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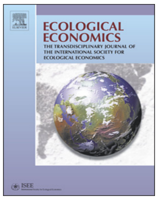

Analysis

The impact of changing rainfall variability on resource-dependent wealth dynamics

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ABSTRACT

Climate change is widely expected to lead to changing rainfall variability and thus to changing frequency of drought. In places where drought is a major driver of agroecosystem dynamics, as in the extensive livestock grazing systems that dominate Africa's sprawling arid and semi-arid lands, changing rainfall variability can fundamentally alter human wealth dynamics. We use subjective livestock herd growth expectations data elicited from Boran pastoralists in southern Ethiopia to generate estimates of herd dynamics conditional on rainfall state. The climate state-conditional estimates permit simulation of herd dynamics under different rainfall patterns. The multiple herd size equilibria observed in multiple pastoralist household data sets from the region appear sensitive to climate regimes. Reduced rainfall variability that significantly reduces drought frequency would eliminate, in expectation, the poverty trap equilibrium that presently exists only for households with herd sizes beneath a threshold level. Conversely, if the drought frequency more than doubles relative to recent patterns, then the whole system becomes a poverty trap, in expectation.

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1. Introduction

Changes in the frequencies of extreme climate events, such as droughts, are widely anticipated to be one of the most significant consequences of climate change, especially in terms of their consequences for human populations (Burke et al., 2006; Katz and Brown, 1992; Lehner et al., 2006; Sheffield and Wood, 2008). Yet this widely accepted projection has not yet been accompanied by analyses of household-level data merged with meteorological data to explore the prospective impact of changing climate variability on human well-being, even though extreme climate events are widely understood to strongly affect human wealth and income dynamics (Dell et al., 2012; Dercon, 2004; Lybbert et al., 2004). The difficulty of estimating rainfall-state-conditional household-level dynamics has posed the main methodological obstacle to such exploration. In this paper, we employ a novel method to resolve that challenge, studying a population for whom climate change is especially important. In particular, we investigate the likely consequences for southern Ethiopian pastoralists' livestock herd dynamics of changing drought frequency associated with changing rainfall variability.

Pastoralists live in the arid and semi-arid lands (ASAL) that comprise roughly two-thirds of the African continent. The socioeconomic systems of ASAL areas rely primarily on extensive livestock grazing by tens of millions of pastoralist peoples who regularly suffer humanitarian crises in the face of recurring droughts. Pastoralist systems, in particular animal husbandry and natural resources management practices and the sociocultural institutions that support those practices, have adapted slowly over centuries to the prevailing climate regime (Behnke et al., 1993; Ellis and Galvin, 1994; Smith, 2005). Relatively rapid shifts in climate patterns, perhaps especially to the frequency of extreme events, could prove especially catastrophic to these peoples.

Although prevailing current estimates emphasize that rural populations in low-income countries will suffer disproportionately from climate change, especially due to impacts on agriculture (Intergovernmental Panel on Climate Change, 2007; World Bank, 2009), such assessments focus overwhelmingly on the likely effects of anticipated changes in average rainfall and temperature on crop output. With few exceptions (such as Ahmed et al., 2009; Easterling et al., 2000), little attention has been paid to the consequences of increased climate variability, nor to the likely effects on livestock systems (Seo and Mendelsohn, 2008, and Seo et al., 2009 are exceptions), much less to the consequences of increased climate variability on livestock holdings (exceptions include Scoones, 2004 or Thornton et al., 2008). Because livestock are the key form in which ASAL populations hold their wealth and herd dynamics depend heavily on the state of the natural environment, climate patterns could well affect household wealth dynamics among this especially vulnerable group.

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Boran pastoralists practice traditional pastoralism in an area spanning southern Ethiopia and northern Kenya. Livestock, predominantly cattle, provide their primary source of food (milk, blood and meat), cash income (from sales of animal products of live animals), savings and social status. Boran herd dynamics commonly follow a "boom and bust" cycle driven mostly by fluctuations in rainfall and associated changes in range conditions that regulate herd mortality and reproduction (Coppock, 1994; Desta and Coppock, 2004). The simplicity of this system, particularly with respect to the measurement of wealth and the limited possibility of livelihood diversification, makes it an ideal setting in which to study the impact of climate variability on wealth dynamics.

