THE DYNAMICS OF LIVESTOCK AND RANGELANDS UNDER COMMON PROPERTY REGIMES

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I. INTRODUCTION

Over 60 percent of the land area of sub-Saharan Africa is used primarily for the rearing of cattle, sheep, goats, and camels (FAO 1986). Most of the natural resources emanating from those rangelands are used collectively by a large number of individuals, households, and residential groups. Three economic models have been developed to depict resoure allocation in such situations: (1) the open-access model, (2) the corporate model of common property, and (3) the coordination or assurance model of common property. Gordon (1954) and Scott (1955) developed the open-access model to depict fisheries utilized by several anglers in the absence of institutional arrangements defining their resource-use patterns. Demsetz (1967), Hardin (1968) and others blurred the distinction between open access and common property until Ciriacy-Wantrup and Bishop's clear exposition of "common property as a social institution" in which property rights in resources are distributed among a number of owners who are "co-equal in their rights to use the resource (1975, p. 714)." More recent elaborations are found in Bromley (1989a, 1989b, 1991), Bromley and Cernea (1989), Larson and Bromley (1990), McCay and Acheson (1987) and a volume from the National Academy of Sciences (1986).

Several definitions of common property and common property regimes have been offered since 1975. We suggest here a definition that reflects the diversity of institutional arrangements and governance structures to be observed in the African rangeland context. In common property regimes, resource use is governed by diverse constellations of institutions -- rights, rules, and conventions -- that are enforced externally by a legitimate source of coercion, or internally by the actions of the resource users themselves. Indeed, some of these institutional arrangements are self-enforcing.

One fundamental difference between an open-access regime and a common-property regime is that a common property regime has a "boundary" that distinguishes between the "owners" and "non-owners" of particular benefit streams generated by collectively-used natural resources. Both the corporate model of common property and the coordination model of common property assume that there is a recognized group of resource owners whose rights to access and utilize particular resource benefit streams are protected by a legitimate unit of coercion that has the power to prevent encroachment by non-members. This structure provides the regime with the <u>external legitimacy</u> needed to differentiate it from an open-access resource.

Where the common property models differ is in their assumptions about the regime's internal institutional structure. The <u>corporate model</u>, as presented by Dasgupta and Heal (1979) and Dorfman (1974), assumes that the co-owners of the resource are able to devise explicit mechanisms for enforcing rules on resource access and allocation. The <u>coordination model</u>, or assurance model, offered by Runge (1981, 1986) proposes that there are certain conditions under which self-enforcing institutions are sufficient to support mutually-beneficial resource use.

We argue that these models are somewhat narrow and must be modified somewhat in their application to African rangeland regimes because they fail to account for the fluidity of the institutions, governance structures, production techniques, and environmental conditions that characterize those pastoral regimes. From our review of the theory and the empirical evidence on common property regimes, we suggest that much of the previous analysis has overlooked these internally enforced institutional arrangements. In this paper we suggest alternative formulations that account for the dynamics of African rangelands, the incentives and expectations of Africa livestock owners, the institutions governing the access and allocation of rangeland resources, and the systems of governance that define and enforce those institutions.

To understand the operations of African common property regimes, it is necessary to examine the decision-making of current and potential resource users. To that end, we develop a dynamic livestock-rangeland model that can be used to analyze the incentives, expectations, and conjectures of rangeland users under a variety of institutional arrangements. A conceptual model and a counterpart simulation model are presented. Two versions of the model are presented. The first version considers interactions between animals and rangeland when there is no human intervention. This formulation is appropriate for examining livestock/rangeland interactions in an uncontrolled environment such as the Serengeti plain of East Africa. The second version considers the livestock/rangeland interactions when there are a number of agents who own and manage the animals. This model is appropriate for examining a variety of institutional arrangements--rights, conventions, rules--that govern resource use in the common property regimes for African rangeland resources.

Before starting, we must note a limitation of this analysis. Specifically, the models used here implicitly accept the validity of the "succession" model of rangeland ecology. The results derived are thus most appropriate for "equilibrial systems" in which grasslands are dominated by perennial grasses and rainfall is relatively high and reliable. The models are less appropriate for "non-equilibrial systems" in which grasslands are dominated by annual species, and rainfall is low and erratic. A state-transition model would be more appropriate for non-equilibrium grazing systems (Behnke and Scoones 1991; Ellis and Swift 1989; Westoby et al. 1989).

