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COMMON PROPERTY AS AN INSTITUTIONAL RESPONSE TO ENVIRONMENTAL VARIABILITY

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Relationships between the potential productivity of land and property rights generally are couched in terms of measures of central tendency or means. However, risk or variance as a measure of uncertainty also is critical in relating property rights and organizational arrangements developed within various property regimes. Meteorological and hydrological research results support the appropriateness of risk-spreading property regimes, especially in semi-arid and arid lands. Spatial diversification models indicate that common property regimes can be a rational response to environmental variability. Efforts by the public sector to privatize and fence grazing lands on the extensive margin may have limited appeal to pastoralists throughout the world.

I. INTRODUCTION

The debate surrounding the efficacy of common property regimes shows that a continuum of property regimes exists. Additionally, an ebb and flow between regimes occurs as societies change. Open access, state, common, and private property represent the major categories along this property continuum. One can differentiate each by decision unit, benefit incidence, and regulations. (i) Open access is a free-for-all where benefits accrue to the agent that can exploit the resource first. No institutional rules limit the agent's behavior. (ii) Government agencies manage state property in such a manner that benefits accrue to agents with permits authorizing access and regulating resource use. (iii) Common property provides for co-equal rights to a bounded resource where group-established rules govern resource use. (iv) Private property empowers owners, who experience the private costs and benefits from their actions subject to broad societal guidelines or constraints.

Economic models stress the management of rules that are established to ensure economically viable common property regimes (Wade, 1987; Stevenson, 1991). Cooperative arrangements in these models, where rules exist to discourage shirking by individuals in the group, can produce a sustainable economic environment. However, these institutional arrangements alone may not give a complete picture of the incentives confronting the individual in a common property regime.

Environmental conditions can play an equally important role in the determination of optimal property regimes. Environmental uncertainty in the form of extreme rainfall variability across time and space produces an incentive to develop cooperative rules that ensure access to widely dispersed fields or grazing areas.

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As Jackson (1978, p. 284) observes:

> A whole village may depend on rainfall conditions within a single square kilometer. Under such circumstances, spatial variations in rainfall for individual days are perhaps more important than is generally realized, except by the peasant farmer. Since a large proportion of the rain occurs in a few days, whether or not a single heavy storm 'hits' an individual small area, particularly at the start of the rainy season or at certain short, critical periods in a crop life cycle, could mean the difference between success and failure.

The analysis here reformulates Bromley's (1989, p. 15) equation relating property rights to economic yield to read,

$$(1) \qquad \text{Property Regime} = f(\mu_p, \sigma_p^2)$$

where μ_p and σ_p^2 are the mean and variance of physical yields, respectively. (Bromley argues that the functional relationship may be written as: Property Right = f[Economic Yield].) One can directly relate the first two moments of the probability distribution for yields to economic welfare through an expected profit equation. One also could include higher order moments. The hypothesis here is that environmental variability is particularly relevant on land at the extensive margin—that is, land in the semi-arid and arid-regions of the world where low mean productivity and high yield variability predominate (Bromley and Cernea, 1989). Other authors have recognized the importance of the second moment in this functional relationship but have failed to verify variability in rainfall with meteorological evidence (Sandford, 1983; Runge, 1986).

The analysis here focuses on environmental variability across space. For subsistence ranchers or farmers with high discount rates, the intertemporal aspects of variability probably are less important than the area distribution of rain within one growing season. The analysis relates the meteorological literature on rainfall variability emphasizing correlation-distance relationships to two risk-spreading models in the economics literature. The analysis here postulates that common property can be a rational response to environmental variability. Other management strategies besides access to geographically dispersed plots of land do exist for spreading risk across a grazing operation. For example, Binswanger and Rosenzweig (1986) demonstrate how farmers use marriage contracts to forge alliances with families in other climatic regions. The analysis here examines grazing systems in Kenya and Mexico, where privatization efforts have been implemented or are being explored.

