LEEC PAPER 89-07

On the Overgrazing Problem

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April 1989
(Revised May 1989)

Abstract. A model of optimal range management is developed which explicitly recognizes the dynamic interaction between livestock and carrying capacity. Compared with the usual bioeconomic model, the ratio of animals to carrying capacity must be "too small" in equilibrium. Furthermore, it may be optimal to overshoot the equilibrium following a drought. It is conjectured that the severe overgrazing in places like Africa's Sahel occurs not in an equilibrium situation but in times of drought when forces compel herders to hold on to their livestock just when optimality demands that they destock as quickly as possible.

Key Words: overgrazing, bioeconomic modeling, open access, desertification, optimal control.

JEL Classification Number: 721.

*This paper is a shortened version of a chapter of my LSE PhD thesis. Partha Dasgupta first interested me in this topic, and I have benefited greatly from his insights. David de Meza and David Pearce provided helpful comments on a previous draft. Financial support for my graduate studies in the form of a scholarship from the American Friends of the LSE and an Overseas Research Student award from the Committee of Vice-Chancellors and Principals of the Universities of the United Kingdom is gratefully acknowledged.

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Overgrazing threatens the productivity of rangelands everywhere. But its effects are felt with particular severity by pastoralists in the Sahel belt of Africa. This is partly because pastoralists depend on livestock almost entirely for their livelihood and partly because drought is a recurrent phenomenon in this region. The effects of overgrazing are magnified at times of drought, and pastoralists are especially vulnerable to famine at these times (Sen, 1981).

The classic explanation for the overgrazing problem is told by Hardin's (1968) famous allegory of the "tragedy of the commons," in which free access by herders to a common range is seen to bring "ruin to all." Pastoralists in the Sahel belt have certainly suffered from overgrazing. But it is unlikely that open access is solely to blame for the overgrazing problem.

First, natural forces will prevent animal numbers from increasing without limit. In all likelihood, an equilibrium will be reached, perhaps after oscillations, with the range supporting a herd of some positive size. True, grazing pressure on an open access range will probably be greater than is optimal; but it is unlikely that the range will be ruined by open access. Second, market forces will also prevent herders from adding to their stocks without limit. As Dasgupta (1982, p. 14) has remarked, "Whether or not the commons will be ruined depends on a number of factors, an important one of which is the price of output (i.e., beef or milk) relative to the cost of rearing cattle. Freedom of the commons does not necessarily bring ruin to all; in fact it may bring ruin to none." To find a fuller explanation for the overgrazing phenomenon we will have to search further than Hardin's simple allegory.

This paper begins this search by developing a model of optimal range management. It is perhaps remarkable that a problem of such fame and importance should have escaped bioeconomic modeling. The reason may be an impression that the overgrazing problem can be explained by a simple modification of the overfishing problem. If so, this impression is mistaken, for while the two problems share certain similarities they differ in one important respect. In the fisheries literature it is usual to take carrying capacity as being fixed. In the range management problem this would be equivalent to assuming that the range does not respond to grazing. But if this were true, one would not be able to comment usefully on when the stock of animals was too large (or indeed too small) relative to rangeland carrying capacity; the overgrazing problem would be assumed away.

An essential feature of the problem, then, is that the dynamics of the herd and rangeland carrying capacity are interrelated. What effect does this dynamic interaction have on the bioeconomic solution? The answer to this question is important not just to analysis of the overgrazing problem but to bioeconomic analysis generally. For while the assumption of a fixed carrying capacity may well be more appropriate for some resources than for others, only in a few circumstances can we really be confident in the assumption (see Caughley, 1976). It is therefore of general interest to know if the conclusions of the usual bioeconomic analysis stand up to alterations in this assumption.

For the particular model developed here, the configuration of the steady state corresponds rather directly to the usual bioeconomic model with carrying capacity fixed (and with population growth obeying the logistic equation). However, the optimal steady state and the optimal approach path to this equilibrium must be modified somewhat. Compared with the usual bioeconomic model in which the marginal product of natural capital must equal the social rate of discount in the optimal stationary state, in the grazing model, with the dynamics of herd size and rangeland biomass interdependent, the ratio of animals to carrying capacity must be "too small." Furthermore, whereas in the usual bioeconomic model (with the Hamiltonian linear in the control variable) it is optimal to approach the equilibrium monotonically (see, e.g., Clark and Munro, 1975; and Spence and Starrett, 1975), allowing for dynamic interaction between the animal stock and carrying capacity implies that it may be optimal to overshoot the equilibrium stock. I must emphasize that these results pertain to a very special bioeconomic model. One lesson of recent bioeconomic research is that results are usually model-specific.[1] Only empirical analysis can demonstrate whether the dynamic interraction modeled here is a good approximation to reality.

As regards the overgrazing problem, I show that it is best to assess the condition of a range not in terms of carrying capacity or herd size alone, but in terms of the ratio of herd size to carrying capacity--what range managers call *grazing pressure.* I distinguish between economic and ecological overgrazing, and show that open access implies economic overgrazing but that it need not imply ecological overgrazing. I also derive corrective taxes which lead an open access range to the socially optimal grazing pressure. Analyses of overgrazing in areas like the Sahel measure the extent of the problem in terms of shortfalls in human carrying capacity--the difference between the number of pastoralists a range can support and the actual population. I demonstrate that this is an inadequate indicator both of the extent of overgrazing and of the capacity of the land to support people. The paper closes with a discussion on the nature and causes of overgrazing. Here I argue that severe overgrazing is caused not so much by open access in an equilibrium situation but by forces which inhibit herders from quickly destocking in times of drought. The challenge to policy is not just to reduce herds at normal times but to reduce them promptly when the rains fail.[2]

I. THE MODEL

1.1 Ecological Considerations

Almost by definition, overgrazing implies the existence of some maximum stock of animals that can be sustained more or less indefinitely. Anthropologists, who have studied the interaction between pastoral societies and their environments in great detail, have proposed three models to explain what happens when this maximum sustainable stock is exceded (Hjort, 1981; Horowitz and Little, 1987). The *equilibrium model* assumes that carrying capacity is fixed and that the stock of animals must ultimately return to its maximum sustainable level. The *degradation model* assumes that the carrying capacity of the range deteriorates irreversibly. The *resiliency model* assumes that the stock of animals and range carrying capacity interact with one another, that the reduction in carrying capacity brings about a reduction in the stock of animals which in turn brings about an increase in carrying capacity and so on in the fashion of a damped oscillation until equilibrium is reestablished.

The equilibrium model is really nothing other than the usual model of population dynamics commonly employed in bioeconomics (such as the logistic equation of population growth). The degradation model is really nothing but a model of resource depletion. The resiliency model captures elements of both the other models. Like the equilibrium model, the resiliency model has one (natural) equilibrium. Like the degradation model, the range will deteriorate if stocking exceeds a certain level. Unlike the degradation model, however, the range can recover if given enough time.