II. A MODEL OF AN UNCONTROLLED RANGELAND

Imagine a well-defined area of rangeland with a permanent source of water that is grazed on a year-round basis by a number of homogeneous livestock. The average quantity of livestock products generated by each animal in each time period (APPt) is a function of the number of animals (Xt), and the rangeland's "pasture potential" (At). Most stocking-rate experiments support the hypothesis that there is a linear relationship between an animal's average physical productivity and the stocking rate (Sandland and Jones 1975). Jones (1981) suggests that the intercept of the linear relationship should be interpreted as a measure of "pasture potential." For current purposes, we define pasture potential as the quantity of livestock products that could be produced by an animal if it were alone on the rangeland during that time period. The slope coefficient (B) measures changes in average product as more animals are added. It can be regarded as a measure of "forage competition."

$$APPt = At - B\ Xt \qquad (1)$$

The total physical product in period t is the multiple of the average physical product (APPt) and the number of animals (Xt). With no other source of herd additions or reductions, changes in livestock capital between periods t and t+1 depend upon the total physical product in period t. Equation (2) is a difference equation that defines the dynamics of the livestock population.

$$Xt+1 - Xt = (At - B\ Xt)\ Xt \qquad (2)$$

Pasture potential (At) is fixed within growing periods but changes between periods as the matrix of forage species is affected by climatic conditions, livestock grazing pressure, and the "herd effect" caused by livestock trampling and agitating the grassland (Savory 1988). Experimental results suggest that rangelands are least sensitive to changes in the stocking rate at relatively high and relatively low levels of pasture potential (Holechek, Pieper and Herbel 1989; Staples and Hudson 1938). To capture this effect, equation (3) defines a variable called "pasture sensitivity" (St) over the feasible range of At (0,1). We assume that changes in pasture potential depend upon pasture sensitivity, livestock capital, and parameters whose values depend on rangeland area and ecological conditions. Relatively little long-term research has been conducted to support assumptions about the specific functional form for this relationship. Equation (4) has an arbitrarily-chosen non-linear functional form.

$$St = At\ (1 - At) \qquad (3)$$

$$At+1 - At = St\ (At - d\ Xt - h\ Xt^2\ )\ g \qquad (4)$$

where St $\equiv$ a measure of the sensitivity of the rangeland;

g, d, h ≡ parameters whose values depend on rangeland area and ecological conditions.

The difference equations (2) and (4) comprise a simple conceptual model of an uncontrolled livestock-rangeland system. To illustrate the model's results more graphically, specific values for the parameters in the two equations are assumed. Equation (5) is a specific form of the equation of motion for livestock capital, while equation (6) is a specific form of the equation of motion for pasture potential. Together, equations (5) and (6) comprise a simulation model of an uncontrolled livestock/rangeland system.

$$X_{t+1} - X_t = (A_t - 0.02\ X_t)\ X_t \qquad (5)$$

$$A_{t+1} - A_t = S_t\ (A_t - 0.0001\ X_t - 0.0008\ X_t^2)\ 0.1 \qquad (6)$$

The simulation model will be employed to give precise illustrations of the results derived from the conceptual model. For example, Figure 1 illustrates the time path that would be followed from an initial state in which the pasture potential equals 0.35 and the livestock capital equals 28. It is important to note that the functional form of equation (6) and the parameter values were selected arbitrarily. A different functional form or different parameter values would have resulted in a model generating different results. One wishing to specify this model for a particular situation would need ecological information collected from several plots over several time periods.

<Insert Figure 1>

II. A RANGELAND "CONTROLLED" BY SEVERAL LIVESTOCK OWNERS

A. The General Model

Suppose now that n independent agents, who may be individuals, families, or herding groups, own the livestock kept on the rangeland. The problem faced by a particular livestock owner, agent i, is to choose the amount of livestock capital (X_{it}) for each period (T) of the planning horizon to maximize the expected sum of discounted future profits derived from the sale of livestock (equation (7)). The equation of motion for pasture potential is presented in equation (8).[i]

$$\underset{\{X_{it}\}}{\text{Max}}\ E_t\{ \sum_{t=0}^{T-1} ß^t\, P\,(A_t - B\,X_t)\,X_{it} - C[A_t, X_{it}] \qquad (7)$$

$$A_{t+1} - A_t = g\,A_t\,(1-A_t)\,(A_t - dX_t - hX_t^2) \quad t = 1,\dots, T-1 \qquad (8)$$

$$X_t = \sum_{i=1}^{n} X_{it} \qquad (9)$$

$$C = C[A_t,X_t] \quad \text{where } \partial C/\partial A_t \le 0;\ \partial^2 C/\partial^2 A_t = 0 \qquad (10)$$
$$\partial C/\partial X_t \ge 0;\ \partial^2 C/\partial^2 X_t \le 0$$

A_0 is given

where $P \equiv$ the fixed price per unit of livestock output;
$C \equiv$ the total cost of herding input;
$y_t \equiv$ income generated in period t;
A_0 = pasture potential in period 0;
T = the terminal date;
$ß \equiv$ discount factor = 1 / (1 + discount rate).

