A Bioeconomic Livestock/Wild Horse Trade-off Mechanism for Conserving Public Rangeland Vegetation

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The objective is to analyze a mechanism for controlling wild horse and livestock densities on public rangeland. The mechanism incorporates key ecological and economic parameters and is designed to be consistent with public interests in: (*a*) the multiple-use and sustained-yield management of rangeland vegetation, (*b*) the protection of wild horses, and (*c*) the prevention of economic harm to the western livestock industry.

Key words: grazing, public lands, wild horses, Bureau of Land Management.

The disposition of overpopulated wild horses on public rangelands is the focal point of a heated conflict between wild horse advocates and livestock interests. The Bureau of Land Management (BLM) is caught in the middle, searching for means to alleviate the grazing pressure exerted by competing herbivore groups on deteriorating public ranges.

Early rancher efforts to relieve the competitive grazing pressure on their livestock, by rounding up and slaughtering wild horses and burros, resulted in the passage of the Wild Free-Roaming Horses and Burros Act of 1971 (WFRHBA). The WFRHBA protects these animals from ". . . capture, branding, harassment, or death. . . ."[1] and directs public managers to ". . . manage wild free-roaming horses and burros in a manner that is designed to achieve and maintain a thriving natural ecological balance on the public lands."[2] The WFRHBA authorizes the BLM to remove animals in excess of the natural ecological balance ("excess animals") from rangeland by rounding them up for private adoption or for destruction if no adoption demand exists or they are old, sick, or lame.[3]

Under legal protection, the wild horse population increased from 17,000 in 1971 to 54,030 in 1978—about 23,000 horses in excess of a natural ecological balance as determined by the BLM (figures cited in this paragraph are found in Nack). Currently, about 7,000 uncaptured excess horses are backed up on rangeland for two major reasons. First, roundups have been impeded by judicial actions brought by animal rights activists.[4] Second, the BLM has not found an easy or inexpensive way to dispose of unclaimed captured horses. The BLM has refused to destroy them because of potentially great public opposition. Moreover, reduction by adoption has been slowed by animal rights activists' recent success in convincing a federal district court to order the BLM to withhold title from adopters who intend to exploit them for slaughter or as bucking stock in rodeos. Further, Congress has refused to authorize the Secretary of the Interior to sell horses outright after roundup.

The evisceration of the statutory wild horse

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[1] 16 U.S.C.A. sec. 1331 (1986), p. 136.

[2] 16 U.S.C.A. sec. 1333(a) (1986), p. 138.

[3] 16 U.S.C.A. sec. 1333(b)(2)(B) (1986).

[4] Cf. *American Horse Protection Association, Inc. v. Frizzell (Frizzell),* 403 F. Supp. 1206 (D. Nev. 1975); *American Horse Protection Association, Inc. v. Kleppe (Kleppe),* 6 E.L.R. 20802 (D.D.C. September 9, 1976).

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removal policy has resulted in the continued illegal slaughtering of uncaptured wild horses and the maintenance at great public expense of unclaimed captured horses (currently numbering about 8,670) in federal pens. Each horse costs taxpayers about $165 to capture and $2.25/day to sustain in captivity. The program has cost $92 million since 1980 (Nack).

Federal courts have directed the BLM to consider policy alternatives for relieving competitive grazing pressure on public rangelands. One alternative which the BLM must consider is to reduce livestock grazing allocated by federal grazing permits, i.e., to trade livestock allocations for excess wild horses (*Kleppe*). The design and mechanics of a livestock/horse trade-off mechanism remain unresolved issues in public rangeland management.

The objective of this paper is to consider a livestock/horse trade-off mechanism as a means of conserving rangeland vegetation. Up to now, the search for such a mechanism has centered on ecological arguments. The intended contribution of this paper is to broaden this conceptual basis to include both ecological and economic parameters.

Design Specifications

Statutory and Common Law Restrictions

A livestock/horse trade-off mechanism must be designed to meet the multiple-use and sustained-yield management principles dictated by the Federal Land Policy and Management Act (FLPMA).[5] Multiple-use management has been interpreted by federal courts to require that a trade-off can give neither livestock nor wild horses an exalted status over the other (*Frizzell*). Hence, the competing grazing groups must be made to coexist unless livestock permittees elect voluntarily for nonuse of their allotments. Sustained-yield management requires that periodic forage consumption by livestock and wild horses be no greater than the periodic growth (sustained yield) generated by a government-determined[6] standing vegetation level. The sustained vegetation level must be adequate to satisfy the needs of nongrazing multiple uses such as the protection of ecosystems (plant, fish, and wildlife) and environmental quality (e.g., watershed protection).[7]

Moreover, a trade-off mechanism should operate compatibly with the federal interest in developing grazing policies that ". . . prevent economic disruption and harm to the western livestock industry. . . ."[8]

Finally, a trade-off mechanism should be designed consistent with the Experimental Stewardship Program instituted in the Public Rangeland Improvement Act of 1978 (PRIA) to ". . . explore innovative grazing management policies and systems which might provide incentives to improve range conditions."[9]

In many ways, these statutory restrictions on the design of a livestock/horse trade-off mechanism are similar to the political constraints imposed in designing pollution reduction policies. In the pollution reduction arena, issues conventionally have revolved around realigning traditional use patterns to effect environmental quality improvement without unduly and adversely affecting original users, often those with historical rights. Recently, emphasis also has been placed on incentive-based mechanisms, such as charges- and right-based systems, rather than systems which allocate by fiat (e.g., standards) (Drayton).

