

Spatial Heterogeneity, Mobility and Access: The Case of Range Management in the Sahel

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Abstract:

In this paper, we develop and calibrate a spatial and intertemporal bioeconomic model of livestock production to the West African Sahel region. The model is then used to investigate the effects of land heterogeneity, range scale, and access rights on long term management of rangeland in the Sahel.

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I. Introduction

The crop and livestock production systems in the Sahel¹ of West Africa have undergone a profound shift in the past few decades. The traditional systems were specialized, but closely linked through trade not only in primary products (grain, meat and milk) but also in secondary products (crop residue and manure). The traditional livestock system involved extensive migration (transhumance) between the northern and drier regions of the Sahel and the wetter southern regions. Crop production was also extensive in nature and tended to be located in more favorable areas with sufficient rainfall. Recently, these systems have been integrated within individual production units.

There are two main factors that have contributed to this shift: population growth and climatic variation. Population growth has resulted in a steady expansion of crop production northward into traditional grazing areas, increasing competition for land and increasing costs of livestock mobility since damage to crops becomes more likely. Severe droughts in the 1970s and 1980s decimated livestock herds and forced the sale of livestock, often to sedentary farmers. As a result, many herders were forced to settle and cultivate grain for their own consumption. The situation today is bleak as rainfall remains below the long-term average and variability appears to be increasing due to climate change (e.g. El Nino).

In the "new" agricultural system, livestock movements are confined to village land, which only enables the herders to exploit the local spatial variation caused by differences in land productivity and variations in rainfall within a region of similar weather patterns. This system may provide additional manure to cropland and improve soil fertility, but it can also lead to

overgrazing and range degradation, particularly in low-rainfall years. The transhumance system continues, but now sedentary farmers entrust their cattle to herders who manage these amalgamated herds over the course of the year. This system may reduce grazing pressure on village land but does not necessarily improve the farmers' ability to manage soil fertility on crop lands and can reduce the ability of the "professional" herders to mitigate risks via stock mobility.

While integration of the agricultural system is not necessarily inefficient, the reduction in pastureland and the new rules regulating access are threatening the viability of the livestock sector, especially in the case of extreme weather events. In this paper, we develop a spatial and intertemporal bioeconomic model to investigate the implications of defining rights of exclusion. We model a representative pastoralist's decision on annual pasture stocking rates, which are then linked to a behavioral model characterizing the pastoralist's mobility. The behavioral model captures the ability of the herders to move the herd throughout the pasture in an attempt to maximize the returns from grazing, subject to some transaction costs associated with moving the stock of animals. The range land ecosystem is assumed to comprise of distinct heterogeneous patches (areas) that have variable and imperfectly correlated returns, which depend upon stocking rates, rainfall, and forage productivity. The model can then be used to address several policy issues surrounding the use of exclusive zones, such as: What are the implications on stocking rates and mobility from imposing spatial restrictions on grazing land and/or crop production? How does the presence of spatial heterogeneity and rainfall variability affect the choice of which patches to select as pastoral zones? The paper is organized as follows. In the next section, we describe the spatial and intertemporal bioeconomic model of the representative pastoralist and derive some preliminary analytical results. In section III, the model is

¹ The arid region south of the Sahara Desert.

parameterized to the West African Sahel with data from the Sahelian Center of the International Crop Research Institute for the Semi-Arid Tropics (ICRISAT-SC) in Niamey, Niger. Finally, in section IV, we conclude with a brief discussion on the strengths and weakness of this approach and directions for future research.

II. Spatial and Intertemporal Model of Livestock Production

Livestock production and management is a very complex process that encompasses multiple dimensions including sex and age characteristics of the stock, range land ecosystems, markets, and institutional characteristics (open-access, regulated access, or sole ownership). While a comprehensive description of the production process is beyond the scope of this paper, we draw and build upon three distinct but connected strands of the livestock production literature, which focus on the interaction between the dynamics of stocking rates and ecosystems, and common-property resources.²

We contribute to this body of literature by developing a simple "two-stage" spatial and intertemporal model of pastoral migration and stocking decisions for the West African Sahel region. We assume that a representative pastoralist begins each grazing season (coinciding with the start of the rainy season) deciding on the amount of animals to stock balancing the current returns from culling with the returns from holding the stock over the next grazing season (Stage

