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LIFESTOCK ASSET DYNAMICS AMONG PASTORALISTS IN NORTHERN KENYA

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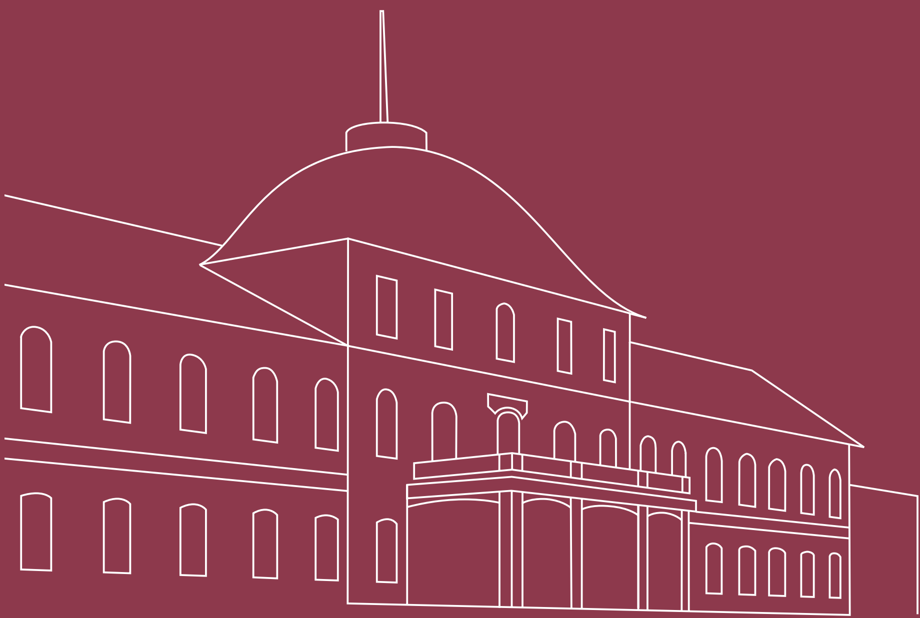

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Livestock asset dynamics among pastoralists in Northern Kenya

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Research Area "INEPA – Inequality and Economic Policy Analysis"

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Abstract

Understanding household-level asset dynamics has important implications for designing relevant poverty reduction policies. To advance this understanding, we develop a microeconomic model to analyze the impact of a shock (for example a drought) on the behavioral decisions of pastoralists in Northern Kenya. Using household panel data this study then explores the livestock asset dynamics using both non-parametric and semi-parametric techniques to establish the shape of the asset accumulation path and to determine whether multiple equilibria exist. More specifically, using tropical livestock units as a measure of livestock accumulation over time, we show not only that these assets converge to a single equilibrium but that forage availability and herd diversity play a major role in such livestock accumulation.

Keywords: Poverty dynamics, pastoralists, livestock, semi-parametric estimation, Kenya

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Introduction

Even though globally the number of people living in extreme poverty declined from 1.9 billion in 1990 to 836 million in 2015, poverty alleviation remains a key challenge for many countries across the world. In sub-Saharan Africa, for example, over 40 per cent of the population still lives in extreme poverty (that is, less than $1.25 per day), which the United Nations hopes to eradicate by 2030 as one of its sustainable development goals (United Nations 2015). Another goal is to halve the proportion of those living in poverty in all its dimensions[1] over the same period (OECD 2013; United Nations 2015). Achieving these aims, however, is dependent on effective policies, whose design requires a clear understanding of the underlying welfare dynamics that determine how households escape from or fall into poverty. One particularly crucial factor for poverty alleviation is household accumulation of assets, particularly productive assets that enable them to raise their incomes.

Among pastoralists living in arid and semi-arid areas the key asset for income, food security, wealth, and social status is livestock (Swift 1986), which researchers therefore use as the primary measure to assess poverty and wealth dynamics within this population. In Kenya for example, the pastoralist flock accounts for 50–70 per cent of Kenya's total livestock production (Idris 2011). Despite this considerable contribution, pastoralist livestock are a relatively risky asset, with changes in herd sizes greatly affected by drought and illnesses (Fafchamps 1998). Pastoralist areas in Northern Kenya are particularly characterized by chronic vulnerability to drought-related shocks which has been leading to declining herd sizes over time (Chantarat et al. 2012). The area has experienced 28 droughts in the past 100 years, four of the largest in the period 1998-2008 (Adow 2008).

This study throws further light on the effect of drought on livestock asset dynamics through a three-stage exploration among pastoral households in Northern Kenya's Marsabit district. First, we develop a microeconomic model with which to analyze the impact of a shock like drought on the pastoralists' behavioral decisions. Second, using tropical livestock units, we apply both nonparametric and semiparametric methods to identify the path of asset accumulation and determine the presence (absence) of single and multiple dynamic equilibria. By doing so, we are able to verify the existence of poverty traps. Third, because livestock is this population's main source of livelihood, we assess how household characteristics and environmental factors influence livestock accumulation over time, an aspect that warrants closer examination given the prevalence of droughts and inadequate insurance mechanisms.

This study contributes to the literature in four ways: First, few of the extant empirical studies on asset dynamics in developing countries provide a theoretical framework that can explain how households react to environmental change. To begin filling this gap, our microeconomic model sheds light on how a shock influences such factors as livestock holdings, consumption, and aid. Second, because our work draws on unique panel data from the International Livestock Research Institute's (ILRI) Index-Based Livestock Insurance (IBLI) project, it is one of the most comprehensive studies to date on asset dynamics among pastoralists. Third, our analysis extends previous research by applying both non- and semiparametric techniques to compare the estimations of livestock asset dynamics. Finally, our investigation identifies the effect of forage availability (proxied by satellite data) on livestock accumulation, which few other studies do.

The remainder of the paper is organized as follows: Section 2 outlines our theoretical model of how a pastoralist household reacts to an external shock. Section 3 then reviews the relevant research on asset welfare dynamics. Section 4 describes our data, after which section 5 explains our methodological approach. Section 6 reports and discusses our results, and section 7 concludes the paper.

Asset dynamics model

Household welfare dynamics tend to be described in terms of three presumptions: unconditional convergence, conditional convergence, or multiple dynamic equilibria (Carter and Barrett 2006). Unconditional convergence hypothesizes that all households tend to move to a single long-term equilibrium, meaning that asset dynamics follow a concave path. Under conditional convergence, welfare dynamics follow a similar path to that in single stable equilibrium except that each household subgroup moves toward its own equilibrium. In both the conditional and unconditional convergence conditions, therefore, poverty traps can only occur if the long-term equilibrium is below the poverty line. Under the multiple dynamic equilibria presumption, however, the welfare path follows a nonconvex pattern with two stable high and low equilibria and an unstable threshold point (Naschold 2013). Households with assets below the unstable threshold point lose their assets and tend toward a chronically poor state, while households with assets above the threshold point tend to accumulate assets and move toward higher levels of welfare.

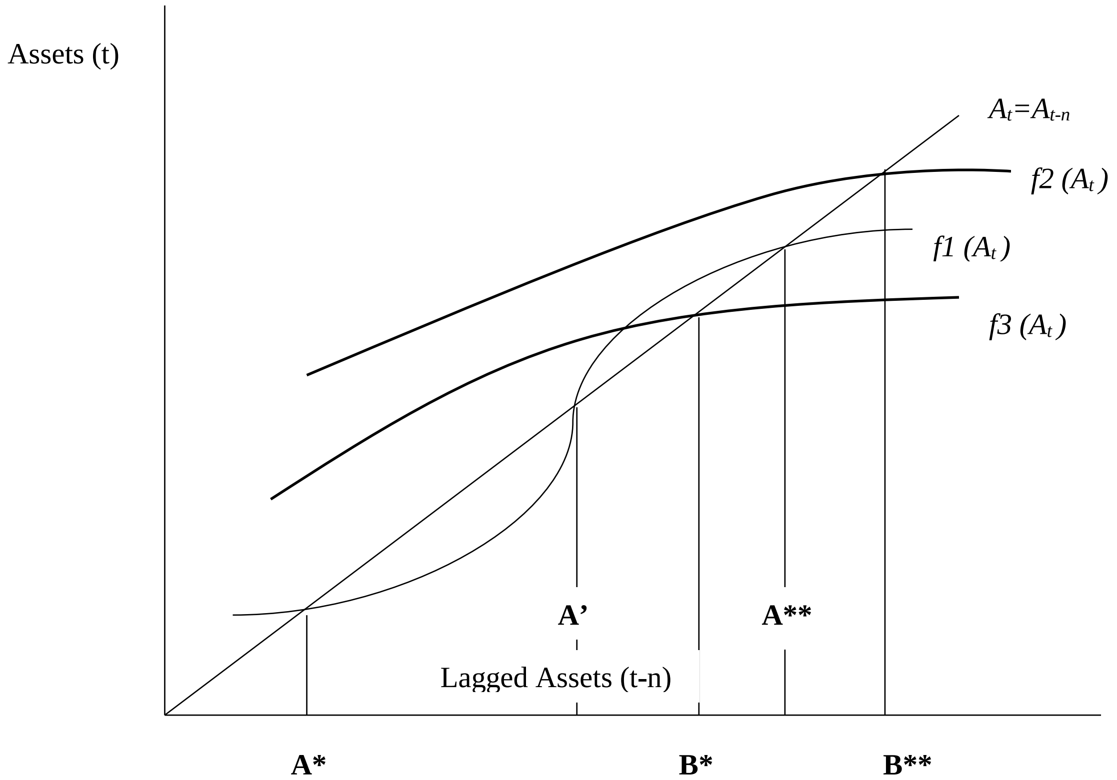

Figure 1. Different asset accumulation paths

In the different paths depicted in Figure 1, the vertical axis shows the current assets (A_t) and the horizontal axis, the lagged asset holdings (A_{t-n}). Unconditional convergence is represented by line f_2 (A_t) for which only a single equilibrium exists at its intersection with the 45^0 line. Conditional convergence is represented by functions f_2 (A_t) and f_3 (A_t) for different household subgroups, each with its own equilibrium. The unconditional convergence represented by functions f_2 (A_t) and f_3 (A_t) implies structural asset poverty if the stable equilibrium points **B*** and **B**** lie below the poverty line. Line f_1 (A_t), which crosses the 45^0 line three times, represents multiple dynamic equilibria, with points **A*** and **A**** designating a stable low-level and high-level equilibrium, respectively, and Point **A'** representing the unstable threshold point at which assets bifurcate. When the poverty line lies below A**, point A' represents the dynamic asset poverty threshold moving above which leads to asset accumulation until long-run equilibrium is reached at point A**. Movement below A' propels households toward the low-level equilibrium at A*.

