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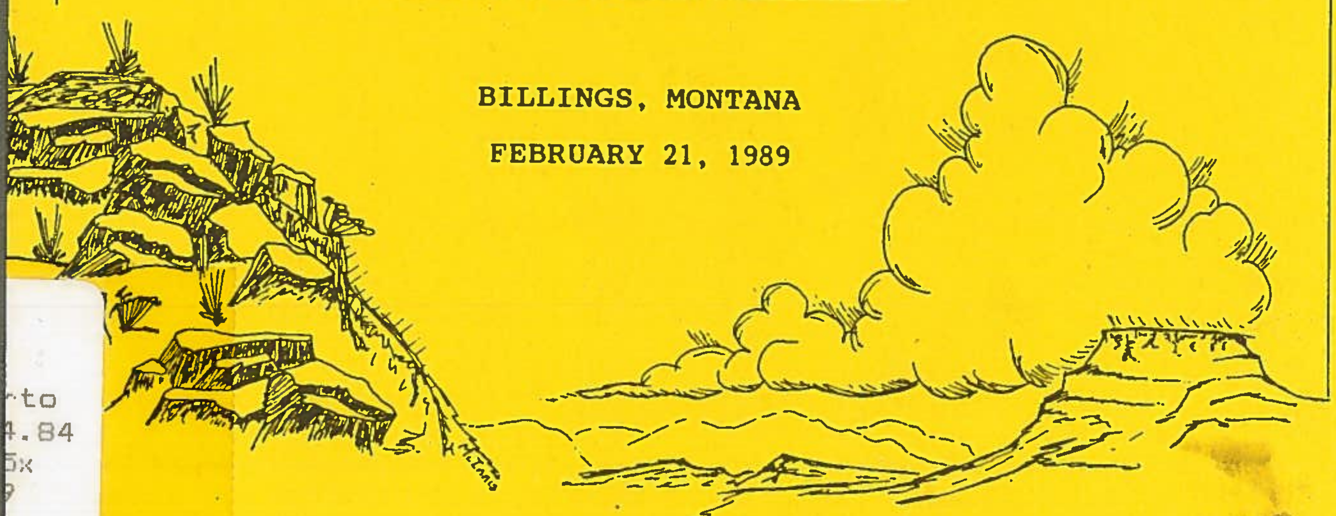

CALIFORNIA'S HARDWOOD RANGELANDS
- A DYNAMIC POLICY ANALYSIS -

by Richard Standiford and Richard Howitt
University of California Dept. of Forestry and Res. Mgmt., Berkeley and
Dept. of Agricultural Economics, Davis

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Introduction

California has 7.4 million acres of oak woodlands or hardwood rangelands (Bolsinger). These areas have at least a 10 percent tree cover, predominantly oak species (*Quercus* sp.), and an understory of annual grassland species. Almost 70 percent of the area is privately owned and has been historically managed for livestock production. Hardwood rangelands are also important habitat for many game and non-game wildlife species with an estimated 110 species of birds (Verner) and at least 60 species of mammals (Barrett). Other public values obtained from these hardwood rangelands include water production, outdoor recreational opportunities, and intangible aesthetic values.

In recent years, concern about the long-term sustainability of oaks on hardwood rangelands due to the apparent poor regeneration of some species in certain geographical areas of the state (Muick and Bartolome; Bolsinger), has resulted in increased pressure to regulate oak tree harvesting. A recent survey indicates that hardwoods on rangelands have decreased by perhaps 1.2 million acres in the period from 1945 to 1973 (Mayer et al). Concern about the potential profitability of traditional range livestock operations on hardwood rangelands, coupled with rapidly escalating land prices due to subdivision pressure in the state's foothill regions, is driving many large areas of open space into small. This is another area of concern in assessing sustainability of the resource. After careful study of several reports (Mayer et al; Muick and Bartolome; Passof and Bartolome), current state policy calls for a program of research, intensive extension outreach, and monitoring to see if adequate oak conservation efforts can be achieved voluntarily.

This heightened political interest in the state's hardwood rangelands makes it important to evaluate whether optimal oak retention levels for hardwood range landowners operating under strictly private incentives without constraints created by public regulations are sufficient to meet public values. The major economic forces impacting oaks in the hardwood range areas of the state through the mid 1970's were firewood harvesting, and oak tree removal for range improvement. However, recent increases in recreational hunting demand has created new market opportunities for hardwood range owners. Since the principal upland game species in the state, namely deer, quail, turkey and feral pig, are all enhanced by stands of oak (Barrett), then landowners who are able to market hunting rights would be able to capture private economic benefits from the retention of oaks, despite the fact that wildlife species are public goods.

Study Objectives

The objective of this study is to develop a dynamic model of hardwood rangeland management activities using current biological and economic data. Firewood production, livestock production, and commercial hunting will be incorporated into a multiproduct objective function to model the supply-side response hardwood range owners. This will allow optimal oak canopy levels to be calculated over time. This information will be of value to policy makers evaluating different policy instruments to achieve society's goals for outputs from hardwood rangelands, and for individual landowners who are seeking to find the optimal mix of products from their hardwood rangelands to maximize economic returns to the land.

A Theoretical Optimal Control Model

An optimal control framework will be used to model the behavior of hardwood range managers. This methodology is used because of the dynamic tree and forage growth, changes in the livestock herd over time, and interaction of the various components of the system over time. The objective function is to maximize the net present value from firewood harvesting, livestock production, and commercial hunting. The state variables for this framework are the stocks of oak trees and livestock density. Amount of oak firewood cut, or livestock sold (or bought) are the control variables. The dynamic bioeconomic system is shown in equation (1) below. A description of the variables arc given in Appendix 1. The equations of motion and production functions will be based on empirical studies.

(1) MAX NPV=

$$\int_{t=0}^{T} e^{-rt}\{PWD_t*WDSEL_t+HR_t(WD_t,exog.)+PRCOW_t*CS_t-HRD_t*VC_t-PFEED_t{}^{f}*[FN(HRD_t)-FOR_t(CLI_t,WD_t,SITE)]-FC_t\}$$

S.T.

$\dot{WD}_t = F(WD_t, SITE, species)-WDSEL_t$ [Equation of motion for oaks]

$\dot{HRD}_t = G(HRD_t)-CS_t$ [Equation of motion for livestock]

$WD_0 = INITWD$ [Initial stock of wood]

$HRD_0 = INITHRD$ [Initial stock of livestock]

$WD_t-WDSEL_t >= 0$ [Wood cutting constraint]

Empirical Estimation of Production Processes

The estimation of the components of the model are described below. The variables for the following equations are described in Appendix 1.