II. ENVIRONMENTAL VARIABILITY OVER SPACE

Analysts often use measures of average annual rainfall to characterize a specific geographic region. These aggregate statistics provide useful information for interregional analysis. However, they do not capture the nature of the variability within a region. For millennia, herders and farmers have understood intraregional variability's importance as a source of risk. Yet the potential importance of spatial variability in rainfall for land use decisions has remained in the background of property regime analysis.

Figure 1 presents three representative correlation-distance functions for rainfall. Empirically, these relationships are estimated using rainfall measurements from a network of rain gauges over a watershed. Pairwise correlations are tabulated for hourly, daily, or monthly rainfall using $r_{ij} = r(d_{ij})$, where r_{ij} is the correlation coefficient between stations i and j and d_{ij} is the distance between the reporting stations or rain gauges. Curves, similar to *A*, *B*, and *C* in figure 1, then are fitted through scatterplots of the individual correlation coefficients.

Three factors affect the slope and location of these spatial correlation relationships. (i) Latitude is a determinant of the

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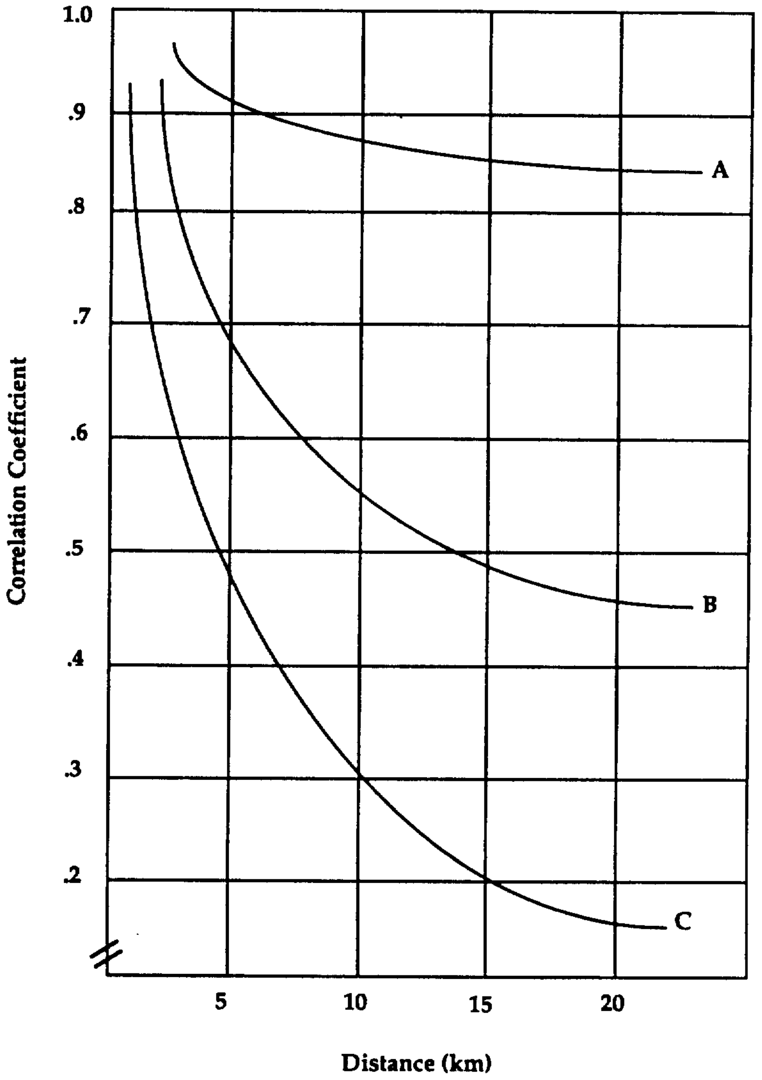
FIGURE 1
Representative Correlation-Distance Relationships for Rainfall



relative mix between convective and frontal storms. Regions in higher latitudes have relatively more widespread frontal storms throughout the year. These storms produce a correlation-distance function resembling *A*. Lower latitude areas where convective storms with high rain intensities for short periods of time are reflected in functions *B* and *C*. (ii) A second determining factor is topography. Orographic effects from mountain ranges and coastal influences produce spatial variability. An orographic effect implies conditions where rain is produced when a mountain or mountain range deflects moisture-laden wind upward. For example, location near mountains sharply rising from a valley floor may produce a rainfall pattern

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dissimilar to the one in the central valley only several kilometers away. (iii) As the interval of observation increases from daily to monthly intervals, for example, the slope of the correlation-distance functions "flattens." Thus, *C* could represent the hourly rainfall relationships while *B* and *A* might reflect the daily and monthly data, respectively.