Mechanism Design

The livestock/horse trade-off mechanism constructed in this article is designed to be consistent with the above restrictions, falling in line with others attempting to generate economic analysis appropriate to the public manager's decision-making environment (Keith and Lyon). First, the trade-off mechanism is constructed around a representative permit granting perpetual grazing rights to an allotment of publicly owned rangeland. Consistent with the PRIA, perpetual grazing rights are intended to give the permittee incentives for sustained management of vegetation that do not exist under the current arbitrary permit renewal policy. The grazing policy proposed by Gardner (1963, 1984) and echoed by Quigley and Thomas also calls for the creation of perpetual permits for the same reason.

Second, consistent with the FLPMA, the trade-off mechanism requires the public rangeland manager to specify the target sustained

[5] 43 U.S.C.A. sec. 1732(a) (1986).

[6] 43 U.S.C.A. sec. 315b (1986).

[7] 43 U.S.C.A. sec. 1702(c) (1986).

[8] 43 U.S.C.A. sec. 1901(a)(5), p.483 (1986).

[9] 43 U.S.C.A. sec. 1908(a) (1986), p. 486.

vegetation level needed to support nongrazing multiple uses. Hence, the mechanism does not attempt to select socially optimal vegetation, cattle, and wild horse population levels by incorporating demand-side analysis of multiple-use benefits. Demand-side information is assumed to enter the mechanism exogenously by affecting the manager's determination of a target sustained vegetation level.

Third, the mechanism is based on policy instruments that the BLM is empowered to employ in manipulating population densities of wild horses and livestock on a given permittee's grazing allotment. Consistent with the WFRHBA, the BLM can manipulate wild horse density by the rate, δ, at which wild horses are captured and removed from the allotment. Consistent with the PRIA, the BLM can manipulate livestock density by increasing (decreasing) the grazing fee assessed in a permit, *gf* [\$/head/time (t)], as an incentive for the permittee to stock less (more) cattle.

The trade-off mechanism operates to determine the combinations of δ and *gf* which induce a permittee to select a cattle stocking density that, when combined with the wild horse density, results in a sustained standing vegetation density satisfying multiple-use criteria under the FLPMA. Moreover, consistent with the federal interest in preventing economic disruption, the mechanism determines the combinations of δ and *gf* which hold the permittee's present value of public grazing steady at an agreed prior level. The Gardner (1984) proposal also calls for the BLM to set the grazing fee in permits at the level necessary to hold present value at the status quo level for equity reasons. The intersection of the two sets provides the unique combination of δ and *gf* which achieves both goals. This unique combination enters the permittee's grazing permit as a decision-making parameter.

This work extends the conceptual underpinnings of the Gardner proposal by providing an analytical framework that: (*a*) endogenously determines a grazing fee which induces the level of grazing desired by public range managers while holding permit value constant, and (*b*) specifically deals with the impact of grazing competition from wild horses.

An Ecological Interaction Model

Let V [lbs. dry matter (d.m.)/acre], H (head/acre), and L (head/acre) be the population densities of standing vegetation, wild horses, and livestock, respectively. Then the net rate of change of standing vegetation over time is

$$(1)\qquad \dot{V} = G(V) - Cn_H(V)H - Cn_L(V)L,$$

where $G(V)$ is periodic growth of vegetation (lbs. d.m./acre/t), and $Cn_H(V)$ and $Cn_S(V)$ are the vegetation consumption rates (lbs. d.m./head/t) by wild horses and livestock, respectively. Following the seminal grazing model of Noy-Meir (1975, 1976), the functions are assumed to be dependent solely on the density of standing vegetation.

Periodic vegetation growth, $G(V)$, is assumed to increase at a decreasing rate when density is low but to decrease at higher densities due to the increased competition among plants for vital resources (e.g., water and sunlight). The logistic curve meets these criteria,

$$(2)\qquad G(V) = a_V V - b_V V^2,$$

where a_V and b_V are positive: a_V is the maximal possible vegetation growth rate, and b_V measures the degree of density dependence. Maximum sustained vegetation yield occurs at $V^{msy} = a_V/2b_V$. In the absence of wild horses and livestock, V reaches an equilibrium at carrying capacity, $V^{cc} = a_V/b_V$.

The vegetation consumption rate for horses and livestock is assumed to be proportional to the vegetation density,

$$(3)\qquad Cn_i(V) = \alpha_i V,$$

where $i = H, L$; and $\alpha_i > 0$. The simplicity of the proportionality assumption is strictly a concession to the complexities added by considering two herbivores. A drawback of a proportional consumption rate is that it permits increasing consumption over all vegetation densities. In reality, there is some maximum periodic consumption rate which can be modeled with a saturation-type function [where $Cn_i'(V) > 0$ and $Cn_i''(V) < 0$]. However, use of a saturation function for both horses and livestock greatly obscures the analytical results. Moreover, the proportionality constant, α, can be set so that (3) approximates a saturation function at a vegetation density of interest (e.g., the level of V satisfying multiple-use criteria).

Finally, the population dynamics of wild horses on the permittee's grazing allotment is assumed for analytical simplicity to be solely dependent on its own density,[10]

(4) $\dot{H} = a_H H - b_H H^2 - \delta H = (a_H - \delta)H - b_H H^2,$

where all parameters are positive: a_H is the maximal possible growth rate of wild horses, b_H measures the degree to which specific density restricts growth, and δ is the rate at which the BLM removes wild horses from the grazing allotment. As $t \to \infty$, H approaches a long-run equilibrium, $H^e = (a_H - \delta)/b_H$. When the removal rate is zero ($\delta = 0$), H approaches $H^{cc} = a_H/b_H$, where H^{cc} is the natural carrying capacity of the range for wild horses.

