Along the Way Back from the Brink

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An optimal control model of wildlife management is developed to analyze the transitory dynamics set forth by the reintroduction of animals that provide benefits but can also come into conflict with humans. The shadow price of these resources can be positive or negative, potentially creating a nonconvexity. The conditions under which reintroduction is not desirable are determined, and those characterizing the initiation of costly population control are investigated. An application to deer management illustrates the relevance of the nonconvexity and the magnitude of losses stemming from delays in implementing optimal management. The impact of distributional concerns on efficiency is discussed. © 2001 Academic Press

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Those of us professionally involved with wolf recovery have traditionally been maligned by anti-wolf people. Now we are vilified by many wolf lovers as wolf enemies because of our acknowledgment that wolves often require control.

L. D. Mech [44, p. 275]

1. INTRODUCTION

The reintroduction and long-term management of valuable species that can come into conflict with human activity pose difficult challenges to wildlife managers and policymakers. The reestablishment of populations of wolves, grizzlies, beavers, or deer provides recreational opportunities and satisfies the preferences of many individuals for an environment populated by free-roaming animals. Unfortunately, their recovery can also expose society to the risks of livestock depredation, attacks on humans, flooding, car collisions, diseases, and other forms of damage.

The number of conflicts between humans and wildlife and between proponents and opponents of population recovery efforts is expected to increase for two principal reasons. First, it is estimated that perhaps as many as 3000 vertebrate species will be in need of a propagation program over the next 50 years [58].

Second, the most common characteristics of animals on the list of species recommended for reintroduction by the World Conservation Union (IUCN) are "1. predators that come into direct conflict with man"; and "2. large, potentially dangerous animals" [64, p. 34]. Yet, very few wildlife management agencies and neither the U.S. Endangered Species Act (ESA) nor the IUCN guidelines for determining whether a species is suitable for reintroduction require an assessment of the costs and benefits of animal restoration programs [66].

This paper presents an analysis of the intertemporal economic trade-offs associated with the reintroduction and management of species that benefit society but can also inflict damage to human health and property. It is explicitly recognized that wildlife management agencies have access to a wide variety of control methods beyond traditional habitat conservation and hunting. Reintroduction, captive breeding, recreational or commercial hunting, and, if need be, "pest" control methods can all be utilized. The properties of optimal wildlife management plans are examined in this context. Conditions under which controversial species should be reintroduced, the consequences of growing stocks, and the requirements for shifts in management policy over time are analyzed.

The theoretical analysis indicates the potential existence of a nonconvexity resulting from the fact that a marginal animal can be either desirable or undesirable to society. The policy relevance of this nonconvexity is established with a numerical analysis of deer management in a suburb of Rochester, New York. Both point to the importance of initiating recovery programs and population control efforts in a timely manner. Consequently, conflicts (between proponents and opponents of reintroductions, and between supporters and detractors of population control measures) that delay the implementation of desirable policies can significantly reduce the efficiency of wildlife management. The effects of distributional concerns on efficiency are also discussed in the paper.

The next section surveys the benefits and costs of wildlife and is followed by a brief historical perspective on animal propagation efforts. A model is then introduced and its general properties are analyzed and discussed. Optimal management plans are then characterized analytically. Next, the model is applied to a current conflict involving a previously extirpated deer herd and a discussion concludes.

2. WILDLIFE BENEFITS AND DAMAGE

Humans derive substantial benefits from wildlife. We visit natural areas, create "bear jams" on park roads, feed birds, and go whale watching. We use public resources to monitor and manage wildlife stocks, make laws to ensure their existence (e.g., Lacey Act, 1900; Federal Aid in Wildlife Restoration Act, 1937; Endangered Species Act (ESA), 1973), and sign treaties to guarantee future flows of benefits (e.g., Canada−U.S. Convention for the Protection of Migratory Birds, 1916). We also voluntarily make substantial contributions to environmental organizations dedicated to wildlife preservation.

Most of us even answer economists' valuation surveys that pertain to measurement of the benefits of preserving endangered species. Loomis and White [39] reviewed this literature and report, for example, that individuals are willing to pay as much as $254 for the continued existence of bald eagles, $33 per year to protect gray whales, and $29 annually for sea otters. Other studies have found that

American households were willing to pay an average of $15 to $37 annually to ensure the survival of the northern spotted owl [56] and between $7.13 and $16.33 for the option and existence benefits associated with the preservation of whooping cranes [63].

Stevens *et al.* [61] also produced evidence of support for wildlife conservation. They estimate that New England residents would pay an average of $5.35 per year to protect coyotes. However, from a separate sample of respondents who were asked to consider the risks posed by the canine, they estimated a mean willingness to pay of $4.20 to support the implementation of population control programs.

Thus, while healthy populations of many species of wildlife may enter human preferences in unambiguously positive ways, the net welfare effect of others can be either positive or negative. The costs of a conflict between humans and wildlife can indeed be substantial. Coyotes, cougars, and bobcats cause losses of livestock estimated at $65 million per year [21], and another 13 species, including black bear, beaver, porcupine, and several groups of birds, are responsible for damage to crop and commercial timber evaluated at $130 million annually [67].

Today's conflicts are sometimes the result of successful conservation efforts. Florida residents make approximately 15,000 requests annually for the removal of once endangered and still protected American alligators [31]. Bisons, which almost went extinct in the late nineteenth century, are a major attraction for the visitors of Yellowstone National Park, but they are now shot when they cross park boundaries in order to protect surrounding cattle herds against the risk of disease [22]. But the white-tailed deer is perhaps the most controversial of all species. Its recovery from near extinction at the turn of the century is described as one of the greatest achievements of conservation biology [16]. Yet, white-tails are the principal reservoir of the bacteria that cause Lyme disease [8, 52] and are involved in perhaps as many as 1.5 million motor vehicle accidents per year in the United States [68]. These accidents cause $2 to $3 billion dollars in vehicle damage annually, injure 25,000 people, and kill between 100 and 200 others [54].

3. A BRIEF HISTORY OF TRANSLOCATION, INTRODUCTION, AND REINTRODUCTION OF WILD ANIMALS[2]

The intentional displacement of wild animals to satisfy human preferences is not a new phenomenon. In ancient China, impregnated fish eggs were collected and transferred to other parts of the country to be hatched, and the young fry were released in flooded rice fields or used to stock ponds [43]. In 1857, George Perkins Marsh published a report on the artificial propagation of fish in which he also explored the effects of deforestation, agriculture, and industry on fish populations

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[2] The following definitions are quoted directly from Seal [58, p. 28] and Griffith *et al.* [24, p. 477]. The World Conservation Union (IUCN) defines *reintroduction* as "the intentional movement of an organism into part of its native range from which it has disappeared or become extirpated in historic times as a result of human activities or natural catastrophe." *Stocking* is "the movement of numbers of plants or animals with the intention of building up the number of individuals of that species in an original habitat." *Introduction* is "the intentional or accidental dispersal by human agency of a living organism outside its historically known range." Encompassing these previous concepts is the notion of *translocation*, defined as "the intentional release of animals to the wild in an attempt to establish, reestablish, or augment the population."

[12]. Since 1871, over 200 fish hatcheries have been constructed by the U.S. federal government to propagate fish to private and public waters [18].

For centuries, species of game animals and birds have also been translocated. The red and fallow deer, European rabbit, ring-necked pheasant, and gray partridge are only a few of the many species imported from Europe and Asia since the eighteenth century [6]. To this day, government agencies continue to raise exotic game birds in captivity to stock wildlife management areas for the benefit of hunters.[3] The wild turkey, eastern cottontail rabbit, gray squirrel, opossum, and bullfrog were moved from the eastern to the western part of North America by settlers seeking to ensure adequate game and food supplies [6].

Reasons behind the introduction and reintroduction of animals also included nonconsumptive benefits. The English skylark was brought to Vancouver Island (Canada) in 1913 in an effort "to perpetuate the ambience of the English countryside" [2, p. 78]. European starlings were introduced to Central Park in 1890, and house sparrows were brought from Europe to Brooklyn in 1850 to control insects [6]. Between 1907 and 1917, the Bronx Zoo released bisons (bred and raised in captivity) on a reserve in Oklahoma and onto ranges in South Dakota, Nebraska, and Montana to establish new herds of what was then a species on the brink of extinction [32].

With growing threats to wild species, the emergence of conservationist preferences, and advances in zoology and wildlife biology, artificial propagation and translocation techniques have become increasingly attractive. Between 1973 and 1986, an average of 700 translocations per year have been conducted in Australia, Canada, New Zealand, and the United States alone, covering 93 different species of native birds and mammals [24]. Despite high failure rates (54% of releases of endangered and threatened species failed to establish a self-sustaining population), the highly publicized recovery of species such as the bald eagle (United States), sea eagle (United Kingdom), peregrine falcon (Canada, United States), swift fox (Canada), Indian rhinoceros (Nepal), and Arabian oryx (Oman) has attracted much attention and spurred additional translocation attempts. Between 1974 and 1981, the average number of translocations per year nearly doubled [24], and the trend is expected to continue as the number of threatened species continues to rise [58].