Which model best explains rangeland desertification? The equilibrium model clearly will not do, for it does not allow a reduction in carrying capacity, which in these models is taken to be vegetative cover. Nor will the degradation model suffice. In many if not most cases, vegetative cover in desertified areas will recover if grazing pressure is reduced. For example, in the wake of the 1973 drought and famine in Ethiopia there was "a remarkable degree of resilience, both in terms of the rapid recovery of the rangelands and also in the recovery of the herds" (Helland, 1980, p. 98). A recent review of these models (Horowitz and Little, 1987, p. 68) concluded:

> "Increasingly, persons with extensive field research in pastoral areas show considerable dissatisfaction with both equilibrium and degradation models, and find the resiliency model to accord better with the empirical situation."

In the biology literature, grazing systems are modelled as dynamic predator-prey interactions. These models capture the important characteristics of the anthropologists' resiliency model.

Let H_t denote herd size and K_t environmental carrying capacity.[3] Then the (unexploited) ecological system can be described by:

$$\mathring{H}_t = F(H_t, K_t) \tag{1}$$

$$\mathring{K}_t = G(H_t, K_t) \tag{2}$$

Meaningful results can be obtained only if we specify explicit functional forms for F and G. There are many possibilities.[4] Here I adopt a simple model of a natural grazing system, which was proposed by May (1981, pp. 85-86). For this system, the herd (predator) obeys

$$\mathring{H}_t = rH_t(1 - H_t/K_t). \tag{3}$$

Eq. (3) is the familiar logistic equation with carrying capacity allowed to vary over time. K_t is the largest herd which the environment can "carry." When the natural system is in equilibrium we will have $H_t = K_t$. But at other times the range will be capable of carrying more or fewer animals than are present at that moment. Growth in carrying capacity (the prey) is assumed to be described by

$$\mathring{K}_t = a(\overline{K} - K_t) - bH_t. \tag{4}$$

$\overline{K}$ is the saturation level of the grazing lands and b the rate of depletion by the herd. The time taken for the vegetation to recover from grazing depends on the difference between the saturation level and K_t, and on $1/a$, the intrinsic regeneration time. Like the ordinary logistic equation, the natural equilibrium for this system is stable; but unlike the logistic equation, the system produces oscillations away from the equilibrium if the rate of depletion is sufficiently high (May, 1981, p. 86).

I.2 Control of the Ecological System

In range systems, the size of the herd is not directly controllable. However, the herd is maintained to yield a harvest of rate h_t, and the rate of harvest *is* subject to control. In the economic model, eq. (3) then becomes

$$\mathring{H}_t = rH_t(1 - H_t/K_t) - h_t. \tag{5}$$

In pastoral societies, livestock are maintained to yield harvests of milk as well as meat. Slaughter of animals obviously reduces herd size. But the taking of milk leaves less for young animals and hence also reduces the rate of growth of the herd. Hence, eq. (5) should serve us well as an approximate description of herd dynamics.[5]

Assume that the herd cannot be added to by means other than natural regeneration, and that there is a maximum harvest rate. That is, assume $0 \leq h_t \leq h^{max}$. The assumption that animals cannot be (profitably) imported is realistic for the Sahel as a whole.[6] The assumption of a harvesting rate ceiling is equivalent to assuming that marginal harvesting costs jump at h^{max}. This may seem unrealistic, but I argue later that forces do act to keep harvest rates low just when huge offtake rates are most needed (that is, just when the constraint h^{max} is operative).

In general, the rate of change in carrying capacity will also be subject to some control. Construction of additional watering points, reseeding and fencing of heavily grazed areas, irrigation, and weeding of noxious vegetation will all increase the number of animals which a range can sustain. However, the principal means of influencing carrying capacity is by adjusting herd size (Caughley, 1976, p. 217), and policies dealing with rangeland desertification rely heavily on this instrument (see, e.g., Ahmad and Kassas, 1987). Let us assume then that the rate of change in carrying capacity cannot be controlled directly.

1.3 Costs

In pastoral economies, costs are related directly to labor requirements, and labor is employed in caring for the herd but not the range. Anthropologists typically relate labor requirements to herd size (see, e.g., Swift, 1986; and Helland, 1980). Labor is mainly employed in watering, milking and supervising the animals. Watering and milking are labor-intensive operations and the relationship between labor requirements and herd size appears to be linear for these operations. Anthropologists see supervisory requirements as obeying a step function, but since herders can combine supervision with the other operations the assumption that marginal herding costs are constant seems reasonable for pastoral economies.

In addition to these variable herding costs, there are also fixed costs. These consist mainly of the opportunity cost of the rangelands. Recognition of this cost is important to determining which lands should be devoted to grazing and which to agriculture and other uses. But this is quite another matter from determining the optimal grazing pressure, and so I ignore fixed costs in this analysis.

1.4 The Economic Model

Assume that the pastoral society's instantaneous social profit can be described by $ph_t - cH_t$, where p (> 0) is the (constant) unit price of the harvest (net of any harvesting costs) and c (> 0) is the (constant) unit cost of maintaining the herd.

The problem then is to

$$\left.\begin{aligned} &\max_{\{h_t\}} \int_0^\infty [ph_t - cH_t]e^{-\delta t}dt,\ \delta > 0 \\ &\text{s.t.}\quad \mathring{H}_t = rH_t(1 - H_t/K_t) - h_t,\ H_0,\ K_0 > 0 \text{ and given} \\ &\qquad \mathring{K}_t = a(\overline{K} - K_t) - bH_t \\ &\qquad 0 \leq h_t \leq h^{max} \\ &\qquad H_t,\ K_t \geq 0. \end{aligned}\right\} \qquad (6)$$

II. THE OPTIMAL STEADY STATE

Problem (6) can be solved by employing the maximum principle for optimal control. The optimal steady state must satisfy (see Appendix):

$$(\lambda F_H - c - \lambda\delta)(G_K - \delta) = \lambda G_H F_K. \qquad (7)$$

where $F_H = r(1 - 2H/K)$, $F_K = r(H/K)^2$, $G_H = -b$ and $G_K = -a$.

Eq. (7) might be called the Golden Rule of Rangeland Conservation. In the "equilibrium model" we would have $G_K = G_H = 0$, and condition (7) would reduce to $\lambda F_H - c = \delta\lambda$. In other words, the optimal herd size would be the one at which the value of the marginal product of the herd net of herding costs equalled the return that could be earned by selling an animal. This is a standard result.[7] However, with the "resiliency model" we require $\lambda F_H - c > \delta\lambda$ in the steady state. That is, we require that a *postitive* net marginal return be earned on livestock; H/K must be "too small" compared to the case where carrying capacity is fixed.

For our problem to be interesting we require an equilibrium at which h, H and K are all positive. Figure 1 shows that there are two candidates. However, only one of these satisfies the necessary conditions for an optimum.