Empirical measurements of rainfall dispersal from various latitudes demonstrate the effects of convective storms, orographic features, and interval of observation on correlation-distance relationships.

A. *Saskatchewan, Canada (Lat. 50° N)*

McConkey et al. (1990) use data over a 34-year period from a combination of 11 rain gauges spaced 800–4,400 m apart. They evaluate spatial variability over this small area by storm and by month. The estimated spatial distribution function related to storms demonstrated a slope similar to the monthly function, but with a lower intercept on the y-axis. Over a distance of 4,000 m, the monthly spatial correlation values declined from 0.99 to 0.95. An extrapolation to 15 km produces a coefficient of 0.85, a gradual rate of decay over a moderate distance. These results are compatible with function *A* in figure 1 and reflect precipitation relationships for relatively higher latitude regions. Hendricks and Comer (1970) and Stol (1972) give other higher latitude examples of correlation-distance relationships. Sharon (1972 and 1979), Berndtsson and Niemczynowicz (1986) and Sumner (1983) give additional research results from lower latitudes.

B. *Illinois, U.S.A. (Lat. 40° N)*

Huff (1970) obtains insights into the spatial distribution of rainfall in the midwestern United States. Huff uses a network of 50 recording rain gauges over an area of 161 kms to obtain a 29-storm sample of 1-minute rainfall rates during the warm seasons of 1952 and 1953. Spatial correlation decayed very rapidly over instantaneous 1-minute rates. Within three kilometers, correlation declined from 1.0 to 0.6. Over a distance of 16 km, spatial correlations fell to 0. These results resemble relationship *C* in figure 1. However, correlating total storm rainfall with the distance between rain gauges produced a totally different picture. In this aggregated case, the data resembled relationship *A*. Spatial correlation declined very slowly to a value of 0.8 after 16 kilometers.

C. *Southwestern U.S.A. (Lat. 32° N)*

The Walnut Gulch Experimental Watershed utilizes a dense system of rain gauges (0.8 km radius per gauge) over an area of 176 km^2. Located on the northern edge of the Chihuahuan Desert, rainfall from this station reflects general precipitation conditions in the southwestern United States and northern Mexico. Using 40 gauges for the period 1961–1972, Osborn et al. (1980) approximate a spatial correlation function for storms in the watershed. At approximately 2 km, correlation varied around a mean of 0.8 but fell rapidly to 0.6 and 0.2 at 5 and 10 km, respectively. The authors fail to find any statistically significant orographic effect in the watershed within the 450 m elevation range. They attribute significant localness in rainfall to the convective nature of the major rain producing storms during the monsoon-like season (July–September).

D. *Tanzania (Lat. 4° S)*

Several researchers have investigated spatial rainfall patterns in tropical Tanzania. Using an eight-year period, Sharon (1974) generates correlation coefficients related to distance for 14 rain gauges over a 30,000 km^2 area in northern Tanzania. The decay over relatively short distances (< 20 km) was dramatic, with correlation coefficients declining from 0.8 at 5 km to 0.1 at 20 km. Sharon (p. 213) states,

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> What may be unique to the tropical area is the fact that a correlation that low applies to daily rainfall *in general* (Sharon's emphasis), and not only to a certain portion of selected raindays, as in higher latitudes. This reflects the predominant role of small-scale convection in the region dealt with. Still, if data for appropriately selected days would have been used here, the resulting correlation coefficients would be even lower, i.e., significant negative values would certainly have resulted.