The first order necessary conditions (assuming an interior solution) are given by equations (11) to (14). Second order sufficient conditions are satisfied by the convexity of the profit function.

$$\frac{\partial L}{\partial X_{it}} = P(A_t - B\,E\{X_t\}) - P\,B\,\partial E\{X_t\}/\partial X_{it} - \partial C_i/\partial X_{it} \qquad (11)$$
$$- \mu_t\,(g\,A_t\,(1-A_t)\,(\partial E\{X_t\}/\partial X_{it}\,(d + h\,2\,E\{X_t\})) = 0 \quad t = 1, \dots, T-1$$

$$\frac{\partial L}{\partial A_t} = P\,X_{it} - \partial C_i/\partial A_t + \mu_t\,(1 + g\,(1 - 2A_t) * \qquad (12)$$
$$(A_t - d\,E\{X_t\} - h\,E\{X_t^2\})$$
$$+ g\,A_t\,(1-A_t)) + \mu_t - 1/ß = 0 \qquad t = 1, \dots, T-1$$

$$\frac{dL}{dA_T} = -\mu_T = 0 \qquad (13)$$

$$\frac{dL}{d\mu_t} = A_t - g\,A_t(1-A_t)(A_t - dE\{X_t\} - hE\{X_t^{2}\}) - E\{A_{t+1}\}) = 0 \qquad (14)$$
$$t = 1, \ldots , T-1$$

Beginning from the initial period (t = 0) and initial state (A_0), the agent makes a series of marketing and purchasing choices on the basis of calculations regarding the present value of expected future profits. With no restrictions on purchases or sales, the agent always chooses to keep the amount of livestock capital such that the marginal benefits and marginal costs are equal for the last unit marketed or purchased. The optimality condition given in equation (11) indicates that the amount of livestock capital is optimal when the value of the marginal product for livestock capital is equal to the sum of marginal herding cost, marginal investment cost, and marginal rangeland user cost in terms of its impact on future pasture potential.

The co-state equation (12), and the terminal value equation (13), together define the time path of the co-state variable (μ_t). By equation (13) the co-state variable will equal 0 in the terminal period. This assumes that the pasture has no salvage or bequest value for the individual agent. While this may seem a questionable assumption, it is one with very little effect on the results for the first 180 periods of a 200-period planning horizon. The time path followed by the co-state variable in periods prior to the terminal date depends upon the impacts of pasture potential on net revenue in the current period, and on pasture potential in subsequent periods. The discount factor (ß) weights the importance of future revenue and revenue-generating capacity relative to current revenue. Everything else being equal, a higher discount factor will yield a lower μ_t relative to μ_{t+1}.

The specification of the optimality condition clearly indicates that agents do not have dominant strategies. This means, inter alia, that the prisoners' dilemma model is not an appropriate game-theoretic formulation of the grazing problem since non-separable externalities affect the value of the marginal product, marginal herding costs, and marginal rangeland user costs. This is consistent with the findings of Runge (1981). Expectations are thus crucial to the outcome. Each agent forms expectations about the entry and exit of others, about his own entry and exit, about the behavior of other incumbents and potential entrants, and about the ways that others' behavior will be affected by changes in their own behavior. Those expectations depend upon the institutional arrangements governing resource use. Entry and exit expectations will depend upon the rights, duties, and rules governing resource access, while conjectual variations will depend on the rules, conventions, and contracts governing resource use within the regime. The model is appropriate for analyzing the operations of a variety of internal institutional arrangements.

B. Equilibrium on a "Contested" Rangeland

Several extreme access conditions can be analyzed with this model. For the "open-access equilibrium" to hold--that is, for the aggregate stocking rate to be such that short-term economic rents are driven to zero--equation (15) must hold with equality. From a comparison of equation (15) with the general optimality condition (11), it is apparent that the following are necessary conditions for the open-access equilibrium to hold: (1) all authority for livestock-range management decisions is vested in the hands of the individual livestock owners; (2) there are no institutional, contractual, or market restrictions on the actions of incumbent or potential rangeland users; and (3) there is a queue of potential "hit-and-run" entrants who enter any endeavor that has the potential to generate short-term profits, and who exit any endeavor that does not.

In every period, agents in the queue are assumed to access the rangeland and add animals to their herds until all short-term economic rents are dissipated. That is, agents in the queue ignore the current costs of their actions in terms of reduced average livestock productivity in the current period (given by the term P B dXt/dXit in equation 11) and the user costs of their actions in terms of reduced pasture potential in future periods (given by the term μt (g At (1-At) (dXt/dXit (d + h 2 Xt)) in equation 11).

$$P(A_t - B X_t) - dC_i/dX_{it} = 0 \qquad (15)$$

What is commonly described as the "open-access equilibrium" thus requires a combination of circumstances beyond the mere absence of institutional restrictions on access. In fact, the necessary conditions approximate those present in a "contested market" as described by Baumol (1982) and Baumol, Panzar, and Willig (1982). We suggest that natural resources exploited under such conditions be referred to as "contestable." There is one key difference between contestable markets and contestable natural resources--short-term profit-taking is said to yield socially desirable outcomes in ordinary markets, but in natural resource settings the outcomes are thought to be socially undesirable.