We use original primary data on rainfall-conditional herd growth dynamics collected among Boran pastoralists in southern Ethiopia to demonstrate the climate state-dependence of herd growth and to reproduce the unconditional herd dynamics observed in previous studies of this and neighboring pastoralist groups. We then simulate herd dynamics under changed climate distributions. The results demonstrate how vulnerable pastoralist systems are to relatively modest increases in rainfall variability, even if mean rainfall and the frequency of drought years relative to very good years do not change (i.e., in response to a symmetric change in rainfall that increases the probability of both droughts and extremely good years). Reduced rainfall variability that results in a sharp reduction of the frequency of drought could eliminate the poverty trap regime that has been documented in multiple prior data sets from this region (Barrett et al., 2006; Lybbert et al., 2004; Santos and Barrett, 2011). Although the projected change in rainfall variability or in the frequency of extreme climate events in this region remains very much an open question (Doherty et al., 2010; Jury and Funk, 2013; Mahowald et al., 2014), several climate projections deem increased drought likely in this region (Dai et al., 2004; Jones and Thornton, 2009). We find that anything more than a doubling of the frequency of drought could have catastrophic effects, driving the entire system into a poverty trap equilibrium.

2. Unpacking Historical Herd Dynamics By Rainfall State

The main herd history study we follow (Lybbert et al., 2004), used 17-year herd history data, collected among 55 households drawn from four communities (*woredas*) in southern Ethiopia (Arero, Mega, Negelle and Yabello) to identify herd dynamics that follow an S-shaped curve with two stable states (i.e., dynamic equilibria), at roughly 1 and 30–40 cattle, separated by an unstable dynamic equilibrium at 12–20 cattle (see their Fig. 4, page 771).[1] This pattern has subsequently been found repeatedly in other data sets from the east African ASAL region of southern Ethiopia and northern Kenya (Barrett et al., 2006; Santos and Barrett, 2011; Toth, forthcoming).

These thresholds appear to reflect the central role of mobility as these pastoralists' primary management strategy to deal with the spatiotemporal variability in forage and water availability (McPeak et al., 2011). As shown by Lybbert et al. (2004) and Toth (forthcoming), a minimum herd size is necessary to undertake migratory herding. Because very young children, the elderly and infirm household members – or the small minority who have non-pastoral employment in fixed locations (typically the region's few small towns) – are typically unable to undertake physically arduous treks taking them away for weeks or months, Boran households typically maintain a semi-permanent base camp with a small number of lactating livestock to support non-migratory family members. Those base camp (*warra*) herds rely on densely stocked pastures near settlements, where range conditions rapidly degrade with overstocking or drought so that the local stable equilibrium herd size is very low, commonly just one cow. Those households that possess enough livestock to provide a second lactating sub-herd can split their herd and send able-bodied members (typically just adult males) on long treks based around mobile satellite camps. These migratory (*forra*) herds take advantage of spatiotemporal availability in forage and water on sparsely stocked, distant rangelands to withstand droughts more effectively and maintain stable equilibrium herd sizes measured in scores of cattle. The result is, effectively, two distinct herding technologies separated by a threshold herd size that separates the sedentary, *warra* herds from the mobile, *forra* herds.

This system perfectly fits canonical theories of poverty traps (e.g., Azariadis and Stachurski, 2005; Barrett and Carter, 2013), wherein multiple market failures occur in a setting characterized by two distinct production technologies, each with markedly different equilibrium productivity levels. In such systems, people sort into one or the other production technology based on their initial conditions, in the present case, herd size. In the Boran region of southern Ethiopia, asymmetric information problems lead to multiple market failures. Both credit and insurance markets fail because of adverse selection and moral hazard problems, making it difficult for households to smooth assets or consumption in the face of major shocks (Santos and Barrett, 2011). And moral hazard problems likewise impede interhousehold herd aggregation occur because households are loathe to entrust their animals to other herders (Barth, 1967); joint herding is instead commonly for the purpose of mutual security (Huysentruyt et al., 2009). Recent innovations in index-based livestock insurance (Chantarat et al., 2013) attempt explicitly to overcome the financial markets failure problem so as to try to break the poverty trap cycle facing these pastoralists.