In a 56, 250 km^2 catchment area in central Tanzania, Jackson (1978) estimates spatial correlation coefficients for 25 stations. Over a 25-year study period, average monthly correlations between stations declined rapidly within the first 20 km. Spatial correlations for most months declined at least 30 percentage points over this short distance. Average monthly correlations varied from 0.3 in April to 0.7 in October. Jackson concludes his article by stating that, "The degree of local differences in rainfall variability patterns could be an argument in favour of fragmentation of holdings" (p. 285).

The meteorological evidence indicates that rainfall variability over space is a fundamental characteristic of nature that normally is not captured in standard economic analysis of agriculture. Nor is this fundamental characteristic of nature recognized in public programs directed at the agricultural sector. The degree of rainfall variability is a function of latitude, storm patterns, and the topography of the region. Variability in rainfall across space may occur at critical flowering or growing periods in the crop or forage biological cycle. As a result, one should expect significant yield and, hence, economic variability—across space as well.

III. SPATIAL DIVERSIFICATION

Natural elements such as pests, rainfall, temperature (e.g., frost), and soil quality, largely determine successful agricultural production. The localness of these environmental conditions is understood by farmers and herders in diverse areas (Netting, 1976; Guillet, 1981). Just as investors diversify their financial portfolios to reduce risk and increase average returns, farmers and herders attempt to diversify their yield portfolios over space to ensure economic sustainability. The following two models of land at the extensive margin show that farmers and herders who diversify geographically may be making reasonable, if not rational, decisions in response to environmental variability.

A. *Statistical Model*

Using area or regional data to reflect economic reality at the firm level raises aggregation issues. In the United States, policy analysts in the agricultural sector often use county and state data. Although aggregate statistics may be the only available data, their use can seriously understate the level of variability experienced by individual farmers.

Nearly 30 years ago, Eisgruber and Schuman (1963) developed a formal statistical relationship for aggregation bias. Assuming that all farm-level variances are the same ($\sigma_1 = \sigma_2 = \ldots = \sigma_n = \sigma$) for all n farms and that the correlation coefficient, r, represents an arithmetic mean of all cross-correlations, the aggregate variance is:

$$(2) \qquad \sigma_A^2 = (\sigma^2/p)[1 + (p - 1)r]$$

where p is the number of farms or plots. The aggregate variance is a declining function of p, and as the correlation between farms declines, so does the degree of overall variability.

Spatial diversification to reduce environmental and economic variability would require an increase in the number of farms holding the average correlation-distance relationship constant. Correlation values approaching one reduce the incentive to diversify over space while lower

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correlation coefficients increase the difference between farm-level variability (σ^2) and the aggregate variability measure (σ_A^2). Therefore, there is more incentive to diversify geographically in the tropics of Tanzania or the deserts of Arizona and Mexico than in the plains of Canada. As the meteorological literature shows, correlation between farms can fall dramatically over a 5 km range in some areas of the world.

B. *A Behavioral Model*

Historical evidence from England during the Middle Ages provides additional insights on the value of spatial diversification (McCloskey, 1975, 1976, 1989). McCloskey's painstaking research suggests crop yields varied markedly across plots as nearby as 5 km. Changing soil quality over short distances as well as other localized events such as pests, disease, rain, and hail caused variations in yields. Scattering of land holdings offered peasants in the English commons a means to insure against vagaries in crop yield.

The behavioral model underlying McCloskey's arguments posits that farmers are concerned with both average yield and variation in yield. Figure 2 displays the potential trade-off between mean yield and the variance of yield that farmers may face. The mean-variance frontier for yields indicates that one can attain higher mean yields only by incurring higher variance of yields. The rate at which a farmer is willing to sacrifice mean yield for a reduction in the variance of yield, I, is a measure of the farmer's aversion to risk. The analysis here refers to the slope

$$I\left(-\frac{\partial\mu/\partial p}{\partial\sigma^2/\partial p}\right)$$

in figure 2 as the value of insurance against disaster.

