THESIS

GRAZING MANAGEMENT IN INNER MONGOLIA, CHINA

Submitted by

Anne Teresa Byrne

Department of Agricultural and Resource Economics

In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Summer 2016

Master's Committee:

Advisor: Joleen Hadrich

Jordan Suter
Maria Fernandez-Gimenez

ABSTRACT

GRAZING MANAGEMENT IN INNER MONGOLIA, CHINA

This thesis takes the form of two essays, both addressing issues of grazing management in Inner Mongolia, China. Inner Mongolia is home to numerous sheep and goat producers. Sheep and goat production has increased substantially in the past two decades as demand for meat in China has risen. This increase in production has placed pressure on the grasslands, leading to degradation and increased incidences of Mongolian locust outbreaks.

The first essay addresses the question of economic vulnerability to grass loss. We use an equilibrium displacement model to model the livestock market in Inner Mongolia and simulate a market shock imposed by pasture grass loss. We find that herders are vulnerable to even small amounts of grass loss (~10%).

The second essay addresses long term management strategies over the typical herder's 30-year leasehold. We find that herders are better off changing their herd size from year to year in response to grass availability and that by using this strategy they can double their long-term profits.

TABLE OF CONTENTS

CHAPTER 1: INTRODUCTION

Inner Mongolian grasslands are vulnerable to a variety of threats that are amplified by the rise of anthropogenic land degradation. While all grassland management comes with ecological risk, herders in Inner Mongolia face the additional risk of locust damage from the Mongolian locust (*Oedaleus asiaticus*). The Mongolian locust and its cousin species can enter biological phases when they swarm, growing in numbers and consuming large quantities of biomass. They have been cited as economically damaging to livestock and crop producers (Brader 1988; Jiang et al. 2003; Cease et al. 2015). Recent study has linked their swarming behavior in livestock pasture to overgrazing (Cease et al. 2012).

This work falls within the broader context of the NSF-funded *Living with Locusts* project, which studies "how human decisions about livestock management practices affect rangeland health" (Cease et al. "Living with Locusts" n.d. web). The *Living with Locusts* project team includes researchers in biology, stoichiometry, ecology, geography, and economics who examine the relationship between livestock management and locusts in three regions: Inner Mongolia (China), New South Wales (Australia), and Senegal. This research focuses solely on Inner Mongolia, but much of the analysis provided could be applied to other regions where migratory locusts pose a threat to livestock producers.

This thesis is organized into two essays. Both address research questions relevant to sheep and goat producers in Inner Mongolia. Both address how political and economic policies specific to China shape optimal management practices. Data for both comes from various studies at Inner Mongolia Agricultural University, including an annual survey of livestock producer households. Ultimately the relationship between locusts and livestock can be examined through the lens of livestock and their feed. Locusts compete with livestock for pasture grass, so a locust swarm lowers the supply of this feed source. Both essays examine locust impacts as the loss of pasture grass.

Chapter two is the first thesis essay, which examines the financial impact on the typical Inner Mongolian herder of grass loss due to locust activity in a single year. This is done through the context of the typical Inner Mongolian herder's farm budget, utilizing an equilibrium displacement model to capture expected market changes from differing severities of grass loss. Results confirm that herders are reliant on having ample pasture grass to remain profitable. We find that they are vulnerable to locusts or any other grass supply shock and that expected profits are negative when more than 10% of pasture grass is lost.

Chapter three is the second thesis essay, which examines long-term strategies for herd management. Using a dynamic programming framework, this model identifies how the selection of herd size on a fixed parcel of land impacts expected profits over a 30-year lease term. This model is parameterized with a bioeconomic model for the state variable of interest: available pasture grass. The bioeconomic model captures the locust threat as a function of past grazing intensity. Results demonstrate that herd size decisions informed by pasture grass availability provide a major improvement over static herd sizes. They also confirm that herd sizes must be decreased in order to reverse degradation currently observed in the field. Optimal herd sizes and decision strategies are presented and discussed.

Results from both analyses suggest that much can be done to maintain profitability of livestock operations in Inner Mongolia and the threats of land degradation and locusts increase. However, we find that it would be necessary for herders in the region to change their current management practices. The actual implementation of these changes could prove difficult. Our next step is to examine how this work could be turned into action in Inner Mongolia.

CHAPTER 2: MODELING THE IMPACT OF A LOCUST EVENT ON INNER MONGOLIAN SHEEP AND GOAT OPERATIONS: FARM BUDGET ANALYSIS

The Locust Threat in Inner Mongolia

In Inner Mongolia, China 65% of the land is grassland, mostly used to produce livestock that feeds the world's largest nation (Xiao et al. 1995). The grasslands are vulnerable to a variety of threats, many of which are amplified by the rise of anthropogenic land degradation. Anthropogenic disturbances are estimated to impact 90% of the grasslands, leaving primary productivity in degraded areas at 50% that of areas where no degradation had occurred (Jiang et al. 2006). With the rise of degradation has come the threat of unpredictable but potentially devastating migratory locust. Locusts in a solitary state (referred to as "grasshoppers") are considered harmless to agricultural production, but under proper ecological conditions they form swarms which can devastate crops and pasture grass, leaving herders with less feed for their animals. In pasture already operating at half its potential primary productivity, herders do not have the grass to spare.

Prior to the 1970's there were few reports of locust damage on agricultural land in Inner Mongolia, but locusts have emerged in recent years as a dominant pest and major threat to the livelihoods of herders (Kang et al. 2007). Enlin (1999) estimated that 20 million ha of rangeland are lost on average to locusts. This translates into 1.6 billion kg of dry grass, enough to feed roughly 2.6 million sheep (as cited in Shi et al. 2007). Kang et al. (2007) suggests that the emergence of locusts as a key grassland pest is one of the three most significant findings in the study of Chinese grassland ecosystems. The rise of the Mongolian locust, *Oedaleus asiaticus*, is of particular concern because related species have caused economic devastation in other regions of the world (Cease et al. 2015). For example, there was little concern about the impacts of a cousin species, the Senegalese locust (*Oedaleus senegalensis*), prior to 1970, but that changed when a plague in the mid-1980's devastated 5 million hectares of agricultural land. Since then numerous swarms have occurred and the Senegalese locust is considered a major pest (Cease et al. 2015).

A study in Inner Mongolia from Cease et al. (2012) attributes the recent surge in locust swarms to overgrazing, which creates nutritional conditions in the grasslands that swarms favor. Thus increased land degradation from overgrazing in Inner Mongolia could incite more locust events. These results also show that there are ways for herders to mitigate swarms by reducing grazing pressures on their pasture, which supports a path to reducing overall degradation (Jiang et al. 2006).

Despite a long literature that documents locusts as an economically damaging pest, there is little written on preventative measures. For example, the book *New Strategies in Locust Control* (1997), Krall et al. report the costs of large outbreaks in various locations, focusing on the desert locust primarily found around the African Sahara. Lomer et al. (2001) review management of migratory locusts, like the Mongolian locust, specifically and note that although the costs of a single migratory locust outbreak may be modest, particularly when compared to a desert locust outbreak, their occurrence in places where most individuals rely on subsistence farming can be devastating to agricultural producers because migratory locust events tend to happen much more frequently than desert locust events. Lomer et al. (2001) also note that economic study of migratory locusts has focused on cost benefit analysis of pesticide treatment on entire systems, which neglect the distributional impacts of a locust event and do not examine counterfactual scenarios where no treatment is used. Thus the literature on the cost and benefits of various response strategies to locust outbreaks has been well covered, but have been virtually no studies that explore preventative measures. While this is largely because causal mechanisms are not well known, recent evidence such as the link between degradation and locust outbreaks (Cease et al. 2012) provides a new potential pathway for management.

In this paper we aim to explore how impacts from locusts might impact livestock production, and thus the economic conditions and decisions of Inner Mongolian herders. We examine these impacts through the context of the typical Inner Mongolian herder’s farm budget by first identifying the budget of a typical herder with and without locust impacts. The changes are determined through a simulation model, which we parameterize with field collected data. We incorporate changes in costs resulting from locust damage and vertical linkages along the livestock and meat marketing chain. After confirming that a locust event would have a sizeable impact on Inner Mongolian herders, we examine impacts on brokers and consumers of meat using an equilibrium displacement model (EDM) in order to identify institutional policies (e.g. taxes, subsidies, profit-sharing, etc.) that could address financial losses experienced by herders. Finally, we examine alternative herd management decisions that may allow herders to decrease the probability and/or impact of a locust event on their long-term profitability.

This paper contributes to the literature on livestock production management in at least three ways. First, our discussion of herder decision-making for locust management is the first to our knowledge to incorporate preventative strategies through reduced grazing. Second, we are the first to examine the economic impacts of migratory locusts on livestock production utilizing primary data. Third, we present a novel application of the EDM framework as a way to value the direct and indirect risks from a natural disaster to livestock producers who depend on pasture grass as their primary input. Additionally, this paper contributes to our understanding of locust impacts in Inner Mongolia, a region where they have not been studied heavily.

Locusts and Livestock Production: An Ecological Context

This study presents economic analysis with ecological constraints imposed by the grassland ecosystem of Inner Mongolia where livestock is produced.

Kang et al. (2007) provided an overview of current knowledge of China's grassland ecosystems at that time along with suggestions for research advancement. They noted that grasslands, particularly those dominating northern China, have traditionally been home to herders producing animals for a variety of animal products. Demand for these products has sharply increased in recent years, placing "tremendous pressures on grassland ecosystems." They also note that while ecological and biological monitoring in Chinese grasslands has been conducted for over 40 years, studies of community dynamics and human interactions have only shown up in the literature since 1996. Most of socio-economic studies were conducted in the past decade.

Additionally, Kang et al. (2007) noted the importance of grasshoppers (Mongolian locusts) in Inner Mongolia and their observed interactions with livestock grazing intensity. With increasing grazing intensity, locusts become more abundant. For this reason, they conclude that "effective grazing management can minimize outbreaks of grasshopper species."

Studies published since the overview provided by Kang et al. (2007) support this story of increased human activity, grassland degradation, and loss of grassland productivity in Inner Mongolia (Schönbach, et al. 2009; John et al. 2009; Han et al. 2009; Zhen et al. 2009; Milchalk et al. 2011; Schönbach, et al. 2011; Li and Huntsinger 2011; Briske et al. 2012; Kemp et al. 2013). Zhen et al. (2010) note that "even a slight intensification of grazing can remarkably reduce the grassland quality and sometimes even lead to the loss of productive grasslands." They also found that Inner Mongolian herders were supportive of government interventions that support grassland ecosystem management (e.g. grazing bans, grazing intensity restrictions, rotational grazing).

We model the feedbacks between grass, locusts and livestock and how these impact the economic system. We focus on small ruminants, sheep and goats, because they are the dominant livestock types in Inner Mongolia and thus have the best data available. A recent study on this feedback loop comes from Cease et al. (2012) who examined *Oedaleus asiaticus* (also referred to as the "Mongolian locust") in lab experiments. They altered plant nitrogen levels to simulate local empirical conditions in ungrazed, moderately grazed, heavily grazed, and overgrazed pasture, then compared their results to observations from actual Inner Mongolian pastureland. They found that locusts were most dense, and thus prefer, the nutritional conditions in heavily grazed pasture. Locust density was much lower in ungrazed and moderately grazed land. Moreover, higher locust density translates into greater consumption of grass per unit area, implying a negative feedback loop where overgrazing leads to greater locusts which leads to greater grass biomass consumption. While other negative consequences of overgrazing, such as soil depletion and erosion, have long been established, the results from Cease et al. (2012) provide additional incentive for herders to avoid overgrazing.

Locusts' consumption of grass is in competition with livestock, and thus directly impacts the herders who produce that livestock. A locusts 'shock' reduces the overall supply of grass on the pasture. This input grass supply shift potentially impacts everyone along the livestock and meat marketing chain. While the economic impacts of migratory locusts have received little consideration in the literature, their more notorious relatives, desert locusts, have garnered much attention for the past two decades. The UN Food and Agriculture Organization have dedicated an entire commission to the desert locust, which monitors their activity and measures their economic impact around the world. This commission has supported and cited several studies on the economic impact of desert locust. Belhaj (1998, 2001) estimated production functions for farmers in North Africa with adjustments for years of locust damage including the cost of chemical treatment, finding that their major loss came from crop loss (38% income loss) and any damage done to their livestock operation was relatively small by comparison (5%). He noted that much of that discrepancy comes from the fact that the farmers studied mostly produced crops. Joffe (1995, 1997) retrospectively use datasets from countries that had measured damages from the desert locust to perform cost-benefit and risk analysis of different treatment options, again focusing on crops.

Locust outbreaks can have compounding impacts beyond short-run economic and agricultural losses, particularly on those who rely on subsistence agriculture as their source of income. Baro and Deubel (2006) note that in Nigeria, a poor cereal harvest in 2004 was exacerbated by a locust outbreak, pushing that nation deeper into food crisis than they otherwise would have experienced. De Vreyer et al. (2015) found adverse educational outcomes for children born in Mali during a locust outbreak. For herders and farmers in Inner Mongolia, locust outbreaks of a similar magnitude could have similar social impacts.

Within this context, we seek to understand the impact of locust shocks on a primarily livestock-producing region at multiple levels of the market. Households in most of Inner Mongolia rarely produce crops, so damages to this sector are not as relevant here. Moreover, damages from the migratory locust are not well studied. Moreover, damages from *Oedaleus* locusts are not well studied. This is likely due to their lower spatial level of damages produced, even though their presence is more consistent and may contribute to even greater total economic losses compared to the desert locust and migratory locust. (Kang et al. 2007; Maiga et al. 2008). We use a simulation approach, informed by in-field ecological study results from Cease et al. (2012) and household field data from Inner Mongolian Agricultural University to estimate changes in quantities, prices and surplus values resulting from locust activity. The results from our analysis allow us to make management and policy recommendations considering economic implication of locust outbreaks across the livestock and meat marketing chain.

The Typical Inner Mongolian Herder

We describe the typical Inner Mongolian herder through a whole farm budget, as shown in Table 2.1. A – F. The budget data comes from Inner Mongolian Agricultural University, specifically from cross-sectional household pasture surveys taken in 2012, 2013, and 2014. This data is supplemented with data from a controlled stocking rate experiment used to measure pasture biomass (grass). Livestock quantity values are reported in “Livestock Units” (LU), defined as a weighted average of sheep and goats in the typical herd.

We separate accounting and economic values to address the opportunity costs of pasture land and the typical herder’s own labor. Opportunity costs were not directly asked in the survey. We estimate labor opportunity costs as the cost of hired labor as reported in the survey. Land opportunity costs were taken from previous study (Li and Huntsinger 2011).

Table 2.1.A shows the size and composition of the typical herd. Sheep comprise the majority (81%) of the typical herd for the median herder. Herders reported that sheep are more profitable, but that goats have a more assertive temperament that allows them to lead the sheep, so a mixed herd with a smaller number of goats is ideal. While the typical herd is 560 head, here we define a single LU as 81% sheep and 19% goat.

Table 2.1.B calculates gross income from the four sources reported in the survey: the sale of sheep, goats, wool and cashmere. Wool and cashmere are secondary products which account for less than 5% of total gross income. Selling prices are taken as the mean price per kilogram reported in household pasture surveys, and we use median quantities sold due to the skewed size of operations. In the years surveyed, the typical herder will sell about 44% of his herd annually, earning 183,905.92 ¥ (~$27,960 USD).

Table 2.1.C shows variable costs for the typical herder. Pasture grass is listed as an economic cost, but not an accounting cost, since pasture grass is grown on land provided at no cost to the herder from the Chinese government. Herders may be able to rent their pasture to neighboring or nomadic herders. Although land markets are thin, at the margin this still represents an opportunity cost when they decide to use the land themselves. The pasture grass cost estimates are derived in three steps: (I) estimating the typical pasture size, (II) estimating grass production per unit area in heavily grazed pasture, and (III) deriving grass prices from rental rates reported in previous literature.

We estimate a typical pasture using explanatory variables because the average values, as well as the number of observations, in the dataset change for each year (2012 – 2014). Pasture area should not change because herders are on 30-year leases, so rather than using the average from our observations directly, we estimate typical pasture size as a function of herd size (Q_L), assuming a linear relationship and using an OLS model. We control for age (Age), education (Ed), livestock price (P_L) and fixed costs (FC), and estimate the following model[1]:

$$Pa = -655.6523 + 1.7203 \cdot Q_L + 1.5038 \cdot Age + 92.611 \cdot Ed + 0.1912 \cdot P_L + 0.0221 \cdot FC$$

[1] Herd size is the number of animals on pasture at time of survey, age is the age of the primary manager (herder), education is a dummy variable where 1 indicates the highest level of education achieved by the primary manager is junior high level or above, livestock prices and fixed costs are taken directly from the survey.