Recognizing this growing need, the IUCN formed the Conservation Breeding Specialists and Reintroduction Specialists groups and published guidelines on the use of wildlife propagation methods [69]. By stressing the need for suitable habitat as an important precondition for propagation attempts, these guidelines indirectly favor animals which have become threatened as a result of unsustainable levels of harvesting rather than through the loss of habitat. This explains the overrepresentation of "predators" and other "large dangerous animals" on the IUCN list of species recommended for reintroduction. These species have often been overharvested in the past precisely because they come in conflict with human activity. It is those species and their effects on welfare over time that the model of the next section seeks to represent.

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[3] For instance, the state of New Jersey continues to raise 42,000 pheasants per year in captivity to support hunting in 26 state wildlife management areas [48].

4. A MODEL OF SPECIES REINTRODUCTION AND MANAGEMENT

Jurisdictional responsibility for reestablishing, protecting, and controlling wild populations ultimately resides with public agencies that hold wildlife in trust for the greater benefit of society [28, 57]. These public agencies have the power and responsibility to fund conservation programs, regulate and enforce protection measures, and can order the destruction of wild animals [40]. They are legally entrusted with the responsibility to manage wildlife for the public good under the terms of wildlife laws that are generally mindful of the stakes of future generations [38]. However, the reality of wildlife management involves a complex mix of private and public land tenure, management strategies, and conflicting interests [51]. Some of these issues will be discussed later in the context of the results of a benchmark model in which a forward-looking wildlife manager chooses feasible stocking and control rates, $Y(t)$, to maximize the discounted flow of benefits to society.

In what follows, it will be useful to keep track of three distinct types of benefits and costs that will together form the object that society wishes to maximize. $V(X(t))$ measures the (rate of) nonconsumptive benefits associated with an animal population at level X at instant t. These benefits include the value of recreational opportunities (e.g., wildlife viewing), existence values, and any other benefits derived directly from nonconsumptive use of the stock itself. Letting subscripts indicate the argument of a derivative, it is assumed that $V(X)$ is increasing and strictly concave with $V(0) = 0$, $V_x > 0$, and $V_{xx} < 0$.

$D(X(t))$ measures the value of damage inflicted by the population $X(t)$. This includes all damage to human health and property caused by the stock, including the loss of cattle, human life, damage to cars, etc. $D(X)$ is assumed to be increasing and convex with $D(0) = 0$, $D_x > 0$ and $D_{xx} \geq 0$. For convenience, the composite function $V(X(t)) - D(X(t))$ will be referred to as the (instantaneous rate of) net stock benefits. Thus, the first derivative of this amalgamated function represents the net marginal stock benefits. It will be useful to define $\bar{X}$ as the population that maximizes net stock benefits. By concavity of the net benefit function, this corresponds to the stock at which the instantaneous benefits of a marginal animal equal the damage it imposes: $\bar{X} = \{X : V_x(X) - D_x(X) = 0\}$.

The third function is $N(Y(t))$. It measures the net rate of benefits resulting from the application of the control $Y(t)$. If $Y(t)$ is positive (harvesting), $N(Y(t))$ are the net benefits at time t derived from harvesting and consuming Y. If Y is negative (stocking), $N(Y(t))$ measures the cost of reintroducing/translocating/breeding at the rate of Y animals per unit of time. Define $Y_{\min}$ and $Y_{\max}$ as technological constraints on the rates of reintroduction and harvesting, respectively. Since $N(Y)$ represents the immediate welfare implications of the control Y, it also accounts for any nonmarket costs of harvesting, such as the disutility associated with the killing of animals felt by those who oppose hunting or other lethal population control measures.

$N(\bullet)$ is assumed to be strictly concave and single-peaked; it reaches its maximum at $\bar{Y}$, with $Y_{\min} < 0 < \bar{Y} < Y_{\max}$, $N(Y < 0) < 0$, and $N(0) = 0$. It is also postulated that $N_y > 0$ for $Y < \bar{Y}$, $N_y(\bar{Y}) = 0$, and $N_y < 0$ for $Y > \bar{Y}$. The existence of $\bar{Y}$ can be explained by increasing marginal harvesting costs or by a finite demand for animal products. Harvesting rates greater than $\bar{Y}$ are interpreted as marginal "pest" control since the marginal cost of harvesting exceeds marginal benefits. Such levels of harvesting must be entertained since a large stock can have

detrimental effects on welfare. For $Y < 0$, $N(Y) < 0$ is the cost of supplementa-tion. Earlier assumptions on $N(\bullet)$ make these costs increasing and convex in the number of animals restocked.[4]

Finally, the animal population evolves over time according to the differential equation $\dot{X} = F(X) - Y$. The natural rate of growth, $F(X)$, is a strictly concave function with $F(0) = F(1) = 0$ and $F(X) > 0$ for $0 < X < 1$ (both X and Y are normalized and expressed as a proportion of the habitat carrying capacity, so that $0 \leq X(t) \leq 1$). The implicitly fixed carrying capacity of the habitat is consistent with the fact that habitat availability is a prerequisite for reintroduction attempts.

It is highly conceivable that nonconsumptive benefits, damages, costs of stocking, benefits of harvesting, and costs of pest control could accrue to different groups in society. For instance, individuals across the United States may receive the benefits of wolves in Yellowstone, while owners of livestock in the vicinity of the park suffer the greatest share of animal damage. This motivates the separable form of the model,

$$\text{Maximize}_{Y(t)} \int_0^\infty e^{-\delta t}\left[V(X(t)) - D(X(t)) + N(Y(t))\right] dt$$

$$\text{Subject to} \quad \dot{X} = F(X(t)) - Y(t)$$

$$Y_{\min} \leq Y(t) \leq Y_{\max}$$

$$X(t) \geq 0$$

$$X(0) = X_0 \text{ given,} \tag{P}$$

where t is an index of time and δ is the instantaneous rate of discount. The current value Hamiltonian $\mathscr{H} = V(X) - D(X) + N(Y) + \mu[F(X) - Y]$ is used to form the Lagrangean expression $\mathscr{L} = \mathscr{H} + \lambda(Y - Y_{\min}) + \eta(Y_{\max} - Y)$, where μ is the costate variable, and λ and η are the Kuhn−Tucker multipliers associated with the constraints on Y.

A solution to this problem is a set of functions $Y^*(t)$, $X^*(t)$, and $\mu^*(t)$ defining the combination of controls, stocks, and implicit prices that maximizes the Hamil-tonian. I demonstrate elsewhere the existence of such a solution [55]. It must satisfy necessary conditions given by Eqs. (1) and (2) [30, 35],

$$N_y - \mu + \lambda - \eta = 0 \tag{1}$$

$$\dot{\mu} - \delta\mu = -[V_x - D_x + \mu F_x], \tag{2}$$

and be consistent with the postulated law of motion:

$$\dot{X} = F(X) - Y. \tag{3}$$

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[4] Imposing $N(0) = 0$ allows for a single piecewise continuous function to represent the benefits of harvesting a very small amount $(Y > 0)$ and the costs of reintroducing a small number of animals $(Y < 0)$. The assumptions $D(0) = V(0) = 0$ are not mathematically required for the analysis. However, they correspond to stylized facts.

Given an initial condition (4), the transversality condition (5) guarantees convergence of the solution,

$$X(0) = X_0 \tag{4}$$

$$\lim_{t \to \infty} e^{-\delta t} X(t) \mu(t) = 0. \tag{5}$$

To ensure that the constraints on Y are respected, the Kuhn−Tucker conditions add the requirements that

$$\lambda \geq 0; \qquad Y \geq Y_{\min}; \qquad \lambda(Y - Y_{\min}) = 0$$
$$\eta \geq 0; \qquad Y \leq Y_{\max}; \qquad \eta(Y_{\max} - Y) = 0. \tag{6}$$

By definition, interior trajectories are those where $Y_{\min} < Y < Y_{\max}$. It follows directly from (6) that these trajectories are characterized by $\lambda(t) = \eta(t) = 0$. Without loss of generality, it is assumed in what follows that the technological constraint $Y_{\max}$ is sufficiently large to be nonbinding for all candidate solutions. Thus, $Y^* < Y_{\max}$ and $\eta(t) = 0$ for all t's. Equations (1) and (6) can then be summarized as

$$Y = \begin{cases} Y_{\min} & \text{if } N_y(Y_{\min}) < \mu \\ Y^* & \text{if } N_y(Y^*) = \mu. \end{cases} \tag{1'}$$

Setting $\lambda = 0$ to analyze interior trajectories, Eqs. 1 and 2 can be given standard capital theoretic interpretations. If a marginal animal is harvested, it yields an instantaneous return δN_y. This is the rate of return obtained by investing the marginal benefits of harvesting at the rate of interest δ. Conversely, if the marginal animal is not harvested, it yields a rate of return equal to $\dot{\mu} + V_x - D_x + \mu F_x$, which represents a capital gain (or loss) in the value of the stock, plus the instantaneous nonconsumptive benefits of the marginal animal, minus the marginal damage it imposes, plus the return associated with the animal's effect on the population's rate of growth. An equilibrium requires that the rates of return on investments in the stock and on harvesting be equal, making the manager indifferent between harvesting or preserving the marginal animal.