Upon substitution we see that eq. (7) is quadratic in H/K, which in the range management literature is referred to as *grazing pressure*. The optimal grazing pressure must satisfy

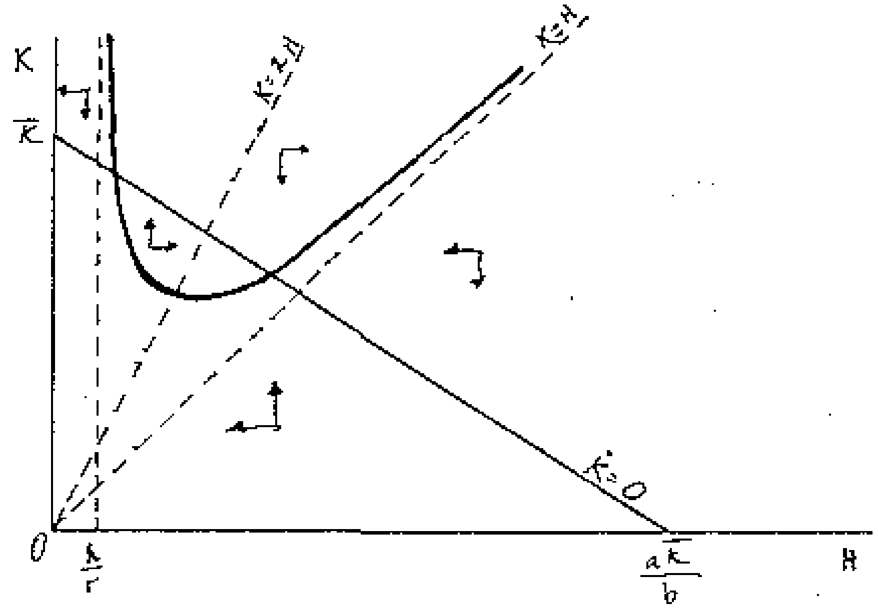
$$(H/K)^* = [(a+\delta)/b]\{-1 \pm \sqrt{\{1 + [b(r-c/p-\delta)/[r(a+\delta)]]\}}\}, \qquad (8)$$

which has two possible solutions. There is, however, only a single positive solution to (8) provided $r > c/p + \delta$, as I assume. This is tantamount to assuming that it is not optimal to drive the herd to extinction.[8] For suppose $r < c/p + \delta$. Then when $H = 0$ the return to holding an animal (rp) is less than the cost ($c + p\delta$). Since the rate of growth of the herd declines as H increases, if it is not optimal to maintain a herd of one animal then it will not be optimal to maintain a herd of any size. Note from eq. (8) that the larger is the cost-price ratio the smaller will be the optimal grazing pressure. Indeed, for some areas the cost-price ratio may be so large that herding will not prove socially profitable at all. Finally, note that the effects of the various parameters on optimal grazing pressure can be complex. For example, it would be natural to suppose that a higher rate of discount would lead to a reduction in grazing pressure. This is by no means clear from (8), however (but see below).[9]

We have thus far proven that if $r > c/p + \delta$ then there exists a unique bioeconomic equilibrium. But which of the two candidates in Figure 1 is the optimum? The lemma given in the appendix shows that the optimal grazing pressure must be less than one-half. It is similarly easy to show that the $\dot{H} = 0$ locus reaches a minimum at $H/K = 1/2$. The right-most equilibrium in Figure 1 occurs at $H/K > 1/2$. Hence if $r > c/p + \delta$ then the optimal bioeconomic equilibrium will be the interior equilibrium on the left in Figure 1.

FIGURE 1

Constant Harvest Rate Isoclines for $0 < h << h^{max}$



I noted earlier that the relationship between optimal grazing pressure and the rate of discount is in general ambiguous. Given values for the parameters in eq. (8), however, we can readily calculate how $(H/K)^*$ will change as δ is increased. Let a = 0.25, b = 0.05, r = 0.50, and c/p = 0.10. Then it is easily confirmed that the optimal grazing pressure will be as follows:

	δ				
	0.00	0.05	0.10	0.15	0.25
$(H/K)^*$	0.38	0.34	0.29	0.25	0.15

In this example, $(H/K)^*$ does indeed fall as δ is increased. In fact, I have not been able to construct a plausible example in which the optimal grazing pressure increases with higher rates of discount.

III. THE OPTIMAL APPROACH TO THE OPTIMAL STEADY STATE

Since rangelands are subject to frequent environmental disturbances, it is of some interest to know how the singular steady state should be approached following a shock. More generally, given that we know the optimal grazing pressure, we will also want to know what sort of investment policy should be pursued in reaching the optimum. The approach will obviously involve a combination of bang-bang and singular control. Our problem, then, is to determine when the different controls should be switched on.

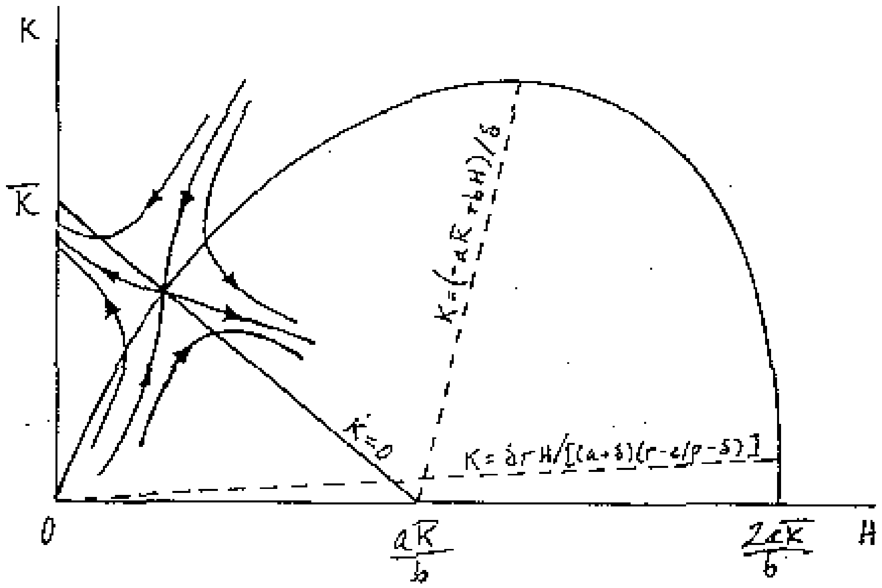
Let us first derive the paths in H-K space along which singular control is optimal. We already know the $\mathring{K} = 0$ locus (see Figure 1). The slope of the $\mathring{H} = 0$ locus under singular control (see Appendix) is given by

$$\left.\frac{dK}{dH}\right|_{\mathring{H}_S=0} = -\frac{\theta_H}{\theta_K} = -\frac{(a\overline{K}+\delta K-bH)}{\delta H - (a+\delta)(r-c/p-\delta)K/r.}$$

There are two cases to consider. If δ is "small," then the two rays $K = -a\overline{K}/\delta + bH/\delta$ and $K = \delta rH/[(a+\delta)(r-c/p-\delta)]$ will intersect. If δ is "large," then these two rays will not intersect. However, in both of these cases the optimal steady state under singular control (H^*,K^*) can be shown to be a saddle point. If δ is "small," we get a picture that looks like Figure 2 (in the limit as δ goes to 0 the $\mathring{H}_S = 0$ locus becomes symmetric about $a\overline{K}/b$). Returning to our hypothetical numerical example, the social rate of pure time preference will be "small" if it is ten percent or lower. This is clearly the case of greatest interest. There may, of course, be values for H and K where singular control is optimal but ruled out by the constraints on the rate of harvest. Here paths satisfying bang-bang control will connect smoothly with the singular approach paths.