An Economic Model of Optimal Stocking on Public Rangeland

The permittee is assumed to stock cattle on public rangeland to gain weight—not to reproduce—and hence the model makes no provision for their fecundity. Thus, the model is applicable to "stocker" operations (wherein animals are purchased, fed on range, and sold after achieving a desired weight) which comprise a significant portion of public rangeland cattle operations. The permittee further is assumed to allocate an exogenously determined initial inventory of stocker cattle between the range and the next-best feeding alternative, e.g., dry-lot feeding. Abstracting from the complexities presented by cattle fecundity and the market dynamics of the overall animal investment decision allows the model to focus on the complexities of selecting an optimal stocking rate for livestock in the face of a competitive herbivore (wild horses).[11]

Weight gain per head of cattle, $W(V)$ (lbs./animal/t), is assumed to be proportional to the vegetation consumption rate,

$$W(V) = mCn_L(V), \tag{5}$$

where $m > 0$ is the forage conversion parameter. A drawback of this weight-gain function is that it permits weight gain even at the lowest forage levels when, in reality, an animal must consume a certain amount of vegetation to maintain current weight. However, a large degree of analytical complexity can be averted by using (5) and scaling down the forage conversion parameter, m, to reflect after-maintenance weight gain at a vegetation level of interest.

Let r be the periodic discount rate, p the price per pound of weight, L the stocking rate, and $C(L)$ the instantaneous costs of holding livestock on range. Then the permittee's economic problem is to select the sustained stocking rate which maximizes the present value of weight-gain net benefits (\$/acre) in the midst of a competing forager,

$$\max_{L} \int_0^\infty e^{-rt}[pW(V)L - C(L)]\, dt, \tag{6}$$

subject to (1), (4), and restrictions on the stocking rate $0 \leq L \leq L^{max}$ (where L^{max} is the maximum number of animals which the permittee can stock in a period). The cost structure, $C(L)$ (\$/acre/t), is modeled as,

$$C(L) = (\pi + gf)L, \tag{7}$$

where π (\$/head/t) represents the sum of incidental and opportunity costs (e.g., the net returns from the next-best feeding alternative such as dry-lot feeding) of holding livestock on public rangeland. The periodic grazing fee assessed by the BLM in grazing permits is gf (\$/head/t).

The linearity of the objective functional in the stocking rate is based on two justifications. First, periodic revenues are linear in the stocking rate because the permittee faces a perfectly elastic demand curve for livestock output. Second, multispecies models such as this often assume costs are linear in the stocking rate for analytical tractability (Wilen and Brown; Mesterton-Gibbons). The costless stocking adjustment formulation is a useful approximation to the costly adjustment formulation since both call for the same type of stocking adjustments needed to approach economically optimal sustained vegetation levels. The problem is that the costless formulation overestimates the rate at which adjustments occur. However, this is not a large problem for the livestock/horse trade-off mechanism developed below. The mechanism's goal is to manipulate steady-state vegetation levels to achieve public policy goals—not to manipulate the rate of approach.

[10] The absence of an interaction term between horses and cattle in (4) is another concession to the analytical tractability of the solution procedure. Attempts to solve a more general model greatly obscured the insights generated by this simplified version.

[11] The market equilibrium dynamics of herd inventory management have been published by Rosen and require the addition of the beef consumer sector of the economy. In focusing attention on inventory management, Rosen abstracts from the feeding problem by assuming a constant feeding cost per animal. Alternatively, we abstract from the inventory problem to focus on the livestock forage problem.

Solution Procedure

This problem is solved most easily using a modified version of the methodology developed by Spence and Starrett for most-rapid-approach problems (MRAP).[12] The essential condition for (6) to be a MRAP is linearity in $\dot{V}$ when augmented by constraints (1) and (4). This condition is met since solving (1) for L,

$$(8) \quad L = [1/Cn_L(V)][G(V) - Cn_H(V)H - \dot{V}],$$

and (4) for the trajectory, $H = H[H(0), t]$, and inserting the results into (6) yields

$$(9) \quad \max_{V,\dot{V}} \int_0^\infty e^{-rt}[M(V, H) + N(V)\dot{V}]\, dt,$$

where

$$M(V, H) = [pmCn_L(V) - (\pi - gf)] \cdot \{[G(V) - Cn_H(V)H]/Cn_L(V)\}$$
$$N(V) = -[pmCn_L(V) - (\pi - gf)]/Cn_L(V),$$

and $W(V) = mCn_L(V)$ by (5).

The methodology converts (9) (expressed in terms of V, $\dot{V}$, and H) into an ordinary calculus problem expressed solely in terms of V and H. First, define $J[V(t)] = \int_{V(0)}^{V(t)} N(\epsilon)\, d\epsilon$. Since $\dot{J} = N(V)\dot{V}$, (9) can be rewritten as

$$(10) \quad \max_{V,\dot{V}} \int_0^\infty e^{-rt}M(V, H)\, dt + \int_0^\infty e^{-rt}\dot{J}\, dt.$$

Next, integrate the second term by parts

$$(11) \quad \int_0^\infty e^{-rt}\dot{J}\, dt = \int_0^\infty e^{-rt}rJ(V)\, dt - J[V(0)],$$

and substitute the result into (10) to obtain

$$(12) \quad \max_{V} \int_0^\infty e^{-rt}[M(V, H) + rJ(V)]\, dt - J[V(0)].$$

The problem in (12) is solved by choosing V^* such that $u(V^*, H) \geq u(V, H)$, where

$$(13) \quad u(V, H) = M(V, H) + rJ(V) = [pmCn_L(V) - (\pi - gf)] \cdot \{[G(V) - Cn_H(V)H]/Cn_L(V)\} - r\int_{V(0)}^{V(t)} e^{-rt}[pmCn_L(\epsilon) - (\pi - gf)] \div Cn_L(\epsilon)\, d\epsilon.$$