The coefficient on Q_L is significant at the 1% level, while all other coefficients are not significant. Based on these estimates, we expect the typical herder (calculated using median values for exogenous variables) to have 493.203 ha of active pasture.

Second, to estimate grass production per unit area, we use data collected by IMAU in their annual controlled stocking rate experiment. In this experiment, they have four plots of land that they have continuously stocked at varying levels. They find that heavily grazed pasture[2] produces an average of 630 kg of feed per ha. At this rate, we multiply the amount of grass per hectare by the area of pasture for the typical herder:

$$630.2576\frac{kg}{ha}\cdot 493.203\ ha = 310{,}844.94\ kg$$

We expect the typical herder to have 310,844.94 kg of available pasture grass each year.

Third, we derive grass prices from rental rates reported in previous literature. While rental rates are difficult to come by and no comprehensive reporting has been done to our knowledge, Li and Huntsinger (2011) estimated that pasture in Inner Mongolia can be rented for 9 ¥ (~$1.37 USD) per head per month, which comes to 96 ¥ (~$14.60 USD) per head per year. We apply these rental rates to the amount of pasture grass identified in (II) and the typical herd size (560 head) to determine that herders sell their pasture grass for 0.18 ¥/kg.

Table 2.1.C also includes fertilizer, corn, hay and salt costs, as reported in the household pasture surveys. For these values, we use mean reported prices and median reported quantities. Additional variable costs include veterinary and health expenses, fuel and labor, also calculated using mean reported prices and median reported quantities. Surveyed herders did not report costs associated with electricity or water, so those have been omitted from the budget. They also did not include their own labor as a cost, so it is included here as an economic cost with the

[2] "Heavily grazed," as defined by IMAU ecologists in charge of the stocking rate experiment

opportunity cost of wages set at the same rate as what herders reported paying hired labor. Table 2.1.C demonstrates that herders are able to cover feed costs with their income from both an accounting and an economic profit estimate; however, they are only able to cover variable costs from an accounting estimate.

Table 2.1.D shows fixed costs. Most herders surveyed reported zero machinery or equipment costs for a single year, and we found no previous studies in which such values were reported for herders in Inner Mongolia, so we estimate these costs from those who did make these purchases and provided in those costs the survey. We assume machinery has a useful lifetime of ten years, over which it depreciates to a resale value of zero. Fencing and miscellaneous costs are estimated using mean price values and median quantity values. The survey data does not specify what is included in "miscellaneous," but these likely include electricity and water since these items are used on most farms we observed in the field but not reported elsewhere in the survey.

Table 2.1.E shows profit in terms of income over costs. We see that from an accounting stance, herders are generating positive profit. From an economic stance, they are generating a negative profit and are unable to cover variable costs.

Table 2.1.F shows breakeven prices for variable and total costs. As noted, herders in our survey sell approximately 44% of their herd each year. The breakeven prices are the prices for which that 44% would have to be sold in order for the typical herder to cover variable or total costs for the entire operation. All breakeven prices reported here are within the range of prices reported in the survey, although the economic breakeven prices are above the average. Since they are within this range, we have evidence that herders are currently operating in circumstances where they can feasibly generate positive profit.

The whole farm budget is used as a reference point for the changes we observe from the EDM simulation results. Percent changes in market prices and quantities from the EDM are used with the baseline farm budget presented in Tables 2.1. A – 1.F to identify expected farm budgets expected after a locust event.

Modeling the Inner Mongolian Livestock and Meat Market

We use an equilibrium displacement model (EDM) to estimate how varying types of locust damage would impact the typical Inner Mongolian herder and the Inner Mongolian livestock and meat producers and consumers. The model estimates changes in feed, livestock, and meat prices, quantities exchanged, and producer and consumer surplus under varying levels of locust damage in the region.

An EDM is a comparative static model used to evaluate changes in market prices and quantities as a result of a single supply or demand shift. Parameterized with biological and market values collected from primary or secondary data, the EDM provides quantitative estimates of comparative static results, which can be used to evaluate current and future policy or better understand a market (Wohlgenant 2011). The EDM approach developed by Muth in 1964 was the first to demonstrate a multi-factor approach, connecting a single product with two inputs across two marketing levels. This basic framework is what we use, reworked to have a single input and a single product connected across three marketing levels.

Since Muth, the EDM model has been applied to numerous settings. Perrin (1980) examined the impact of the shift from traditional to component pricing on soybeans and milk, finding that producers would be minimally impacted by new pricing schemes. Mullen et al. (1988) estimated the distribution of surplus gains from changes in beef processing, finding that cattle producers would receive at least 57% and perhaps up to 72% of surplus gains from these changes in processing. Mullen et al. (1989) determined the impact of research and development on returns to the Australian wool industry, finding that research completed off-farm had a greater relative impact on financial returns to producers than technological improvements made on-farm. Brester et al. (2004) estimated the impact of country-of-origin labeling on cattle and pork producers, finding that a 4.05% increase in beef demand (4.45% for pork) would offset any losses in producer surplus over a 10-year period. Pendell et al. (2011) used an EDM to examine the impacts of adjustments in international market access and animal identification within the red meat market, finding that a "modest increase" in domestic beef demand would offset the costs of animal identification systems. We follow the structure of these models in our identification of our model and our estimations of changes in surplus.

While much of the EDM literature has focused on equilibria shifts resulting from changes in the producer or consumer decision set, there have been studies that have examined the impact of exogenous shocks to markets from environmental changes. Hoddle, Jetter and Morse (2003) employed an EDM to determine the changes in market prices and producer surplus in the California avocado market as a result of damage from thrips, a winged insect and exotic pest in the region. They generated supply and demand equations, parameterized with market and biological data, and calculated the change in surplus between avocado farms impacted by thrips and those not impacted by the pest. They found that producers were unable to adjust to the impacts of the pests in the short-run, but could reallocate resources in the long-run to mitigate thrips infestations and losses in surplus. Following Hoddle, Jetter and Morse (2003), we employ an EDM to estimate changes in Inner Mongolian livestock equilibrium prices and quantities resulting from a locust swarm.

Structural Model

A general structural model of supply and demand relationships in the sheep and goat industries lays the foundation for developing an equilibrium displacement model. The livestock and meat industry is modeled as a series of primary and derived supply and demand relationships along the marketing chain from input to livestock to meat. [3] These relationships are shown in bold in Figure 2.1 with variable definitions provided in Table 2.2. The structural model is used to determine aggregate changes to supply and demand within the livestock marketing chain.

The livestock marketing chain includes three sectors: input, livestock and meat. To begin our definition of the structural model, we start at the input level. IMAU household pasture survey data shows that supplemental feed is generally purchased from neighbors or other herders from within the province and not from sources outside of Inner Mongolia. We define primary supply of feed as the sum of pasture grass, Q_G, and supplemental forage, Q_{SF}, which is a function of its own price, P_{SF}. The kinked line in Figure 2.1 graphically represents this for total feed supply (1). The horizontal portion represents grass on pasture, priced at zero to reflect accounting costs.[4] The kink is at the quantity at which there is no more pasture grass available and supplemental feed must be purchased. Algebraically, this supply function is:

$$Q_F = Q_G + f_1(P_{SF}) \qquad (1)$$

where $Q_{SF} = f_1(P_{SF})$ and the underlying form of f_1 is unknown.

Feed demand is derived from herders who must feed their livestock. Following Wohlgenant (2011), we use Shephard's lemma to define an input demand function that requires the price of an input to equal marginal cost in the long run. The quantity of feed, Q_F, is a

[3] Primary supply (demand) is the original supply (demand), which exists regardless of the supply chain construction. Derived supply (demand) is the supply (demand) of intermediary goods, which exist solely to connect primary supply to primary demand.

[4] If we wanted to reflect economic costs and include the opportunity cost of pasture grass, the input supply line would shift up by the value of the grass.

function of input price, which in this case is the price of supplemental feed, Q_{SF}, and the quantity of Inner Mongolian livestock at the farm-level equilibrium, Q_L^I. Graphically, this is represented by curve (2) in Figure 2.1 and defined by:

$$Q_F = f_2(P_{SF}, Q_L^I) \qquad (2)$$

where the underlying form of f_2 is unknown.

At the farm level, the product is livestock, an intermediate good between feed and meat for consumption. The farm level supply and demand represent all sheep and goats produced in China. Following Hoddle, Jetter and Morse (2003) farm level supply of livestock is generated such that a portion of livestock comes from Inner Mongolia, where prices and quantities are shifted by locust activity, and the rest comes from elsewhere in China where locusts have not had an impact. The total livestock in China, Q_L, is the sum of livestock from Inner Mongolia, Q_L^I, and livestock from the rest of China, Q_L^X. The proportion of livestock in Inner Mongolia, α, and the proportion of livestock from the rest of China, $(1 - \alpha)$, sum to one. The supply of Inner Mongolian livestock is a function of the price of feed, Q_{SF}, and the price of livestock, Q_L. Graphically, this is curve (3) in Figure 2.1 and represented as:

$$Q_L = \alpha Q_L^I + (1 - \alpha) Q_L^X \qquad (3)$$

where $Q_L^I = f_3(P_{SF}, P_L)$ and the form of f_3 is unknown.

The derived demand for livestock is determined in the same manner as the derived demand for feed. The quantity of livestock, Q_L, is a function of the price of livestock, P_L, and the quantity of meat, Q_M. Graphically, this is curve (4) in Figure 2.1. Algebraically defined as:

$$Q_L = f_4(P_L, Q_M) \qquad (4)$$

where the underlying form of f_4 is unknown.

At the retail level, the product is defined to be all meat produced and consumed in China. We neglect imports and exports because China's imports and exports of mutton (sheep and goat meat) are small (Zhou et al. 2014). The derived supply of meat is captured as the change in the output (meat) price, P_M, as a result of a change in the price of the input (livestock), P_L. Graphically, the quantities, Q_M, for which this relationship holds plotted against the price of meat is shown as curve (5) in Figure 2.1. Algebraically, this relationship is defined:

$$P_M = f_5(P_L) \qquad (5)$$

where the underlying form of f_5 is unknown.

The primary demand for meat is shown as curve (6) in Figure 2.1. The quantity demanded, Q_M, is a function of the price of meat, P_M, such that:

$$Q_M = f_6(P_M) \qquad (6)$$

where the underlying form of f_6 is unknown.

The vertical relationships are captured by the fact that the equilibrium quantities are proportional to one another and shift in primary supply moves prices and quantities at all three levels (Figure 2.1).

Equilibrium Displacement Model

The EDM is set up as a series of linear-in-logs differential equations parameterized with elasticities which estimate the underlying supply and demand functions from the structural model. To obtain the linear-in-logs differential equations, we begin with the structural equation and apply operator *E*, such that $EX = \frac{\Delta X}{X} = \frac{dX}{X} = d\ln X$. The linear-in-log functions are weighted by elasticities of supply, ε_i, where *i* denotes the product (feed, livestock or meat), and the own-price elasticities of demand, η_i, as appropriate.[5] The linear-in-log differential equations are shown in Table 2.3 alongside the corresponding structural equations. We assume constant elasticity of transformation between feed and livestock and between livestock and meat.

The linear-in-log specifications from equations (1) – (6) are put into matrix notation (eq. 7) as follows:

$$\mathbf{AY} = \mathbf{X} \qquad (7)$$

where,

$$\begin{array}{c} \text{Eq.} \\ (1) \\ (2) \\ (3) \\ (4) \\ (5) \\ (6) \end{array} \quad \overset{\mathbf{A}}{\begin{bmatrix} 1 & -\varepsilon_{SF} & 0 & 0 & 0 & 0 \\ 1 & \eta_S & -1 & 0 & 0 & 0 \\ 0 & \alpha & 1 & -\alpha\varepsilon_L & 0 & 0 \\ 0 & 0 & 1 & \eta_L & -1 & 0 \\ 0 & 0 & 0 & 1 & 0 & -1 \\ 0 & 0 & 0 & 0 & 1 & \eta_M \end{bmatrix}} \overset{\mathbf{Y}}{\begin{bmatrix} EQ_F \\ EP_{SF} \\ EQ_L \\ EP_L \\ EQ_M \\ EP_M \end{bmatrix}} = \overset{\mathbf{X}}{\begin{bmatrix} EQ_G \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}}$$

Changes in the endogenous variables (**Y**) resulting from changes in the exogenous variable (**X**) are calculated by inverting matrix **A** and solving equation (7) for **Y**:

$$\mathbf{Y} = \mathbf{A}^{-1}\mathbf{X} \qquad (8)$$

The values calculated for **Y** are used to calculate the new market prices and quantities for feed, livestock, and meat. These values are then used to populate new farm budgets, which can be compared to the typical herder farm budget presented in Table 2.1 A- F. They are also used to estimate changes in surplus, which we use to determine the relative impact of a locust event on participants in the marketing chain. These relative impacts inform our policy recommendations and allow us to determine which policies are most feasible.

[5] Reported values for ε_i and η_i are absolute values. Because we assume feed, livestock and meat are normal goods they all have negative own-price elasticities of demand and positive own-price elasticities of supply.

Calculating Changes in Surplus

Changes in consumer and producer surplus created by a locust shock can be estimated from changes in prices and quantities by assuming linearity of all supply and demand functions. At the input level, because of the nature of the feed supply the entire surplus is consumer surplus. For any quantity along the supply curve, the producer is receiving payment equal to the value he is willing to accept, so he enjoys no surplus. The consumer is always paying the lowest value the producer is willing to accept, so the difference between that value and his demand curve represents the surplus he enjoys. At the farm and retail levels, both producer and consumer surplus have positive values. The changes are calculated with equations (9) consumer surplus at the input level, (10) consumer surplus at the farm and retail levels, and (11) producer surplus at the farm and retail levels. Equations (9) – (11) refer to price and quantity values identified in Figures 2.2 and 2.3. Figure 2.2 shows changes at the input level and Figure 2.3 shows changes at the farm and retail levels (these calculations are done in the same manner). We use the generic Q^1, Q^2, P^1, and P^2 to identify to the quantities and prices before and after the locust shock at the specified market level. We use Q_0^1, Q_0^2, P_0^1, and P_0^2 to identify the intercepts before and after the locust shock at the specified market level.

$$\Delta CS_I = 0.5(Q^2 - Q_0^2)P^2 + 0.5(P^2 - P^1)(Q^1 - Q^2) + 0.5(Q^1 - Q^2 + Q_0^1 - Q^2)P^1 \quad (9)$$

$$\Delta CS_{F,R} = 0.5(Q^2 + Q^1)(P^2 - P^1) \quad (10)$$

$$\Delta PS_{F,R} = 0.5(P^1 - P_0^1)Q^1 - 0.5(P^2 - P_0^2)Q^2 \quad (11)$$

In our analysis, we refer to “herder,” “broker,” and “retail consumer” surplus, because these are the participants in the marketing chain. The farmer surplus is the sum of input level consumer surplus, where herders are consuming feed as an input, and farm level producer surplus, where herders are producing livestock. Similarly, broker surplus is the sum of consumer surplus at the farm level and producer surplus at the retail level. Lastly, retail consumer surplus is the consumer surplus at the retail level.

Elasticities

The elasticity estimates used in this analysis are collected from previous literature and are reported in Table 2.4. It should be noted that values were not available for some regions or products. We use similar products in China or the same products in regions other than China, as indicated in the notes for Table 2.4.

The elasticities of supply differ because of the nature of the products. Feed production can be increased or decreased relatively quickly because it simply requires a change in water and fertilizer, both of which can be obtained faster than a new animal can be bred. Livestock production is less elastic because livestock require more planning to produce. In order to increase production in response to a price increase, herders must either breed or purchase additional animals. Breeding takes several months and purchasing animals reduces any expected profit gain because they are facing higher purchase prices. If herders respond to lower selling prices, they may keep animals off the market, but doing so will require additional feed and health costs, which may hurt their profit more than selling them at a lower cost.

The demand elasticities are less elastic for herders and brokers because their demand is for their own production. While there may be substitutes, such as alternative feed sources or alternative types of livestock, their business depends on these inputs. Alternatively, we see a more elastic demand for meat from consumers because they can easily find other meat substitutes.