FIGURE 2

Singular Phase-Plane Diagram When δ is "Small"



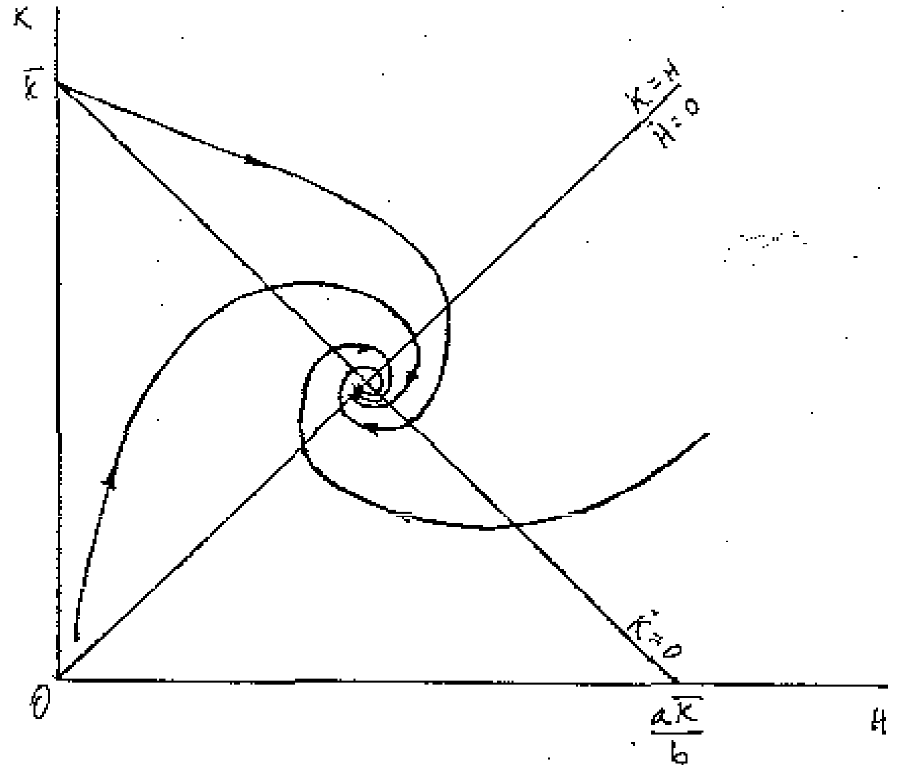
Unless the system happens to begin on one of the singular approach paths, the optimal approach will involve bang-bang control. Consider first the case where $h = 0$. This is the "natural" system, and it is characterized by two equilibria, one at $(0,\bar{K})$ and one at $[a\bar{K}/(a+b),a\bar{K}/(a+b)]$. It is easily shown that the former equilibrium is a saddle point and that the latter is a stable node if $a(a-2r) + r(r-4b) > 0$, and a stable focus if $a(a-2r) + r(r-4b) < 0$. In our hypothetical example, this equilibrium is a stable focus, and in nature the dynamic behavior of herbivore-vegetation systems does seem to exhibit the pattern of a stable focus (Caughley, 1976, p. 197):

> "When ungulates are introduced into a previously unoccupied area they increase to a peak density and then crash steeply to a considerably lower level. Subsequent oscillations are heavily dampened and density finally steadies well below the initial peak. The vegetation follows a reciprocal trajectory, first falling in density as the population rises, increasing again as the animals crash, and finally settling to a density and rate of production at equilibrium with a relatively constant pressure of grazing."

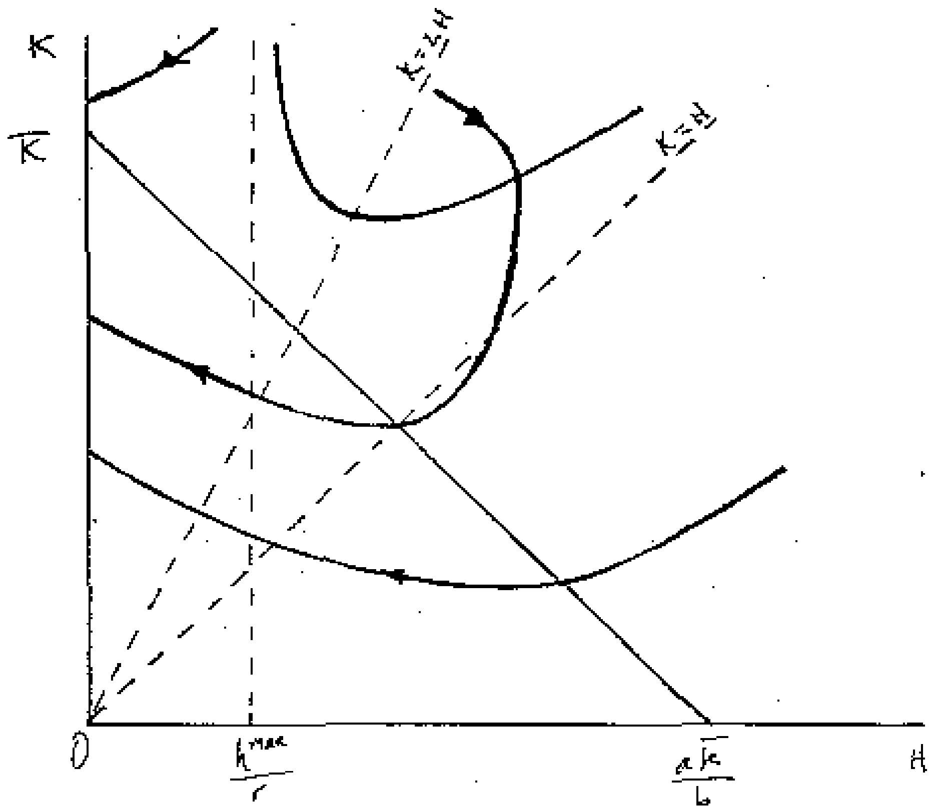
The most likely case corresponding to $h = 0$--that is, the case where the natural equilibrium is a stable focus--is illustrated in Figure 3a.[10] Trajectories corresponding to $h = h^{max}$ are illustrated in Figure 3b. It is assumed here that h^{max} is "large" so that "extinction" of the herd is feasible.

