Analyzing and Addressing Localized Degradation in the Commons

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ABSTRACT. *Social scientists are paying increasing attention to the implications for commons management of user and resource heterogeneity. This study considers the example of localized degradation of a shared rangeland where users and rangeland sub-areas differ in characteristics. A model of land-use decisions is developed. Longitudinal data on land-use decisions are investigated. The impact of proportionate reduction and uniform quota policies are evaluated by simulating estimation results. The study finds recognizing heterogeneity allows insight into the causes of localized degradation, and explains how policies intended to increase the efficiency of exploitation can go awry if heterogeneity is not recognized.* (JEL Q22, Q24)

I. INTRODUCTION

Social scientists are paying increased attention to the implications of heterogeneity in the commons. Two types of heterogeneity have received particular attention in recent literature: heterogeneity of individuals sharing a resource and heterogeneity of the resource itself. To date, the policy implications arising when both user and resource heterogeneity characterize a jointly exploited resource have not been explored. The current study addresses a gap in the literature by investigating the implications of user and resource heterogeneity in a commonly held rangeland.

Studies investigating the impact of user heterogeneity on exploitation of the commons have found Olsen's (1965) speculation that increasing inequality makes provision of collective goods more likely is not necessarily true, as the influence of inequality on efficiency in the commons is ambiguous (Baland and Platteau 1997; Dayton-Johnson and Bardhan 1998). This ambiguity also characterizes the efficiency gains from regulation using second-best policy measures (Baland and Platteau 1998; Gardner et al. 2000).

A separate theme in recent literature investigates the implications of joint exploitation of a heterogeneous resource. One set of studies finds that if rainfall realizations are spatially heterogeneous, rangeland users' risk exposure is reduced through shared access to multiple resource areas (Nugent and Sanchez 1998; Goodhue and McCarthy 1999). A second set of studies investigates how differences in the economic characteristics of resource sub-areas influence exploitation patterns (Sanchirico and Wilen 1999; Smith and Wilen 2000). Sanchirico and Wilen argue that including a spatial dimension in bioeconomic models of heterogeneous resource exploitation is critical, as studies focusing on aggregate exploitation levels may overlook information on spatial patterns of economic behavior that is of policy relevance.

In addition to exploring theoretical, empirical, and policy issues arising when user het-

Land Economics • November 2003 • 79 (4): 515–536
ISSN 0023-7939; E-ISSN 1543-8325

The author is assistant professor, Department of Public Administration and Department of Economics, Syracuse University. Work on this manuscript was conducted while the author was supported by the Pastoral Risk Management Project of the Global Livestock Collaborative Research Support Program, funded by the Office of Agriculture and Food Security, Global Bureau, USAID, under grants DAN-1328-G-00-0046-00 and PCE-G-98-00036-00. The opinions expressed do not necessarily reflect the views of the U.S. Agency for International Development. Financial support for this study was provided by an International Predissertation Fellowship from the Social Science Research Council and the American Council of Learned Societies with funds provided by the Ford Foundation, the Mellon Foundation, and the Graduate school of the University of Wisconsin–Madison. The author thanks Ken Baerenklau, Michael Bennett, Chris Barrett, Cheryl Doss, Bill Provencher, Riccardo Scarpa, Matthew Turner, and the reviewers from this journal for helpful comments. All errors and omissions remain those of the author.

erogeneity and resource heterogeneity are combined in the commons, this study also contributes to a debate in the range ecology literature concerning the nature of the relationship between livestock populations and rangeland condition in arid and semi-arid areas. While it has long been argued that higher then optimal stocking levels of commonly held rangelands result in degradation (Brown 1971; Doran, Low, and Kemp 1979; Lamprey 1983; Hu, Ready, and Pagoulatos 1997), recent studies question the applicability of the perspective in arid and semi-arid areas (Homewood and Rogers 1987, McCabe and Ellis 1987; Hellden 1991). It is argued that under the climatic conditions characterizing such areas,[1] frequent droughts ensure livestock populations rarely reach levels adversely affecting rangeland condition (Sanford 1982; Westoby, Walker, and Noy-Meir 1989; Ellis and Swift 1988; Abel 1993; Biot 1993; Scoones 1993).

Empirical studies tend to support this hypothesis, finding that widespread degradation of arid and semi-arid rangelands is not currently a problem. However, the absence of widespread degradation does not necessarily mean that no degradation is occurring. Many studies identify localized degradation of key resource areas within jointly exploited rangelands (Lusigi 1984; Schwartz, Shaabani and Walther 1991; Dodd 1994; Keya 1998; Turner 1998a, 1998b).

The current study explicitly recognizes spatial differences in rangeland areas in order to analyze the causes of localized degradation. The study focuses attention on factors leading to a sub-optimal distribution of animals within the commons. This contrasts with the traditional common property model's focus on factors leading to a higher than optimal exploitation level of the commons. The added modeling effort is required in this case, as policies addressing localized degradation must explicitly address incentives that influence the spatial distribution of stocking pressure within the commons. As will be elaborated on below, understanding how both user and resource heterogeneity influence spatial patterns of exploitation in the commons leads to new insights on policies that will arrest degradation.

The outline of the study is as follows. Section 2 orients the reader to important facts about the area in northern Kenya where data for this study was gathered. Section 3 draws on these facts to develop a dynamic model of resource exploitation. Parametric differences between rangeland sub-areas that lead to long run differences in the condition of these sub-areas are identified. The estimation results of Section 4 reveal how changes in household level variables and time-period specific variables influence exploitation patterns in a commons. Section 5 uses estimation results to simulate the impact of two different policy measures on stocking pressure in degraded rangelands: proportionate reductions in household herd size, and uniform household herd size quotas. The final section discusses the implications of this study's findings, and suggests areas of further research.

II. STUDY AREA

Data for the current study were gathered in rangelands surrounding the towns of North Horr and Kalacha in Marsabit District, Kenya, in 1997–1998. The ethnic group resident in this area are the Cushitic speaking Gabra. The Gabra practice nomadic pastoralism with their herds of camels, cattle, sheep, and goats in northern Kenya and southern Ethiopia. Gabra herders have the right to reside and graze their animals anywhere in the area historically occupied by Gabra, as land is viewed as belonging to all Gabra rather than to any one individual. However, Gabra strive to keep herders from other ethnic groups from encroaching on their territory. In this sense, Gabra rangelands are a commonly held resource rather than an open access resource.[2]

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[1] Specifically, it is argued that areas with mean annual rainfall levels below 400 mm per year and coefficients of variation for rainfall greater than 30 (Coppock 1993) production conditions make it unlikely that animal populations are the fundamental cause of changes in rangeland productivity.

[2] Gabra property rights have not changed in the ways Ensminger (1996) documents for the linguistically related Orma in Kenya. It should be noted that efforts currently under way to introduce environmental management committees in this area may lead to a situation similar to that identified by Ensminger.

Gabra herders rely almost completely on livestock and livestock products for meeting their consumption needs, either through home consumption or through market exchange. The data collected for this study reveal the dependence of surveyed households on animals to meet consumption needs. If market values are assigned to all home consumed goods, on average 61% of consumption is from home consumed milk, 21% is from market goods purchased through livestock sales, 15% is from home consumed meat, and the remaining 3% is accounted for by market goods purchased by milk sales, hide sales, or remittances. The average cash value of consumption per-person per-day is equivalent to $0.61, suggesting the average herder is below a $1 per-person per-day poverty line.

Gabra raise their animals on the most arid rangelands in east Africa (FAO 1971). Median annual rainfall is below 300 millimeters for the vast majority of the rangeland area, making rain-fed cultivation impossible (Schwartz, Shaabani, and Walther). In addition to experiencing low median annual rainfall levels, the area is also characterized by a high variability in annual rainfall: the coefficient of variation for annual rainfall in the study area is 58.[3]

High rainfall variability corresponds to high variability in forage production, as forage growth is almost exclusively dependent on rainfall. Widespread herd losses result during periods when forage is insufficient. An example of one such event is recorded in the data set. In late 1996, surveyed households experienced an average 49% herd loss over a six-month period. Herders attribute these losses to the cumulative impact of three successive sub-average rainy seasons. Tablino (1999) reports droughts are a frequent occurrence in this area, reporting recent droughts in 1973, 1976, 1980, 1983, 1991, and 1996.