Oak Tree Growth

The dynamic optimization process requires that tree growth can be assessed for differing stand densities to evaluate selective firewood harvesting impacts on future stand structure. Hardwood tree canopy stock impacts yields from livestock, recreation, and firewood enterprises.

Eighty-one study sites were selected covering a wide geographic range throughout the extent of the hardwood range area of the state in stands of pure blue oak (*Quercus douglasii*), mixed blue oak and interior live oak (*Q. wislizenii*) stands in the Sierra Nevada foothills, and mixed blue oak and coast live oak (*Q. agrifolia*) stands in the coastal foothills. Details on the methods followed for tree growth estimation are contained in Standiford and Howitt.

The results of the regression analysis of oak cubic foot growth is shown below.

(2) $\ln(PAI) = -6.2382 + .61157 * \ln(WD) + 1.2090 * \ln(SITE) \qquad R^2 = .79$

(12.54) (5.32)

(note: t values shown in parenthesis: all coefficients significant at .05 level)

Volume - Crown Cover Relationship

Crown cover is the most commonly used tree measure in range management and is highly correlated with wildlife habitat suitability and range forage production. The development of management recommendations for thinning hardwood range areas for multiple use outputs requires knowledge of the relationship between cubic foot volume and crown cover. This relationship is shown below.

(3) $\ln(CC) = -6.4860 + .42681 * \ln(WD) + .83366 * \ln(SITE) \qquad R^2 = .63$

(8.58) (3.59)

(note: t values shown in parenthesis: all coefficients significant at .05 level)

These relationships can be used to assess oak growth on hardwood rangelands with at least 50 percent of their basal area in blue oak.

Forage Production

A data set of 142 observations of forage production in the open and under several different oak canopy densities was collected from 4 different studies, representing time series ranging from 2 to 22 years (Jensen; McClaren and Bartolome; Kay; Heady and Pitt). The data set included forage yield for several different times within a given year, and crown cover percentage. McClaren and Bartolome have shown that overstory effect varies in different climatic regions, so seasonal rainfall and accumulated annual degree days were added to the data set (IMPACT, and RRIS).

A combined cross-section analysis for the 5 sample sites in the data set and time series analysis for the various years of data was carried out to predict forage yield as a function of overstory density and climatic variables. Accumulated seasonal rainfall was shown to be the most significant weather variable for explaining the interaction between forage yield and oak crown cover. The results of the regression analysis are shown below.

$$
\begin{aligned}
(4)\ \ln(FOR) = {} & 4.3314 \underset{(-5.53)^{**}}{- 2.8807*HFS} \underset{(-6.74)^{**}}{- 2.2442*SFS} \underset{(.40)}{+ .25612*SJER} \underset{(-2.62)^{**}}{- 1.6785*SF} \\
& \underset{(-3.20)^{**}}{- 2.0226*SIN} \underset{(-.73)}{- .0566*\ln(CC)} \underset{(6.23)^{**}}{+ .0188*\ln(CC*RN)} \\
& \underset{(-4.74)^{**}}{- .000185*\ln(CC*RN^2)} \underset{(8.00)^{**}}{+ .0162*HFS*DAY} \underset{(14.98)^{**}}{+ .0162*SFS*DAY} \\
& \underset{(4.39)^{**}}{+ .0126*SJER*DAY} \underset{(6.41)^{**}}{+ .0187*SF*DAY} \underset{(7.33)^{**}}{+ .0208*SIN*DAY}
\end{aligned}
$$

$R^2 = .86$

(note: t values shown in parenthesis: all coefficients significant at .05 level with **)

Hunting Production

90 ranches with recreational hunting programs were identified and a random sample of 60 was chosen and surveyed. Personal interviews were scheduled with the owner-operator and data was collected on the type of hunting lease, price of the hunting lease, number of hunters, hunter success, ranch location, wildlife habitat on the ranch, and detailed cost summaries. The major game species of interest in these surveys were deer, wild turkeys, and wild pigs. 55 usable surveys were obtained from these interviews. 28 of these ranches had more than one type of hunting. 49 of these ranches had deer hunting enterprises, 17 ranches had turkey hunting, and 25 had wild pig hunting.

Total revenue per acre and cost per acre functions were estimated using hedonic regression techniques (Rosen, 1974) to decompose the costs and revenues to the various physical and biological attributes of the hunting club. Since deer hunting was found on 49 of the 55 ranches, it was decided to restrict the analysis to areas with deer hunting, with the value from pig and turkey hunting that operated jointly on deer areas evaluated. The hunting revenue per acre function (HRA) is shown below.

$$(5)\ \ln(HRA) = \underset{}{2.8872} + \underset{(2.11)^{**}}{.0839*\ln(CC)} + \underset{(2.55)^{**}}{.726*\ln(SCEN)} + \underset{(2.22)^{**}}{.126*\ln(HINC)} +$$

$$\underset{(1.24)}{.0457*\ln(DRTRP)} + \underset{(1.99)}{.131*\ln(DRAUM)} + \underset{(3.06)^{**}}{.138*\ln(PPIG)} - \underset{(-2.80)^{**}}{.234*\ln(ACRE)} + \underset{(1.92)}{.108*\ln(ADVA)}$$

$R^2 = .69$

(note: t values shown in parenthesis: all coefficients significant at .05 level with **)

Total operating costs were normalized to a per acre basis. The linear cost function for the hunt club (HCA) is shown below.

$$(6)\ HCA = .71185 + \underset{(21.84)^{**}}{2.2893*ADVA} - \underset{(-1.19)}{.3818*GUIDE} + \underset{(1.80)}{.6787*TAG}$$

$R^2 = .91$

(note: t values shown in parenthesis: all coefficients significant at .05 level with **)

Firewood Harvesting

Firewood price offered to ranchers incorporates market value of the wood less any harvesting and processing costs. Since there is essentially no information on ranch level firewood prices for California, overall firewood harvesting and processing costs were estimated from data in Dammann and Andrews. All cost and production data was transformed to thousand cubic feet (MCF) per year for scaling purposes in the optimization estimation, and a standard 1000 foot skidding distance and 50 mile transportation distance assumed, and expressed in constant 1987 dollars.

