Managing a Multiple-Use Resource: The Case of Feral Pig Management in California Rangeland

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Many wildlife populations cause damage in agricultural systems but are also valued resources, either for their recreational value or for their existence and contribution to biological diversity. As a result, the nature of a given species—whether it is considered a “pest” or a “resource”—is often determined by the economic and regulatory environment in which the species exists. In this paper we develop a bioeconomic model of one such environment. We apply the model to the case of feral pigs in California rangeland and consider the potential for recreational hunting as a policy for population control.

I. INTRODUCTION

Of the many wildlife populations that cause damage in agricultural systems, some are also the object of recreational activity for hunters or other types of outdoor recreationists. If agricultural landowners can capture part of the benefits generated from these activities, say from the sale of hunting or viewing rights, should the animal causing damage be considered an agricultural pest or an economic resource? Tisdell [1] poses this question for the feral pig (Sus scrofa) in Australia, which is both a significant agricultural pest in Australian rangeland and a valued hunting resource. Other examples include migratory bird populations that

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establish nesting grounds in rice paddies and deer populations that inhabit private timber stands. One way of viewing this issue is to consider a given parcel of agricultural or forest land as a multiple-use resource: it can be used in agricultural or forest production, but may also serve as habitat for a wildlife resource that has economic value.

The potential dual role of an animal species as both a pest and an economic resource reflects the ambiguous and somewhat arbitrary distinction of some animals as “pests.” Agriculturists and other landowners who, through entrepreneurial effort, are able to transform a pest into a resource can replace “pest control” efforts with “resource management” strategies, so that what defines a pest depends as much on one’s perspective and on economic opportunities as on the ecology of a given species.

The purpose of this paper is to model the management of an animal population with these perspectives in mind. Doing so is important because most existing analyses of wildlife-management issues do not recognize the potential interaction of a wildlife resource with other production activities, and because existing prescriptive analyses of optimal farm-level pest-control strategies generally ignore possible multiple-use benefits (e.g., Hone [3]; Carlson and Wetzstein [4]).

Barbier et al. [5] and others (e.g., Schulz and Skonhoft [6]; Kremer and Morcom [7]) consider land use conflicts and the economics of poaching in studying conservation of endangered large game animals. In these analyses, poorly defined property rights create an open access problem, limiting the extent to which landowners can capture recreational benefits from animals that exist on (or occasionally pass through) their lands. In this paper, we consider a model in which property rights can be perfectly defined and enforced, so that our analysis is relevant only for animal populations that are not highly mobile or for which protected ownership rights can be established. Landowners have two options available for controlling animal populations on their land. They can trap and kill the animals themselves at some cost, or, if the government allows and there is a market, they can sell hunting rights.

In what follows we develop a framework for evaluating these options from the perspective of a representative private landowner. We first define the properties of the key biological relationships—the nature of agricultural damage as a function of total animal population and animal population dynamics—and then introduce the landowner’s optimization problem. We analyze the properties of the optimal solution under three different management regimes—hunting and trapping together, just hunting, and just private trapping. We focus only on these management regimes because they represent stylized versions of the policy options currently under debate in California for control of feral pig and deer populations (Updike and Waithman [9]).

We then consider the relationship between steady-state population levels under each management regime. The size of the animal population that exists in each case is an important object for analysis because state and federal wildlife managers often confront a situation where a given animal population is considered either too

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3 The collection of essays by Anderson and Hill is a notable exception [2]. These essays take a property rights approach to analyzing legal and institutional arrangements for wildlife management in the United States, focusing in particular on barriers to further use of markets in mapping wildlife populations.

