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Analysis

Managing apparent competition between the feral pigs and native foxes of Santa Cruz Island

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ABSTRACT

This paper presents a model of pest impacts in a multispecies framework. Strong detrimental relationships often form between pest populations and other biota, damaging ecosystem services and reducing social welfare. Under these circumstances, optimal pest management must account for the interactions between pests and other species. The bioeconomic model of competition developed in this manuscript is illustrated using the case of feral pigs (*Sus scrofa*) on Santa Cruz Island, California. The presence of the pigs, an introduced species, resulted in the near extirpation of the native island fox (*Urocyon littoralis*) before managers intervened and removed the pigs from the island. The application compares a policy of pig eradication with one of perpetual control, which is found to involve initially over-culling the pigs relative to the equilibrium level. To protect the foxes of Santa Cruz Island, the results suggest that pig eradication rather than pig control is the optimal strategy.

1. Introduction

Pests, both indigenous and exotic, are a form of biological pollution that significantly harms social welfare. Their impacts include billions of dollars in lost marketable goods and control costs, as well as biodiversity loss. It is estimated that more than half of all endangered species are at risk due to competition with or predation by nonindigenous species (Pimentel et al., 2005), although indigenous species, too, have been implicated in endangering native wildlife (DeCesare et al., 2010). A major policy goal in natural resource management is the restoration of habitat conditions and wildlife in high-valued ecosystems impacted by invasives (NISC, 2008). Physical removal or harvesting of pests and harmful invasives is a key method in managing these adverse impacts (Olson, 2006).

A large portion of the pest control literature analyzes damage mitigation policies using dynamic bioeconomic models. This approach is useful because pests are biological resources, although it also complicates the analysis (Burnett et al., 2008). Perhaps for this reason, most of the literature limits the bioeconomic model to the pest species itself and explores innovations in control programs. These models have been used to study problems with insects (Ceddia et al., 2009), weeds (Burnett et al., 2006; Eiswerth and van Kooten, 2002; Pannell, 1990) and invasive species (Burnett et al., 2008; Eiswerth and Johnson, 2002; Zivin et al., 2000), as well as generic pest control policies such as eradication (Olson and Roy, 2008).

An important consideration in the control of a pest is its interaction with other wildlife (Barbier, 2001; Eppink and van den Bergh, 2007). When these interactions significantly impact ecosystem functions, efficient management strategies must account for the secondary species effects from managing pests and invasives (Zavaleta et al., 2001). Ignoring these interactions means ignoring spillover effects, which can result in inefficient pest control policies. This was recognized early by Feder and Regev (1975), who showed that when pest control applications harm the predator of a pest, myopic decision making can actually increase pest damages. Subsequent work has investigated other situations in which the pest is a predator (Melstrom and Horan, 2014; Settle and Shogren, 2002; Settle et al., 2002), prey (Fenichel et al., 2010; Harper

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and Zilberman, 1989), competitor (Barbier, 2001; Frésard and Boncoeur, 2006) and parasite (Sims et al., 2010).[1] However, most of this research has focused on pests that generate market damages rather than those that have significant nonmarket impacts.

This paper is concerned with the situation of an exotic pest competing with valuable native wildlife. The theoretical multispecies model is akin to that of Barbier (2001) and Frésard and Boncoeur (2006) who also analyze a pest engaged in interspecific competition, although there are key differences. First, the native wildlife is valued through its existence rather than through some commercial or recreational activity, e.g. harvests. The paper therefore builds on prior work by analyzing ecosystem interactions involving an exotic species and nonmarket impacts. Second, because there is no incentive to harvest the valued wildlife, the system is managed only through predator removal. Optimal control theory is used to solve for the removal policy that maximizes social welfare over time.

The optimal removal policy is illustrated for the case of the endangered island fox (*Urocyon littoralis*) and feral pig (*Sus scrofa*) on Santa Cruz Island, California. Although exotic species were long recognized for causing damage to the natural resources of the island (NPS, 2002), the pigs' impact on fox survival became a special concern in the late 1990s when the fox population fell to extremely low levels (Coonan, 2003). Rather than directly competing with each other's forage and reproduction activities, the foxes and pigs interact through apparent interspecific competition because they help sustain a common predator. Pig removal was a dominant management issue until an eradication program was successfully carried out in 2006. This paper examines the optimal pig removal policy where pig damages are a function of the fox population, which only has existence value. The model is used to compare several different removal policies designed for fox conservation per se, including perpetual pig control, eradication and doing nothing. The results provide insights into the design of pest control strategies aimed at recovering nonuse valued wildlife and ecosystem services.