As suggested in previous literature, we use Monte Carlo simulations where elasticities are drawn from selected distributions in order to ensure that our results are not predicated on point estimates (Davis and Espinoza 1998; Brester, Marsh, and Atwood 2004; Rickard and Sumner

2008; Pendell et al. 2010). For all elasticities, estimates are drawn from a triangular distribution with a low at the minimum reported value, a high at the maximum reported value, and a peak at the median reported value (Table 2.4). These are incorporated into our simulation design, discussed in the next section.

Simulating a Locust Event

The EDM is designed such that any pasture loss will result in an increase in variable costs, offset by an increase in livestock prices. Our dataset does not include any years with reported locust damage. Without the presence of locusts, herders are able to cover both their variable and fixed costs. As more pasture is lost to locusts, costs rise. Herders are able to raise livestock selling prices slightly, but overall profit decreases. While locust damage remains somewhat unpredictable, we identify three scenarios for which a locust event will have a different economic impact.

The bounds of pasture loss for each scenario are identified from the feed costs, variable costs, total costs, and revenue estimated from a single iteration of the EDM using median elasticity values. We use triangle distributions for each pasture loss range, with lower and upper bounds covering a ra20nge that falls in the region as described with peaks in the middle of these ranges. These curves and the boundaries of the scenarios are shown in Figure 2.4. The scenarios are described as follows:

Scenario (A) assumes a minor locust event occurs. The loss of pasture to each herder is triangularly distributed between 0 and 4%, with a peak at 2%. Over this range, herders should continue to earn a positive accounting profit, but their profit margin will shrink.

Scenario (B) assumes herders maintain enough pasture to cover all variable costs, but not fixed costs. In the short-run, herders in such a scenario would not want to exit the market, but would face negative accounting profit. The loss of pasture for the moderate damage scenario is triangularly distributed between 8 and 12% with a peak at 10%.

Scenario (C) assumes herders are only able to cover variable feed costs, but are unable to cover remaining variable costs. In such a scenario, herders are financially better off culling their herd than continuing to pay for all the variable costs associated with their herd size. We would expect them to want to exit the market, culling all livestock, in such a scenario. Pasture loss in this scenario is distributed triangularly with a low and a peak at 12% and a high at 17% loss.

Each scenario is simulated for 500 iterations, using the Monte Carlo-generated elasticities according to the aforementioned distributions, with Monte Carlo random draws for pasture loss based on chosen distribution listed in scenarios (A) – (C). For each simulation, the EDM is populated with elasticities and pasture loss and eq. (8) is solved for **Y**. These values of **Y** are used to calculate resulting prices, quantities and changes in surplus values due to a locust shock. After 500 iterations are complete, simulated results are analyzed to determine the expected changes and the robustness of results against changes in elasticity estimates for the specified range. Our model examines a one-year period and assumes herders maintain the same proportions of sheep and goats irrespective of herd size.

Simulation Scenario Results

Mean simulated percent changes in feed quantities (EQ_G, EQ_{SF}, EQ_F), livestock quantity (EQ_L), supplemental feed price (EP_{SF}), and livestock price (EP_L) are reported in Table 2.6. Results demonstrate low percentages of pasture loss yield high percent increases in the amount of supplemental feed purchased. Matching our anecdotal evidence, herders are reliant on ample pasture grass to remain profitable and are vulnerable to locusts or any other shock that lowers their pasture grass supply. Thus our model suggests that a locust event, even one where less than 10% of pasture grass is lost, would have a significant impact on the typical Inner Mongolian herder.

Impacts on Farm Budgets

The estimated changes to the typical herder's farm budget given the pasture loss as described for scenarios (A), (B), and (C) are presented in Table 2.7 (full farm budgets can be found in the appendix). In general we find that as more pasture is lost, herders face greater feed costs and decreased profits. For the 500-simulation run, the mean pasture loss in scenario (A) is 1.98%, with a standard deviation of 0.81% (Table 2.6). Scenario (A) shows herders' feed prices that have increased by 1.62%, raising their accounting feed costs per head from 162.74 ¥ (~$24.75 USD) to 196.33 ¥ (~$29.85 USD). While they are able to pass some of this cost along the marketing chain in the form of higher livestock prices (up 0.523%), they must still decrease the size of their herd and accept a lower overall profit. Herders' increase in livestock income does not offset their increase in feed costs. We notice that their breakeven price is still lower than expected prices for livestock and they still receive a positive profit, though they experience a 56% decrease in profits.

Scenario (B) results in a mean pasture loss of 10.08% with a standard deviation of 0.81%. In this case, herders yield a positive accounting value for income over variable costs, but a negative overall profit for the same reasons they experiences losses in scenario (A). They are able to raise prices slightly due to the fact that demand is not completely elastic, but they still face high feed costs. Because they have lost pasture grass, which has an accounting cost of zero, their options are to accept the additional costs for feed or to cull their herd. In a single-period, as we have here, culling may be a reasonable option. However, in reality herders are not operating in a single period. Unless they are operating in their final year, they are better off accepting the additional feed costs and lower profit because of the loss of future production potential that comes with culling a herd.

Lastly, we examine the estimated changes in scenario (C) as presented in the Table 2.7. In this case, the average pasture grass loss is 13.71%, with a standard deviation of 1.17%. Even at what may seem like a low percentage loss, herders face negative income over variable costs, with an overall profit loss of 156.7%.

Overall, herders are negatively impacted by any size locust shock. It seems they are likely able to absorb small events, but they are increasingly vulnerable to increasingly larger shocks.

Changes in Surplus

For each simulation, we estimated changes in herder, broker, and consumer surplus. Examining surplus values, we find that the typical consumer loses between 0.65 ¥ in scenario (A) and 4.52 ¥ in scenario (C) (~$0.10 - $0.69 USD) in consumer surplus per year from the changes introduced by locust activity. While herders may experience profit losses of 38% or more, the typical consumer will barely notice a change. For this reason, we cannot expect a consumer response that would adequately address the losses experienced by herders and must consider institutional policies that would allow consumers to take some of the burden off livestock producers.

Individual retail consumer surplus changes are small, but China is a market of over 1.3 billion consumers. Figure 2.5 shows aggregate herder surplus loss and aggregate retail consumer surplus loss for each of the three scenarios. For all three scenarios aggregate retail consumer surplus loss is roughly twice what aggregate herders lose in surplus, however per capita retail consumer surplus loss is far less than per capita herder surplus loss. We consider this in our policy suggestions.

Robustness of Results

We can evaluate the robustness of our results against changes in assumed elasticity values by analyzing the simulation elasticity values and corresponding results. The Monte Carlo simulation randomly draws elasticity estimates from our given distributions. This ensures that our results are robust against reasonable changes in any of the elasticities used to parameterize the model. We examined the full range of values for new market prices and quantities. We examined the correlation coefficients of each measure of surplus change with each elasticity to find most were uncorrelated. This indicates that the surplus changes we observe are not sensitive to slight changes in any elasticity value. The one exception is the correlation between the elasticity of demand for meat and retail consumer surplus. The elasticity of demand for meat represents how much consumers will change their consumption of meat given changes in prices of meat. In the EDM, it is also one of the determining factors of how much a shock at the input level can be passed down the marketing chain to consumers. We expect this correlation to be present because if meat demand is completely elastic, then consumers will experience no surplus loss from a price change; the more inelastic their demand the more consumers will suffer surplus loss from an increase in price. The range of values we use for elasticity of demand for meat is broad enough to capture a range of retail consumer surplus changes. Ultimately, all of these changes are small for the individual retail consumer, so our analysis of how their surplus loss impacts policy decisions does not change; we conclude that they would not suffer a major loss from a locust shock.

Policy Recommendations

It is clear from our analysis that herders impacted by locusts will suffer economic losses due to increased feed costs and elastic demand for their livestock. Elastic meat, and therefore livestock, demand reflects the negligible loss to individual consumers resulting from a locust event. For locust events on the scale described in scenario (A) (<5% pasture loss), herders earn a positive profit that is lower than they would earn without the presence of locusts. In the short and long run, they will continue producing given these circumstances, so there is no market failure and no policy needed.

Scenario (B) demonstrates locust events where 8 – 12% of pasture is lost and herders are unable to cover fixed costs. In the short run, they will continue to produce, accepting negative profit. If these conditions continue in the long run, producers will want to exit the market. However, herders in Inner Mongolia face unique constratins, namely constraints on exiting the market due to (usually) 30-year land leases which cannot be sold or transferred, and restrictions on relocating the household due to the household's registration status, or *hukou* . Herders are registered as agricultural workers in the village in which they live, making it difficult for them to simply pack up as a household and move locations for individuals in the household to wholesale change careers. The ecological conditions resulting from a locust event may induce a market failure due to these restrictions whereas herders that want to exit the market may be unable to sell their labor elsewhere.

Scenario (C) establishes conditions where herders would desire to exit the market in both the short and long runs because they are unable to cover variable costs. As in scenario (B), they face regulations preventing them from doing so and resulting in a market failure.

Scenarios (B) and (C) require intervention from herders, government entities, or consumers in order to correct market failures. We provide a selection of possible interventions and discuss their benefits and limitations in the following section.

Meat Tax and Farm Subsidy

One potential solution is charging a tax on meat products at the time of purchase and placing the money collected in a fund to be distributed to herders if and when a locust event occurs. This policy can be justified by comparing the relative aggregate surplus losses of retail consumers and herders. In all three scenarios, herders lose less than retail consumers on the aggregate. A tax and subsidy scheme could be devised whereby retail consumers pay less than their own surplus loss and more than herders' surplus loss in taxes. Such a tax would be a Pareto improvement from doing nothing and allowing both parties to experience the surplus loss. The benefits of a tax and subsidy combination are that it doesn't require oversight, can be easily implemented and provides a Pareto improvement over doing nothing.

There are limitations to using a meat tax and farm subsidy. It would be difficult to determine the level of tax required *ex ante* because it depends on a locust event which has not yet occurred. The Chinese government could determine and apply the tax *ex post*, but that would require them to provide the funds before collecting them from consumers which may not be a politically desirable solution. Additionally, current Chinese national agricultural regulations do not include direct payments to livestock producers. When support is needed by livestock producers, it comes from local and regional governments (Gale 2013). There is no precedent set for this type of support where the national system is supporting a local system and it would be difficult to set that precedent. These political constraints make a tax and subsidy combination unlikely to succeed.

Land Rental Market

In all scenarios, profit is lost so herders so they may want to seek actions that will recover some or all of their profits. There is an informal rental market in Inner Mongolia where lease-holding herders can rent land to their neighbors or nomadic herders (referred to as “otor”). Typically, this is not a reliable source of income because neighboring herders already have their own pasture leaseholds and nomadic herders are not always present. When demand is present, we expect degraded pasture or that has little grass to be in low demand from other herders. And finally, if herders still rent pasture when grass levels are low, they make themselves vulnerable to long-term damage and degradation on their leasehold. While renting may be a short-term solution for recouping costs, it is not ideal in the long term.

Changes in Lease Agreements

In scenarios (B) and (C), herders may want to exit the market but cannot due to their lease agreements. A simple solution to correct this market failure may be to simply change the lease agreements. One possibility is to shorten lease terms, so that a herder would not be stuck in an unprofitable enterprise. Herders could exit the market and take their labor elsewhere. This would not correct surplus loss in the short run, but herders could avoid additional surplus loss in the long run and earn income as laborers in another sector.

A potential negative outcome of shorter lease terms is that it may disincentivize herders from maintaining grassland health and avoiding degradation. If herders know that they will discontinue use of a parcel of land, they may overuse it in order to gain the largest possible production benefits in their final period of use. Shortening leases may also remove a sense of stability for herders who want to the security that comes with holding long-term tenure rights.

They may want to stay on the land, but would worry that the government will remove them after the end of their lease term.

Shortening lease terms may correct a market failure that arises when herders are unable to produce on their leased land, but it may also introduce more problems in the form of land degradation and tenure insecurity. In short, this should be a Pareto improvement, but it is not compatible with China’s current political philosophy.

Chemical Locust Treatment

Ideally, a locust event could be prevented or stopped during early stages. The policies we’ve discussed so far are economic interventions. To mitigate a locust outbreak, biological interventions are necessary. Locusts have frequently been treated using chemical pesticides. Chemical treatment has been an effective strategy for managing migratory locusts in Australia (Hunter et al. 1999). However, concerns have been raised about the environmental and ecological impacts of chemical pesticides, so there has been an increased interest in alternative management (Shi et al. 2007).

Biological Treatment

Shi et al. (2007) focuses on the use of biological pesticides as an alternative to chemical pesticides. They studied the use of *Paranosema (Nosema) locustae*, a microbial agent that infects locusts and increases their rates of mortality. For the locust species used in the Cease et al. (2012) study, *O. asiaticus*, Shi et al. (2007) found a 68.33% reduction in the year the locusts were treated with *P. locustae* and found that the agent persisted for ten years in treated locust populations. They concluded that the agent could be used to “substantially reduce” outbreaks in *O. asiaticus* for a “number of years” but that it would possibly then decline and cease to be an effective control.

The mortality rates seen in the Shi et al. (2007) study are encouraging, but the fact remains that this particular biological control would be a good short term solution at best. Livestock production will continue in Northern China for the foreseeable future, so long term solutions are necessary.

Changes to Herd Management

Locusts are influenced by livestock activity, so herd management is a key option to explore. As noted by Cease et al. (2012), overgrazing can induce locust events. Using this information, we pose the question: how much can herders reduce grazing intensity while earning a positive profit? By answering that question, we can provide insight that may be coupled with ecological understanding of the livestock-locust feedback loop to determine if livestock grazing intensity can be reduced enough to prevent locust events.

To determine the minimum herd size required to earn a positive profit, we solve the optimization problem presented in eq. 12 using a nonlinear solver. Variable definitions for eq. 12 are presented in Table 2.8.

(9) $$\min_{Q_L} I = P_L Q_L - P_{SF} Q_{SF} - VC_X - FC \qquad \text{subject to: } I \geq 0$$

Where, Q_{SF} and VC_X are functions of Q_L. We parameterize this model with the values in our original farm budget (Table 2.1: A – F). We find that for a herder to cover all costs and earn a positive profit at current market prices and estimated grass production levels, he must produce 425 livestock units on the typical pasture. This translates to a stocking rate of 0.862 LU/ha. Further study is needed to determine if this herd size is low enough for herders to prevent or reduce the probability of a locust event. If a reduction from current herd sized to this "break even" level is insufficient to mitigate locust outbreaks, herders may require larger parcels of land, subsidized feed, or a combination of the two to produce livestock at low enough stocking rates. If it is sufficient to mitigate locust events, then there is likely some number of years over which preventative measures would result in the same profit, aggregated over the multi-year period, as stocking at high rates and suffering the profit loss associated with a locust event.

Preventative management through reduced stocking rates addresses ecological concerns as well. It provides an environmentally sustainable mechanism for mitigating locusts and avoiding grassland degradation. This is appealing from both a public and private (herder) and perspective. For herders, reduced stocking rates may help maximize long-run net present value. This analysis shows that preventative management certainly deserves further study.

Conclusion

Concerns about locust damage in Inner Mongolia have risen. New research on the biology and ecology of locusts has helped reveal new potential management levers via their role in grassland ecosystems in recent years. Our contribution is to analyze the management component of this system and deepen our understanding of how a locust event impacts livestock producers and how those impacts affect the rest of the livestock and meat marketing chain. We find that locust events resulting in 4% pasture loss cause herders to lose over 30% of their profit. Locust events resulting in 8 – 12% pasture loss cause herders to lose their ability to cover fixed costs and events where more pasture is lost result in herders being unable to cover variable costs.

These results do not depend on what causes that pasture to be lost, so another ecological or institutional shock that results in the same amount of pasture loss would have the same financial impacts on herders. However, if pasture is lost because of a locust event, then the constraints on the typical herder's decision set will change. Herders may be able to anticipate such financial losses and adjust their herding intensity so as to prevent a locust event from occurring. We examine alternative policies and management strategies, but find that all have major limitations that could inhibit their success. Management at the farm level appears to be the most likely to succeed.

We expect that this problem is unfortunately not going away. Additional study is critical if we are to enable herders in this region to protect themselves against devastating losses. The work presented here gives a one-year analysis. A multi-year analysis would be an improvement.