Clearly identifying the levels and shape of household welfare dynamics has important policy implications. For a single dynamic equilibrium, the key question is whether the equilibrium is below or above the poverty line. If above the poverty line, then policy needs to focus on how to support households in maintaining and raising their welfare levels so as to speed up the convergence process. If the equilibrium is below the poverty line, households are likely to be trapped in poverty, implying a need for structural changes that raise household welfare levels. In the case of pastoralists, this latter could take the form of more livestock provision accompanied by such asset protection measures as livestock insurance and forage preservation. In the presence of multiple equilibria, it is the household's initial condition that matters. If the household starts above (below) the critical threshold, it can be expected to move toward higher (lower) welfare levels. This situation thus requires policy measures that ensure households do not fall below the threshold, especially after adverse shocks. In this case, designing efficient policies requires clear identification of the threshold point (Naschold 2012; Giesbert and Schindler 2012).

To assess how shocks that shift pastoralists away from such an equilibrium translate into behavioral changes, we develop a model based on standard neoclassical growth (Romer 1994; Mixon and Sockwell 2007; Walsh 2000). We focus on a representative pastoralist agent characterized by the following utility function:

$$u\left(c_t, l_t^h, l_t^e\right) = c_t^\alpha + \beta ln\left(1 - l_t^h\right) + \gamma ln(1 - l_t^e) \quad (1)$$

where c_t is consumption in period *t*, l_t^h is labor time allocated to one's own livestock in period *t*, and l_t^e is labor time on the local labor market, where $\alpha \in (0,1]$ and $\beta, \gamma \in \mathbb{R}_+$ represent the output elasticities. The pastoralist agent must thus choose between l_t^h and l_t^e while taking the following time constraint into consideration:

$$l_t^h + l_t^e + F_t = \omega_t \quad (2)$$

where $F_t = \mathrm{F}$ is leisure time, and $\omega_t = \omega$ is total available time. Normalizing $\omega - F \equiv 1$ then yields the following constraint:

$$l_t^h + l_t^e = 1 \quad (3)$$

Because our setting is intertemporal, the pastoralist agent faces the following optimization problem (with $\xi \in (0,1]$ being the pastoralist's intertemporal discount factor and E_0 the expectations operator):

$$max_{c_t, l_t^h, l_t^e, k_{t+1}} E_0\left[\sum_{t=0}^{\infty} \xi^t u\left(c_t, l_t^h, l_t^e\right)\right] \quad (4)$$

This latter is subject to the following constraints:

$$k_{t+1} = {k_t}^\tau - \delta {k_t}^\tau + l_t^h {k_t}^\tau - c_t + w_t l_t^e + (\mu) * ex\,p(z_t) * k_t^\tau + A(k_t, z_t) \quad (5a)$$

$$l_t^h + l_t^e = 1 \quad (5b)$$

$$\lim_{t \to \infty} \xi \frac{u'(c_{t+1})}{u'(c_0)} k_t = 0 \quad (5c)$$

$$z_t = \rho z_{t-1} + \varepsilon \qquad \epsilon \sim N(0, \sigma^2) \quad (5d)$$

Equation (5a) describes the transition equation of capital (k) (that is, the motion of livestock over time, with $\tau \in (0,1)$ being the elasticity of livestock accumulation). Capital in k_{t+1} is thus influenced by the time-independent depreciation rate δ (where $\delta \in (0,1)$), the pastoralist consumption c_t in *t*, and the share of time devoted to l_t^h and l_t^e. This last aspect, time allocation, is the crucial decision for pastoralists in rural areas who can either tend their own livestock or work for a certain wage w_t in the labor market. Capital stock can also be influenced by the shock term $(\mu) * exp(z_t)$, where z_t is assumed to be an *AR(1)* autoregressive shock process (where $\rho \in (0,1)$), and μ (where $\mu \in \mathbb{R}_+$) reflects the impact of the shock on the pastoralists' livestock. We further assume that the pastoralists receive aid, represented by the function A: $\mathbb{R}^2 \longrightarrow \mathbb{R}_+$, where $A(k_t, z_t) > 0, \frac{\partial A(k_t, z_t)}{\partial k_t} < 0 \ \nabla\, k_t \in \mathbb{R}\backslash\{0\}$ and $\frac{\partial A(k_t, z_t)}{\partial z_t} < 0 \ \nabla\, z_t \in \mathbb{R}$. The second constraint is given by the time constraint from Equation (5b), the third constraint (Equation 5c) is the so-called transversality condition, which ensures that ultimately, no capital is left. Because the marginal benefit of working in the labor market is determined by wage w_t, our model also includes the optimization problem for a representative firm:

$$max_{l_t^e} Q(l_t^e) = y(l_t^e) - \varphi(l_t^e) \tag{6}$$

with y and φ given by:

$$y(l_t^e) = P(l_t^e)^{\Gamma} exp(z_t)$$

$$\varphi(l_t^e) = w_t l_t^e$$

For the sake of simplicity, we assume that firms only use labor l_t^e as an input factor in the production function y, where $(P \in \mathbb{R}_+)$ is the total factor productivity and Γ $(\Gamma \in (0,1))$ is the output elasticity. We also normalize prices to 1. Again, $exp(z_t)$ represents the impact of the *AR (1*) shock process on the firm's output, while $\varphi(l_t^e)$ reflects the explicit cost function. The representative firm maximizes its profit $Q(l_t^e)$ by choosing the optimal amount of labor l_t^e in each period *t*.

If we solve both optimization problems (Equations (4) and (6)), we can reformulate the resulting calculations to obtain equations (7a), (7b) and (7c) and combine with equations (5a), (5b) and

(5d) as the following set of characterizing equations for the model (detailed description of the derivation and proofs are given in the Appendix):

$$\xi E_t\{c_{t+1}^{(\alpha-1)}[(l_{t+1}^h + 1 - \delta + (\mu)exp(z_{t+1}))\tau k_{t+1}{}^{\tau-1} + \frac{\partial A(k_{t+1},z_{t+1})}{\partial k_{t+1}}]\} = c_t^{(\alpha-1)} \tag{7a}$$

$$\frac{(1-l_t^h)}{(1-l_t^e)}\frac{\gamma}{\beta} = \frac{w_t}{k_t{}^\tau} \tag{7b}$$

$$w_t = P\Gamma l_t^{e(\Gamma-1)} exp(z_t) \tag{7c}$$

$$k_{t+1} = k_t{}^\tau - \delta k_t{}^\tau + l_t^h k_t{}^\tau - c_t + w_t l_t^e + (\mu) * ex\,p(z_t) * k_t^\tau + A(k_t, z_t)$$

$$l_t^h + l_t^e = 1$$

$$z_t = \rho z_{t-1} + \varepsilon$$

Equation (7a) can be interpreted as the Euler equation that links consumption in period *t* to consumption period *t+1*. It is evident that the intertemporal consumption decision depends not only on the expected work time allocation in the next period but also on expectations of the marginal benefits of next period's aid. We also observe that the proportion of l_t^h and l_t^e is related to both capital stock and wage (equation 7b) and that wage is positively influenced by the pastoralist's external labor force participation (equation 7c). Given our interest in how a shock affects equilibrium, we must first solve for a steady state. Because we cannot solve for a steady state algebraically without restricting our model, we compute the steady state results numerically.[2]

The analysis also requires that we specify an explicit form for our aid function *A*:

$$A(k_t, z_t) = \frac{\theta}{exp(k_t)} + r - \zeta exp(z_t), \tag{8}$$

This specification satisfies the conditions for the aid function outlined above; that is, it is characterized by a constant stream of aid, $r \in \mathbb{R}_+$, and two parameters $\theta \in \mathbb{R}_+$ and $\zeta \in (0,1]$, which represent an aid sensitivity factor with regard to livestock and the extent of the aid flow's reaction to shock, respectively. The aid stream thus depends inversely on the pastoralists' capital stock, as well as on the impact of particular shocks. Based on previous literature and economic considerations (Wang et al. 2016; Liebenehm and Waibel 2014; Poulos and Whittington 2000; Holden et al. 1998 for time preferences), we use the parameter values in Table 1 to compute the steady state:[3]

Table 1. Parameter values used to compute the steady state

α	β	γ	ξ	ζ	μ	δ	θ	r	P	τ	ρ	σ	Γ
0.5	*1*	*2*	*0.8*	*0.5*	*1*	*0.05*	*3*	*2*	*1*	*0.78*	*0.92*	*0.1*	*0.8*

These parameters yield one single stable equilibrium characterized by the following steady state values:

Table 2. Estimated steady state values

Variable	$\bar{c}$	$\bar{l}^{e}$	$\bar{l}^{h}$	$\bar{k}$	$\bar{z}$	$\bar{w}$	$\bar{A}$
Steady state value	*10.15*	*0.08*	*0.92*	*14.19*	*0*	*1.33*	*1.5*

In equilibrium, we obtain a relatively high value for consumption relative to that for livestock (approximately 71% of the livestock score), which might be expected to give our assumption of a high discount rate (and thus a low discount factor). In our model, the low discount factor forces our representative agent (the pastoralist) to consume his livestock in the current period instead of saving it to produce more livestock tomorrow, which is in line with the empirical findings by (Liebenehm and Waibel 2014; Holden et al. 1998). The allocation of time to internal and external labor forces also shows a plausible pattern: our pastoralist devotes about 92 per cent of his time to his own livestock and only about 8 per cent to working elsewhere in the local economy. Figure 2 illustrates the k_t policy function, which maps the livestock of period *t-1* onto the livestock in period *t* while all other variables remain unchanged (that is, it is a function of the form $k_t = g(k_{-1})$). As expected in second order Taylor polynomial approximation, the policy function k is concave and intercepts with the 45° line at about 14.1, the same steady state value for livestock computed previously. This outcome indicates that the pastoralist accumulates livestock until a value of about 14.1, which is the stable equilibrium. If a positive or negative shock occurs, the livestock returns to its initial value. The function's special concave pattern, which includes a diminishing slope,[4] is a result of using a second-order Taylor polynomial approximation in calculating the steady state.