A frequent assertion is that the contested-resource equilibrium is identical to the equilibrium attained by a unitary agent who has an infinitely-high discount rate.[ii] However, an important difference between the two cases is that the unitary agent considers the effects of additional animals on the average productivity of the remaining animals, while agents in the contestable setting ignore these effects. Short-term rents are maximized in the case of the unitary agent, but are completely dissipated in the case of contestable natural resources.

The simulation results presented in Figure 2 illustrate the potential differences between the equilibria generated in the two situations. The results for the unitary agent with an infinitely high time preference rate were derived by assuming particular values of the parameters and solving equations (11), (12) and (14) for the situation of Xit equal to Xt and ß equal to 0. On the contrary, in the case of contestable resources, the results were derived by assuming the same base parameter values and solving equations (12), (14) and (15) with ß equal to 0.9. To be consistent with the "uncontrolled rangeland" case presented above, the terminal date is set equal to 200. A simple cost function is assumed in the simulation model: marginal cost is assumed to be constant for all levels of Xt and At.[iii]

<Insert Figure 2>

C. Conventions in Common Property Regimes

It has already been noted that individual agents do not have dominant strategies in the multiple-agent model. That is, agents' expectations of others' behavior affect their own actions and so the aggregate outcome. One possibility in this situation is that agents recognize their mutual interdependence and develop self-enforcing institutions to coordinate mutually-advantageous behavior. This is the assumption on which Runge's (1981, 1986) coordination model of common property is based.

Recall that a convention is a self-enforcing social institution providing agents with assurance regarding the behavior of others. An institution is regarded as self-enforcing if agents abide by its terms when they have assurance that at least a minimum subset--a coalition--of the other agents will do likewise. Consider a social institution that proscribes that each agent should keep no more than Xct units of livestock in period t. Suppose that the ith agent has assurance that m agents ($0 \leq m \leq (n - 1)$) will comply with the terms of the institution in period t and that all agents are identical. Assuming no punishment for deviance, the institution is a convention in period t as long as agent i calculates that the expected present value of compliance is greater than the expected present value of deviance, assuming that there is no punishment for deviance. In terms of the agent's optimization problem, she will comply if her optimum Xit (Xit^*) is less than or equal to Xct, and she will deviate if the optimum Xit is greater than or equal to Xct. Xit^* is defined by the solution to equations (16) to (19).

$$P\,(At - B\,(n - m - 1)\,Xjt - 2\,B\,Xit - B\,m\,Xct) - dCi/dXit \qquad (16)$$

$$- \mu t\,(g\,At\,(1-At)\,(d + h\,2\,(Xit + (n - m - 1)\,Xj\backslash i + m\,Xct))) = 0$$

$$t = 1, \ldots, T-1$$

$$P\,Xit - dCi/dAt + \mu t\,[\,1 + g\,At\,(1-At) \qquad (17)$$

$$+ g\,(1 - 2\,At)\,(At - d\,(Xit + (n - m - 1)\,Xj\backslash it + m\,Xct)$$

$$- h\,(Xit + (n - m - 1)\,Xj\backslash it + m\,Xct)^2)] - \mu t\text{-}1 / ß = 0$$

$$t = 1, \ldots, T-1$$

$$\frac{dL}{dAT} = - \mu T + \frac{dF}{dAT} (n) = 0 \quad (18)$$

$$\frac{dL}{d\mu t} = At + g\, At\, (1-At) \quad (19)$$

$$* (At - d\, (Xit + (n - m - 1)\, Xj \backslash it + m\, Xct)$$

$$- h\, (Xit + (n - m - 1) Xit + m\, Xct)^{2}) - At{+}1 = 0 \quad t = 1, \ldots, T-1$$

where m ≡ number of agents expected to comply with the rule.

An obvious candidate for the ceiling (Xct) is the corporate optimum--the level which maximizes discounted profits summed across all time periods and across all n agents, divided by the number of agents in the group. The problem of finding the corporate optimum is mathematically equivalent to the problem faced by a unitary agent who has access to the rangeland.

Simulations were conducted to examine agents' incentives to cooperate with, or deviate from, the rule that Xit be set at Xct. Consider a case in which three agents share a rangeland, one or two of whom are expected to comply. The third agent considers whether to comply or to deviate. The upper panel in Figure 3 illustrates the time path of livestock capital that would be consistent with the corporate optimum and optimal deviations from that optimum when (m = 1) or (m = 2). In both cases, agent i has an incentive to deviate in every period. Thus the rule could not be a self-enforcing convention.

