Valuing Wildlife Management: A Utah Deer Herd

John E. Keith and Kenneth S. Lyon

Managers of public wildlife resources generally are concerned with enhancing the quality of recreation by increasing wildlife through habitat manipulation. However, current recreation valuation studies have focused upon variables that are inappropriate for use in these management decisions. The economic criterion for these decisions should be the value of a change in the stock of the wildlife population compared to its cost. An estimate of such a value was made for the Oak Creek deer herd in Utah, using a household production function approach in an optimal control framework. The value of an additional deer in the herd was estimated to be approximately $40.00.

Economists have been providing wildlife managers with recreational values which are not appropriate for most management decisions. The values currently applied to publicly-provided wildlife-related recreation have been based on estimates of average visitation or harvest values in inframarginal contexts. Marginal analysis of management practices has generally been ignored, as has the difference between the value of a harvested animal and benefits and costs of adding to the reproducing stock [Batie and Shabman]. For example, Sorg and Loomis reported 15 valuation studies on big-game hunting, all of which were based upon visitor-days, as opposed to valuing the wildlife directly. Although a relationship among visitor-days, hunter success, and big-game populations could have been estimated, the values generated in those studies (consumer's surplus per visitor-day) fail to provide sufficient information for mangement decisions.

The correct economic analysis of public decisions about wildlife management should include three aspects: 1) the value to users of increases or decreases in wildlife populations; 2) the relationship between the current wildlife stocks and future wildlife populations; and 3) the costs of providing increments of wildlife populations through habitat manipulations and/or other management alternatives. These considerations are generally found in a "bioeconomic" approach to the analysis.

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Bioeconomic Analysis

There have been several bioeconomic analyses, which have used optimal control or dynamic programming approaches, reported in the literature. Many of these studies involve commercial fisheries because there are relatively few problems with benefit estimations and data on commercial fish populations are available. Most of these bioeconomic studies focus on open-access fishery management in a very theoretical way [Anderson; Wilson; and Crutchfield are recent examples]. Some have focused upon the empirics of a specific fishery [e.g., Crutchfield and Zellner; Bell; and Lewis]. Models of recreational activities are few.

The seminal article on wildlife-related recreation management was published by Brown and Hammack in which waterfowl hunting in the Pacific Flyway was examined. In their study, a bidding game was used to find hunter willingness-to-pay for annual hunting privileges. This value was regressed against the annual kill to obtain the value per duck killed. An estimate of the proportion of the duck population harvested was used as the population/harvest relationship; the relationship between duck populations and an environmental variable (breeding ponds) was estimated; and the cost of producing added ponds was obtained. An optimal control approach was used to generate the optimal stock of ducks and ponds for the Pacific Flyway. The authors' approach meets the requirements for bioeconomic modeling, although the individual hunter choices were not modeled and the biological parameters were very aggregated.

Two other recent theoretical (rather than empirical) studies incorporated the household production function into bioeconomic models [Bockstael and McConnell, McConnell and Sutinen]. This approach involves modeling decisions which are made by utility-maximizing households given their time and budget constraints [e.g., Becker and/or Lancaster]. Bockstael and McConnell conclude that there may be serious empirical difficulties with this approach when quantity and quality parameters are endogenous. However, they also show that the household production approach, under certain conditions, generates empirical equations similar to those of the travel cost methodology. Further, the approach accommodates the inclusion of site quality as an argument in the utility function. Thus, direct consideration of the value of quality is possible. It is the value of these quality changes that is crucial to wildlife management.

The Benefit Model

This paper focuses on deer herd valuation and management as an example of the application of a bioeconomic approach. The relationships among herd dynamics, hunter utility, and the marginal value of the herd are derived from the household production function approach.

The population dynamics of the deer herd depend upon the physical characteristics of the area, weather, natural predators, biology of the habitat, and the hunter harvest. Let

$$\frac{dx}{dt} = f(x) - h \qquad (1)$$

summarize these relationships, where h is the hunter harvest and f(x) captures the effect of the other elements. The quantification of population dynamics for the species under consideration is necessary for valuation of the marginal stock changes. Several publications deal with mathematical models of population dynamics [e.g., Lotka and/or Clark]. The hunter harvest is the result of the interaction of utility-maximizing, price-taking hunters and the deer in the area. The resulting harvest depends upon hunting laws and restrictions, tastes, prices, roads, technology, and the deer population. Assuming that laws, tastes, and other variables are constant,[1] then

$$h = h(x). \qquad (2)$$

The population dynamics are captured in equations (1) and (2) and the initial herd size, x_0. Let the problem

$$dx/dt = f(x) - h(x)$$

have the solution

$$x(t) = g(x_0, t). \qquad (3)$$

This equation identifies the time profile of the herd size for the initial herd size (x_0), reproduction rate, and the interaction of the hunters and the deer in the herd area.