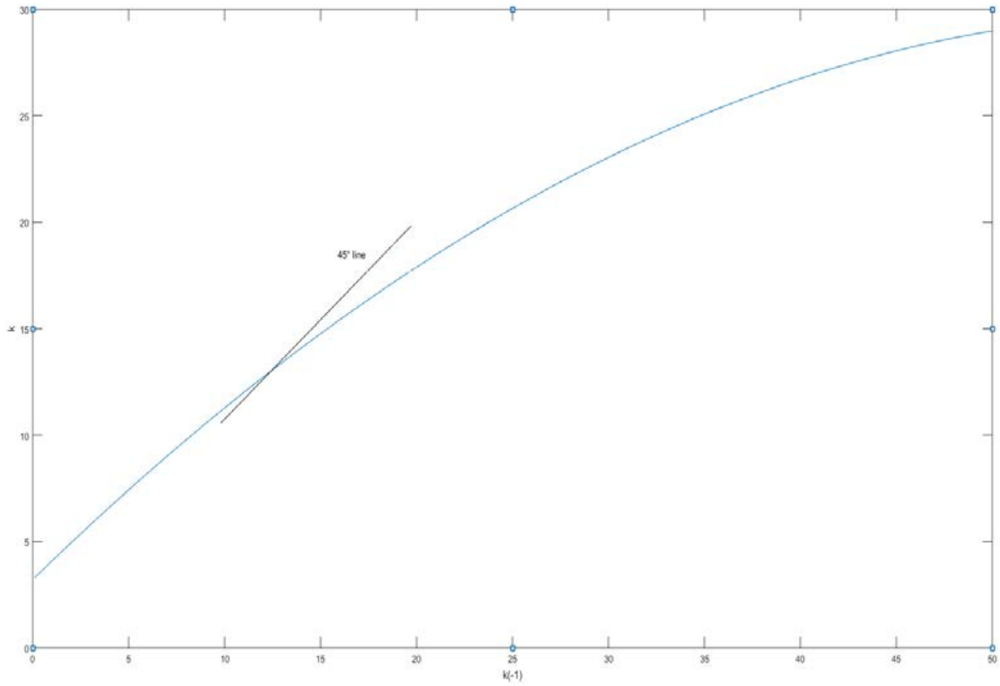

Figure 2: Policy function for k_t

Of particular interest to our analysis is the effect of a shock on the transition back to the steady state. To shed light on this issue, we use the impulse response function graphs displayed in Figure 3. In this analysis, we consider a negative one standard deviation shock to the system, with all variables set to their steady state values in the initial situation (and a normalized steady state value of 0 for all variables). The shock influences the economy in several ways. First, it forces a one standard deviation decrease in the *AR(1)* process in the first period with a smooth and monotonic increase back to the steady state value thereafter. Because the shock term is also included in the aid function, aid immediately has a positive reaction to the negative shock. However, the aid function is also influenced by a second factor: the shock's negative influence on the pastoralist's livestock, which is reflected in the graph by the decrease in capital stock k_t in the first period. Because aid is assumed to be negatively related to the pastoralist's livestock, this influence again leads to a reinforcement of aid's positive reaction. The shock also engenders a decrease in wages, which in turn has an immediate feedback effect on the pastoralist´s decision on time allocation for labor and thus on capital accumulation. The fact that our livestock accumulation function is concave in *k* produces higher marginal returns with a lower capital stock, which results in the pastoralist allotting more time to tending his own livestock. This effect is again reinforced by the negative wage effect in the labor market, which decreases his incentives to seek work in the local economy.

As regards consumption, the pastoralist reduces consumption slightly up to a certain point but then increases it again until it reaches the old equilibrium. In fact, comparing the different shock reactions of capital and consumption shows no sudden reduction in consumption during the first period but rather a smooth (and thus delayed) adjustment that leads to a reinforcement of capital stock reduction in the following period and consequently, a reduction in consumption. This process continues until the capital stock starts to grow again (due to the reinforcement of the pastoralist tending his own livestock), which also drives an increase in consumption. As regards the time needed for the economy to adjust, it takes about 60 periods for consumption, capital, aid, the *AR(1)* process, and the wage to return to equilibrium. Both labor time allocations (l_t^e, l_t^h) reach their initial steady state values after about five to eight periods, which is the same point in time that capital and consumption are at their lowest levels. During this period, the pastoralist increases the time spent working in the local economy while decreasing the time taken tending his own livestock relative to the steady state value. After this short increase (decrease) in labour, the work time decisions converge (with slight fluctuations) back to the steady state, reaching initial values after about 40 periods.

In sum, a negative shock like a drought leads to an immediate decrease in livestock followed by a smooth reduction in consumption. Because the shock also affects the local economy, it prompts a wage decrease, which reinforces the pastoralist's incentives to tend his own livestock and reduce time spent in the external labor market. Whereas the pastoralist's labor time allocation shows a pattern of quick convergence, however, the adjustment of other variables takes much longer. Finally, although aid initially increases in response to the shock, thereafter it converges smoothly.

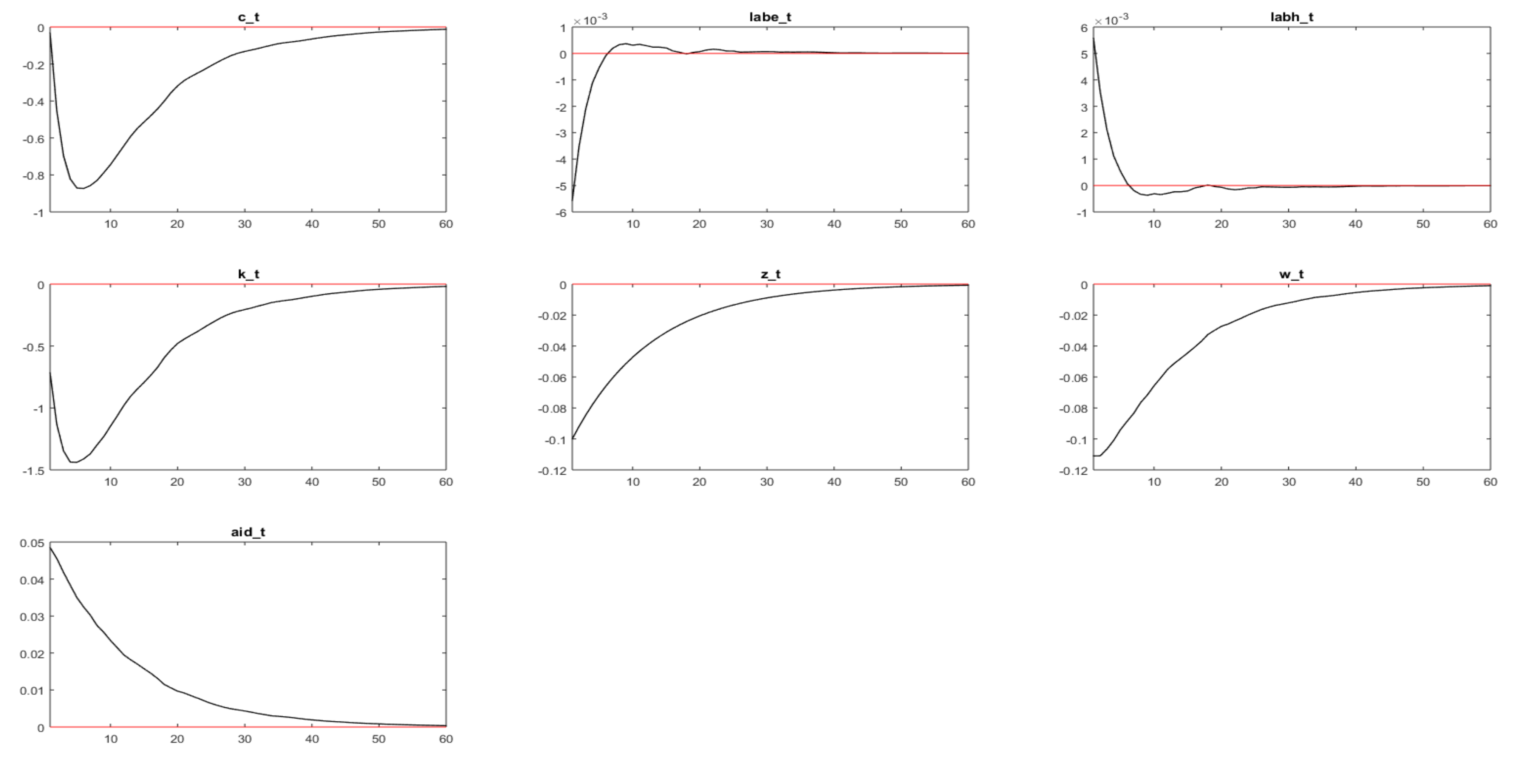

Figure 3. Impulse response functions of a one standard deviation shock of $\boldsymbol{\varepsilon}$

Note: The horizontal axes are time periods. The vertical axes can be interpreted as deviations from the generalized steady state (for more information, see (Pfeifer 2014)
Source: Authors' own calculations using Dynare.

In addition to assessing immediate reactions to a shock, we also examine how the local pastoralist economy develops over time. To do so, we simulate the economy based on our randomized shock distribution and compute the time paths for the variables of interest. We run our simulations twice: once assuming a comparatively low volatility for shocks ($\sigma = 0.1$) and again assuming a comparatively high volatility ($\sigma = 0.2$). Figure 4, which illustrates the different time patterns for internal and external labor, capital, and consumption for different values of σ, reveals several interesting insights. First, the lower bound of the fluctuations in capital and consumption reveals no large differences in the fluctuation patterns of low versus high volatility cases, implying that shock volatility plays no crucial role in determining the (absolute) negative impact on a pastoralist's livestock. This observation suggests that higher shock volatility does not necessarily lead to an increase in periods with very low capital stocks. This finding does not hold, however, for the upper bound in which higher volatility leads to more and longer periods of higher capital accumulation (and higher consumption).