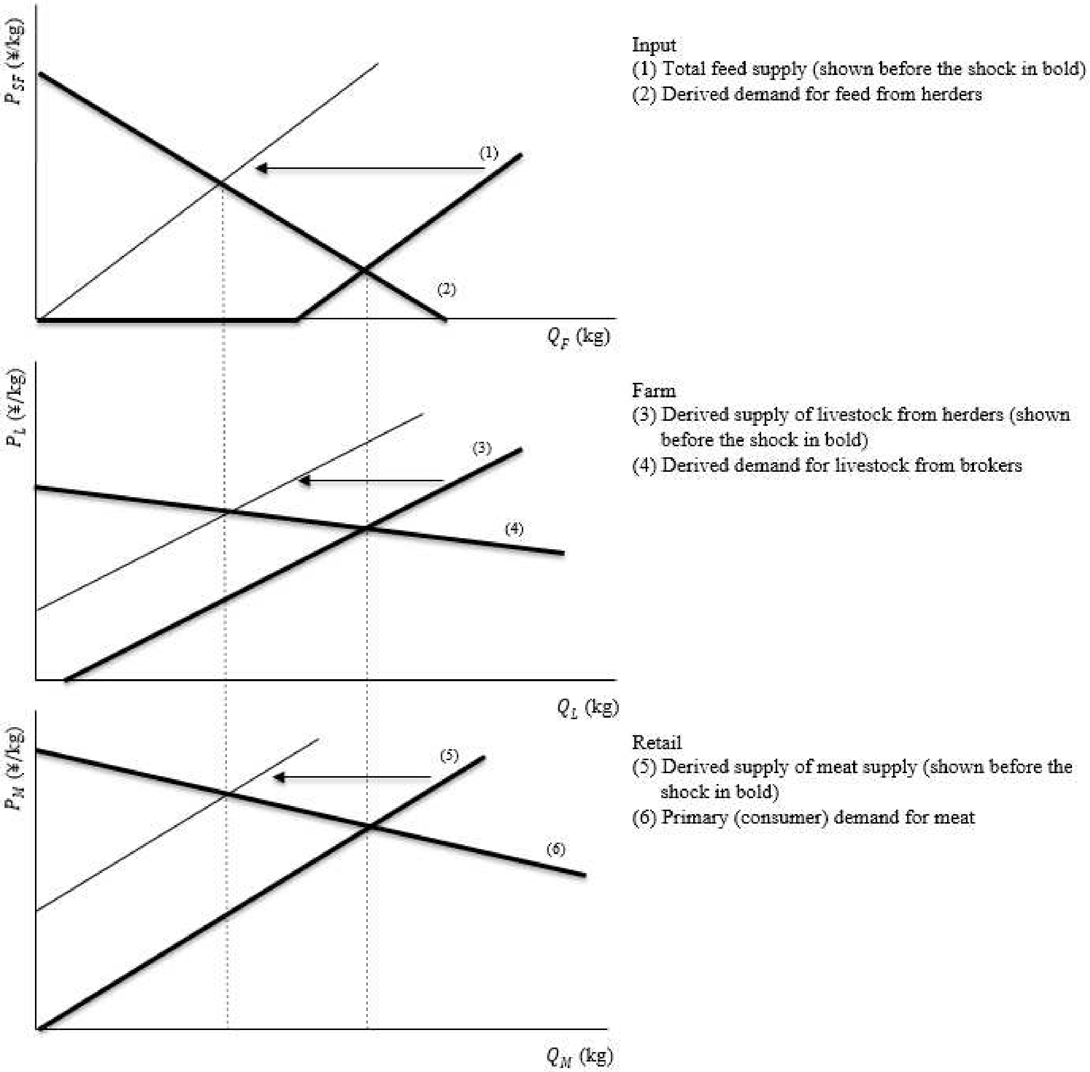

Figure 2.1. Supply and Demand at Input, Farm and Retail Levels Before and After a Locust Shock

(Note: Supply/Demand Curve numbers correspond to equation numbers (1) – (6))

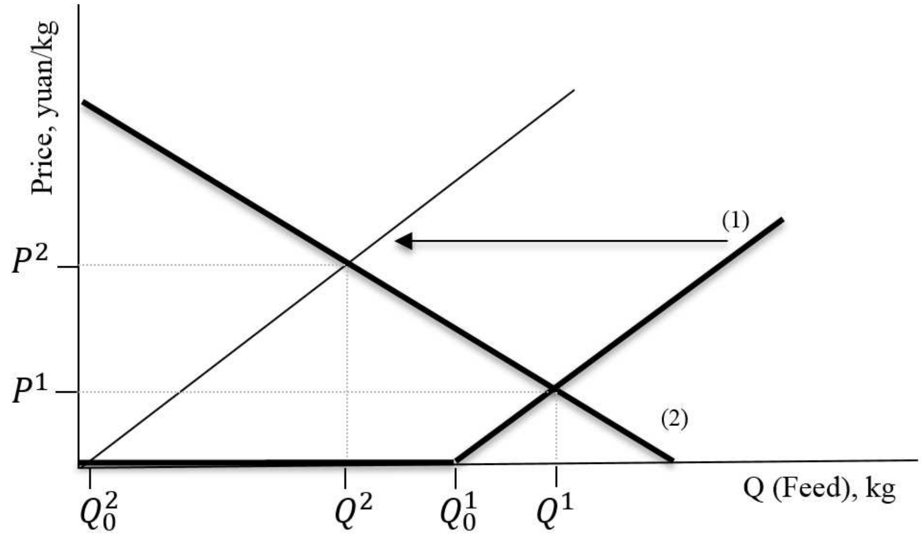

Figure 2.2. Surplus Calculations at the Input Level

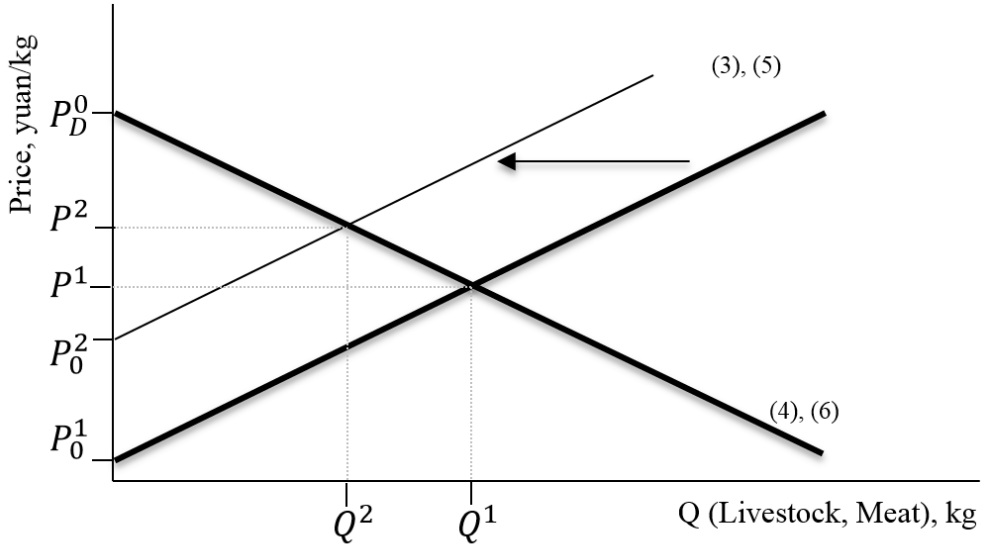

Figure 2.3. Surplus Calculations at the Farm and Retail Levels

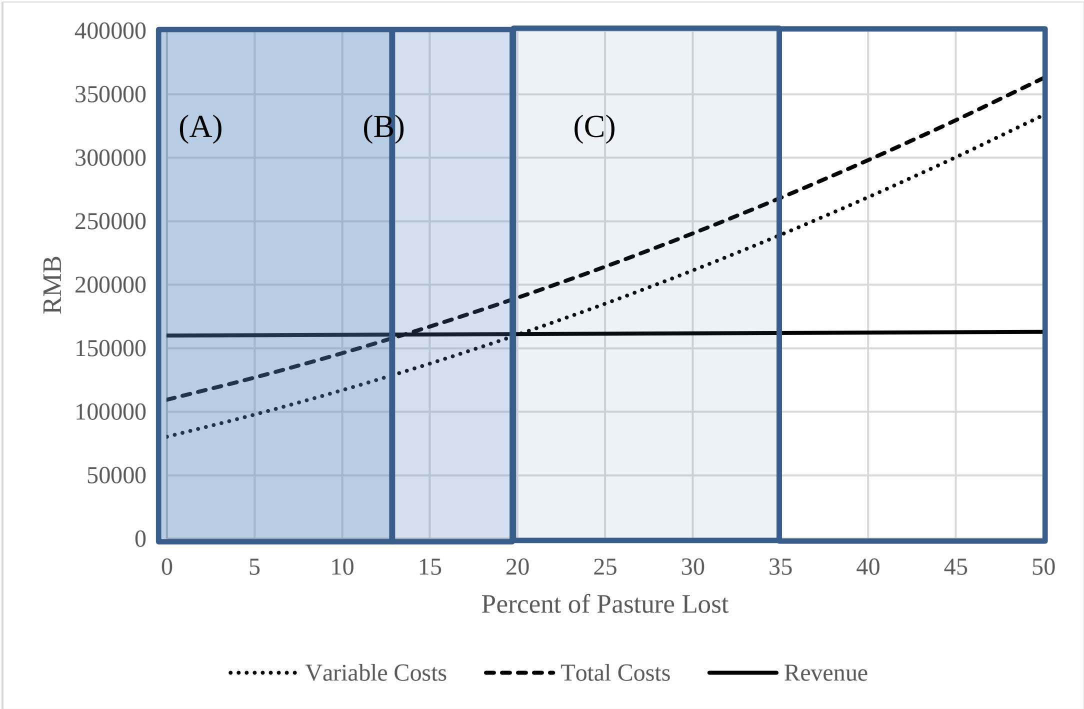

Figure 2.4. Variable Costs, Total Costs and Revenues in Scenarios (A), (B), and (C) Simulating Pasture Loss

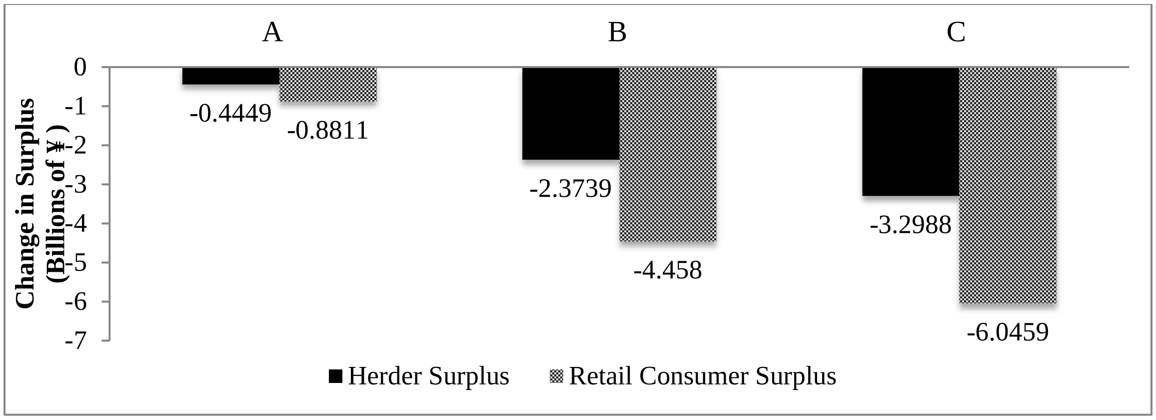

Figure 2.5. Aggregate Herder and Retail Consumer Surplus Losses

Table 2.1.A. Typical Herder Farm Budget: Herd Characteristics

	Composition of LU	Quantity in Herd	Unit
Sheep	0.81	453.6	head
Goats	0.19	106.4	head
Total	**1.00**	**560.00**	**head**

Table 2.1.B. Typical Herder Farm Budget: Income

	Price	Unit	Quantity		Unit		Total		Value Per LU	
Sheep	733.98	¥/head	x	200	head	=	146,796.00	¥	262.14	¥
Goats	655.79	¥/head	x	48	head	=	31,477.92	¥	56.21	¥
Wool	8.00	¥/kg	x	669	kg	=	5,352.00	¥	9.56	¥
Cashmere	170.00	¥/kg	x	40	kg	=	6,800.00	¥	12.14	¥
Gross Income (Accounting and *Economic*)							**190,425.92**	¥	**340.05**	¥

Table 2.1.C. Typical Herder Farm Budget: Variable Costs

Feed Costs											
	Price	Unit		Quantity	Unit		Total		Value Per LU	
Pasture	0.18	¥/kg	x	310,845	kg	=	55,952.10	¥	96.00	¥
Fertilizer	7.00	¥/kg	x	10,000	kg	=	70,000.00	¥	125.00	¥
Corn	1.73	¥/kg	x	6,000	kg	=	10,380.00	¥	18.54	¥
Hay	1.25	¥/kg	x	7,500	kg	=	9,375.00	¥	16.74	¥
Salt	2.46	¥/head	x	560	head	=	1,377.60	¥	2.46	¥
Total Feed Costs (Accounting)							**91,132.60**	¥	**162.74**	¥
Total Feed Costs (Economic)							***147,084.70***	¥	**258.74**	¥
Vet & Health	4.20	¥/head	x	560	head	=	2,352.00	¥	4.20	¥
Fuel							7,600	¥	13.57	¥
Labor	1,797.00	¥/month	x	12	months	=	21,564.00	¥	38.51	¥
Labor (self)	*1,797.00*	*¥/month*	x	*12*	*months*	=	*21,564.00*	¥	*38.51*	¥
Total Variable Costs (Accounting)							**122,648.60**	¥	**219.02**	¥
Total Variable Costs (Economic)							***200,164.70***	¥	***357.44***	¥

Table 2.1.D. Typical Herder Farm Budget: Fixed Costs

Machinery & Equipment Depreciation						=	260.00	¥
Fencing	4.20	¥/meter	x	4,150	meters	=	17,430.00	¥
Miscellaneous						=	1,000.00	¥
Total Fixed Costs (Accounting and *Economic*)							**18,690**	¥

Table 2.1.E. Typical Herder Farm Budget: Profit

	Total		Value Per LU	
Gross Income (Accounting and *Economic*)	190,425.92	¥	340.05	¥
Total Variable Costs (Accounting)	122,648.60	¥	219.02	¥
Total Variable Costs (Economic)	*197,972.60*	¥	*353.52*	¥
Income Over Variable Costs (Accounting)	**67,828.40**	¥	**121.12**	¥
Income Over Variable Costs (Economic)	***(7,495.60)***	¥	***(13.39)***	¥
Total Fixed Costs (Accounting and *Economic*)	18,690	¥		
Total Costs (Accounting)	141,338.60	¥		
Total Costs (Economic)	216,662.60	¥		
Income Over Total Costs (Accounting)	**49,138.40**	¥		
Income Over Total Costs (Economic)	***(26,185.6)***	¥		

Table 2.1.F. Typical Herder Farm Budget: Breakeven Prices

Breakeven Selling Price for Variable Costs (Accounting)	494.55	¥/head
Breakeven Selling Price for Variable Costs (Economic)	*798.28*	¥/head
Breakeven Selling Price for Total Costs (Accounting)	569.91	¥/head
Breakeven Selling Price for Total Costs (Economic)	*873.64*	¥/head

Table 2.2. Structural Model Variable Definitions

Variable	Definition
Q_G	Pasture grass (kg)
Q_{SF}	Supplemental feed (kg)
Q_F	Total feed (kg)
Q_L^I	Quantity of livestock raised in Inner Mongolia (kg)
Q_L^X	Quantity of livestock raised in China out of Inner Mongolia (kg)
Q_L	Total livestock in China (kg)
Q_M	Quantity of meat sold in China (kg)
P_{SF}	Selling price of supplemental feed (¥/kg)
P_L	Selling price of livestock (¥/kg)
P_M	Selling price of meat (¥/kg)
α	Proportion of Chinese livestock coming from Inner Mongolia

Table 2.3. Structural and Linear-in-Log Model Specifications for All Marketing Levels

