Bioeconomic Theory and the Red Kangaroo: an initial investigation

Attwater, R.C.* and Lindner, R.K.#

* Centre for Resource and Environmental Studies, Australian National University
# Department of Agricultural Economics, University of Western Australia

Abstract

The management of wildlife resources, such as populations of the Red Kangaroo, is complicated by the lack of local population data, and the differing value judgements of interest groups. The use of a simple bioeconomic framework was investigated as a basis for determining a socially optimal level of exploitation which accounted for economic returns to shooters, damage costs to pastoralists and preservation benefits to conservationists. An application is presented using data from the Gascoyne management zone, Western Australia, and discussed in terms of the applicability of simple bioeconomic models, the observed harvest effort and management implications.

paper prepared for the 37th Annual Conference
Australian Agricultural Economics Society,
University of Sydney,
9 - 11 February 1993

1. Introduction

The management of wildlife resources, such as Red Kangaroo (*Macropus rufus*) populations is complicated by the lack of information about the status of local populations, and the differing value judgements of interest groups. As well as the direct economic benefits to kangaroo shooters, the harvesting of kangaroos impacts upon a range of social values. The Red Kangaroo can be regarded as an asset which generates economic benefits for professional shooters, aesthetic benefits to conservationists, or as a pest which causes damage costs to pastoralists (Collins and Menz 1986).

From an economic perspective markets may fail to optimally allocate resources due to the common property nature of kangaroo populations with their extensive home ranges (Tisdell, 1972; Collins and Menz 1986). Alternative methods are needed to determine socially optimal levels of harvest. Bioeconomic theory has been developed for common property fishery resources, based upon the analysis of harvest and effort data. The dissipation of economic rent was first described by Gordon (1954), and a static normative bioeconomic model of rent maximisation was proposed by Schaefer (1957), and discussed further by Clark (1976) and Waugh (1984).

The objective of this study was firstly to apply a simple bioeconomic model to harvest and effort data collected for Red Kangaroos, and secondly to incorporate wider social values into the analysis.

2. Traditional bioeconomic model

The traditional bioeconomic model, as proposed by Schaefer (1957), can be developed as follows:

Economic rent, π, is defined by

$$\begin{aligned} \pi &= TR - TC \\ &= PH - CE \end{aligned} \quad (1)$$

where TR = total revenue from harvesting kangaroos
TC = total harvesting cost
P = price per unit harvested
C = cost per unit effort
H = harvest
E = harvest effort

In any given year, harvest is determined by shooting effort and population levels as follows:

$$H = Q(X, E) = A\,E\,X \quad (2)$$

where X = population
A = catchability coefficient

Population dynamics for kangaroos are represented by the first derivative of the logistic growth function:

$$dX/dt = rX(1 - X/K) \qquad (3)$$

where r = intrinsic rate of increase
K = carrying capacity
t = time

The economic production function (2) assumes: only two factors of production, population, X, and harvest effort, E; no decreasing returns to effort, or population effects; infinite elasticity of demand for products and supply of inputs; and the cost per unit effort is equal to the opportunity cost of effort. The biological production function (3) assumes: population fluctuations are either insignificant or cancel out over time; and population size is independant of environmental changes and age structure.

Expression (4) specifies the conditions for a steady-state which provides a basis for an expression of sustainable population. This is a useful abstraction for policy purposes.

$$dX/dt = H \qquad (4)$$

The traditional bioeconomic model can then be expressed as the maximisation of economic rent subject to this steady-state assumption. This assumes: no external values, and a social discount rate of zero.

Rearranging to describe sustainable population in terms of harvest effort (5), expressions for the sustainable harvest (6), and sustainable rent (7) can then be derived. From this point all expressions of economic rent, harvest effort, harvest and population will refer to these sustainable parameters.

$$X = (r - AE)K/r \qquad (5)$$

where X = sustainable population
E = sustainable effort

$$H = AKE - (A^2K/r)E^2 \qquad (6)$$

where H = sustainable harvest

$$\pi = (PAK - C)E - (PA^2K/r)E^2 \qquad (7)$$

where π = sustainable economic rent

In principle, the bioeconomic model can be used for two purposes:
• to estimate the level of harvest in a totally deregulated situation,
• to estimate the optimal level of harvest, and the associated kangaroo population.