The observed multiple equilibrium herd dynamics repeatedly found in historical data from this system result from a mixture of different climate state-dependent herd growth patterns under different environmental conditions. To understand the likely consequences of change in rainfall distributions, one must first unpack the state-unconditional herd history data into its state-conditional components. These can then be combined with historical rainfall data to simulate the effect of changes in climate variability.

We perform this analysis in the context of the Pastoralist Risk Management (PARIMA) project, which began collecting household survey data at quarterly frequency, March 2000–June 2002 and then annually each September–October in 2003 and 2004, including among 150 randomly selected households in five communities in southern Ethiopia (McPeak et al., 2011).[2] In 2004 we supplemented these data with a novel instrument to elicit subjective expectations of herd dynamics conditional on rainfall states from 116 of the Ethiopian household respondents who were ethnically Boran, as in Desta (1999) and Lybbert et al. (2004).

Although many studies now use elicited subjective expectations data (see Delavande et al. (2011) for a review), it is worth explaining in some detail how we elicited these data, as ours appears to be the first effort to elicit subjective expectations conditional on exogenously variable states of nature, especially with random assignment to initial conditions. We started by randomly selecting four hypothetical initial herd sizes for each respondent – [1,5), [5, 15), [15, 40) and [40, 60] – with the intervals defined to roughly coincide with the different equilibria depicted in Lybbert et al. (2004). The lowest range corresponds to the neighborhood of the low-level *warra* equilibrium. The next lowest is the range just beneath the estimated herd size threshold of 15 head of cattle, where herd size is most vulnerable to collapse. The next highest range is the zone of most rapid herd accumulation, as herds become migratory just beyond the 15 head threshold. The highest interval is at or above the equilibrium *forra* herd size. We asked each respondent

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[1] The data are described in detail in Desta (1999). Those data were gathered through detailed interviews held with entire extended families whose collective recall permitted the construction of reliable longitudinal herd history data, including mortality, marketing, gifts and loans, slaughtering and calving. Prior studies have confirmed the reliability of herd history recall data collected among African pastoralists (Assefa, 1990; Ensminger, 1992; Grandin, 1983).

[2] The survey data and rainfall data are described in detail and available online at http://aem.cornell.edu/special_programs/AFSNRM/Parima/projectdata.htm.

to assume a cattle herd of standard composition for the region, in terms of age and sex of the animals. We also asked whether they had ever managed a herd approximately equal in size to the initial (random) herd value assigned.

Respondents were then asked about their expectations for rainfall next year choosing between good, normal or bad, following the trinomial forecast used by meteorological agencies in the region (Luseno et al., 2003; Lybbert et al., 2007). Because the information about rainfall was asked well into to the rainy season, these are not uninformed priors that could possibly reflect differences in respondents' idiosyncratic degree of optimism or pessimism; they likely reflect real weather conditions. The spatial distribution of the answers reinforces this claim; in one site, 90% of the respondents expected a bad year, while in another, 90% of the households expected a good year, consistent with the early season rainfall patterns.

We also elicited the respondents' subjective expectations of herd growth for the extreme conditions of drought or very good year. In particular, we asked respondents to consider herd evolution "as if" in 1999, the last major drought prior to our survey (which we label a 'very bad' year in the analysis that follows), or "as if" in a very good year, which we asked them to define based on their own experience. Due to time limitations, this questionnaire was fielded in only one site (Yabello).

After thus framing the problem with the survey participants, we asked each respondent to define the maximum and the minimum herd size s/he would expect to have one year later if s/he started the year with that randomly assigned initial herd size, given the just-identified expectations about the rainfall state for the year just started. These bounds provide a natural anchor for the next step, in which we asked respondents to distribute, on a board, 20 stones among herd sizes between the minimum and the maximum previously elicited, thereby describing their subjective herd size distribution one year ahead conditional on the randomly assigned initial herd size. The elicitation of respondents' subjective probability distribution function is an appropriate technique under these circumstances (Morgan and Henrion, 1990), allowing us to compute state-conditional herd growth distributions.