Note that the objective function of the problem and the law of motion (3) are jointly concave in (X, Y). However, conditions (1') to (5) do not suffice to guarantee optimality since the costate variable μ can be either positive or negative. The animals are valued for the nonconsumptive and harvesting benefits they provide, but also hold the potential to impose damage. A marginal animal may therefore have a positive or a negative shadow price (even in an optimal program). As a result, the Hamiltonian of the optimal program is not necessarily concave, and sufficiency requirements are in general violated [59]. The problem could therefore have multiple equilibrium candidates.

Shadow prices with an indeterminate sign are reported in the recent work of Zivin *et al.* [70] and in an earlier paper by Feder and Regev [20]. The former study private hunting and trapping as two possible approaches to controlling the damage inflicted by feral pigs on private rangeland. While they do not explicitly consider public stock benefits, they note that the shadow price of the pig stock can be either positive or negative and they link the sign of the shadow price to the optimal

choice of management technique. The latter admit the possibility of ambiguously signed user costs in their work on the optimal use of pesticides to control a pest in a predator–prey relationship. They show that the user cost plays a crucial role in determining the optimal policy and whether or not decentralized pest control will produce shortage or excess pesticide application relative to the optimum.

In the analysis presented below, the shadow price (μ) plays a central role in determining the type of harvesting carried out and the optimal timing for the initiation of "pest" control measures.

5. SOLUTIONS, TOPOLOGIES, AND DYNAMICS

The dynamics of the present model of wildlife management shares several characteristics with the nonconvex dynamic problems analyzed by Huffaker and Wilen [27] and Tahvonen and Salo [65]. In [27], the objective function of a rancher stocking cattle is nonconcave due to the presence of a plant–herbivore (prey–predator) relationship. The resulting phase diagrams are remarkably similar to those produced in this paper. However, the analysis of Huffaker and Wilen focuses on a system where cattle is temporarily stocked on grazing land for the sole purpose of commercial gain. Here, the nonconvexity is traceable to the presence of stock-related damage. Finally, whereas they emphasize comparative dynamics, I am mostly interested in documenting events along the species' path of recovery from the brink of extinction.

Tahvonen and Salo's thorough analysis of transitory dynamics in a pollution accumulation problem with a concave–convex stock decay function details many of the analytical tools required to qualify and interpret adjustment paths. Many of these techniques are applied below. Thus, unless departures from previously introduced methods warrant additional remarks, only a sketch of the solution is presented along with the results.[5]

To construct phase diagrams, differentiating (1) with respect to time, substituting for μ and $\dot{\mu}$ in (2), and rearranging yields

$$\dot{Y} = \frac{-V_x + D_x + (\delta - F_x)N_y - \dot{\lambda}}{N_{yy}}, \tag{7}$$

which defines changes in harvesting rates over time along a trajectory meeting necessary conditions. Together, (3) and (7) form a dynamical system in the $X–Y$ space. Equation 3 readily defines the $\dot{X} = 0$ isocline as $Y = F(X)$. This is a biological equilibrium condition that states that the stock is stable whenever the harvesting and natural growth rates are equal. Setting $\dot{\lambda} = \dot{Y} = 0$ in (7), we obtain the interior expression for the harvesting (Y) isocline:

$$\delta = F_x + \frac{V_x - D_x}{N_y}. \tag{8}$$

Equation (8) is a variant of the fundamental equation of renewable resources. It can be thought of as an economic equilibrium condition. This version states that an

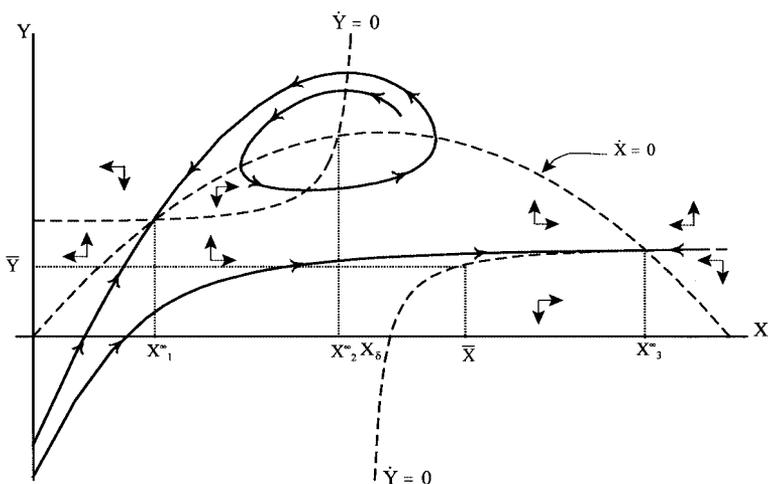[5] Detailed derivations can be found in [55].

FIG. 1. $X_\delta < \overline{X}$.

equilibrium harvesting rate must equate the external rate of return (δ) to the stock's own rate of return, composed of its natural marginal growth (F_x) and the rate of return (in the form of net stock benefits) on foregone control benefits (or translocation costs): (($V_x - D_x$)/N_y).

The Y isocline has a slope

$$\left.\frac{\partial Y}{\partial X}\right|_{\dot{Y}=0} = \frac{N_y^2 F_{xx} + N_y(V_{xx} - D_{xx})}{N_{yy}(V_x - D_x)}. \tag{9}$$

This slope is generally ambiguous since the signs of ($V_x - D_x$) and N_y are not restricted. Different configurations of the isocline and phase plane arise depending on whether $\overline{X}$ is smaller than, equal to, or greater than X_δ (where $X_\delta = \{X : F_x(X) = \delta\}$) and conditioned on the magnitude of N_y.

Figures 1, 2, and 3 illustrate some of the topologies that can emerge. In these figures, the $\dot{X} = 0$ isocline is the dome-shaped curve, while intermittent curves form the $\dot{Y} = 0$ (harvesting) isocline. There is a notable discontinuity in the Y isocline at $X = X_\delta$. When $\overline{X} > X_\delta$ (Fig. 1), the Y isocline asymptotically goes to infinity (minus infinity) as X approaches X_δ from below (above). These limits are reversed if $\overline{X} < X_\delta$ (Figs. 2 and 3). The discontinuity is attributable to the fact that in Eq. 8, $[\delta - F_x]N_y = 0$, regardless of the value of Y, and $V_x - D_x \neq 0$, unless it coincidentally happens that $\overline{X} = X_\delta$.

The systems illustrated in Figs. 1, 2, and 3 are characterized by three interior steady states, although in general, any number of stationary points is possible.[6]

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[6] Note that in the phase diagrams of Figs. 1 to 3, one can always find a range of stocks for which the slopes of the X and Y isoclines are either both positive or both negative. Furthermore, the harvesting isocline could have a number of inflection points. As a result, any number of steady states is possible. The dynamic properties of any steady state can be determined using the approach discussed below. Note also that large harvesting benefits relative to stock benefits or vice versa can lead to a single interior steady state. Finally, large values of $\overline{X}$ and $\overline{Y}$ can leave the corner pairs $(X, Y) = (0, 1)$ and $(1, 0)$ as the only stationary points.
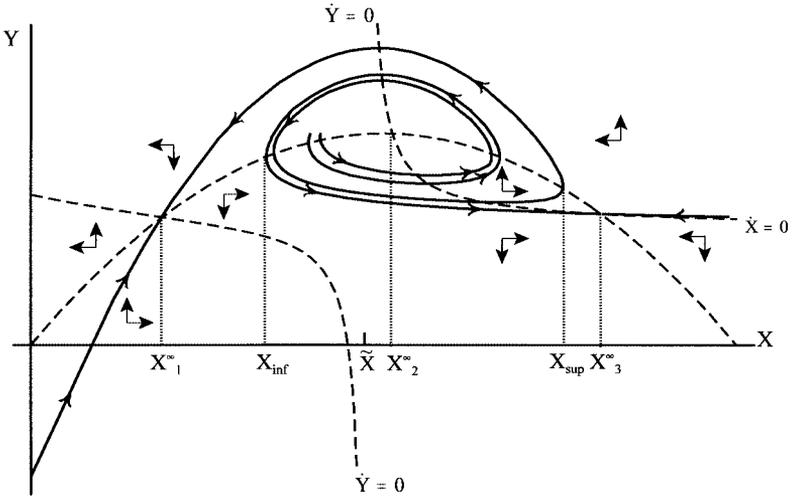
FIG. 2. $\overline{X} < X_\delta$, basins of attraction.