Households also face a risk of idiosyncratic herd loss due to livestock theft by armed raiding parties from other ethnic groups. Over the four-year span recorded in the data set, 18% of households lost animals to armed raiders. Those experiencing raids lost an average of 32% of their herd in the raid. Robinson's (1985) discussion of Gabra history reports such raids have been a constant feature of Gabra life from the middle of the nineteenth century to the present.[4]

Two separate land-use decisions characterize the Gabra production system: a base camp location decision and a satellite camp location decision. A base camp consists of a moveable hut that is approximately 4 meters in diameter surrounded by night enclosures for animals that are constructed of thorny branches. Women and children tend to be permanent residents of the base camp. By selecting a base camp site, the household head selects an area for animals in the household herd to graze as well as the distance base camp residents will be required to walk to the nearest town. Towns offer relative security against armed raiders, due both to the presence of government security forces and to their location in the interior of the Gabra rangelands. Towns also are the distribution points for food aid, which is frequently provided to herders by government agencies and non-governmental organizations.

Satellite camps are more mobile than base camps, and are designed to make use of rangelands infrequently utilized due to their relative remoteness. A satellite camp also has night enclosures for the animals, and may also contain a windscreen behind which residents sleep and cook. Younger male family members tend to reside in satellite camp. Animals are sent to satellite camps to enhance herd growth in normal years and to minimize herd loss in drought years. However, satellite camps are more likely to suffer raids due to their distance from town-based security forces and frequent proximity to the ethnic boundary of the commons. In addition, resi-

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[3] Rainfall data was graciously provided by the Catholic mission in North Horr and the A.I.C. mission in Kalacha. The coefficient of variation is calculated for annual rainfall data covering the period 1977-1996 in North Horr.

[4] Robinson also makes it clear that historically, Gabra have been the raiders as much as they have been the raided. Gabra raiding is not represented in this study for two reasons. First, the downside risk of suffering a raid is clearly more important to a study of land-use decision making. Second, during the study period, Gabra were much more frequently raided than they were raiders.

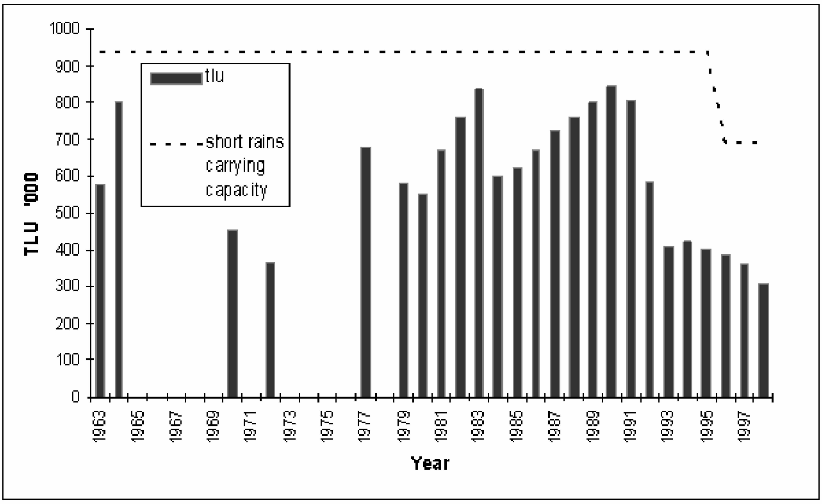

FIGURE 1
ESTIMATED HERD SIZE 1963–1998 COMPARED TO ECOLOGICAL CARRYING CAPACITY.

dents of satellite camps must travel long distances to access food aid provided in town.

Research on the ecological status of rangelands in Marsabit District has been extensive. The U.N.-funded Integrated Project in Arid Lands (IPAL) was active in this area from 1976 to 1983 ''with the aim of finding direct solutions to the most urgent environmental problems associated with desert encroachment and ecological degradation.'' (Lusigi 1984, Introduction). O'Leary (1987, 65) summarizes the project's final findings as follows: ''IPAL range and livestock scientists calculated that generally at the macro-level, the range resources could support current livestock populations. Range degradation is confined to areas surrounding trading centers and permanent water; but this is compensated by vast areas which are underutilized.''

O'Leary's observation that range resources at the macro-level are sufficient to support current livestock populations is supported by comparing livestock population estimates obtained at the Marsabit office of the Ministry of Livestock Development with Schwartz, Shaabani, and Walther's (1991) maximum stocking rate guidelines. Figure 1 indicates that no year from 1963–1998 for which data are available is characterized by ecological overstocking when the 56,000 km^2 of the District's rangelands are taken as a whole.[5]

In addition, O'Leary's impressions on the spatial distribution of degradation are supported by a separate assessment of the District's rangelands reported by Schwartz, Shaabani, and Walther (1991). This evaluation categorizes 80% of the rangeland areas as good (not degraded); 18% as fair (showing impact of use by livestock below a level seriously impairing livestock productivity); and 2% of the rangeland is poor or very poor (exhibiting significant decreases in productivity attributable to overuse). These overused areas are almost all within 20 km of the small market towns in the District.

To the extent that the Gabra commons reflects conditions in the District as a whole, the observed degradation in this area is not resulting from too many animals using the commons. This suggests a livestock population level below carrying capacity of the total commons is a necessary, rather than a suffi-

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[5] The District level carrying capacity reported in Figure 1 was derived by summing carrying capacity estimates for 23 sub-areas of the District defined in the Range Management Handbook. This was necessary, as livestock population estimates are only available for the District as a whole.

cient, condition for the prevention of degradation in a heterogeneous commons. To analyze localized degradation, it is necessary to refine the spatial scale of analysis so that spatial heterogeneity within the commons can be recognized. The focus of the investigation is then placed on factors influencing the spatial pattern of resource exploitation in a heterogeneous commons.

The following section presents an analytical investigation of how heterogeneity in the commons influences household-level exploitation decisions. The model is designed to reflect characteristics of the study area. As such, it is not cast as a general model of heterogeneous commons exploitation, but rather as an analytical framework through which to explore possible causes of localized degradation in the study area drawing on the description of the study area presented above.

III. A MODEL OF HETEROGENEOUS RANGELAND USE

In this section, a dynamic model of heterogeneous rangeland use is developed. The objective of this section is to illustrate how parametric differences between rangeland sub-areas within a commons interact with land-use choices to lead to patterns of localized relative degradation.

To motivate the development of this model, consider briefly a standard ‘‘tragedy of the commons’’ model. In the standard model, the individual accumulates more livestock than is socially optimal. Unless herders can agree on a management regime that will mitigate this problem, the individual’s failure to internalize the negative externalities he or she imposes on other users will lead to an aggregate stocking level larger than socially optimal. This leads in the long run to pasture degradation, thus making all users worse off than they would have been if the negative externality was internalized by each individual. The standard model identifies source of potential tragedy in the tenure arrangement, and indicates limits to stocking levels or tenure reform are desirable policy responses.

The discussion in the previous section suggests the standard model is inadequate for our current needs. There are two main flaws with the basic model in this setting. First, when we considered the available information on aggregate herd size, we found that although the evidence does not support the contention that aggregate herd size is, or has been, at a level above ecological-carrying capacity, degradation is occurring. This calls into question the effectiveness of policies that reduce stocking levels. Second, the ecological evidence indicates that certain sub-areas of the commons are degraded while others are not, even though both degraded and undegraded areas are subject to the same tenure regime. This calls into question the effectiveness of tenure reform policies. For both of these reasons, it is necessary to extend the common property model to investigate situations where degradation results from a sub-optimal distribution of capital within a commons, rather than a larger than optimal level of capital being used in the commons.

To arrive at such a model, we take steps that differ from common property models previously presented in the literature on common property pasture exploitation. Previous models of common property pasture exploitation specify the individual as choosing a privately optimal herd size (Scoones 1993; Perrings and Walker 1995, Fafchamps 1998; Goodhue and McCarthy). However in the previous section, frequent herd losses in droughts and raids were described. This suggests the ability of the individual to choose a herd size is questionable given the production conditions facing herders in arid and semi-arid Africa. The individual’s choice in this production environment is more accurately cast as offtake from a given herd rather than choice of herd size. We draw on the basic insights of Clark, Clarke, and Munro (1979) to develop a dynamic model of livestock accumulation, although we specify in the model that capital accumulation is subject to stochastic asset shocks.

