Optimal management of renewable resources with Darwinian selection induced by harvesting ☆

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ABSTRACT

We present a bioeconomic analysis of the optimal long-term management of a genetic resource in the presence of selective harvesting. It is assumed that individuals possessing a particular gene have a lower natural mortality rate and are more valuable to capture. Highly selective harvesting may cause such a gene to lose its fitness advantage, and hence change the evolutionary path of the species. Results indicate that in a zero-cost harvesting regime, the decision to preserve the valuable gene depends on the natural rate of selection against less valuable individuals and the interest rate. On the other hand, the decision to let the less valuable gene become a significant fraction of the genes depends only on biological parameters. If marginal costs are positive, it is never optimal to let a valuable gene become extinct. Further, for some parameter values, the system exhibits multiple equilibriums. Therefore, optimal regulation may depend on initial conditions.

For decades, biologists have been aware of the possibility that selective harvesting could alter the genetic pattern of a resource [12]. Recent empirical evidence suggests that this effect is substantial [4,5,11,14,21] and that this issue deserves more attention from resource economists. Potentially, substantial value may be lost in terms of resource rents if genetic resources are not considered in the management of renewable natural resources.

In principle, all nonrandom harvesting will result in some degree of genetic selection. Two important cases of selective harvesting have received recent attention in the literature: trophy hunting and selective fishing. First, trophy hunters have preferences for specific physiological traits in their prey, such as body size or the size of antlers or horns [10]. Other examples of the effects of hunting on gene frequencies are provided by [12,15,17,26,30,31]. Second, there is the selective nature of commercial fishing, which often targets traits such as catchability or size, as discussed in Refs. [5,11,13,14]. Some of these papers have examined the implications of selective harvesting for optimal resource management and maximum sustainable yield (MSY) [13]. However, as MSY can be a desirable goal only if the opportunity cost of capital is zero, it may result in misleading policy recommendations [27].

The management of genetic resources has received some attention in the resource economics literature. First, some authors have discussed the management of genetic resources as an integral part of biodiversity. Refs. [33,34] assigned benefits to genetic variation, whereas Refs. [24,25] considered how to value these benefits and how to regulate ecosystems with diversity measures as policy objectives. Second, Refs. [18,19] modeled the evolution of resistance to pathogens.

However, the genetic models used in these papers are somewhat more suitable to organisms that reproduce nonsexually as the models are not directly rooted in the Mendelian genetics of sexually reproducing species. Third, Ref. [2] modeled the economic value of genetic diversity through the value of the services provided by the genes. This is a model where a pest may develop resistance to agricultural commodities that are genetically modified to be pathogenic to the pest. The model used in Ref. [2] explicitly assumed sexual reproduction.

To a large extent, managing genetic resources in nature is equivalent to managing genetic selection and evolution. Therefore, a suitable model must have a population genetics component. In this paper, we examine the optimization problem of a resource manager faced with a biological resource, the value of which depends on the genetic composition of the individuals in the resource. We introduce a genetic model into a classic bioeconomic model to analyze the effect of selective harvesting on genetic frequency for one specific gene in terms of the socially optimal, long-term management of the resource. This objective depends solely on the profits generated by harvesting, given selective harvesting. Models of harvesting-induced selection for animals must recognize that harvesting of sexually reproducing species occurs and that it requires the use of genetic models of sexual reproduction, which unfortunately implies complicated nonlinear models. The model presented here is, to our knowledge, the first economic model to examine the effect of selective harvesting on the genetic configuration of the harvested species and the second, after Ref. [2], to explicitly consider the genetics of a sexually reproductive species. Our model shares some features with Ref. [2] in that we both present a model where a sexually reproducing species is subject to genetic selection mechanisms. Our model differs from Ref. [2] in that we combine the genetic model of the species with a population model of the species that is subject to selection.[1] In addition, our work differs from the previous literature in that we emphasize the possibility and implications of multiple equilibria in the management of genetic resources.

Our model may be thought of as describing the optimal management of a pelagic fishery, involving fish such as capelin or anchovy, mainly used in the production of fishmeal. Fishmeal is an important ingredient in feed for poultry, pigs and carnivorous farmed fish such as salmon, and has proven to have few substitutes. However, regardless of the increasing demand for fishmeal, the world catch has not increased over the past 20 years, and has in fact been declining in the past few years [16]. This indicates that world pelagic fish stocks are under considerable harvesting pressure. In general, there has been widespread concern among scientists regarding harvesting pressure and the consequences that it has for biodiversity and ocean ecosystems [22,36].

An individual capelin or anchovy is small and its market value is low. However, pelagic fisheries are profitable owing to the tendency of pelagic fish to form large groups, known as schools, which permits the simultaneous capture of large numbers of individuals. In fact, it is unlikely that commercial harvesting would be possible if schooling did not occur. These schools represent adaptations to the natural environment where the individuals in schools obtain advantages such as less energy use and reduced mortality [23]. Although the schooling behavior reduces mortality in the absence of fishing, fishing may negate this advantage and cause a reduction in the frequency of genes that control schooling behavior. For simplicity, we assume that the behavioral impetus to form schools is controlled by variations in a single gene. Our model addresses the question of how to manage such a resource, given that there exists a mutated gene, which suppresses the behavioral impulse to form schools. This interpretation allows an analytically tractable model that is also relevant to important real-world resource management problems.

The topic necessitates some use of nomenclature that may be unfamiliar to some economists, so a brief glossary is provided in Appendix A.

1. A model with population and genetic dynamics

1.1. Population dynamics

Consider a population with two phenotypes, labeled "bad" (B) and "good" (G). The B phenotype is labeled "bad" as it is assumed that fish of this type have no harvest value. The G phenotype is labeled "good" because fish of this type have economic value to fishermen.[2] The biomass of each phenotype at any given time is given by x_i, $i = G, B$. Total biomass is given by $x = x_G + x_B$. The population dynamics of each phenotype is assumed to be driven by the following differential equations:

$$\dot{x}_i = r_i x_i \left(1 - \frac{x_G + x_B}{K}\right) - \delta_i x_i - h_i, \quad i = G, B. \tag{1}$$

Here, r_i and δ_i are the growth rate and the mortality rate, respectively, with both being positive parameters, K is the carrying capacity and h_i is harvesting of biomass belonging to phenotype i. The total change in biomass is given by $\dot{x} = \dot{x}_G + \dot{x}_B$. We want to consider the regulation of the population when different phenotypes have a different biological productivity. It is assumed that phenotype B is biologically less productive than phenotype G. We model this by assuming that $r_B = r_G = r$ and

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[1] In Ref. [2], there is a population dynamics model of plants, but there is not one of the pest.

[2] There are two sets of assumptions that could lead to this particular phenotype. One can assume that the price of the bad phenotype is zero and that no individuals of this phenotype are caught as bycatch. Alternatively, one can assume that the catchability coefficient of the bad phenotype is zero. It is the latter interpretation that is intended here.