The graphs for internal and external labor follow the same pattern, with the lower bound (external labor) and higher bound (internal labor) of the two fluctuation patterns showing little difference. The upper bound (external labor) and lower bound (internal labor), however, reveal stronger differences in the labor time allocation in the high volatility case, which can also be linked to the pattern of consumption and capital. Comparing the two upper and two lower graphs reveals that the pastoralist tends to increase his external labor force only in periods during which the economic cycle reaches its peak, implying that when volatility is low, he focuses mainly on tending his own livestock.

Overall, these findings suggest that when shock volatility is comparatively low, pastoralists focus on tending their own livestock, but simulating an economy with high volatility produces higher positive fluctuations in both capital and consumption. In periods with high capital stock, these fluctuations tend to move pastoralists away from tending their own livestock (internal labor) toward working in the local labor market (external labor). The underlying rationale is that in boom phases of the economy, both livestock and wages are quite high, so the marginal utility of external labor (wages) is higher and more beneficial to the pastoralist, than the marginal utility of internal labor.

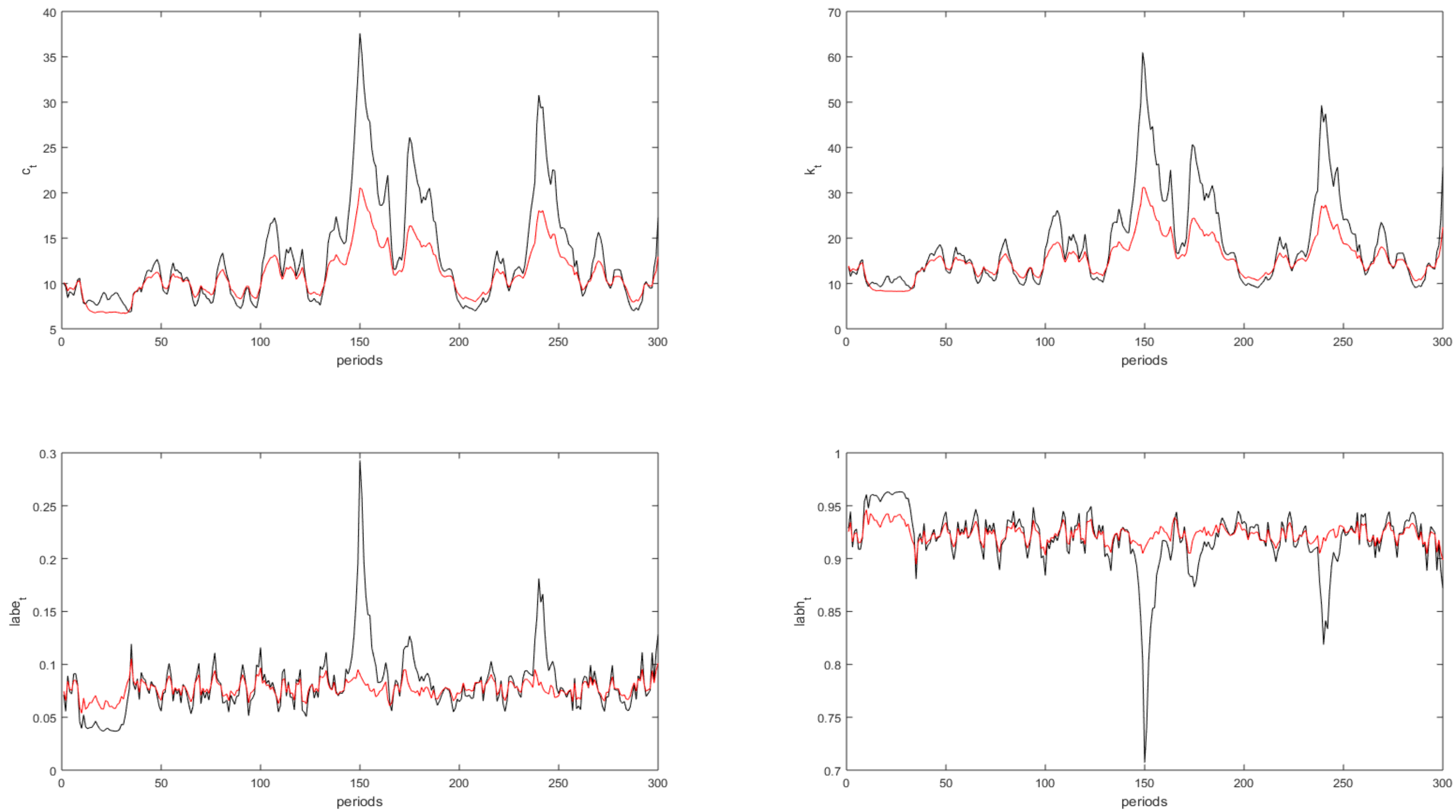

Figure 4. Simulations of the economy with low ($\boldsymbol{\sigma = 0.1}$, red line) and high volatility ($\boldsymbol{\sigma = 0.2}$, black line)
Source: Authors' own calculations using Dynare**.**

Previous research

Although several studies have investigated household welfare dynamics, their conclusions differ: some point to only a single equilibrium, while others identify multiple equilibria. For example, in a longitudinal exploration of asset accumulation determinants in Bangladesh aimed at explaining why some households are trapped in poverty, Quisumbing and Baulch (2013) identify a single low-level equilibrium with no evidence for multiple equilibria. Likewise, Naschold (2012), in a study of poverty dynamics in rural semi-arid India, finds only a single stable equilibrium ranging between 2.8 poverty line units (PLUs) for a one-year lag and 3.2 PLUs for a three-year lag. A similar convergence to a single equilibrium close to the poverty line (about 9.95 PLUs or approximately US147 dollars annual income per adult) is also reported by Giesbert and Schindler (2012) in their exploration of welfare dynamics among rural households in Mozambique. On the other hand, Barrett et al.'s (2006) analysis of panel data from five different sites in rural Kenya and Madagascar identifies multiple dynamic equilibria. Specifically, herd dynamics bifurcate at five to six TLU[5] per capita, above which level herd size grows to a higher equilibrium of 10 TLU per capita and below which it tends to decline to a low-level equilibrium of less than one TLU per capita. A similar analysis by Lybbert et al. (2004) using 17 years of herd history data (1980–1997) from four communities in Southern Ethiopia's Borana plateau also reveals two stable lower and higher asset equilibria at herd sizes of one and 40–75 animals, respectively. The threshold point for the unstable equilibrium is at around 10–15 animals. Such multiple equilibria are not identified, however, in Mogues' (2004) nonparametric analysis of livestock asset dynamics in Ethiopia, which shows only a convergence to 3.5 TLUs over a three-year period. Nevertheless, Liverpool-Tasie and Winter-Nelson's (2011) estimation of asset and expenditure-based poverty using 1994–2004 panel data for Ethiopia reveals both a low and high stable equilibrium, although it is worth noting that these authors used an asset index based on a range of household assets.

The research also indicates that social, economic, and environmental shocks are important determinants of household poverty. For example, Quisumbing and Baulch (2013) show that negative shocks have negative effects on asset accumulation, while positive shocks such as remittances and dowry lead to asset accumulation. For pastoralists specifically, Lybbert et al. (2004) establish that both household characteristics (such as income) and covariate risks (most notably drought) play a major role in wealth dynamics. Indeed, the serious effects of drought and hurricanes on poor households in Ethiopia and Honduras are clearly illustrated by Carter et al. (2007), who demonstrate that during times of food shortage, these households destabilize their consumption and preserve the few assets they own for future survival. The families even reduce the number of meals per day or serve smaller food rations. Zimmerman and Carter (2003) further show that because poor households have less profitable assets, when faced with income shocks, they pursue asset smoothing rather than consumption smoothing. This observation is confirmed by Hoddinott (2006), who finds that poor households faced with income losses smooth their assets, while non-poor households sell livestock to smooth consumption.

The extant research also underscores the major role of social networks in building household resilience. For example, several studies show that social capital is key in mitigating the risks faced by households and thus helping them recover after loss (Fafchamps 2000; Fafchamps and Minten 1999; Mogues 2004; Liverpool-Tasie and Winter-Nelson 2011). Both household social ties and the nature of relationships affect the levels of asset holding over time. For instance, in the pastoral setting, informal sharing of livestock allows households to borrow livestock after loss as an informal insurance arrangement. Conversely, persistently poor households are systematically excluded from social networks that could provide credit that would enable them to respond to shocks (Lybbert et al. 2004; Santos Barrett 2011). Hence, in an environment in which formal insurance and credit markets are unavailable, social groups and networks serve an important role in risk management and the provision of cheap credit. Studies also show that gender-based associations and kinship groups allow farmers to overcome periods of climatic and economic difficulties (Goheen 1996).

Study Area and Data

Study area

Our study area, Marsabit district, is characterized by an arid or semi-arid climate (rainfall of up to 200 mm/year in the lowlands and 800mm/year in the highlands), drought, poor infrastructure, remote settlements, low market access, and low population density (about 4 inhabitants per km^2). This area, which covers about 12 per cent of the national territory, is home to about 0.75 per cent of the Kenyan population and encompasses several ethnicities – including Samburu, Rendille, Boran, Gabra, and Somali – each with its own distinct language, culture, and customs. These pastoral communities live in semi-nomadic settlements in which livestock, the main source of livelihood, is moved across vast distances in search of grazing pastures, especially during the dry season. Largely dependent on milk from livestock (mainly camels or cattle) for home consumption, these communities also trade or sell animals (primarily goats and sheep) to purchase food and other commodities (Fratkin et al. 2005). Marsabit has two major ecological/livelihood zones: an arid and primarily pastoral upper zone and a semi-arid, more agro-pastoral lower zone.

Data

Because the households in our study area face persistent shocks arising mainly from drought, it is most important to develop a clear understanding of livestock accumulation paths across households. To do so, we use panel data collected as part of the International Livestock Research Institute's (ILRI) Index-Based Livestock Insurance (IBLI) project, implemented in the Marsabit district of Northern Kenya, which administered a pre-intervention baseline survey in 2009 complemented by annual follow-ups from 2010 to 2015. For all these survey waves, information was collected in 16 sublocations using a sample proportionally stratified on the basis of the 1999 household population census. First, households are classified into three wealth categories based on livestock holdings converted into TLUs: low (<10 TLU), medium (between 10 and 20 TLU), and high (>20 TLU). Within each sublocation, one third of the location-specific sample is randomly selected from each of these wealth categories, which are then used to randomly generate a list of additional households to be used as replacements when needed. For example, if a low, medium, or high wealth household cannot successfully be re-interviewed, it is replaced by an equivalent household during subsequent surveys, yielding a consistent sample of 924 households across all surveys. Our analysis uses the five survey waves (2009-2013).