Species are far more likely to generate multiple equilibria if the stock and harvesting benefits are such that $\overline{X} < 1$ and $\overline{Y} < F(X_{msy})$. To see this, note that the pair $(\overline{X}, \overline{Y})$ solves (8) and is therefore located on the harvesting isocline. Note also that the locus of points forming the Y isocline must be located above $\overline{Y}$ everywhere other than for stocks between X_δ and $\overline{X}$. Finally, by virtue of (9), its slope is unambiguously negative between 0 and $\overline{X}$ when $\overline{X} < X_\delta$. Given the limits
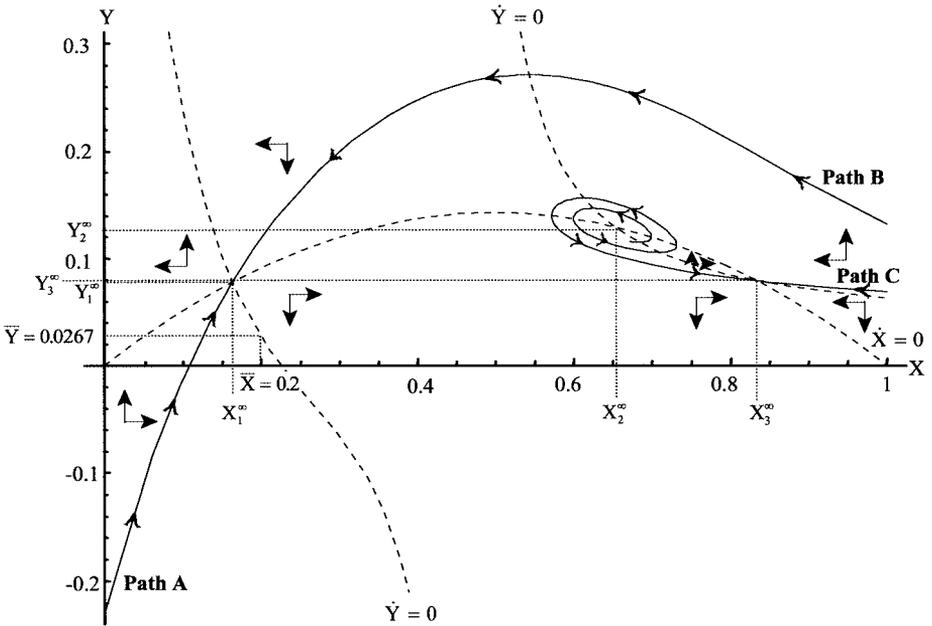
FIG. 3. $\overline{X} < X_\delta$ and calibration results.

of the isocline around X_δ, multiple equilibria emerge in all cases when $\bar{X} < 1$, $\bar{Y} < F(X_{msy})$, and $\bar{X} < X_\delta$; and in most cases when $\bar{X} > X_\delta$ and there is no more than a single inflection point in the Y isocline.[7]

By transformation and linearization, the characteristic roots of the system (2) and (3) are given by $r_1, r_2 = \{\delta \pm \sqrt{\{\delta^2 - 4|\mathbf{J}|\}}\}/2$, where $|\mathbf{J}| = F_x(\delta - F_x) + (D_{xx} - V_{xx} - N_y F_{xx})/N_{yy}$. In this system, determining the sign of the Jacobian requires knowing not only the sign and relative magnitudes of the slope of the isoclines at an equilibrium of interest (X^∞, Y^∞), but also the location of X^∞ relative to X_δ. The slopes are ordered around zero, and the location of $X^\infty$ relative to X_δ determines the sign of $\delta - F_x = (V_x - D_x)/N_y$ (8). For example, if the slopes of the X and Y isoclines are such that

$$F_x > 0 > \left[N_y^2 F_{xx} + N_y(V_{xx} - D_{xx})\right]/\left[N_{yy}(V_x - D_x)\right], \qquad (10)$$

multiplying the left-hand side by $(\delta - F_x)$ and the right-hand side by its equivalent $(V_x - D_x)/N_y$ yields the elements required to sign $|\mathbf{J}|$. If $\delta - F_x(X^\infty) < 0$, then

$$F_x(\delta - F_x) < 0 < (N_y F_{xx} + V_{xx} - D_{xx})/N_{yy} \qquad (11)$$

and $|\mathbf{J}| < 0$. Using (10), we can determine that the characteristic roots are both real with $r_1 > 0$ and $r_2 < 0$, and thus, the steady state is a saddle point.

In other cases, the sign of $\delta - F_x(X^\infty)$ and the relative slopes of the isoclines produce a positive Jacobian. Several types of steady states can then arise. If $d = \{\delta^2 - 4[F_x(\delta - F_x) + (-V_{xx} + D_{xx} - N_y F_{xx})/N_{yy}]\} > 0$, $r_1 > 0$ and $r_2 > 0$, and the solution is an unstable improper node. If $d < 0$, both roots are complex with a positive real part equal to $\delta/2$, and the steady state is an unstable spiral. If $d = 0$, $r_1 = r_2 = \delta > 0$, the equilibrium is unstable, but when a linearized approximation is used, it is not possible to determine analytically with certainty whether it is a proper node, an improper node, or a spiral point [4].[8] Finally, in the absence of discounting ($\delta = 0$), $r_1 = bi$ and $r_2 = -bi$, where $i = \sqrt{-1}$ and b is the coefficient of the complex part of the solution. In this case, the equilibrium of the almost

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[7] The most telling fact about animal populations that produce multiple equilibria is that maximum direct benefits from harvesting are obtained at a catch level below the maximum rate of growth of the stock ($\bar{Y} < F(X_{msy})$). These confer little consumptive benefit on society. Examples of animals that may fall into this category include those for which harvest from the wild only displaces an established supply system (e.g., alligator farming), for which there does not exist a strong market/recreational hunting demand, and for which other factors such as the risks of personal injury from harvesting make their removal very costly (e.g., urban deer), and, finally, species that generate large disutility when animals are killed (e.g., whales). Technically speaking, these conditions reduce the value of the objective function so that for large stocks, the negative shadow price combines with the weight of the law of motion to make the Hamiltonian nonconcave.

[8] The true dynamic properties of the system are dependent on nonlinear terms which are dropped after taking the Taylor series expansion. The linear approximation does not provide an exact configuration of roots, and some indeterminacy exists about the type and stability properties of the stationary points. A proper node is a steady state with linear trajectories leading to it (stable) or projecting from it (unstable). An improper node can have both linear and nonlinear trajectories leading to it (stable) or projecting from it (unstable). Finally, a spiral point (also called a focus) has strictly nonlinear trajectories circumventing the steady state and leading to it (stable) or emerging from it (unstable). See [35, pp. 96–107] for a complete classification of stability properties in systems of differential equations.

linear system is either a center or a spiral point with indeterminate stability property.

Accordingly, the steady states on the far right and far left of Figs. 1, 2, and 3 are saddle points. Steady states at intermediate stock levels are unstable, although whether they are spirals, improper nodes, or nodes depends on particular functional forms and parameter values. In the simulations presented here, numerical computation of eigenvalues shows that the intermediate steady states are unstable spirals.

The diagrams of Figs. 1 to 3 illustrate why Eqs. (1′) to (5) are insufficient to guarantee global optimality. In all three systems, there exists a range of initial conditions from which it is possible to adopt more than one trajectory leading to a steady state (either X_1^∞ or X_3^∞). To discriminate between these competing candidate solutions, we make use of key properties of the maximized Hamiltonian. From our assumptions on $V(X)$, $D(X)$, $N(Y)$, and $F(X)$ and by (1′), (2), (3), and (7), it can be shown that

$$\mathcal{H}(X_0, Y_0)/\delta = (1/\delta)\big\{[V(X_0) - D(X_0) + N(Y_0)]$$
$$+ [N_y(Y_0) + \lambda_0][F(X_0) - Y_0]\big\}$$
$$= \int_0^\infty e^{-\delta t}[V(X(t)) - D(X(t)) + N(Y(t))]\, dt. \qquad (12)$$

Equation (12) states that the net present value of a wildlife management program that respects the maximum principle and converges to a steady state (the right-hand side) is equal to receiving at every instant and the chosen initial control Y_0 (the left-hand side). Intuitively, this result holds because the shadow price μ_0 incorporates the value of all future management actions along the adjustment path. Define $M(X_0, Y_0) = (1/\delta)\{[V(X_0) - D(X_0) + N(Y_0)] + [N_y(Y_0) + \lambda_0][F(X_0) - Y_0]\}$, set $\lambda_0 = 0$ (for an interior path), and take the partial derivative with respect to Y_0:

$$\frac{\partial M}{\partial Y_0} = \frac{N_{yy}[F(X_0) - Y_0]}{\delta} \begin{cases} < 0 & \text{if } Y_0 < F(X_0) \\ = 0 & \text{if } Y_0 = F(X_0) \\ > 0 & \text{if } Y_0 > F(X_0). \end{cases} \qquad (13)$$

The result indicates the effect of increasing the initial rate of harvesting on the net present value of a program leading to a steady state. The direction of this effect is ambiguous: for a given initial stock level X_0, the value of a management plan is decreasing in Y_0 if $Y_0 < F(X_0)$ and increasing if $Y_0 > F(X_0)$. Using the strategies of [65] and [27], we can nonetheless conclude that, in topologies where there is a single spiraling path leading to a steady state (i.e., Figs. 1 and 3), paths originating from the spiral can never be globally optimal. Rather, the efficient program is a monotone separatrix leading to a saddle point.