This study builds on recent literature that defines rangeland condition as an endogenous variable (Perrings and Walker 1995; Hu, Ready, and Pagoulatos 1997; Duraiappah and Perkins 1999). This is accomplished by allowing rangeland carrying capacity to vary over time in response the history of stocking pressure. This study extends this basic insight by allowing carrying capacities for sub-areas within the commons to follow different evolutionary paths. A particular sub-area is allowed to be relatively more or less degraded than other sub-areas, even though all sub-areas are under the same tenure regime. Thus, the particular trajectory found for carrying capacity within a particular sub-area reflects past use patterns of the sub-area, and use patterns reflect parametric differences between sub-areas.

Define $j = 1, \ldots, Z$ integer indexed rangeland sub-areas of equal size A, so that the total commons is of size $Z \cdot A$. As indicated above, rangeland degradation in the study area is associated with areas around towns. To represent this, assume there is one town at the end of the commons, and define sub-areas of increasing distance from this town.

Define the carrying capacity of sub-area j as the number of animals that can be placed in rangeland sub-area j at time t without causing a decline in j's productive potential. Carrying capacity in sub-area j at time t is a function of two variables: realized rainfall and a rainfall response parameter $y_j(t)$. Assume rainfall is characterized by a time-invariant distribution with parameters $(rf, \sum_{rf})$ where **rf** is a **(Z × 1)** vector of sub-area specific rainfall means, and $\sum_{rf}$ is a $(Z \times Z)$ variance-covariance matrix recording rainfall variability. Rainfall realizations at time t are denoted by $rf_j(t)$ $j = 1, \ldots, Z$. The rainfall response parameter converts realized rainfall into an allowable number of animals that can be placed in sub-area j. Degradation in this model is viewed as a decrease in a sub-area's carrying capacity brought about by a decrease in the sub-area's response to rainfall. A simple multiplicative specification for carrying capacity in sub-area j at time t, $cc_j(t)$, is used in this model. This is written $cc_j(t) = rf_j(t) \cdot y_j(t)$.[6]

Access to the Z areas is restricted to $i = 1, \ldots, N$ members $\forall t$. Also, assume that the N individuals only place their animals on commonly held areas $j = 1, \ldots, Z$. Individual i may place all of his herd $k^i(t)$ in one sub-area, or to divide the herd among different sub-areas. Individual i ends period $t - 1$ with his herd distributed among the sub-areas according to the $(Z \times 1)$ state variable $s^i(t - 1)$. The herder begins period t by deciding how to adjust these shares according to the $(Z \times 1)$ choice variable $a^i(t)$, with $a_j^i \in [-1, 1]$, $\sum_{j=1}^{z} a_j^i = 0$. The size of the herd placed by herder i in sub-area j at time t is thus $(s_j^i(t - 1) + a_j^i(t)) \cdot k^i(t)$.[7] The share and adjustment variable define a state equation recording changes over time to herd shares of individual i in sub-area j as recorded by $s_j^i(t) = s_j^i(t - 1) + a_j^i(t)$. The share allocated to the furthest zone Z is arbitrarily defined to be $s_Z^i(t - 1) + a_Z^i(t) = 1 - \sum_{j=1}^{Z-1}(s_j^i(t - 1) + a_j^i(t))$, as the sum of the share variable over the Z sub-areas is logically bounded above by 1.

Individual i obtains utility from consumption at time t defined by $U(c^i(t))$. Consumption is comprised of animals taken from individual i's herd at time t and consumed, milk production from the share of the household herd placed in each sub-area, and food aid provided by outside sources to family members accompanying animals in each sub-area. Subtracted from this is energy expended on moving animals from their locations in the previous period. The caloric contribution of offtake from the herd to consumption, $ot^i(t)$, is the numeraire value. Assume the milk produced by all animals placed in a sub-area is represented by a logistic function with parameter τ. Let τ reflect the total caloric value of milk produced in a particular sub-area divided by the numeraire value. The total caloric value of milk production to households placing animals in sub-area j at time t is equal to

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[6] Schwartz, Shaabani, and Walther (1991) define carrying capacity as forage production in an area times the percent allowable offtake of this forage divided by animal forage requirements per day times the maximum number of days of allowable use. All but the animal forage requirements are specified as functions of mean annual rainfall. The functional form of the forage production function is defined to be $a + b$ * rainfall. In simplest terms, changes to the variable y can be considered as changes to the parameter b, although a broader lumped parameter interpretation is possible.

[7] It is assumed that a share of the household labor force proportionate to the share of the herd is required to supervise the animals sent to a particular zone and that adjustment decisions are made after the rainfall variable is observed.

$$\tau_j\left[\left(\sum_{i=1}^{N} s_j^i(t)\cdot k^i(t)\right)-\left(\left(\sum_{i=1}^{N} s_j^i(t)\cdot k^i(t)\right)^2\Big/ cc_j(t)\right)\right].$$

Following Baland and Platteau (1997), assume each individual obtains a share of the benefits of the commonly held resource proportional to their share of the overall exploitation level. Therefore, milk consumed by household i in area j is derived by multiplying $s_j^i(t)\cdot k^i(t)/\sum_{i=1}^{N} s_j^i(t)\cdot k^i(t)$ by total value of milk produced in the sub-area. Define a ($\boldsymbol{Z}\times\boldsymbol{1}$) vector recording the relative caloric contribution of food aid to consumption by $\pi_j\, j = 1, \ldots, Z$. This value reflects the caloric benefit of food aid minus the caloric cost of walking to town to obtain this food from sub-area j relative to the numeraire value. Finally, assume there is a cost of adjusting the past location of the herd in the current period. Define the relative caloric expenditure of the household on rearranging herd shares over sub-areas by $\sum_{j=1}^{Z}\varepsilon\cdot(a_j^i(t))^2$, with $\varepsilon\geq 0$. This results in the following representation of the utility function.

$$U(c^i(t)) = U\left[ot^i(t)+\sum_{j=1}^{Z}\tau_j\cdot\left(s_j^i(t)\cdot k^i(t) - \left(s_j^i(t)\cdot k^i(t)\cdot\left(\sum_{i=1}^{N} s_j^i(t)\cdot k^i(t)\right)\Big/ cc_j(t)\right)\right) + \sum_{j=1}^{Z}\pi_j\cdot s_j^i(t)-\sum_{j=1}^{Z}\varepsilon\cdot(a_j^i(t))^2\right], \qquad [1]$$

where $\partial U/\partial c > 0$, $\partial^2 U/\partial c^2 \leq 0$, $\lim_{c\to 0}\partial U/\partial c = \infty$, $\lim_{c\to\infty}\partial U/\partial c = 0$.

A logistical functional form for herd growth is specified in this model, in line with previous models of herd growth on commonly held rangelands (Scoones 1993; Perrings and Walker 1995; Fafchamps 1998). Note that this model contrasts with these earlier studies in that the carrying capacity measure used in the logistic equation is endogenously determined rather than being defined as an exogenous constant. Total herd growth in a sub-area follows a logistic function with parameter α,[8] and maps into household level herd size changes through the share function $s_j^i(t)\cdot k^i(t)/\sum_{i=1}^{N} s_j^i(t)\cdot k^i(t)$, so that household i's herd growth in sub-area j at time t is defined by

$$\alpha_j\cdot\left(s_j^i(t)\cdot k^i(t)-\left(\left(s_j^i(t)\cdot k^i(t)\cdot\sum_{i=1}^{N} s_j^i(t)\cdot k^i(t)\right)\Big/ cc_j(t)\right)\right).$$

Assume that sending animals to a particular sub-area exposes the herder to a risk that armed raiders will take some of these animals. Assume only adult animals are at risk, raid losses are proportional to the individual's herd size, all individuals face the same probability distribution over proportionate raid losses, and losses occur after time period t decisions have been made. Define proportionate herd loss to follow a time-invariant distribution with parameters (θ, Σ_θ).[9] The ($\boldsymbol{Z}\times\boldsymbol{1}$) vector of means has components $\theta_j\in[0, 1]$, and the variance-covariance matrix Σ_θ is $(Z\times Z)$. Each individual receives his own set of realizations of this variable after adjusting the share of animals in each rangeland sub-area and choosing an offtake level, so that individual i placing animals in sub-area j at time t is informed just prior to the start of period $t+1$ that he has experienced a herd loss of size $\theta_j^i(t)\cdot s_j^i(t)\cdot k^i(t)$. The share decision made at time t is calculated based on the individual's expectation of this ran-

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[8] Note that both the milk production function and the herd growth function assume the stocking level at which production declines occur is identical to the stocking level at which ecological degradation occurs. Although it is assumed here for simplicity, this need not be the case.