The estimated firewood cost function (FCOST) is shown below.

$$(7)\ \ln(FCOST) = 7.396 - \underset{(8.021)^{**}}{.139*\ln(WDSEL_t)}$$

$R^2 = .90$

(note: t value shown in parenthesis: coefficient significant at .05 level with **)

To estimate actual firewood prices paid to ranchers, the entire optimal control model which will be described in subsequent sections was run, constrained by the actual firewood harvested over a 14 year period for different hardwood range forest types (Bolsinger). The shadow prices of the harvest constraint based on actual rancher cutting behavior represent the marginal cost of firewood harvesting. The marginal cost curve was integrated to give a firewood adjustment cost function (AC_t).

$$(8)\ AC_t = (586.274 + 2.939 * WDSEL_t) * WDSEL_t$$

Specification of the Model

The empirical estimates were used to develop a hardwood range owner's optimal control model using the general framework described in equation 1. The model was specified as a discrete time model with 3 seasons within the year for the range forage production, and yearly time increments for hunting and wood volume production. The ranch parcel size used for estimation was 1000 acres.

Objective Function

The objective function for this hardwood range model is to maximize discounted net revenue received from firewood harvesting, hunting revenue, and livestock revenue. Equation (9) below shows the objective function.

$$(9)\ \text{MAX} \sum_{t=1}^{T} \{DF_t * (WR_t + LR_t - LC_t + HR_t - HC_t)\} + TV_T$$

Equation (10) below shows the revenue from firewood in time t from the relationships derived in equations (7) and (8) above. The quantity of wood sold, $WDSEL_t$, is a control variable in this system.

$$(10)\ WR_t = (PWD - 1629.45 * (.01 + WDSEL_t)^{(-.139)} - 586.274 - 2.939 * WDSEL_t) * WDSEL_t$$

The livestock enterprise is assumed to be a cow-calf operation, the predominant type on hardwood rangelands in California (CDF). The livestock revenue in time t is composed of the sale of feeder calves (steers and heifers) and the sale of cull cattle.

The number of steers sold is a function of the calving percent of the herd, and the size of the herd. Herd size, HRD_t, is a state variable for this dynamic system. Calving percent is exogenous to the system.

$$(11)\ STSEL_t = HRD_t * (CLF/2)$$

The number of heifer calves sold is the difference between the number of heifer calves born and the number used as replacement heifers in the herd. The number of replacement heifers added to the herd is a control variable for herd size, and is determined in solution of the control model. The constraint below shows this relationship.

$$(12)\ HRD_t * (CLF/2) = HFSEL_t + REP_t$$

The overall livestock revenue equation for this system incorporates the sale of feeder calves as discussed above as well as any cull cattle sold in time t. There is an assumption of a 20 percent herd replacement, which means that cows are culled every 5 years, after 1 year as a replacement heifer. The weight and prices for the different classes of livestock marketed are determined exogenous to the model.

$$(13)\ LR_t = (STSEL_t *WTST*PRST) + (HFSEL_t *WTHF*PRHF + REP_{t-6}*WTCC*PRCC)$$

Costs of the livestock enterprise include variable costs and feed costs. Variable costs are based on the herd size, and the feed costs are based on the amount of feed purchased per season, which is a control variable estimated in the optimization.

$$(14)\ LC_t = HRD_t * VC + \sum_{j=1}^{3} PFEED_t*(FED_{j,t})$$

Hunting revenue and cost for the hardwood range parcel in time t is estimated based on the relationships in equations (5) and (6).

$$(15)\ HR_t = HUNT *17.942 * CC_t^{0.0839} *SCEN *^{0.726} *HINC^{0.126} *DRTRP^{0.0457} *(DRAUM_t/ACRE)^{0.131} *PPIG^{0.138} *ACRE^{(-0.234)} *ADVA_t^{0.108} * ACRE$$

$$(16)\ HC_t = HUNT * (.71185 + 2.2893*ADVA_t - .3818*GUIDE + .6787*TAG)*ACRE$$

The terminal value was assumed to be an infinite stream of future earnings for firewood, hunting, and livestock. Future firewood harvest was assumed to occur as an infinite series of 20 year cutting cycles with harvest equal to the 20 year oak growth. The future earning stream for hunting and livestock was assumed to be an infinite series of annual returns equivalent to the value in period T. Equation (25) shows the terminal value equation with is derived from equations (18) through (24).

$$(17)\ TV_T = DF_T*\{(HR_T - HC_T + LR_T - LC_T)/i\ +((PWD-1629.45*(.01+20*PAI_t)^{-.139} - 586.274-2.939*20*PAI_t)*20*PAI_t)/((1+i)^{20}-1)\}$$

Oak Equation of Motion

The oak equation of motion is composed of the parcel volume in the previous period plus the annual growth derived in equation (2) less the volume harvested for sale. The oak wood volume is a state variable for this optimal control model, and the quantity of wood sold is a control variable.

$$(18)\ WD_t = WD_{t-1} + (.00195*WD_{t-1}^{0.61157}*SITE^{1.209}) - WDSEL_t$$

The identity which converts wood volume to crown canopy in equation (3) to allow for the interaction of the oak cover with range production and hunting revenue enters the system as an equality constraint.

An additional constraint is added to to ensure that more wood cannot be sold than there is on the site.

$$(19)\ WD_t - WDSEL_t \geq 0$$

Cattle and Forage Equations of Motion

The cattle equation of motion is based upon the stock of cattle in the previous time period plus the number of cows added as replacement heifers, less the number of cattle culled and lost to mortality.

$$(20)\ HRD_t = (1\text{-}MORT)*HRD_{t-1} + REP_t - REP_{t-6}$$

The seasonal forage equation of motion assumes that forage growth on the annual grassland range occurs only in the first two seasons (i.e. September 1 through May 31), with the residual forage left in the summer available as low quality dry forage. The forage equation of motion, derived from equation (4) for the winter and spring seasons are shown below. The forage available is expressed in terms of total AUMs available for the season.

$$(21)\ FOR_{j=1,2,t} = AVL_j *(\exp((-0.057+ 0.0189* RN_{j,t} - 0.000185 * RN_{j,t}^{2}) *\ln(100-CC_t) + 4.3314 +SIINT + SISLP_*DAY_j)) *ACRE/FORQUNT_j$$

The total forage available in the summer is the difference between total production (peak standing crop) and what has been consumed in the winter and spring by cattle and livestock. The quantity of feed used in previous seasons enters the equation since this reduces consumption of the range forage, leaving more to consume during the summer period. This summer residual dry matter in the annual range is degraded due to the effects of shattering and nutrient leaching. The forage equation of motion for summer available forage is shown below.