To estimate the level of harvest in a totally deregulated situation then only the economic or resource rent consisting of returns to shooters is considered. If there are open access conditions, then rent will be totally dissipated. The open access level of effort (8), harvest (9), and population (10) are as follows.

$\pi_0 \quad = 0 \qquad \text{(TR = TC)}$

where π_0 = totally dissipated economic rent

$$E_0 = (PAK - C)/(PA^2K/r) \tag{8}$$

where E_0 = open access level of sustainable effort

$$H_0 = (AK)E_0 - (A^2K/r)E_0^2 \tag{9}$$

where H_0 = open access level of sustainable harvest

$$X_0 = (r - AE_0)K/r \tag{10}$$

where X_0 = open access level of sustainable population

If the social objective is the maximisation of economic rent, then this will occur when MR = MC, i.e. $d\pi/dE = 0$,. The optimal level of economic rent (11) [illegible] (12), harvest (13), and the subsequent population (14) can be derived as follows.

$$\pi_\pi = (PAK - C)E_\pi - (PA_2K/r)E_\pi^2 \tag{11}$$

where π_π = optimal level of sustainable economic rent

$$E_\pi = (r/2A) - (Cr/2PA^2K) \tag{12}$$

where E_π = optimal level of sustainable effort

$$H_\pi = (AK)E_\pi - (A^2K/r)E_\pi^2 \tag{13}$$

where H_π = optimal level of sustainable harvest

$$X_\pi = (r - AE_\pi)K/r \tag{14}$$

where X_π = optimal level of sustainable population

3. The inclusion of external benefits and costs

As well as the private revenue and costs which accrue to the kangaroo shooter, the value of the damage by kangaroos to grazing enterprises, and the preservation value to conservationist need to be considered. The difficulty in valuing these aspects has not been resolved in this study. Instead simplified functional forms have been assumed and questimates of parameter values used to obtain illustrative results.

It was assumed that both the damage and preservation values are constants for each individual kangaroo, so total damage and preservation values are a function of value per individual and the population level. The net social value from harvesting can then be described as a combination of these two values (15).

$$NSV = (D - Q)(K - X)$$

$$= (D - Q)(AK/r)E \quad (15)$$

where D = damage value per kangaroo
Q = preservation value per kangaroo
NSV = net social value of harvesting

The sustainable social rent, Π, can then be described as the sum of the economic rent and the net social value, expressed in terms of effort (16).

$$\pi = (PAK - C)E - (PA^2K/r)E^2 \quad (7)$$

$$\Pi = \pi + NSV$$

$$= [PAK - C + (D - Q)(AK/r)]E - 2(PA^2K/r)E^2 \quad (16)$$

where Π = sustainable social rent

This expression can then be solved for a level of effort which maximises social rent (17).

$$E_{\Pi} = [PAK - C + (D - Q)(AK/r)]/(2PA^2K/r) \quad (17)$$

where E_{Π} = socially optimal level of sustainable effort

The corresponding harvest and population levels can be derived by substituting this level of effort back into expressions (6) and (5) to provide expressions for the socially optimal levels of harvest (18) and population (19).

$$H_{\Pi} = AKE_{\Pi} - (A^2K/r)E_{\Pi}^2 \quad (18)$$

where H_{Π} = socially optimal level of sustainable harvest

$$X_{\Pi} = (r - AE_{\Pi})/K/r \quad (19)$$

where X_{Π} = socially optimal level of sustainable population

4. Estimating these parameters

Though the steady-state assumption (4) can facilitate manipulation, and may be valid for long-run policy analysis, the assumption is less valid when applied to the distribution of data used for parameter estimation. Actual kangaroo populations are subject to stochastic environmental conditions, and the system is not normally in long-run equilibrium.