When competing candidates exist, we conclude by (13) that the path with the most aggressive initial program is optimal. For the situation depicted in Fig. 1, this corresponds to the trajectories leading to X_3^∞.[9] For Fig. 3, the paths to X_1^∞ maximize welfare. In Fig. 2, either saddle point can be reached from initial stock

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[9] It can easily be shown that this result holds if the constraint on the rate of reintroduction is binding in the initial reintroduction phase [55].

levels in the vicinity of X_2^∞. Successive applications of (13) lead to the conclusion that the configuration of Fig. 2 creates basins of attraction. Thus, there exists a stock level $\tilde{X}$ such that $X_{\inf} < \tilde{X} < X_{\sup}$ below which it is optimal to adopt a management plan leading to X_1^∞ and above which welfare is maximized by choosing a program leading to X_3^∞.

6. ALONG THE WAY: PROPERTIES OF AN OPTIMAL POPULATION RECOVERY PLAN

6.1. *Reintroduction and Supplementation*

Under certain conditions preventing the existence of interior steady states, it will not be beneficial to reintroduce an extirpated species to its former habitat. Recall that an interior steady state stock must solve (8). Since neither the harvesting of animals nor their existence is deemed essential ($N_y(0)$ and $V_x(0)$ are finite), and given that $F(\bullet)$ is strictly concave with $F(0) = F(1) = 0$, the marginal benefits from harvesting can take only a limited range of values in the interval $[N_y(0), N_y(F(X_{msy}))]$. If $F(X_{msy}) < \bar{Y}$, then $N_y(F(X)) \geq 0$. It follows that if $V_x(0) - D_x(0)$ is sufficiently small (or even negative), and if the discount rate is greater than the marginal growth rate of the first unit of the stock ($\delta > F_x(0)$), then no interior steady state will exist. By assumption, reintroduction of the first animal is always more costly than the benefits society would receive from harvesting it.[10] With small or negative nonconsumptive benefits and a discount rate greater than the return from the natural growth of a small stock, investing in the stock for future returns is inefficient and it never pays to reintroduce the species.

These conditions closely match the rules under which it is optimal to harvest a species to extinction in pure harvesting models [9–11]. The consistency with previous results should not be surprising since requiring that net marginal nonconsumptive benefits be minimal essentially reduces the problem to an analysis of pure harvesting. The conditions under which reintroduction should not be implemented are also consistent with the result of Olson and Roy [49], who find in a discrete time setting with stock benefits that for monotonic optimal stock programs, global extinction can only be efficient if there is not a strictly positive steady state.

6.2. *Conservation, De-listing, and Controlled Harvesting*

For species worth reintroducing, the initial stocking puts society on a trajectory toward a high (Fig. 1) or low (Figs. 2 and 3) population equilibrium. Over the infinite horizon of the ensuing optimal management plan, the entire panoply of available management tools will be used.

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[10] By construction, $N_y(0) > 0$ and $N_{yy}(0) < 0$. Continuity at $X = 0$ ensures that the marginal cost of reintroduction is greater than the marginal benefits of harvesting the "first" animal. This assumption is supported by the history of species propagation costs. Estimates of the cost of species recovery effort range between \$145,000 and \$154 million per species [5, 45, 46]. Breeding and translocation costs are only part of these expenses but are nonetheless very high [32] and likely exceed the immediate benefits of harvesting.

Y

$\dot{Y} = 0$

$\dot{X} = 0$

$F(X_d)$
$\overline{Y}$

X_d $\dot{Y} = 0$ $\overline{X}$ X^∞ X

Pest Control

Reintroduction

Controlled
Harvesting
(beneficial)

Stocking
program

Net stock
benefits at
their
maximum

Asymptotic
steady
state (unstable)

- De-listing

- No active
  management

- Shadow price = zero
  (changing sign)
- Instant preceding initiation of
  "Pest Control"
- Maximum benefits from
  harvesting
- Value of M(X₀,Y₀) maximized

FIG. 4. Along an optimal wildlife management program.

Figure 4 illustrates an optimal management plan and the series of events and policy shifts that must occur along a recovery path. Beginning at (X_0, Y_0), the costly initial reintroduction and stocking phase is driven by high marginal nonconsumptive benefits and low damage rates. The species' shadow price is positive, resulting in relatively aggressive reintroduction efforts. This stocking phase continues until X_d is reached and the stock is sufficiently large to discontinue supplementation. For a brief instant, the stock is left to natural regulation and should neither be supplemented nor harvested. As the population increases further, however, the population should become the subject of limited profitable harvesting (recreational or commercial). Thus, X_d is a logical stock size at which to remove the animal from the list of endangered species. Even though formal endangered species protection is removed and harvesting is resumed, further growth of the population remains desirable. Care should therefore be taken to ensure that removal rates do not exceed natural growth.

Enforced limits on harvesting may thus be necessary. In Fig. 4, the natural growth of the stock at the time of de-listing $[F(X_d)]$ is greater than $\overline{Y}$.[11] This implies that a monopolist harvester would take fewer animals than natural growth produces. While this results in further stock increases, the optimal harvesting level can only be ensured if the monopolist also captures all stock benefits and damage (in other words, only if the monopolist solves (P)). If benefits accrue elsewhere in the economy, monopoly harvesting would exceed the optimal level because of the failure of the harvester to account for the positive net stock externality. An open access regime would only exacerbate this problem since harvesters would be expected to completely dissipate the harvesting sector rents, killing more than $\overline{Y}$ animals, lowering the stock, and re-endangering the species.

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[11] It is easy to construct an example in which $\overline{Y} > F(X_d)$ that preserves the topology of Fig. 4.

6.3. *Pest Control Measures*: *Switching Shadow Price*

As the stock increases beyond X_d, the limit on harvesting must gradually increase up to the point where $Y = \bar{Y}$ and society obtains the largest possible instantaneous gains from harvesting. Yet, restrictions on harvesting may still be necessary to prevent open access harvesters or individuals who suffer stock damage from harvesting beyond $\bar{Y}$.

Costly population control measures should be initiated at the next instant, even though the nonconsumptive stock benefits of a marginal animal continue to exceed the damage it imposes.[12] It is optimal to initiate pest control before X reaches $\bar{X}$ because the natural growth potential of a marginal animal must be accounted for in determining the rate of harvesting. While the marginal animal would itself yield positive net instantaneous benefits $V_x > D_x$, the prospect of it and its "offspring" inflicting future damage and the cost of controlling a larger population offset current benefits and justify its removal.

There are two interesting technical details associated with the optimal adoption of pest control. From (1′), it coincides with a change in the sign of the shadow price μ. Once the shadow price has signaled the beginning of pest control, society is required to incur control costs forever to lower the growth rate and limit the damage inflicted by animals.[13] The second point is that the stock level at which pest control is initiated corresponds to the herd size that a welfare maximizing manager would select if she were free to choose any initial condition X_0. To see this, consider the change in welfare resulting from a marginal change in initial condition along the optimal path:

$$\frac{\partial M(X_0, Y_0)}{\partial X_0}$$

$$= \frac{1}{\delta}\left\{V_x - D_x + N_y F_x + N_y \frac{\partial Y_0}{\partial X_0} + N_{yy}\frac{\partial Y_0}{\partial X_0}[F(X_0) - Y_0] - N_y \frac{\partial Y_0}{\partial X_0}\right\}.$$

Using (3) and (7) to form an expression for the slope of an interior trajectory $(\dot{Y}/\dot{X})$, substituting and simplifying yields

$$\frac{\partial M(X_0, Y_0)}{\partial X_0} = N_y(Y_0). \tag{14}$$

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[12] Proposition 1 (in the Appendix) establishes this result formally for the case where $\bar{X} \geq X_{msy}$ (Fig. 1). While the proof does not generalize to all possible cases, inspection of Figs. 2 and 3 leads to the same conclusion. In these topologies, the optimal trajectories for a low initial stock never cross the Y isocline, implying that $X(t) < \bar{X}$ for all t since the pair $(\bar{X}, \bar{Y})$ is on the Y isocline and interior to $F(X)$. At the same time, the initial harvesting rate goes from negative to a steady state, $Y_1^\infty > \bar{Y}$ (Proposition 2 of the Appendix). The continuity of the trajectory implies that there exists a finite time when pest control is initiated, even if the instantaneous nonconsumptive benefits from a marginal animal always exceed marginal damage rates.

[13] Public agencies may not actually need to invest public resources in control measures. Private harvesters in open or limited access regimes and those who suffer the stock damage may be prepared to voluntarily harvest beyond $\bar{Y}$. This may limit political opposition to costly population control programs, but the dissipation of potential rents in the harvesting sector or the net control costs of those who face animal damage remain real welfare losses. These approaches simply shift the burden of control costs from society at large to those harvesting the resource. See Zivin *et al.* [70] for a treatment of private control measures.

According to Eq. (14), if it was possible to make a costless change in the initial stock level while remaining on the optimal trajectory, the net present value of the infinite wildlife management program leading to a steady state would change by the value of the marginal harvesting benefits at the initial point. Setting (14) equal to zero and using (1') implies that $\partial M(X_0, Y_0)/\partial X_0 = N_y(Y_0) = 0 = N_y(\bar{Y}) = \mu$. As claimed, the initial stock that would maximize the net discounted value of the wildlife management program is the stock level which corresponds to $\bar{Y}$ on the optimal trajectory.