$$(22)\ FOR_{j=3,t} = AVL_j* (1-DEG_j) *(FOR_{j-1,t}-CAUM_{j-1,t}-DERAUM_{j-1,t} + FED_{j-1,t} + FED_{j-2,t})$$

Livestock nutritional requirements were determined exogenously using the program COWFLOW (Bell) in which producers set livestock weights and target rates of gain allow seasonal AUMs to be calculated. Seasonal AUMs include the cows, bulls and calves depending upon the percent calving of the cows, and the percent bulls in the herd. Equation (23) below shows the determination of AUMs required by the livestock.

$$(23)\ CAUM_{j,t} = HRD_t * NUT_j$$

Forage availability constraints were determined by balancing forage availability against nutritional needs of the livestock. Forage availability was composed of forage production and the quantity of supplemental feed. The quantity of feed in season j and the allocation of AUMs to the hunting operation were control variables.

$$(24)\ FOR_{j,t} + FED_{j,t} - CAUM_{j,t} - DERAUM_{j,t} -RESID*ACRE \geq 0$$

The annual AUMs deferred from cattle production, which we are considering as allocated to deer production, contributes to the hunting revenue function in equation (15) above. This value is determined from the equation below, which balances out seasonal fluctuations in allocations to deer.

(25) $DERAUM_{j,t} \geq DRAUM_t$

Initial conditions for the stock of cattle and wood volume are specified in the model.

(26) $HRD_0 = INITHRD$
(27) $WD_0 = INITWD$

There are nonnegativity constraints on all state and control variables.

Results

With equation (9) as the objective function and equations (3) and (10) through (27) as constraints to the system, this discrete time optimal control model was solved for four control variables, namely forage allocation to hunting ($DRAUM_t$), supplemental feed purchased ($FED_{j,t}$), the number of cattle to hold off the market as replacement heifers (REP_t), and the quantity of firewood sold ($WDSEL_t$), and two state variables, namely the number of cow-calf pairs (HRD_t), and the standing volume of oak trees (WD_t). This system was solved using the GAMS/MINOS system (Brooke, Kendrick and Meeraus) for nonlinear optimization on an IBM-PC/AT clone. GAMS/MINOS utilizes a reduced gradient algorithm (Wolfe) combined with a quasi-Newton algorithm (Davidson) for solution of the nonlinear problem. The problem was solved over a 20 year planning horizon (T=20).

This initial phase of the research was completely deterministic. Future studies will concentrate on stochastic prices and weather conditions and evaluate how this variability influences optimal decisions. Appendix 1 shows the fixed parameters used for this analysis which represents average prices for 1987 (Doak and Stewart; CDFA; USDA). A number of different scenarios were evaluated. Three different range sites were evaluated based on the forage prediction equations developed in equation (4) above, namely Hopland Field Station (a relatively poor range site evaluated), Sierra Foothill Range Field Station (a medium quality range site), and the San Joaquin Experimental Range (a high quality range site). Initial livestock density (INITHRD) was kept constant for each individual site, with 50 cow-calf pairs on the poor range site, 60 cow-calf pairs on the medium site, and 150 on the high range site. Three different oak site indexes were evaluated, namely site index 30, 40 and 50, to represent poor, medium, and good oak stand growth conditions. Five different initial oak volume levels (INITWD) were evaluated, namely 250, 500, 750, 1000, and 1500 cubic feet per acre (or thousand cubic feet per 1000 acres). The effect of hunting was evaluated by solving the optimal control model with hunting present, and also without hunting. This range of conditions resulted in 90 different optimal solutions.

Effect of Hunting on Total Financial Return

As the introduction pointed out, total ranch profitability is one of the most important factors impacting conversion of hardwood rangelands to subdivisions and other more urbanized uses of the resource, and away from the large expanses of extensively managed open space that characterizes most hardwood range operations. The hypothesis is that hunting and firewood harvesting offers a broadened market base for hardwood range managers and improved conditions for better economic returns to the land, which may help to reduce conversions.

Figure 1 shows the net present value per acre (NPV) for a medium quality hardwood range site with 750 cubic feet per acre. This figure shows the major impact that hunting has on the total economic value of hardwood range management. On the poor hardwood range site, NPV is increased by 183 percent with hunting (from $84 to $238 per acre), and hunting is the dominant economic value on the site. On the good range site, hunting increases the NPV by 32 percent (from $467 to $616 per acre), although cattle production is the dominant economic value on this site. This figure shows the relatively minor contribution that firewood harvesting makes to the total economic value of the operation, with 4 percent of the NPV for the poor range site with hunting, and less than 1 percent for the good range site with hunting.

Figure 2 shows similar relationships for the poor and good range sites. As tree volume increases from 250 to 1500 cubic feet per acre, the trend is for the net present value for cattle to decrease and revenue from wood harvesting to increase.

Optimal Wood Harvest Levels

Figure 3 shows the cumulative firewood harvest over the 20 year control period for a medium quality oak site (site index 40) and a high quality oak site (site index