The statistical model in section IIIA indicates that one can reduce aggregate variance in some circumstances by choosing more plots of land. Because the aggregate variance formula in equation (2) refers to variance per unit of land, the variance on the farmer's total hectares, N, can be restated following McCloskey's approach

$$\sigma_a^2 = \frac{N^2\sigma^2}{p}[1+(p-1)r]. \tag{3}$$

Choosing a larger number of plots reduces aggregate variance, *ceteris paribus.* If there are costs and inefficiencies associated with farming on dispersed plots, choosing a larger number of plots likely would reduce average yields, however. Average total yield on a land holding of N hectares may be represented by

$$\mu = N\alpha(N/p)^{\eta} \tag{4}$$

where η measures the percentage loss in yield as plots become more scattered and α indicates the productivity of the farmer's resources and factors of production.

Both average yield and the variance of yield depend upon the farmer's choice of the number of plots. Because the productivity parameter, α, does not enter the variance equation (3), productivity increases have no effect on the variance of yield. Whether increased productivity increases or decreases the variance of yield is an empirical question whose answer depends upon the nature of the technology adopted. Given a particular value of insurance against disaster, the optimal number of plots, p^*, is

$$p^* = N\left[\frac{I\sigma^2(r-1)}{\alpha\eta}\right]^{\frac{1}{1-\eta}} \tag{5}$$

where $\eta \neq 1$ [see the appendix for an explanation of equation (5)]. Note that the larger the average correlation in yields, r, the smaller the optimal number of plots. To the extent that yields and rainfall are highly correlated, the meteorological evi-

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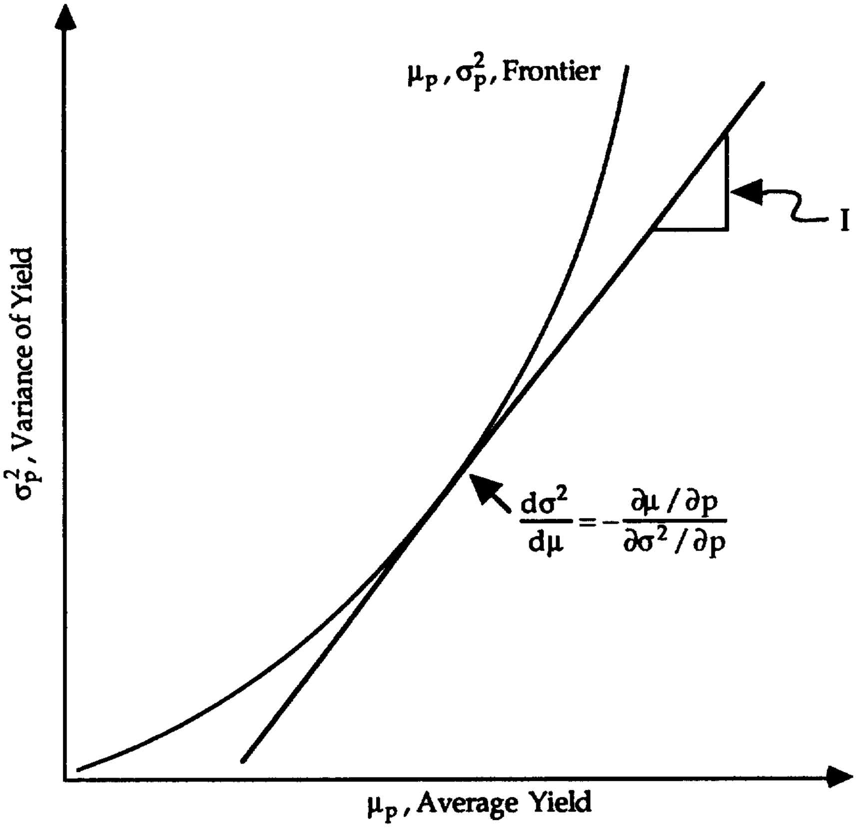
FIGURE 2
The Tradeoff between Average Yield and the Variance of Yield



dence and the relationship between p^* and r in equation (5) suggest that scattering of holdings will not occur in high latitudes. In arid, semi-arid, and tropical climates where correlation values decline rapidly over short distances, the optimal number of plots in equation (5) also increases as the average variance on individual plots, σ^2, increases. Thus, where the localness of convective rain showers or orographic effects increases the variance of rainfall on any given plot, the incentive to scatter land holdings increases.