In principle we should have 464 values of expected herd size one year ahead (four initial starting values for each of 116 respondents). In 23 cases, however, we do not have a herd size prediction, either because respondents were unwilling to make predictions about rainfall or because they were unable to distribute the stones across the board. The latter problem occurred mainly for bigger initial herd sizes, when the difference between the maximum and the minimum was sometimes quite large. Of the remaining 441 observations, in 285 cases (64.6%) the respondents had prior personal experience managing a herd of comparable size. In the analysis that follows, we use only those observations where the respondent had prior personal experience managing a herd of comparable size, ensuring that the analysis reflects the respondents' range of historical experience.

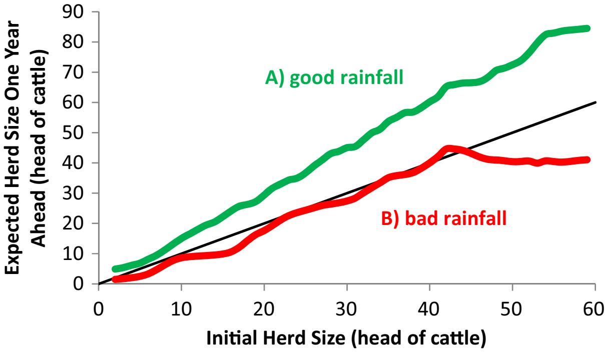

Fig. 1. Expected one year ahead herd dynamics, based on nonparametric kernel regression, with (A) good rainfall (green solid line) or (B) poor rainfall (red solid line) conditional on randomly assigned initial herd sizes. The solid black diagonal line reflects stable herd size. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 1 presents the nonparametric kernel regression relating expected herd size one year ahead to randomly assigned initial herd size, conditional on the respondent ever having had a herd with a similar size and on expectations of good rainfall (line A) or poor rainfall (line B), respectively.[3] The solid diagonal line from the origin represents the points where expected herd sizes are equal across periods, reflecting no expected change (i.e., a dynamic equilibrium).

Not surprisingly, conditional herd growth expectations differ dramatically based on climate. Under good rainfall conditions, pastoralists almost uniformly expect herds to grow, roughly in proportion to initial herd size as reflected by the essentially linear relationship plotted in Fig. 1. Under poor rainfall conditions, little if any herd growth is expected, on average, and there is considerable dispersion in expected herd growth.

These patterns are replicated in parametric regression estimation, where we control for respondent-specific effects. Conditional on each of four rainfall scenarios (r = very poor rainfall, poor rainfall, normal/good rainfall, very good rainfall), we estimated the herd growth function mapping initial herd size (h0) into one-year-ahead expected (h1) herd size with a respondent fixed effects regression to take advantage of repeated observations of individuals across different herd size intervals[4]:

$$h1_{ir} = f(h0_{ir}) + \alpha_i + \varepsilon_{ir} \tag{1}$$

where f(.) is a polynomial function of initial herd size, α_i is the fixed effect for respondent i, and ε_{ir} is the mean zero, homoskedastic error term that is, by construction, uncorrelated with the randomly assigned $h0_{ir}$.

Table 1 presents the estimation results, which replicate quite closely the nonparametric estimates depicted in Fig. 1. A clear, intuitive relationship exists between rainfall state and herd growth, with herds growing quickly in good and very good years and not growing, or shrinking, in poor and very poor ones. Less intuitively, a clear nonlinear relation between initial herd size and expected herd size one year ahead emerges under very poor and poor rainfall conditions, following a classic S-shaped pattern with positive (negative) and statistically significant second- (third-) order polynomial terms. As indicated by the r^2 goodness-of-fit statistics, there is considerably more dispersion of observations around the estimated regression line in the bad and very bad rainfall states, relative to the near-complete explanatory power of the regressions in the more favorable rainfall regimes, under which herd growth is effectively linear, just as in Fig. 1, line A.[5]

3. Consistency Between State-Conditional and Observed Unconditional Herd Histories

In order to understand whether pastoralists' expectations with respect to state-conditional herd growth are consistent with observed herd histories, which reflect a mixture of poor and good rainfall years, we integrate information on rainfall-conditional expected herd growth patterns with monthly rainfall data from the survey sites, 1991–2001, in

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[3] All figures display the results of Nadaraya–Watson nonparametric regressions with the Epanechnikov kernel and bandwidth selected using Silverman's (1986) rule of thumb as determined by the "bounds for Stata" package (Beresteanu and Manski, 2000).