[9] The time invariance of the distribution is adopted to simplify matters. As we will see below, there may be seasonal issues involved with the risk of raids. It could also be reasonably argued that theta is a decreasing function of the aggregate stocking level in a sub-area, due to a positive security externality. As the insights generated by considering endogenously provided security do not differ significantly from those considering exogenously provided security, we adopt the simpler course of assuming exogenously provided security.

dom variable. Together, the starting period herd size, the share of time allocated to each sub-area, the offtake decision, and the growth functions determine next period's herd size according to the following state equation.

$$k^i(t+1) = \sum_{j=1}^{Z} s_j^i(t) \cdot k^i(t) \cdot (1 - \theta_j(t)) + \sum_{j=1}^{Z} \alpha_j \cdot \left(s_j^i(t) \cdot k^i(t) - \left(\left(s_j^i(t) \cdot k^i(t) \cdot \sum_{i=1}^{N} s_j^i(t) \cdot k^i(t) \right) \Big/ cc_j(t) \right) \right) - ot^i(t). \qquad [2]$$

The variables representing sub-area specific rainfall response parameters are recorded by $y_j(t)$ $j = 1, \ldots, Z$ that evolve according to current period realizations of this variable as well as the total number of animals allocated to the sub-area. When stocking rate is below carrying capacity for a particular zone, the next-period, rainfall response parameter increases. In contrast, exceeding carrying capacity leads to a decline in the rainfall response parameter. The function governing the evolution of the rainfall response parameter in area j is as follows.

$$y_j(t+1) = y_j(t) + \gamma_j \left(1 - \left(\sum_{i=1}^{N} s_j^i(t) \cdot k^i(t) \Big/ cc_j(t) \right) \right). \qquad [3]$$

In equation [3], it is assumed $\gamma_j \geq 0$. This is similar in structure to other simple dynamic models of resource use as it balances a fixed renewal parameter against the negative impact of aggregate use (Hu, Ready, and Pagoulatos 1997; Gardner et al. 2000).

The utility of consumption is assumed to be additively separable over time. Future consumption is discounted by $(1 + r)^{-1} \in [0, 1]$, where r is a measure of the discount rate that is assumed to be identical across individuals. The individuals are assumed to make non-cooperative decisions.[10] Individuals are specified to form Nash best-response strategies to the herd sizes, herd shares, and adjustment decisions of the other $(N - 1)$ herders. Define $\mathbf{k(t)}$ as the $\mathbf{(1 \times N)}$ vector with component, $k^i(t)$, $s(t-1)$ as the $\mathbf{(Z \times N)}$ matrix with component $s_j^i(t-1)$, $a(t)$ as the $\mathbf{(Z \times N)}$ matrix with component $a_j^i(t)$. Also define $y(t)$ as the $\mathbf{(Z \times 1)}$ vector with component $y_j(t)$.

To summarize, events proceed in this model as follows. The individual begins period t with herd size $\mathbf{k(t)}$ distributed according to last period's shares $s(t-1)$, and observes this information for other users of the commons. Rainfall in the Z sub-areas of the commons and the corresponding carrying capacities are then observed. The individual then chooses the herd offtake level and the adjustments to be made to shares of the herd allocated to various sub-areas. Following these decisions, the individual discovers realizations of proportionate herd loss in the various sub-areas. Taken together, the individual's problem is written in the following Bellman's form.

$$V[k(t), y(t), s(t-1); rf, \Sigma_{rf}, \theta, \Sigma_\theta] = \underset{ot^i(t),\, a^i(t)}{\text{Max}}\, U(c^i(t)) + (1/(1+r)) \cdot E_t[V[k(t+1), y(t+1), s(t) : rf, \Sigma_{rf}, \theta, \Sigma_\theta]], \qquad [4]$$

subject to [1], [2], [3], $k(0)$, $y(0)$, $s(1)$ $\forall$ $i = 1, \ldots, N$ given, $t = 0, \ldots, \infty$.

To reduce notational complexity, assume $Z = 2$ and all variables are at time t unless otherwise noted. Consider the following result derived from maximization of this problem.

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[10] Individuals are more interdependent in reality than is implied by this assumption. For example, households tend to move as groups, and cooperate in terms of labor, provision of consumption goods, and general ''neighborliness.'' However, we ignore such interdependencies for two reasons. First, fissioning of these groups is common (Torry 1973), suggesting households are able to decide migration decisions on their own. Second, the fact that herd size has been below ecological carrying capacity yet degradation has occurred suggests land use decisions are not cooperative, and that a non-cooperative model is appropriate.

$$0=\left(\frac{\partial U}{\partial c^i}\right)\cdot\left\{\begin{array}{l}\cdot\left(1-\sum_{i=1}^{N}s^i\cdot k^i\Big/ cc_1-s^i\cdot k^i/cc_1\right)-\tau_2\cdot\left(1-\sum_{i=1}^{N}(1-s^i\cdot k^i)\Big/ cc_2-(1-s^i\cdot k^i)/cc_2\right)\\ \dfrac{\pi_1-\pi_2-4\cdot\varepsilon\cdot(a^i)}{k^i}-E[\theta_1^i(t)]+E[\theta_2^i(t)]\\ \alpha_1\cdot\left(1-\sum_{i=1}^{N}s^i\cdot k^i\Big/ cc_1-s^i\cdot k^i/cc_1\right)-\alpha_2\cdot\left(1-\sum_{i=1}^{N}(1-s^i\cdot k^i)\Big/ cc_2-(1-s^i\cdot k^i)/cc_2\right)\end{array}\right\}$$

$$+\left(\frac{1}{1+r}\right)\cdot\left(E\left[\frac{\partial V}{\partial y_2(t+1)}\right]\cdot\frac{\gamma_2}{cc_2}-E\left[\frac{\partial V}{\partial y_1(t+1)}\right]\cdot\frac{\gamma_1}{cc_1}+E\left[\frac{\partial V}{\partial s^i}\right]\cdot\frac{1}{k^i}\right) \qquad [5]$$

Equation [5] shows that the decision to adjust shares of animals between rangeland sub-areas balances relative marginal milk production, relative food aid contributions, the marginal cost of adjusting shares between time periods, relative expected herd loss shocks, relative marginal herd growth, relative marginal values of the rainfall response parameters, and the shadow value of ending the period with a given share distribution. Note that the herd sizes and shares of the other $(N-1)$ individuals enter as arguments into the computation of these values. The individual's optimal share allocation decision is made as a best response to the actions and states of other individuals.

In the previous section, food aid and raiding were discussed as factors leading herders to move closer to towns. Consideration of the transition dynamics of this model identifies how sub-area specific differences in these variables influence short-run decision-making. Given the complexity of the model, closed form transition dynamics can only be identified by making simplifying assumptions. Confine attention to the range of values over which household level milk production and herd growth are increasing functions of the herd share allocated to the area, assume that adjustment of shares between periods is costless, and hold sub-area specific variables and parameters except the one in question to be equal. Sub-area 1 will be used more intensively than in sub-area 2 by herd $k^i(t)$ under either of the following conditions:

1) The contribution of food aid to consumption in sub-area 1 is higher than in sub-area 2 $(\pi_1 > \pi_2)$;
2) The expected raid loss in sub-area 2 is greater than in sub-area 1 $(E_t\lfloor\theta_1^i\rfloor < E_t\lfloor\theta_1^i\rfloor)$.

The long run implications of these transition dynamics are derived by solving equation [5] for an interior steady state equilibrium (see Appendix 1). Two steps are taken to derive a closed form expression for this equilibrium. First, the stochastic variables of rainfall and herd loss are set at their means. Second, all individuals are assumed to have identical herd sizes in equilibrium. The following condition results:

$$\begin{aligned}&(\tau_1+\alpha_1)/n+\pi_2/k+\theta_1\\&\qquad+\frac{\gamma_1\cdot rf_1\cdot(\tau_1+\alpha_1)}{r\cdot n^2\cdot s\cdot k-n\cdot\gamma_1\cdot rf_1}\\&\qquad=(\tau_2+\alpha_2)/n+\pi_1/k+\theta_2\\&\qquad+\frac{\gamma_2\cdot rf_2\cdot(\tau_2+\alpha_2)}{r\cdot n^2\cdot(1-s)\cdot k-n\cdot\gamma_2\cdot rf_2}.\end{aligned} \qquad [6]$$

Equation [6] indicates that sub-area 1 will be less intensively used than sub-area 2 in steady state if the food aid contribution to consumption is greater in sub-area 1 or if mean raid loss is higher in sub-area 2.[11] The use of sub-area 1 more than sub-area 2 on the path to the steady state as a result of parametric differences leads sub-area 1 to be in relatively worse condition than sub-area two when the steady state is reached. Of particu-

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[11] Analysis of equation six also indicates use of sub-area 1 will also be higher than use of sub-area 2 in steady state equilibrium if $\tau_1 > \tau_2$, $\alpha_1 > \alpha_2$, $\gamma_1 > \gamma_2$, or $rf_1 > rf_2$.

lar interest for our purposes, the intensive use of sub-area 1 resulting from differences in food aid or raid loss identified in the transition dynamics leads to a long run difference in the rainfall response parameters of the respective sub-areas. The steady state version of equation [3] provides direct insight into the finding that if pasture condition is endogenous, sub-areas that are parametrically more attractive will only be possible to use relatively less in steady state all else equal. Taking sub-area 1 to be the zone around town described in the previous section, the pattern of degradation in the study area can be partially explained by the fact that food aid is distributed from towns and raids are more likely away from towns.