Setting $u'(V) = 0$ yields an implicit function in V^*:

$$(14) \quad G'(V^*) - Cn_H'(V^*)H = r - \frac{(\pi + gf)Cn_L'(V^*)[G(V^*) - Cn_H(V^*)H]}{Cn_L(V^*)[pmCn_L(V^*) - (\pi + gf)]}.$$

Equation (14) represents a type of "modified golden-rule equilibrium" prevalent in renewable resource models, wherein the basic marginal-productivity (or golden) rule governing equilibrium—that the marginal productivity of the renewable resource stock, $G'(V^{gr})$, equals the discount rate, r—is modified by stock-dependent terms. The second left-hand-side term measures the negative impact of wild horse grazing on the marginal productivity of forage in livestock production and hence acts to decrease the steady-state vegetation level, V^*, from V^{gr}. The second right-hand-side term is a nonnegative "marginal livestock effect" that reduces the impact of the discount rate and thus acts to increase V^* from V^{gr}.

Substituting (2) and (3) for $G(V)$, $Cn_H(V)$, and $Cn_L(V)$, respectively, into (14) results in a time-dependent quadratic equation in V^* whose positive root yields an explicit expression for the singular path as a function of $H = [H(0), t]$,

$$(15) \quad V^*(H) = \tfrac{1}{2}\{-A(H) + \sqrt{A(H)^2 + 4r(\pi + gf)/2b_V pm\alpha_L}\},$$

where $A(H) = -[(a_V - r - \alpha_H H)pm\alpha_L + b_V(\pi + gf)]/2b_V pm\alpha_L$. Since $V^{*\prime}(H) < 0$ and $V^{*\prime\prime}(H) > 0$, the time-dependent singular path is a negatively sloped convex curve in $V - H$ space (figure 1).

Long-run Equilibrium

Long-run equilibrium occurs along the $V^*(H)$ curve at the intersection of the vegetation (VI) and wild horse (HI) zero-growth isoclines (figure 1). Zero-growth isoclines are generated by setting differential equations (1) and (4) equal to zero and solving for the resulting functions of V in H,

$$(16) \quad VI = (a_V - \alpha_L L)/b_V - (\alpha_L/b_V)H, \text{ and}$$

$$(17) \quad HI = H^e = (a_H - \delta)/b_H \geq 0.$$

Vegetation tends to decrease (increase) over

[12] Wilen and Brown used a similar modification to solve a multispecies problem where the harvested species feeds upon a prey species.

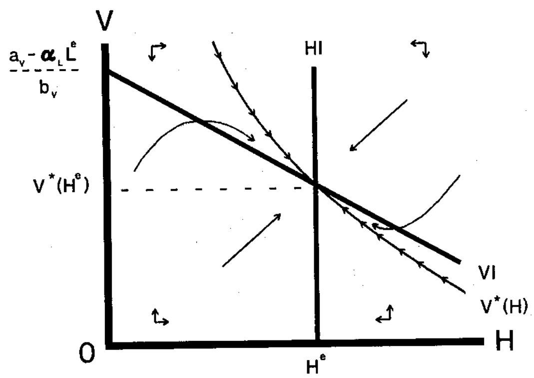

Figure 1. Long-run equilibrium

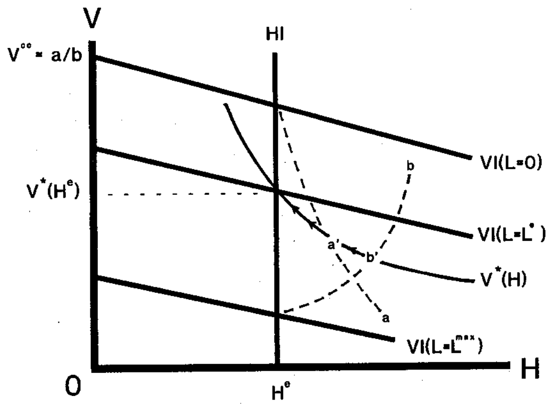

Figure 2. Optimal approach to equilibrium

time to the right (left) of VI since $\dot{V}'(H) < 0$ [by (1)]. The wild horse density tends to increase to the left of HI since population growth is greater than the constant removal rate. It tends to decrease to the right of HI since removal is greater than growth. Nonnegativity of long-run wild horse densities, H^e, implies that the long-run removal rate, δ, cannot exceed the maximum possible growth rate, a_H.

The optimal sustained vegetation stock at long-run equilibrium is $V^*(H^e)$ [by (15)]. The stocking rate, L^e, sustaining $V^*(H^e)$ is [by (8)],

$$(18)\quad L^e = (1/\alpha_L)[a_V - b_V V^*(H^e) - \alpha_H H^e] \geq 0,$$

where $\dot{V} = 0$ (since the system is in equilibrium). The equilibrium stocking rate, L^e, appears in the V-axis intercept of VI in figure 1. Equation (18) has a nice ecological interpretation. The first two bracketed terms, $a_V - b_V V^*$, measure the average sustained growth (ASG) of vegetation at the optimal sustained stock, i.e., $ASG = G(V^*)/V^*$, where $G(V)$ is given by (2). The third bracketed term, $\alpha_H H^e$, measures the average sustained consumption (ASC) of vegetation by wild horses at their long-run equilibrium level, H^e, i.e., $ASC = Cn_H H^e/V$, where Cn_H is given by (3). Hence, the entire bracketed term measures the residual average growth available for consumption by livestock, and (18) states that the long-run stocking equilibrium, L^e, will be proportional to this average residual. Nonnegativity of long-run stocking densities requires that the average residual also be nonnegative.