[4] We also tried other specifications that replace the fixed effect with respondent-specific characteristics such as age, gender, herding experience, migrant status, etc. The estimation results with respect to herd size are qualitatively quite similar, but none of those variables proved individually statistically significant, so we omit those results in favor of the fixed effects specification, many of which are statistically significantly different from zero and control for respondent-specific unobservables as well as observable characteristics. Alternative regression specifications (i) without fixed effects and (ii) without fixed effects and a constant (available by request) likewise yield qualitatively identical results.

[5] In the results reported in Table 1, we omit higher order polynomial terms in the very good and good/normal rainfall year specifications because they added nothing, reflecting the essentially linear herd growth function depicted in Fig. 1, line A.

Table 1
Estimates of expected one year ahead herd size conditional on rainfall regime (columns) and randomly assigned initial herd size (h0). P-values in parentheses; estimates statistically significant at the five percent level in bold.

Variable	Rainfall Regime			
	Very good	Good/normal	Bad	Very bad
h0	**1.293**	**1.477**	0.538	0.246
	(0.0003)	**(0.019)**	(0.224)	(0.246)
$h0^2$			**0.026**	**0.009**
			(0.010)	**(0.010)**
$h0^3$			**−0.00039**	**−0.00017**
			(0.0001)	**(0.0001)**
Constant	0.897	0.179	0.513	−0.575
	(0.448)	(0.416)	(1.185)	(1.083)
N	61	93	192	61
R^2	0.986	0.994	0.792	0.589

order to estimate the unconditional herd growth dynamics. For these sites, annual rainfall (in millimeters) during the 1991–2001 period followed a roughly N(490,152) distribution, with a minimum (maximum) of 259 mm in 1999 (765 mm in 1997). We cannot reject the null hypothesis of a normal distribution given the skewness and kurtosis of the empirical rainfall distributions. We also cannot reject the null hypothesis that the historical rainfall series are serially uncorrelated, so that each year's rainfall is a statistically independent draw from this distribution. When matching the historical records of rainfall with the different states described above (from very bad to very good), it is important to recognize that there is no universally accepted definition of "drought" for this region. We use a threshold of 250 mm/year, roughly equal to the minimum observed since 1991. Given that definition of drought and the estimated rainfall distribution for the region, the estimated probability of drought (<250 mm) is roughly $\pi = 0.06$ in the recent climate record for this part of southern Ethiopia.

Given the estimated rainfall distribution and the rainfall-conditional expected herd dynamics estimated in Table 1, we can simulate herd evolution over a longer period of mixed rainfall states.[6] The simulation procedure is quite simple. We start with an initial herd size, then randomly draw a rainfall state from the historical distribution described above.[7] If the random rainfall draw falls in the lower π of the probability distribution, we classify this as a very poor rainfall year (a drought year), while (π, 0.50] is the poor rainfall year, (0.50, 1-π) is the good rainfall year, and above 1-π probability coincides with a year of very good rainfall. Given the randomly assigned rainfall regime, we then call the regime-specific regression function from Table 1 to predict next year's expected herd size. We repeat the process for ten years and replicate each decadal simulation 500 times for each integer herd size between 1 and 60.

We also impose a few basic biological rules on the simulations: i) herd size is strictly non-negative; ii) calves born in year t will only contribute to future herd growth at year $t + 2$, reflecting the biological lags needed for calves to reach reproductive age[8]; and iii) the predicted values for initial herd sizes above 52 (bad rainfall) and 45 (very bad rainfall) are made linear, with growth at rates equal to those for herds at 51 and 44 cattle, respectively, (specifically, 0.03309 and 0.00913, respectively) in order to prevent initial herd sizes from causing negative growth, as would be predicted by the low-order polynomial specification at the boundaries of our sample.