While the steady state results are unambiguous, the use patterns described for the transition dynamics were only possible to identify by making restrictive assumptions. An alternative approach to identifying the effect of parametric differences on sub-area use is to use empirical methods to investigate land use choices. This is the approach taken in the following section.

A second objective of the empirical analysis conducted in the following section is to explore how user heterogeneity influences land use decisions. As is seen in equation [5], although the individual's herd size enters as an argument in the optimal decision rule, the influence of herd size on land-use decisions is ambiguous. The empirical analysis presented in the following section allows identification of the relationship between herd size and land use decisions.

IV. EMPIRICAL ANALYSIS OF LAND-USE DECISIONS

Data for this study were gathered from 39 Gabra nomadic households in the Chalbi basin of Marsabit District, Kenya. The data set records household specific information for four time periods (two rainy seasons and two dry seasons)[12] per-year from 1993 to 1997. The longitudinal nature of the data allows empirical exploration of how land-use decisions made by users of a common rangeland change in response to changes in the state of nature as well as changes in the household's own characteristics.

The data gathering methodology was retrospective, and the sampling framework was based on a transect. Enumerators walked between towns of the study area, interviewing herders at compounds they encountered along their way. As Gabra are nomadic herders, the logistics involved with sampling from a population list were prohibitively expensive. As seven of the households have incomplete information in certain periods, and some households were interviewed later in 1997 than were others, the longitudinal data set used in the estimation is unbalanced.[13]

The focus of the analysis presented in this section is recovery of empirical patterns corresponding to the variables $s^i(t-1) + a^i(t)$ in the model presented above. We focus on temporal variation in food aid availability and raid risk under the assumption that the net caloric value of food aid is a decreasing function of distance from town and the risk of raid loss is an increasing function of distance from town.[14] The first decision considered is the herder's base camp location. A herder settling a base camp in a particular sub-area is equivalent to sending a share of the herd to this sub-area. The base camp distance variable measures the hour's walk it takes to travel from the base camp to the nearest town.[15] Also included in the estima-

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[12] There are two rainy seasons per year in northern Kenya. What is called the long rains occurs in March–May while the short rains occur in mid-September–mid-December. Two dry seasons of approximately three months length separate the rainy seasons.

[13] For each household, there are between 16 and 20 observations. There are 677 total observations. A limitation of the current study is that it is based on data drawn from a relatively small number of households.

[14] Raids occur almost exclusively in the extensive grazing area away from towns. While it is perceived in the area that moving away from town in the north-east direction is less risky than other directions, herders perceive moving away from town in any direction as more risky than moving closer to town. With regard to other parametric differences between zones, we can safely assume they are constant over the four-year period covered by the data.

[15] A drawback of this definition is that it is a one-dimensional representation of a two dimensional location. The one-dimensional measure was chosen because it is a simple measure that allows direct comparison of locations to the pattern of degradation in the study area.

tion, is a variable recording the base camp location in the previous period. This reflects the fact that base camp moves may be costly, as such moves require dismantling, loading, and reconstructing the base camp dwelling.

A herder's decision to send labor to a satellite camp is viewed as sending animals to the furthest rangeland sub-area Z.[16] The satellite camp decision is recorded by a variable indicating the share of the household labor force sent to a satellite camp.[17] Satellite camps are easily established and dismantled, so no record of the previous-period, satellite camp use is included in the estimation. Together, the base camp distance from town and the satellite camp labor variables capture decisions that determine the share of a herder's animals allocated to different rangeland sub-areas in different time periods.

The food aid variable used in the estimation records total maize deliveries recorded at Kalacha and North Horr for each time period.[18] Maize is the main component of food aid in this area. Food aid was available from 1993 until mid-1995 and again in early 1997. Food aid was provided to households regardless of their wealth status, and the amount given per household is based on the number of members in a household recorded in an official list. All households in the sample were on a distribution list in either Kalacha or North Horr town. Food aid is distributed in town, sometimes monthly, sometimes biweekly. If households on the list are not able to be present on the distribution day, their food aid will be held in town for them by either relatives or the distribution center, and will be picked up on their next visit to town.

Rainfall conditions are included as exogenous variables in the estimation procedure. Three variables are used to capture these changing conditions. The first records the average of North Horr and Kalacha rainfall in a given six-month period. The second and third are dummy variables indicating whether the three month period in question is either of the annual rainy seasons. Rainy seasons have countervailing influences on location decisions. First, during rainy seasons, the availability of surface water allows herders to exploit areas left vacant during dry seasons. As towns are built in areas with permanent water, this leads herders to move animals further from town during rainy seasons. However, use of areas near town may become more intense after rains fall as the flush of pasture growth makes it possible to move closer to town and enjoy town based amenities. In addition, use of the area around town may increase during rainy seasons since raids are more common in rainy seasons because the availability of surface water and the relatively good condition of animals make flight with stolen animals easier. This leads herders to move animals closer to town.

An attempt is made to control for the influence of raid threats on location decisions by including a dummy variable that records periods when raids occurred. This information was gathered in a meeting with community elders, where they were asked to report any period in which a raid occurred in the grazing lands used by people from this area.[19]

A record of a herder's subjective evaluation of the pasture availability in different sub-areas is used in the estimation. This variable records relative differences in sub-area specific stocking pressure. Herders were asked to rank pasture availability at each point in time for the area within a five-hour walk of town and the area outside this circle on a scale of one to five. Pasture availability was defined as a composite measure of sub-area stocking pressure and sub-area forage production. The variable used in estimation

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[16] Base camps within one hour of town are defined as being in town (0 distance) as they effectively are using the rangelands of the town. While there is no upper limit imposed on how far a base camp can be from town, only 1% of base camps were reported to be located more than 24 hours from town. Most satellite camps are located more than 24 hours from town.

[17] In this area, herders rarely send animals to other herders' satellite camps, and in no case established more than one satellite camp. The variable recording household labor allocation to satellite camp was selected over a variable recording the number of animals sent to satellite camp, as respondents often were not able to answer the latter with any certainty.

[18] Data were obtained by the author at the Catholic mission in North Horr and the A.I.C. mission in Kalacha.

[19] Given the retrospective nature of the data collection, this variable is unfortunately an ex post description of when a raid occurred rather than an ex ante description of when raids were anticipated.

TABLE 1
MEANS AND STANDARD DEVIATIONS OF VARIABLES

Variable	Mean	Standard Deviation
Distance base camp to town in hours' walk	5.13	4.78
Percentage of labor force at satellite camp	0.12	0.15
Rainfall in mm over past six months	58.39	42.09
Long rains dummy	0.27	0.45
Short rains dummy	0.24	0.43
Ratio of pasture availability in zone one to zone two	0.78	0.26
Raid dummy	0.43	0.49
Food aid deliveries in tons per period	72.37	88.97
Age of household head	47.12	14.33
Age ratio husband and wife	1.38	0.50
Household size in adult equivalents	5.04	2.17
Herd size (TLU)	42.67	31.13
Herd size per adult equivalent (TLU/AE)	9.07	5.14
Number of pack camels	2.04	1.74

Note: 677 observations, 39 households.

is constructed by dividing a herder's evaluation of pasture availability near town by the evaluation away from town. As there are reasons to be concerned about the endogeneity and accuracy of this variable, results are presented for alternative specifications that exclude this variable.

