Using Land as a Control Variable in Density-dependent Bioeconomic Models

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February 2002

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Abstract

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The bioeconomic analysis of endangered species without consumptive values can be problematic when analysed with density-dependent models that assume a fixed environment size. Most bioeconomic models use harvest as a control variable, yet when modelling non-harvestable species, frequently the only variable under control of conservationists is the quantity of habitat to be made available. The authors explore the implications of this in a model developed to analyse the potential population recovery of New Zealand's yellow-eyed penguin. The penguin faces severe competition with man for the terrestrial resources required for breeding and has declined in population to perilously low levels. The model was developed to estimate the land use required for recovery and preservation of the species and to compare the results to current tourism-driven conservation efforts. It is demonstrated that land may serve as a useful control variable in bioeconomic models and that such a model may be useful for determining whether sufficient incentives exist to preserve a species. However, the model may generate less useful results for providing a specific estimate of the optimal allocation of land to such a species.

1. INTRODUCTION

The modelling of endangered species has developed principally out of the literature of fisheries economics. For example, Clark (1973) bases his model of species extinction on Gordon's (1954) seminal fisheries model in order to examine the conditions under which the elimination of a species may appear to be the most attractive policy to a resource owner. This work forms the foundation of much of the species extinction modelling that has followed.

More recently, Swanson (1994) examines ways of making this model more readily applicable to terrestrial species by generalising the analysis to consider terrestrial resource allocations. He provides a theoretical framework for the economics of extinction that considers the elimination of species as a result of human choice into which resources they hold. Swanson argues that mankind has a 'portfolio' of productive assets and that substitutions are made between those assets (less productive assets being replaced by more productive assets) through a process of investment and disinvestment.

The marginal productivity of a biological asset generally declines as population levels approach carrying capacity, so there is typically some identifiable optimal level of species stock. Whenever returns to the asset are less than the market rate of return, disinvestment will occur. In the case of endangered species, this disinvestment often takes the form of the reallocation of the primary resources required for species survival.

Swanson's model implies that the stock of a particular resource will move to the level that equates its rate of return to the rates of return of other competing assets in our portfolio. Extinction is seen as a complete disinvestment of a wildlife resource, which occurs because it is perceived as not being worthy of investment (*see also* Swanson and Barbier, 1992).

These and similar models have generated important insights into the behaviour exhibited by resource managers, property owners and harvesters of open-access resources, but they are limited in the characteristics of species to which they apply. For example, both the Clark and Swanson models consider only the consumptive value of the species in question. Models have been developed that add tourism value and even existence value, but they are still driven by harvest, both as a principle means of value generation and as the variable through which

a population is controlled by resource managers (see, for example, Bulte and van Kooten, 1999; Alexander, 2000).

While there are a great many species for which these approaches do apply, there are many others for which they do not. The question arises as to the applicability of such bioeconomic models to species for which there is no harvest value. In such a case, we must consider 1) the nature and magnitude of values generated by the species, and 2) the nature of the control humans exercise over that species. The purpose of this article is to examine the affect on the standard bioeconomic model of changing the model assumptions such that value arises only from non-consumptive uses and that, while growth may be density-dependent, land is the variable we control and so is not fixed.

New Zealand's yellow-eyed penguin (*Megadyptes antipodes*) is used as a case study to examine these issues. The yellow-eyed penguin is not harvested, but does generate some significant tourism value. The decline of the species arises principally from loss of terrestrial habitat, for which they compete with domesticated agricultural species. The yellow-eyed penguin nests under brush on land within a kilometre of the ocean. When that land is cleared for pasture, the penguin has nowhere to breed and raise its young. Thus, the control humans exhibit over the penguin is not in directly adding or removing stock, but in the provision of land needed for nesting.[1]

Section 2 provides a brief review of some classic and recent density-dependent bioeconomic models. The development of the non-harvest species model is shown in Section 3. Finally, some general implications and conclusions are discussed in Section 4.

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[1] Predation from exotic species is also an issue in the decline of yellow-eyed penguin numbers, but will not be addressed in this article. As penguin predators tend to favour the pasture-bush boundary over pure native bush, land conversion introduces both effects simultaneously.