² Numerous papers investigate the issues surrounding rangeland management and stocking rates in both static and dynamic contexts. Huffaker, Wilen and Gardner (1989) investigate the optimal stocking rate when a farmer's returns depend not only on the stock but also on the quality of the rangeland (forage levels). Huffaker and Wilen (1991) use a similar model to investigate different types of stocking policies throughout a season both in a single and multi-year framework. Hu et al. (1997) expand upon the models of Huffaker et al. to investigate the soil conservation dimension of range land management by explicitly including soil dynamics within a social planner's objective where returns from the stock along with the returns from maintaining top soil levels are jointly maximized. Perrings et al. (1995) model the dynamics of the range to investigate the effects of endogenous structural change of the pasture (invasion of low quality types of forage) resulting from grazing pressure. There is also a considerable amount of literature analyzing the use of common property regimes in the presence of high levels of production risk typically attributed to rainfall in regions with incomplete or missing markets (see, for example, Swallow (1994), Baland et al. (1998), Nugent and Sanchez (1998), Janvry et al. (1998), Bromley (1998), Zimmerman et al. (1996), and Goodhue and McCarthy (1998)). For example, the ability to move "freely" within a range allows the individual herder to counteract the effects of extreme weather events (e.g. drought, floods) in their local environment. In addition to the theoretical models there is a growing but small literature investigating the empirical relationships between pastoral mobility, policy variables (food aid), agricultural

I). Present returns from culling are a function of the current market conditions and the returns from holding the stock depend on the returns from milk production, grazing pressure on the range, and on the expected quality of the range over the next grazing season.³

After the decision on the amount of stock to carryover to the next grazing season (including any purchases), the herders are assumed to choose whether or not to move the herd throughout the pasture lands (patches) over the grazing season (Stage II).⁴ The decision to move a herd from patch i depends upon whether or not the returns from grazing are higher in patch i relative to the other patches in the system. The returns in each patch are measured in terms of the weight gain/loss, which is a function of the forage and grazing pressure in the patch. Given these linkages, we would expect to observe herds migrating into patch i when it is experiencing high amounts of rainfall relative to the other patches.

The two stages, stocking (yearly) and grazing (monthly) decisions, are assumed to be separable, but linked via the initial stocking rates and the terminal forage level in each patch. For example at the beginning of the rainy season in year two, the optimal stock level is chosen based on the year-one terminal stock levels, and the expected quality of the forage over the year given the quality of the range at the end of year one. After deciding on the stock level at the beginning of year two, the within season grazing model determines the spatial allocation of the stock levels. Over the course of the grazing season in year two, the stock biomass can increase or decrease depending on the forage availability, which are conditional on year one's terminal levels and

encroachment on pasture lands, and the evolution of property rights institutions (see, for example, Nugent and Sanchez (1998), McPeak (1998), and Sserunkuma et. al.(1998)).

³ In order to simplify the analysis, we abstract away from sex and life cycle aspects of herd management by assuming that the stock is measured in terms of biomass.

⁴ This is analogous to the situation where the herd owner determines the optimal stock level given a well-defined objective function. He or she then entrusts the cattle to a herd manager. In the second stage, we assume that there does not exist the management structure in the region necessary to determine the optimal placement of the stock in any given period (in a sense the rangeland is "open-access").

rainfall. This two-stage decision iteration continues ad infinitum where each year's decisions are conditional on the past histories of grazing pressure and range quality.

In the remainder of this section we describe in detail the stocking and grazing decision models.

Stage I: Stocking Decision

In stage I the representative pastoralist decides how much stock to hold, trading off at the margin the returns from selling with the returns from holding. For example, if the returns from holding onto the stock are high relative to the returns from selling, then we would expect there to be higher initial stock levels throughout the range in the next grazing season. With less stock being sold on the market, however, the price per unit of weight could increase creating incentives for pastoralists to sell more stock. At the optimum, we would expect a chosen stock level such that the marginal returns from culling are directly offset by the marginal expected returns from holding onto the stock through the season.