The simulation results, represented by the central, black curve depicted in Fig. 2, are remarkably similar to the ten-year-ahead herd dynamics revealed by herd history data from these same Boran communities (Lybbert et al., 2004). The mean observations exhibit an S-shape with a low-level dynamic equilibrium at 1 cattle, a higher dynamic equilibrium in the 35–40 range, and an unstable equilibrium around 10–15 cattle, as in the historical herd data. The rainfall-conditional herd growth expectations elicited from Boran pastoralists, once mixed appropriately with observed rainfall patterns, suggest that these herders understand quite well the prevailing livestock herd dynamics that characterize the pastoral system they inhabit under current climate distributions. This allows us to employ the estimated expected rainfall-conditional herd growth functions to simulate herd dynamics under rainfall distributions not observed, under the maintained hypothesis that the institutions and technologies of the system remain unchanged. So long as one is prepared to accept that the institutions and technologies may change more slowly than – and perhaps in response to – climate, then these simulations permit us to study the unobservable counterfactual of how the system would behave if only climate changed.

4. Simulating Pastoralist Wealth Dynamics Under Changed Rainfall Variability

Because our estimated rainfall-conditional herd growth functions replicate historical herd growth patterns quite well, these estimated rainfall-conditional herd growth functions present an uncommon opportunity to simulate herd dynamics under climate regimes not yet observed. As already established, under good and very good rainfall regimes, expected herd growth is effectively linear in initial herd size. But when rainfall is below the historical mean, herd losses are common and give rise to nonlinear herd dynamics. If more frequent droughts impose increased losses and reduce herd recovery time, the resilience of pastoralist systems may be compromised by increased climate variability. By contrast, if drought were to occur less frequently, perhaps the low-level equilibrium herd size associated with the pastoralist poverty trap might disappear as the robust, essentially-linear growth characteristic of good rainfall years increasingly prevails. We therefore seek to answer the

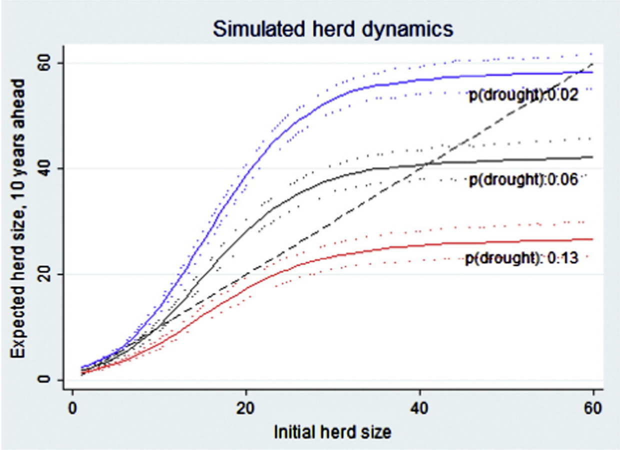

Fig. 2. Expected ten year ahead herd dynamics under different levels of drought risk (probability of rainfall <250 mm/year). Dotted lines (in the same colors) represent the 95% bootstrapped confidence bands. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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[6] Note that in order to predict out-of-sample, we must draw on the estimated parametric relationships reported in Table 1, rather than using the nonparametric relationships depicted in Fig. 1.

[7] An alternative approach would be to use predictions from climate models rather than drawing from the historical climate record. The central problems with the former approach are that (i) there are many different models and their predictions rarely agree with respect to rainfall variability and the resulting frequency of drought (Mahowald et al., 2014), (ii) most models' spatial resolution is far too coarse for the specific place and population we model (Mahowald et al., 2014), and (iii) we expressly need to match observed herd histories with the local climate record over the relevant period and then explore how changing the underlying climate distribution would affect observed herd dynamics. The statistical local climate record that we use enables us to do that; we could not find a published climate systems model that generates the necessary climate data for our spatial resolution and location.