2. HARVEST MODELS OF EXTINCTION

A Sole-Owner Fishery Model

The Clark model explains the possible extinction of species as resulting from three factors: (1) open access to the resource, which results in overexploitation of the resource and the driving of economic rents to zero; (2) the relationship between price and marginal cost of harvesting the resource; and (3) the growth rate of the resource is low relative to the discount rate (Clark, 1973; *see also* Clark, 1976; Clark and Munro, 1978; Clark *et al.,* 1979).

If either condition one or conditions two and three are met, then resource extinction may result. Condition 1 illustrates the well-known *tragedy of the commons* result in which the discount rate facing each harvester is infinite. Any stock not harvested by one individual is harvested by another, so no incentive exists for husbandry of the resource. Regarding conditions two and three, Clark adds, "if price always exceeds unit cost, and if the discount rate…is sufficiently large, then maximisation of present value results in extermination of the resource."

The Clark model provides a societal objective of maximising the appropriated return from its natural assets as follows.

$$\max_{h} \int_0^{\infty} e^{-\delta t} \left[p\big(h(t)\big)h(t) - c\big(x(t)\big)h(t) \right] dt \tag{1}$$

$$\text{s.t.} \quad \dot{x} = F\big(x(t)\big) - h(t),$$

where *x(t)* is the population of the endangered species in time *t, h(t)* is the harvest of the species in time *t, p(h(t))* is the inverse demand curve defined as a function of harvest, *c(x(t))* is the unit cost of harvest as a function of the stock level, *F(x(t))* is the growth function of the resource as a function of stock, and δ is the marginal returns to capital in the society. For notational convenience, the time notation will be omitted from this point on, but it is understood to be implicit in all control and state variables.

To maximise its investment in this resource as well as in the other resources available, society balances the level of each resource against other productive opportunities in its 'asset portfolio'. When modelled in an optimal control framework, a set of Pontryagin necessary conditions is derived for maximisation

of the objective function. The condition associated with optimal harvest (h^*) is shown in equation (2) and that associated with optimal Stock levels (x^*) is shown in equation (3).

$$\lambda = p\left[\frac{1}{\varepsilon_d} + 1\right] - c\,, \qquad\qquad (2)$$

$$\delta = F'(x) - \frac{c'(x)h}{\lambda} + \frac{\dot{\lambda}}{\lambda}\,, \qquad\qquad (3)$$

where λ is the shadow value of the resource, and ε_d is the elasticity of demand for the resource.

Equation (3) represents a modified form of the *golden rule* condition common in renewable resource models. In its unmodified form, the golden rule condition would indicate that the stock level of the resource be maintained such that the marginal growth rate of the renewable resource stock, *F'(x)*, is equal to the returns to the resource owners opportunity cost of capital, δ.

This relationship suggests that if *F'(x)* < δ for all population levels, *x*, then extinction will result as the model's optimum strategy for the resource owner. Only if *F'(x)* = δ at some positive population level do incentives exist to maintain a positive population at equilibrium. Modifications to the golden rule equation, such as those in equation (3), may hinder or help the slow growth species as it attempts to 'pay its way' as a competitive resource. In this case, modifications include the effects of stock-dependent harvest costs, $-\dfrac{c'(x)h}{\lambda}$, and of the proportional rate of change to the value of the stock, $\dfrac{\dot{\lambda}}{\lambda}$.

A Terrestrial Model

In his 1994 paper, Swanson proposes amendments to Clark's fishery-based model by including the allocation of terrestrial resources required for a species' survival. Swanson points out that, while humans do not compete for many of the ocean resources used by marine species, they do compete for the same land-based resources used by terrestrial endangered species. Thus he argues that terrestrial species must not only generate growth in value to compete with other capital

opportunities, they must also generate growth in value to compete with the opportunity costs of the resources they need for survival.