Let, $S_{i,t}$ and $E[F_{i,t+1} | F_{i,t}]$ denote the biomass level in area i in year t and the expected quality of forage throughout the next season ($t+1$) conditional on the previous year's level. Let, $h_{i,t}$ denote the harvest level in area i in period t , which is defined here as the difference between the initial stock and the optimal stock (i.e., $h_{i,t} = S_{i,t} - S_{i,t+1}$), and $p(h_{i,t})h_{i,t}$ is the return from selling off biomass in area i and period t (e.g., $p(h_{i,t})h_{i,t} = (\alpha_i - \beta_i)h_{i,t}$).⁵ The return from holding the stock over the course of the grazing season is $z_i + \eta W_i$ where z_i is the return per unit of biomass (e.g. milk production) and ηW_i is the expected value per unit of biomass from holding the stock over the next season (e.g., $W_i = (q_i E[F_{i,t+1} | F_{i,t}] - c_i S_{i,t+1}) / E[F_{i,t+1} | F_{i,t}]$). For example, if the

⁵ Markets, particularly for meat and milk are thin due to low demand and correlated production risks, hence the downward sloping demand curve. In other research, we incorporate a more realistic market structure for livestock where the output markets are linked across the patches in the system. We accomplish this by assuming that the returns from harvest depend not only on the

expectation is that the forage levels will be low over the next year, then the returns from holding the stock will decrease making it more likely that farmers will sell off more stock, everything else equal ($\partial W_i / \partial E[F_{i,t+1} | F_{i,t}] > 0$).

The representative pastoralist's first stage problem is

$$\begin{aligned} \max_{S_{i,t+1}} \mathbf{p} = & \sum p(h_{i,t}) h_{i,t} + (z_i + W_i(S_{i,t+1}, E[F_{i,t+1} | F_{i,t}]) S_{i,t+1}) \\ \text{s.t.} \quad & h_{i,t} = S_{i,t} - S_{i,t+1} \\ & S_{i,t+1} \geq 0 \end{aligned} \quad (1)$$

The solution to (1) characterizes the representative agent's choice on the optimal stock level to carryover to next years grazing season. Due to the recursive nature of the problem, we can solve out for the optimal level of stock for any season as a function of the bioeconomic parameters in the patch and the expected quality of the range over the next grazing season. In this simplest of cases, the optimal level with $\eta=1$ is

$$S_{i,t+1}^* = \frac{E[F_{i,t+1} | F_{i,t}]}{2(\mathbf{b}_i E[F_{i,t+1} | F_{i,t}] + c)} (z_i + 2\mathbf{b}_i S_{i,t} - \mathbf{a}_i + q_i E[F_{i,t+1} | F_{i,t}]) \quad (2)$$

As expected the optimal initial stocking biomass from stage I is a function of the market conditions, expected forage levels, the stock biomass levels existing at the end of the previous year, and the returns from holding the stock. From (2) we can derive some simple comparative static results. For example, if the choke price increases in patch i , then the returns from selling off the stock increase in patch i and the optimal level to hold decreases ($\partial S_i^* / \partial c_i < 0$). On the other hand, if the daily minimum intake requirement increases⁶ then the potential returns from holding the stock throughout the system decrease resulting in greater supplies in all of the markets ($\partial S_i^* / \partial c < 0, \forall i$).

harvest in patch i year t , but on the total harvest across the system. In this case, the returns from selling stock would be $p(\sum_i h_{i,t}) \sum_i h_{i,t}$ and as a result, the optimal stocking rates are interdependent ($S_{i,t+1}^* = f(S_{j,t+1}^*)$).

⁶ This could be due, for example, to a decline in the nutrient quality of the forage.

Stage II: Spatial model of Grazing

Once the pastoralist decides on the stock level ($S_{i,t+1}^*$), the herders are faced with the decision on where to graze the herd. In the semi-arid West African Sahel the decision will depend upon the quality of the forage throughout the potential range (patches). For example, in this region there is a well-documented northern migration in the early part of the rainy season where the herders are trying to capitalize on the seasonal rains and corresponding forage growth in the region. After the rainy season, the herders return to the southern regions of the range where rainfall is higher and forage more durable over the year⁷. The pastoral mobility throughout the rangelands and within the season is modeled via the stock biomass equations. Within the season, we assume that the herders are updating and responding myopically to the environmental conditions throughout the grazing season by moving the stock to the pastures with the highest current weight gain.⁸

Let $S_{i,m,t+1}$ and $F_{i,m,t+1}$ denote the patch specific levels of stock and forage biomass respectively in patch i in month m and year $t+1$, and let $W_{i,m,t+1}(F_{i,m,t+1}, S_{i,m,t+1})$ be the corresponding return in patch i in month m and year $t+1$ (weight gain/loss function).⁹ We assume that the returns from grazing in patch i in month m are increasing at a decreasing rate in forage levels and decreasing in stock levels. In addition, if the animals do not have a sufficient amount of forage to consume, then the biomass levels will fall, holding stock levels constant. An example of a return function satisfying these criteria is: $W_{i,m}(F_{i,m}, S_{i,m})=q_i F_{i,m} - c S_{i,m}/F_{i,m}$ where q is a biomass conversion factor and c is a congestion parameter.