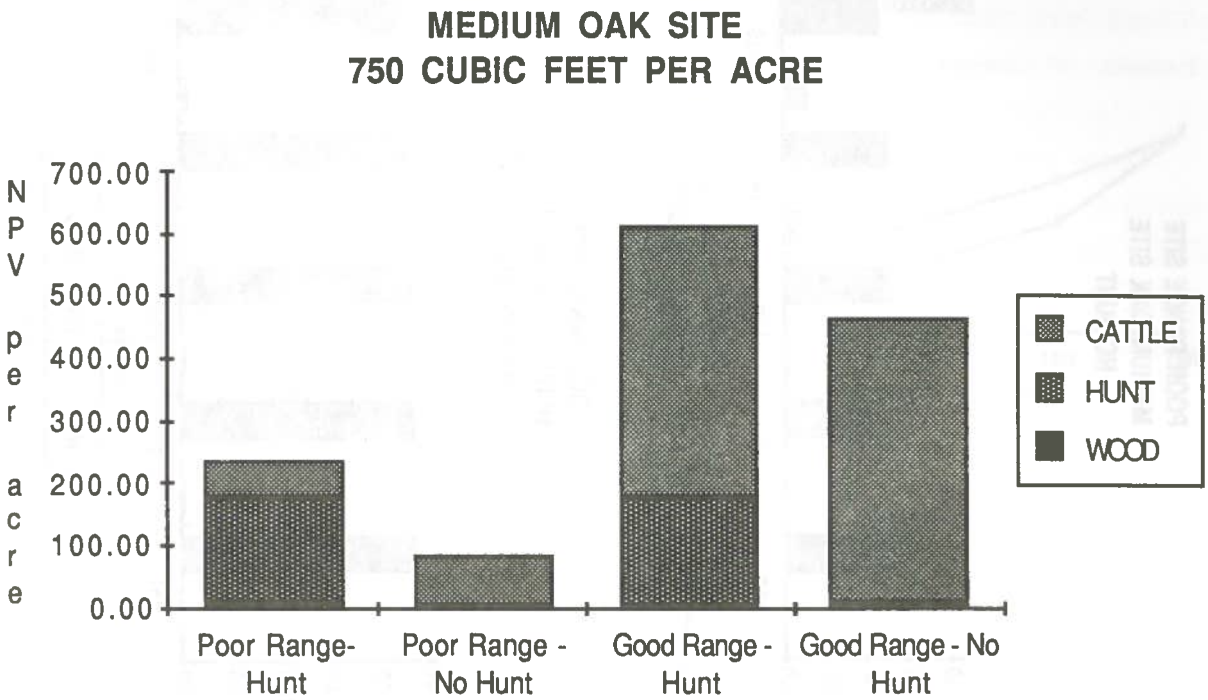

FIGURE 1. The effect of hunting, firewood harvest, and cattle production on net present value per acre for a medium quality oak site and a poor and good range site.

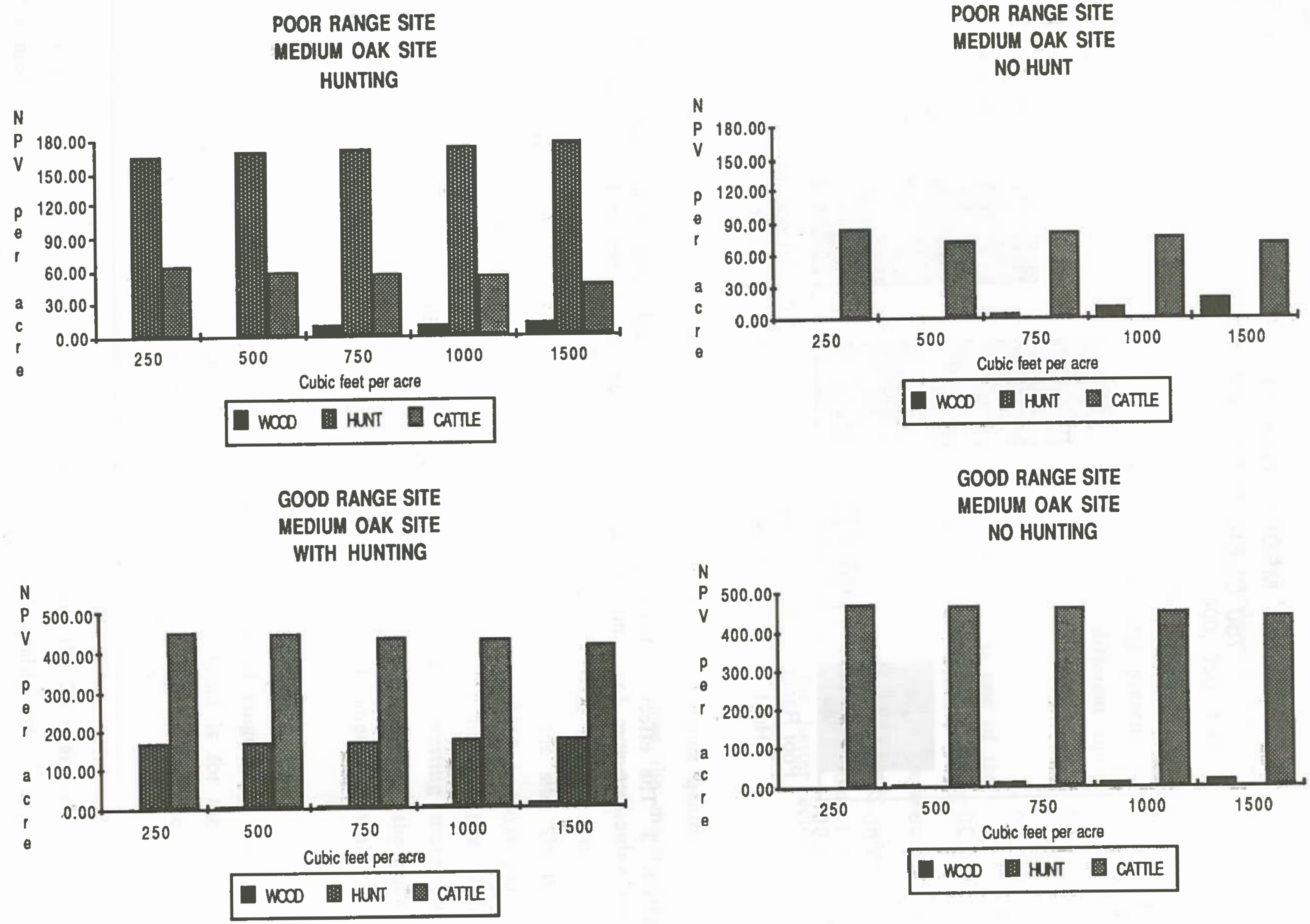

FIGURE 2. Contribution of firewood harvest, hunting revenue, and cattle to net present value for poor and good range sites and medium quality oak sites for different initial oak tree volumes per acre.