Function	Structural Specification	Linear-in-log Specification
(1) Input: Total Primary Feed Supply	$Q_F = Q_G + f_1(P_{SF})$	$EQ_F = EQ_G + \varepsilon_{SF} EP_{SF}$
(2)Input: Derived Feed Demand	$Q_F = f_2(P_{SF}, Q_L^I)$	$EQ_F = -\eta_S EP_{SF} + EQ_L$
(3) Farm: Derived Livestock Supply	$Q_L = \alpha f_3(P_{SF}, P_L) + (1-\alpha) Q_L^X$	$EQ_L = \alpha(\varepsilon_L EP_L - EP_S)$
(4) Farm: Derived Livestock Demand	$Q_L = f_4(P_L, Q_M)$	$EQ_L = -\eta_L EP_L + EQ_M$
(5) Retail: Derived Meat Supply	$P_M = f_5(P_L)$	$EP_M = EP_L$
(6) Retail: Primary Meat Demand	$Q_M = f_6(P_M)$	$EQ_M = -\eta_M EP_M$

Table 2.4. Elasticity Estimates

Parameter	Estimate *(Min, Median, Max)*	Source
ε_S: Absolute value of own-price elasticity of supply for feed	0.8[1] 0.978 – 1.018[2] *(0.8, 0.978, 1.018)*	Tweeten and Quance (1969) McKay et al. (1980)
ε_L: Absolute value of own-price elasticity of supply for livestock	0.131[3] 0.104, 0.129[4] 0.2[5] 0.01[6] *(0.01, 0.129, 0.2)*	Zhuang and Abbott (2007) Shumway et al. (1988) Tweeten and Quance (1969) Whipple and Menkhaus (1989)
η_S: Absolute value of own-price elasticity of demand for feed	0.104, 0.117[7] *(0.104, 0.1105, 0.117)*	Shumway et al. (1988)
η_L: Absolute value of own-price elasticity of demand for livestock	0.113 – 0.246[8] *(0.113, 0.1795, 0.246)*	McKay et al. (1980)
η_M: Absolute value of own-price elasticity of demand for meat	0.35 - 0.5[9] 0.339[10] 0.309, 0.384[11] *(0.309, 0.35, 0.5)*	Ortega et al. (2009) Zhuang and Abbott (2007) Fan et al. (1995)

[1]Feed in U.S. in the short-run [2]Materials for Sheep in Australia [3]Pork in China [4]Livestock in U.S. [5]Livestock in U.S. in the short-run [6]Lamb in the U.S. in 1 year [7]Feed grains in the U.S. [8]Livestock (sheep) in Australia [9]Beef, Mutton and Pork in China [10]Pork in China [11]Meat in China

Table 2.6. Mean Percentage Changes of Input and Farm Level Market Values for Scenarios (A), (B), and (C)

	Scenario		
	A	B	C
EQ_G: Percent change of pasture grass	-1.98	-10.08	-13.71
EQ_F: Percent change of total feed	-0.47	-2.40	-3.27
EQ_{SF}: Percent change of supplemental feed	34.32	174.47	237.25
EQ_L: Percent change in livestock quantity	-0.29	-1.49	-2.03
EP_{SF}: Percent change in supplemental feed price	1.62	8.26	11.23
EP_L: Percent change in livestock price	0.52	2.66	3.61

Table 2.7. Budget Values for Scenarios (A), (B), and (C)

	Initial		Scenario (A)		Scenario (B)		Scenario (C)	
	Total	Per LU	Total	Per LU	Total	Per LU	Total	Per LU
Income (¥)	183,905.92	328.40	178,376.32	320.31	174,669.34	311.91	171,146.58	305.62
Feed Costs (¥)	91,132.60	162.74	109,942.95	196.33	129,971.82	232.09	145,339.19	259.53
Total Variable Costs (¥)	122,648.60	219.02	141,368.35	262.56	161,307.62	311.95	176,610.17	352.05
Total Costs (¥)	141,338.60		160,058.35		179,997.62		195,300.17	
Profit (¥)	42,567.32		19,317.97		-5,328.28		-24,153.59	
Percent Change in Profit from Initial Budget	-		-54.6%		-112.5%		-156.7%	
Herd Size (LU)	560		538.43		517.10		501.66	
Breakeven Selling Price for Variable Costs (¥/LU)	494.55		592.87		704.40		794.95	
Breakeven Selling Price for Total Costs (¥/LU)	569.91		645.40		725.80		787.50	

CHAPTER 3: OPTIMAL HERD SIZE DECISIONS OF THE TYPICAL INNER MONGOLIAN SHEEP AND GOAT PRODUCER

Introduction

Sheep and goats have been raised on open grassland pasture in Inner Mongolia for generations, but increases in production are putting new pressures on Inner Mongolian grassland ecosystems. Inner Mongolia is one of China's biggest mutton (sheep and goat meat) producers and one of the fastest growing producers in the world ("Country Report: China Sheep Meat" 2013). Jointly, these grasslands are vulnerable to changes in ecological conditions that may reduce grass availability. Grass is the primary input for livestock, so a reduction in grass can have major consequences on livestock production enterprises. Additionally, if current grazing trends continue, it is likely that these grasslands will become permanently degraded. Inner Mongolia has already experienced major grassland degradation. Jiang et al. (2006) note, "current grassland primary productivity is only about 50% of that of the undegraded[6] steppe," which is widely believed to have caused the increase in devastating sandstorms in the region. They note the "urgent need" for ecosystem management in this region in order to secure the environmental and economic future of the region.

While any grassland used for livestock production requires management in order to prevent degradation, Inner Mongolian grasslands have an additional negative impact beyond explicit grass lost to overgrazing. A recent study from Cease et al. (2012) showed that overgrazing could induce outbreaks of the economically damaging locust (*Oedaleus asiaticus*). Locusts in an outbreak consume pasture grass, leaving less for livestock and limiting the short-

[6] "undegraded steppe" refers to grasslands that have the same primary productivity as grasslands that have not been used for agricultural production at all

term profitability of livestock operations. Thus, overgrazing in this particular region can have the explicit consequence of overgrazing compounded with the implicit consequence resulting from an increased risk of locust damage.

This research builds on previous work addressing grassland management in Inner Mongolia that examined economic losses in a single year due to the loss of pasture grass. The previous work found that any loss of pasture grass decreases herders' profits and losses by10% or more cause a cost increase that herders are unable to cover with income in a single year (Byrne et al. forthcoming). While those results provided useful information about the vulnerability of herders in Inner Mongolia, this work provides comprehensive analysis of long-term grassland management strategies. Specifically, we show how incorporating information about the livestock-locust feedback loop into long term planning can enable herders to maximize their profits over the long-run planning horizon.

An Overview of Grassland Management

We assume that herders in Inner Mongolia are motivated by profit-maximization. However, as noted by Workman (1986), problems of overuse (including overgrazing) are not a necessary consequence of profit-motivated management. In order to harmonize economic and ecological goals, proper planning and policies are necessary. Herders in Inner Mongolia maintain their own parcels of land that they lease from the Chinese government for 30-year terms. This land right policy provides many of the same incentives for land stewardship that come from fully private ownership, so we do not expect to see degradation as a result of the oft reported "tragedy of the commons" (Hardin 1968). However some of the literature that responded to Hardin's "tragedy of the commons" provides pathways for disincentivizing degradation. Shifting from short-term planning to long-term planning is noted as a key way to alleviate opposition between profit objectives and prevention of land degradation (Workman 1986; Torell et al. 1991).

The key herd management decision of interest in this study is the choice of herd size given a fixed acreage of land. This is analogous to a “stocking rate” choice model, where managers seek the optimal number of animals per unit area. Our choice of herd size can easily be translated into stocking rates by simply dividing by the total area managed by the typical herder. The choice of herd size may be motivated by a response to the system at the time the decision is made. We first identify the optimal trajectory using our dynamic program. This provides the upper NPV limit for the typical herder. We then identify response strategies and compare them to the optimal and to one another in order to determine if such heuristics can allow herders to feasibly improve their profits over time. We begin with the baseline “unresponsive” strategy, where herders simply maintain the same herd size throughout their leaseholds. We assume that herders can improve upon this strategy by incorporating information about the ecological system into their herd size decision, which we test using alternative response strategies. We find that herders are significantly better off including basic ecological information into their decision-making. Their returns improve as they increase the precision and complexity of their ecological understanding, but these improvements are modest. While none of the heuristics allow herders to reach the NPV identified by the optimal trajectory, they all provide significant improvements over the unresponsive strategy.

The Typical Herder

We use the typical herder defined in previous work by Byrne et al. (*forthcoming*). The key characteristics of the typical herder’s finances are captured by the farm budget elements highlighted in Table 3.1. Section A defines the composition of a "livestock unit." Section B identifies the typical selling price of a livestock unit. Section C identifies prices for inputs.

The typical herder is expected to have some discount factor, meaning that profits in the current period are worth more than profits in the future, ceteris paribus. However, discount factors vary between individuals. We seek to estimate discount factors typical of similar producers to the herders of Inner Mongolia. Existing literature provides a range of annual discount factors from 4% (Pétry 1995) to 6% (Lence 2000). We consider the variability of individuals' discount factors in our analysis and find results that are robust to small changes in this measure.

Model Development

We identify expected profits over the 30-year leasehold using a dynamic programming framework. In this framework, we estimate the amount of pasture grass available and the expected profit in each year. The pasture grass available each year is determined using a stochastic bioeconomic model that incorporates intrinsic grass growth, livestock consumption, and locust predation (a function of past livestock grazing intensity). Our model is based on the simplest version of the bioeconomic model from Berry et al. (*forthcoming*). In each year, herders select a herd size. Their herd size, along with the pasture grass availability and exogenous market prices, is used to calculate their expected profit for that year. After all calculations are made for a given year, pasture grass availability for the next year can be estimated. The process is repeated until herd sizes for all years have been selected, pasture grass has been estimated, and expected profits have been calculated. Expected profits are discounted and summed to obtain the net present value (NPV). This process is explicitly defined throughout the remainder of this section.

All variable definitions, including objectives, decisions, state and exogenous variables, and their corresponding units can be found in Table 3.2.

Dynamic Programming Framework

Dynamic programming provides a framework for modeling multi-stage decision processes. It is appropriate for scenarios in which decisions are sequential, irreversible, and dependent on the outcomes of previous decisions in the sequence, which is what we have here (Taylor 1993). An objective function for the multi-period problem is decomposed into smaller sub-problems that can be solved for optimal single-period decision values. These sub-problems are linked through the state variable, which captures a quantifiable characteristic that influences and is influenced by the decisions made in each period. In this case, the amount of pasture grass available is the state variable; it influences profit in the current period and is influenced by previous herd size choices.

Dynamic programming models have been used in several studies of rangeland management and stocking rate decision-making. Pope and McBryde (1984) were one of the first to use a multi-year approach to determine optimal stocking rates by including a fixed carrying capacity specific to rangeland in south Texas. They demonstrated how extending the planning horizon over which profit is maximized can eliminate the incentive to overgraze, and thus decrease grassland degradation. Also focusing on south Texas, Karp and Pope (1984) presented a dynamic stocking rate model with the inclusion of periodic treatments with an unknown impact, thus introducing a stochastic element to the dynamic program. They demonstrated how this method can be used to determine the optimal timing for a specific rangeland treatment. Rodriguez and Taylor (1988) presented a dynamic programming model of stocking rates with the inclusion of stochastic rainfall, finding that herders could maximize long-term profitability by increasing stocking rates and relying more heavily on supplemental feed. Torell, Lyon and Godfrey (1991) compared optimal stocking rates obtained through a dynamic programming model to those found in a single-period model to justify the need to make stocking rate determinations using long-term models in order to maximize long-term profit and mitigate negative impacts on rangeland. Quaas et al. (2007) introduced a spatial component, presenting a dynamic model where stocking rates were heterogeneous across a manager's land, finding that farmers who are highly risk averse will choose ecologically sustainable grazing patterns. Finnoff, Strong and Tschirhart (2008) integrated a deterministic bioeconomic model into their dynamic program for determining optimal stocking rates with the consideration of an invasive species threat in order to identify how the relative proportions of grass types changed with stocking rates.

Our work builds on previous literature by examining stocking rates through dynamic programming in a region where this has not yet been done. We also take a slightly different approach from most of the literature by using the dynamic programming platform as a way to test long-term strategies, rather than single-period decisions. Finally, we include a bioeconomic model for pasture grass availability specific to this region, including the threat of locust damage when overgrazing occurs.

Objective Function

Herders producing in Inner Mongolia must make production decisions each year while maximizing their long-term profit potential. The objective is to maximize the net present value (NPV) of expected profit earned over the entire lease term (30 years). The objectives each year, or sub-problem objectives, are to maximize the expected value of that year's profit, $E[\pi_t]$ where $t = 1,2, \dots, 30$. We seek to optimize net present value, meaning that after year 1, expected profits are discounted by discount factor δ. Our objective function can be written algebraically as follows:

(1) $NPV = \sum_{t=1}^{30} \delta^{t-1} E[\pi_t]$.

Herders seek to utilize the herd size strategy that yields the highest NPV. Specific strategies are discussed in more detail in the "Decision Response Function" section.

Profit Function for Livestock Production

In order to maximize NPV, we must identify our annual profit function, π_t. Using what we know about the typical Inner Mongolian herder, we define profit to be income from the sale of livestock less feed costs, other variable costs, and fixed costs. The sale of livestock is the price of livestock, P^L, multiplied by the number of livestock sold in that period, L_t^S. Feed sources are pasture grass, which herders do not pay for, and supplemental feed, which is purchased at market price P^F. Herders purchase supplemental feed only if necessary. Feed is necessary if the size of the total herd, $\overline{L_t}$, multiplied by the feed conversion ratio (i.e. the amount of feed required per head per year), τ^{FL}, is greater than the quantity of pasture grass available, Q_t^G. If the product of $(\tau^{FL} \cdot \overline{L_t})$ exceeds Q_t^G, then the amount by which is exceeds Q_t^G is the amount of feed that must be purchased at the market price. Other variable costs are bundled and added as a per head price of P^V, so additional variable costs are $(P^V \cdot \overline{L_t})$. Fixed costs, FC, are also subtracted. We use average fixed costs for each year, so while in reality fixed costs may differ from year to year, they remain constant in this model. Algebraically, the annual profit function is:

(2) $\pi_t = P^L L_t^S - P_t^F \cdot \min[(\tau^{FL}\overline{L_t} - Q_t^G), 0] - P^V \overline{L_t} - FC$

Prices and the feed conversion ratio are exogenous, so the only variables in this model over which herders have control are the number of livestock sold, L_t^S, the size of the herd, $\overline{L_t}$, and the quantity of pasture grass, Q_t^G. As mentioned, the quantity of grass, Q_t^G, is a function of herd size and unobservable variables, which we describe in the next section. To some extent L_t^S is a function of $\overline{L_t}$ because herders cannot sell more than they have and there is an optimal time to sell a sheep or goat. Based on observation in the field, herders sold roughly 50% of their herd each year. For simplicity we assume $L_t^S = \frac{1}{2}\overline{L_t}$. Thus, the size of the herd, $\overline{L_t}$, is the only decision variable considered in this model.

Modeling Changes in Pasture Grass

We model the state variable of pasture grass using an ecological model where the amount of grass on pasture in year $t+1$ is equal to the pasture grass in the previous year, plus newly grown grass, less grass consumed by livestock, less grass consumed by locusts (Berry et al. *forthcoming*). We also include a term, ϵ, to capture unexplained causes of grass growth or loss. Algebraically,

(3) $Q_{t+1}^G = Q_t^G + \mathrm{NG} - \mathrm{LVC} - \mathrm{LCC} + \epsilon$

New grass, NG, is estimated by multiplying the current amount of grass, Q_t^G, by the intrinsic rate of grass growth, r^G, which measures the expected percentage increase of pasture grass biomass over a given period of time if nothing else changes this value. Algebraically,

(4) $\mathrm{NG} = r^G \cdot Q_t^G$

Grass consumed by livestock, LVC, is the product of the number of head in the herd, $\overline{L_t}$, and the feed conversion ratio, τ^{LF}.

Algebraically,

(5) $\mathrm{LVC} = \tau^{LF} \cdot \overline{L_t}$

Locust predation, LCC, is a function of grazing intensity, which we represent with the ratio of herd size to grass quantity, $\frac{\overline{L_t}}{Q_t^G}$. Using the results found by Cease, et al. (2012), we assume a functional form where locust predation is low when grazing is moderate or low, but quickly increases when grazing is heavy. An exponential function can be parameterized to capture this effect as follows:

(6) $\text{LCC} = \left(a \cdot \frac{\overline{L_t}}{Q_t^G}\right)^b$ where a, b are constants.