FIGURE 3

Constant Harvest Rate Trajectories



(a) h = 0
stable focus



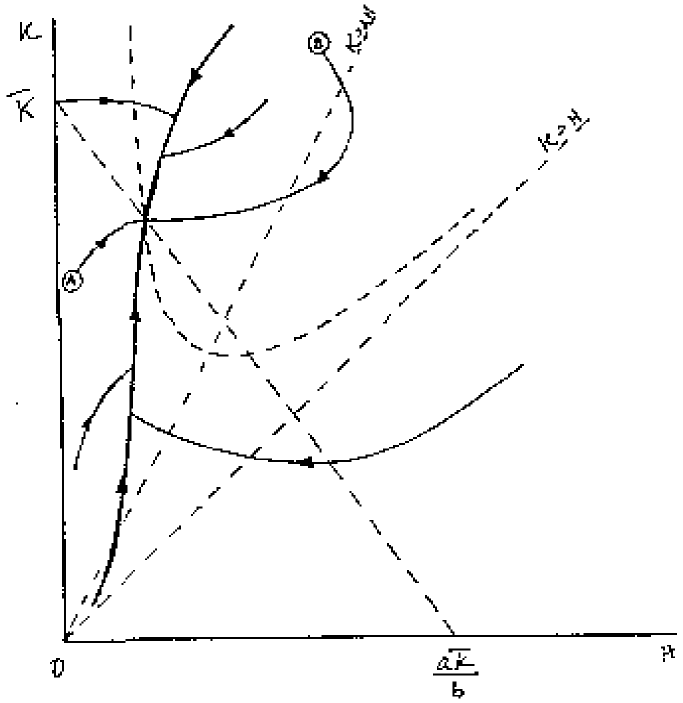
(b) h = h^{max}

Although a rigorous proof seems difficult, intuition suggests a fairly simple optimal approach policy. It is optimal to adopt singular control along the singular approach paths. Hence, if the system begins on one of these paths it is optimal to stay on it. If the system begins to the left of the singular approach paths (see Figure 4) then it is optimal to set $h = 0$ at first because this policy will lead the system to one of the singular approach paths in the shortest time (indeed, choosing $h = h^{max}$ will lead the system *away* from the optimum). Similarly, if the system begins to the right of the singular approach paths, then it is optimal to set $h = h^{max}$ at first.

If the system does not begin on one of the singular approach paths, or on the bang-bang trajectories leading to the optimum (trajectories A and B in Figure 4), then it is optimal to use a combination of singular and bang-bang control. If the system begins to the left of the singular approach paths but below trajectory A, where both H_0 and K_0 are "small," then it is optimal to set $h = 0$ until the lower singular approach path is reached, and to then follow this path to the optimum. In this case it is optimal to "*undershoot*" the optimum in the sense that harvesting should begin before the optimum is reached. If this policy were not pursued, the delayed response of carrying capacity to increasing herd size would mean that the environment was incapable of supporting H^*; there would be economic overgrazing. "Undershooting" is also optimal if H_0 and K_0 are both "large."

FIGURE 4

Solution of the Optimal Grazing Problem

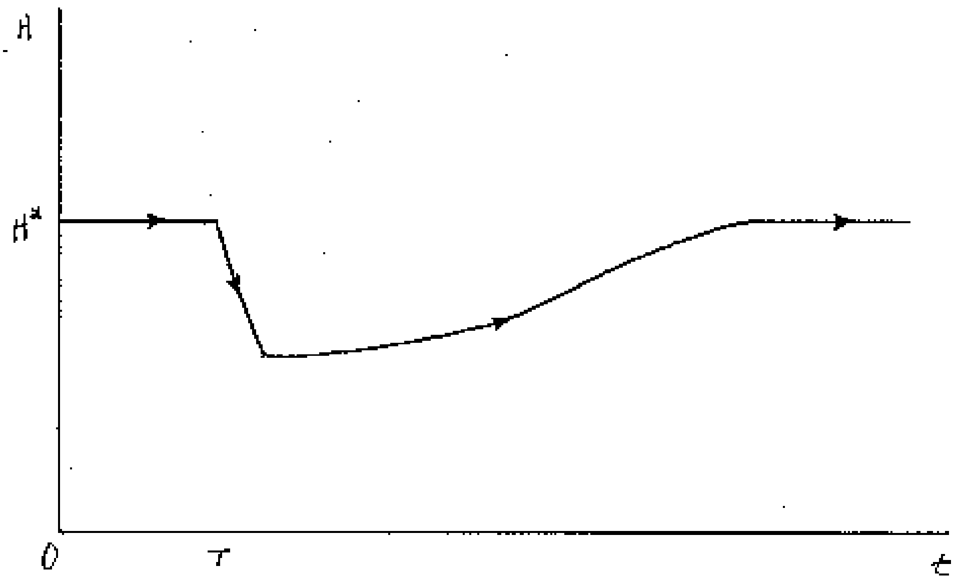


In the case of drought, carrying capacity will be reduced temporarily below K^*; that is, the system will begin to the right of the singular approach paths and below trajectory B. The optimal response to this shock is to set $h = h^{max}$ until the singular approach path is reached, and to then follow this path to the optimum; *overshooting* is optimal (see Figure 5; overshooting is also optimal if H_0 is "small" and K_0 "large"). This optimal response to drought, which lets carrying capacity recover to where it will be capable of supporting the optimal herd size, has not been missed by policy analysts. In a recent World Bank publication on desertification control, Bonfiglioli (1988, p. 53) has stated:

> "A further way of raising pastoral productivity would be to facilitate de-stocking in drought years and re-stocking afterwards, enabling the herds to track more closely the changes in food availability."

FIGURE 5

Optimal Response to an "Instantaneous and Unexpected" Drought at Time T



The foregoing analysis is summarized in the following proposition.

Proposition 1. *There exists a unique optimal grazing pressure for problem (6) defined by*

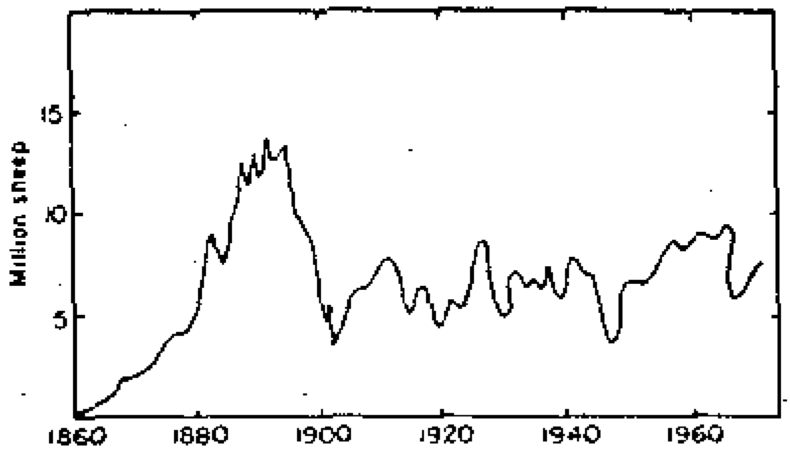
$$(H/K)^* = \begin{cases} [(a+\delta)/b]\{-1 + \sqrt{\{1 + b(r-c/p-\delta)/[r(a+\delta)]\}}\} & \text{if } r > c/p + \delta \\ 0 & \text{if } r \leq c/p + \delta. \end{cases}$$

If r ≤ c/p + δ, then the optimal policy is to choose $h = h^{max}$ *until the herd is driven to extinction. If r > c/p + δ, then the optimal approach to the optimum will consist of a phase of bang-bang control followed by a phase of singular control (unless the system happens to begin on one of the two stable arms or on one of the two bang-bang trajectories leading to the optimum). Depending on the intial conditions, it will be optimal to either overshoot the optimum or to approach the optimum gradually (unless the system happens to begin on one of the two bang-bang trajectories leading to the optimum).*

Does the theory presented here fit the facts? Evidence is sketchy, but suggests that the theory at least cannot be rejected. Figure 6 charts the population of sheep in the western division of New South Wales between 1860 and 1972. Mabbutt (1986), noting that sheep numbers tend to stabilize at about one-third of the peak value, interprets this figure as providing evidence of overgrazing. Noy-Meir (1975) argues that the figure supports the hypothesis that range systems are discontinuously stable. Caughley (1976) interprets the same figure as demonstrating the usual pattern of ungulate population growth--the same general pattern as would emerge from simulations of the natural system comprising eqs. (3) and (4). What all these authors forget is that the population of sheep is subject to management; and in this regard it can be seen that the general pattern in Figure 6 conforms to the prediction of the model given here--namely that it is optimal for a managed grazing system starting at $(0,\bar{K})$ to overshoot the equilibrium. Fluctuations after this time can be interpreted as responses to environmental disturbances.