In order to determine the value of a

[1] Further refinements of the model would include the effects of these variables, as well as the stochastic nature of population dynamics. Also, hunters are assumed to know both bag limits and success rates.

change in the stock of deer, define the aggregate benefits as a function of the stock of deer at any time, t:

$$B = \int_0^\infty \exp(-rt)s(x(t))\,dt \qquad (4)$$

where $\exp(\cdot)$ is the natural exponential function (discount function), r is the appropriate interest rate, $s(\cdot)$ is the aggregate compensating variation consumers' surplus function, x(t) is the herd size at time t, and the starting time is zero. Note that the relationship between herd size and consumers' surplus is implicit. The aggregate surplus function is

$$s(x) = \sum_{j=1}^{n} s^j(x), \qquad (5)$$

where $s^j(x)$ is the compensating variation consumer's surplus for the j^{th} hunter and n is the maximum number of hunters who hunt in the unit. Assume $s^j(x)$ equals zero if a hunter does not hunt in the unit under the prevailing conditions.

Inserting equation (3) into (4) yields

$$B^* = \int_0^\infty \exp(-rt)s(g(x_0, t))\,dt. \qquad (6)$$

The present value of the surplus stream now depends upon the starting population (x_0), the biological growth rate, the interreactions of hunters and deer ($g(\cdot)$), the aggregate consumers' surplus function ($s(\cdot)$), and the interest rate. Differentiating B^* with respect to x_0 yields the shadow value of a deer in the initial population. This derivative is

$$\frac{\partial B^*}{\partial x_0} = \int_0^\infty \exp(-rt)\frac{ds}{dx}\frac{\partial g}{\partial x_0}\,dt, \qquad (7)$$

where ds/dx is the marginal consumers' surplus of herd size at each point in time, and $\partial g/\partial x_0$ is the additional deer at each point in time causing an additional deer at time zero. The derivative $\partial g/\partial x_0$ can be analyzed numerically or, for some f(x) and h(x) functions, solved analytically. The marginal consumers' surplus resulting from the change in deer population (stock) is determined by

$$\frac{ds}{dx} = \sum_{j=1}^{n} \frac{ds^j(x)}{dx} \qquad (8)$$

and the hunter's utility maximization problem:

$$\text{Maximize } U(Z) \qquad (9)$$

subject to:

$$\begin{aligned}
Z_1 &= F^1(y^1, t^1)\\
Z_2 &= F^2(y^2, t^2)\\
Z_3 &= F^3(y^3, t^3, x)\\
Z_4 &= F^4(y^4, t^4)\\
&p\cdot(y^1 + y^2 + y^3 + y^4) - (b + Z_4 w) = 0\\
&t^1 + t^2 + t^3 + t^4 - T = 0,
\end{aligned}$$

where Z_1 is a composite commodity, Z_2 is the quantity aspect of hunting, Z_3 is the quality aspect (which is assumed to be hunter success[2]), Z_4 is hours of work, $F^i(\cdot)$ are the household production functions, y^i are vectors of purchased goods, p is a vector of goods prices, t^i is time spent producing Z_i, T is the total quantity of time in the time period, b is nonlabor income, and w is the wage rate.

In order to generate an expression for $ds^j(x)/dx$ (equations (7) and (8)), the dual problem is invoked:

$$\text{minimize: } b = p\cdot(y^1 + y^2 + y^3 + y^4) - Z_4 w \qquad (10)$$

subject to the time and commodity production constraints in (9). This yields the compensated nonlabor income function.

Differentiation of this solution function (b^*) using the envelope theorem yields:

$$\frac{\partial b^*}{\partial x} = \xi_3 \frac{\partial F^3}{\partial x}, \qquad (11)$$

where ξ_3 is the Lagrangean multiplier for $F^3(\cdot) - Z_3 = 0$. Further, it can be shown that this derivative is the negative of the derivative of compensating variation consumers' surplus:

$$\frac{ds^j(x)}{dx} = -\frac{\partial b^*}{\partial x} = -\xi_3 \frac{\partial F^3}{\partial x}. \qquad (12)$$

[2] Many variables may enter into the hunter's assessment of quality. Several studies have shown that hunter success is a dominant quality factor. The time variable, t^3, would include all time in information gathering, scouting, and gaining experience.