4 For example, feral pigs (which we use as an example later in the paper) have a limited home range and generally do not move very far unless subjected to an extreme disturbance (Choquenot et al. [8]).
high (when the animal species is a pest) or too low (when the animal species is endangered).\(^5\) In such cases, although it is usually difficult to determine the socially optimal population size, governments may wish to increase or decrease existing population levels. Such an outcome can be achieved with policies that influence the private cost of trapping (e.g., cost of depredation permits and fines for illegal kills) or affect possibilities for fee hunting.\(^6,7\)

In the final section we illustrate the key points of our analysis with an application to feral pigs in California rangeland and briefly consider the role of external damages in determining which of the policy regimes would be preferred for this example. We construct an empirical model for a hypothetical piece of coastal rangeland, using published research by Barrett et al.\(^{10}\), Pech and Hone\(^{11}\), and Sterner and Barrett\(^{12}\). The empirical model allows us to resolve an important ambiguity in our theoretical model (at least for the specification we provide) and provides a framework in which to conduct comparative statics. For example, we consider the influence of a change in marginal trapping costs and the price of hunting on steady-state equilibria. Both of these parameters have policy-relevant counterparts: the cost of “depredation” permits for trapping and the cost of license fees for hunting.

II. MODEL

Consider an agricultural landowner operating with potential per-acre profits (with no pest damage), given by \(\bar{R}\). For simplicity, we ignore nonland inputs and assume constant returns to scale on \(A\) total square kilometers of land. Total agricultural revenues are therefore given by \(R = \bar{R}A\). An animal population of size \(N\) causes proportional damage \(D(N)\) to agricultural production, which is assumed to be strictly increasing.\(^8\) Actual agricultural revenues, \(Y\), are a decreasing function of the animal population:

\[
Y = \bar{R}[1 - D(N)].
\]

\(^5\) Earlier we indicated that the animal population we model is limited in its range and can therefore be treated as though it exists on the land of a single range manager. Yet, if the animal population is “too low” or “too high” from the government’s perspective, then some form of externality must exist. While modeling such an externality directly may provide some useful insight, in the present paper we only suppose that there is an interest in the population level (thus implying some form of externality), without specifying the source of this interest. The types of externalities that are relevant for the specific example considered later in the paper include contamination of public water supplies and occasional roaming of an individual landowner’s animal population in years of drought when food is scarce. Note that in the first of these examples, the animals need never leave the manager’s land to cause “external” damage.

\(^6\) Interestingly, for-fee hunting is often promoted as a possible solution to some animal pest problems (e.g., deer, pigs, and squirrels). However, by transforming a typical range manager’s problem into one of maximizing returns from his multiuse resource, for-fee hunting may actually justify a larger steady-state animal population relative to a myopic control strategy where such benefits are ignored (or are impossible to attain because of regulatory restrictions on hunting).

\(^7\) Existing population levels might also be increased or decreased by changing management strategies on public lands. In this paper we focus on the incentives for private landowners to conserve (or destroy) animal populations that act as both pests and economic resources.

\(^8\) We suppose that \(D(N)\) is independent of \(A\), implying that damages are uniformly spread across each unit of land.
The animal population is assumed to grow at rate $g(N)$, where $g'(N)$ may be positive or negative, where $g''(N) \leq 0$, and where primes denote differentiation.

In the following sections, we will examine two strategies to reduce population growth: trapping and hunting. The key difference between these two strategies is that trapping is an activity undertaken by the landowner at some cost, while hunting can generate revenue through the sale of hunting rights.

Per-animal trapping costs are assumed to be a decreasing function of the animal population, because trapping animals becomes progressively more difficult as animal populations become small (Hone [3]; Sterner and Barrett [12]).

Let $K_s$ denote the number of animals trapped per period, and let $\nu(N)$ represent per-unit trapping costs, where $\nu(N) > 0$, $\nu'(N) < 0$.

In the hunting market, we assume that each hunting permit is good for one kill and that kill occurs with certainty. The animal hunting market is characterized by an inverse demand function, $P(K_h)$, where $K_h$ denotes the number of animal hunting permits sold per period and permit prices are decreasing in the number of kills.

Thus, the landowner maximizes profit through the joint production of agricultural products and animal hunting activities. Of course, the animals still cause damage to agricultural production, so the optimal animal eradication program will involve some weighing of the economic damages to agriculture and the revenue generated from selling hunting permits. Letting $\delta$ denote the time rate of discount, the landowner chooses $K_s$ and $K_h$ to solve

$$
\max \int_0^T \left[ \left[ R(1 - D(N)) \right] - \nu(N)K_s + P(K_h)K_h \right] e^{-\delta t} dt
$$

subject to

$$
\dot{N} = g(N) - K_s - K_h
$$

$$
K_s \geq 0; \quad K_h \geq 0, \quad N \geq 0.
$$

The population at time zero is assumed to be given, and for ease of notation we have suppressed time indices. The equation of motion for the state variable $N$ in (2) indicates that animal population growth is reduced by trapping, $K_s$, and hunting, $K_h$, in each period.