Now consider the case in which the group contains 100 members. These results are illustrated in the lower panel of Figure 3. When the agent expects as many as 50 others to comply with the institution, her optimal strategy is to comply with the institution for the first few periods, then deviate for the remainder of the planning horizon. When the number of expected compliants is increased to 95, the optimal strategy is to deviate throughout the planning horizon.

Why would it be optimal for the agent to deviate in some periods and not in others? It appears that the individual finds it to be in her interest to comply during the early periods to permit pasture potential to build up, then take advantage of that pasture potential with a greater stocking rate in later periods. With (m = 95), that incentive is outweighed by the incentive to deviate and take advantage of others' compliance.

These results indicate that individuals have an incentive to deviate from those rules in almost all cases, and in almost all time periods. The results presented here support the hypothesis that the incentive to deviate increases with the number of agents who are expected to comply. While the agents in this model are not party to a prisoners' dilemma, neither are they party to a coordination game.

<Insert Figure 3>

D. Cournot Conjectures in Common Property Regimes

The results presented above suggest that neither the prisoners' dilemma game nor the coordination game are entirely appropriate theoretic conceptualizations of the interactions between agents in common-property regimes. We now offer two alternatives. In the "Cournot" model of common property it is assumed that access to the benefit streams generated by a commons is limited to n agents, each of whom has expectations that other agents will not change their behavior -- either in the current period or in future periods -- if they change their's. That is, each agent regards it possible to deviate without others also deviating. Conjectures of this type are known as Cournot conjectures in the theory of noncooperative games (Kreps 1990, p. 443). If an agent with Cournot conjectures reduces her herd by one animal, she assumes that the total herd will be reduced by only that one animal--others will not follow her lead. In terms of the dynamic optimization model, the agent in a Cournot common-property regime chooses Xit with the expectation that the remainder of the herd will remain unchanged. If agents are assumed to be identical, then the fraction (Xj\i) will be equal for all j and all Xi. Equation (20) defines the expected value of Xt for the Cournot common-property regime.

$$E\{Xt\} = (n-1)\ Xj\backslash it + Xit \qquad (20)$$

Substitution of E{Xt} into equations (11) to (14) produces equations (21) to (24) as the first order necessary conditions for the Cournot model.

$$\frac{dL}{dXit} = P\ (At - B\ (n-1)\ Xj - 2\ B\ Xi) - dCi/dXi \qquad (21)$$

$$- \mu t\ (g\ At\ (1-At)\ (d + h\ 2\ (Xit + (n-1)\ Xj))) = 0 \quad t = 1, \ldots, T-1$$

$$\frac{dL}{dAt} = P\ Xit - dCi/dAt \qquad (22)$$

$$+ \mu t\ (\ 1 + g\ At\ (1-At) + g\ (1 -2At)\ (At - d\ (Xit + (n-1)\ Xjt)$$

$$- h\ (Xit + (n-1)\ Xjt)^2)\ ) - \mu t\text{-}1\ /\ ß = 0 \quad t = 1, \ldots, T-1$$

$$\frac{dL}{dAT} = - \mu T + \frac{dF}{dAT}(n) = 0 \qquad (23)$$

$$\frac{dL}{d\mu t} = At + g\ At\ (1-At)\ * \qquad (24)$$

$$(At - d\ (Xit + (n-1)\ Xjt) - h\ (Xit + (n-1)\ Xit)^2) - E\{At+1\} = 0$$

$$t = 1, \ldots, T-1$$

If the agents are identical then they all face the same optimization problem and reach identical decisions about the optimal number of animals -- Xjt will equal Xit for all j not equal to i. Substitution of (Xt/n) for Xjt and Xit in equations (21), (22) and (24) yields equations (25), (26) and (27). Those equations can be solved to derive the equilibrium time paths for Xt, At and μt. The equilibrium time path of the control variable (Xt) is the Cournot-Nash equilibrium for the n-person dynamic game.

$$P\,(APP_t - B\,X_t/n) - dC_i/dX_{it} - \mu_t(\,g\,A_t(1-A_t)(d + 2\,h\,X_t)) = 0 \qquad (25)$$

$$t = 1, \ldots, T-1$$

$$P\,X_t/n - dC_i/dA_t - \mu_{t-1}/\beta \qquad (26)$$

$$+\,\mu_t\,(1 + g\,A_t\,(1-A_t) + g\,(1 - 2\,A_t)\,(A_t - d\,X_t + h\,X_t^2)) = 0$$

$$t = 1, \ldots, T-1$$

$$A_t + g\,A_t\,(1-A_t) * (A_t - d\,X_t - h\,X_t^2) - E\{A_{t+1}\} = 0 \qquad (27)$$

$$t = 1, \ldots, T-1$$

Equilibria in Cournot regimes are sensitive to the number of agents who share access to the collectively-used resource. The simulation model was run for three different values of n. Holding all other variables constant, results are simulated for n equal two, 10, and 100. These results are displayed in Figure 4. As expected, the more agents, the higher the stocking rate, and the lower the pasture potential. It is noteworthy that, everything else equal, the results for the Cournot regime with (n = 100) differ significantly from those found for the contested-resource case (Figure 2). That is, agents in large groups, even if they have Cournot conjectures, do not behave like the hit-and-run entrants in the contested-resource model.