A method of estimation has been presented by Uhler (1980) for a discrete formulation of the deterministic Schaefer model as follows. This relaxes the steady-state assumption in expression (20).

$$X_{t+1} - X_t = F(X) - H_t$$

$$= rX_t[1 - (X_t/K)] - H_t \quad (20)$$

where t = discrete time period

$$H_t = AE_tX_t \quad (2)$$

Defining a proxy variable, U_t (21), then an estimating equation can be derived (22). Linear regression can then be used to estimate the coefficients. When using ordinary least squares this estimation still suffers from interdependance of the error term and U_t.

$$U_t = H_t/E_t \quad (21)$$

$$(U_{t+1} - U_t)/U_t = r - (r/AK)U_t - AE_t$$

$$= B_0 + B_1U_t + B_2E_t + e \quad (22)$$

5. An application: The Gascoyne management zone, W.A.

Monthly harvest and effort records recorded for the Gascoyne management zone by the Department of Conservation and Land Management, W.A., from 1972 to 1987 were used. The data from 1972 until 1979 is presented in Prince (1984), from 1980 until 1987 from Prince (unpubl. data). Missing data occured for 5 months in 1985 and 1 month in 1984 so the data was scaled, on the basis of monthly data for each of those years.

An application of Uhler's estimation method yielded the following coefficients.

Table 1. Estimates of coefficients derived by Uhler's method

Coefficient	B_0	B_1	B_2
estimate	0.399	-0.058	-1.0×10^{-5}
standard error	0.124	0.061	1.6×10^{-5}
est./s.e.	3.2	-0.95	-0.8

The predicted coefficients have a correct sign, but only B_0 is significant ($P<0.01$), and the overall fit of the model is poor, $R^2 = 0.11$. This non-steady state estimation defines a response to a level of effort between consecutive points in time, rather than an aggregation of instantaneous responses in a steady-state formulation. This could make Uhler's method more sensitive to stochastic influences. From these coefficient estimates, the intrinsic rate of increase, r, the carrying capacity, K, and the catchability coefficient, A, can be derived as follows:

Table 2. Estimates of parameters derived by Uhler's method

Parameter	Estimate
intrinsic rate of increase (r)	0.399 per year
carrying capacity (K)	519 440 kangaroos
catchability coefficient (A)	1×10^{-5}

The estimated intrinsic rate of increase of 0.399 compares favourably with an estimate based upon body weight by Caughley and Krebs (1983) of 0.4, and the mid-range of estimates of maximum rate of increase by Priddel (1987) of 0.4. The estimated carrying capacity of 519 440 kangaroos may be reasonable (Prince pers.comm.) though higher than the estimate of 120 000 made in 1983 by Short *et al.* (1983). Carrying capacity, as a steady state concept, cannot easily be related to the dynamic variability of rainfall, vegetation response, and subsequent rate of increase of kangaroo populations. The catchability coefficient reflects the response in the harvest levels to the levels of effort and population and may vary in response to variable conditions.

Base case assumptions

The market price used of $5.82 per kangaroo was based on a price paid at the chiller of $0.32 / kg (Ellery pers.comm.), and an average carcase weight of 18.2 kgs (Prince, unpub. data). A cost per hunting hour of $13.80 was based on the cost per kangaroo of $2.64 estimated by Collins and Menz (1986), and the scaled total harvest and effort data of 411 436 kangaroos from 78 716 hunting hours.

An estimate of the total loss to agricultural production due to kangaroos has been carried out by Gibson and Young (1987), which included an estimate for the Gascoyne region. An empirical model was used to estimate the total economic loss of $ 1 260 280. Their population estimate of 374 195 kangaroos provides an estimated damage value of $3.37 per kangaroo. No estimation of preservation values for kangaroos was found in the literature,so a base case of $1.00 was used.