Household characteristics are also included as exogenous variables in the estimation procedure. A quadratic representation of the age of the household head is utilized, as is a measure recording the size of the household in adult equivalents.[20] Because ownership of baggage camels may reduce the cost of changing locations, a separate variable records the number of pack camels owned by the household. Also included is a quadratic representation of a household's animal wealth recorded in Total Livestock Units (TLUs).[21] Household specific variables are defined to reflect conditions at the start of the three-month period in question, and are thus exogenous to the land-use decisions within the period. An alternate specification combines the herd size and household size measures into a single variable. The specification is estimated using a quadratic representation of the household herd size per adult equivalent. Table 1 reports the descriptive statistics of the variables used in the estimation.

Three major issues must be confronted when estimating the decision rules described above. First, both dependent variables are by definition non-negative and have a significant number of observations at zero (7% for the distance variable, 53% for the satellite camp variable). Second, the two decision variables are obviously related to each other. Third, the data set is longitudinal in nature.

The first two issues are addressed by use of simultaneous tobit estimation methodology following Amemiya (1974) and Maddala (1983). The third is addressed by explicitly controlling for household specific effects. Define d as the distance from town variable, sat as the satellite camp variable, γ as coefficients on endogenous variables, β as coefficients on exogenous variables, x as exogenous variable matrices, a as time-invariant

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[20] The household equivalent scale follows Martin (1985). Males and females older than 15 years old equal 1 household adult equivalent, ages 5–14 equal 0.6 household equivalent, ages 2–5 equal 0.3 household equivalent, and ages below 2 equal 0.1 household equivalent.

[21] Herd size is measured in Tropical Livestock Units (TLUs), where 0.7 camel = 1head of cattle = 10 smallstock. This differs slightly from the weighting scheme reported in Schwartz, Shaabani, and Walther (1991), as this source suggests 11 goats = 10 sheep = 1 TLU. The data set records the combined smallstock herd size, so no distinction is made between sheep and goats.

household specific effects, and u as unobserved terms. Define the following tobit model, where i indexes households and t indexes time.

$$
\begin{aligned}
&d^i_t = \gamma_1 sat^i_t + \beta_1' x^i_{1_t} + a_{1_i} + u^i_{1_t} \quad \text{if} \quad RHS > 0\\
&d^i_t = 0 \quad \text{if} \quad RHS \leq 0\\
&sat^i_t = \gamma_2 d^i_t + \beta_2' x^i_{2_t} + a_{2_i} + u^i_{2_t} \quad \text{if} \quad RHS > 0\\
&sat^i_t = 0 \quad \text{if} \quad RHS \leq 0. \qquad [7]
\end{aligned}
$$

The approach taken in this study to control for household specific effects follows Mundlak (1978) by defining a household specific effect for the base camp decision by $a_{i_1} = \lambda_1' \bar{x}_i + \omega_{i_1}$ and for the satellite camp decision by $a_{i_2} = \lambda_2' \bar{x}_i + \omega_{i_2}$. Let $\bar{x}_i$ record the mean of household specific variables for household i, $t = 1, \ldots, T$. In the estimation procedure, household specific means are included for the age of the household head, the age ratio of the husband or eldest son to his wife or mother, the size of the household herd, and the size of the household in adult equivalents. The random effects represented by the ω parameters are dealt with through the use of simulated maximum likelihood. Assume that ω_{1_i} is drawn from a $N(0, \sigma^2_{\omega_i})$ distribution and ω_{2_i} is drawn from a $N(0, \sigma^2_{\omega_2})$ distribution. Take (n, H) pseudo-random draws from two separate $N(0, 1)$ distributions, and assign all $t = 1, \ldots, T$ observations for household $I = 1, \ldots, n$ in draw $h = 1 \ldots, H$ a unique pair of these draws. The $2 \times (n, H)$ draws are multiplied by a (2×1) scaling parameter vector $\boldsymbol{\delta}$. The parameter $(\delta_1)^2$ provides an estimate of $\sigma^2_{\omega_1}$, and $(\delta_2)^2$ provides an estimate of $\sigma^2_{\omega_2}$. Gourieroux and Monfort (1993) state that provided n and H go to infinity in such a way that $\sqrt{n}/H \rightarrow 0$, the parameters resulting from this estimation are consistent and asymptotically efficient. In the results presented below, $n = 39$, $H = 500$. Table 2 presents the results of the alternative model specifications described above.

The parameters for the endogenous variables in all specifications satisfy the coherency condition described by Amemiya, and indicate that herders view increasing distance from town and increased use of satellite camp as substitutes. The Wald test results indicate the fixed effect coefficients are jointly significant for the satellite camp equation in all three specifications, and for the base camp equation in specification three. The random effect scaling parameters are significant for both equations in all model specifications. The unobserved terms in all specifications are positively correlated, ranging from 0.75 to 0.70. Joint tests of parameter significance indicate that each equation is significant in all specifications considered. The best fit to the data as evaluated by the log-likelihood ratio is provided by specification 3.

The food aid delivery variable has a significant effect on satellite camp use, suggesting that as the availability of food aid increases, herders decrease their use of satellite camps. Herders become less willing to move animals to remote areas when there is food being distributed from towns.

The coefficients for the rainy season dummy variables indicate use of areas near town tends to increase during rainy seasons. There are two possible interpretations of this finding. First, herders move closer to towns when pasture conditions permit to take advantage of town-based opportunities such as marketing livestock, or socializing and catching up on news. A second interpretation is that herders move animals out of areas they think will become insecure during these periods, as raids tend to occur in the rainy seasons. Thus, we can interpret this finding as providing indirect evidence that raid risk influences location decisions, although other interpretations are also possible. With regard to direct evidence on the impact of raiding, although we find negative signs for the coefficients of the dummy variable recording when raids occurred, in no case are these coefficients statistically significant. Further research on how ex-ante perceptions of raid risk influence land-use decisions would help to clarify the influence of security concerns on migration decisions.

All three models indicate use of satellite camps increases in response to relatively low rainfall realizations over a six-month period, although rainfall levels have no significant

TABLE 2
FULL INFORMATION SIMULATED MAXIMUM LIKELIHOOD PARAMETER ESTIMATES

	Specification One		Specification Two		Specification Three	
	Distance Base Camp to Town (in hours)	% of Labor Force Sent to Satellite Camp	Distance Base Camp to Town (in hours)	% of Labor Force Sent to Satellite Camp	Distance Base Camp to Town (in hour)s	% of Labor Force Sent to Satellite Camp
γ_d	—	−0.1680***	—	−0.1587***	—	−0.1661***
		(0.0363)		(0.0337)		(0.0356)
γ_{sat}	−1.7134***	—	−1.6541***	—	−1.5320***	—
	(0.3078)		(0.2570)		(0.2533)	
Herd size (-10^{-2})	0.6499***	0.4677***	0.6229***	0.4543***	—	—
	(0.2454)	(0.1159)	(0.2363)	(0.1152)		
Herd size^2 (-10^{-4})	−0.1601**	−0.1006**	−0.1531**	−0.0948**	—	—
	(0.0759)	(0.0391)	(0.0730)	(0.0383)		
Household size ($\times 10^{-1}$)	−0.6433	−0.1837	−0.6570	−0.2070	—	—
	(0.7000)	(0.3008)	(0.7098)	(0.3027)		
Herd size/AE ($\times 10^{-2}$)	—	—	—	—	0.5502***	0.4532***
					(0.1684)	(0.0856)
Herd size/AE ($\times 10^{-4}$)	—	—	—	—	−0.1489***	−0.1289***
					(0.0559)	(0.0284)
Pasture availability ratio ($\times 10^{-1}$)	−0.3464	−0.4463	—	—	—	—
	(0.7055)	(0.3117)				
Rainfall ($\times 10^{-2}$)	0.3146	−0.6068**	0.2862	−0.7077***	0.4504	−0.6041**
	(0.5289)	(0.2598)	(0.5187)	(0.2539)	(0.5154)	(0.2572)