Optimal Approach Paths

Consider for a moment the optimal approach to long-run equilibrium from an initial condition away from it (figure 2). Since this is a most-rapid-approach problem, the solution involves selecting a sequence of stocking rates which approaches the singular path, $V^*(H)$, as rapidly as possible. If the initial vegetation density, $V(0)$, is below the singular path, $V^*(H)$, and to the right of H^e (point a), the rancher stocks at the minimum rate, $L^{min} = 0$, until vegetation grows up to $V^*(H)$ (point a'). If $V(0) > V^*(H)$ and $H > H^e$ (point b), the rancher stocks at the maximum rate, L^{max}, until vegetation is consumed down to $V^*(H)$ (point b'). As figure 2 shows, each stocking rate defines a new vegetation isocline whose dynamics must be obeyed while exercising that rate. Once the vegetation density is driven to the singular path, $V^*(H)$, the rancher tracks $V^*(H)$ toward equilibrium, $V^*(H^e)$, by stocking [using (8)]

$$(19)\quad L^* = (1/\alpha_L)\left[a_V - b_V V^*(H^e) - \alpha_H H^e - \frac{\dot{V}^*(H^e)}{V^*(H^e)}\right].$$

Construction of a Trade-off Mechanism

The objective of a trade-off mechanism is for the BLM to manipulate livestock densities (via the grazing fee, gf) and wild horse densities (via the wild horse removal rate, δ) on a grazing allotment in order to induce a sustained vegetation density satisfying multiple use, V^{mu}, while holding the permittee's present value of public grazing at some predetermined level. This section begins by deriving an iso-vegetation curve which is defined as the locus of δ and gf combinations that induce V^{mu} as a long-run equilibrium. An iso-present value curve then is derived as the locus of δ-gf combinations that hold present value constant.

Iso-Vegetation (I-V) Curve

The I-V curve is derived from (15) by: (*a*) setting vegetation density at V^{mu} and wild horse density at its long-run equilibrium value, $H^e = a_H - \delta/b_H$; and (*b*) solving for δ in terms of gf,

$$(20) \quad \delta^{I\text{-}V} = \left[a_H - \frac{b_H(r + b_V V^{mu})\pi}{\alpha_H pm\alpha_L V^{mu}} - \frac{b_H(a_V - 2b_V V^{mu} - r)}{\alpha_H} \right] - \frac{b_H(r + b_V V^{mu})}{\alpha_H pm\alpha_L V^{mu}} gf.$$

The long-run equilibrium densities of wild horses and livestock along the I-V curve are [by (17) and (18), respectively],

$$(21) \quad H(\delta^{I\text{-}V}) = [a_H - \delta^{I\text{-}V}]/b_H \geq 0 \text{ , and}$$

$$(22) \quad L(\delta^{I\text{-}V}) = (1/\alpha_L)[a_V - b_V V^{mu} - \alpha_H H(\delta^{I\text{-}V})] \geq 0.$$

The I-V curve has the following important characteristics. First, it is defined over the domain $gf^{H=0} \leq gf \leq gf^{Hcc}$ (figure 3). The removal rate associated with $gf^{H=0}$ along I-V is $\delta^{I\text{-}V}(gf^{H=0}) = a_H$, which implies that $H(\delta^{I\text{-}V}) = 0$ by (21). Removal rates above a_H imply negative long-run wild horse densities and thus are biologically irrelevant. Moreover, removal rates below the horizontal axis (i.e., $\delta < 0$) are policy irrelevant since the BLM is not looking to add wild horses to the range. The removal rate associated with gf^{Hcc} along I-V is $\delta^{I\text{-}V}(gf^{Hcc}) = 0$, which implies that $H(\delta^{I\text{-}V}) = H^{cc}$ by (21). The associated equilibrium stocking rate, L^e, is positive (zero) if the average residual growth after consumption by wild horses is positive (zero). [Refer to discussion after (18).]

Second, there is an inverse relationship along the I-V curve between gf and δ, reflecting the trade-off that must occur between wild horses and livestock in order to sustain V^{mu}. As gf increases from $gf^{H=0}$, $\delta^{I\text{-}V}$ decreases [by (20)], $H(\delta^{I\text{-}V})$ increases [by (21)], and $L(\delta^{I\text{-}V})$ decreases [by (22)].

Third, the I-V curve shifts downward with a decrease in a_H (maximum growth rate of horses), an increase in b_H (degree to which self-crowding limits horse population growth), or an increase in π (unit stocking costs). The first two changes relieve the grazing pressure exerted by wild horses and the last relieves the grazing pressure exerted by livestock since higher unit costs induce a lower cattle stocking rate. The downward shift indicates that when grazing pressure is reduced, lower wild horse removal rates are required to sustain a given vegetation level for all grazing fees. Note that if grazing pressure is sufficiently "low," the δ-axis intercept of the I-V curve can be negative. However, this will occur only in policy-irrelevant cases where negative removal rates (requiring that wild horses be added to the range) are necessary over a wide domain of grazing fees to increase consumption so that vegetation does not grow beyond V^{mu}.