<Insert Figure 4>

III. DYNAMIC IMPLICIT CONTRACTS IN COMMON PROPERTY REGIMES

Two types of conjectures have been considered thus far: (1) convention conjectures in which agents expect others to comply or deviate from conventions, and (2) Cournot conjectures in which agents disregard the impacts of their behavior on others' behavior. The theoretical literature on internally-enforced contracts suggests other possibilities. For example, agents could expect others to abide by the terms of contracts enforced by explicit "hedging" arrangements involving hostages, collateral, hands-tying actions, gain sharing, or partial surrender of autonomy (Bowles and Gintis 1988; Kronman 1985). Agents could also expect others to abide by the terms of internal contracts supported by credible threats of future retaliation for past deviations. These are called dynamic implicit contracts in game theory (Crawford 1985).

Dynamic implicit contracts are supported by the strategies of the agents themselves. Game theorists have considered four types of strategies that can support dynamic implicit contracts: (1) trigger strategies (Friedman 1971); (2) stick-and-carrot penal codes (Abreu 1986); (3) exclusion (Hirshleifer and Rasmusen 1989); and (4) tit-for-tat strategies (Axelrod 1984).

An agent following a trigger strategy will comply as long as everyone else complies, but will revert to Nash equilibrium behavior (ignoring others' reactions to his or her actions) if anyone should deviate (Friedman 1971, 1986). An agent following a stick-and-carrot penal code will respond to others' deviations by imposing a harsh but short-lived punishment, followed by compliance (Abreu 1986). An agent following an exclusion penal code will take steps to exclude deviants from future access to the resource (Hirshleifer and Rasmusen 1989). Finally, an agent following a tit-for-tat penal code will mimic others' actions--cooperation will be rewarded with cooperation, deviation will induce prompt deviation as punishment (Axelrod 1984). Tit-for-tat is perfectly symmetrical reciprocity.

We follow Hirshleifer and Rasmusen (1989) in considering dynamic implicit contracts supported by exclusion. Two factors support this choice. First, there is evidence that exclusion and its stronger form, banishment, are used as punishments in some pastoral societies (Schapera 1956, p. 25). Second, only exclusion can suppport dynamic implicit contracts in finite-period games with unique single-period equilibria and known termination dates.

Each agent has the following expectations: (1) the n current users will have access to the benefit streams in all periods of the planning horizon; (2) no other agents will enter the group during the planning horizon; and (3) current-period actions are unknown when the other incumbents choose their actions for the current period.

Agents following exclusion strategies condition their current-period actions on others' actions in the preceding period. An exclusion strategy proscribes different actions during three distinct phases. The compliance phase is if (t < T) and all agents acted cooperatively in period (t - 1), then keep Xct of livestock capital in period t, where (Xct * n) is the group optimum stocking rate. The punishment phase is if (t < T) and any of the other agents deviated in period (t - 1), then blacklist the deviant(s) and keep the livestock capital consistent with the Nash equilibrium for (n - d) number of livestock keepers. The terminal phase is if (t = T), then keep the livestock capital that is defined by the Cournot model.

It is assumed that the group of agents can exclude from the group, for a single period, any agent who is accused and found guilty of deviating from the terms of a particular implicit contract in the preceding period. It is further assumed that temporary exclusion is costless both to the individual who makes the accusation, and to those who enforce the punishment. Finally, it is assumed that all accusations are immediately verifiable by the other members of the group and that only verified deviations are punished.

Proposition. There are ranges of feasible values for the biological (A0, B) and economic (P, mc, n, ß) parameters of the dynamic livestock/rangeland model such that there exists a subgame perfect Nash equilibrium with agents playing the compliance phase of exclusion strategies in period one through (T - 1), and the terminal phase in period T.