Define $\mu$ as the co-state variable associated with the state variable $N$. Then the current-value Hamiltonian corresponding to (2) is given by

$$
\hat{H}(N, K_s, K_h, \mu) = R[1 - D(N)] - \nu(N)K_s + P(K_h)K_h
$$

$$
+ \mu(g(N) - K_s - K_h),
$$

which, together with complementary slackness and nonnegativity conditions for $K_h$ and $K_s$, yields the following first-order conditions for an optimum:

$$
\frac{\partial \hat{H}}{\partial K_s} = -\nu(N) - \mu \leq 0
$$

$$
\frac{\partial \hat{H}}{\partial K_h} = P(K_h) + P'(K_h)K_h - \mu \leq 0
$$

For example, Sterner and Barrett describe a feral pig eradication experiment on Santa Cruz Island in California in which, although eradication was achieved, removal of the last pig cost over $10,000 [12].
\[
\dot{\mu} = RD'(N) + \nu'(N)K_s - \mu(g'(N) - \delta) \\
\dot{N} = g(N) - K_s - K_h.
\]

For the remainder of this paper, we will denote the marginal revenue from hunting, \( P(K_h) + P'(K_h)K_h \), in Eq. (4), as \( z(K_h) \), and will assume that the conditions stated above represent a maximum. The non-negativity constraints on trapping and hunting levels, together with complementary slackness conditions corresponding to Eqs. (3) and (4), yield three equilibrium scenarios where some form of animal control occurs: trapping and hunting, trapping only, and hunting only. Each of these will be discussed in turn.

II.A. Trapping and Hunting in the Steady-State Equilibrium

In this scenario, the landowner engages in both trapping and hunting in the steady state and Eqs. (3) and (4) hold with equality. This implies that the shadow value of an animal at each point in time equals the marginal cost (benefit) of animal removal, \( \mu(N) = -\nu(N) = z(K_h) \). Because marginal trapping costs are strictly positive for all values of \( N \), the shadow value of the animal is strictly negative. Thus, Eq. (4) can only hold with equality when the marginal revenue from animal hunting is negative. Intuitively, one can think of trapping as a backstop technology, where animals are hunted until marginal revenue is driven below the marginal cost of trapping, after which they are trapped. This situation is depicted graphically in Fig. 1.

![Figure 1](image_url)

**FIG. 1.** Steady-state equilibrium under the joint hunting and trapping regime.
Equation (5) determines the rate of change in the shadow value of an animal. The first two terms account for the marginal impact of the animal stock on agricultural damages and the cost of trapping, respectively, and the last term represents minus the value marginal product of the animal stock, net of the opportunity cost of investment. Equation (6) is a restatement of the growth constraint in (2).

In the steady state, the shadow value of the animal and the animal population are constant over time: $\dot{\mu} = \dot{N} = 0$. When this is true, Eqs. (3)–(6) provide an expression that implicitly defines the steady-state animal population,

$$\delta = g'(N^*) + \frac{RD'(N^*) + \nu'(N^*)[g(N^*) + z^{-1}(\nu(N^*))]}{\nu(N^*)},$$ (7)

where $N^*$ represents the steady-state equilibrium with joint trapping and hunting. Equation (7) states that the discount rate equals the rate of change in the animal population growth rate plus the marginal stock effect. In this case, the stock effect has two components: the effect on agricultural damage and the effect on the cost of animal removal. Thus, we see that numerous forces, including the discount (interest) rate, the destructiveness of animals, harvesting costs, and the demand for recreation, interact to determine steady-state populations and in turn steady-state shadow values. Given the concavity of $g(N)$ and other nonlinearities, the effect of a change in any one component is analytically ambiguous. The behavior of this equilibrium and of the cases considered in each of the two subsequent sections are discussed in greater detail in Section II.D and analyzed empirically in Section III.F.