⁷ Our model does not consider another important driving force behind the timing of these movements: water availability, which becomes limiting in the north.

⁸ It is important to point out that this will not be the optimal spatial distribution of the stock in any given period due to the open-access nature of the range lands. If we were instead to set this up from the perspective of a social planner (or an efficient common property structure over both stages of the decision), then we could combine the two-stages into a single decision framework where the stock levels are chosen optimally in each period.

In the Sahel, three fundamental forces drive forage availability. First, rainfall is seasonal and stochastic implying variable forage growth. Second, after the rainy season, forage begins to die off or lose quality. Finally, livestock consume a certain quantity of the forage in every period. Let $G_{i,m}(F_{i,m}, \sigma_{i,m}(\mu_{i,m}, \varepsilon_{i,m}))$ be the forage growth function in patch i and month m where $\sigma_{i,m}(*)$ is the realized rainfall in patch i month m . Following Noy-Meir (1975), the growth function is assumed to be logistic, however, we include a stochastic growth rate and natural mortality parameter to better characterize the Sahel ecosystems. Specifically, let $G_{i,m}(F_{i,m}, \sigma_{i,m}(\mu_{i,m}, \varepsilon_{i,m})) = [b_i \sigma_{i,m}(\mu_{i,m}, \varepsilon_{i,m})] F_{i,m}^* (1 - F_{i,m}/K_i) - d_{im} F_{im}$, where b_i is the intrinsic growth rate of the forage in patch i , K_i is the carrying capacity of patch i and d_{im} is the natural mortality rate. As we mentioned earlier the rainfall in this region follows a seasonal pattern, which is captured by the mean monthly rainfall in patch i ($\mu_{i,m}$) and deviations from the seasonal pattern are captured by a random shock parameter($\varepsilon_{i,m}$). Forage consumption per head is assumed to be proportional (θ_i) to the amount of forage in the patch in any period.

Putting these components together, we can hypothesize that the level of stock and forage in patch i will change from one month to the next within year $t+1$ according to:

$$\begin{aligned}
 & S_{i,m} S_{i,\bar{m}} S_{i,\bar{m}} \bar{S}_{i,\bar{m}} \bar{I}_{\bar{m}} \bar{W}_{i,\bar{m}} \bar{W}_{i,\bar{m}} S_{i,m} + \sum_{j=1}^n \sum_{j \neq i}^n [W_{ij} (W_{i,m} S_{i,m} d_{ij} W_{ij} W_{j,m} S_{j,m}) - I_{ij} (W_{j,m} S_{j,m} - d_{ij} W_{i,m} S_{i,m})] \\
 & F_{i,m} F_{i,\bar{m}} F_{i,\bar{m}} \bar{F}_{i,\bar{m}} \bar{G} \bar{G} (F_{i,m} F_{i,\bar{m}} S_{i,\bar{m}} a_{i,\bar{m}} b_{i,\bar{m}} \theta_i - q_{i,\bar{m}} F_{i,m} F_{i,\bar{m}} S_{i,\bar{m}} d_{i,\bar{m}} F_{i,\bar{m}} F_{i,m}) \\
 & \text{s.t. } S_{i,m,t+1} = S_{i,t+1}^*, F_{i,m=0,t+1} = F_{i,m=12,t} \\
 & \text{s.t. } S_{i,m,t+1} = S_{i,t+1}^*, F_{i,m=0,t+1} = F_{i,m=12,t}
 \end{aligned} \tag{3}$$

In this specification, stock in patch i changes in response to two fundamental forces. The first is the level of returns (weight/gain loss) from maintaining the herd in patch i , captured in the first term. When the conditions are such that the animals are gaining weight in patch i then the

⁹ For expositional purposes, we will drop the subscript denoting the year ($t+1$) with the explicit recognition that the variables in this stage, unless otherwise stated, are all defined over three dimensions area (i), month(m), and years(t).

biomass level in i will increase from grazing in patch i , the rate at which this occurs is captured by λ_{ii} . The second fundamental force operating on each patch's biomass levels is depicted by the second term. This consists of the sum of pair wise spatial dispersal rates, each proportional to the return differentials across space between the patch in question and alternative patches at the rate λ_{ij} . Hence there will be stock movements from patch j to patch i if returns to grazing in i exceed those in j taking into account the loss from moving the stock (weight loss associated with moving the herd, $\delta_{ij} < 1$), and movements from j to i if the net difference is negative.¹⁰ At any point in time, patch i may be contributing to a subset of patches experiencing higher relative returns and drawing from a subset experiencing relatively lower returns. For the system of range patches, these spatial forces will tend redistribute the stock over space and time taking into account the seasonal patterns embedded in forage growth.