Long rains dummy	−0.2542***	−0.2183***	−0.2493***	−0.2218***	−0.2334***	−0.2232***
	(0.0539)	(0.0245)	(0.0511)	(0.0236)	(0.0502)	(0.2376)
Short rains dummy	0.0219	−0.0496**	0.0253	−0.0497***	0.0307	−0.0467**
	(0.0445)	(0.0189)	(0.0437)	(0.0188)	(0.0431)	(0.0187)
Raid dummy	−0.0198	−0.0031	−0.0206	−0.0044	−0.0134	−0.0012
	(0.0368)	(0.0161)	(0.0365)	(0.0162)	(0.0361)	(0.0161)
Food aid ($\times 10^{-2}$)	−0.0300	−0.2378*	−0.0513	−0.2743**	0.0664	−0.2232*
	(0.3115)	(0.1323)	(0.3032)	(0.1286)	(0.3055)	(0.1348)
Age HH head ($\times 10^{-2}$)	1.9530	−1.3317	1.9065	−1.5699	1.8729	−1.4400
	(2.4037)	(1.3348)	(2.4627)	(1.1979)	(2.1653)	(1.2376)
Age HH head^2 ($\times 10^{-4}$)	−2.4223**	−1.6206*	−2.3982**	−1.5549**	−2.2693**	−1.5311*
	(0.9095)	(0.8346)	(0.9543)	(0.6307)	(0.8919)	(0.7853)
Number of pack camels	−0.0061	—	−0.0037	—	−0.0076	—
	(0.0147)		(0.0143)		(0.0138)	
Last period distance	0.4035***	—	0.4094***	—	0.4077***	—
	(0.0427)		(0.0403)		(0.0399)	
Constant	−0.1543	−0.1403	−0.2223	−0.1170	−0.4720***	−0.4857**
	(0.2090)	(0.1821)	(0.2062)	(0.1390)	(0.2193)	(0.1671)
σ	0.4259***	0.1716***	0.4236***	0.1710***	0.4179***	0.1696***
	(0.0166)	(0.0075)	(0.0152)	(0.0074)	(0.0145)	(0.0074)
σ_{12}	0.0550***		0.0523***		0.0496***	
	(0.0082)		(0.0072)		(0.0077)	
δ	−0.0929***	0.1250***	−0.0928***	0.1349***	0.0909***	0.1275***
	(0.0258)	(0.0276)	(0.0267)	(0.0231)	(0.0248)	(0.0221)
χ^2 $\lambda = 0$	6.8	29.2***	5.4	30.5***	16.6***	37.9***
χ^2 $\lambda = 0, \beta = 0$	601.5***	251.3***	602.9***	244.0***	639.7***	263.6***
LnL	463.2		463.7		457.4	

Notes: standard errors in parentheses; *, **, ***, indicate significant at 0.1%, 0.05%, and 0.01%, respectively.

impact on the base camp decision. This is consistent with the argument that mobility is a risk-mitigating strategy, as use of extensive grazing lands increases in response to lower rainfall. Additional support is given to this interpretation by the results for the relative pasture availability measure in specification one. The coefficients indicate that a higher ratio increases use of the area near town, although in neither case are the coefficients statistically significant.

The variable recording last period's base camp location is significant in all three specifications. Current period base camp location decision is conditioned on previous period base camp location. This suggests there is a cost to moving the base camp. However, the cost of this movement does not appear to be reduced by ownership of pack camels, as this variable is not significant in any specification.

These findings support model predictions that were identified by making simplifying assumptions in the previous section. Herder land-use decisions do appear to respond to differences between sub-areas. Direct evidence is presented that increased food aid availability decreases satellite camp use, and indirect evidence is provided that can be interpreted to support the argument that fear of raids during rainy seasons leads herders to move animals closer to towns. These results support the contention that parametric differences between sub-areas influence use patterns.

A second objective of the empirical analysis was to identify how user heterogeneity influences use patterns. In particular, the model indicated that household herd size plays a role in determining land-use decisions although the direction of this influence was not possible to identify. The empirical results clarify how wealth influences land-use decisions. All three specifications indicate that as a household's herd size increases, both base camp distance from town and satellite camp use increase.[22] These results are statistically significant in all specifications. Examining the policy significance of these findings is the objective of the following section.

V. SIMULATION OF ESTIMATION RESULTS

Decreasing livestock numbers as a means to address degradation of shared rangelands has been proposed in a variety of settings. Hu, Ready, and Pagoulatos (1997) discuss such a policy applied at the regional level in China. Doran, Low, and Kemp (1979) suggest reduction of stocking levels as a response to grazing-induced degradation on commonly held rangelands throughout eastern and southern Africa. Scoones (1993) describes how such policies have been used in Zimbabwe, and Sobania (1979) and Kerven (1992) discuss their use in Kenya.

While such policies may be sensible as a means to halting widespread degradation of a commons, the estimation results indicate such policies may have an ambiguous influence on arresting localized degradation within a commons. This is because policies that remove animals from household herds also influence household land-use decisions. Policies reducing household herd size must balance decreases in stocking levels in degraded areas against potential increases due to land-use decisions.[23] This section uses simulation methodology to investigate how policies that alter household wealth status influence stocking rates on degraded rangeland sub-areas.

Simulation results are presented considering the impact of two second-best policy mechanisms discussed in recent literature on

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[22] As reviewers expressed concerns about the exogeniety of the herd size variable, a Smith and Blundell test was conducted. Results do not support the hypothesis of herd size endogeneity ($\chi^2_2 = 3.35$, R^2 in the first step = 0.87).

[23] Consider the following (non-exhaustive) set of possibilities. The size of a household's herd in the degraded area after a herd reduction policy is implemented can be: unchanged if a household has all animals at a base camp that is outside the degraded area even after the policy is implemented; increased if the household has all animals at a base camp that is moved from outside the degraded area into the degraded area when the policy is implemented; decreased if the household had all animals at a base camp within the degraded area before the policy was implemented; ambiguous if animals are moved from a satellite camp to a base camp in the degraded area due to the policy.

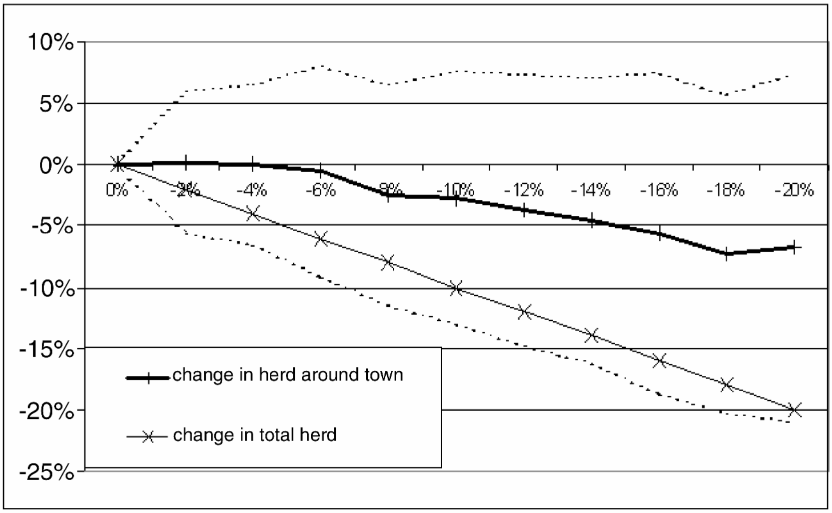

FIGURE 2
Simulation Results of a Proportional Herd Size Reduction Policy

regulating the commons: a proportional reduction (Baland and Platteau 1998; Gardner et al. 2000), and a uniform quota (Baland and Platteau 1998). The proportional reduction policy removes from all households an equal proportion of their herd. In the simulations, this ranges from a 2% reduction to a 20% reduction. The uniform quota policy imposes a maximum upper limit on the herd size a household is allowed to place on the commons. This is defined for quotas imposing a maximum of 9 TLU/AE up to 27 TLU/AE.

The simulation methodology considers the joint impact of a given policy regime on the base camp and satellite camp decisions using reduced form estimates of specification three. The number of draws used to represent the ω random effect parameters is 10,000.

The post-policy herd size of all households predicted to settle their base camp in the degraded area (within five hours' walk of town) is calculated. The post-policy satellite camp herd size is also calculated.[24] These results are used to calculate the expected total number of livestock units that will be placed on degraded rangelands in each time period for each policy considered. The percentage change from the baseline stocking pressure resulting from a given policy is calculated. This exercise is conducted for a given policy for each of the various states of the world represented by the 17 different time periods.

Figures 2 and 3 report the average and the standard deviation of the proportionate change in the herd around town generated from the simulation results. For each figure, these calculations are based on results generated for each policy increment in each of the 17 time periods covered in the data set. The heavy solid line represents the average reduction in herd size around town brought about by the policy. The dashed lines bracketing this line represent one standard deviation above and below this average. The lighter solid line represents the average change in the total herd size of sample households resulting from a given policy.