II.B. Trapping Only in the Steady-State Equilibrium

In this scenario, $K_h = 0$ and the landowner engages strictly in trapping; Eq. (3) holds with equality and $\mu(N) = -\nu(N)$. This would only occur if the marginal revenue from hunting were more negative than minus the per-unit costs of trapping for all relevant hunting levels. While this would be unlikely to occur in the present model, one could easily generate such an outcome by including an arbitrarily large potential liability cost associated with hunting, or alternatively by simply presuming that hunting is illegal. In this case, the shadow value of an animal equals minus the trapping costs of removal.

In the steady state ($\dot{\mu} = \dot{N} = 0$), expressions (3), (5), and (6) implicitly define the equilibrium animal population,

$$\delta = g'(N^*_s) + \frac{RD'(N^*_s) + \nu'(N^*_s)g(N^*_s)}{\nu(N^*_s)},$$ (8)

where $N^*_s$ represents the steady-state equilibrium under trapping. Equation (8) states that the marginal net growth rate plus the marginal stock effect equals the opportunity cost of capital, i.e., the rate of return of rival assets. This rate of return can be thought of as analogous to the resource’s (animal’s) internal rate of return. The only difference between this expression and (7) is captured in the stock effect on the cost of animal removal. In this case, the marginal cost of animal removal is only influenced by trapping activities, as there are no hunting activities.
II.C. Hunting Only in the Steady-State Equilibrium

In this scenario, the landowner engages only in hunting and Eq. (4) holds with equality. This scenario would occur if over the relevant range of hunting levels, marginal revenue from permit sales were greater than minus the per-unit cost of trapping. This obviously holds true in the special case where hunting permits are sold at a positive and constant price. The interpretations of Eqs. (4)–(6) are the same as before, except that in this case the shadow value of the animal equals the marginal revenue from hunting, \( \mu(N) = z(K_h) \), and can be positive, indicating its status as a resource rather than a pest. This can be verified by inspecting (4) and noting that the marginal revenue from hunting can be positive or negative. In both (5) and (6), \( K_s \) is equal to zero. The simplified Eq. (5) states that the change in the shadow value of the animal equals the marginal benefit of removing the animal minus the value of the marginal product of the animal stock, net of the opportunity cost of investment. Again, Eq. (6) restates the equation of motion for the animal population.

In the steady state (\( \dot{\mu} = \dot{N} = 0 \)), expressions (4)–(6) implicitly define the equilibrium animal population,

\[
\delta = g'(N_s^\ast) - \frac{RD'(N_h^\ast)}{z(g(N_h^\ast))},
\]

where \( N_s^\ast \) represents the steady-state population under a hunting regime, and Eq. (6) determines the equilibrium level of hunting. Equation (9) again states that the net marginal growth rate plus the marginal stock effect equals the rate of return on rival assets. The key difference here, relative to (7) and (8), is that the marginal stock effect from hunting has only one term representing the marginal stock effect on agricultural revenues. Unlike the case of trapping, the animal stock has no direct effect on the price of control hunting, although the equilibrium animal stock does determine equilibrium growth and harvest and thus indirectly influences the price of hunting permits.

II.D. Steady-State Comparisons

A discussion of animal shadow values for each scenario reveals one of the main points of this paper: recognition of alternative uses for a resource can transform a “pest” into an economic “asset.” When hunting is illegal or economically infeasible, animals are removed through trapping and animal population shadow values are negative. This negative value suggests animals are a pest whose presence decreases revenue on a parcel of land. When hunting is feasible, the value of this resource increases. This value may be positive, reflecting a positive price paid by hunters for the marginal animal, or it may be negative, implying that landowners are paying hunters to remove animals, but at a price that is less costly than trapping. In the former case, the animal can be thought of as an asset or economic resource, and in the latter case, the animal is a pest, but less of one than under the trapping-only scenario.

