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Analysis

Real Options for Endangered Species

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ABSTRACT

Endangered species often exhibit low or negative intrinsic growth rates and experience random environmental shocks that can significantly affect population abundance. Geometric Brownian motion has been shown to be a valid model for an endangered species (Dennis et al. 1991). This paper argues that an endangered species should be viewed as a quasi-public good and shows how real option theory can be used to determine the optimal timing of a conservation intervention that might prevent extinction. When a species goes extinct we assume society incurs a biodiversity loss, that can be measured in dollars. Regret is the interest cost on that loss. Social anxiety increases toward regret as the population of an endangered species declines toward extinction. The complete model requires information on (1) the drift and standard deviation rates before and after the conservation intervention, (2) the social cost (anxiety) from endangerment, (3) the fixed and variable costs of the conservation intervention, and (4) the social rate of discount. The model is illustrated with data on the captive breeding program for the California condor.

1. Introduction

The term “anthropocene” has been proposed as a name for our current geological epoch where human activity is changing climate and altering ecosystems. A consequence of this impact has been an acceleration in the rate of extinction of indigenous flora and fauna in terrestrial, aquatic, and marine ecosystems. Kolbert (2014) refers to this acceleration as the “sixth extinction,” and after reviewing the scientific literature predicts that 20% to 50% of the currently existing plant and animal species will be extinct by the end of the 21st century.

Weisbrod (1964) viewed the provision of certain “quasi-public goods” (for example, parks and hospitals) as not only providing benefits to the users of those goods, but also providing *option value* to current nonusers who may want or need the services of those goods in the future. Weisbrod's insight led to a series of articles seeking to refine the nature of option value as it related to irreversible development, as in Arrow and Fisher (1974), and the expected value of information when making irreversible decisions that pose a risk of future environmental damage, as in Conrad (1980).

Should an endangered species be regarded as a quasi-public good? Pure public goods are typically characterized as being “non-rival and non-exclusionary” in their provision of social benefit. An endangered species can provide at least two benefit flows. The first is through wildlife observation. The benefit of observation today can be limited to individuals who pay an admission fee to a park or tour a operator and can be exclusionary. The second benefit flow is existence value, the positive utility obtained by individuals who are unable or unlikely to observe an endangered species in the wild, but who want to preserve the option of observation (in the wild) for future generations. Existence benefits are non-rival and non-exclusionary, similar to a pure public good. Because one benefit flow (observation today) can be exclusive, but the other benefit flow (existence value) is non-rival and non-exclusionary, we argue that an endangered species should be viewed as a quasi-public good.

Consider the North Atlantic right whale and the black rhino, both critically endangered species. The remaining population of the North Atlantic right whale (*Eubalaena glacialis*) is estimated to be about 400 individuals. Observation is exclusive to those willing to pay the price of a whale-watching tour, but the existence value from actions and policies to reduce right-whale mortality from ship strike are non-exclusionary and shared among all humans concerned about right whale survival.

The black rhino (*Dicero bicornis*) is found in southern Africa and is the target of international poaching syndicates. The remaining population, estimated to be around 2300 individuals, is distributed across both national parks and private game preserves. Observation of the black rhino is restricted by entrance fees, but the existence value from increases in rhino abundance resulting from anti-poaching patrols is both non-rival and non-exclusionary.

The literature on the economics of endangered species is relatively sparse. Weitzman (1992, 1993) developed a theory of diversity and applied it to the conservation of the 15 extant species of crane, many of

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which were endangered. Weitzman's theory of diversity was based on the genetic distance between a species and its next closest living relative, as portrayed in a maximum-likelihood, taxonomic tree. The diversity value of a species was determined by its genetic proximity to other extant species within its clade (its branch in the taxonomic tree) and the probability of extinction faced by both that species and its closest living relative. An endangered species that was genetically close to an abundant species (with a low probability of extinction) was less valuable than an endangered species with no close relative and whose extinction would result in the irreversible loss of an entire clade.

Perhaps the closest "relative" to this paper is Ben Abdallah and Lasserre (2012) who take a real option approach to the use of habitat critical to the survival of an endangered species. They specifically consider a commercial activity, logging, which adversely affects the habitat for caribou, an endangered species in Central Labrador, Canada. Their model builds on the important paper by Dixit (1989) which identified critical price triggers for the entry or exit of a firm into an industry. Now, the habitat needed for survival of the endangered species evolves stochastically, declining in expectation when logging is allowed, but increasing in expectation when logging is banned. Instead of price triggers that determine the entry and exit of a firm in an industry, habitat triggers (perhaps measured by the area of suitable forest) determine when it is optimal to allow logging and when logging should be banned. The optimal habitat triggers depend on the parameters of two mean-reverting processes that govern the evolution of habitat (with and without logging), the social value of the endangered species, the net revenue from logging, and the social rate of discount. The model also allows one to compute the expected length of time when logging would be allowed and the expected length of time when logging would be banned.