To address this, Swanson adds another control variable to the problem, which represents the land resources allocated to a species as shown in equation (4) below:

$$\max_{h} \int_0^\infty e^{-\delta t} \left[p(h)h - c(x)h - \delta \rho_R R \right] dt \tag{4}$$

$$\text{s.t. } \dot{x} = F(x; R) - h,$$

where R is a unit of terrestrial resources upon which the species depends for survival, and ρ_R is the price of a base unit of that land resource. This method discards the assumption, implicit in fisheries-based models, that a species' required resources are free goods that do not require investment. This generates one of Swanson's "alternative routes to extinction" through the addition of another first-order condition.

$$\delta = \frac{\lambda F_R}{\rho_R} \tag{5}$$

Similar in concept to the golden rule equilibrium discussed above, this condition requires that land-based resources be allocated to a species only in proportion to its ability to generate a competitive return. Note that this condition is in addition to those shown in equations (2) and (3) above. When taken together, these conditions offer some further insight into the issues surrounding species extinction. In particular, it is shown that, even when Clark's conditions are not met—that is, when growth rates are greater than the discount rate or when unit price is less than unit cost— a species may still move toward extinction if it does not provide a competitive return for the natural resources it requires for survival.[2]

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[2] Swanson also introduced a similar condition, not considered here, requiring returns to management services.

Adding Non-consumptive Values

An important limitation of both the Clark and Swanson models is that each of them considers only the consumptive value of the species in question;[3] that is, under both frameworks the species must be harvested for any benefits to be realised. Yet many endangered species, such as the yellow-eyed penguin, have no harvest value. The models we have just seen would imply that such a species has no value as a resource since it is not harvested for commercial purposes.

Alexander (2000) explores the potential for representing non-consumptive values of wildlife resources, using a framework arising from the Clark and Swanson models. The model hypothesises an objective function of a society maximising net social welfare by including terms to express the non-consumptive existence and tourism values of the African elephant (Loxodonta africanus). Acknowledging these non-consumptive values provides added incentives for mankind to include such species in our asset portfolio. The problem, though, is one of appropriation, as not all of these values are actually appropriated in practice.

In a simplified analytical form of the model, the societal objective with regard to elephants is shown in equation (6),

$$\max_{h} \int_0^{\infty} e^{-\delta t} \left[\left(P_M + P_I + P_S - C(x) \right) h + P_U U(x) + N(x) - P_R R x \right] dt \tag{6}$$

s.t. $\dot{x} = F(x) - h$

where x is the elephant population, h is harvest, P_M is the value of the non-ivory products of harvest, P_I is the value of ivory per animal, P_S is the per animal value of safari hunting, $C(x)$ is the unit cost of harvesting, P_U is the unit price of one tourist day, $U(x)$ is tourist days as a function of population, $N(x)$ is the non-market existence value of elephants as a function of population, P_R is the unit value of land resources used by elephants, $R \cdot x$ is quantity of land resources used by elephants as a constant proportion of population, and $F(x)$ is the growth rate of the elephant population.

Note that, unlike the terrestrial model and the model developed in this paper, land resources allocated to elephants are not expressed as a control variable.

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[3] At one point, Swanson does describe the benefits in a more general sense as the "flow of social benefits," but still expresses them as a function of harvest.

Rather, it is suggested that, if society is subjected to the appropriate incentives (including the appropriation of the aforementioned tourism and existence values), then the market will, of its own accord, transfer such land resources from alternative uses.

Using the Pontryagin conditions for maximisation of this problem, a new version of the *golden rule* equation is derived as shown in equation (7).

$$\delta = F'(x) + \frac{-C'(x)F(x) - P_R R + P_U U'(x) + N'(x)}{P_M + P_I + P_S - C(x)} \tag{7}$$

The LHS and the first term on the RHS carry the same *golden rule* interpretation as in the sole-owner fishery model. All other terms on the RHS modify that relationship. The modifications take into account the stock-dependent terms of the original objective function, all expressed in proportion to the unit net revenue of harvesting the resource.

The first modification term, $C'(x)F(x)$, represents stock dependent costs and acts to increase equilibrium populations.[4] The second term, $-P_R R$, acts to lower the effective marginal productivity of the stock by requiring the stock to meet the proportional returns to land available from the next best opportunity. The third term is the marginal revenue from tourism. This is one way in which the total value people place on elephants is expressed in the market. These revenues act to support the existence of the elephant as it competes against other opportunities in society. The fourth term is the marginal existence value, aside from any use value (either harvest or tourism), that people place on knowing elephant species continues. As used in this model, it actually represents the marginal existence value that is appropriated by the resource owner, but of course few of those actually are appropriated.

Inclusion of these non-consumptive values of a wildlife resource provides a fuller picture of the social benefits of maintaining that resource. It illustrates the tourism values, which require no harvest of the species, and the existence values, which are not accounted for in organised markets. These two types of values become particularly important when considering a species with no commercial consumptive value.