2. Multispecies Bioeconomic Model

The model should capture the feedbacks between a pest and the flora and fauna within an ecosystem. To keep the analysis tractable, the affected part of the ecosystem is modeled as a single stock *f*. This stock could be viewed as the biomass for all wildlife in an ecosystem, the biomass of an umbrella species or the population of a charismatic species. The pest stock is notated by *p*. The biological interaction between the pest and affected wildlife consists of a pair of impacts that determine whether the relationship is one of amensalism, competition or predation. This paper focuses on the competitive case, i.e. that a pest negatively impacts the stock of wildlife and vice-versa. The stock dynamics are therefore modeled as

$$\frac{df}{dt} = g(f) - m(f,p) \tag{1}$$

$$\frac{dp}{dt} = q(p) - n(f,p) - h(t) \tag{2}$$

where $g(\cdot)$ is the natural growth of *f*, $q(\cdot)$ is the natural growth of *p*, $m(\cdot)$ is the reduction in growth of *f* due to competition with the pest and $n(\cdot)$ is the corresponding reduction in *p* from competition. The final term in Eq. (2) is the reduction in the growth of the pest due to management, which is modeled as a harvest rate.

A manager wants to maximize the net benefits of the multispecies system or, equivalently, minimize the damages from the pest plus control costs. The pest creates social damages by reducing *f* and its ecosystem service value, which is denoted by $V(f)$ with $V_f > 0$ and $V_{ff} < 0$, where the *f* subscript denotes a derivative. The cost of pest control—specifically, pest removal—is defined as $c(p)h(t)$. The term $c(p)$ is the per-unit cost of removing a pest, where $c_p < 0$ and $c_{pp} > 0$. Removal costs are increasing and convex because it becomes increasingly costly to find and remove pests as the population of pests diminishes (Horan and Melstrom, 2011). The management objective is to

$$\max_{h(t)} \; SNB = \int_0^\infty [V(f) - c(p)h(t)]e^{-\rho t}dt \tag{3}$$
$$\text{subject to (1), (2), } 0 \le h(t) \le h_{\max}, f(0) = f_0, p(0) = p_0$$

where ρ is the discount rate. The current value Hamiltonian for problem (3) is

$$H = V(f) - c(p)h(t) + \lambda(t)[g(f) - m(f,p)] + \mu(t)[q(p) - n(f,p) - h(t)] \tag{4}$$

where $\lambda(t)$ and $\mu(t)$ are the adjoint or co-state variables (Clark, 1990).

The solution to problem (3) involves choosing *h* to maximize *H*. The marginal impact of *h* on *H* is

$$\frac{\partial H}{\partial h} = -c(p) - \mu(t). \tag{5}$$

The right-hand side (RHS) of Eq. (5) includes the marginal costs of removal, $-c(p)$, and the marginal intertemporal benefit of culling a pest, $-\mu(t)$ (the pest co-state will be negative). It is optimal to set $h = 0$ when Eq. (5) is negative and $h = h_{\max}$ when Eq. (5) is positive. The singular, interior value for *h*, h_{SV}, is optimal when Eq. (5) is zero. That is, h_{SV} requires

$$\mu(t) = -c(p) \tag{6}$$

which suggests that the pest should only be removed when it has negative value. Assuming the optimal equilibrium strategy does not occur at $h = 0$ or $h = h_{max}$, then Eq. (6) is a necessary condition for a solution.

A solution must also satisfy two adjoint equations:

$$\frac{d\lambda}{dt} = \rho\lambda(t) - V_f - \lambda(t)\left[g_f - m_f\right] + \mu(t)n_f \tag{7}$$

$$\frac{d\mu}{dt} = \rho\mu(t) + c_p h(t) + \lambda(t)m_p - \mu(t)\left[q_p - n_p\right] \tag{8}$$

Eqs. (7) and (8) show how the co-states should evolve over time. If continuous pest removal proceeds optimally, then Eq. (7) says that $\lambda(t)$ will vary depending on its own current value, the discount rate, the marginal value of *f*, the marginal net growth of *f*, the pest co-state and the marginal effect of *f* on pest growth. Likewise, Eq. (8) says that $\mu(t)$ will vary depending on its own current value, the discount rate, the marginal cost of removal with respect to *p*, the removal rate, the wildlife co-state, the marginal effect of *p* on wildlife growth and the marginal net growth of *p*.

Focusing on the interior solution, efficient pest control is determined by using Eqs. (6), (7) and (8). The singular solution for *h* is found by taking the time derivative of Eq. (6) to get

$$\frac{d\mu}{dt} = -c_p \cdot \frac{dp}{dt} = -c_p[q(p) - n(f,p) - h(t)]. \tag{9}$$

[1] Several other papers do not analyze multispecies pest control specifically but study related problems. In regard to pest management, Skonhoft and Olaussen (2005) study pest harvesting strategies to improve the value of a metapopulation system, Finnoff and Tschirhart (2005) model plant competition to help identify successful invasive plant species, and Gutierrez and Regev (2005) model a multiple trophic level system to show how species maximize their adaptedness over time, which can result in local extinctions for other species. For a review of multispecies bioeconomic modeling in general, see Tschirhart (2009).