[8] Because respondents were only asked for one-year-ahead subjective expectations of herd sizes, they would not have factored in newborn calves becoming fertile beyond the horizon of our questions.

question: if climate change leads to changed rainfall variability, and changed frequency of droughts (π), what are the likely consequences for the nature of Boran's wealth dynamics, in particular the existence of multiple equilibria? We explore that question by simulating the effect of a mean-preserving, symmetric decrease or increase in rainfall variance, by varying π in the simulation routine previously described.[9]

This simulation approach is obviously highly stylized. It assumes a symmetric change in the rainfall distribution. It assumes no change in husbandry or resource management practices or in the institutional framework within which livestock management decisions are made that could potentially change the underlying herd dynamics and that are potential human responses to changes in the rainfall distribution.[10] Given that no clearer evidence exists with which to undertake more refined simulations, this simple, parsimonious approach has clear merit. Nonetheless, we emphasize that these results are not predictions of anticipated outcomes. They are merely illustrations of what might happen under different scenarios of changes in the frequency of extreme events and in the absence of sufficiently timely and substantive change in the institutional and technological features that lead to observed herd dynamics conditional on climate patterns.

The results are reflected in Fig. 2, which plots expected herd dynamics at decadal scale, and the associated bootstrapped 95% confidence bands, for three values of π: the prevailing recent rainfall patterns (drought frequency: 6%), the highest level of drought frequency at which all herders are expected to accumulate wealth and escape poverty (drought frequency falls to 2%) and the lowest level of drought frequency at which all herders are expected to decline into poverty (drought frequency increases to 13%, more than doubling the recent frequency of drought). Not surprisingly, seemingly small changes in drought frequency have a pronounced effect on livestock herd dynamics and, perhaps less intuitively, can lead to fundamental shifts in the nature of those dynamics. If climate change strongly reduces the prospect of very low rainfall events in the area, the low-level herd size dynamic equilibrium would disappear in expectation and all herds, no matter their initial starting size, would be expected to grow to or beyond the upper range of our simulation (60 head of cattle) over the course of a decade. Such a change would have a dramatic effect on poverty among pastoralists in the region (Little et al., 2008). Our results also strongly suggest that drought frequency is central to the existence of the pastoralist poverty trap well established in the recent literature (Barrett et al., 2006; Behnke et al., 1993; Little et al., 2008; Lybbert et al., 2004). Of course, substantial increase in aggregate herd size could overtax the rangelands, changing the underlying herd dynamics and inducing stocking density-driven crashes (Coppock, 1994; Desta and Coppock, 2004). But such endogenous induced change in system behavior carries us well beyond the defensible reach of our data and methods.

Conversely, once the probability of severe drought roughly doubles from its present approximate level, no growth is expected at any initial herd size and the upper-level herd size dynamic equilibrium vanishes in expectation as all household herds decline toward a unique stable state of a single animal. Put more starkly, the whole system would be expected to collapse into a poverty trap, with one low-level equilibrium. Given that some prominent climate scientists' recent projections anticipate more frequent drought in the region (Williams and Funk, 2011), this is a striking and alarming result. Indeed, the prospect of such results has motivated various innovations in range and risk management in an effort to reduce drought-related herd losses and accelerate herd recovery so as to maintain the viability of pastoralism in the east African ASAL.

5. Conclusions

This paper has used novel primary data eliciting southern Ethiopian pastoralists' expert assessment of rainfall state-conditional herd dynamics to simulate the likely effects of a mean-preserving change in rainfall variability – and thus the frequency of drought – on the herd dynamics that underpin household well-being in this agroecosystem. We demonstrate that these elicited state-conditional dynamics reconcile quite well with observed historical patterns of herd dynamics. This enables us to use the state-conditional dynamics to simulate herd dynamics under climate regimes unobserved in the historical record.

We find that the historically observed herd dynamics, characterized by multiple stable dynamic equilibria that leave households with herd sizes below a threshold level of 10–15 cattle in a poverty trap, appear very sensitive to drought frequency. Halving or doubling that frequency relative to recent levels (six percent), would, in expectation, fundamentally change the herd dynamics that characterize this system.