In our analysis, we measure drought risk using remote sensing data from the NDVI (Normalized Difference Vegetation Index), a satellite-generated indicator of the amount of vegetation cover based on levels and amount of photosynthetic activity (Tucker et al. 2005). When the lack of sufficient rainfall reduces the levels of vegetative greenness, the lower NDVI values indicate forage scarcity. NDVI data are used not only in several studies that apply remote sensing for drought management (Rasmussen 1997; Kogan 1995; Unganai and Kogan 1998) but also by the IBLI, which is being implemented in Northern Kenya and Southern Ethiopia to provide a market-mediated livestock insurance among pastoralists (Chantarat et al. 2012). Research confirms that NDVI values are particularly reliable in arid and semi-arid areas with little cloud cover (Fensholt et al. 2006). The NDVI uses the intensity of photosynthetic activity to gauge the amount of vegetation cover within a given area. NDVI image data, which are available from the U.S. National Aeronautical and Space Administration (NASA), are gathered by a moderate resolution imaging spectroradiometer (MODIS) on board NASA's Aqua and Terra satellites (Tucker et al., 2005). These values are translated into a standardized NDVI Z-score, originally generated in designing the livestock insurance index for Northern Kenya (Chantarat et al. 2012), by computing the value for any pixel i of a 16-day d in year t:

$$zndvi_{idt} = \frac{ndvi_{idt} - E_d(ndvi_{idt})}{\sigma_d(ndvi_{idt})} \tag{9}$$

where $ndvi_{idt}$ is the NDVI image of pixel i for period d of year t and $E_d(ndvi_{idt})$ and $\sigma_d(ndvi_{idt})$ are the long-term mean and long-term standard deviation, respectively, of NDVI values for 16-day ds of pixel i taken over 2000–2009. Positive (negative) values represent better (worse) vegetation conditions relative to the long-term mean. As is evident, the NDVI is a good indicator of the extent of greenness – and thus the amount of vegetation – in a given area. Because livestock in pastoral production systems depend almost entirely on available forage for nutrition, the NDVI serves as a strong indicator of forage availability. It is also directly correlated with rainfall and hence considered a good measure of biomass productivity (Fensholt et al. 2006).

To ensure that our analysis accounts for such regional differences as agroecology, herd composition, and climatic patterns, we divide the study area into four regions: Central and Gadamoji, Maikona, Laisamis, and Loiyangalani.[6] We then extract for these four regions the average ZNDVI values for the long rainy season (March, April, and May) in each survey year, allocating to each household the annual NDVI Z-score for its respective region (Chantarat et al. 2012).

Descriptive statistics

The descriptive statistics for our key variables (see Table 3) show a declining trend in the number of livestock owned (represented by TLUs) between 2009 and 2013. This decline is more pronounced from 2011 onward, possibly because of drought experienced in 2009 and 2011. The average family has six members, while the average age of the household head is about 50 years. The uptake of livestock insurance is highest in 2010 (26.3%) but then declines at an overall mean rate of 13.6 per cent of the uptake. Herd migration is quite common, with an average of 72.4 per cent of households moving their livestock in the 2009–2013 period. This migration enables pastoralists to respond to changes in forage and water availability at different times across rangelands. One aspect that shows an increase over time is membership in women's groups, which enable members to save and borrow money for household needs such as food and school fees. In terms of other assistance, more households are receiving cash aid than food aid, although with an increase in both types in the drought years of 2009 and 2011. The mean livestock diversity remains quite constant, indicating that households kept the same types of animals over the study period.

Table 3. Summary of key household characteristics

Key variables	Full	2009	2010	2011	2012	2013
TLUs	13.8	16.1	16.5	11.5	11.9	12.7
Age of head (years)	48.8	47.9	47.7	48.5	49.5	50.4
Household size	5.9	5.6	5.7	5.6	6.4	6.4
Have livestock insurance (%)	13.6	0.0	26.3	24.4	8.7	8.8
Moved livestock[a] (%)	72.4	63.2	76.7	72.7	75.6	74
Belong to women's group[b] (%)	35.9	28.7	34.7	38.1	37.6	40.8
Receiving food aid (%)	8.3	8.5	4.8	18.5	6.5	3.4
Receiving cash aid (%)	32.6	20.9	26.1	33.7	48.1	34.6
Herd diversity index[c]	0.38	0.37	0.36	0.39	0.38	0.38
ZNDVI long rains[d]	-0.05	-0.75	0.61	-0.78	0.27	0.42

Notes: Results are based on IBLI data for a consistently sized sample of 924 households
[a] Percent of households that migrated their livestock in search of grazing pastures
[b] Percent of households with a member belonging to a women's group
[c] Shannon-Weiner Diversity Index
[d] ZNDVI is the standardized normalized difference vegetation index for the long rain season (March-May season) for each year

The average herd diversity index is 0.38 for the full sample based on a range from one, high diversity, to zero, no diversity. In both 2009 and 2011, the study area suffered major drought whose severity is reflected by the low NDVI Z-scores for those years. The notable improvement in NDVI Z-scores since 2012, on the other hand, indicates improved forage availability in the rangelands. The mean TLUs of livestock owned during the survey period, shown in Table 4, indicate consistently declining ownership, which implies that the households were becoming steadily livestock poorer over time. Given that livestock is the key productive asset among the surveyed households, this consistent decline means diminishing wealth and standard of living, especially when non-livestock economic opportunities are limited. Further disaggregation of livestock owned by sublocation, reveals that households in the Sagante, Dirib Gombo and Loiyangalani sublocations have the smallest herd sizes.

Table 4. Mean TLUs of livestock owned during the survey period

Livestock type	2009	2010	2011	2012	2013
Camels	7.1	7.7	6.4	6.3	6.4
Cattle	4.5	3.8	2.3	2.5	2.9
Sheep/goats	4.6	5.1	3.1	3.4	3.6

Note: The TLUs are computed for each animal species from all households owning livestock at the time of each survey, which numbered 854, 859, 858, 869, and 860, respectively.

The livestock data also reveal interesting trends in the drivers of livestock accumulation and de-accumulation across the survey period. Specifically, they show rather low livestock offtake transactions, with the sales of sheep and goats being more common because they are easier to sell for ready cash to meet urgent household needs. The reasons for livestock sales are varied: a need for cash income (46.1%), as a coping strategy in times of drought (38.5%), and/or for cultural reasons such as dowry (5.0%). The highest livestock losses are recorded for sheep and goats, especially in 2011, whereas camels, being more adapted to drought conditions and more able to withstand prolonged dry periods, are least affected. Livestock losses are mainly attributable to death from drought or starvation (45.7%), disease (31.1%), or predation (10.4%). The number of cattle sold and the number lost have a positive correlation coefficient of 0.30, indicating that livestock sales and losses occur simultaneously. This latter may indicate that households sell cattle mostly as a coping mechanism when faced with the risk of losing their herd, especially during drought periods. Similarly, few animals are slaughtered, except in 2011 when more sheep and goats are slaughtered than other livestock types. The main reasons for slaughtering are home consumption (42.3%) and ceremonies (41.1%), with only 8 per cent slaughtered for sale (mostly camels and cattle). Households obtain livestock in various ways: as gifts (47.7%), purchases (19.1%), loans (18.7%), or dowry payments (7.7%). After losing animals, usually from drought or disease, households borrow mainly female animals from relatives or friends in the community. They benefit from the milk but are expected to return the animal upon calving or after a certain period. The main reasons for livestock intake are expanding stock (46.0%), restocking after losses (15.0%), or as a traditional or cultural right (14.1%). As expected, more sheep and goat births are reported than cattle or camel births because of the shorter gestation period. These livestock births make the highest contribution to livestock accumulation (approximately 80% in all rounds), with livestock intake in the form of purchases or gifts contributing little (about 20%). Natural reproduction is thus the main driver of herd accumulation, which could explain the slow growth in herd size over the study period given that calving is affected by both the animals' condition and forage availability. Livestock de-accumulation is mainly attributable to losses from starvation or disease fatalities, which at 70 per cent is highest in the drought year of 2011. In fact, the data indicate that starvation and disease account for 47 per cent and 30.5 per cent of livestock losses, respectively. Moreover, although livestock offtake is relatively low, it does show an increase from 20 per cent in 2011 to 40 per cent in 2013. Given the low rate of livestock slaughter, livestock losses must necessarily be the dominant factor in these diminishing livestock trends.

Methodology

Because our primary research interest is in assessing the relation between past and future assets (expressed as TLUs), we estimate a function of the following form:

$$A_{it} = f(A_{it-n}) + \epsilon_{it} \tag{10}$$

where A_{it} represents household i's assets at time period t, A_{it-n} represents the lagged assets, and ϵ_{it} is the error term that is normally distributed with a zero mean and constant variance. In estimating Equation (10), we use both nonparametric and semiparametric methods to allow for a nonlinear relation between current and lagged assets. One important assumption for these estimations is that all households have the same underlying asset accumulation path.

Nonparametric estimations

Nonparametric estimation involves fitting a function to the data that is assumed to be smooth and have covariates that are uncorrelated with the error term. This error term is in turn assumed to be normally and identically distributed with an expected value of zero. We employ the locally weighted scatterplot smoother (LOWESS), also used by Lybbert et al. (2004) and Barrett et al. (2006) in their dynamic asset equilibrium analyses, a method attractive for its use of a variable bandwidth and its robustness to outliers, which minimizes boundary problems (Cleveland 1979; Cameron and Trivedi 2009). LOWESS performs a locally weighted regression of two variables and displays the plotted graph.