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[4] $C'(x) < 0$, rendering the term positive.

3. MODELLING NON-HARVESTED SPECIES

The modelling of a species such as the yellow-eyed penguin is a logical next step in the process that has just been illustrated. Endangered species modelling began with Clark's fisheries model, which was then modified by Swanson to incorporate the importance of terrestrial resource allocations. Alexander extends this framework to include non-consumptive values of wildlife resources and now we consider a species with no consumptive potential at all. Of course, these three models do not, in any sense, provide a comprehensive review of the bioeconomic literature on extinction. Rather, they define something of the conceptual evolution that lead to the questions addressed in this paper.

The principle cause of the reduction in yellow-eyed penguin populations is the conversion of nesting habitat into farmland. This has resulted in increased predation of the penguin and disturbances to nesting, breeding and rearing habits.

Naturally, the conversion of such land is not intended to harm the penguins; their fate is incidental. The land in question has simply been put to its perceived most productive use, as the economic incentives faced by landowners dictate their choices.

The obvious questions, then, are what needs to happen if the yellow-eyed penguin is to avoid extinction, and can a bioeconomic model predict whether human behaviour is likely to act for or against eventual extinction without external intervention?

We attempt to answer these questions with a new bioeconomic model in which the objective function represents the net returns to society, the value to be maximised, and the constraint represents the change over time of penguin populations, as a function of the current population and the land resources available. Many of the terms of a standard bioeconomic model no longer apply, so this model is significantly different from those reviewed above. The goal of a society with regard to the values derived from the yellow-eyed penguin is expressed by the following objective function and constraint,

$$\max_{L} \int_0^\infty e^{-\delta t} \left[P_T T(x) \cdot L - C_L \cdot L - C_O \cdot L \right] dt \tag{8}$$

$$\text{s.t. } \dot{x} = F(x, L),$$

where x is the population of yellow-eyed penguins, P_T is the price of one tourist visit to see wild penguins, $T(x)$ is the total number of tourist visits as a function of population, C_L is the cost per unit of land resources required by the penguin, L is an index of the quantity of land resources used by the penguin, and C_O is the costs of operation of the tourism enterprise.

The general principle behind the new model is similar to that given by Swanson (1994) but deviates in two important ways. The first is a lack of any harvest value. Since the penguin is not being hunted for food, feathers or hide, there are no consumptive values to incorporate into our model. A lack of tangible harvest return removes that incentive and, in the absence of some other value, the resource owner will reallocate his resources to disinvest in the non-productive asset. The benefits to be accrued from the yellow-eyed penguin are restricted to non-consumptive tourism and non-market existence values. Although some public efforts to preserve the species exist, this paper will focus on non-consumptive tourism values.

The lack of harvest has the further implication that the control variable must change. Traditional bioeconomic models use harvest as a control variable positing that a society will set harvest at that level which maximizes net social well-being. In our model, because our effective influence on the penguins' preservation status is in the allocation of resources, the control variable is land allocation, L. The extent to which people assign their resources to different investment opportunities will influence the availability of the penguin's required habitat ultimately determining the survival of the species.

Having recognized the social objective function and growth constraints, the current value Hamiltonian is:

$$H = R(L) + \lambda \cdot [F(x, L)] \tag{9}$$

Where $R(L) = \left[P_T T(x) - C_L - C_O \right] L$ represents the net benefits from tourism and $F(x,L)$ represents the state equation, which in this case is just the penguin growth function.

Taking the partial derivatives of the Hamiltonian with respect to the control variable, the state variable and the shadow price yields the following Pontryagin necessary conditions for a maximum:

$$\frac{\partial H}{\partial L} = R_L(L) + \lambda[F_L(x,l)] = 0 \tag{10}$$

$$-\frac{\partial H}{\partial x} = -\lambda F_x(x,L) = \dot{\lambda} - \delta\lambda \tag{11}$$

$$\frac{\partial H}{\partial \lambda} = F(x,L) = \dot{x} = 0 \tag{12}$$

Combining and manipulating the first two necessary conditions yields the following result expressed as a modified *golden rule* equilibrium condition:

$$F_x(x,L) = \delta + \frac{\dot{L}[-R_{LL}F_L + R_L F_{LL}]}{R_L F_L}. \tag{13}$$