In this formulation, $-\xi_3$ is the shadow value of hunter success (Z_3) and $\partial F^3/\partial x$ is the change in hunter success with a change in herd size. Thus:

$$\frac{ds^j(x)}{dx} = \begin{pmatrix}\text{shadow value of}\\ \text{hunter success}\end{pmatrix} * \begin{pmatrix}\text{marginal responsiveness of}\\ \text{hunter success to herd size}\end{pmatrix} \quad (12')$$

Equation (12′) indicates that for the j^{th} hunter, the marginal value of deer in the herd is the product of the shadow value of the quality variable (hunter success) and the marginal responsiveness of hunter success to herd size. Equation (8) indicates that the individual shadow values are summed to obtain the aggregate shadow value of deer at a point in time. Finally, the shadow value of an additional deer in time zero is identified by the integral in equation (7) to be the discounted, aggregate shadow value of the stream of current and future effects of this additional deer.

Value of the Oak Creek Deer Herd

In the empirical application, the value of an additional deer in the Oak Creek deer herd in Utah was estimated. This required estimating the value of hunter success coupled with the relationship between hunter success and the deer population.

The initial step was to estimate the shadow value of the hunter success ($-\xi_3$). This shadow value is an implicit commodity price in the household production function literature [Pollak and Wachter] and is the implicit price of quality (hunter success). At equilibrium for the individual hunter, this implicit price equals the implicit marginal cost of hunter success; that is, the last dollar spent on increasing the success of the hunting trip yields utility loss just equal to the utility gain of increased success. A hunter can influence the probability of success in several ways, such as preseason scouting, equipment purchases or rentals, and traveling to more productive areas. Assuming continuous functions, the hunter will equate the marginal cost of increasing the probability of success for all of these activities.

The data used to estimate the shadow value of success were taken from Wennergren *et al.* Their data were gathered from a survey of resident hunters in Utah for the 1970 hunting season. There are significant omissions within this data set; only the destination hunting unit, the time on site, the place of origin of the hunter, and number of party members for each trip were collected. Thus, only the travel cost approach could be used. Although the analysis is therefore restricted, travel costs are relevant in the hunter choice model, and hunter success was found to be the only consistently significant quality variable in the Wennergren *et al.* study. Round trip miles from each place of origin to each hunting unit were multiplied by ten cents per mile to obtain the travel cost. The average success rates for each unit was published by the State of Utah and was reported by the media, and it was assumed that the hunter knew the array of success rates of the various destination hunting units. No information regarding hunter attempts to increase success were available from the data set. Travel cost was regressed against hunter success, to determine if a higher expected success rate induced hunters to travel extra distances and thereby incur higher costs. Given the assumption of hunter equilibria, the marginal cost of achieving higher success can be equated with marginal benefit (ξ_3).

Two approaches to estimating the relationship between travel cost and expected success were used. First, all 785 observations were used in the aggregate in a linear regression.[3] The resulting estimate of the marginal cost of hunter success (the

[3] Semi-log and log-linear regressions were also used, but results did not differ significantly from the linear regressions.

added distance traveled to obtain higher success rates) was \$0.5615 per percentage point increase in success. The standard deviation was \$0.068 and the R^2 was 0.08. Thus, there was a small confidence interval about the estimate but little of the variation in travel cost was explained. However, this approach does not address the choices of sites that a given hunter might have. For this reason, regressions for each of several points of origin were run so that the distribution of trips to sites for an average hunter from a given origin could be analyzed.

Nine major points of hunter origin were identified: Brigham City, Cache County, southwest Utah including Cedar City and St. George, Ogden, Price, Provo, Salt Lake City, Tooele, and Vernal. The three dominant places of origin and their respective number of observations were Salt Lake City (229), Provo (128), and Ogden (105). Regression coefficients for these origins were \$0.741, \$0.626, and \$0.672, respectively, and all were significant at greater than the .0001 level. Each of the coefficients fell within two standard deviations of the other coefficients and all were within one and one-half standard deviations of their weighted average, \$0.695. The R^2 was considerably higher than the aggregate estimate, ranging from 19 to 22 percent.

Results for the smaller places of origin were mixed. Of the six places only four exhibited regression coefficients that were significant at greater than the 0.1 level. The estimated coefficients were \$1.30 for Brigham City, \$0.916 for Vernal, \$0.919 for Tooele, and \$0.643 for Cache County. All of these coefficients were within one and one-half of their own standard deviations of a weighted average of the large origin results.

