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Learning-by-catching: Uncertain invasive-species populations and the value of information

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Abstract

This paper develops a model of invasive species control when the species' population size is unknown. In the face of an uncertain population size, a resource manager's species-control efforts provide two potential benefits: (1) a direct benefit of possibly reducing the population of invasive species, and (2) an indirect benefit of information acquisition (due to learning about the population size, which reduces uncertainty). We provide a methodology that takes into account both of these benefits, and show how optimal management decisions are altered in the presence of the indirect benefit of learning. We then apply this methodology to the case of controlling the Brown Treesnake (*Boiga irregularis*) on the island of Saipan. We find that the indirect benefit—the value of information to reduce uncertainty—is likely to be quite large.

Keywords: Invasive species; Uncertain population; Learning; Value of information; Brown Treesnake

1. Introduction

An emerging problem in natural resource policy is how to design efficient strategies for managing invasive species.[1] Damages from invasive species are ecological as well as economic. These include lost biodiversity and reduced ecosystem services, as well as direct and indirect economic damages such as health damages or lost productivity. Caterpillars from the Asian gypsy moth (*Lymantria dispar*) cause extensive defoliation, reduced growth and mortality of host trees throughout the northern hemisphere, and hairs on larvae and egg masses lead to allergies in some people. The Nile perch (*Lates niloticus*) was introduced to Africa's Lake Victoria in 1954 and has since contributed to the extinction of more than 200 endemic fish species through predation and competition for food. *Caulerpa taxifolia* is a marine alga widely used as a decorative aquarium plant. The alga was accidentally introduced into the Mediterranean Sea in wastewater, where it has now spread over more than 13,000 ha of seabed. This invader forms dense monocultures that prevent the establishment of native seaweeds and exclude almost all marine life. Tamarisk (*Tamarix ramosissima*) is a shrubby tree that can be found where its roots reach the water table, such as floodplains, along irrigation ditches and on lake shores. Tamarisk can tolerate a wide range of saline or alkaline soils and is able to dominate floodplain communities in the deserts of the Southwest United States due to its ability to tolerate water stress for extended periods of time. Tamarisk supports few native insects and thus is poor habitat for birds.

The well-known invasion of the Brown Treesnake (*Boiga irregularis*) on the island of Guam poses a real and immediate threat to the state of Hawaii, due to the large and increasing volume of military transport between to the locales, as well as commercial air and sea traffic. The snake has extirpated 11 native bird species on Guam, causes hundreds of hours of power outages a year, and sends a stream of citizens to the hospitals each year to treat

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[1] Invasive species are defined as those plants, animals, and microbes that are nonnative to an area and have caused or have the potential to cause economic and or ecological damage threaten natural resources, biodiversity, and human health worldwide (from President Clinton's Executive Order 13112, signed February 3, 1999).

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venomous snakebites. Eight individual Brown Treesnakes (hereafter, BTS) have been intercepted at the ports in Hawaii, accompanied by hundreds of credible snake sightings resulting in zero captures.

While the economic literature on invasive species has been growing rapidly, most analyses are based on simplifying assumptions that limit their applicability. One aspect of invasive species control that makes practical implementation particularly difficult is that the actual population of the species is almost never known. The only variables that a typical resource manager observes with certainty are the number of the invasive successfully harvested and the effort required to achieve that harvest. Like most renewable resource problems, the literature to date typically assumes a given initial population of the stock of interest. In our paper we develop a model in which the invasive species population is known neither in the initial period nor in subsequent periods. Instead of setting harvest directly, managers set effort levels in each period and then observe the harvest.

In the context of renewable resource use, several studies have analyzed the case where the resource stock is uncertain due to lack of information or measurement error (Clark and Kirkwood, 1986; Roughgarden and Smith, 1996; Sethi et al., 2005). Economic studies of biological invasion have focused on the case of deterministic species population. Some studies analyze special cases where the optimal control under uncertainty is identical to that of the underlying deterministic model (Reed, 1979; Knowler, 2005). Recent studies analyze uncertain aspects of biological invasion more explicitly. Olson and Roy (2005) examine optimal prevention and control strategies for a randomly introduced biological invasion, assuming that prevention can be effective with certainty and that the population size is observable once invasion occurs. Saphores and Shogren (2005) allow growth to be uncertain, although stock is always accurately observed. We depart from these existing models on invasive species management by assuming uncertain species population size and allow for managers to adjust their subjective probability distributions of population according to catch.

Through species management, the managers obtain new information each period about the probability distribution of the species population size. Borrowing from the literature on renewable resources and learning, we model the connections between observable data (effort and harvest) and the unobservable invasive stock using Bayesian methods. If the effort-harvest function is stochastic but known, the model allows for beliefs about the invasive population to be updated each period and the manager is therefore able to tailor the control strategy appropriately.

Section 2 sets up the baseline case where the population is known with certainty. Section 3 outlines the optimal strategy when the population is uncertain and considers a simplified functional form to characterize the optimal solution. Section 4 illustrates the methodology for the case of BTS control on the island of Saipan. Section 5 concludes the paper with some suggestions for future research.

2. Method I: harvest with observable pest population

The usual renewable resource problem begins with a resource manager who maximizes the present value of a resource. Optimal management of an invasive species can be approached in a similar fashion. Maximizing the value of invasive species management is the same as minimizing the total present value of the expected costs of removing the species as well as the expected damages caused by the species.

In our model, the invasive species reproduces, causes damages, and is harvested in discrete time periods. We assume that population growth and ecological damages are deterministic, while the manager's harvest of the species is stochastic. The assumption of deterministic growth will help us isolate the information effects we are looking for later in the paper.

Let X_t denote the population of the invasive at time t. Each period this population causes $d(X_t)$ dollars worth of damage to the local ecosystem. Managers are able to reduce the population through stochastic harvesting. We denote e_t as the effort exerted to reduce the population, and $c(e_t)$ the cost the manager bears given e_t.

In the case where population is observable each period, the manager is able to set effort decisions based upon the observed harvest. The total present value (or cost, denoted PV) of the stock of the invasive, X, can be thought of as the optimal control costs today, the damages today, and then a discounted sum of the stream of control costs and damages into the future. We denote the discount factor as δ. The harvest in period t, h_t, is a function of the stock of the invasive X_t, the effort level e_t, and a random variable, ε_t.

$$h_t = h(X_t, e_t, \varepsilon_t). \tag{1}$$

The variable ε represents the stochastic relationship between harvests, efforts, and population size. Future populations of the invasive will depend on the post harvest population and the species specific growth function, g:

$$X_{t+1} = g(X_t - h_t). \tag{2}$$

The resource manager's objective is to maximize the discounted total expected present value of species management:

$$E\left\{\sum_{t=0}^{\infty} \delta^t(-c(e_t) - d(X_t))\right\}, \tag{3}$$

subject to the harvest and species growth constraints (1) and (2) for all t given an initial population size $X_0 > 0$. Given this setup, the following functional equation for stochastic dynamic programming characterizes the optimal solution:

$$\mathrm{PV}(X_t) = \max_{e_t}\left\{-c(e_t) - d(X) + \delta E[\mathrm{PV}(X_{t+1})]\right\}, \tag{4}$$