Subgame perfection is the standard test of equilibrium in dynamic games. An equilibrium is subgame perfect "if the relevant portions of an equilibrium strategy are Nash equilibria for every subgame of the original game, whether or not that subgame is reached in equilibrium" (Hirshleifer and Rasmusen 1989, p. 93). The proof of the above proposition is found in the appendix. This proposition re-enforces an important principle for resource regimes. Namely, it is possible for agents sharing a common-pool resource to maintain mutually beneficial patterns of resource use without articulated institutions or contracts. Abreu (1986), Friedman (1971), and Hirshleifer and Rasmusen (1989) have proven the validity of this principle for situations in which payoffs are identical in every period. Bernheim and Whinston (1990) have extended this result to include situations in which payoffs depend upon the magnitude of a random variable. We have further extended the result to include situations in which the productivity of a common pool resource depends upon past resource use.

Two aspects of this analysis may limit its applicability to common property regimes for African rangeland resources. First, there are a number of random climatic variables affecting rangelands and the efficacy of dynamic implicit contracts. The results of Rotemberg and Saloner's (1986) analysis of implicit contracts in oligopolistic markets with fluctuating demand would tend to support the hypothesis that implicit contracts will be less effective when climatic conditions are favourable than when they are unfavourable. Second, the model assumes that access to the rangeland resource is restricted to a fixed group of livestock owners. While consistent with most of the theoretical literature on dynamic implicit contracts, it is not consistent with the empirical evidence on African rangelands. In general, access to common-pool rangelands is not fixed but is instead conditional upon a number of technical, environmental, and economic factors.

A small number of studies have considered the possibilities for collusive market outcomes when incumbent firms recognize a threat of potential entry. Applied to rangeland situations, these studies suggest the following. First, existing users of a common rangeland will consider the actions of both potential and current rangeland users when deciding current actions. Second, users will consider making fixed cost investments to lower their marginal production costs and thus to deter potential entrants. Third, outcomes will be defined in terms of stocking rates, the rate of new entry, and the strategies that incumbents adopt to deter potential entry.

Our analysis supports the proposition that individual agents can enforce mutually-beneficial resource use by following strategies that punish deviants while simultaneously advancing their own individual interests. Single-period exclusion is only one of the possible penal codes that could support dynamic implicit contracts among resource users. Exclusion could also be multiple-period, permanent, or involve more than one resource. Another possible penal code could involve the exclusion of deviants from public goods that are generated by the group of resource users, thus increasing their herding and investment costs. A credible threat in many African rangeland situations is theft: an agent who does not cooperate with the terms of a dynamic implicit contract could face a greater risk of livestock theft.

This is not to imply that African livestock owners rely exclusively on dynamic implicit contracts to coordinate their behavior. On the contrary, observations from across Africa indicate that common property regimes are generally comprised of diverse constellations of rights, rules, and conventions. Different institutional forms may hold for different aspects of individuals' strategies (e.g. rules governing pasture opening and closing dates and contracts governing stocking rates) or for different levels of the social hierarchy (e.g. rights and duties governing inter-group interactions and contracts governing inter-personal interactions).

IV. CONCLUSIONS

Several outcomes of the foregoing analysis extend current economic theory regarding common-property regimes. First, it is shown that the absence of institutional restrictions on access is only one of the conditions necessary for the open-access equilibrium to hold. In fact three conditions are necessary: (1) all authority for livestock-range management decisions must be vested in the individual agents; (2) there can be no institutional, contractual, or market restrictions on the entry of agents into livestock production or the access of agents to rangeland resources; and (3) there is a queue of potential "hit-and-run" entrants, who enter any enterprise that has the potential to generate short-term profits and exit any enterprise that does not. In every period, agents in that queue are assumed to access the rangeland and add animals to their herds until all short-term economic rents are dissipated. The term "contestable resource" describes resources exploited under such conditions.

Second, while short-term economic rents are dissipated in cases of contestable resources, they are maximized in cases when a single agent with an infinitely high time preference rate has access to a natural resource. As a result, outcomes generated under the two regimes are significantly different.

Third, it is shown that there are a number of conditions, in addition to separable externalities as noted by Runge (1981), that affect the potential viability of self-enforcing conventions on resource use. In particular, the results imply that individuals generally have incentives to deviate from -- rather than comply with -- institutions governing common-pool resource use. Additionally, the incentives to deviate increase -- rather than decrease -- with the number of agents expected to comply. This challenges the general applicability of the coordination or assurance model to common pool resource situations.

Two new models of common-property regimes are developed. The Cournot model is based on the assumption that agents ignore the effects of their actions on the actions of others. The implicit contract model is based on the assumption that agents condition their actions on the past actions of others. Dynamic implicit contracts, supported by exclusion, are shown to be potentially viable in finite-period games in which a state variable measuring resource productivity is allowed to change from period to period.

We note, however, that this approach is limited when resources are subject to large random and episodic shocks. In some ways, the deficiencies reflect the status of the theoretical literature on which the model is based. For example, in the fourteen years since Caves and Porter (1977) presented their ideas about the integration of mobility, entry, and equilibrium, analysis has not progressed beyond the consideration of one incumbent and one potential entrant. In other respects these deficiencies reflect the limitations of deterministic economic and bio-economic modelling for depicting the variety of institutional arrangements and dynamic processes that affect common-property regimes.