While the relationship between resource shadow values under each regime is clear, the relationship between steady-state population levels in each case depends on model specification. For simplicity, consider the two extreme cases of hunting
only or trapping only. Intuitively, one might expect the steady-state population under the hunting regime to be higher than that under a pure trapping regime because the landowner can generate additional revenues from having animals on his land. This intuition is only part of the story. To see why, define the carrying capacity of the land as the level of the animal population \( N_c > 0 \) such that \( g(N_c) = 0 \). Then if private damages are not too high and trapping costs are prohibitively expensive, the optimal solution in the trapping regime may be to let the animal population exist at carrying capacity. In this case, the steady-state population under the hunting regime is likely to be lower than that under the trapping regime.

More formally, note that for any concave growth function with a carrying capacity, there exists a population associated with the concept of maximum sustainable yield (MSY), which we will denote as \( N_{MSY} \). Populations smaller than \( N_{MSY} \) are characterized by increasing growth, \( g'(N) > 0 \), and populations larger than \( N_{MSY} \) are characterized by decreasing growth, \( g'(N) < 0 \). For the trapping scenario, inspection of Eq. (8) and rearranging terms reveals that \( g'(N^*) \) can be either positive or negative, suggesting that the population growth rate at the steady-state optimum can be increasing or decreasing. This implies that, theoretically, the optimal animal population can be smaller or larger than \( N_{MSY} \). Furthermore, examination of Eq. (8) reveals the importance of trapping costs and the marginal benefit from animal removal to the ultimate determination of the steady-state animal population.

The results in the case of hunting are also ambiguous. Equation (9) suggests that the sign of \( g'(N^*_h) \) will depend on the sign of the marginal revenue from hunting, \( z(K_h) \). If marginal revenue is positive, the steady-state hunting optimum will yield an increasing growth rate and the steady-state animal population will be to the left of \( N_{MSY} \). If the marginal revenue from hunting is negative, the steady-state growth rate may be positive or negative. This will depend on whether the absolute value of marginal damages per unit of marginal revenue is greater than or less than the return to rival assets (the discount rate). If it is greater, the equilibrium growth rate is negative and the steady-state animal population will be to the right of \( N_{MSY} \). If it is smaller, the opposite obtains and the steady-state animal population will be to the left of \( N_{MSY} \).

In the following section we simulate optimal steady-state population levels, using California feral pigs as an example. As will be demonstrated, the steady-state pig population will be higher under the hunting regime than under the trapping regime for most reasonable specifications of our model.

III. EMPIRICAL STUDY: FERAL PIGS IN CALIFORNIA RANGELAND

Wild pigs are nonnative to California—they were introduced in the mid-1500s with the arrival of Spanish settlers and have gradually expanded their range with the help of numerous additional introductions by humans (Mayer and Brisbin [13]). Prior to 1960 their distribution was limited primarily to a few coastal counties, whereas they are now believed to populate more than 40 of California’s 58 counties; current estimates place the statewide population at more than 130,000 pigs (Sweitzer et al. [14]). Wild pigs were designated as a wild game mammal in 1956 and since that time have been associated with an increasing number of human
conflicts (e.g., Wilson [15]). For some, wild pigs are the source of weekend recreational opportunities, while for others they represent an obnoxious, highly reproductive pest.

The dual role of wild pigs as both an agricultural pest and game mammal presents a significant challenge to state wildlife managers. The current management strategy relies almost entirely on hunting as a means of controlling statewide populations: an average 127 pigs per year were killed under State depredation permits during 1992–1995, representing only 0.4% of hunted pigs during the same period (Updike and Waithman [9]). In response to agricultural interests, the California legislature recently passed legislation that makes depredation permits easier to obtain, thus making private trapping cheaper. However, as we saw in the previous section, sanctioned hunting can make private trapping irrelevant by providing a revenue-generating source of pig control. Indeed, although our model focuses on the decisions of a single rangeland manager, its implications seem to accord well with the limited use of depredation permits (private trapping) cited above.

In this section we draw from empirical studies of wild-pig population dynamics and pig damage in California to develop an empirical illustration of optimal pig management. The empirical analysis allows us to investigate a few important ambiguities in our theoretical model. In particular, we establish that for a typical piece of rangeland in California, the optimal steady-state pig population is considerably higher when hunting is sanctioned and offers a positive price than when it is illegal. This is significant because the results suggest that current legislation that makes private trapping cheaper may do very little to provide further control of long-run pig populations.