The intertemporal distribution of costs and benefits is therefore skewed and may hinder the timely implementation of optimal management decisions. The current generation may not wish to incur the cost of reintroduction or supplementation. Alternatively, later generations may find it difficult to begin harvesting and then initiate costly population control activities to slow the rate of growth of an otherwise enjoyable stock level. In both situations, we should suspect that a lack of foresight or conflicts between stakeholders preventing the timely adoption of optimal management actions will leave future generations with too few or too many animals and result in significant opportunity costs. The next section presents a numerical application of the model to deer management. It illustrates the potential magnitude of losses stemming from delaying reintroduction and failing to adopt control measures in a timely manner. It also establishes the policy relevance of the shadow price nonconvexity identified above.

7. REINTRODUCING WHITE-TAILED DEER?

7.1. *Context and Calibration*

Many communities in the eastern and midwestern United States have recently implemented deer culling programs with the objective of reducing the number of car collisions, the amount of damage to trees and gardens, and the incidence of Lyme disease [14, 16, 33, 34, 36, 50]. This is a remarkable turn of events, considering that less than 100 years ago, the white-tailed deer had been extirpated from most places in the northeast. The adoption of the Lacey Act (1900) and of the Federal Aid in Wildlife Restoration Act (1937), the creation of the National Wildlife Refuge (1903) and National Parks (1916) systems, and the spending of millions of dollars in federal and state funds to restore habitat and propagate deer populations were instrumental in ensuring the survival of this species. In light of the damage imposed by deer today (more than \$2 billion per year in vehicle repairs alone), one may question the wisdom of past conservation efforts and wonder whether controls to limit population increases should have been implemented some time ago.

This numerical simulation is inspired by the experience of the town of Irondequoit, New York, a suburb of Rochester, where a (human) population of approximately 53,000 resides. Deer were extirpated from the area at the turn of the century and returned through natural migration in the late 1950s or 1960s. The first signs of trouble appeared in 1974 when damage to a local orchard was reported [26]. The annual number of recorded deer–car collisions in Irondequoit grew steadily from 61 in 1985, when statistics were first kept, to 237 in 1992, when the deer population was estimated at 850 head [47].

In response to public concerns, primarily over the number of deer−car collisions, a citizen task force (CTF) was formed to advise town, county, and state officials on deer management issues within town limits. The CTF assembled 11 members of the community representing animal welfare and conservation groups, as well as citizens advocating a sharp reduction in the number of deer. After several months of deliberation, it adopted a resolution (by a vote of 10 to 1) recommending that the deer population be reduced to a level interpreted by biologists to mean between 10% and 20% of the population at the time. To achieve this objective, a lethal bait-and-shoot approach was recommended with the same vote count [13]. The culling program implemented in Irondequoit is typical: designated areas in large city parks are baited with corn during winter months, allowing sharpshooters with rifles (and a limited number of skilled private archers) to fire at close range from elevated platforms.

These programs are costly because of the security measures required to address obvious safety concerns associated with the discharge of hunting weapons in urban areas. In 1996, removing 66 animals cost $51,904 (Hauber, personal communication). Using this information, $N(Y)$ was calibrated, assuming a quadratic function reaching its maximum at $\bar{Y} = 0.0268$ (representing 23 animals taken by private archers normalized by the carrying capacity of 858 animals). Details of the calibration are presented in Table I. The control benefit function is given by $N(Y) = 470{,}282Y - 8{,}771{,}780Y^2$. Accordingly, net private benefits from harvesting

TABLE I

Model Calibration

Functional form	Parameter values	Source/method
$F(X) = rX(1-X)$	$r = 0.5703$ Normalized for a carrying capacity of 858 animals ($X = 1$ corresponds to 858 deer)	Estimated as a discrete time (annual) change in deer population [47], converted to a differential equation without adjustment for continuous time

$V(X) = p(1 - e^{-gX})$
 $D(X) = mX$
	$p = 594{,}705$; $g = 16.073$
	 $m = 383{,}988$
	 $\bar{X} = 0.2$
		Calculate m based on
		    $\bar{X} = 0.2$ (the upper bound of the CTF recommendation)
		 The annual rate of car collisions is given by
		    Collision $= 223.51X$ [55];
		 The average repair cost per collision $= \$1718$
		    (\$ of 1996) [15].
		 Calibrate $V(X)$ by solving
		    $V_x(\bar{X}) - D_x(\bar{X}) = pge^{-gX} - m = 0$ and
		    $V_x(1) - D_x(1) = pge^{-gX} - m = 1 - m$
		    for p and g

$N(Y) = aY - bY^2$	$a = 470{,}282$ $b = 8{,}771{,}780$ $\bar{Y} = 0.0268$	23 animals taken by hunters ($\bar{Y} = 23/858$) (Hauber, personal communication) An additional 66 deer taken by sharpshooters at a cost of \$51,904 (\$ of 1996) Solve $N_y(\bar{Y}) = 0$ and $N(\bar{Y} + 66/858) - N(\bar{Y}) = -51{,}904$ for a and b
	$\delta = 0.04$	Arbitrary

are estimated at \$274 per animal at the maximum of the function, the marginal benefits from hunting the first animal equal \$536, and the marginal cost of translocating a first deer from another location to Irondequoit would be \$560. This last figure is comparable to the cost of capturing and translocating live deer reported by Ishmael *et al.* [29].

A linear estimate of the relationship between the number of deer and the rate of damage to motor vehicles translates into a damage function $D(X) = \$383,988\,X$ per unit of time [55]. This corresponds to an annual damage of \$448 per deer. The estimated damage function is used in conjunction with the assumptions that $V(X)$ has a Gompertz form and that $\bar{X} = 0.2$ (the upper bound of the CTF population target) to yield a calibration $V(X) = 594,705(1 - e^{-16.073X})$. This translates into total nonconsumptive benefits of approximately \$11,000 for a first animal and \$571,000 for a stock at a target of $\bar{X} = 0.2$ (172 animals). The corresponding willingness to pay for nonconsumptive benefits alone does not appear to be unrealistic at slightly more than \$11.00 per resident (per year).

7.2. *Results*

The graphical representation of the calibrated solution to (P) was previously introduced as Fig. 3. Numerical results are presented in Fig. 5 along with additional graphs that trace the time paths of the state and control variables for trajectories labeled A, B, and C. These adjustment paths are three candidate solutions.[14] For an extirpated species ($X(0) = 0$), path A is the only candidate solution. The efficient management plan calls for the swift reestablishment of a deer population at an initial rate of reintroduction of 0.2298. Aided by rapid natural population growth, supplementation rates optimally decline to zero in less than 1 year before controlled harvesting is introduced. This program converges to the steady state $(X_1^{\infty}, Y_1^{\infty}) = (0.1633, 0.0779)$. While the stock is never allowed to reach $\bar{X} = 0.2$, the optimal control of the population requires the implementation of a costly culling program ($Y > \bar{Y} = 0.068$) less than 6 years following reintroduction. Despite the need for future controls, the reintroduction is clearly worthwhile, providing welfare improvements with a net present value (NPV) of \$11.6 million to town residents.

Paths B and C offer two choices of trajectories for an initial stock $X_0 = 1$. Both involve reducing the deer herd and lie entirely above $F(X)$. Consistent with the analysis presented above (in particular with Eq. 13) the more aggressive program B confers the greatest level of benefits: \$9.08 million on path B to the steady state $X_1^{\infty} = 0.1633$ compared with \$6.29 million on path C to $X_3^{\infty} = 0.8346$. Thus, a policy of aggressive population reduction below the CTF target is desirable. Bringing the population below the maximum of the net benefits function is optimal for the same reason that pest control should be initiated before this maximum is reached: the steady state balances outside opportunity costs against the stock's own rate of

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[14] Results were estimated by numerically solving the system of differential equations backward in time, using Mathematica 4.0. Starting from an arbitrarily small distance $|\epsilon| < 1 \times 10^{-6}$ away from the desired steady state, integrating back until either $X = 0$ or $X = 1$ (depending on the source of the trajectory) permits recovery of the value of $Y(0)$ by interpolation. The NPVs of programs reported in Fig. 5 are then obtained by substituting $X(0)$ and $Y(0)$ in Eq. 12. The programming code is available upon request.

return, which must account for marginal changes in the stock's natural growth rate and the foregone benefits of additional harvesting.

Beyond demonstrating the relevance of the theoretical analysis developed in this paper, the numerical model can also be used to investigate the magnitude of foregone opportunities resulting from the failure to reintroduce when natural recovery is possible, or to adequately control a growing population. In Irondequoit, a minimum of 40 years elapsed between extirpation and natural recolonization. The population then naturally recovered to approximately 850 animals ($X = 0.99$). This scenario, followed by an optimal reduction of the stock (along path B) to X_1^∞, has a NPV of approximately \$1.6 million, or less than 15% of the value of the optimal reintroduction program. Failing to reintroduce a valuable species and to initiate population control measures can therefore result in significant delay costs.