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Appendix Proof of Proposition

To prove the proposition we must show that all single-period games have Nash equilibria and that there are combinations of feasible parameter values such that no player who follows an exclusion strategy ever has an incentive to deviate from that strategy.

According to Friedman (1986, pp. 25-39), a game has at least one Nash equilibrium if the following conditions hold: (1) all agents have complete information; (2) the strategy set for each player is compact and convex; (3) the payoff functions are defined, continuous and bounded for all strategies and all players; (4) the payoff function of each player, holding the strategies of the other players constant, is concave with respect to the other players' strategies, for all strategies and all players; (5) the players are not able to make binding agreements; and (6) each player's strategy choice is made without prior knowledge of the choices made by the other players. Conditions (1), (3), (4), (5) and (6) hold by construction of the model. Condition (2) can be satisfied by formally restricting the stocking rate choices available to each agent to be not less than zero and not more than the amount at which average physical product is zero.

It needs to be shown that there are combinations of parameter values such that no player has an incentive to deviate from an exclusion strategy during any phase of the overall game. There are three ways that agents can deviate from an implicit contract -- they can deviate from the compliance phase, from the punishment phase, or they can fail to undertake the actions necessary to enforce punishments on other agents who deviate in the previous period.

Consider a time period ($0 < t < T$) when all agents are in the compliance phases of their strategies. An individual has an incentive to deviate in period t only if the expected present value of deviation for period t and t+1 is greater than compliance during those two periods. Assuming that the potential deviant expects no other agent to deviate in either the current period or the following period, the expected net present value from deviation is given in equation (15) as Vdt, while the expected net present value from compliance is defined in equation (16) as Vct. Vct will be less than Vdt for some combinations of the parameter values and greater than Vdt for other combinations.

$$Vdt = P \{At - B [Xdt + Xct ((n - 1)/n)] \} \; Xdt - C [Xdt] \quad (28)$$

$$Vct = P [At - B \, Xct] \, Xct/n - C [Xct/n] \quad (29)$$

$$+ ß \{ P [At+1 - B \, Xct+1] \, Xct+1/n - C [Xct+1/n] \}$$

where Xct ≡ stocking rate consistent with maximization of group profits;
Xdt ≡ stocking rate consistent with maximization of short-term individual profits.

Now consider a time period ($0 < t < T$) when agents are in the punishment phase of their strategies. Again assuming that the potential deviant expects no other agent to deviate in either the current period or the following period the expected net present value of deviation is given by equation (30) and the expected net present value of punishment is given by equation (31). As for the cooperation phase, Vdt is greater than or less than Vct depending upon the value of the parameters.

$$Vdt = P \{At - B [Xdt + Xct * (n - 2)/n]\} * Xdt - C [Xdt] \quad (30)$$

$$Vct = P [At - B * Xct * (n - 1) / n] *Xct - C [Xct] \quad (31)$$

$$+ ß \{ P [At+1 - B \, Xct+1] - C [Xct+1] \}$$

To prove the proposition all that remains is to show that agents have incentives to report others' deviations and to conduct the actions necessary to exclude those found guilty of deviation. The incentives are identical in the two cases. An agent who reports a deviation or enforces punishment avoids the possibility of being punished himself, and gains additional revenue by reducing the number of agents sharing the rangeland in the following period. This concludes the proof.

NOTES

i. The results generated from this model are invariant to the choice of function among the class of expected utility functions. For the sake of simplicity, the expected profit function is used. Assuming that stocking rate is the only control variable both simplifies the problem, and makes the exposition more transparent. It is important to note, however, that there are many other range management options available to the users of common pool rangelands--herd movement regulations, closing and opening dates to key patches of rangeland, burning, or livestock breed improvement.

ii. For instance, see Conrad and Clark (1987, pp. 87-89).

iii. The system is quite complicated, involving (3*199) unknowns--At, Xt, and μt for 199 time periods--and (3*199) non-linear equations. Numerical methods were used to solve this optimal control problem. The solution method relies on the fact that A0 is exogenously determined and that the terminal value of the co-state variable can be derived from equation (13). A Gauss program was written using the Gauss-Seidal method (the method of successive corrections) as the overall solution algorithm (Noble and Daniel 1969, p. 305). Within each iteration of the overall solution procedure, the first order conditions were used to derive values of At, Xt and μt. Analytical solutions were possible for equations (12) and (14), while a numerical solution method was used to solve the optimality condition (11). The Gauss procedure NLSYS (which uses a quasi-Newton method) was used to solve the optimality condition for Xt.