Semiparametric estimations

We find it necessary to add semiparametric estimation into our analysis because both parametric and nonparametric estimation techniques have limitations. Whereas parametric specifications have difficulty identifying unstable points in areas with few observations and need large samples if fitted polynomial functions are to accurately reflect the few observations around the thresholds, nonparametric estimation is limited in how much it can control for (Naschold 2013). Semiparametric techniques, in contrast, have a flexible functional form for asset path dynamics and can also control for other variables linearly. We represent our semiparametric model as follows:

$$A_{it} = \beta_0 + f(A_{it-n}) + X_{it}\,\beta_1 + N_{it}\,\beta_2 + T_i\,\beta_3 + R_i\,\beta_4 + \ \epsilon_{it} \qquad (11)$$

where A_{it} represents household i's current TLUs owned, A_{it-n} its lagged TLUs owned, and X_{it} include a set of household control variables that could influence livestock dynamics. These include; age of household head, household size, a dummy for membership in a women's group, and a dummy for households purchasing livestock insurance during the survey period. Because diversifying herds is an important risk minimization strategy for pastoralists (that is, mixing small and large stock optimizes grazing pasture use), we include herd diversity index derived from the Shannon-Weiner Diversity Index[7] that captures both species dominance and evenness (Achonga et al. 2011). This index, which ranges from zero, no diversity, to one, high diversity, yields an average of 0.38. Here, N_{it} represents the average ZNDVI values for the long rainy season in each year; T_i represents the time period dummy, R_i the regional dummy, and ϵ_{it} the error term. The X_{it}, N_{it}, and T_i variables are estimated linearly, whereas the relation between assets (A_{it}) and lagged assets (A_{it-n}) is estimated non-parametrically. We also use the Hardle and Mammen (1993) test to determine whether the polynomial adjustment is of 1 or 2 degrees.[8] Specifically, to check the robustness of the changes in livestock assets over time, we estimate a fourth-order polynomial regression of the lagged assets while controlling for household, regional, and time-specific variables:

$$A_{it} = \beta_0 + f(A_{it-1}) + (A_{it-1})^2 + (A_{it-1})^3 \ + (A_{it-1})^4 + X_{it}\,\beta_1 + N_{it}\,\beta_2 + T_i\,\beta_3 + R_i\,\beta_4 + \ \epsilon_{it} \qquad (12)$$

Although the TLUs are greater than 100 in a few cases, for this analysis, we consider them outliers and thus exclude them to obtain a clear asset path. These excluded cases represent less than 1 per cent of the entire sample.

Results and Discussion

Nonparametric results

The nonparametric estimations for the locally weighted scatter plot smoother (LOWESS) are graphed in Figure 5, which shows trends in 2009 and 2013 for a one-year and four-year lag, respectively. The curves of both these lags intersect the 45° line only once, indicating only one stable equilibrium to which household livestock accumulation converges. The one-year lag curve intersects the 45° line at around 18 TLUs, while the four-year lag curve does so at a lower level (15 TLUs).

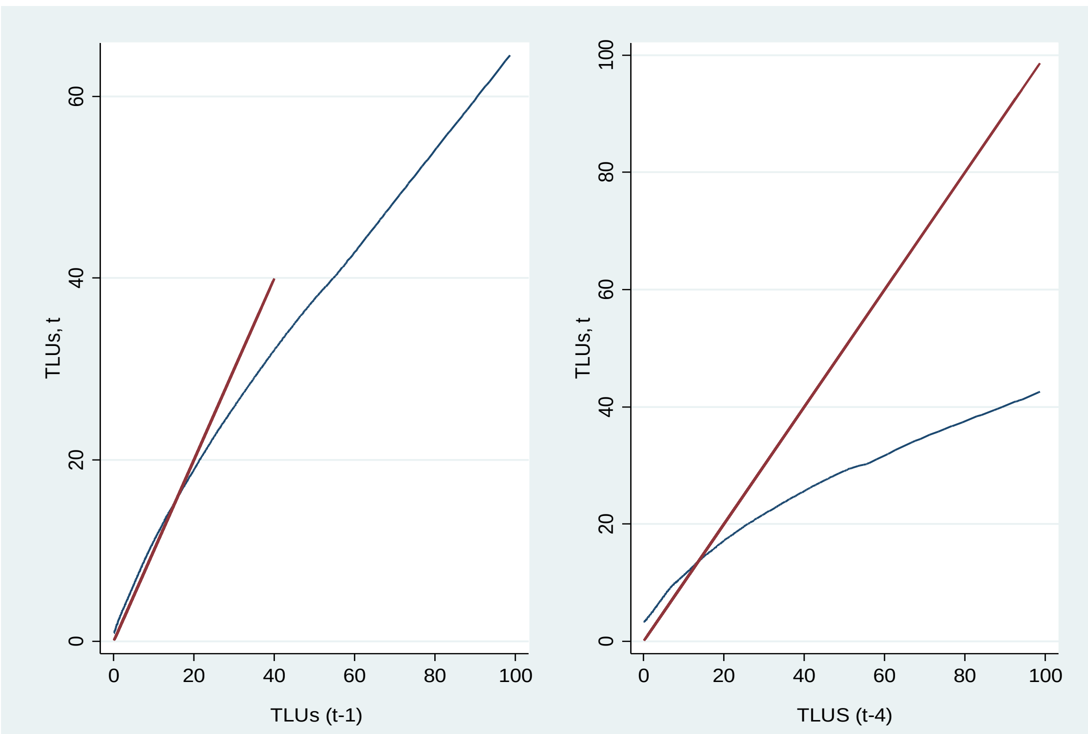

Figure 5. Nonparametric estimation of lagged TLU dynamic path (one-year and four-year lags

Because the nonparametric estimation does not control for covariates that could also influence asset accumulation, we use a semiparametric estimation to take such factors into account (see Figure 7). After controlling for other key covariates, the stable equilibrium decreases to around 10–13 TLUs at the lower confidence interval with a slope that is flatter than in the nonparametric case.

As Figure 6 clearly illustrates, we observe one single equilibrium,[9] a converging path that may partly reflect contrasting household strategies. That is, whereas livestock endowed households faced with limited credit access tend to smooth consumption during food shortages by selling or slaughtering livestock, livestock poor households use such coping strategies as meal reduction or rely more on food aid rather than depleting their already small livestock holdings. This interpretation is in line with Hoddinott's (2006) finding that poorer households, when faced with income loss, tend to preserve their few animals to ensure a future herd while those with more livestock smooth consumption through livestock sales. Similar findings are reported by Giesbert and Schindler (2012) and Carter et al. (2007).

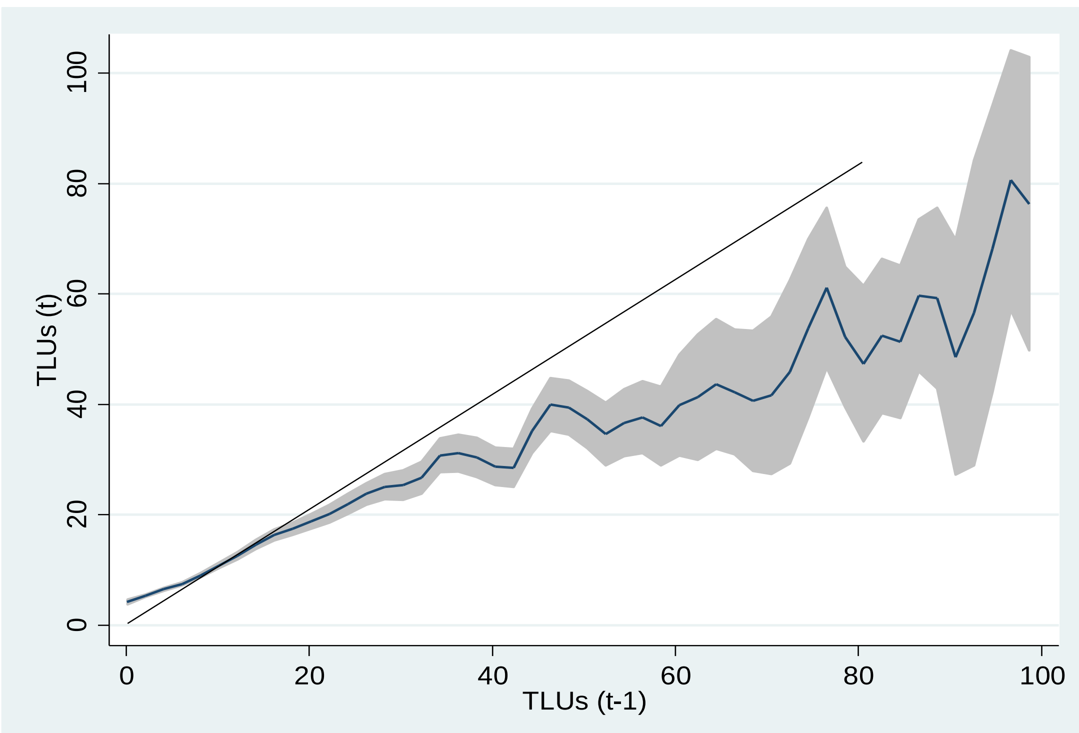

Figure 6. Semiparametric estimation of TLU-based dynamic path

To better understand the livestock assets convergence path, we look at how households actually cope during times of food shortage, We specifically examine the proportion of households that sell or slaughter livestock during times of food shortage. Our results show that 37.2 per cent of the households sell livestock, 39.9 per cent reduce the number of meals, and 5.8 per cent increase non-livestock activities. These responses are in line with the predictions of our theoretical model that following a shock, both consumption and livestock holdings will decline. Interestingly, households that sell livestock as a primary coping strategy own more livestock (an average of 20.1 TLUs), while households that reduce the number of meals or increase the number of non-livestock activities own fewer animals (an average of 9.7 TLUs and 5.9TLUs, respectively).

Semiparametric and polynomial estimates

The semiparametric and polynomial regression coefficient estimates are presented in Table 5, which shows that the average NDVI Z-score for the long rainy season have a positive and statistically significant effect on livestock accumulation. More specifically, in the parsimonious model, a one standard deviation increase in NDVI Z-score leads to a 2.76 increase in TLUs, although this effect declines slightly to 2.46 TLUs once we control for other covariates. Herd diversity is also positive and statistically significant: a one unit increase in herd diversity leads to a 4.8 unit increase in TLUs, a figure that changes little when other covariates are controlled for. Evidently, by keeping different livestock species in their herd, pastoralists can manage risks like drought and optimize grazing pastures more fully. More specifically, small livestock like sheep and goats can browse well in areas with minimal pastures, while camels can survive better during prolonged periods of drought.