FIGURE 6

Population of Sheep in the Western Division of New South Wales, 1860-1972



Source: Caughley (1976)

IV. INTERPRETATION OF THE STEADY STATE

IV.1 On the Concept of Overgrazing

We are now in a position to give a precise definition to the term "overgrazing." Following the economics of fishing literature (see, in particular, Clark, 1976), it will prove useful to distinguish between biological (or, perhaps more appropriately in our case, ecological) overgrazing and economic overgrazing. *Ecological overgrazing* may be defined as occuring whenever equilibrium grazing pressure exceeds

$$(H/K)^{MSY} = (a/b)[-1 + \sqrt{(1+b/a)}],$$

the grazing pressure which maximizes the sustained yield of livestock. *Economic overgrazing* may be defined as occuring whenever the equilibrium grazing pressure exceeds $(H/K)^*$ (as defined by eq. (8) with the $\pm$ sign changed to a +). Notice that whereas in the economics of fishing literature overfishing is defined in terms of the stock of fish, overgrazing may be usefully defined only in terms of the herd-carrying capacity *ratio*, or grazing pressure. Overgrazing is a site-specific phenomenon.

By inspection it is clear that $(H/K)^* < (H/K)^{MSY}$ for $c/p > 0$ and $\delta = 0$. But for $\delta > 0$ the inequality sign could go either way. To see more clearly how these measures of grazing pressure compare, consider the numerical example given previously. We have already calculated $(H/K)^*$ for various rates of discount. It is easy to show that $(H/K)^{MSY} = 0.48$. If δ is even as low as 0.05, then a range managed to maximize sustainable yield will have a grazing pressure which exceeds the optimum by 40 percent. If the cost-price ratio is 0.25 instead of 0.10, then $(H/K)^{MSY}$ will be twice as great as $(H/K)^*$ even at a zero rate of discount. The range management literature, much like the fisheries and forestry literatures, often takes maximization of sustained yield to be the objective of management. But this can clearly lead to rather large losses in present value social profit.

IV.2 Problems of Open Access

If the range is subject to open access, no herder will earn positive profits. Hence, open access implies $ph = cH$. The open access range must also obey eqs. (4) and (5). Combining the zero profit condition and (5) we obtain the equilibrium open access grazing pressure

$$(H/K)^{OA} = (r - c/p)/r. \qquad (9)$$

We then have

Proposition 2. *Open access implies economic overgrazing but it need not imply ecological overgrazing.*

Proof. See Appendix.

Proposition 2 substantiates Dasgupta's claim quoted in the Introduction: whether or not open access implies ecological overgrazing depends on the cost of herding relative to the output price. In our numerical example, open access implies that grazing pressure will exceed the MSY level by two-thirds and the optimum by a factor greater than two (whatever the rate of discount). However, if the cost-price ratio were equal to 0.30 instead of 0.10, then grazing pressure under open access would be lower than $(H/K)^{MSY}$.

How should the rangelands be regulated to achieve the socially optimal grazing pressure? One approach would involve establishing and enforcing exclusive rights to the rangelands. Demsetz (1967) argues that such rights will in fact emerge when economic forces make internalization of externalities attractive; and Anderson and Hill (1977, pp. 206-207) have interpreted the evolution of property rights on the American Great Plains within this framework. Access to common rangelands in the Sahel has historically been regulated by tribal groups. But this form of control has eroded in recent years. Traditional rules for range management have not been recognized by central governments. And access to new pumping stations, constructed by central governments, has not been restricted to particular pastoral groups.[11] Recently, there have been some attempts to revive traditional methods of managing common rangelands. An example is the *Hema* system in which grazing rights are restricted to members of herder cooperatives.

A second approach to achieving the optimal grazing pressure is privatization. In the American West, exclusive ownership of rangelands became economic in the 1870s when newly-invented barbed wire greatly reduced the cost of restricting access. Similarly, property rights in water were defined and enforced when water became scarce. Anderson and Hill's (1977, p. 214) analysis of overgrazing on the Great Plains concludes by saying: "as the ill effects of common ownership manifested themselves, individual efforts were channeled toward transforming the nature of ownership in land, livestock, and water." But these developments were facilitated by the U.S. government. In most poor countries, communal management and private ownership have been actively discouraged by central governments (Mortimore, 1987, p. 12):

> "While governments blame 'common' rights to pasturage for overgrazing, they are reluctant to define land rights in such a way that pastoral communities can enjoy the security of tenure that is the necessary condition for improved management."

Privatization may not even be an attractive option in the drylands of Africa, for it is essential that pastoralists be able to move their herds to seasonal rangelands. Direct control over animal numbers may therefore prove more effective in regulating grazing pressure on these rangelands. One approach would be to issue grazing permits, as the U.S. government does for access to public rangelands. Another approach would be to tax herders.[12] The following proposition determines optimal taxes for the bioeconomic model described by problem (6).

Proposition 3. *The social optimum can be sustained by imposing a tax on either each head of livestock or on the sale of livestock products. The optimum tax on* h *is*

$$\tau_h = p - c/\{r[1 - (H/K)^*]\}, \qquad (10)$$

and the optimum tax on H *is*

$$\tau_H = rp[1 - (H/K)^*] - c, \qquad (11)$$

where $(H/K)^*$ *is determined by eq. (8).*

Proof. See Appendix.

Returning to our hypothetical example, if $\delta = 0.05$ then the optimal tax on harvested livestock τ_h would amount to 70 percent of the slaughter price. The optimal tax on animals τ_H would be about 23 percent of this price.

Taxes are already levied on livestock in many Sahelian countries, so that this policy would seem to have some chance of success. However, it should be noted that the problem is not just one of there being too many animals *per se* but of the livestock being poorly distributed across the landscape. In Niger there appear to be too many animals around the open access pumping stations--but perhaps too few at other places (Mabbutt and Floret, 1980). Some mechanism to encourage herders to spatially disperse their livestock may therefore also be required.