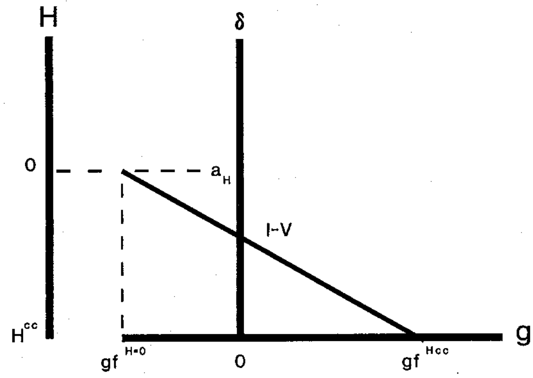

Figure 3. The iso-vegetation curve

Iso-Present Value (I-PV) Curve

The I-PV curve is derived by equating steady-state present value under the trade-off mechanism to that under a predetermined status quo (*sq*), i.e., $PV^{mu} = PV^{sq}$, or in terms of (6),

$$(23) \quad DF_t[pmCn_L(V^{mu}) - (\pi + gf)]L[H(\delta)] = DF_t[pmCn_L(V^{sq}) - (\pi + gf^{sq})]L^{sq},$$

where DF_t is the appropriate discount factor, and $L[H(\delta)]$ on the left-hand side is the long-run equilibrium livestock density given by (18). Solving (23) for δ in terms of gf yields,

$$(24) \quad \delta^{I\text{-}PV} = \gamma_1 + \gamma_2[\gamma_3/(\gamma_4 - gf)],$$
$$\gamma_1 = a_H - (b_H/\alpha_H)(a_V - b_V V^{mu}),$$
$$\gamma_2 = [pmCn_L(V^{sq}) - (\pi + gf^{sq})]L^{sq},$$
$$\gamma_3 = (\alpha_L/\alpha_H)b_H, \text{ and}$$
$$\gamma_4 = pmCn_L(V^{mu}) - \pi.$$

Routine algebra shows that $\gamma_1 \leq 0$ for $L^e \geq 0$ in (18). Parameter γ_2 measures periodic profits under the status quo and is assumed to be positive when $L^{sq} > 0$. Parameter $\gamma_3 > 0$ mea-

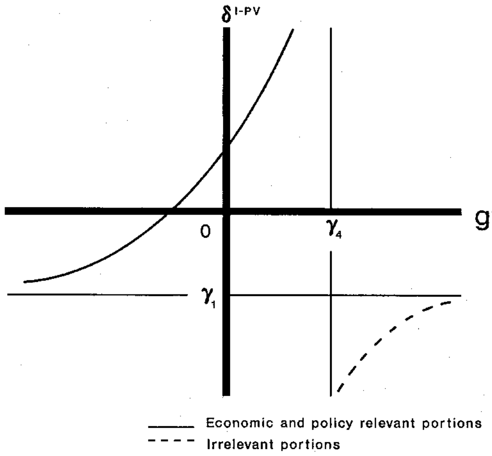

Figure 4. The iso-present value curve

sures the grazing efficiency of livestock relative to wild horses. Parameter $\gamma_4 > 0$ measures periodic profits under the trade-off mechanism before the grazing fee is paid.

For $\gamma_1 \leq 0$, and $\gamma_2, \gamma_3, \gamma_4 > 0$, the following can be shown (figure 4): (*a*) the *I-PV* curve has a horizontal asymptote at γ_1 and a vertical asymptote at γ_4, and hence is split into two sections; (*b*) the *I-PV* curve has a positive slope over the entire domain of *gf* and is convex for $gf < \gamma_4$ (leftward section) and concave for $gf > \gamma_4$ (rightward section), hence the leftward section monotonically increases from the horizontal asymptote to the vertical asymptote, and the rightward section monotonically increases from the vertical asymptote to the horizontal asymptote; and (*c*) parameters γ_2, γ_3, and γ_4 determine the marginal rate of removal needed to sustain permit value at PV^{sq}, i.e., $\delta^{I\text{-}PV\prime}(gf) = \gamma_2\gamma_3/(\gamma_4 - gf)^2 > 0$. Parameters γ_2 and γ_3 are directly related and γ_4 is inversely related to this marginal removal rate.

Portions of the *I-PV* curve below the horizontal axis imply a negative wild horse removal rate and are policy irrelevant as previously explained. Portions of the curve to the right of γ_4 imply negative periodic profits from stocking under the trade-off system and thus are economically irrelevant since the permittee is assumed not to stock under such conditions. Hence, the rightward section of *I-PV* is both policy and economically irrelevant.

Intersection of the I-V and I-PV Curves

The intersection of the *I-V* and *I-PV* curves yields the grazing fee/removal rate combination ($gf^{L/H}$, $\delta^{L/H}$) that generates livestock and horse densities satisfying both multiple-use and equity objectives. Setting the *I-V* and *I-PV* curves equal results in a quadratic equation in *gf* whose roots are given by

$$(25)\quad gf^{L/H}_{+,-} = \gamma_4 \pm \sqrt{\alpha_L\gamma_2(\gamma_4 + \pi)/(r + b_V V^{mu})}.$$

Call the root resulting from adding the second right-hand-side term $gf^{L/H}_{+}$ and the other root $gf^{L/H}_{-}$. Root $gf^{L/H}_{+}$ is always positive but irrelevant since it corresponds to the intersection of the *I-V* curve with an irrelevant section of the *I-PV* curve (i.e., the section occurring to the right of γ_4 and below γ_1). The other root, $gf^{L/H}_{-}$, can be either positive or negative. In figure 5, for example, if $I\text{-}V_1$ is the relevant iso-vegetation curve, then $gf^{L/H}_{-} = gf^{L/H}_{1}$ is positive. However, if $I\text{-}V_1$ shifts down to $I\text{-}V_2$, the intersection of the curves occurs at $gf^{L/H}_{2} < 0$. The associated removal rate, $\delta^{L/H}$, is given by either (20) or (24). The removal rate $\delta^{L/H}$ also can be either positive or negative; however the negative case is policy irrelevant.