Private and socially optimal levels of effort

In an unregulated, open access system, if an economic incentive exists to harvest the resource then competition for the resource will lead to an increase in the level of effort until the total revenue just equals total costs and economic rent is dissipated. This is the upper limit to 'rational' private exploitation from the perspective of the private kangaroo shooting industry. If no externalities occur then the social objective is the maximisation of private economic rent accruing to the kangaroo shooter.

Table 3. Optimal levels and observed data

levels/year	Max. Social Rent Π.	Max. Private Rent π	Open Access	Observed minimum	average	maximum
Rent ($)	737 748	89 085	0			
Effort (hours)	31 204	10 942	21 686	2 568	4 982	10 245
Harvest (kangaroos)	35 325	41 251	51 421	14 260	26 420	51 636
Population (kangaroos)	113 208	378 276	237 113	?	?	?

The socially optimal level of effort of 31 204 hunting hours per year generates a social rent of $737 748 which is far higher then the maximum economic rent of $89 085 from 10 942 hunting hours per year. The socially optimal level of effort is also higher than the open access level of effort of 21 686 hunting hours per year. The levels of effort which maximum economic rent and maximise social rent are both higher than the observed effort from 1972 until 1987 which ranges from 2 568 to 10 245 hunting hours a year with an average of 4 920 hours. Subsequently, the observed harvest levels are less than those generated from optimal and open access levels of effort, though in the case of the socially optimal levels the subsequent sustainable population level is lower. No observed population data is available for comparison and future application of this approach would be greatly enhanced if local population data was available for comparison with information generated from harvest and effort data.

6. Sensitivity Analysis

Due to uncertainty concerning the base case values used it is important to test how sensitive the solutions are to changes in these values. The following section presents sensitivity analyses of the major economic parameters to illustrate the sensitivity of the model results.

Price per unit harvest

The price per unit harvest sets the scale of the revenue derived by the shooter. As private value increases, compared to the damage value, it becomes socially optimal to maintain larger populations and harvest greater numbers, so the private and social optima converge. If a marketing drive occurred for human consumption then the market price may rise significantly above the $5.82 used in this study (Table 4).

Cost per unit effort

The cost per unit effort, C, with the harvest revenue, determines the private economic rent. The solutions are not particularly sensitive to the cost per unit effort, and incurred costs can be expected to slowly rise above the $13.80 per hour used here (Table 5).

Damage and preservation values

The influence of damage reduction and preservation values will depend upon the relative difference between these two values, and the comparative magnitude of these values as against the private economic returns. The solution is highly sensitive to these values; the perceived damage value may be more site specific and may fall below the value used of $3.50. Preservation values are an example of the problem of the free-rider problem, where the action of one individual in enjoyed by others, and so markets fail to reflect these values. No estimates of preservation values for kangaroos could be found so an arbitrary base case of $1.00 was used (Table 6).

Table 4. Sensitivity of results to the price per kangaroo

Price ($/kangaroo)	$3.50	$5.50	$7.50	$10.50
E_0	10 000	21 000	26 000	30 000
H_0	38 000	52 000	47 000	39 000
X_0	394 000	251 000	184 000	131 000
economic rent π_π	10 000	76 000	162 000	303 000
E_Π	39 000	32 000	29 000	26 000
H_Π	6 000	33 000	42 000	47 000
X_Π	16 000	105 000	146 000	178 000
social rent Π_Π	681 000	726 000	803 000	937 000

Table 5. Sensitivity of results to the cost per unit effort

Cost per unit effort ($/hour)	10.00	12.50	15.00	17.50
E_0	27 000	23 000	20 000	17 000
H_0	46 000	50 000	52 000	50 000
X_0	172 000	215 000	258 000	301 000
economic rent π_π	135 000	104 000	76 000	53 000
E_Π	34 000	32 000	30 000	29 000
H_Π	27 000	33 000	37 000	42 000
X_Π	80 000	102 000	123 000	145 000
social rent Π_Π	861 000	779 000	701 000	627 000