As the tradeoff between average yields and variance is valued more highly (*I*), one would expect a desire for more plots. That is, risk-averse agents such as subsistence farmers and herders prefer scattering. The value of insurance against disaster likely depends not only on the farmer's aversion to risk but on the degree to which household income varies with agricultural production. Households relying solely upon agricultural production will value insurance against disaster more than will households having reliable sources of off-farm income. Therefore, subsistence farming households are more likely to diversify spatially.

Insights into the complementarity between spatial diversification and common property regimes emerge from the optimal plot equation (5). Where the loss in average yield due to scattered plots, η, is small,

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the incentive for more plots is stronger. For lands at the extensive margin, the value of η likely is small because access to dispersed areas is not prohibited physically or institutionally. Common property regimes on the extensive margin can reduce the transactions costs of managing scattered plots and thus reduce the loss in average yields due to scattering.

Technical progress and the modernization of agriculture (measured by α) diminish the number of optimal plots. Technological advances in crop varieties, animal genetics, irrigation, and management practices generate increases in average yields so that the optimal number of plots can be consolidated. As farms and ranches become more productive, incentives will emerge to reduce scattering, encourage enclosure, and, possibly, privatize common lands.

IV. RESPONSES TO ENVIRONMENTAL VARIABILITY

A. *Kenya*

The Ngisonyoka Turkana in northwest Kenya herd camels, cattle, goats, and sheep over 100,000 km^2 of arid and semiarid range land (McCabe et al., 1988). These semi-nomadic people live in *awi,* which is a family unit of an adult male herder, his wives, and his children. During most of the year, these family groups move within their tribal boundaries in search of forage. During the rainy season, multiple *awi* form a larger community or *adakar* and remain settled in one location until the local forage supply is depleted.

Spatial variability in rainfall within and across seasons produces dispersed microhabitats where the quality and quantity of forage varies. The Turkana respond to this environmental variability using two range management strategies. First, they divide their herds in the dry season by animal type according to the available forage: grazers (e.g., cattle) feed on the remaining grasslands while the browsers (e.g., camels and goats) forage on more marginal lands. Second, the family unit is divided into multiple herding units, and the herds are moved throughout the tribal boundaries in search of the appropriate forage for a specific type of animal. These family sub-units may not join one another until the onset of the rainy season.

In this harsh, unpredictable environment, herd-owners rely on their perceptions of the spatial nature and intensity of rainfall to sustain their herds. Researchers traveling with the Turkana have noted significant variability in individual herd movement during any single year and between years. Flexibility in herd size and animal type, as well as freedom of movement, increases the probability that the animals and the *awi* will survive until the next rainy season.

McCloskey's behavioral model [equation (5)] captures the Turkana's grazing environment. The low spatial correlation in rainfall (r), the high risk aversion of subsistence pastoralists (I), the small loss in yield as plots become more scattered (η), and the low productivity of existing resources (α) produce a large, optimal number of plots for this grazing system. Arguably, under current management practices, the Turkana are achieving optimal levels of herd productivity subject to their environmental constraints.

In some areas of Africa, commercial open-ranging is displacing pastoral nomadism such as the Turkana practice (Behnke 1984). These communally-managed grazing schemes produce greater incentives for water development and sustainable grazing practices than do the Turkana's nearly open-access system. But efforts to further intensify grazing management with fenced ranching have a predictable history. During the 1960s and 1970s, externally-funded development projects were designed to replace African management techniques on open-range systems with more "modern" enclosure or fenced ranching. These efforts to enclose communally-managed grazing systems

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were rejected by the people they were designed to assist. Citing experiences in Uganda, Botswana, and Kenya, Behnke, (1984, p. 278) states:

> It is now clear that African pastoralists and open-range ranchers rejected all components of these projects which did not meet their immediate needs, and persistently rejected the use of fencing. Botswana and Maasai livestock producers cite a consistent set of reasons for this rejection. Fences, say the Botswana, would trap herds on ranches that were periodically untenable due to borehole breakdown, veldt fires, and localized drought. Maasai, on the other hand, stress the problems of erratic rainfall and insufficient resources on particular ranches. Like subsistence pastoralists, open-range ranchers rely on mobility as a technique for balancing localized deficiencies in resources needed by the herd. In this way they maintain within a wide geographical region a total livestock population far greater than that which could be sustained, *ceteris paribus*, by independent herds operated separately on small plots of land.