Figure 3.1 demonstrates how this functional form relates grazing intensity to locust grass consumption. It also shows how the identification of parameters a and b impact the shape of the curve. We find that with $a \approx 2000$ and $b \approx 10$, we get a functional form that aligns with the results found by Cease et al. (2012) in the field. There are likely other functional forms that would also align with their results and this function is a simplification of the system; it is reasonable for in-sample analysis, but cannot be considered reasonable for grazing conditions that are out of sample.

Combining equations (4) – (6), we can rewrite the equation for pasture grass as follows:

(7) $Q_{t+1}^G = Q_t^G + r^G \cdot Q_t^G - \tau^{LF} \cdot \overline{L_t} - \left(a \cdot \frac{\overline{L_t}}{Q_t^G}\right)^b + \epsilon.$

Herd Dynamics

Herders are constrained in their selection of herd size by natural breeding limitations. While they can decrease their herd size as much as they want by selling or culling their animals, the magnitude of a herd size increase is limited by how quickly the animals can breed. Herders do have the option of purchasing additional animals if they want to increase their herd size by more than breeding will allow, but we do not see this in practice in Inner Mongolia and thus assume no additional animals are purchased.

In a given period, t, the herd will begin with only females.[7] Each of these females gives birth to a lamb, with a 50% chance that the lamb will be female and a 50% chance the lamb will

[7] Rams (intact males) are held for breeding, with one ram per ~100 females. In this model, rams are defined as capital, rather than part of the herd. Castrated males are sold by the end of each period.

be male. Some of the new lambs will die shortly after birth, which we estimate using the lamb mortality rate, r_M, of 10%, meaning 10% of lambs will die shortly after birth (Berger 1997). Because the newly birthed males cannot breed, they will be sold within that period. The remaining animals can be sold or can be kept for breeding in the next period. The herd size in period $t + 1$ is described in equation (8):

(8) $\overline{L_{t+1}} = \overline{L_t} + (1 - r_M)\overline{L_t} - L_t^S$

Where $(1 - r_M) \cdot 0.5 \cdot \overline{L_t} \leq L_t^S \leq (1 - r_M)\overline{L_t}$

Simulation Model

We simulate 30-year planning horizons to reflect the lease terms of the typical Inner Mongolian herder. Herders begin with 310,844 kg of pasture grass on 493 ha in the first year, which is the estimated quantity of grass in typical pastures that have not experienced economic damage from locusts (Byrne et al., forthcoming). Herders select their herd size in the first year, $\overline{L_1}$, and then adjust it each year according to a decision rule. They face market prices for feed, veterinary and medical costs, and livestock. Their selected herd size, $\overline{L_t}$, and their pasture grass quantity, Q_t^G, are used to calculate their profit according to equation (2). The quantity of grass available in the next year, Q_{t+1}^G, is determined using equation (7). These steps are repeated until all expected profits are calculated. Then, using equation (1), we calculate the NPV for the entire 30-year planning horizon.

Optimal Trajectory

The optimal trajectory is found by solving the dynamic program for the maximum NPV, subject to herd size constraints as described in "Herd Dynamics." We use backwards recursion, removing stochastic terms, to identify the optimal herd sizes, corresponding grass quantities, and profits in each period. While herders who are certain they will end their lease term after 30 years may want to follow this trajectory, we primarily use it as a basis for comparing response functions.

Decision Response Functions

We generate three decision rules with corresponding response functions that dictate how a herder will choose his stocking rate in each period after the first period ($t = 2,3, \ldots ,30$). We seek to examine how these response functions determine optimal stocking rates in the first period considering the decisions made in periods 2-30. The decision response functions are defined as follows:

(a) "Unresponsive": In this scenario, the herder chooses an initial stocking rate in the first period and maintains the same stocking rate in subsequent periods. The response function is algebraically defined as:

(9) $\overline{L_{t+1}} = \overline{L_t}$

(b) "Qualitative Grass Response": In this scenario, the herder observes whether or not the quantity of pasture grass has increased or decreased since the last period. If pasture grass has increased, the herder increases the herd size by some proportion, ρ ($0 \leq \rho \leq 1$), in the next period. If pasture grass has decreased, the herder decreases the herd size by ρ in the next period. This response function is algebraically defined as:

(10) $$\overline{L_{t+1}} = \begin{cases} (1+\rho) \cdot \overline{L_t} & if\ Q_t^G > Q_{t-1}^G \\ (1-\rho) \cdot \overline{L_t} & if\ Q_t^G \leq Q_{t-1}^G \end{cases}$$

(c) "Quantitative Grass Response": In this scenario, the herder chooses a stocking rate proportional to the quantity of grass available in the most recent observable period. He may change his herd size by up to 20% in either direction. This response function is algebraically defined as:

(11) $\overline{L_{t+1}} = \frac{Q_t^G}{\omega}$ where ω is a constant

We don't expect the unresponsive response function to be ideal, but we include it to have a baseline for comparison and because observation in the field shows that many herders do not adjust their herd size over time. We expect that choosing a herd size with consideration for grass availability will be an improvement over maintaining a constant herd size. We use this analysis to estimate how much it improves NPV and whether or not a qualitative response is sufficient or if herders will benefit more greatly from a qualitative response.

Exogenous Variable Estimates

We use random variables, drawn from uniform distributions, because the model's exogenous variables are either unknown (as is the case with locust predation parameters "a" and "b" as well as the discount factor) or stochastic (as is the case with feed conversion ratios and prices). In all cases, they are out of the herder's control. We want to capture a range of possibilities as well as identify any variables to which our results are sensitive. Sensitivity analysis and marginal effects of changes in these exogenous variables are discussed in the "Results" section.

For each of the response functions, we run 1000 simulation trials where exogenous values in equations (1), (2) and (7) are randomly drawn. Specifically, for equation (1), we randomly draw a discount factor, δ. For equation (2), we randomly draw a livestock price, P^L, a feed price, P^F, and a feed ratio, τ^{LF} (also used in equation 3). For equation (3), we randomly draw from uniform distributions an intrinsic grass growth rate, r^G, and locust consumption parameters a and b. We also draw values for ϵ for each of the 30 years in the planning horizon, also from a uniform distribution. Results from Wang et al. (2014) show that grasslands in Inner Mongolia produce between 630 and 1056 kg/ha, which translates to a range of ~350,000 kg to ~590,000 kg of grass per year for the typical herder. They linked this grass production to precipitation. However our analysis is projecting into the future and future precipitation is unknown. For this reason, we allow ϵ to take on random values distributed $U(-100{,}000, +100{,}0000)$ to capture changes in pasture grass availability resulting from climatic conditions.

The feed conversion ratios, livestock prices, and feed prices capture the ranges reported by herders in household surveys conducted by Inner Mongolia Agricultural University (IMAU) in 2012, 2013, and 2014.

The intrinsic rate of grass growth is collected from a study by Berry et al (*forthcoming*). They estimate the intrinsic rate of grass growth in Inner Mongolian grasslands to be $0.0008 \frac{kg}{kg \cdot day}$, which means that we expect 1 kg of grass today to be 1.0008 kg of grass tomorrow, assuming no consumption. This means that over the course of a year, 1 kg of grass would become 1.3389 kg of grass ($(1.008)^{365} = 1.3389$), so our annual intrinsic rate of grass growth is $\sim 0.3389 \frac{kg}{kg \cdot year}$.

For the locust predation parameters, we have identified values ($a = 2000$, $b = 10$) for which the locust predation function of grazing intensity matches locust behavior seen by Cease et al. We vary these parameters by 10% in both directions in order to identify the degree to which our model is robust against changes in these values.

The discount factor is specific to the individual herder and his preferences. We examine a range of discount factors between 1% (indicating a high value for future profits) and 10% (indicating a much lower value for future profits) in order to capture a range of preferences. Because the response functions do not change over time and do not rely on discount factors, the discount factor will not influence decisions or the relative optimality of outcomes. It will, however, influence the calculated NPV’s.

We use random variables because these exogenous variables are either unknown (as is the case with locust predation parameters “a” and “b” as well as the discount factor) or stochastic (as is the case with feed conversion ratios and prices). We want to capture a range of possibilities as well as identify any parameters to which our results are sensitive. Sensitivity analysis and marginal effects of changes in these exogenous variables are discussed in the “Results” section.

Selection of ρ and ω

In both the qualitative and quantitative response strategies, we expect there to be optimal values for ρ and ω, respectively. Our baseline selection for ρ is 0.10. In the context of the qualitative decision strategy, this means that when a herder observes that grass is more abundant that in the previous year, he increases his herd size by 10%. If he observes that grass is less abundant, he decreases his herd size by 10%. In this decision rule, the magnitude by which grass has increased or decreased is not taken into account.

Our baseline selection of ρ is 1600. In the context of the quantitative decision strategy, this means that the herder calculates how much grass is available on pasture and chooses a herd size. When $\omega = 1600$, he will select a herd size equal the amount of grass on pasture (in kg) divided by 1600, as long as this doesn’t cause him to increase his her by more than 20% (constraint from sheep and goat breeding). This value is more than double the average livestock feed ratio, so it is intended to be a conservative allotment of grass.

We find our first results using these baseline selections of ρ for the qualitative response and ω for the quantitative response. After confirming that these strategies are substantial improvements upon the unresponsive strategy, we estimate optimal values for ρ and ω.

Calculating NPV

In each simulation trial, we parameterize the model with the exogenous variables discussed in the previous section with random draws for each of their values (Table 3.2). We then randomly draw an initial herd size, $\overline{L_1}$, between 0 and 600 head. This is the herd size that the herder chooses for the first year. From this initial herd size, subsequent grass quantities and herd sizes are calculated using the response function of interest (unresponsive, qualitative response, or quantitative response). This generates the 30-year planning horizon with grass quantities, herd sizes, livestock sales and profits for each year. These are then used, along with the given discount rate δ for that trial, to calculate annual profits using the single-year profit equation, as described in eq. (2). Finally the NPV can be calculated from $\pi_1 \ldots \pi_{30}$ and δ, as described in eq. (1).

Determining Optimal Initial Herd Sizes

We use a *k-nearest neighbors* estimation to identify the optimal herd size for each strategy. This is a nonparametric modeling strategy, which is appropriate because we only want to find the initial herd size where expected NPV is maximized. We are not concerned with the underlying functional form. NPV estimates are determined for each initial herd size by taking the *k* nearest neighbors in the dataset (nearest neighbors defined to be the data points with the *k* closest initial herd sizes) and calculating the average NPV for all of the neighbors. This value becomes the NPV estimate for that data point. This process is repeated for all points in the dataset. We use this estimation strategy using $k = 50, 75, 100$ for each response strategy in order to determine the optimal initial herd size and the expected NPV when the herder is optimizing.

Results

Significant gains can be made in increasing the expected NPV of a typical herder by introducing dynamic herd sizes either through the optimal trajectory or qualitative and quantitative decision response functions.

Optimal Trajectory

By solving the dynamic program, we find the optimal trajectory as shown in Figure 3.2. The expected NPV for this trajectory is ¥3,206,271.85. This maximum NPV is achieved by building small herds into larger herds over several years, culminating in large sales where most of the herd is sold. This process is repeated every seven to twelve years, with the entire herd sold in the final year.

Response Functions

Initial herd sizes and their corresponding NPV values for each response strategy using the k-nearest neighbor estimates are shown in Figure 3.3. We find that for an unresponsive strategy, NPV is optimized with an initial herd size of 171 and expected to be ¥634,960. For a qualitative response strategy ($\rho = 0.1$), NPV is optimized with an initial herd size of 155 and expected to be ¥1,291,193. And for a quantitative response strategy, NPV is optimized with an initial herd size of 75 and expected to be ¥1,524,383.

Optimal ρ

To determine the optimal value for ρ, we run another 1000 simulation trials using the qualitative response strategy while varying ρ between 0 and 0.2. We hold all other exogenous variables constant at their mean and initial herd size constant at 155. The changes in NPV as a result of changes in ρ are displayed in Figure 3.4. We see a clear optimal value at $\rho = 0.085$.

Optimal ω

To determine the optimal value for ω, we run another 1000 simulation trials using the quantitative response strategy and varying ω between 0 and 5000. We hold all other exogenous variables constant at their mean and initial herd size constant at 75. We find that that ω is not binding for values less than 1500. This is due to the biological constraints imposed from sheep and goat breeding capacity, which are more binding when ω is small. When ω is large, it decreases NPV because it causes herders to select herd sizes more conservatively than necessary. Between 1500 and 1815, ω is binding in some years and not in others. There is a slight advantage when $\omega = 1765$ as that is the value that maximizes NPV, ceteris paribus. The changes in NPV as a result of changes in ω are displayed in Figure 3.5.

Herd Sizes Over Time

Figure 3.6 shows the herd size trajectory for each response strategy when optimized and when all other parameters are held constant at their means. We see that regardless of the response strategy, herders are always better off with smaller herd sizes than are currently observed in the field. This result aligns with patterns of degradation and overuse which are a current concern in Inner Mongolia; if current herd sizes were sustainable, we wouldn't see the dramatic signs of degradation currently observed. In simulation trials where herders are able to adjust herd size, they are best off starting with a small herd size and allowing several years for grass to build up from current levels. After grass abundance has increased to primary productivity, they maintain a relatively constant herd size over time. In cases where herders do not adjust their herd size (unresponsive strategy), they are best off beginning with a small herd size (as compared to herd sizes observed in the field today) and maintaining it over time in order to avoid degradation and/or a locust event.

Exogenous Variable Impacts

While the exogenous variables (feed prices, livestock selling prices, intrinsic grass growth rate) are out of the control of herder's decision set, they still impact herders' NPV's. By design, higher feed prices and livestock conversion ratios will decrease NPV. Similarly, higher livestock selling prices and intrinsic grass growth rates will increase NPV. We seek to determine the magnitude of these variables' marginal effects because that will allow us to see what exogenous factors make herders most vulnerable.

In order to examine the impact of these exogenous variables for a given response strategy, we employ a linear regression where initial stocking rate is held constant at its optimal value. Similarly, ρ and ω are held constant at their optimal values for qualitative response and quantitative response, respectively. Additionally, we hold the discount factor, δ, constant at its mean (0.05). We then take 1000 simulation trials, varying all of the exogenous variables, to generate the data used to determine estimates for the linear regression model. These estimates provide marginal effects for each of the exogenous variables at their mean. We use the following models for this analysis, where the subscripts indicate the response strategy (UR = unresponsive, LR = qualitative response, TR = quantitative response):

(12) $$E[NPV_{UR}] = \beta_0 + \beta_1 r^G + \beta_2 \tau^{LF} + \beta_3 P^L + \beta_4 P^F$$

(13) $$E[NPV_{LR}] = \beta_0 + \beta_1 r^G + \beta_2 \tau^{LF} + \beta_3 P^L + \beta_4 P^F + \beta_5 \overline{L_{30}}$$

(14) $$E[NPV_{QR}] = \beta_0 + \beta_1 r^G + \beta_2 \tau^{LF} + \beta_3 P^L + \beta_4 P^F + \beta_5 \overline{L_{30}}$$

Coefficient Estimates for Eq. (11) – (13) are provided in Table 3.3. All signs are in the expected direction for $\beta_1, \beta_2, \beta_3$ and β_4, however β_4 is not significant for any response strategy. This is likely due to the fact that when optimized, herders are not relying on supplemental feed, but rather are feeding their herds entirely with pasture-grown grass. If they are not purchasing feed, then feed price should be irrelevant to their NPV. We see that the price of livestock has a greater marginal impact in the qualitative and quantitative response strategies than it does in the unresponsive strategy. This can be attributed to the fact that herders ultimately raise (and therefore sell) far more head over their entire 30-year lease hold when they optimize for the quantitative and quantitative response strategies than they raise when they optimize for the unresponsive strategy. We also see that the final herd size is significant and positive for the qualitative response. This makes intuitive sense; we expect herders ending their lease term with large herds to have sold more animals and therefore have larger NPV's, ceteris paribus.

Sensitivity Analysis for Climate Variability

Climate variability is modeled through the selection of ϵ made each year in each simulated trial. The distribution of ϵ is centered at 0 and by design it will increase the variance of NPV but not its expected value. We perform sensitivity analysis on the bounds of ϵ, E, where $\epsilon \sim U(-E, +E)$.

We find that given optimal choices for initial herd size and ρ and ω, increased variability (E) only lowers NPV. If herders are not already optimizing their herd size, there are instances where increased variability allows them to achieve an NPV higher than their expected NPV, but it is not recommended that herders rely on this outcome because it is quite unlikely.