Table 6 Sensitivity to damage and preservation values (values shown are D - Q)

D - Q ($)	- 1.5	- 1	0	1	3	3.5
E_Π	-2 000	2 000	11 000	19 000	36 000	41 000
H_Π	-11 000	11 000	41 000	52 000	16 000	-5 000
X_Π	546 000	490 000	378 000	266 000	43 000	-13 000
social rent Π_Π	3 000	4 000	89 000	286 000	1 016 000	1 268 000

7. Discussion

This paper shows how bioeconomic theory can be applied to the management of wildlife resources such as kangaroo populations. The following discussion will cover the applicability asd extension of this type of model, a comparison with observed data, and the management implications.

Bioeconomic models

This application is an example of a simple model which can be applied to available data. Many more sophisticated approaches could be devised, including: Clark and Munro's (1975) capital theory model; the replacement of the logistic function with an interactive series of rainfall, vegetation biomass and population rate of increase (May *et al* 1976; Caughley 1987); non-linear functions and thresholds (Tisdell 1984); or cohort analysis and dynamic pool models (Gulland 1977). Throughout the development of this variety of approaches, the need for robust applications which operate with small amounts of information has been noted by Beverton and Holt (1957) and May *et al* (1978). Though Caughley (1977) considered the analysis of harvest and effort data unsuitable for the analysis of populations of mammals, due to the buffering ability within age classes, the information needs of dynamic pool models, which take account of age structure, has precluded their widespread application (Gulland 1977).

Harvest effort and economic incentives

The observed level of effort from 1972-1987 are much lower than the levels of effort which would maximise private rent, or the maximum private effort which would dissipate private rent (Table 3). This suggests that either the economic incentive is low compared to alternative activities, i.e. a high opportunity cost, or that the current regulatory is restricting effort.

Professional shooters consider diversification of income as important (Young and Delforce 1986) so their level of shooting activity will be sensitive to the opportunity cost of their hunting effort. This may indicate that if the market price were to increase, due to an improved demand for kangaroo products, then the level of effort may increase substantially as currently licenced shooters focus their labour on kangaroo shooting. As there is no market for licences it is difficult to determine the demand for extra licences and whether more licenced shooters would add significantly to the observed levels of effort.

In the base case analysis, with the social optima greater than the maximum private effort, a harvest system based purely on the incentive of private returns can not achieve a socially optimal level of effort, harvest, and population. The private and social optima could converge if the market price were to increase and the perceived damage value were to fall.

An increase in market price may reduce the socially optimal level of effort, as the magnitude of private returns to shooters increases compared to the value of damage mitigation. This means that the private and social optima may converge. This will also occur if the perceived damage value were to decrease. This change in perception by pastoralists could occur in conjunction with an increase in market value if pastoralists were able to look to harvesting kangaroos as a realistic alternative enterprise.

Management Implications

The tradeoffs between interest groups has been discussed by Tisdell (1979) in terms of a 'Kaldor-Hicks' tradeoff between conservationists and farmers, a tax/subsidy approach to the tradeoffs between interest groups has been made by Collins and Menz (1986), and an exercise in terms of pest control by Young (1984). Bounties have been discussed by Tisdell (1979). There is the question of who pays, and little evidence of the operation of any successful bounty systems (Whitehouse 1986). Solutions based on tax systems are generally inflexible, and politically sensitive (Waugh 1984).

The other main option to a government mandated financial incentive is that of vesting property rights in a sole owner. The basic rationale for attempting to internalise social costs is so there is an incentive for management in the interests of society (Gordon 1954, Tisdell 1972). Furthermore, privatisation does not ensure conservation, as this will depend upon the price received per kangaroo relative to the value of the foregone stock (Tisdell 1972). One major problem for mobile wildlife is the question of scale. The appropriate scale for sole owners may be at the management zone scale, perhaps with responsibility vested in local bodies similar to catchment and landcare groups.

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