Privatizing and fencing the range land would require a sizable capital investment. Additionally, parcelizing open-range ranching would expose the herder to unacceptable levels of environmental uncertainty due to the spatial variability of resources and rainfall.

B. *Mexico*

Current modernization efforts in Mexico's agricultural sector focus on the privatization of the *ejidos*, which control 48 percent of the agricultural land in the country. Thompson and Wilson (1994) provide an in-depth evaluation of privatization efforts in Mexico's *ejido* sector. The *ejido* is a common property regime with roots in the indigenous past of Mexico (Rincon, 1980). Current privatization programs will legalize the renting and in some instances the selling of parcelized *ejido* lands to other farmers and investors. Corporations, both domestic and foreign, now can own these lands. The intent of these institutional changes is to modernize the *ejido* sector, which is 30–50 percent less productive (measured as output value per hectare) than comparable private farms (Yates, 1981).

The two types of *ejido* land are parcelized and communal. The parcelized lands generally are used for crop production. These lands remain with the family and are divided among the heirs, thereby producing unproductive minifundia in many instances. Communal lands, particularly in the northern half of the country, are unfenced property used for grazing and forestry purposes where open access can be a problem. (Wilson and Thompson [1993] describe *ejidatarios'* current coalition building behavior in response to spatial variability.) One also should note that parcelized lands as a percentage of total *ejido* lands range from less than 1 percent in Baja California Sur to 84 percent in Veracruz (Instituto Nacional de Estadistica, 1988). Nationally, approximately 28 percent of the *ejido* lands are parcelized and subject to privatization. In the arid and semi-arid North Pacific region irrigated *ejido* land represents 45 percent of the agricultural lands in the region (not including communal lands). Yet this area represents only 5 percent of the *ejido* lands, parcelized plus communal. Only 3.5 percent of *ejido* lands at the national level are irrigated.

Meteorologically, one should not expect correlation-distance functions for rainfall in Mexico to depart substantially from the results in the existing literature. Researchers at the Southwest Watershed Research Center, operated by the Agricultural Research Service of the U.S. Department of Agriculture, indicate that their data from the northern Chihuahuan desert (Walnut Gulch) is applicable to all of the North Pacific and North regions of Mexico (Weltz, 1992). These regions represent nearly 60 percent of the national land area controlled by *ejidos*. Hastings and Turner

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(1965) and Hastings and Humphrey (1969) strongly support the proposition of significant rainfall variability across space in northern Mexico.

Given the predominance of common land in *ejidos* located in northern Mexico, where high variability in rainfall prevails, McCloskey's behavioral model [equation (5)] yields several insights into the likely outcome of new *ejido* sector reforms. (i) Clearly not all of the 95 million hectares of *ejido* land will be privatized, at least not in the foreseeable future. The majority of the land is held in common on arid lands where average productivity (α) is low, loss in mean yield with increased plots (η) also is low, correlation between rainfall events (r) is quite low, and the large number of subsistence households on those common *ejido* lands suggests little willingness to trade off increases in mean yield for increases in the variance of yields (I). Hence, the optimal number of plots in these areas will be relatively large. In addition, land reform regulations create higher transactions costs for privatizing communal lands than for parcelized plots. These higher transactions costs will discourage investors from acquiring common grazing lands. (ii) Herders on non-irrigated *ejidos* that experience convective storms in the critical growing months of June, July, and August will continue to favor scattering under a common property regime. At least in the northern half of Mexico, investors lack the economic incentives to lobby the government to include communal lands in the privatization scheme. A single individual could capture the localness feature by controlling a large expanse of grazing land on the extensive margin, yet higher returns on investments in other areas of the economy will discourage such decisions. (iii) Equation (5) indicates that the introduction of modern technology can encourage the enclosure of the commons. For this reason, the irrigated *ejidos* likely will be the first *ejidos* to be privatized. These circumstances lower risk averseness, reduce yield variability by supplemental irrigation, make the use of fertilizer more viable, and enhance the incentive to produce high value crops. In the irrigated *ejidos*, according to McCloskey's model, the optimal number of plots for economic sustainability is less than the number for economic viability in non-irrigated *ejidos*.