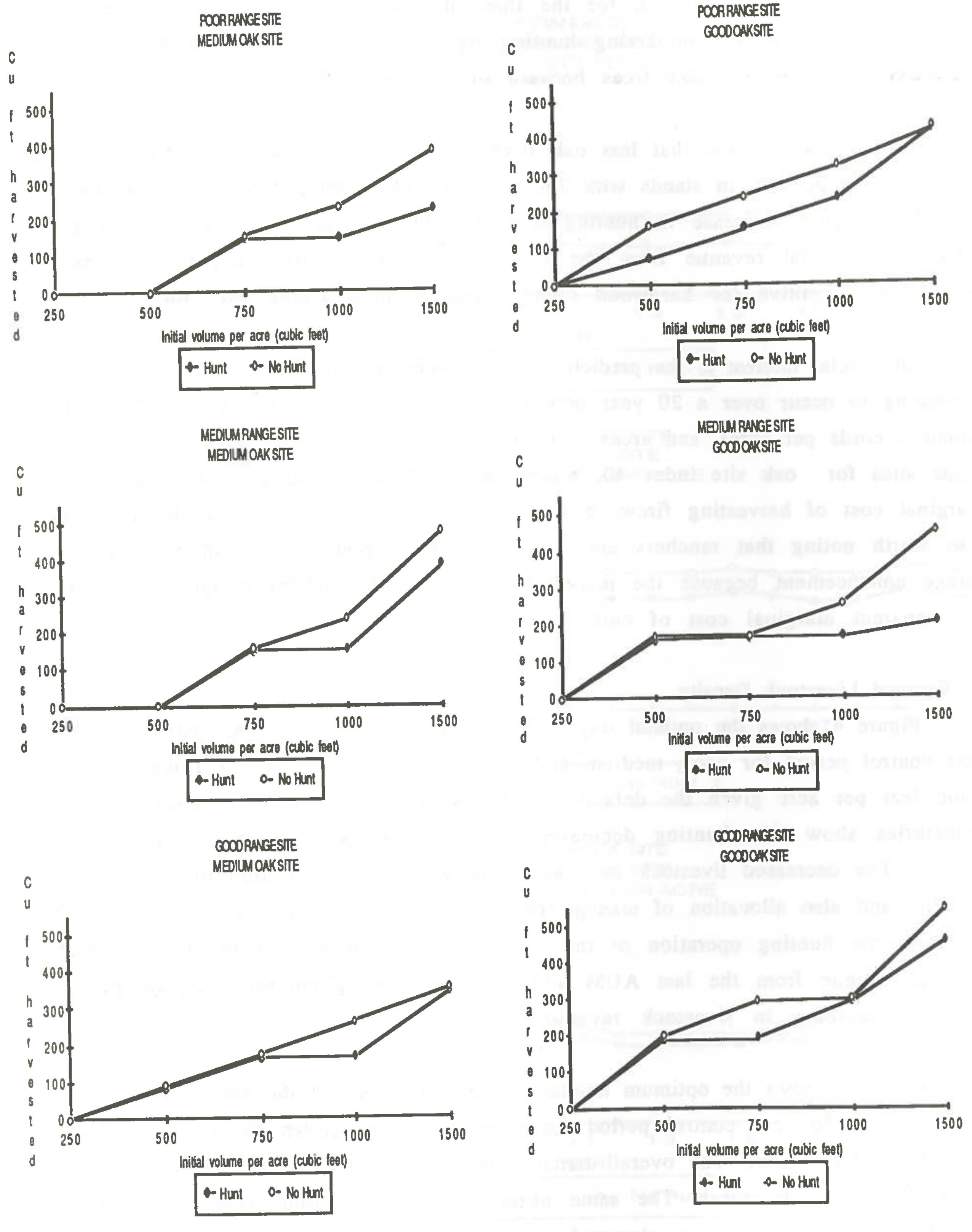

FIGURE 3. 20 year cumulative firewood harvest on two oak sites and three range sites for five different initial oak volumes per acre.

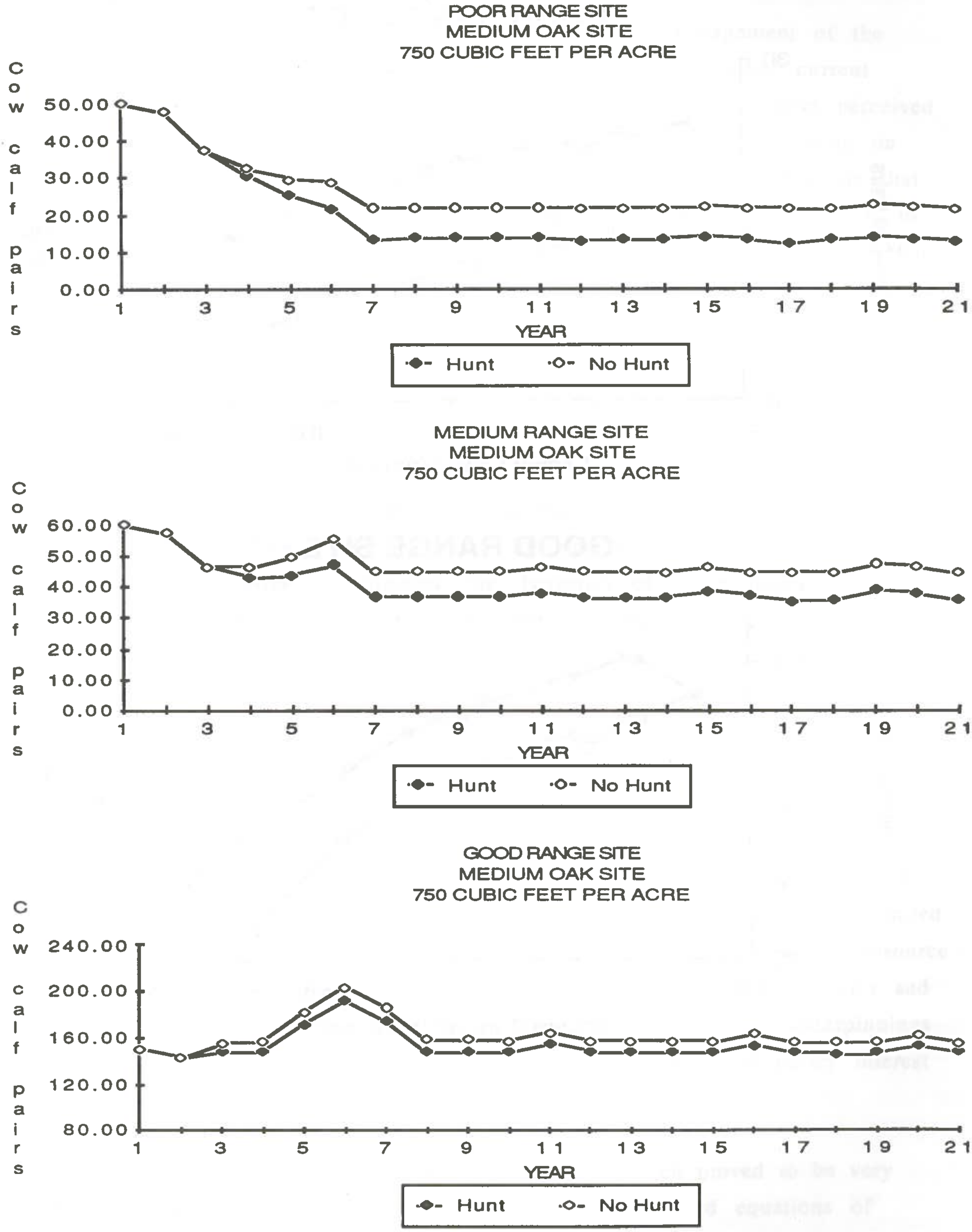

FIGURE 4. Optimum 20 year trajectory of cow-calf pairs on three range sites with an oak overstory of 750 cubic feet per acre.