Conclusion

These results indicate that a minor adjustment in herd management may lead to major gains for Inner Mongolian herders and for the grasslands on which they live. While more precise understanding of their grass availability would be optimal, it would also require additional skills and resources that these herders may not possess. Any response strategy, either qualitative or quantitative, is also an improvement in grassland management and degradation avoidance because it means that herders are intentionally avoiding overgrazing.

We find that herders are much better off using a qualitative response strategy than an unresponsive strategy, which only requires that they be able to compare grass availability in a given year to grass availability in the previous year. Simply observing if grass is more abundant could be done using pictures of a simple notebook. This could improve herders' financial outcomes while preventing grassland degradation and locust damage.

Examining herd sizes over time for the qualitative and quantitative response strategies confirms what we already know: grazing intensity must be reduced in order to allow the Inner Mongolian grasslands to return their primary productivity. While the grasslands can be restored if herders simply lower the number of head in their herds, as we see with the unresponsive strategy, they can achieve a Pareto improvement by adopting responsive grazing strategies.

Our results indicate that herders should be grazing at lower levels regardless of their strategy than what we currently see in the field. While they may be ultimately better off stocking 150 head on their pasture, typical herders are stocking more than double that amount right now. Decreasing their herd sizes sufficiently represents a major change to current operations and would likely represent a loss of profit in the short-run. While our results indicate that they will do better in the long-run if they lower herd sizes, they would need to be convinced that this is true and they would need to have the appropriate discount factor. An alternative approach would be to use the tools presented here to find out optimal grazing strategies given initial herd sizes that we currently observe in the field. While it would certainly be a second-best option when compared to optimal herd sizes presented here, it would likely be an improvement over doing nothing.

Finally, it is important to note that none of the response strategies provide expected NPV's close to the optimal trajectory. The optimal trajectory shows a more cyclical stocking strategy, which may require more flexibility in capital or cooperation with other herders. While the feasibility of such a trajectory needs to be investigated further, the promise of major economic gains merits investigation into rotational or cyclical stocking strategies.

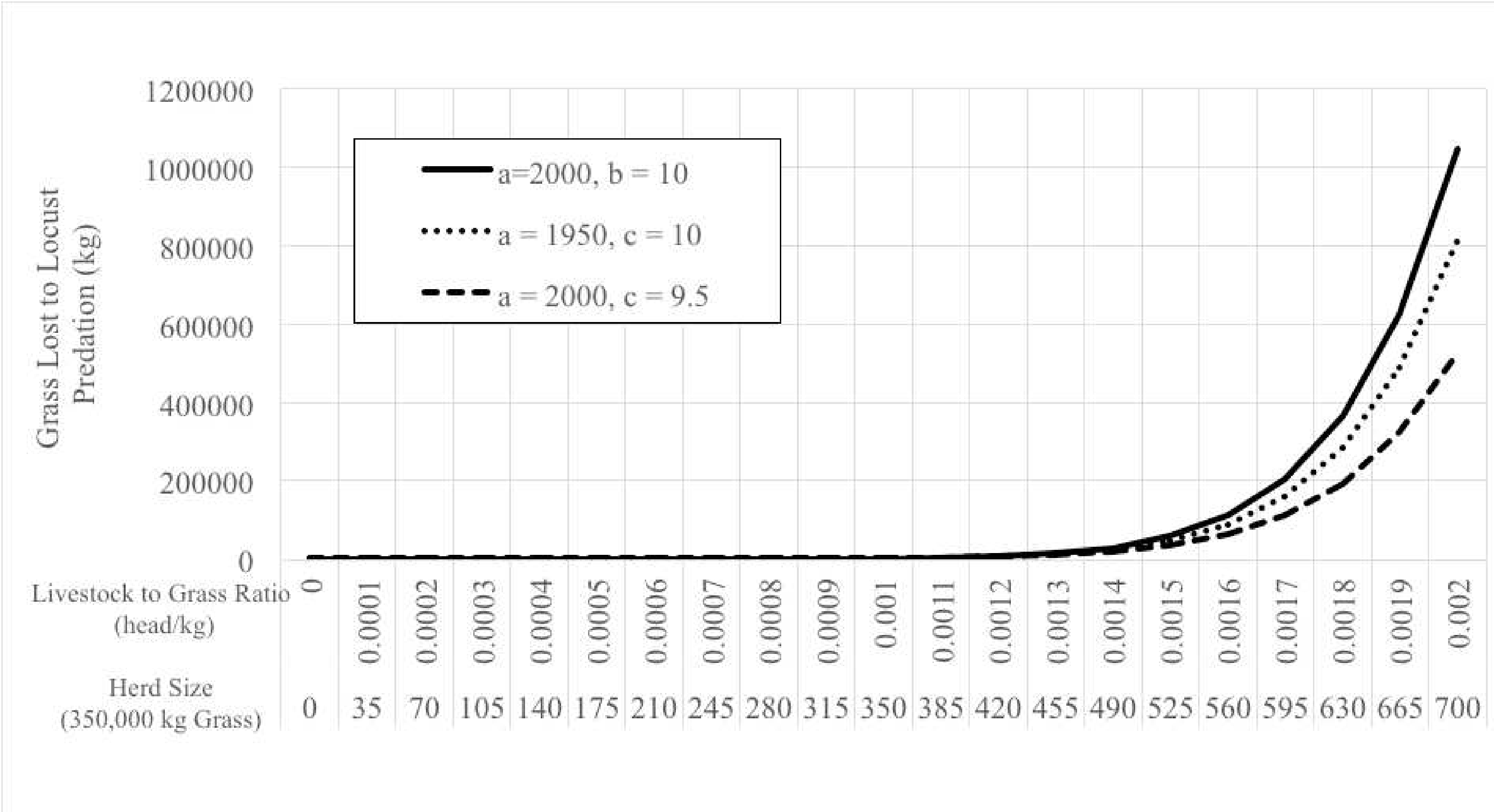

Figure 3.1: Locust Predation as a Function of Grazing Intensity

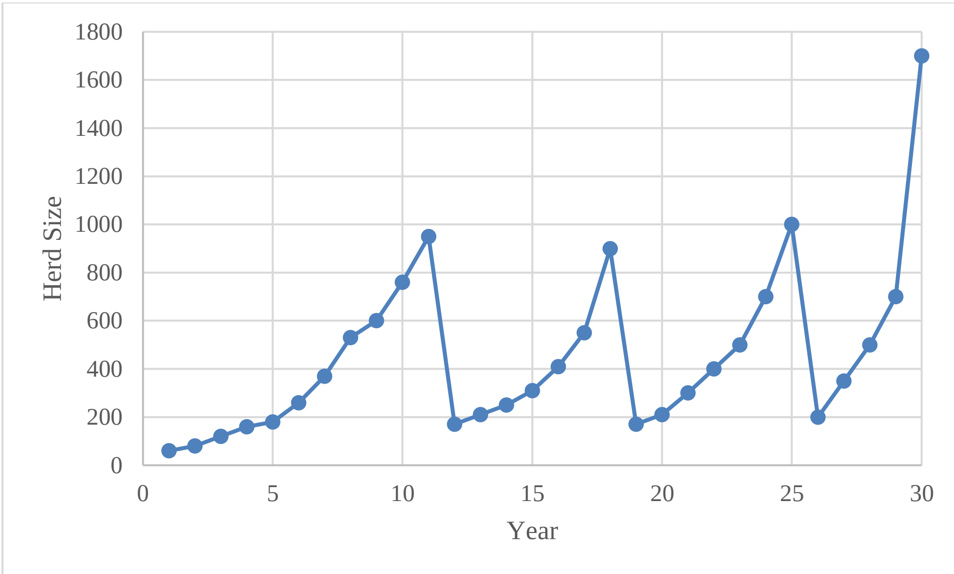

Figure 3.2: Optimal Trajectory

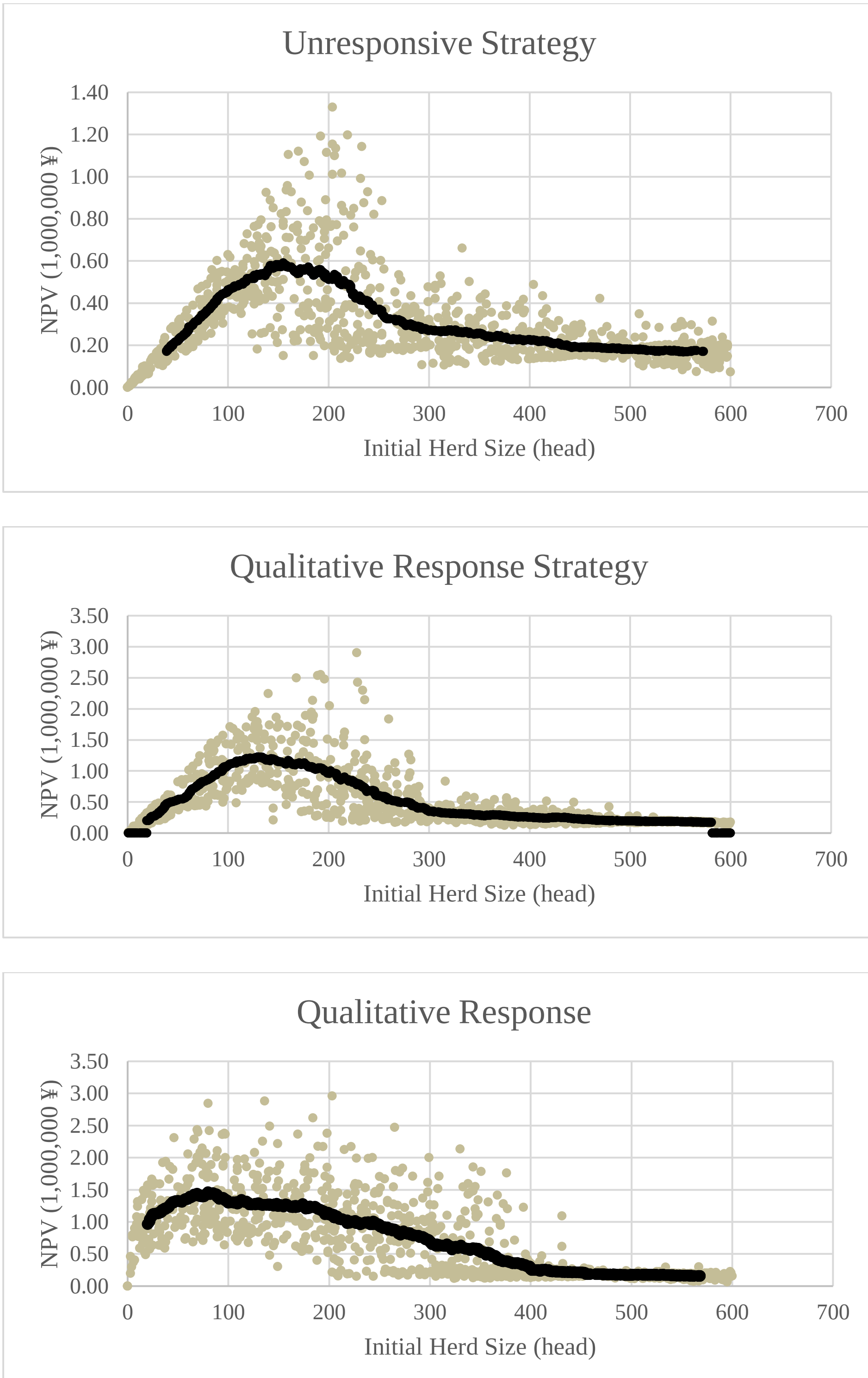

Figure 3.3: Simulation Results (Initial Herd Size vs. NPV)