Note that $gf^{L/H}$ greater (less) than gf^{sq} (status quo grazing fee) implies that $PV^{L/H}$ is greater (less) than PV^{sq}, and hence that grazing fees must be raised (lowered) from gf^{sq} to maintain permit value constant as PV^{sq}. A negative value for $gf^{L/H}$ implies that PV^{sq} so outweighs $PV^{L/H}$ that the permittee must be subsidized in the amount $gf^{L/H}$ in order to maintain PV^{sq}.

Numerical Illustration

As an example, values of $gf^{L/H}$ and $\delta^{L/H}$ can be calculated for a representative stocker operation on public rangeland. Such an example can only be illustrative at this time since the data needed to estimate the biological and economic parameters in the model generally are not available. Hence, the calculated values of $gf^{L/H}$ and $\delta^{L/H}$ cannot be compared meaningfully with their actual counterparts. However, some information is available on the empirical magnitudes of some key parameters. The standard values are recorded in table 1 along with footnotes detailing the sources. Hopefully, an illustration based on these rough calculations is valuable in pointing out the type of information the government should collect and one way of using it.

The status quo is assumed to be the following: the grazing fee is set by law at \$1.35/animal-unit-month (AUM) or about \$.045/head/

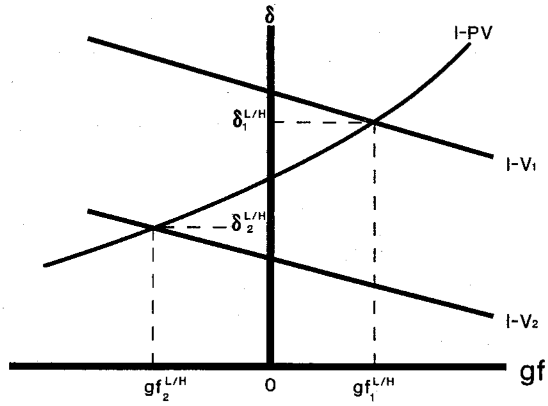

Figure 5. Intersection of iso-vegetation and iso-present value curves

day. The status quo stocking rate is regulated by the BLM. The average stocking rate on federal lands in the west is reported to be .15873 head/acre in a study by the U.S. Forest Service (FS) and the BLM. This figure is probably high for BLM land where wild horses roam since FS grazing land can generally sustain more cattle. Hence, L^{sq} is discounted down to .085 head/acre. The standing vegetation level sustained by this stocking rate is calculated to be 491.73 lbs./acre by (16). The current wild horse population is about 38,000 head—about 7,000 head in excess of a natural ecological balance as determined by the BLM (Nack). Assuming that 31,000 head is the long-run equilibrium that the BLM is approaching implies a status quo removal rate of .04% per day [by (17)]. Discounting the flow of economic rents over a single 150-day grazing season (and assuming that the grazing system is in equilibrium the entire season) results in a present value of grazing of $2.85/acre.

Public range managers typically have sought to control stocking rates to achieve vegetation levels maximizing sustained yield (Libecap). Hence, the vegetation target is assumed to be $V^{mu} = V^{msy} = 500$ lbs./acre.

The *I-V* (20) and *I-PV* (24) curves are

(26) $$\delta^{I\text{-}V} = .00044 - .00161\, gf, \text{ and}$$

(27) $$\delta^{I\text{-}PV} = -5.42E{-}20 + .0000922/(.2761 - gf),$$

and are plotted in figure 6. The combination

Table 1. Parameter Values Used in Illustration

Symbol	Meaning	Units	Value
α_L[a]	Consumption rate of veg. by cattle	acre/head/day	0.015
m[a]	Livestock feed conversion	—	0.05
α_H[b]	Consumption rate of veg. by horses	acre/head/day	0.036
a_H[c]	Max. growth rate of horses	day^{-1}	0.000411
b_H[c]	Density dependence of horses	$(\text{head/acre})^{-1}\ \text{day}^{-1}$	0.011508
a_V[d]	Max. growth rate of veg.	day^{-1}	0.00257
b_V[d]	Density dependence of veg.	$(\text{lbs. d.m./acre})^{-1}\ \text{day}^{-1}$	2.57E−6
π[e]	Stocking cost	$/head/day	0.01
p[f]	Beef price	$/lb.	0.7628
r[g]	Real daily rate of interest	—	0.000154

[a] The maximum rate of dry matter (d.m.) consumption by a 750-lb. steer placed on the range is reported to be 15 lbs. d.m. per day (Holechek). The steer is assumed to gain .75 lbs. per day. α_L is calculated assuming that livestock consume at the maximum rate when vegetation is at its carrying capacity, V^{cc}. A reasonable carrying capacity of western rangeland for vegetation is about 1,000 lbs. d.m./acre. Hence, $\alpha_L = 15/1{,}000 = .015$ [by (3)]. m is calculated as $.75/15 = .05$ [by (5)].

[b] The maximum rate of dry matter consumption by a horse on range is reported to be 36 lbs. d.m. per day (Holechek). α_H is calculated assuming that horses consume at the maximum rate when vegetation is at its carrying capacity, $V^{cc} = 1{,}000$ lbs. d.m./acre, so that $\alpha_H = 36/1{,}000 = .036$ [by (3)].

[c] The wild horse population grows on western rangeland at approximately 15% per year (.0411% per day). The carrying capacity is approximately 28 acres/head (.0357 head/acre). Taking the growth rate to be the maximum possible rate, a_H, the density dependent parameter can be calculated as $b_H = .000411/.0357 = .011508$. (Consultation with Frederick Wagner, College of Natural Resources at Utah State University.)