Next, the marginal responsiveness of hunter success to herd size ($\partial F^3/\partial x$) was estimated using Oak Creek deer herd data. The hunter success and deer population data for the Oak Creek deer herd were reported in *The Oak Creek Mule Deer Herd in Utah* by Robinette *et al.* Hunter success is most likely a function of more than just herd size, although no data were available to expand the analysis. The data required, as they often do, the use of a "typical" hunter instead of many individual hunters. To estimate $n(\partial F^3/\partial x)$ for the Oak Creek unit, it was assumed that the hunter harvest was proportional to herd size[4]; thus, equation (4) has the form

$$h = h(x) = \gamma x \tag{13}$$

where γ is a positive parameter. Multiplying both sides of equation (13) by $1/n$ yields an equation for hunter success. Differentiating this result with respect to herd size (x) yields the proxy for the marginal responsiveness of hunter success to herd size ($\partial F^3/\partial x$). Multiplying this derivative by n yields $n(\partial F^3/\partial x) = \gamma$. Using the "typical" hunter approach, the combination of equations (8) and (12) is

$$\frac{ds}{dx} = n(-\xi_3)\frac{\partial F^3}{\partial x}$$

where n is the number of hunters. Thus

$$\frac{ds}{dx} = (-\xi_3)\gamma.$$

The Oak Creek hunter harvest and deer herd data from 1947 to 1957 were used to estimate γ. The estimate was 15.81 percent, the standard deviation was 0.59, and the R^2 was 0.27. Each year approximately 16 percent of the herd is legally harvested. Combining the estimates for $-\xi_3$(\$0.695) and γ(15.81), ds/dx is estimated to be \$10.99.

To complete the task of estimating the shadow value of a deer, equation (7) was used. Treating ds/dx as a constant (from the constant marginal cost of success), equation (7) can be written

$$\frac{\partial B^*}{\partial x} = \frac{ds}{dx}\int_0^\infty \exp(-rt)\frac{\partial g}{\partial x_0}\,dt. \tag{14}$$

[4] The data are consistent with the assumption for Oak Creek herd; however, this relationship may differ for other sites or times.

Assuming a logistic function for herd reproduction, f(x) in equation (1) is

$$f(x) = \alpha x - \beta x^2 \qquad \alpha, \beta > 0. \tag{15}$$

Combining equations (1), (13), and (15) yields

$$\frac{dx}{dt} = (\alpha - \gamma)x - \beta x^2. \tag{16}$$

This differential equation with its initial condition $x(0) = x_0$ following solution:

$$x(t) = g(x_0, t) = \left[\left(\frac{1}{x_0} - \frac{\beta}{\alpha - \gamma}\right) \cdot \exp(-(\alpha - \gamma)t) + \frac{\beta}{\alpha - \gamma}\right]^{-1} \tag{17}$$

and

$$\frac{dx(t)}{dx_0} = \frac{dg}{dx_0} = \left[\frac{x(t)}{x_0}\right]^2 \exp(-(\alpha - \gamma)t). \tag{18}$$

Note that equation (17) is also a logistic curve, and for $\alpha - \gamma$ positive the limit of x(t) as t increases without bound is $(\alpha - \gamma)/\beta = \hat{x}$. A random component, such as weather, could be expected to yield fluctuations around $\hat{x}$.

Letting x_0 equal $\hat{x}$ so as to estimate the shadow value of deer in an average or normal herd size, equation (18) becomes

$$\frac{dg}{dx_0} = \exp(-(\alpha - \gamma)t), \tag{19}$$

and equation (14) is

$$\frac{\partial B^*}{\partial x} = \frac{ds}{dx}\int_0^\infty \exp(-(r + \alpha - \gamma)t)\, dt \tag{20}$$

$$= \frac{ds}{dx}\frac{1}{r + \alpha - \gamma}. \tag{21}$$

Using Oak Creek deer herd data for changes in herd size for 1947 through 1956, $\alpha - \gamma$ and β were estimated to be 0.56959 and 0.00026, with standard deviations of 0.29731 and 0.00013, respectively. The R^2 was 0.32.

Using equation (21), the estimates reported above, and a discount rate of 6 percent yields a shadow value of a deer in the Oak Creek herd of \$17.47.[5] The Wennergren *et al.* study was based on 1970 data; therefore, this estimate is in 1970 dollars. Using the same GNP implicit price deflator for 1982 as Sorg and Loomis, the current shadow value of a deer is \$39.52.