IV.3 On the Concept of Human Carrying Capacity

Priorities for intervention in heavily grazed areas have been based on comparing human populations with the carrying capacity of the land in terms of *people*. Human carrying capacity is usually defined as the maximum number of people a region can support without trade (see, for example, Muscat, 1985; and Kirchner *et al.*, 1985). For pastoral societies, human carrying capacity has been calculated by determining the maximum number of livestock an area is capable of sustaining, and then multiplying this figure by the number of people that can be supported by each livestock unit (see, e.g., Gorse and Steeds, 1987).

The definition of livestock carrying capacity implicit in this calculation is what I have called the "natural equilibrium." Our model has shown, however, that the optimal grazing pressure will generally be far less than the ecological maximum (in our model, the maximum sustainable value of H/K is one; the optimum is less than one-half). Contrary to popular opinion, anthropological research has shown that pastoralists do *not* seek to maximize the size of their herds (Watts, 1986). Furthermore, pastoral households engage in substantial trade, selling livestock products and purchasing grains and other commodities (Swift, 1986). And grain can be far more efficient than livestock at satisfying peoples' nutritional requirements. Estimates of human carrying capacity should take into account the price of grain and the purchasing power of households as well as their nutritional requirements. What matters is a household's ability to command food, not its ability to eke out a subsistence living. The fact that there are more people than can be sustained on a subsistence basis from a maximum herd does not necessarily mean that there are too many people. The optimal grazing pressure supports fewer animals but generates greater profit and hence can support *more* people. This effect is reinforced when calories can be obtained more cheaply from grain.

A related problem with human carrying capacity measures is that they are static, and yet pastoralists are especially vulnerable to famine at times of drought. The reason for this vulnerability is not simply that drought kills animals and that smaller herds can support fewer people. As we shall soon see, during a drought the purchasing power of herders drops and the price of grain rises. The problem then becomes much worse than measures of human carrying capacity would indicate. True, the subsistence level drops. But the ability of herders to command food drops even more sharply.

V. THE NATURE AND CAUSES OF OVERGRAZING

If one accepts the model constructed here, then one must also accept the proposition that livestock numbers cannot exceed carrying capacity for very long. In an unmanaged situation ($h = 0$ always), natural forces will tend to move the system to where animal numbers are at their ecological maximum. In a managed situation, herders--even on an open access range--will have an incentive to reduce stock numbers to a level that is less than the ecological maximum.

Accounts of the overgrazing problem suggest that animal numbers often exceed rangeland carrying capacity (implying $H/K > 1$). Our model suggests that this is possible in the short run when carrying capacity is drastically squeezed, as in times of drought. Overgrazing can persist following such disturbances if there are forces which limit maximal herd offtake (h^{max}) (although if the rate of offtake is restricted long enough, animals will starve). Evidence on overgrazing suggests that such forces do indeed exist, and that they are particulary pronounced in times of drought. An analysis of case studies on desertification concluded (Mabbutt and Floret, 1980, p. 274):

> "Many of the studies illustrate the inherent difficulty of reducing stock numbers, at the onset of drought, from levels attained in foregoing wetter years, and the social and economic forces that hinder this."

What are these forces? One is open access. A herder on an open access range will realize that he or she can facilitate recovery of the range by increasing the rate of offtake at times of drought. But only a small portion of this benefit will be realized by this herder. Hence, on an open access range, herders have an incentive to limit their rates of offtake, even if this means that some livestock will not survive the drought. But open access is only one of the forces operating at these times. To answer this question more fully, we will have to depart from some of the assumptions that make up our simple model.

One assumption to discard is that price remains at all times constant. When a drought hits, maximal harvesting will be optimal if price is fixed. But the demand curve for livestock products will ordinarily have some slope, and in offering more livestock for sale price will fall. This effect is reinforced by the fall in farm incomes that accompanies drought. Meat is a superior good, and hence the demand for meat products falls during droughts. As price falls, the optimal grazing pressure will also fall (assuming herding costs are constant), reinforcing the incentive to destock in times of drought. Of course, the drought will be seen to be transitory; herders will recognize that when the rains return price will once again rise, and so they will have an incentive to hold on to more of their stock than they would if the price change were permanent. Nevertheless, price adjustment should encourage further destocking in times of drought. Unfortunately, price controls often interfere with the price adjustment mechanism. The consequences of such controls can be devastating (Horowitz and Little, 1987, p. 78):

> "In [drought] years, the number of animals that come on the market is very high, causing producer prices to fall. While it becomes a buyer's market, state-imposed consumer prices are kept up in the cities, rather than allowed to fluctuate according to supply and demand conditions. This inflexibility greatly limits the absorptive capacity of the domestic meat market (which tends to be concentrated in urban areas), and allows private traders to reap considerable profits by buying cheaply and selling dearly in the urban marketplace. None of this value added is received by the producer. In Kenya, urban prices were not changed during the 1984 drought, although producer prices in the range areas dropped by as much as 65%. Even then herders had difficulty finding outlets for their surplus stock. The result

was that up to 50% of cattle died in certain regions, where markets could not be found. The figure would have been higher had not the government increased its purchases of meat for the country's canning facilities."

The second assumption to discard is that herders are profit maximizing firms and not utility maximizing households. In times of drought, not only do livestock prices fall but grain prices rise; pastoral households, who depend on grain for much of their nutrition intake, are twice hurt. Sen (1981, Table 7.7) estimates the total exchange entitlement loss owing to the change in relative prices during the Ethiopian famine of 1973 at between 62 and 72 percent. How do herders respond to such losses? One response is to dissave. But saving for pastoralists often takes the form of animals on the hoof, and the cost to herders of losing their assets can be enormous; in practice, disinvestment tends to be irreversible and leads to permanent impoverishment (Mortimore, 1987, p. 7; Horowitz and Little, 1987, p. 79). In areas controlled by some pastoral communities, households who lose their herds to drought may have their grazing rights revoked. And credit is usually not available to facilitate restocking. Herders could seek wage employment, and often do; cities swell with displaced pastoralists during times of severe drought. But employment opportunities are very limited at such times. Indeed, based on recent work by Dasgupta and Ray (1986, 1987), we can speculate that displaced pastoralists may have trouble finding wage employment *precisely because they are assetless and hence have no non-wage income.*[13] According to this theory, herders will be reluctant to destock because upon doing so their chances of obtaining wage employment may well diminish.

Since drought is a recurrent phenomenon in the Sahel, one might think that the appropriate response of herders would be to purchase insurance or to insure themselves by, say, investing in alternative assets. Unfortunately, the necessary financial institutions do not exist in pastoral areas.[14] The only means of self insurance available to herders, apart from diversification into farming or wage employment, is to amass large herds and limit offtake rates. Larger herds insure against drought because they yield higher survival rates (see Sen, 1981, pp. 128-129). But such behavior only exacerbates the overgrazing problem.

The tragedy is documented by Heiland's (1980, p. 99) account of the response of the Afar community in northeastern Ethiopia to the 1973 drought:

"...during the 1973 famine Afar households tried to keep their productive herds as long as possible, hoping the rains would return. Some animals were sold, but grain prices were high and livestock prices were falling. As the animals were emaciated, they fetched even poorer prices and provided little food when slaughtered. A number of households probably fell below the viability threshold without obtaining any assistance and people were starving. When the animals started to die, they died more rapidly than they could be consumed. Animals continued to die until the rains returned and people were dying until relief supplies were poured into the area in late 1973."