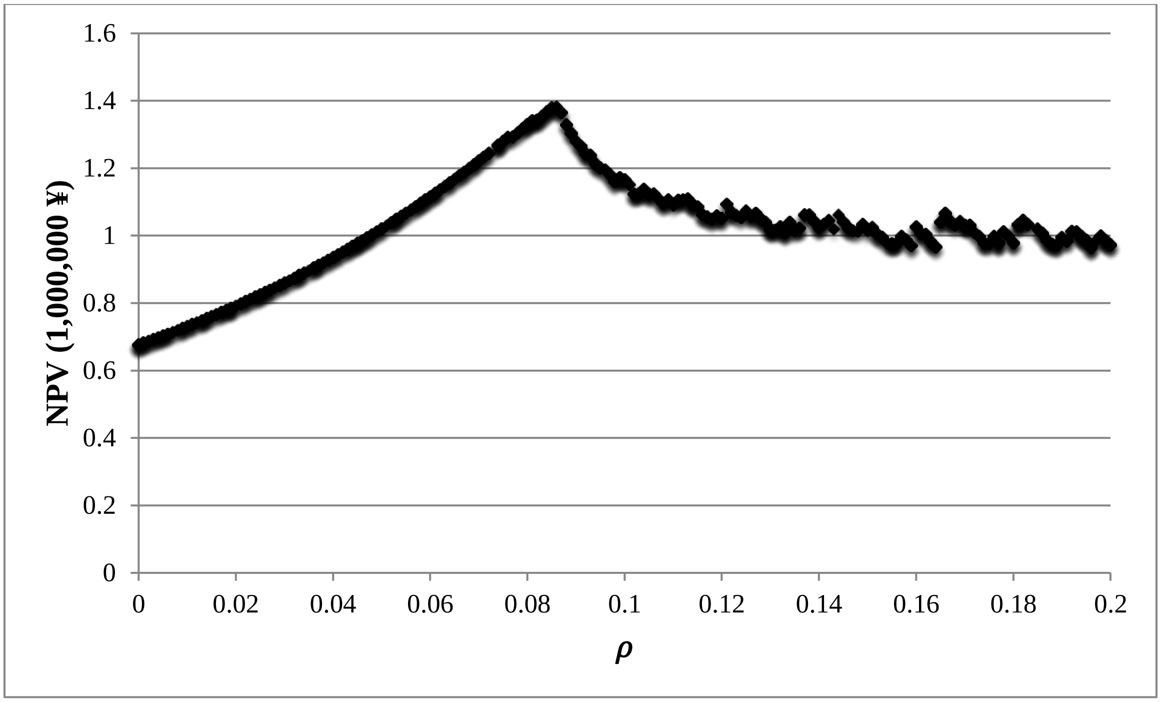

Figure 3.4: Identification of the Optimal ρ

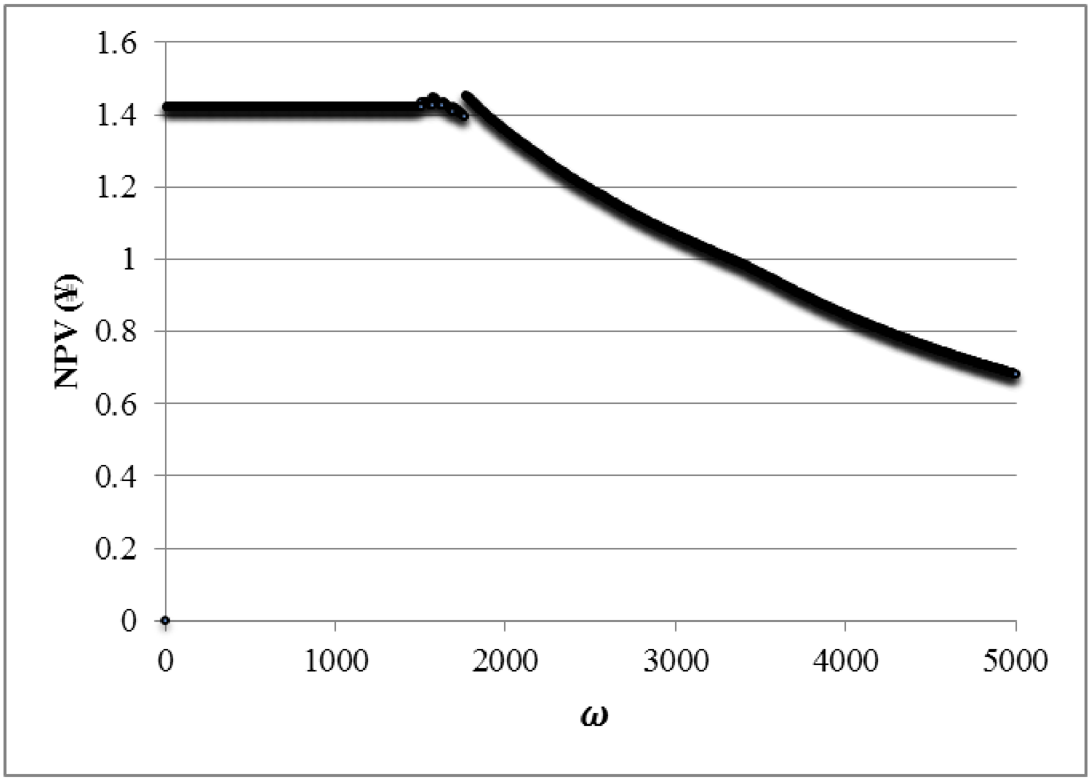

Figure 3.5: Identification of the Optimal *ω*

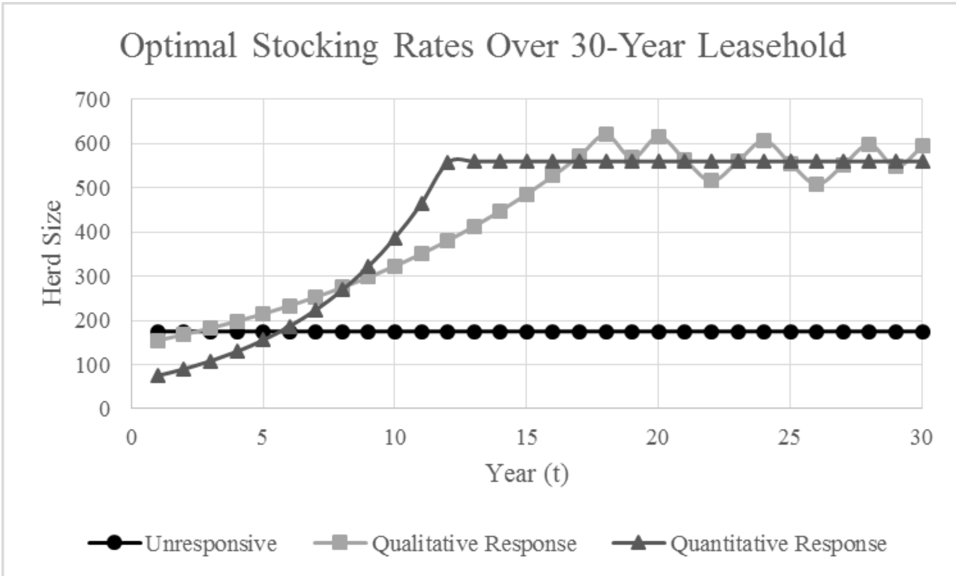

Figure 3.6: Herd Size Trajectories for Optimized Initial Herd Sizes

Table 3.1. Typical Herder Budget Characteristics

A. Herd Characteristics

	Composition of on LU
Sheep	81%
Goats	19%
Total	**100%**

B. Selling Prices

	Price	Unit				
Sheep	733.98	¥/head	x	0.81	=	¥594.52
Goats	655.79	¥/head	x	0.19	=	¥124.60
Total Price per LU						**¥719.12**

C. Input Prices

	Price	Unit
Corn (Feed)	1.73	¥/kg
Hay (Feed)	1.25	¥/kg
Vet & Health	4.20	¥/head
Salt	2.46	¥/head

Table 3.2: Variable Definitions and Distributions for Simulation Trials

Variable	Unit		
		Objectives	
NPV: Net Present Value	¥		
π_t: Profit in year t	¥		
		Decision Variables	
$\bar{L}_t$: Herd Size in Year t	$head$		
		State Variables	
Q_t^G: Quantity of Grass in Year t	kg		
		Exogenous Variables (with Distributions for Simulation Trials)	
		Distribution	Source
τ^{LF}: Feed Conversion Ratio	$\frac{kg}{head}$	U(500,700)	IMAU Survey Data 2012, 2013, 2014
r^G: Intrinsic Rate of Grass Growth	$\frac{kg}{kg \cdot year}$	U(0.25,0.45)	Berry, et al. (forthcoming)
a: Locust Predation Parameter "a"	unitless	U(1800,2200)	Identified to align with results from Cease et al. (2012)
b: Locust Predation Parameter "b"	unitless	U(9,11)	Identified to align with results from Cease et al. (2012)
P^L: Price of Livestock	¥	U(650,750)	IMAU Survey Data 2012, 2013, 2014
P^F: Price of Feed	¥	U(1.2,1.5)	IMAU Survey Data 2012, 2013, 2014
δ: Discount Factor	unitless	U(0.01,0.10)	Pétry 1995; Lence 2000
ϵ: Stochastic Residual	¥	U(-100,000, 100,000)	Wang et al. (2014)

Table 3.3: Coefficient Estimates for Eq. (11) – (13)

		Estimate (Standard Error)		
	Associated Exogenous Variable (Mean Value, Unit)	Unresponsive	Qualitative Response	Quantitative Response
β_0	constant (¥)	18,340.5 (343,594.3)	-542,208.7*** (91,495.37)	-825750.9*** (186067.9)
β_1	r^G: Intrinsic Rate of Grass $(0.35 \frac{kg}{kg \cdot year})$	2,493,215*** (772934.9)	1,012523*** (176,333.5)	3,015,437*** (194,003.6)
β_2	τ^{LF}: Livestock Feed Conversion Ratio $\left(600\ \frac{kg}{head \cdot year}\right)$	-1,204.03*** (122.41)	-413.92*** (84.57)	-1,025.209*** (95.31)
β_3	P^L: Price of Livestock $(700 \frac{¥}{head})$	639.64*** (231.66)	1688.49*** (84.93)	2,186.64*** (174.65)
β_4	P^F: Price of FEed $(1.35 \frac{¥}{kg})$	-12,684.68 (79083.52)	-11,205.4 (40,917.24)	-105,968.5 (82,960.04)
β_5	$\overline{L_{30}}$: Final Herd Size (head)	-	1130.502*** (31.81)	-48.6607 (76.30)

Levels of Significance: $* \leq 0.05, ** \leq 0.01, *** \leq 0.001$

CHAPTER 4: CONCLUSIONS

Our results demonstrate possible outcomes for herders in Inner Mongolia. In our first analysis, we find that these herders could lose significant profit if impacted by a locust event. In our second analysis, we find that choosing herd sizes in response to grass availability would allow herders to dramatically increase their expected profits over time. However none of this analysis allows us to say what the future holds for Inner Mongolian herders. That, ultimately, is up to them. A next step is to utilize pathways for communicating our findings and those of our colleagues to the herders and other stakeholders in Inner Mongolia. As we continue our conversation with them, we can improve our models and help them to improve their grazing practices.

As mentioned in the introduction to this thesis, our research fits within the broader scope of the *Living with Locusts* project, which examines the relationship between livestock producers and migratory locusts in three locations: Inner Mongolia (China), New South Wales (Australia), and Senegal. All research done by this group is shared with collaborators in the US, China, Australia and Senegal. The models presented here could and should be applied to the other two locations of interest (Australia and Senegal) in order to deepen our understanding of the conditions faced by Australian and Senegalese livestock producers.

REFERENCES

Baro M, Deubel TF. 2006. “Persistent hunger: Perspectives on vulnerability, famine, and food security in sub-Saharan Africa.” Annual Review of Anthropology. 35: 521–538.

Belhaj, M. (1998). Environmental Economics of Desert Locusts, The Case of Morocco and Sudan (Draft Report)

Belhaj, M. (2001). The Economics of Desert Locusts, The Case of Eriteria (Draft Report).

Brader, L. 1988. “Control of grasshoppers and migratory locusts.” Brighton Crop Protection Conference, Pests and Diseases. 1: 283 - 288

Cease, Arianne, James Elser, Eli Fenichel, Brian E. Robinson, Joleen Hadrich, and Jon Harrison. "Living with Locusts." Living with Locusts. NSF-CNH Team: Living with Locusts, n.d. Web. 5 May 2016.

Cease, A. J., J. J. Elser, C. F. Ford, S. Hao, L. Kang, and J. F. Harrison. 2012. "Heavy Livestock Grazing Promotes Locust Outbreaks by Lowering Plant Nitrogen Content." *Science* 335(6067): 467-69.

Cease, A. J., J. J. Elser, E.P. Fenichel, J.C. Hadrich, J.F. Harrison, and B. E. Robinson. 2015. “Living with Locusts: Connecting Soil Nitrogen, Locust Outbreaks, Livelihoods, and Livestock Markets.” *Bioscience* 65(6): 551 – 558.

Clark, Colin Whitcomb. 2010 Mathematical Bioeconomics: The Mathematics of Conservation.

Clark, Colin Whitcomb, and Marc Mangel. 2000. Dynamic State Variable Models in Ecology: Methods and Applications. New York: Oxford UP.

“Country Report: China Sheep Meat.” 2013. United Kingdom. Agriculture and Horticulture Development Board

De Vreyer P, N. Guilbert, and S. Mesplé-Somps. 2015. Impact of natural disasters on education outcomes: Evidence from the 1987–89 locust plague in Mali. Journal of African Economies 24: 57-100.

Fan, Shenggen, Eric J. Wailes, and Gail L. Cramer. 1995. “Household demand in rural China: A two-stage LES-AIDS model.” American Journal of Agricultural Economics. 77(1): 54 – 63.

Finnoff, David, Aaron Strong, and John Tschirhart. 2008. “A Bioeconomic Model of Cattle Stocking on Rangeland Threatened by Invasive Plants and Nitrogen Deposition.” American Journal of Agricultural Economics. 90(4): 1074 – 1090.

Hardin, G. 1968. “The Tragedy of the Commons.” Science. 162: 1243 – 48.

Hoddle, Mark S., Karen M. Jetter, and Joseph G. Morse. 2003. "The Economic Impact of Scirtothrips Perseae Nakahara (Thysanoptera: Thripidae) on California Avocado Production." Crop Protection 22(3): 485-93.

Holechek, Jerry, Rex D. Pieper, and Carlton H. Herbel. Range Management: Principles and Practices. Englewood Cliffs, NJ: Prentice Hall, 1989. Print.

Hunter, D.m, R.j Milner, J.c Scanlan, and P.a Spurgin. "Aerial Treatment of the Migratory Locust, Locusta Migratoria (L.) (Orthoptera: Acrididae) with Metarhizium Anisopliae (Deuteromycotina: Hyphomycetes) in Australia."Crop Protection 18.10 (1999): 699-704.

Jiang X. Maimaitiming, Zhang L. 2003. “Nocturnal Migration of Grasshopper (Acrididae: Oedaleus asiaticus)”. Dept. of Entomology, China Agricultural University

Jiang, Gaoming, Xingguo Han, and Jianguo Wu. 2007. "Restoration and Management of the Inner Mongolia Grassland Require a Sustainable Strategy." AMBIO: A Journal of the Human Environment 35(5):269-70.

Kang, L. Han X., Zhang Z., Sun O.J. 2007. “Grassland ecosystems in China: Review of current knowledge and research advancement.” Philosophical Transactions of the Royal Society. B 362: 997 – 1008.

Karp, Larry and Arden C. Pope. 1984. “Range Management under Uncertainty.” American Journal of Agricultural Economics. 66(4): 437 – 446.

Krall, S., R. Peveling, and D. Ba Diallo. 1997. New Strategies in Locust Control. Basel: Birkhauser Verlag,

Lence, Sergio H. "Using Consumption and Asset Return Data to Estimate Farmers' Time Preferences and Risk Attitudes." American Journal of Agricultural Economics 82.4 (2000): 934-47. Web.

Li, Chunli, Xiying Hao, Mengli Zhao, Guodong Han, Walter D. Willms. 2008 “Influence of historic sheep grazing on vegetation and properties of a Desert Steppe in Inner Mongolia.” Agriculture, Ecosystems & Environment. 128(1-2): 109 – 116.

Li, Wenjun and Lynn Huntsinger. 2011. “China’s Grassland Contract Policy and its Impacts on Herder Ability to Benefit in Inner Mongolia: Tragic Feedbacks.” Ecology and Society. 16(2)

Lomer, C.J., R.P. Bateman, D.L Johnson, J. Langewald, and M. Thomas. 2001. “Biological Control of Locusts and Grasshoppers.” Annual Review of Entomology. 46: 667 – 702.

Maiga, I.H., Lecoq, M. & Kooyman, C. 2008 Ecology and management of the Senegalese grasshopper Oedaleus senegalensis (Krauss 1877) (Orthoptera: Acrididae) in West Africa: review and prospects. Ann Soc Entomol Fr 44, 271-288.

McKay, Lloyd, Denis Lawrence and Chris Vlastuin. 1980. “Input Demand and Substitution in the Australian Sheep Industry.” Review of Marketing and Agricultural Economics. 48(2): 57 – 70.

Miranda, Mario J., and Paul L. Fackler. Applied Computational Economics and Finance. Cambridge, MA: MIT, 2002

Ortega, David, H. Holly Wang, and James S. Eales. 2009. “Meat demand in China.” China Agricultural Economic Review. 1(4): 410 – 419.

Pandey, Sushil. "A Stochastic Dynamic Programming Framework for Weed Control Decision Making: An Application to Avena Fatua L." 1991. Agricultural Economics 6(2): 115-28.

People's Republic of China. Ministry of Agriculture. Agri-product Wholesale Market Information Network. Wholesale Prices for Selected Non-staple Agri-food Products - Nov. 10, 2015. N.p., n.d. Web. 10 Nov. 2015.

Pétry, F. Sustainability Issues in Agricultural and Rural Development Policies. Trainer's Kit. Rome: Food and Agriculture Organization of the United Nations, 1995. Print.

Pope, C. Arden and Gary L. McBryde. 1984. “Optimal Stocking of Rangeland for Livestock Production.” Western Journal of Agricultural Economics. 9(1): 160 – 169.

Quaas, Martin F., Stefan Baumgärtner, Christian Becker, Karin Frank, and Birgit Müller. 2007. “Uncertainty and sustainability in the management of rangelands.” Ecological Economics. 62: 251 – 266.

Rodriguez, Abelardo and R.G. Taylor. 1988. “Stochastic Modeling of Short-Term Cattle Operations.” American Journal of Agricultural Economics. 70(1): 121 – 132.

Shi, Wang-Peng, Yan-Yan Wang, Fen Lv, Cheng Guo, and Xu Cheng. 2008. "Persistence of Paranosema (Nosema) Locustae (Microsporidia: Nosematidae) among Grasshopper (Orthoptera: Acrididae) Populations in the Inner Mongolia Rangeland, China." BioControl. 54(1): 77-84.

Shumway, Richard C., Roberto R. Saez, Pablo E. Gottret. 1988. “Product Supply and Input Demand in U.S. Agriculture.” American Journal of Agricultural Economics. 70(2): 330 – 338.

Taylor, C. R. Applications of Dynamic Programming to Agricultural Decision Problems. Boulder: Westview, 1993.

Torrell, L. Allen, Kenneth S. Lyon, and E. Bruce Godfrey. 1991. “Long-Run versus Short-Run Planning Horizons and the Rangeland Stocking Rate Decision.” American Journal of Agricultural Economics. 73(3): 795 – 807

Tweeten, Luther G. and C. Leroy Quance. 1969. “Positivistic Measures of Aggregate Supply Elasticities: Some New Approaches.” American Journal of Agricultural Economics. 51(2): 342 – 352.

United States. USDA. Economic Research Service. China Agricultural and Economic Data. N.p., 2010. Web. 10 Nov. 2015.

Vallentine, John F. Grazing Management. San Diego: Academic, 1990.

Wang, Zhongwu, Shuying Jiao, Guodong Han, Hengli Zhao, Haijun Ding, Xinjie Zhang, Xiaoliang Wang, Eldon L. Ayers, Walter D. Willms, et al. 2014. “Effects of Stocking Rate on the Variability of Peak Standing Crop in a Desert Steppe of Eurasia Grassland.” Environmental Management. 53(2): 266 – 273.

Whipple, Glen D. and Dale J. Menkhaus. 1989. "Supply Response in the U.S. Sheep Industry." American Journal of Agricultural Economics. 71(1): 126 – 135

Wohlgenant, Michael K. 2011. "Consumer Demand and Welfare in Equilibrium Displacement Models," in Lusk, J., J. Roosen, and J. Shogren, ed., Handbook on the Economics of Food Consumption and Policy (Oxford University Press), chapter 11.

Workman, J.P. 1986. Range Economics. New York: Macmillan Co.

Xiao, X., D. S. Ojima, W. J. Parton, Z. Chen and Z. Chen. "Sensitivity of Inner Mongolia grasslands to climate change." Journal of Biogeography. 22: 643 – 648.

Zhuang, Renan and Philip Abbott. 2007. "Price elasticities of key agricultural commodities in China." China Economic Review. 18(2): 155 – 169