The current paper differs from Ben Abdallah and Lasserre (2012) and previous work in ecology in that it introduces an "anxiety" function that measures society's concern over the declining abundance of a single endangered species. As abundance declines, anxiety grows. Anxiety is a social cost. Extinction, if and when it occurs, results in "regret" at each instant for the rest of time. Introducing anxiety and regret into a model where the dynamics of an endangered species can be approximated by geometric Brownian motion (as in Dennis et al., 1991) allows one to determine the optimal population size when a conservation intervention, say captive breeding, should be undertaken. The intervention has the ability to alter the mean drift and standard deviation rates of the stochastic process determining the abundance of the endangered species. Increasing the intrinsic growth rate or reducing the standard deviation rate will increase the modal time to extinction. Captive breeding programs or other conservation interventions are costly, and the optimal population size that triggers intervention will depend on the mean drift and standard deviation rates, both before and after intervention, the anxiety function, the cost of intervention, and the social rate of discount. The key research question becomes "What is the population level that triggers a costly conservation intervention which might prevent the extinction of an endangered species?"

The rest of this paper is organized as follows. In the next section we review extinction metrics when the abundance of an endangered species evolves according to geometric Brownian motion (GBM). In Section 3, we introduce our anxiety function, derive its properties as the abundance of an endangered species declines, and posit the existence of regret if the species goes extinct. In Section 4 we develop the real option model which allows one to determine the critical level of abundance when a costly conservation intervention should be undertaken.

In Section 5, we apply our real option model to historical data for the California condor (*Gymnogyps californianus*). The remnant wild population of California condors, which had declined to 22 individuals, was captured in 1987 and transported to zoos in San Diego and Los Angeles where captive breeding programs had previously been established, in 1984. The success of the captive breeding program allowed the reintroduction of eight captive-reared condors in southern California in 1992. Since then, the California condor has been successfully reintroduced at the north rim of the Grand Canyon in Arizona, the Baja Peninsula in Mexico, and the Pinnacles National Park and the Big Sur, both in central California. Section 6 concludes with a discussion of conservation options when there are multiple, but isolated, meta-populations of an endangered species.

2. Geometric Brownian Motion as a Model for the Dynamics of an Endangered Species

Dennis et al. (1991) view extinction as a chance event. At low population levels, a random environmental shock that reduces survival might be sufficient to induce species extinction. Starting from a low level, the stochastic evolution of species abundance is unlikely to exhibit the compensatory effect of carrying capacity, which at higher levels of abundance might reduce the proportional growth rate. Let $N = N(t)$ denote the population abundance of an endangered species at instant t. The model of logistic growth, where $dN/dt = \dot{N} = rN(1 - N/K)$, has parameters $r > 0$, the intrinsic growth rate, and $K > 0$, the environmental carrying capacity. The proportional rate of growth is defined as $\dot{N}/N = r(1 - N/K)$. When N is positive but small relative to K, so that $N/K \approx 0$, $\dot{N}/N \approx r$, while as $N \to K$, $\dot{N}/N \to 0$. For an endangered species, far below current carrying capacity, but subject to random environmental shocks that affect survival, GBM where

$$dN = rNdt + \sigma N dz \tag{1}$$

can provide a good first-order approximation to population dynamics as also discussed by Lande and Orzack (1988). In Eq. (1), r is once again the intrinsic growth rate, which for an endangered species might be negative, $\sigma > 0$ is called the standard deviation rate, and $dz = \epsilon(t)\sqrt{dt}$ is the increment of a Wiener process where $\epsilon(t)$ is a standard normal random variate. $N(t)$ will be log-normally distributed with an expected value at $t > 0$ of $\mathbb{E}[N(t)] = N(0)e^{rt}$ and a variance of $\mathbb{V}[N(t)] = N(0)^2 e^{2rt}(e^{\sigma^2 t} - 1)$.

If we define $x = x(t) \equiv \ln N(t)$, where $\ln(\bullet)$ is the natural log operator, then Itô's Lemma implies

$$dx = (r - \sigma^2/2)dt + \sigma dz \tag{2}$$

and $x(t)$ will be normally distributed with $\mathbb{E}[x(t)] = x(0) + \mu t$ and a variance $\mathbb{V}[x(t)] = \sigma^2 t$, where $\mu = r - \sigma^2/2$. Tuljapurkar (1989) has shown that Eq. (2) can provide a good statistical approximation to the behavior of the stochastic Lewis–Leslie model when age-specific fecundity and survival rates are drawn from independent multivariate distributions.

The normal distribution for $x = x(t)$, with the variance increasing linearly in time, implies that x could potentially cross any lower threshold, x_e, starting from $x_0 = x(0) > 0$. If $N(t) = 1$ implies extinction, then $x_e = \ln(1) = 0$ can be regarded as the extinction threshold. Denoting $x_d = x(0) - x_e$ as the current distance from the extinction threshold, Lande and Orzack (1988) show that the probability that $x(t)$ will reach x_e is given by

$$\pi(x_d, \mu, \sigma^2) = \begin{cases} 1, & \text{if } \mu \le 0 \\ e^{-2\mu x_d/\sigma^2} & \text{if } \mu > 0 \end{cases} \tag{3}$$

Conditional on all sample paths (realizations) that reach the extinction threshold, the amount of time, τ, before the threshold is first reached (first-passage time) is a positive, real-valued, random variable with a cumulative distribution that can be written in terms of the cumulative normal distribution and is given by

$$Pr[\tau \le t] \equiv G(t; x_d, \mu, \sigma^2) = \Phi\left(\frac{-x_d + |\mu|t}{\sigma\sqrt{t}}\right)(1 + e^{2x_d|\mu|/\sigma^2}),\ 0 < t < \infty. \tag{4}$$

where $\Phi(\bullet)$ is the normal cumulative distribution function (cdf). The probability density function (pdf) of this distribution is given by $\partial G(\bullet)/t$ and takes the form