III.A. Population Growth

Considerable work has been done on modeling feral pig population growth. For this paper, we will rely on the model presented and estimated in Pech and Hone [11]. They employ a logistic model, which implies rapid growth when the population is small and resources are abundant and slow growth, tapering off to zero, when the population is large and resources are limited. The equation for pig growth is

$$g(N) = rN(1 - N/\Theta),$$

where $r$ is the instantaneous growth rate (0.5840/year) and $\Theta$ is the carrying capacity of the habitat (15 pigs/km$^2$).

III.B. Damage to Rangeland

Damage to rangeland, measured as a percentage loss of total revenue, is modeled as a linear function of pig population density (Barrett [16]):

$$D(N) = cN.$$
90%. Because there is considerable uncertainty associated with this parameter, we vary this coefficient and examine its impact on steady-state results.

III.C. Trapping Costs

Evidence on the cost of trapping was obtained from Sterner and Barrett [12]. In this study, the authors investigate the incremental cost associated with pig removal at various pig densities. For population densities above 15 pigs/km², the cost of pig control is negligible. When population densities reach a level of less than 1 pig/km², the cost of pig control can exceed $1000 per pig. To be consistent with these observations, and for analytic tractability, we specify a hyperbolic functional form for trapping costs,

\[ \nu(N) = \frac{B}{N}, \]

where \( B \) is a constant. We initially set \( B \) to 40 and then evaluate the influence of changes in \( B \) on the equilibrium steady-state population under the trapping regime.

III.D. Hunting Permit Prices

In the absence of any previous work that estimates the demand for feral pig hunting, we assume that demand for pig hunting is similar to that for deer hunting. Demand is modeled as a linear function of the form

\[ P(K_h) = Q - XK_h. \]

Based on reported price elasticity measures for deer hunting (Creel and Loomis [18]) and using pig hunting permit prices from coastal areas of California (Barrett [16]), we set \( Q = 150 \) and \( X = 17.21 \). Given these values, \( 2(K_h) = -34.42K_h \), and marginal revenue from hunting is negative when \( K_h > 4.35 \). In the following section we experiment with alternative parameterizations of hunting demand.

III.E. Rangeland Revenues and the Discount Rate

Potential revenue (with no pig damage) from rangeland activities is set at $100/km² based on average figures from San Luis Obispo County (University of California Cooperative Extension [19]). The discount rate is set at 0.1, but is then varied between 0.01 and 0.25. Table I summarizes all our parameter values.

III.F. Results

Given our empirical specification and the parameter values summarized in Table I, we can derive steady-state populations and profits under hunting and trapping. In the case where trapping is the only population control method, the steady-state pig population is 0.90 pigs/km², and steady-state profits from rangeland activities
are $73/km^2$. When hunting is allowed and the inverse demand function for hunting is given by the expression $P(K_h) = 150 - 17.21K_h$, only hunting occurs in the steady state and the pig population increases to 5.27 pigs/km$^2$ with combined profits from ranching and permit sales equal to approximately $299/km^2$. Thus, although our theoretical analysis indicates ambiguity, the empirical analysis is clear: Hunting leads to a significantly higher steady-state pig population than trapping. Furthermore, when hunting is allowed, the steady-state equilibrium involves strictly hunting rather than a combination of hunting and trapping.

To examine the robustness of this result, we compare the relationship between steady-state populations when hunting is prohibited and when it is legal by varying each of our parameters. Specifically, we vary the discount rate, the potential rangeland revenue, the marginal rangeland damage from pigs, the trapping costs, and the slope of the hunting demand curve. Note that for all specifications of hunting demand when hunting is allowed, the steady-state solution involves only hunting. This, however, does not preclude the employment of both trapping and hunting on the path to a steady state. Profits under the hunting regime are always higher than under the trapping regime because the manager is not restricted from using for-fee hunting as a control strategy. Comparative static results for our model specification are reported in Table II. Rangeland revenue and the marginal damage from pigs collectively determine the marginal benefit of pig removal. As the marginal benefit of pig removal increases, steady-state populations under both regimes decrease. An increase in the discount rate requires that pigs must have a higher net real marginal product, leading to a lower steady-state population. With trapping, a similar logic applies, but in reverse. Figure 2 shows that, as the slope of the hunting demand curve becomes steeper, the optimal steady-state population under hunting decreases. In other words, as the price hunters are willing to pay for