The relative importance of these two sources of inefficiency can be isolated by comparing the following results: 1) The scenario in which natural recovery occurs naturally after 40 years, followed by the adoption of the control Y_1^∞ as soon as X reaches X_1^∞, has a NPV of \$1.9 million. 2) The scenario in which the 40-year wait for natural migration is followed by optimal management has a NPV of \$2.3 million. 3) A program in which the population begins recovering immediately after extirpation and grows naturally to 850 animals before being optimally reduced (along path B) has a net worth of \$7.8 million. Thus, failing to implement a recovery plan has an opportunity cost ranging from 80% to 85% of potential gains, while delays in imposing population control measures result in a loss of approximately 32% of total potential benefits.

8. DISCUSSION

The tale of the Irondequoit deer herd confirms that it may be desirable to implement population recovery plans in spite of the important damage that a growing stock can inflict. The simulation also documents the costs of delaying the adoption of optimal policies.

In many instances, proposals to reintroduce potentially dangerous species pit the beneficiaries of the project (e.g., broad segments of society; environmentalists) against smaller, geographically concentrated groups who stand to bear the costs of animal damage [37, 42, 62]. The protracted debates that ensue have been shown to substantially slow the process of adding species to the Endangered Species List and delay the implementation of population recovery plans [1]. In these conflicts, "people are concerned with the redistribution of wealth in regional conflicts" [5, p. 15] rather than by matters of intertemporal efficiency [60]. Yet, the two are inextricably linked since conflicts stemming from equity issues prevent the implementation of welfare-enhancing programs.

The most infamous example is perhaps the controversy that deferred the reintroduction of wolves to Yellowstone National Park for perhaps as many as 20 years. Duffield and Neher [17] estimated the annualized net benefits of reestablishing wolf populations in Yellowstone at between \$5.8 and \$9.2 million. At the 7% discount rate they use, the delay costs amount to between \$65 and \$97 million.

To resolve conflicts over the reintroduction of dangerous species, it has been argued that those who receive the benefits of species protection should bear its
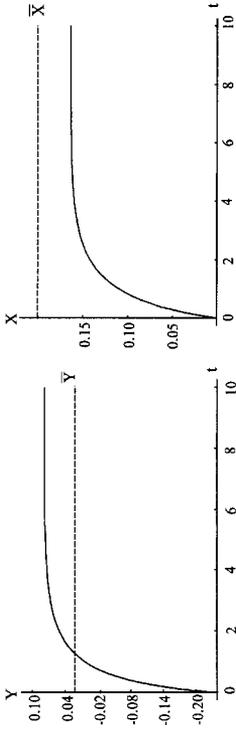
Trajectory A

Initial Conditions:
$X(0) = 0$
$Y(0) = -0.2298$

Steady State:
$X_1^\infty = 0.1633$
$Y_1^\infty = 0.0779$

NPV = $11.57 million

Trajectory B

Initial Conditions:
$X(0) = 1$
$Y(0) = 0.1318$

Steady State:
$X_1^\infty = 0.1633$
$Y_1^\infty = 0.0779$

NPV = $9.08 million
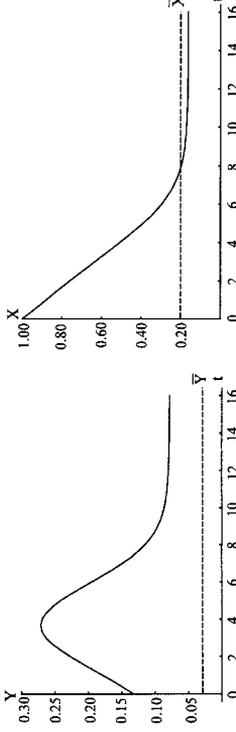
Trajectory C

Initial Conditions:
$X(0) = 1$
$Y(0) = 0.0682$

Steady State:
$X_3^\infty = 0.8346$
$Y_3^\infty = 0.0787$
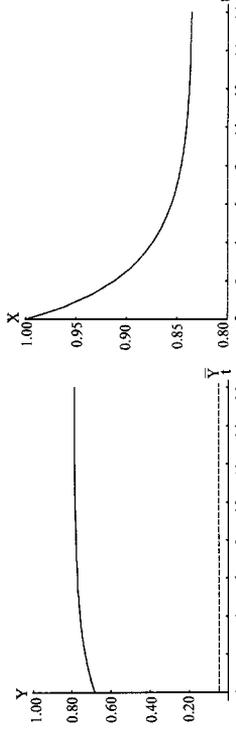
NPV = $6.29 million

FIG. 5. Additional calibration results and time paths.

costs, including those arising from wildlife damage to private interests [25, 28]. The creation of the Defenders of Wildlife's Wolf Compensation Trust has been hailed as a unique example of a market-based mechanism allowing those whose welfare is enhanced by wild roaming wolves to compensate livestock owners for losses due to depredation. The fund is a voluntary Coasian scheme whereby Defenders of Wildlife provides direct compensation to ranchers for confirmed wolf depredation of livestock. The fund undoubtedly fosters a more equitable distribution of the costs and benefits of wolf reintroduction, but it has also been criticized for lacking a legally binding long-term commitment to compensation [3].

The criticism can be traced to two fundamental market failures. The first is a classic public goods problem. Individuals who benefit from wildlife reintroduction can free ride on the contributions of others to the voluntarily compensation fund. This implies that amounts received by compensation funds understate the true benefits of species reintroduction and, at the margin, result in inadequate funding to compensate for wildlife damage. The second market failure relates to the impossibility of setting up legal contracts with and between future beneficiaries and victims of today's conservation efforts. An efficient application of the willingness-to-pay principle and Pareto compensation test would require that future beneficiaries of reintroductions contribute toward the initial translocation and recovery costs and help compensate for later damage.

Resolving the public good failure and alleviating intertemporal constraints may require setting up legally binding government-funded compensation programs [28]. Compensation programs introduce inefficiencies of their own (moral hazard) by reducing the incentives for potential victims to adopt prevention measures [25, 54]. They can also be difficult to implement if claims of losses are not easily verified or assessed. Fortunately, many types of damage by wildlife can be assessed with relative ease and precision. Yet, the U.S. Federal Government has thus far refused to provide compensation for damage caused by the species it protects, and current jurisprudence indicates that it is shielded from being forced to make such payments [3, 7]. While compensation stemming from general conservation practices may not be necessary under current assignments of property rights, the courts have hinted that governments may have ownership responsibilities if the offending animals were deliberately released into the wild after a period of captivity [7]. Thus, reintroduction programs that rely on "skillful capture" and temporary control of animals (e.g., captive breeding) could be required to include a compensation mechanism for damage by these animals and their progeny.

As long as the perverse incentives of compensation are minimal or can be mitigated by appropriate program design, the emergence of compensation programs would be consistent with the willingness-to-pay principle and with rent maximization. Those who benefit from reintroduced wildlife would pay for damage, and a greater centralization of responsibility would put management authority at a level where the broad flow of benefits across society can be accounted for in the decision-making process. This would be consistent with the historical evolution of wildlife (game) laws and policies, which tend to become more centralized when animals and the benefits they confer span large areas and several administrative jurisdictions [40, 41].

However difficult it may be to reconcile differences of opinion on the reintroduction of dangerous animals, finding ways to optimally implement limited harvesting and pest control appears to pose an even greater challenge. Recall that measures

to limit population growth must be initiated at a time when $V_x > D_x$. Thus, even in the absence of conflicts between opponents and promoters of wildlife conservation, a myopic society would not adopt pest control measures in a timely manner. Furthermore, the increasingly successful use of ballot initiatives to impose restrictions on hunting and limit the power of state wildlife management agencies reflects a growing disapproval of animal control measures by large segments of the population [19, 23, 44]. This opposition not only comes from individuals who would benefit from a larger stock, but also from those who suffer a direct loss of utility when animals are killed (e.g., animal rights advocates).

Since claims of losses of nonuse benefits and from the killing of animals cannot be verified, compensation schemes are impractical, and very few alternatives may be available to alleviate conflicts over the removal of animals. One imperfect approach may ironically be to allow takings at the outset under rules similar to those governing the management of experimental populations under the ESA. Defining precise geographical territories where animals can roam free and where, in contrast, they stand to be shot may also be a pragmatic compromise [44].

9. CLOSING REMARKS

Reintroduction attempts and recovery efforts have the explicit objective of establishing self-sustaining population. For species that provide stock benefits but also impose damage, the success of conservation efforts necessarily implies future costs. To study the management of these species, a renewable resource model was developed that allows species reintroduction and other enhancement programs, profitable harvesting, and costly pest control. The model admits a positive or negative shadow price that substantially affects its solution and features prominently in the characteristics of optimal intertemporal management plans.

The theoretical and numerical analysis underscore the importance of timely decision making. The opportunity cost of myopic decisions can be very high, and delays created by an adversarial approach to wildlife reintroduction only exacerbate the magnitude of these loses. Conflicts between supporters and detractors of reintroductions, and between proponents and opponents of population control measures, are not simply matters of concerns over the regional redistribution of wealth; they directly affect the degree of efficiency with which wildlife is managed.