Although these values are based on several quite restrictive assumptions and sets of incomplete data, the methodology is appealing. The values generated represent the increased benefits (consumers' surplus) which would result from a one-deer increase in the Oak Creek deer herd. This value should be compared to the costs of increasing that deer herd by one individual in order that economically efficient herd management be achieved.

Conclusions

Much of the recreation valuation information on which resource managers base allocation decisions is inappropriate, particularly for wildlife management. Since managers generally are limited to either habitat manipulation or harvest constraints, it is necessary to focus valuation on the marginal value of these efforts. This requires analyzing the marginal value of changes in the stock of wildlife, rather than an average value of visitor days. Furthermore, optimal management must involve considering the effectiveness of habitat manipulation, or other controls, on the stock of wildlife as well as the cost of those practices. Given that public agencies will likely continue to be the major provider of public recreation activities, it is essential that biologists and economists cooperate in research which will lead to the appropriate information being collected and analyzed in a theoretically correct way.

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[5] A discount rate of 0.06 and $\alpha - \gamma$ equal to 0.56959 yields $1/(r + \alpha - \gamma)$ equal to 1.59. This capitalization factor of 1.59 times \$10.99, the estimate for ds/dx, yields $\partial B^*/\partial x$ = \$17.47.

References

Anderson, L. G. "The Share System in Open-Access and Optimally Regulated Fisheries." *Land Economics* 58(1982): 435–49.

Batie, S. S. and L. Shabman. "Valuing Nonmarket Goods and Empirical Issues Discussion." *American Journal of Agricultural Economics* 61(1979): 931–32.

Becker, G. S. "A Theory of the Allocation of Time." *Economic Journal* 75(1965): 492–517.

Bell, W. "Technological Externalities and Common-Property Resources: An Empirical Study of the U.S. Northern Lobster Fishery." *Journal of Political Economy* 70(1972): 148–58.

Bockstael, N. E. and K. E. McConnell. "Theory and Estimation of the Household Production Function for Wildlife Recreation." *Journal of Environmental Economics and Management* 8(1981): 199–214.

Brown, G. M., Jr. and J. Hammack. "A Preliminary Investigation of the Economics of Migratory Waterfowl." In *Natural Environments: Studies in Theoretical and Applied Analysis,* John V. Krutilla (ed.), Johns Hopkins University Press, Baltimore, 1974.

Clark, C. *Mathematical Bioeconomics: The Optimal Management of Renewable Resources.* Wiley, New York, 1976.

Crutchfield, J. A. and A. Zellner. "Economic Aspects of the Pacific Halibut Fishery." U.S. Department of the Interior, Washington, D.C., 1962.

Crutchfield, S. R. "A Bioeconomic Model of an International Fishery." *Journal of Environmental Economics and Management* 10(1983): 310–28.

Lancaster, K. J. "A New Approach to Consumer Theory." *Journal of Political Economy* 74(1966): 132–57.

Lewis, T. R. "Optimal Resource Management Under Conditions of Uncertainty: The Care of an Ocean Fishery." Unpublished Ph.D. Dissertation, University of California, San Diego, 1975.

Lotka, A. J. *Elements of Mathematical Biology.* Dover, New York, 1956.

McConnell, K. E. and J. G. Sutinen. "Bioeconomic Models of Marine Recreational Fishing." *Journal of Environmental Economics and Management* 6(1979): 127–39.

Pollak, R. A. and M. L. Wachter. "The Relevance of the Household Production Function and Its Implications for the Allocation of Time." *Journal of Political Economy* 83(1975): 255–77.

Robinette, W. L., N. V. Hancock, and D. A. Jones. *The Oak Creek Mule Deer Herd in Utah.* Utah State Division of Wildlife Resources, Salt Lake City, Utah, 1977.

Sorg, C. F. and J. B. Loomis. "Empirical Estimates of Amenity Forest Values: A Comparative Review." Rocky Mountain Forest and Range Experiment Station General Technical Report RM-107, Fort Collins, Colorado, 1984.

Wennergren, E. B., H. H. Fullerton, and J. C. Wrigley. "Estimation of Quality and Location Values for Resident Deer Hunting in Utah." Utah Agricultural Experiment Station Bulletin 488, Utah State University, Logan, Utah, 1973.

Wilson, J. A. "The Economical Management of Multispecies Fisheries." *Land Economics* 58(1982): 417–34.