The evidence presented here suggests that the most severe overgrazing occurs not in an equilibrium situation but during periods of drought when drastic destocking is optimal but forces compel herders not to slaughter their animals. It is true that economic or even ecological overgrazing will reduce social profit. But neither will bring ruin. The ruin that occurs in the Sahelian rangelands is more likely caused by forces which slow the response of pastoralists to changing environmental circumstances. Policies intended to correct the overgrazing problem will have to redirect these forces; famine relief is not a long run solution. One suggestion would be to combine livestock taxes, to reduce overstocking at normal times, with social security payments guaranteeing food entitlement and subsequent restocking of herds, to speed destocking when the rains fail.

APPENDIX

Maximum Principle Formulation. Let λ_t be the shadow price of the herd and μ_t the shadow price of carrying capacity. For problem (6), the maximum principle requires either bang-bang control, in which case

$$h = 0 \quad \text{if} \quad \lambda > p \tag{12a}$$

$$h = h^{max} \quad \text{if} \quad \lambda < p, \tag{12b}$$

or singular control, in which case

$$h \in [0, h^{max}] \quad \text{if} \quad \lambda = p. \tag{12c}$$

We also require

$$\mathring{\lambda} = \lambda[\delta - r(1-2H/K)] + \mu b + c \tag{13}$$

$$\mathring{\mu} = \mu(\delta + a) - \lambda r(H/K)^2. \tag{14}$$

Eq. (7) can be solved by combining eqs. (13) and (14).

Derivation of $\mathring{H}_S = 0$ Locus. Along the singular paths, $\lambda = p$. Since p is assumed to be constant, λ must also be constant along the singular approach paths. Setting $\mathring{\lambda} = 0$ in eq. (13), differentiating the resulting equation with respect to time and substituting gives

$$\mathring{H}_S = a\overline{K}(H/K) + \delta H - bH^2/(2K) - (a+\delta)(r-c/p-\delta)K/(2r), \tag{15}$$

where the subscript s denotes singular control.

Lemma. $(H/K)^* < 1/2$.

Proof. Suppose the contrary. Then from (8) we have

$$[(a+\delta)/b]\{\sqrt{(1 + b(r-c/p-\delta)/[r(a+\delta)]\}} - 1\} \geq 1/2.$$

Some algebra shows that this implies

$$\delta \leq -c/p - br/[4(a+\delta)].$$

But by assumption $\delta > 0$. Hence we have a contradiction. | |

Proof of Proposition 2. The first part of the proposition is true if and only if eq. (9) is greater than (8). Suppose the contrary. Then a little algebra shows that this implies

$$1 + b(r-c/p)/[r(a+\delta)] < \sqrt{\{1 + b(r-c/p-\delta)/[r(a+\delta)]\}}.$$

But this inequality is false since by assumption $r > c/p + \delta$. Hence $(H/K)^{OA} > (H/K)^{*}$.

To prove the second part of the proposition we must show that $(H/K)^{OA}$ can be greater or less than $(H/K)^{MSY}$. Open access grazing pressure exceeds MSY grazing pressure if and only if

$$1 + b(r-c/p)/(ar) < \sqrt{(1 + b/a)}.$$

But this statement is true only if c/p is sufficiently small; if the cost-price ratio is sufficiently large, open access grazing pressure will be less than MSY grazing pressure. | |

Proof of Proposition 3. The social optimum is found by solving eqs. (8), (4) and (5) with $\mathring{H} = \mathring{K} = 0$. Open access herders obey (9) instead of (8). The optimum tax τ_H is found by setting the RHS of (8) equal to $[r-(c+\tau_H)/p]/r$. The optimum tax τ_h is found by setting the RHS of eq. (8) equal to $[r-c/(p-\tau_h)]/r$. Eqs. (10) and (11) are obtained by simply solving these two equations. | |

NOTES

1 For example, the Schaefer model of the economics of fishing yields a unique optimal equilibrium stock. But more general models may posess multiple solutions or no solutions at all. I suspect that the same will be true when alternative models of the dynamic interaction between the stock and carrying capacity are employed.

2 For an alternative view of "the Sahel problem," see Sinn (1988), who argues that aid should be channeled to neighboring fertile regions and not directly to the Sahel.

3 In the range management literature, H would be measured in animal units (AUs) or tropical livestock units (TLUs) or standard stocking units (SSUs). Carrying capacity is defined in terms of H. But it will sometimes seem more appropriate to relate carrying capacity to vegetative cover as well as to herd size. Let V_t denote vegetation biomass (measured in tons or kilograms). Then we can write $K_t = \sigma V_t$, where σ is a constant which when multiplied by V_t yields the largest herd which the environment can carry.

4 Some general predator-prey ecological models can be found in May (1974, 1981) and Maynard Smith (1974). Models proposed specifically for grazing systems can be found in Caughley and Lawton (1981), May (1981) and Noy-Meir (1975).

5 I am, of course, overlooking much that is important in range management, such as the distribution of the herd in terms of the age and sex of individual animals. Further, it may well be that herding "effort" may alter the normal growth process of a population. Veterinary care may increase fecundity. More intensive monitoring may reduce losses to natural predators. And so on.

6 It is not realistic for particular localities. Helland (1980, p. 101), for example, reports that "In the northeastern rangelands of Ethiopia, ...it seems that imports of productive livestock as part of local restocking strategies are of great importance." To allow for imports we need only specify a negative minimum harvest rate. The qualitative results derived in this chapter will not be affected by such a change.

7 Set $c = 0$, as is usual in the fisheries literature. Then we have $F_H = \delta$, a well known result.

8 It is well known that if harvesting costs are negligible and growth is logistic then extinction is optimal provided $r < \delta$ (see, e.g., Clark ,1973).

9 The ambiguity arises from the dynamic interaction. Ragozin and Brown (1985) also fail to find a simple relation between the discount rate and the steady state position.

10 This analysis of the natural equilibrium pertains only to the neighborhood of the interior equilibrium point. I have not been able to rule out the possibility of a limit cycle. However, Caughley (1976) notes that ungulate populations have never been observed to cycle.

11 In Niger, pumping stations were not allocated to particular groups for fear that such allocations would intensify rivalries between ethnic and tribal groups. See Mabbutt and Floret (1980, p. 135).

12 The Bureau of Land Management in the United States charges a fee for grazing on public rangelands. However, the fee is not used as a regulatory device. See Johnson and Watts (1989).

13 Dasgupta and Ray's (1986, 1987) work explains involuntary unemployment of the assetless, arguing that since productivity is a function of nutrition intake when intake is low, people with alternative sources of income will have higher nutrition intake and hence higher productivity than people without assets. People with assets will therefore have an advantage over the assetless in the labor market. Dasgupta and Ray demonstrate that redistribution of assets, or food transfers, can increase output and reduce both unemployment and malnutrition.

14 Interestingly, pastoral groups do have mechanisms for restocking herds of poor families. But the resources of such groups are limited, and when severe drought hits, these mechanisms fail.

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