V. CONCLUDING REMARKS

Natural resource endowments matter in the study of property regimes. As in Africa, existing property regimes can be a human response to variable environmental conditions. Extensive margin lands, characterized by low mean productivity and high variances in yield, constrain the institutional choice set for farmers and herders. Community-oriented or risk-spreading regimes may be preferred to other institutional arrangements in these harsh environments. Research has shown that in Kenya and Mexico communally managed range lands may be a rational and efficient response to existing resource conditions. Blanket condemnations of common property may reflect a limited understanding of the risky environment that farmers and herders face in many areas of the world. Governmental efforts to improve the economic status and resource base of grazing lands on the extensive margin must reflect understanding and take account of herders' ongoing rational responses to their natural environment.

APPENDIX

Optimality Condition for the Behavioral Model

McCloskey's behavioral model belongs to a class of mean-variance models. Some versions of the model are consistent with a safety-first approach (see McCloskey, 1976). The optimality conditions for these models indicate that the

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choice of the endogenous variables—in this case, the number of plots, p—gives the combination of mean and variance levels of output consistent with the individual's preference. In graphical terms, the individual's utility is maximized when an indifference curve is just tangent to the mean-variance frontier in figure 2.

For a well behaved utility function such as $U = U[\mu(p), \sigma^2(p)]$, an indifference curve takes the form

$$\text{(A1)} \qquad dU = \partial\mu / \partial p \, d\mu + \partial\sigma^2 / \partial p \, d\sigma^2$$

Thus, the slope of the indifference curve in mean-variance space in figure 2 is

$$\text{(A2)} \qquad I = \frac{d\sigma^2}{d\mu} = -\frac{\partial\mu / \partial p}{\partial\sigma^2 / \partial p}$$

where I represents the willingness to sacrifice mean yield as the variance in yield increases. Equating the slope of the indifference curve with that of the mean-variance frontier gives the optimality condition.

The placement and shape of the mean-variance frontier is determined by the specific parametric forms of μ and σ_a^2 specified in equations (4) and (3). The following derivatives give the rates of change in μ and σ_a^2 as the number of plots is varied.

$$\text{(A3)} \qquad \frac{\partial\mu}{\partial p} = -\alpha \, \eta (N/p)^{1+\eta}$$

$$\frac{\partial\sigma_a^2}{\partial p} = \frac{N^2\sigma^2(r-1)}{p^2}$$

Equation (A2) defines the point of tangency between the indifference curve and the mean-variance frontier. Substituting (A3) for the partial derivatives in the right-hand side of (A2) gives

$$\text{(A4)} \qquad I = \frac{\alpha\eta(N/p)^{1+\eta}}{\frac{N^2\sigma^2(r-1)}{p^2}} = \frac{\alpha\eta(N/p)^{\eta-1}}{\sigma^2(r-1)}$$

Solving for p^* yields equation (5)

$$\text{(A5)} \qquad p^* = N\left[\frac{I\sigma^2(r-1)}{\alpha\eta}\right]^{\frac{1}{1-\eta}}$$

The parameters α and η reflect the nature of technology and, possibly, infrastructure such as roads and fencing. Environmental conditions determine the parameters σ^2 and r. The total land area available, N, is predetermined in this equation. For *ejidos*, a predetermined N is appropriate because land reform institutions have fixed the size of common lands on *ejidos*. For some grazing areas, total grazing area is fixed for any given season. The choice variable in this problem is p, the number of plots.

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