The results presented in figures 2 and 3 indicate that for the policy scenarios considered, a given reduction in overall herd size is never matched by an equal size reduction in stocking pressure on the degraded area. First,

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[24] The simulation uses a result from the data set that, on average, 1 adult equivalent at satellite camp herds 19 livestock units.

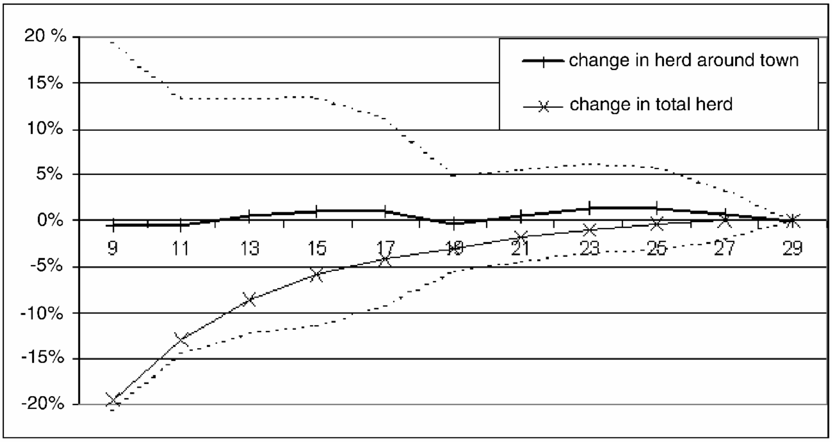

FIGURE 3
SIMULATION RESULTS OF A UNIFORM QUOTA POLICY

consider the proportionate reduction policy presented in figure 2. In every case considered, the decrease in the herd around town is less than the decrease in the total herd. For reductions of up to 6%, proportionate reduction policies have no significant impact on stocking pressure around town. In the case of the uniform quota policy, the results are even more graphic. For the majority of uniform quota policy increments considered, imposition of the quota leads to small increases in stocking pressure in the area around town. These increases occur in spite of the reduction in total herd size.

While contrasting the average change in the total herd with the average change in the area around town is informative, it is also important to recognize the influence of time-period specific effects on policy outcomes. The dashed lines in figures 1, 2, and 3 indicate that the proportional reduction in stocking pressure around town achieved by a given policy varies widely over the 17 time periods considered. Such temporal variability suggests a long time period will be required to assess the impact of a given policy. It also raises the question of whether long-run average change in the stocking pressure around town is the most important outcome from an ecological standpoint.

Drawing policy implications from these simulations must be done with caution. Implementation of the policies considered in this section could change the parameters of land-use decisions. In addition, it is assumed in the simulations that the size of the degraded sub-area remains constant in spite of the implemented policies. However, the results establish that user heterogeneity combined with resource heterogeneity can have serious implications for policies designed to address degradation. Differences in household herd sizes, and the relationship between herd size and the spatial pattern of exploitation, can lead policies designed to address degradation to be less effective than envisioned. In some cases, the policies can actually exacerbate localized degradation.

V. CONCLUSION

This study examines the implications of user and resource heterogeneity for exploitation patterns and policy measures in a commons. Recognition of user and resource heterogeneity helps explain how localized degradation can occur even though the total commons is not overstocked. Total livestock population below the commons' carrying capacity is a necessary, rather than a sufficient, condition for the prevention of degradation in a heterogeneous commons. This provides an important qualification to recent range ecology literature that suggests stochastic shocks to aggregate herd size are sufficient to prevent rangeland degradation from occurring.

The study presents a dynamic model of capital accumulation in a heterogeneous commons. Development of a relatively complicated model is required because the simple common property model is logically flawed in this context. The simple model explains resource overuse as the result of incentive problems originating in the tenure arrangement. However, this cannot be the explanation for why degradation is occurring in the study area because degraded areas are under the same tenure regime as undegraded areas. Applying the simple model to degraded areas exclusively leaves unexplored the higher order economic question of how some areas within a commons became degraded while others did not even though both types of areas are under the same tenure regime.

A second reason for explicitly recognizing spatial heterogeneity in the analysis is to improve policy recommendations. Applying the simple model to the degraded area exclusively generates the policy implication that since there are too many animals grazing in this area, some must be removed. This is an incomplete result, as it does not make use of the information that overused areas are adjacent to underused areas. Incorporation of this information reveals a variety of policy alternatives available to reduce animal numbers in degraded areas that are not identified by the simple model. Recognizing there are parametric differences between degraded and undegraded areas reveals these policy alternatives. For example, the spatial model suggests use of rangelands around towns will decrease if food aid is distributed in remote rangeland sub-areas and if security is increased in areas currently underutilized due to fear of raids. A weakness of the current study is that it does not provide direct evidence on the relative potential of such policies to decrease localized stocking pressure. Further research will be needed to assess the costs and benefits involved with implementing such policies to address degradation.

In a similar fashion, important insights were gained by explicit recognition of user heterogeneity in this study. Herd size heterogeneity at the household level was found to play a critical role in determining the spatial pattern of resource exploitation. Explicit recognition of user heterogeneity led to the conclusion that a change in the total herd size has an ambiguous relationship with the change in stocking pressure in degraded subareas. At best, herd size reductions have a dampened impact on stocking pressure in degraded areas. At worst, they can backfire and lead to an increase in stocking pressure in these areas. As herders in this area rely on their livestock almost exclusively for the generation of household income, policies that reduce household herd size will reduce household welfare in the short run. The results of this study indicate that the long run welfare benefits such policies are designed to attain may be overstated or even nonexistent in the presence of user and resource heterogeneity.

The broader implication of this study is that policy implications derived from common property models that assume user and resource homogeneity may be inappropriate if applied to settings that violate these assumptions. It is also found that explicit recognition of user and resource heterogeneity can lead to the discovery of policy measures not identified by simpler models. This study finds that if user and resource heterogeneity exist in a commons, appropriate analysis and policy definition require explicit attention be paid to the influence of these factors on the common property system under analysis.

APPENDIX 1

DERIVATION OF STEADY STATE EQUATION [6]

From one of the first order conditions of the Bellman's equation [4], we know that

$$\frac{\partial V}{\partial ot^i(t)} = \frac{\partial U}{\partial c^i} - \left(\frac{1}{1+r}\right) E_t\left[\frac{\partial V}{\partial k(t+1)}\right] = 0. \qquad [A1]$$

We can also calculate from equation [4], the shadow value of the rangeland productivity parameter for sub-area j.

$$\frac{\partial V}{\partial y_j(t)} = \frac{\partial U}{\partial c^i}\cdot\left(\frac{\tau_j\cdot s_j^i\cdot k^i\cdot\sum_{i=1}^{N} s_j^i\cdot k^i\cdot rf_j}{(rf_j\cdot y_j)^2}\right) + \left(\frac{1}{1+r}\right)\cdot E_t\frac{\partial V}{\partial k^i(t+1)} \cdot\left(\frac{\alpha_j\cdot s_j^i\cdot k^i\cdot\sum_{i=1}^{N} s_j^i\cdot k^i\cdot rf_j}{(rf_j\cdot y_j)^2}\right) + \left(\frac{1}{1+r}\right)\cdot E_t\frac{\partial V}{\partial y_j(t+1)} \cdot\left(1+\frac{\gamma_j\cdot\sum_{i=1}^{N} s_j^i\cdot k^i\cdot rf_j}{(rf_j\cdot y_j)^2}\right). \qquad [A2]$$

In steady state, the state equation for the rainfall response parameter is not changing over time, so that the following condition holds.

$$y_j(t+1) = y_j(t) + \gamma_j\left(1-\frac{\sum_{i=1}^{N} s_j^i\cdot k^i}{rf_j\cdot y_j}\right) \rightarrow \sum_{i=1}^{N} s_j^i\cdot k^i = rf_j\cdot y_j. \qquad [A3]$$

If herd sizes are assumed to be equal, we can write this as $Nsk = rf_j\cdot y_j$. Substitute condition [A1] in equation [5] to replace the discounted expected shadow value of livestock capital with the marginal utility of consumption. Assume there are only two sub-areas, and define shadow values for the rainfall response parameter in sub area one and sub area two following [A2]. Modify equation [5] to be in steady state, so time subscripts are no longer relevant, and hold all stochastic variables at their mean value, so expectation operators are no longer necessary. Substitute the steady state shadow values of the rainfall response parameters derived from [A2] into equation [5]. Substitute the share and herd size values for the rainfall and rainfall response parameters in the resulting equation, following [A3]. Rearranging the terms of the resulting equation leads to [6].

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