50), with and without hunting, for the three different range productivity classes. The hypothesis was that the marketing hunting rights would provide a market mechanism to conserve oaks trees because of their wildlife habitat value.

These graphs show that less oak firewood harvesting occurs when hunting value is received, especially in stands with 750 to 1000 cubic feet per acre. This indicates that the marginal decrease in hunting revenue due to oak canopy changes is greater than the marginal revenue from the firewood harvest. Hunting apparently does provide an incentive for hardwood range managers to conserve oak trees.

Of special interest is the prediction that the optimum decision is for no firewood harvesting to occur over a 20 year period on areas with only 250 cubic feet per acre (about 3 cords per acre), and areas with 500 cubic feet per acre on poor and medium range sites for oak site index 40, regardless of whether hunting occurs. The marginal cost of harvesting firewood exceeds the market price at these levels. It is also worth noting that ranchers are not likely to completely clear their ranges for forage enhancement because the marginal revenue of the added forage is less than the apparent marginal cost of cutting trees.

Optimal Livestock Density

Figure 4 shows the optimal trajectory for the number of cow-calf pairs over the 20 year control period for poor, medium and good range sites for an oak canopy of 750 cubic feet per acre given the default initial conditions for herd size. These trajectories show that hunting decreases livestock density over areas without hunting. The decreased livestock use can be thought of as allocation of forage to wildlife, and also allocation of management effort to wildlife. The allocation of AUMs to either the hunting operation or the livestock operation are set so that marginal hunting revenue from the last AUM added to the hunting enterprise equals the marginal decrease in livestock revenue.

Figure 5 shows the optimum number of cow-calf pairs on the 1000 acre parcel following the 20 year control period for a range of oak crown canopy cover ranging from 25 to 90 percent. The overall trend is that as crown cover increases, the livestock density decreases. The same observation of decreased livestock intensity with hunting noted above is observed in these figures.

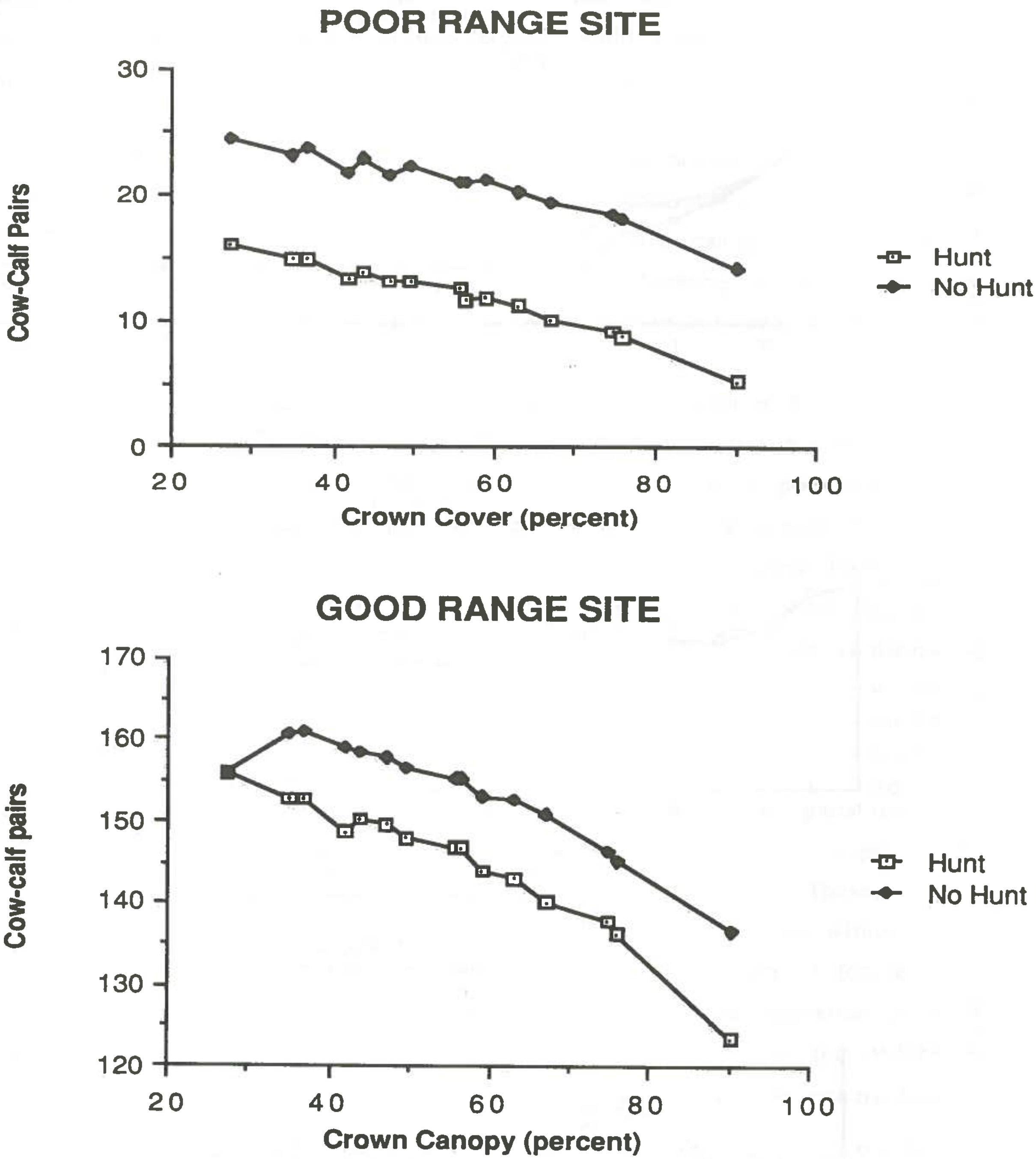

FIGURE 5. Optimum cow-calf pairs for different oak crown cover percents at the end of the 20 year control period for two range sites.