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**TABLE I**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R$</td>
<td>Potential rangeland revenue ($)</td>
<td>100</td>
</tr>
<tr>
<td>$c$</td>
<td>Marginal rangeland damage (pigs$^{-1}$)</td>
<td>0.06</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Discount rate</td>
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</tr>
<tr>
<td>$B$</td>
<td>Trapping cost parameter ($)</td>
<td>40</td>
</tr>
<tr>
<td>$Q_c$</td>
<td>Hunting demand—intercept ($)</td>
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</tr>
<tr>
<td>$X$</td>
<td>Hunting demand—slope ($) /pig</td>
<td>17.21</td>
</tr>
<tr>
<td>$\Theta$</td>
<td>Carrying capacity (pigs)</td>
<td>15</td>
</tr>
<tr>
<td>$R$</td>
<td>Intrinsic pig growth rate (year$^{-1}$)</td>
<td>0.5840</td>
</tr>
</tbody>
</table>
hunting becomes more responsive to the number of hunting permits sold, the rangeland manager reduces the equilibrium animal population. When the steady-state population is to the left of the MSY, as is the case for our specification, this implies a reduction in steady-state animal growth and thus a decrease in the number of animals hunted, enabling landowners to keep permit prices high. Figure 3 indicates that as trapping costs become large, trapping activities become less attractive, resulting in a large steady-state pig population. In fact, when the coefficient for trapping costs exceeds roughly $105/pig, the hunting regime results in a smaller steady-state pig population than the trapping regime.

Inspection of Table III reveals that under a wide range of parameter values, the steady-state pig population under trapping will be smaller than that under hunting.
### TABLE III
The Effects of Parameter Changes on Steady-State Populations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Trapping</th>
<th>Hunting</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Population (pigs/acre)</td>
<td>Profit ($/acre)</td>
</tr>
<tr>
<td>Rangeland revenue ($R$)</td>
<td>25</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>2.77</td>
</tr>
<tr>
<td></td>
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<td></td>
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<td>0.54</td>
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<td>0.38</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>0.14</td>
</tr>
<tr>
<td>Rangeland damage ($c$)</td>
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</tr>
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<td></td>
<td>0.02</td>
<td>9.04</td>
</tr>
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<td></td>
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<td>1.64</td>
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<td></td>
<td>0.06</td>
<td>0.90</td>
</tr>
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<td>0.08</td>
<td>0.62</td>
</tr>
<tr>
<td></td>
<td>0.10</td>
<td>0.47</td>
</tr>
<tr>
<td>Discount rate ($\delta$)</td>
<td>0.01</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td>0.05</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td>0.15</td>
<td>1.35</td>
</tr>
<tr>
<td></td>
<td>0.20</td>
<td>1.80</td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>2.25</td>
</tr>
<tr>
<td>Trapping costs ($B$)</td>
<td>20</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>1.64</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>2.77</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>4.75</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>9.04</td>
</tr>
<tr>
<td></td>
<td>140</td>
<td>15</td>
</tr>
<tr>
<td>Hunting demand ($X$)</td>
<td>10</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td>17.21</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td>75</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td>125</td>
<td>0.90</td>
</tr>
</tbody>
</table>

Only when potential rangeland revenue or marginal rangeland damages are small, or when trapping costs are high, will the reverse be true. Thus, when the marginal benefit from removing a pig is small or the marginal cost of trapping is high, ranchers may find it optimal to maintain a relatively large pig population on their property. For example, if pig damage at carrying capacity is less than or equal to 45% of rangeland revenue ($c \leq 0.03$), the steady-state population under trapping will be larger than that under hunting. Although not inconceivable, this damage figure is well below most current estimates of potential damage at carrying capacity.
IV. EXTERNALITIES