Since R_{LL} equals zero, this simplifies to:

$$F_x(x,L) = \delta + \frac{\dot{L} F_{LL}}{F_L}. \tag{14}$$

We assume the growth function, *F(x)* is represented by a modified Verholst logistic function in which natural steady states exist at population levels of zero and the carrying capacity, *k*. The original (unmodified) logistic function is represented by the formula:

$$F(x) = r \cdot x \cdot \left(1 - \frac{x}{k}\right) \tag{15}$$

where, *r* is the intrinsic growth rate of the population, *x* is the population, and *k* is the carrying capacity. This formulation characterises the concept of density-dependence, in which population grows rapidly at first and then, upon reaching a maximum growth rate, begins to decline such that

$$F'(x) > 0, \ F''(x) < 0 \ \text{for all} \ x < \frac{k}{2}, \ \text{and}$$

$$F'(x) < 0, \ F''(x) > 0 \ \text{for all} \ x > \frac{k}{2}.$$

The cause of this behaviour is the self-limiting nature of populations, as the density of a population increases and competition for available resources limits

net growth. Implicit in this formulation is the assumption of a fixed environment size.

Since loss of land is the principal cause of decline in yellow-eyed penguin numbers, any change in the amount of land available to the penguin effectively alters the carrying capacity of the population on the land. Similarly, increasing the size of the available habitat increases the total population that the habitat is capable of supporting.

This implies a modification to the growth function as follows,

$$F(x) = r \cdot x \cdot \left(1 - \frac{x}{k \cdot L}\right) \tag{16}$$

where L represents an index of the suitable habitat available to the yellow-eyed penguin, the control variable from above.

Substituting equation (16) and its derivatives into equation (14) yields a specific form of the modified golden rule,

$$\delta = r \left[1 - \frac{2x}{kL}\right] + \frac{2\dot{L}}{L}. \tag{17}$$

This expression is consistent with the results suggested by the previous models, indicating that the penguin must generate sufficient growth, not only to meet the opportunity cost of capital, but also to offset the opportunity cost of the land resources it consumes. The specific implications for management depends upon the population, the intrinsic growth rate and the social discount rate.

Since δ, r and L are all positive, the sign of the first term on the right-hand side is dependent on the population level as shown in equation (18). If the population is small (less than one-half of the carrying capacity), the term is positive. If the population is large (greater than one-half of the carrying capacity), the term is negative.

$$\left[1-\frac{2x}{kL}\right]>0, \quad \text{if} \quad x<\frac{kL}{2}$$

$$\left[1-\frac{2x}{kL}\right]=0, \quad \text{if} \quad x=\frac{kL}{2} \qquad (18)$$

$$\left[1-\frac{2x}{kL}\right]<0, \quad \text{if} \quad x>\frac{kL}{2}$$

The implication is for the sign of the second term on the right-hand side as this represents how we use our control over land to balance the equality as shown in equation (19).

$$\text{If a large population, then} \quad \left[1-\frac{2x}{kL}\right]<0, \quad \text{and} \quad \dot{L}>0$$

$$\qquad (19)$$

$$\text{If a small population, then} \quad \left[1-\frac{2x}{kL}\right]>0, \quad \text{and} \quad \begin{array}{l} \dot{L}<0 \ \text{if} \ r>\delta \\ \dot{L}>0 \ \text{if} \ r<\delta \end{array}$$

If the population is large (the first term is negative), the optimal control will be to increase land availability through time. Even, if the population is small, the optimal control may be to increase land if the rate of growth of the population is less than that of other opportunities in society. Doing so effectively shifts the population leftward, relative to the carrying capacity, as in a shift from X_2 to X_1 in Figure 1. This increases the marginal growth rate until the entire right-hand side is equal to the discount rate.
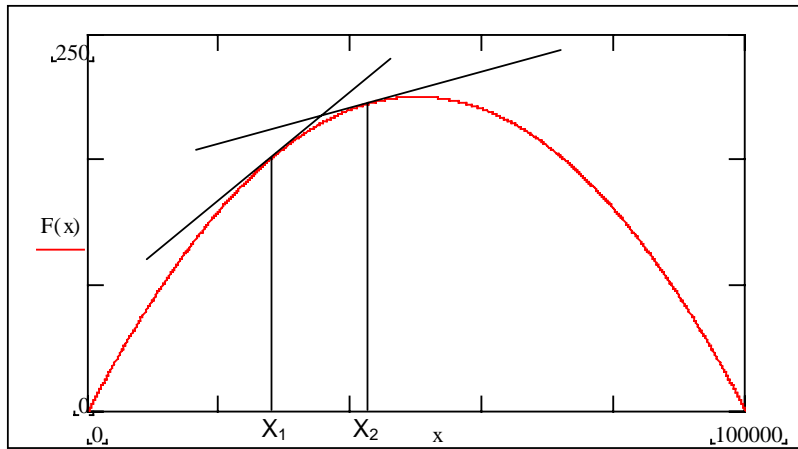