III. Numerical Analysis¹¹

We first calibrate the model to simulate how the variability and correlation of rainfall across the spatial gradient, ecological heterogeneity of the local environments, degree and rate of mobility, and stocking rates all contribute to the traditional patterns migration. To account for crop production in the southern regions, forage availability is restricted to 60-70% during the growing season. Forage (crop residues) continues to grow, but becomes available for animal

¹⁰ The transportation costs are assumed to be proportional to the returns in the patch and are analogous to "iceberg" transportation costs. For example, if 10 miles separate the two areas and there is an associated weight loss of .05 kilo per mile per head, then only if the current weight gain in patch i is less than (.05*10) the current weight gain in patch j would the stock be moved from patch i to patch j .

¹¹ Due to space limitations, we are not able to illustrate some of the simple but rich analytical solutions that can be derived from this model. For example, if we assume that there is only a seasonal component to rainfall (i.e. no random shock $\varepsilon_{i,m}=0$) then we derive the cyclical "equilibrium" to the stage II problem and substitute it back into the stage I solution to derive the harvest/stock/forage spatial and intertemporal "equilibrium" pattern. In addition, if we assume that there is only constant rainfall over the course of the year ($\sigma_{i,m}=\sigma_i$ with $\varepsilon_{i,m}=0$) we can derive the steady-state levels in each of the areas and again substitute these back into equation (2) to derive the steady-state harvest/stock/forage levels. Instead we choose to illustrate the predictive nature of the model with a parameterized simulation for the Sahel.

consumption only after the harvest.¹² Migration follows the expected pattern with movement to the north during the rainy season and southward migration during the dry season, as shown in Figure 1. The northward migration occurs because crop production reduces forage availability in the south and because the annual species in the north respond rapidly to rainfall, despite the fact that rainfall levels are lower. Because of transaction costs and the sluggish response in the model, migration continues throughout the rainy season. It tapers off and shifts to a net movement southward in December and January when the harvest is completed in the south, making all the forage produced there available for consumption. The higher forage decay rate in the north also provides a less favorable environment later in the season. Figure 2 displays the total changes in stock level that includes the typical weight gain/loss pattern observed in the Sahel and migration impacts. Thus stock levels grow rapidly in the north due to forage availability and entry into the region before declining, partly due to weight loss as forage becomes more scarce and partly due to movement back south.

One advantage of this approach is that the myopic behavior mimics well the sequential decision making of herders in response to climatic shocks and production risks. This is illustrated in Figure 1 (Net Movement from South to North, Drought in North beginning in August) where rainfall is cut in half. Up until the drought occurs in the North (we assume the drought begins in August) herders follow the same pattern as before. Once the impacts of the drought are prevalent, we find that the rate of migration into the north slows down. A large southward movement does not occur because the amount of pastureland (forage availability) is still constrained by the crop production. In addition, we find that stock levels do not increase as much as in the case of normal rainfall. If rainfall continues at lower levels in a second year with

¹² Again due to space limitations, we were unable to include the table of parameters in the text. The table is available upon request from the authors.