Although the index-based livestock insurance offered enables households to mitigate risks related to livestock deaths from drought, its effect is positive but not significant, perhaps because of the low number of households insured. Households in Loyangalani region are worse off than households in the Central and Gadamoji region. The coefficients for all survey years are negative (although only significant for wave two), indicating a consistent decline in livestock owned over the five-year period. The polynomial estimates are quite similar to the semiparametric results, with a significantly negative lagged cubed TLU that indicates diminishing marginal returns to assets. The predicted curve for the fourth-degree polynomial regression is shown in the Appendix.

Table 5. Factors influencing livestock accumulation over time

	(1) Semiparametric	(2) Semiparametric	(3) Semiparametric	(4) Polynomial
ZNDVI (long rains)	2.7613***		2.6997***	2.7961***
	(0.301)		(0.308)	(0.315)
Herd diversity index		4.8447***	5.0742***	4.9392***
		(0.611)	(0.616)	(0.608)
Household size			0.0502	0.0406
			(0.073)	(0.075)
Have insurance (1 = yes)			0.0057	0.0446
			(0.401)	(0.405)
Belong to a women's group (1=yes)			0.4916	0.4427
			(0.329)	(0.334)
Receive food aid (1=yes)			-0.5238	-0.4301
			(0.627)	(0.629)
Receive cash aid (1=yes)			-0.3617	-0.3372
			(0.327)	(0.332)
Lagged TLU				0.8327***
				(0.111)
Lagged TLU squared				0.0067
				(0.008)
Lagged TLU cubed				-0.0003*
				(0.000)
Lagged TLU quadruped				0.0000**
				(0.000)
Constant				-0.4365
				(0.577)
N	3197	3197	3196	3196
Adj. R^2	0.028	0.017	0.047	0.617

Note: Robust standard errors are in parentheses; * p < 0.1, ** p < 0.05, *** p < 0.01. Region and time dummies are estimated but not shown.

Because we also recognize that despite the rich set of covariates in our dataset, certain important characteristics might still be unobservable, we exploit the longitudinal nature of the data by also including a fixed effects model to account for time-invariant individual characteristics (see Table

6). The models within transformation also eliminates invariant unobservables that might be correlated with our covariates of interest.

Table 6. Fixed effects regression estimates of factors influencing livestock accumulation

	(1) FE	(2) FE	(3) FE
ZNDVI (long rains)	0.5124***		0.8194***
	(0.190)		(0.219)
Herd diversity index		6.8349***	6.9992***
		(1.212)	(1.214)
Household size			-0.4784**
			(0.220)
Have insurance (1 = yes)			-0.0945
			(0.401)
Belong to a women's group (1 = yes)			-0.7611
			(0.464)
Receive food aid (1 = yes)			-0.3968
			(0.548)
Receive cash aid (1 = yes)			-1.3859***
			(0.343)
Constant	13.8212***	11.0405***	17.2954***
	(0.008)	(0.489)	(1.375)
N	4258	4258	4257
Adj. R^2	0.001	0.016	0.039

Note: Robust standard errors are in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Region and time dummies are estimated but not shown

The results of the fixed effects model support the semiparametric regressions. Herd diversity and NDVI Z-score are positive and significant with minimal change when other covariates are controlled for. We also note that cash aid received is negative and significant, which could be interpreted as reverse causality in that cash aid tends to go to households with few livestock. Household size is also negative and significant, perhaps because larger families sell or slaughter more livestock than smaller families. The regression analysis also implies that forage availability as proxied by NDVI Z-score and herd diversity is a key determinant of livestock accumulation among pastoralists.

Conclusions

The livestock dynamics of pastoral households are especially important because of the disrupting influences of regular and severe droughts in the study area. According to the microeconomic model developed in this study, such droughts negatively affect both livestock holdings and consumption. The model also indicates that the adjustment of capital, consumption, aid, and wages back to the long-term steady state equilibrium takes longer than the transition of internal and external labor supply. Our results also reveal that, in contrast to the case of low volatility, higher shock volatility does not necessarily lead to an increase in the number of periods with very low capital accumulation and low levels of consumption. This observation is in line with the theoretical model that shows that pastoralists only greatly increase their participation in external labor when volatility is high and the economic cycle, peaking. In other circumstances, they tend to concentrate primarily on tending their own livestock.

Our nonparametric and semiparametric analyses also point to the existence of a single equilibrium, although the semiparametric penalized splines which control for other covariates that affect livestock accumulation produces lower equilibria values than the nonparametric results. As previously stressed, such convergence to a stable equilibrium could result from households with more livestock smoothing their consumption during times of food shortage by drawing on their herds for sale or consumption while livestock poor households smooth their assets by using coping strategies such as relying more on food aid or reducing the number of meals that do not deplete their few livestock holdings. Poor households thus destabilize their consumption to buffer and protect their few assets for future income and survival. These results also imply that forage availability and herd diversity influence livestock accumulation over time.

Although these findings are similar to those in several studies on asset dynamics and poverty traps (Naschold 2012; Mogues 2004; Quisumbing and Baulch 2009), other studies based on pastoral livestock holdings identify multiple equilibria (for example Barrett et al. 2006; Lybbert et al. 2004). These latter, however, cover much longer time lags (13 and 17 years, respectively) in different economies suggesting that our five-year interval may simply not be long enough to illustrate long-run livestock dynamics given the slow changes observed in livestock assets. This possibility apart, the consistently declining livestock trends and few options for livestock intake available among the households in our sample support the notion of a movement toward a single low-level stable equilibrium. Such a conclusion is also in line with Lybbert et al.'s (2004) evidence that to sustain mobile pastoralism on the East African rangelands, a household should have at least 10–15 animals. In our study, only 30 per cent of the households have a herd size of more than 15 animals, suggesting that holding more than this herd size is unsustainable; holdings greater than the equilibrium will eventually collapse to the equilibrium value.

In the presence of the single low-level stable equilibrium observed here, household asset poverty can only be alleviated through structural change that raises the equilibrium asset level. Ways to effect such change include interventions that raise the returns to existing assets and the provision of a broad range of physical, social and human productive assets that eventually raise the level of the welfare equilibrium. In addition, because accumulation of livestock in the study area is greatly hindered by drought, households should be supported in strengthening their risk management mechanisms against negative shocks. Our findings also suggest that implementing welfare enhancing measures such as safety nets and forage conservation is crucial to lifting these poor households out of asset poverty.

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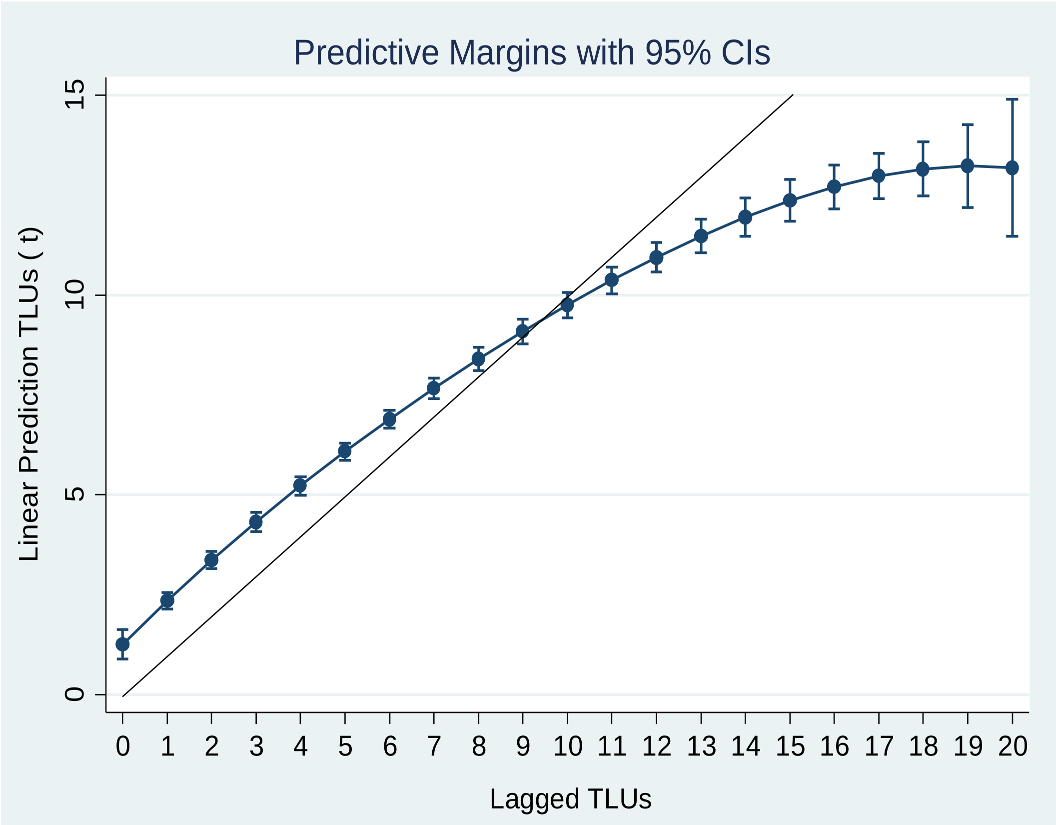
Appendix. Fourth-order polynomial prediction of lagged livestock assets



Note: Four-year lagged livestock in TLUs (2009–2013)

Mathematical Appendix

Proposition 1: *The Euler equation links the consumption of the household and takes the following form:*

$$\xi E_t\{c_{t+1}^{(\alpha-1)}[(l_{t+1}^h + 1 - \delta + (\mu)exp(z_{t+1}))\tau {k_{t+1}}^{\tau-1} + \frac{\partial A(k_{t+1}, z_{t+1})}{\partial k_{t+1}}]\} = c_t^{(\alpha-1)}$$

Proof:

The Bellman equation of the household´s optimization problem has the following form:

$$V(k_t) = max_{c_t, l_t^h, l_t^e, k_{t+1}}\{u(c_t, l_t^h, l_t^e) + \xi E_t V(k_{t+1})\}$$

s.t. $k_{t+1} = {k_t}^\tau - \delta {k_t}^\tau + l_t^h {k_t}^\tau - c_t + w_t l_t^e + (\mu) * ex\,p(z_t) * k_t^\tau + \frac{\theta}{exp(k_{t)}} + r - \zeta exp(z_t)$

$$l_t^h + l_t^e = 1$$

$$\lim_{t\to\infty} \xi \frac{u'(c_{t+1})}{u'(c_0)} k_t = 0$$

$$z_t = \rho z_{t-1} + \varepsilon \qquad \epsilon \sim N(0, \sigma^2)$$

Setting up the Lagrangian function yields the following equation:

$$V(k_t) = max_{c_t, l_t^h, l_t^e, k_{t+1}}\{c_t^\alpha + \beta ln(1 - l_t^h) + \gamma ln(1 - l_t^e) + \xi E_t\{V(k_{t+1})\}\}$$
$$+\lambda_t[k_{t+1} - ({k_t}^\tau - \delta {k_t}^\tau + l_t^h {k_t}^\tau - c_t + w_t l_t^e + (\mu) * ex\,p(z_t) * k_t^\tau$$
$$+ \frac{\theta}{exp(k_{t)}} + r - \zeta exp(z_t))]$$

The first order conditions of $V(k_t)$ with respect to $c_t, l_t^h, l_t^e, k_{t+1}$ and λ_t are then given by:

(1) $\alpha c_t^{\alpha-1} + \lambda_t = 0$

(2) $\frac{-\beta}{1-l_t^h} - \lambda_t {k_t}^\tau = 0$

(3) $\frac{-\gamma}{1-l_t^e} - \lambda_t w_t = 0$

(4) $\xi E_t\{V'(k_{t+1})\} + \lambda_t = 0$

(5) $$k_{t+1} - ({k_t}^{\tau} - \delta {k_t}^{\tau} + l_t^h {k_t}^{\tau} - c_t + w_t l_t^e + (\mu) * ex\,p(z_t) * k_t^{\tau} + \frac{\theta}{exp(k_{t)}} + r - \zeta exp(z_t)) = 0$$

To obtain the Euler equation we need first to compute $V'(k_t)$:

$$V'(k_t) = \frac{\partial u(c_t, l_t^h, l_t^e)}{\partial c_t}\frac{\partial c_t}{\partial k_t} + \frac{\partial u(c_t, l_t^h, l_t^e)}{\partial l_t^h}\frac{\partial l_t^h}{\partial k_t} + \frac{\partial u(c_t, l_t^h, l_t^e)}{\partial l_t^e}\frac{\partial l_t^e}{\partial k_t} + \xi E_t\left\{V'(k_{t+1})\frac{\partial k_{t+1}}{\partial k_t}\right\} + \frac{\partial \lambda_t}{\partial k_t}[k_{t+1} - ({k_t}^{\tau} - \delta {k_t}^{\tau} + l_t^h {k_t}^{\tau} - c_t + w_t l_t^e + (\mu) * ex\,p(z_t) * k_t^{\tau} + \frac{\theta}{\exp(k_{t)}} + r - \zeta exp(z_t))] + \lambda_t[\frac{\partial k_{t+1}}{\partial k_t} - (\tau {k_t}^{\tau-1} - \delta\tau {k_t}^{\tau-1} + (\frac{\partial l_t^h}{\partial k_t}{k_t}^{\tau} + l_t^h \tau {k_t}^{\tau-1}) - \frac{\partial c_t}{\partial k_t} + w_t\frac{\partial l_t^e}{\partial k_t} + (\mu) * ex\,p(z_t) * \tau k_t^{\tau-1} - \frac{\theta}{exp(k_{t)}})]$$

$$= \alpha c_t^{\alpha-1}\frac{\partial c_t}{\partial k_t} - \frac{\beta}{1-l_t^h}\frac{\partial l_t^h}{\partial k_t} - \frac{\gamma}{1-l_t^e}\frac{\partial l_t^e}{\partial k_t} + \xi E_t\left\{V'(k_{t+1})\frac{\partial k_{t+1}}{\partial k_t}\right\} + \frac{\partial \lambda_t}{\partial k_t}[k_{t+1} - ({k_t}^{\tau} - \delta {k_t}^{\tau} + l_t^h {k_t}^{\tau} - c_t + w_t l_t^e + (\mu) * ex\,p(z_t) * k_t^{\tau} + \frac{\theta}{\exp(k_{t)}} + r - \zeta exp(z_t))] + \lambda_t[\frac{\partial k_{t+1}}{\partial k_t} - (\tau {k_t}^{\tau-1} - \delta\tau {k_t}^{\tau-1} + (\frac{\partial l_t^h}{\partial k_t}{k_t}^{\tau} + l_t^h \tau {k_t}^{\tau-1}) - \frac{\partial c_t}{\partial k_t} + w_t\frac{\partial l_t^e}{\partial k_t} + (\mu) * ex\,p(z_t) * \tau k_t^{\tau-1} - \frac{\theta}{exp(k_{t)}})]$$

$$= (\alpha c_t^{\alpha-1} + \lambda_t)\frac{\partial c_t}{\partial k_t} + \left(-\frac{\beta}{1-l_t^h} - \lambda_t {k_t}^{\tau}\right)\frac{\partial l_t^h}{\partial k_t} + \left(-\frac{\gamma}{1-l_t^e} - \lambda_t w_t\right)\frac{\partial l_t^e}{\partial k_t} + \xi E_t\left\{(V'(k_{t+1}) + \lambda_t)\frac{\partial k_{t+1}}{\partial k_t}\right\} + \frac{\partial \lambda_t}{\partial k_t}\left[k_{t+1} - \left({k_t}^{\tau} - \delta {k_t}^{\tau} + l_t^h {k_t}^{\tau} - c_t + w_t l_t^e + (\mu) * ex\,p(z_t) * k_t^{\tau} + \frac{\theta}{\exp(k_{t)}} + r - \zeta ex\,p(z_t)\right)\right] - \lambda_t(\tau {k_t}^{\tau-1} - \delta\tau {k_t}^{\tau-1} + l_t^h \tau {k_t}^{\tau-1} + (\mu) * ex\,p(z_t) * \tau k_t^{\tau-1} - \frac{\theta}{exp(k_{t)}})$$

The last term in combination with the first order conditions yields:

(6) $$V'(k_t) = -\lambda_t(\tau {k_t}^{\tau-1} - \delta\tau {k_t}^{\tau-1} + l_t^h \tau {k_t}^{\tau-1} + (\mu) * ex\,p(z_t) * \tau k_t^{\tau-1} - \frac{\theta}{exp(k_{t)}})$$

Combination of (1) and (4) yields the following expression:

(7) $$\alpha c_t^{\alpha-1} = \xi E_t\{V'(k_{t+1})\}$$

Taking (6) one period forward and inserting in (7) while replacing $-\lambda_t$ using equation (1) yields the Euler equation:

$$\xi E_t\{c_{t+1}^{(\alpha-1)}[(l_{t+1}^h + 1 - \delta + (\mu)exp(z_{t+1}))\tau {k_{t+1}}^{\tau-1} - \frac{\theta}{exp(k_{t)}}]\} = c_t^{(\alpha-1)}$$

***Lemma**: The marginal rate of substitution between time allocated to tend the own livestock in period t, and time allocated to work on the local labor market is given by* $\frac{(1-l_t^h)}{(1-l_t^e)}\frac{\gamma}{\beta} = \frac{w_t}{{k_t}^{\tau}}$

Proof:

Dividing equation (3) by equation (2) yields the result.

***Proposition 2:** Wages are determined by the firm optimization problem and are given by* $w_t = P\Gamma l_t^{e^{(\Gamma-1)}} exp(z_t)$

Proof:

The firms optimization problem is given by:

$$max_{l_t^e} Q(l_t^e) = y(l_t^e) - \varphi(l_t^e)$$

with y and φ given by:

$$y(l_t^e) = P(l_t^e)^{\Gamma} exp(z_t)$$

$$\varphi(l_t^e) = w_t l_t^e$$

This yields the following first order condition:

$$P\Gamma(l_t^e)^{\Gamma-1} exp(z_t) - w_t = 0$$

Rearranging then yields:

$$w_t = P\Gamma l_t^{e^{(\Gamma-1)}} exp(z_t)$$

Endnotes

[1] Poverty dimensions encompass a range of deprivation factors, including poor health, lack of income and education, inadequate living standards, poor work quality, and threat of violence (OECD 2013).

[2] For both the steady state computation and the analysis, we use the Dynare software package implemented in Matlab. Because Dynare solves for steady state using a nonlinear Newtonian solver that does not work in all specifications, in these latter cases, we derive valid results by applying the homotopy concept (for more information see (Whitehead 1978)).

[3] Because we assume that the disutility of working in the external labor market is higher for pastoralists than tending their own livestock, we set $\gamma > \beta$. We also use the regional sensitivity analysis implemented in Dynare to check for parameter values which can cause no stable solutions of the system (Ratto, 2009). By using the Kolmogorov-Smirnov test statistic we identify only ξ, μ and τ as being potential driver for instability. In particular, low values of ξ will lead to a non-convergence of the model.

[4] Using a first-order approximation does not affect the steady state value, but the policy function is linear rather than concave.

[5] The TLUs help to quantify the different livestock types in a standardized manner. Under resource driven grazing conditions, the average feed intake among species is quite similar, about 1.25 times the maintenance requirements (1 for maintenance, and 0.25 for production; that is, growth, reproduction, milk). Metabolic weight is thus considered the best unit for aggregating animals from different species, whether for the total amount of feed consumed, manure produced, or product produced. The standard used for one tropical livestock unit is one cow with a body weight of 250 kg (Heady 1975), so that 1 TLU = 1 head of cattle, 0.7 of a camel, or 10 sheep or goats.

[6] The North Horr region is not covered in the household survey and is thus excluded from our analysis.

[7] $H = -\sum_{i=1}^{r} p_i ln p_i$ After calculating the proportion of livestock species *i* relative to the total number of species TLUs (p_i), we multiply it by its natural logarithm (lnp_i), sum the resulting product across species (camel, cattle, sheep, and goats), and multiply it by -1.

[8] Hardle and Mammen (1993) suggest the use of simulated values obtained by wild bootstrapping, in which inability to reject the null (that is, acceptance of the parametric model) means that the polynomial adjustment is at least of the degree tested. We reject the null hypothesis ($p < 0.05$) for the two tests and thus accept the use of the semiparametric model.

[9] Re-running the analysis using two-year and three-year lags does not change the results: the estimated curves show only a single dynamic equilibrium.

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