Figure 0. Effect of population shift on marginal rate of growth.

Finally, if the population is small and the intrinsic rate of growth exceeds the discount rate, the optimal control will be to decrease the land allocated to the species. Such a decrease has the same effect as shifting the population rightward, relative to the carrying capacity, as in a shift from X1 to X2 in Figure 1. This reduces the marginal growth rate, again bringing the right-hand side into equality with the discount rate.

4. IMPLICATIONS AND CONCLUSIONS

Implications for the Penguins

Howard McGrouther, director of the yellow-eyed penguin reserve in Dunedin reports that the current annual rate of growth for their population has remained at a constant twelve percent for the past several years[5]. The annual opportunity cost of capital facing landowners in the Otago peninsula is around 6.25 percent.[6] Clearly, the growth rate of the resource is well in excess of the rate required under the unmodified *golden rule*. McGrouther further reports that the carrying capacity of the reserve is around 760 birds, with a current population of approximately 260 birds. Thus, we have the case described above, in which the population is small and the intrinsic growth rate exceeds the discount rate.

Accordingly, on the optimal path, the rate of change of land allocation with respect to time will be negative, given our current initial conditions. This implies that the current population density is too low on the land presently available. To put it another way, the current yellow-eyed penguin population on this tract of land could be supported on a much smaller area.

The implication of this result for penguin management and preservation is a positive one. The current allocation of land to the yellow-eyed penguin is capable of supporting a substantially larger population than it is at present. Although the model indicates that the same result could be achieved with less, it is

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[5] Personal Communication 11-11-98.

unrealistic to treat land allocation as an infinitely divisible resource that can be gradually increased to keep pace with the optimal population density.

Implications for the Model

The question remains as to the applicability of the bioeconomic model to this type of problem. We have really explored two issues: whether the model is useful for species for which there is no harvest value, and whether land is an acceptable control variable.

To the first, the model demonstrates the ability to deal with non-harvest values as the sole source of value in the model. Previous models have included non-consumptive values in addition to harvest, but this model provides a reasonable explanation of optimal economic behaviour based on non-consumptive values alone. However, it is also the case that this model dramatically simplified the nature of revenues arising from tourism values. For mathematical tractability, revenues were modelled as constant and not dependent on population. While this is probably not correct, it is also the case that revenues are not likely to be based on an infinitely increasing function of population. In all likelihood, tourism revenues for a particular location will increase for low populations, but after some point, will level off. A tourist may choose not to pay for a visit if the probability of a sighting is small, but once that probability reaches a level of near-certainty, additional population is not likely to generate additional visits. The model would have to be significantly more complex to take this behaviour into account, yet that may be necessary for the model to predict behaviour in a useful way.

As to using land as a control variable, Swanson (1994) has already demonstrated the conceptual value of considering land as an additional control variable. This model demonstrates that land may also be a reasonable choice as the sole control variable in a problem. If there is a weakness in the concept it is in the unrealistic result that an optimal decision will be to restrict land initially and to introduce land at a rate that holds the population at an optimal density. In hindsight, it is obvious why the model does this, and it is an economically sound result. However, it is not a particularly realistic scenario for the real world and

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6 Term Investment Rate for term in excess of five years as quoted by Bank of New Zealand, Palmerston North Branch, as of 18 January 1999.

so one must question its use in empirical applications. It is likely that such a model is better used for making a binary determination of whether or not the incentives facing land owners is likely to cause a total disinvestment in a particular species and its habitat, than for attempting to model specific optimising behaviour.

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