stochastic model of invasive species management, following a deterministic version of the dynamic model in Kotani et al. [9]. Our model below is developed by posing an invasive species control as the problem of a stochastic dynamic programming with Markovian transitions of multiple uncertainties, especially growth and measurement uncertainties. The specification of our dynamic models basically follows the pioneering works of [2,25,24,21,16], all of which employ a stock-recruitment model in renewable resource management. In particular, we follow [21] with respect to the specification for various uncertainties.

In this paper, we pay attention to growth and measurement uncertainties since an interplay between the two provides an interesting result. We assume that there are two random variables, Z_t^g and Z_t^m, capturing growth and measurement uncertainties in each period t, respectively. The random variable Z_t^g reflects uncontrollable stochasticity associated with the stock growth of invasive species, while Z_t^m reflects potentially controllable uncertainty.[2] These variables are independent of each other and of period t. We assume that Z_t^g and Z_t^m are respectively distributed over some finite intervals $[1-z^g, 1+z^g]$ and $[1-z^m, 1+z^m]$ with the mean of unity, where $0 < z^k < 1$, according to a common distribution function Φ^k, for $k = g, m$. The specification of uncertainty implies that the distribution is mean-preserving spread with respect to z^k. We choose this specification since an increase in z^k can be interpreted as a rise in the degree of the corresponding uncertainty (see [21]).

The responsible officials of management agencies are assumed to know the statistical distribution for each of these random variables. The stock (population) of existing invasive species in period t is governed by the following state equation:

$$x_t = Z_t^g F(s_{t-1}), \tag{1}$$

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[2] For instance, if more efforts on identifying the current stock size of invasive species through extensive field survey are devoted, measurement uncertainty is expected to be reduced.