Discussion

Currently, there is great interest in California about the management of the hardwood range resource. Policy discussion is focusing upon whether current private market incentives provide for adequate stocks of oak trees to meet perceived public needs. New markets have developed recently for recreational hunting on private lands, and the preliminary results of the optimal control runs indicate that these markets may provide some incentive for mangers of hardwood rangelands to reduce their level of tree harvesting. This research indicates that it is unlikely that any level of firewood harvesting will occur on oak stands with low volumes per acre. The optimum livestock density shows that hunting will reduce the intensity of livestock use, which will reduce the pressure to enhance the forage base with tree harvest. There is no pressure to clear dense oak stands for improvement for livestock use based on the range of prices and costs used in this research.

Because of the dynamic nature of range problems, range economics is a classic subset of resource economics. However, it is surprising how little theoretical and empirical work has occurred investigating the dynamics of range resource problems. The typical approach has been to ignore the feedback between production periods, and treat range as an annual commodity rather than a resource, or to develop production curves of expected response over time to different management practices and evaluate management alternatives using partial budgeting.

One of the first uses of dynamics in range economics by Burt (1971) generated debate as to whether that this approach was unnecessarily sophisticated given the data limitations in providing adequate validation of the results (Martin; Burt, 1972). This debate about the appropriateness of dynamic analysis of range decisions limited the development of range economics in addressing the complex problems of resource protection, sustainability, and multiple use, while the fields of forest economics and fisheries economics made great strides in establishing the theoretic underpinnings that have been used in analysis of the complex resource problems of policy interest in today's resource management fields.

The optimal control methodology employed in this research proved to be very useful in assessing the dynamic nonlinear objective function and equations of motion. The model developed for this policy question had two state variables and four control variables, and could be solved on a personal computer using the GAMS/MINOS software. These technological breakthroughs in the field of operations research should enable range economists to employ techniques such as those described here.

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APPENDIX 1: List of Variables

ACRE = Acres in parcel
AC_t = Firewood adjustment cost
$ADVA_t$ = advertising spent per acre
AVL_j = percent forage available in season j
$CAUM_{j,t}$ = Cattle AUMs in season j, year t
CC_t = oak crown canopy percent
CLF = calving percent
$CLI_{j,t}$ = climatic variables in season j, year t
CS_t = calves sold in time t
DAY_j = Julian day (September 1 = day 1) at end of season j
DEG_j= forage degrade in season j=3
$DERAUM_{j,t}$ = AUMs allocated to deer in season j
DF_t= discount factor for time t
$DRAUM_t$ = AUMs allocated to deer on parcel (AUM's taken from livestock for hunting)
DRTRP = percent trophy deer
e^{-rt} = continuous time discount factor
FC_t= Fixed costs at time t
FCOST = Firewood harvest and process cost
$FED_{j,t}$ = supplemental feed in season j in year t
$FOR_{j,t}$ = forage quantity available in AUMs in season j, year t
$FORQUNT_j$ = pounds of forage required in season j per AUM
$FN(HRD_t)$= Livestock forage needs at time t
G = function describing change in livestock vector over time
GUIDE = guide service dummy
HCA = Hunting cost per acre
HC_t = hunting costs in time t
HFS = Hopland Field Station dummy
$HFSEL_t$ = number of heifer calves sold in time t
HINC = percent of hunters in high income category
HRA = Hunting revenue in dollars per acre per year
HRD_t = herd size in cows at time t
HR_t = hunting revenue in time t
HUNT = Hunting dummy (1=hunt; 0 = no hunt)
i = real interest rate
INITHRD = Initial stock of cattle at time 0.
INITWD = Initial stock of wood at time 0.
LC_t = livestock costs in time t
LR_t = livestock revenue in time t
MORT = percent of herd lost to mortality
NUT_j = seasonal AUMs required per cow
PAI = periodic annual increment in ft3/acre/year
$PFEED_t$ = price of supplemental feed in year t
PPIG = percent of area with pig hunting

PRCC = price of cull cows
$PRCOW_t$ = price for vector of livestock classes
PRHF = price per pound for heifer calves
PRST = price per pound for steers
PWD = Firewood price per 1000 cubic feet
REP_t = number of replacement heifers added to herd in time t
$RN_{j,t}$ = cummulative seasonal rainfall in season j, year t
SCEN = scenery quality
SF = San Felipe Ranch dummy variable
SFS = Sierra Field Station dummy variable
SIINT = range site intercept for forage equation
SIN = Sinton Ranch dummy variable
SISLP = range site slope coefficient for forage equation
SITE = oak woodland site index
SJER = San Joaquin Experimental Range dummy variable
$STSEL_t$ = number of steers sold in time t
T= terminal time period
TAG = a dummy for whether deer tags are provided
TV_T = terminal value of system at time T
VC = variable costs per cow
$WDSEL_t$ = volume of wood sold in MCF per 1000 acres
WD_t = wood volume in MCF per 1000 acres
WR_t = revenue from wood harvet in time t
WTCC = weight of cull cows
WTHF = weight of heifer calves sold
WTST = weight of steer calves sold

EXOGENOUS PARAMETERS

ACRE = 1000
$ADVA_t$ = $0.25
$AVL_{1,2}$ = 0.60
CLF = 0.90
DAY_1 = 150
DAY_2 = 270
DAY_3 = 365
DEG_3= 0.40
DRTRP = 44%
$FORQUNT_j$ = 800
GUIDE = 0
HINC = 100%
HUNT = 1=hunt; 0 = no hunt
i = 0.04
INITHRD (Hopland) = 50 head
INITHRD (Sierra) = 60 head
INITHRD (San Joaquin) = 150 head
INITWD = 250, 500, 750, 1000, 1500 cu. ft./ac

MORT = 0.05
NUT_1 = 4.9
NUT_2 = 10.9
NUT_3 = 5.9
$PFEED_t$ = $45.0
PPIG = 1.00
PRCC = $0.47 per pound
PRHF = $0.72 per pound
PRST = $0.76 per pound
PWD = $1769 per MCF
SCEN = 3
SITE = 30, 40, 50
T= 20 years
TAG = 0
VC = $120 per cow
WTCC = 1000 pounds
WTHF = 490 pounds
WTST = 550 pounds