[d] a_V and b_V are constrained to satisfy

$$b_V = (1/V^{cc})[2\alpha_H(a_H/b_H)], \text{ and}$$
$$a_V = V^{cc} b_V.$$

The equation for b_V assumes that $\gamma_1 = 0$ in (24), i.e., that no cattle are stocked when horses are at their carrying capacity, H^{cc}, at V^{mu}.

[e] No information was located to help calculate a value for π. Hence, π was adjusted in the numerical simulations to reach a "reasonable" outcome.

[f] p is the average of feeder steer prices for July and August 1987 (when steers are assumed to come off the range) [U.S. Department of Agriculture].

[g] r is the daily interest rate on AAA corporate bonds for June 1987 less the percentage change in price from June 1986–87 (Federal Reserve Bulletin).

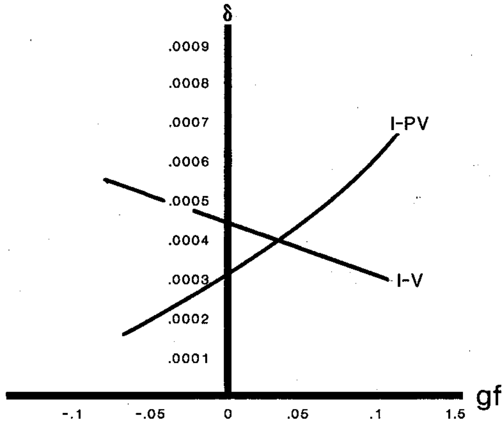

Figure 6. Illustration

of grazing fee and removal rate that induces livestock and horse densities sustaining both $V^{msy} = 500$ lbs. d.m./acre and $PV = \$2.85$/acre is $gf^{L/H} = \$.037$/head/day and $\delta^{L/H} = .039\%$ per day. Hence, the trade-off mechanism requires that the status quo grazing fee be reduced by $.008/head/day ($.24/AUM) and the status quo removal rate be decreased by 2.5% (.0004 to .00039 head/day). The permittee maximizes profits subject to $gf^{L/H}$ and $\delta^{L/H}$ by reducing the long-run equilbrium stocking rate by about 6% (.085 to .08 head/acre). Wild horse densities increase by about 152% (.0008825 to .0022385 head/acre), so that the total population increases from 31,000 to 78,124 horses (on 34.9 million acres of public grazing land).

Concluding Comments

The trade-off mechanism's design must be kept in mind when evaluating its results. The mechanism is designed consistent with the institutional framework in which the public range manager operates. In that framework, the manager is directed to specify the target level of sustained vegetation that satisfies multiple-use criteria. The values that the public places on various uses enter the specification indirectly through the manager's decision. Hence, the trade-off mechanism is not derived from an economic model maximizing social welfare as a function of the public demand for multiple rangeland uses. It follows that the mechanism's results cannot be judged on the basis of consistency with those generated by a social welfare-based model (Cory and Martin). Instead, inconsistent results between the two models must be viewed as reasons why the pursuit of objectives outlined in federal grazing statutes may be economically inefficient.

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References

Cory, D. C., and W. E. Martin. "Valuing Wildlife for Efficient Multiple Use: Elk Versus Cattle." *West. J. Agr. Econ.* 10(1985):282–93.

Drayton, W. "Getting Smarter about Regulations." *Harv. Bus. Rev.* 59(July–August 1981):38–52.

Federal Reserve Bulletin. Washington DC: Board of Governors, Federal Reserve System. June 1987.

Gardner, B. D. "A Proposal to Reduce Misallocation of Livestock Grazing Permits." *J. Farm Econ.* 45(1963): 109–20.

———. "The Role of Economic Analysis in Public Range Management." *Developing Strategies for Rangeland Management.* Boulder CO: Westview Press for National Research Council/National Academy of Sciences, 1984.

Holechek, J. "An Approach for Setting the Stocking Rate." *Rangelands* 10(1988):10–14.

Keith, J. E., and K. S. Lyon. "Valuing Wildlife Management: A Utah Deer Herd." *West. J. Agr. Econ.* 10(1985):216–22.

Libecap, G. *Locking Up the Range: Federal Land Controls and Grazing.* San Francisco: Pacific Institute for Public Policy Research, 1981.

Mesterton-Gibbons, M. "On the Optimal Policy for Combining Harvesting of Predator and Prey." *Nat. Resourc. Mod.* 3(1988):63–90.

Nack, W. "Bad Time for Wild Horses." *Sports Illust.*, pp. 28–35. New York: Time Inc., April 25, 1988.

Noy-Meier, I. "Rotational Grazing in a Continuously Growing Pasture: A Simple Model." *Agricultural Systems,* pp. 87–112. London: Applied Science Publishers Ltd., 1976.

———. "Stability of Grazing Systems: An Application of Predator-Prey Graphs." *J. Ecology* 63(1975):459–81.

Quigley, T., and J. Thomas. "Range Management and Grazing Fees on the National Forests—A Time of Transition." *Rangelands* 11(1989):28–32.

Rosen, S. "Dynamic Animal Economics." *Amer. J. Agr. Econ.* 69(1987):547–57.

Spence, M., and D. Starrett. "Most Rapid Approach Paths in Accumulation Problems." *Int. Econ. Rev.* 16(1975): 388–403.

U.S. Department of Agriculture. *Livestock and Poultry Situation and Outlook Report.* Table 45, November, 1987.

U.S. Forest Service and Bureau of Land Management. *Appraisal Report Estimating Fair Market Value of Grazing on Public Land.* PB84-242205 (1984):13–19.

Wilen, J., and G. Brown, Jr. "Optimal Recovery Paths for Perturbations of Trophic Level Bioeconomic Systems." *J. Environ. Econ. and Manage.* 13(1986):225–34.