Projected increases in the need for artificial propagation of predators and other dangeous animals alert us to the potential proliferation of these conflicts unless suitable mechanisms are put in place to ease the distributional concerns they raise. Cost−benefit considerations dictate that reintroduction and stocking decisions be made with these long-term consequences in mind. Admitting economic analysis into recovery planning, acknowledging that harvesting and controls may be justified in the future, and, if possible, simultaneously laying out plans for the recovery of small populations as well as for the future management of recovered stocks could only foster efficiency and help diffuse conflicts. Without a more conciliatory approach to species reintroduction and management, we face the threat that natural scientists will avoid initiating recovery plans, discouraged by the prospect of future confrontations over the need to control growing populations [19, 44]. Delays and lost opportunities violate intertemporal efficiency requirements and unduly increase the risk of global extinction of the species involved.

APPENDIX

PROPOSITION 1 (Pest control is initiated prior to X reaching its nuisance level).
*If $\bar{X} \geq X_{\text{msy}}$, the instant T at which pest control is initiated for the first time is
characterized by $X(T) \leq \bar{X}$.*

Proof. Since the globally optimal trajectory is monotone in X, we obtain an
expression for the shadow price by substituting (1) (with $\lambda = 0$ for an interior
trajectory) into (2), multiplying by $e^{-\delta(\tau - t)}$, and integrating over an infinite horizon:

$$\int_t^\infty e^{-\delta(\tau - t)} \dot{\mu} \, d\tau - \int_t^\infty \delta e^{-\delta(\tau - t)} \mu \, d\tau = - \int_t^\infty e^{-\delta(\tau - t)} \left[V_x - D_x + N_y(Y) F_x \right] d\tau.$$

For a trajectory leading to a nonzero steady-state stock level, Eq. 5 implies
$\lim_{\tau \to \infty} \mu(t) e^{-\delta(\tau - t)} = 0$. Using this result in the integration by parts of the first
term simplifies the expression to

$$\mu^*(t) = \int_t^\infty e^{-\delta(\tau - t)} \left[V_x(X^*) - D_x(X^*) + N_y(Y^*) F_x(X^*) \right] d\tau, \quad \text{(A1)}$$

where asterisks denote the optimal trajectory. Now, suppose that the proposition is
false. Then, $X(T) > \bar{X}$, and since $X(0) < \bar{X}$ and the trajectories are piecewise
continuous, there exists an instant $\bar{T} < T$ when $X = \bar{X}$. By (A1),

$$\mu^*(\bar{T}) - e^{-\delta(T - \bar{T})} \mu^*(T)$$

$$= \int_{\bar{T}}^\infty e^{-\delta(\tau - \bar{T})} \left[V_x(X^*) - D_x(X^*) + N_y(Y^*) F_x(X^*) \right] d\tau$$

$$- \int_T^\infty e^{-\delta(\tau - \bar{T})} \left[V_x(X^*) - D_x(X^*) + N_y(Y^*) F_x(X^*) \right] d\tau.$$

By (1) and the definition of T and $\bar{Y}$, $\mu^*(T) = N_y(\bar{Y}) = 0$, leaving

$$\mu^*(\bar{T}) = \int_{\bar{T}}^T e^{-\delta(\tau - \bar{T})} \left[V_x(X^*) - D_x(X^*) + N_y(Y^*) F_x(X^*) \right] d\tau.$$

For all instants from $\bar{T}$ to T, $X^*(t) > \bar{X} \geq X_{\text{msy}}$, making $V_x - D_x < 0$ and $F_x \leq 0$,
and since pest control is initiated for the first time at $t = T$, $Y^* < \bar{Y}$ implies that
$N_y > 0$. Hence, the integral is negative. Along the optimal trajectory, the equality
between the shadow price and the marginal benefits from harvesting implies that
$N_y(Y^*(\bar{T})) = \mu^*(\bar{T}) < 0$ and $Y^*(\bar{T}) > \bar{Y}$. But this contradicts the fact that pest
control is first initiated at $T > \bar{T}$ and that $Y^*(\bar{T}) < \bar{Y}$.   QED

PROPOSITION 2. *If $(\bar{X}, \bar{Y})$ is interior to $Y = F(X)$ in the sense that $\bar{Y} < F(\bar{X})$
(assumption A1), and if $\bar{X} < X_\delta$ (A2), then an interior steady state (X^∞, Y^∞) of the
system (1) to (5) must be such that $Y^\infty > \bar{Y}$.*

Proof. At any interior steady state, facts F1 and F2 hold directly from Eqs. 3
and 8:

F1. $Y^\infty = F(X^\infty)$ and

F2. $N_y(Y^\infty)[\delta - F_x(X^\infty)] = V_x(X^\infty) - D_x(X^\infty)$.

In addition, by Eq. 8, the pair $(\bar{X}, \bar{Y})$ is located on the Y isocline:

F3. $N_y(\bar{Y})[\delta - F_x(\bar{X})] = V_x(\bar{X}) - D_x(\bar{X}).$

Suppose that the proposition is false. Then $Y^\infty \leq \bar{Y}$.

A. Suppose that $Y^\infty = \bar{Y}$. Then, by F2 and F3, it follows that $X^\infty = \bar{X}$ and $Y^\infty = F(\bar{X})$, but this contradicts A1. Therefore, $Y^\infty \neq \bar{Y}$.

B. Suppose that $Y^\infty < \bar{Y}$. Then $N_y(Y^\infty) > 0$. Next, analyze all possible values of X^∞.

B1. Suppose that $X^\infty < \bar{X}$. By A2, we have that $X^\infty < \bar{X} < X_\delta$ and $F_x(X^\infty) > F_x(X_\delta) = \delta$ since $F_{xx} < 0$. It follows that $N_y(Y^\infty)[\delta - F_x(X^\infty)] = V_x(X^\infty) - D_x(X^\infty) < 0$. But this equality requires $X^\infty > \bar{X}$, a contradiction.

B2. Suppose that $X^\infty = \bar{X}$. Then $Y^\infty = F(\bar{X}) > \bar{Y}$ by A1, but this contradicts the fact that $Y^\infty < \bar{Y}$ set in B.

B3. Suppose that $\bar{X} < X^\infty \leq X_{msy}$. By F1 and A1, $Y^\infty = F(X^\infty) > F(\bar{X}) > \bar{Y}$, another contradiction of the assumption that $Y^\infty < \bar{Y}$.

B4. As a last possibility, suppose that $X_{msy} < X^\infty$. Then $F_x(X^\infty) < 0 \leq \delta$. By F2, $N_y(Y^\infty)[\delta - F_x(X^\infty)] = V_x(X^\infty) - D_x(X^\infty) > 0$. This equality requires that $X^\infty < \bar{X} < X_\delta \leq X_{msy} < X^\infty$, a contradiction.

B1 to B4 exhaust all possible values of X^∞ for $Y^\infty < \bar{Y}$ and lead to contradictions in all cases. Hence, it must be that $Y^\infty \geq \bar{Y}$. But we know from A that $Y^\infty \neq \bar{Y}$. Therefore, we conclude that any interior steady state must have $Y^\infty > \bar{Y}$.

<div align="right">QED</div>

LIST OF SYMBOLS

X	the wildlife population stock level
X_0	initial condition on X
$\tilde{X}$	a particular initial population level
$\bar{X}$	maximum of the function $V(X) - D(X)$
X^*	an optimal stock level along a trajectory
X_δ	the stock level such that $F(X_\delta) = \delta$
X^∞	a steady-state stock level
X_{msy}	the stock level that generates the highest instantaneous growth
$\dot{X}$	instantaneous change in X
X_{inf}	a local lower limit stock on a spiraling trajectory
X_{sup}	a local upper limit stock on a spiraling trajectory
Y	the level of harvesting
Y_0	initial harvesting level selected
$\bar{Y}$	maximum of the function $N(Y)$
Y^*	an optimal harvesting level along a trajectory
Y^∞	a steady-state harvesting level
$\dot{Y}$	instantaneous change in Y
Y_{min}	technical constraint on the smallest value Y can take
Y_{max}	technical constraint on the upper bound of Y
t	index of time
τ	index of time

T	instant at which $Y = \bar{Y}$ along an optimal path
δ	discount rate
η	a Kuhn–Tucker multiplier
λ	a Kuhn–Tucker multiplier
ϵ	a small number
μ	the shadow price of X
$\dot{\mu}$	the rate of time change in μ
$\mathbf{J}$	a Jacobian matrix
$|\mathbf{J}|$	the determinant of the Jacobian matrix
$F(X)$	a concave function of the rate of growth of X
$V(X)$	instantaneous rate of nonconsumptive benefits from X
$D(X)$	instantaneous rate of damage from X
$N(Y)$	a concave function of harvesting benefits from Y
$M(X,Y)$	value of the maximized Hamiltonian
$\mathcal{L}$	Lagrangean
$\mathcal{H}$	Hamiltonian
r_1	characteristic root number 1
r_2	characteristic root number 2

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