Although briefly mentioned in the Introduction, externalities have mostly been ignored in this paper. We have done this because externalities are difficult to quantify and therefore impossible to incorporate into our empirical analysis. This does not change the fact that externalities need to be considered to compare steady-state populations under each of the two regimes we analyze with the socially optimal population size. In this section we briefly consider how incorporation of a strictly positive and strictly increasing “external” damage $E(N)$ would influence optimal population management. These damages may be due to physical damages inflicted on neighboring land or perhaps to the spread of disease. Because of these damages, the steady-state pig population under either the hunting or private trapping regimes may be higher than is socially desirable. An interesting question is then: In the absence of a first-best solution, which regime is preferred? To answer this question, we must compare social welfare under each of the two regimes.

It is immediately obvious that if the steady-state population under hunting were lower than that under trapping, the hunting regime would be preferred. This is true because both private and external damages would be lower, and pig removal is a revenue-generating activity rather than a cost. If the steady-state population under the hunting regime is higher than that under the trapping regime, the preferred regime cannot be determined without comparing social welfare under each. Instantaneous steady-state social welfare under the hunting regime is composed of rangeland revenues (net of pig damage) plus hunting revenues, less external damages. Under the trapping regime, social welfare is composed of the same terms (evaluated at different populations), but hunting revenues are replaced by trapping costs. The hunting regime will therefore be socially preferred if the revenues generated from this regime, relative to those under the trapping regime, more than offset the increased external damage associated with a higher pig population.

Without any information on the shape or magnitude of the external damage function $E(N)$, it is impossible to evaluate this criterion. However, using equilibrium population levels from the hunting and trapping regimes analyzed earlier, we can determine the difference in external damages, $E(N_h^*) - E(N_t^*)$, for which hunting would be the preferred regime. We perform this calculation using the parameters from Table I and the equilibrium values for the steady-state population under the hunting and trapping regimes (5.27 and 0.9 pig/km$^2$, respectively). Our results indicate that 4.37 additional pigs would have to cause no more than approximately $226 additional external damage for hunting to be the preferred regime.

V. CONCLUSION

The existence of agricultural pests that simultaneously generate hunting, viewing, or other recreational benefits is an important problem that has received little attention in the economics literature. This paper develops a model to address this

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12 Wild pigs are believed to be important sources of Cryptosporidium and Giardia in public water supplies (Atwill et al. [20]).
issue and compares two alternative population management regimes: one where population control is achieved at a cost, and another where population control generates revenue through the sale of hunting permits. These two regimes can be viewed as stylized versions of existing policy options that include such things as reducing the cost of private trapping by making depredation permits easier to obtain and allowing for-fee hunting on private land.

Although fee hunting may create an incentive for landowners to establish a relatively large steady-state animal population, our theoretical analysis demonstrates that the relative sizes of optimal steady-state populations under each regime are in fact ambiguous. For example, if the animal population causes very little economic damage, there may not be much incentive to incur the cost of trapping, or alternatively, very high trapping costs may make private control unattractive. Both of these scenarios would result in a steady-state population that is higher under the trapping regime than under the fee-hunting regime. Thus, the theoretical model is inadequate for addressing relative magnitudes of the steady-state population under each regime.

However, at least for the case of feral pigs in California, we show that with most reasonable empirical specifications of our model, recognizing the recreation benefits associated with wild pigs results in a larger steady-state population and increased returns to rangeland managers, relative to the trapping regime. This outcome is consistent with the observation that feral pig populations in California began a phase of rapid growth (in both numbers and range) shortly after 1960, just a few years after state wildlife managers made feral-pig hunting legal (Updike and Waithman [9]). Thus, arguments by some that private hunting is an effective means of reducing wild pig populations may be ignoring the powerful incentive that for-fee hunting creates to establish and maintain viable pig populations on private land. Of course, which regime is preferred will depend on the relative size of the steady-state pig populations and on a comparison of social welfare under each regime. Even if the steady-state pig population under hunting is higher than under trapping, the hunting regime will still be preferred if the revenues generated from hunting more than offset the increase in damages associated with a higher population.

REFERENCES


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