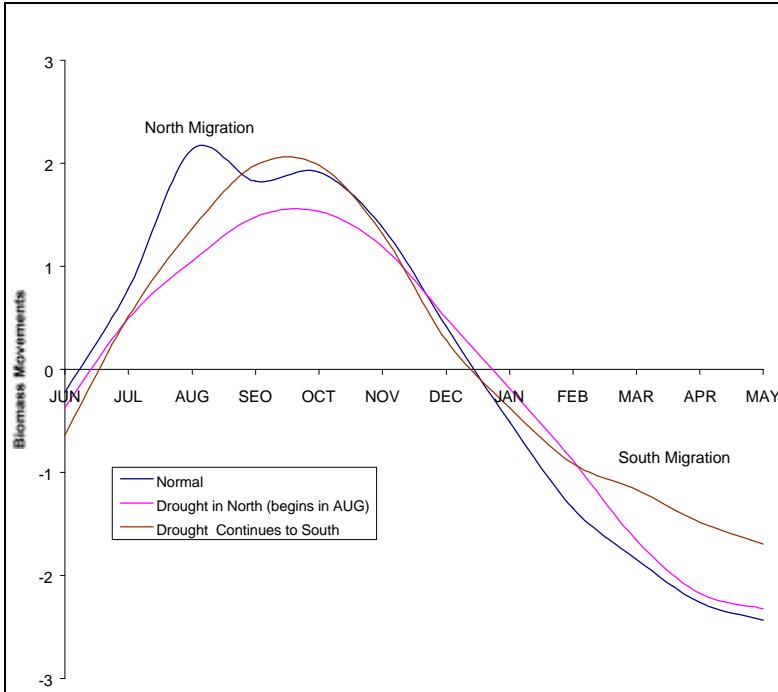


Figure 1: Migration Patterns: Net Movement between North and South

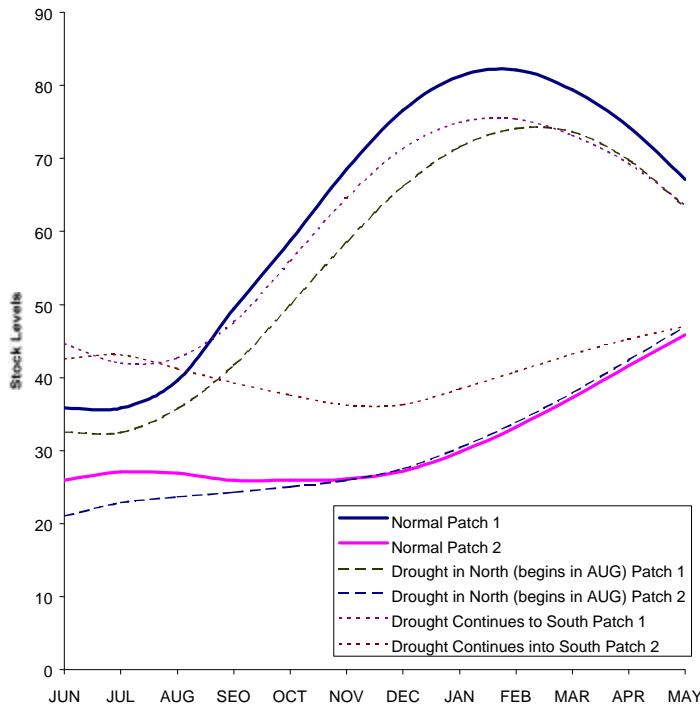


Figure 2: Spatial and Intertemporal Distribution of Stock Levels

the case without a constraint on land, everything else equal. Both of these results approximate a possible behavioral response of the herders' resulting from the their inability to mitigate the risks

the drought spreading to the south (Figure 1), the migration pattern returns to normal, since relative forage is similar to the normal pattern. Stock levels throughout the system however, decrease, as the amount of forage is now lower in both patches.

We can also look at the impact of agricultural encroachment on grazing land, for example, if grazing land is constrained simultaneously with a weather shock. In this case, we find that the movement of stock is lower and the southward migration is occurs later in the year than

stemming from extreme weather events due to the reduction in pastureland. Furthermore, stock levels drop in the rainy season and only recover after the harvest, which seems to indicate an increased reliance on crop residues for forage.

Conclusion

With the calibrated model for the semi-arid Sahel region, we simulate how the seasonal variability of rainfall across the spatial gradient, ecological heterogeneity of the local environments, degree and rate of mobility, and the grazing pressure all contribute in a predictable way to the traditional patterns of pastoral mobility in the region. The model is then used to simulate the effects of weather shocks and encroachment of agricultural land onto traditional grazing areas. As expected, we find that limiting stock movements to protect croplands decreases herders' ability to adapt to inter-annual rainfall variation.

While the simple representation of the Sahelian livestock systems in this paper provides a rich set of predictions, which were briefly illustrated here, the formulation is sufficiently flexible to address a variety of policy issues regarding spatial closures and spatially defined pastureland areas. Some questions we can address, for example, are; how does the presence of heterogeneity and rainfall variability affect the choice of which patches to select as pastoral zones? What are the economic and ecological factors that will most likely lead to improved livestock production systems after the introduction of pastoral zones? What is appropriate scale of these pastoral zones? What are the implications of policies that increase the costs of mobility, for example, from the introduction of a fee system?

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