Pastoralism scholars disagree as to whether east African pastoral systems are already in crisis due to apparent increases in the share of (near-)stockless, sedentarized pastoralists, or if pastoral systems remain well adapted to maintain resilience in the face of climate change and other pressures (Desta and Coppock, 2004; Ellis and Galvin, 1994; Little et al., 2008; Moritz et al., 2009; Sandford, 2006; Scoones, 2004). If climate change leads to increased drought frequency, thereby reducing pastoralists' herds' capacity to recover after a drought and reduces or even eliminates the long-term sustainability of larger migratory herds, this could necessitate significant socioeconomic adjustments and have considerable consequences for range ecology in the region. Conversely, if drought frequency were to decrease, all else held constant, the same system's dynamics could stabilize around a higher long-run equilibrium herd size. Climate change could thus either resolve or exacerbate the crisis of 'too few livestock' that some long-time observers claim now afflicts the East African ASAL region's pastoralists (Sandford, 2006). Given the notable lack of consensus in the climate modeling community over the likely impact of climate change on drought frequency in this part of the world (Doherty et al., 2010; Mahowald et al., 2014), the prospect of remarkably different systemic change merits attention.

Indeed, researchers and policymakers have been working to obviate the prospective consequences of increased drought frequency, in particular through innovations in improved rangeland and risk management among vulnerable pastoralist populations such as the Boran pastoralists we study in southern Ethiopia. If the rainfall-conditional herd dynamics that characterize the present system are vulnerable to collapse due to an increase in drought frequency, this would seem a strong reason to work actively to improve system resilience. Otherwise, increased uninsured drought risk threatens the viability of traditional livelihoods and could have calamitous effects by changing the underlying wealth dynamics of the pastoralist system and potentially sparking increased conflict over scarce, contested water and rangeland resources or mass migration to towns and cities outside the rangelands.

The traditional way of dealing with stockless pastoralists in east Africa – through migration to outside areas and merging with non-pastoralist groups, as a way to avoid death (Iliffe, 1987) – may become attractive again if current disaster relief (e.g., food aid, restocking, food for work programs) becomes too expensive as it becomes more frequent. Alternatively, technological development and institutional experimentation, such as with index-based livestock insurance (Chantarat et al., 2013), may enable more accelerated recovery from drought-related herd losses, thereby maintaining the viability of the system by changing the underlying state-conditional herd dynamics pastoralists have experienced to date. However, because climate change may increase the price of such insurance, the viability of innovations such as index insurance remains to be seen.

Our approach of eliciting state-conditional subjective expectations to unpack the historical record and then simulate under a different

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[9] We do not explore the likely impacts of changes in mean rainfall, as the clear ordering of the state-conditional herd growth functions makes those results fairly obvious: more (less) good and very good (poor and very poor) years will stimulate greater herd growth and increase equilibrium herd sizes and vice versa.

[10] For example, we do not model what might happen if recent attempts to introduce index-based livestock insurance in this environment are successful, but see the discussion in Chantarat et al. (2013, 2014).

distribution of climate variables is a novel method for exploring the prospective impacts of climate change under current institutional and technological conditions. Although we applied it to a relatively simple system in which livestock is the only non-human asset widely held by households, there is nothing that intrinsically prevents its use in other, potentially more complex settings, as suggested by previous experience.[11] Some other, contextually appropriate, continuous indicator of well-being or wealth could be used as the state variable, in place of herd size in this reduced form simulation. Similar, multiple equilibrium poverty trap phenomena have been identified in mixed crop-livestock settings using such welfare indicators (Adato et al., 2006; Barrett et al., 2006; Michelson et al., 2013; Kwak and Smith, 2013). The deeper challenge, especially in more diverse settings, would be to relax the assumption that institutional conditions remain unchanged as one would anticipate general equilibrium response in factor (e.g., labor, land) markets in response to climate shocks (Zimmerman and Carter, 2003).

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[11] Others have used subjective distributions data to calibrate dynamic decision models of cotton (Dillon, 2013), analyze the effects of market liberalization of coffee (Hill, 2010) or estimate the impacts of soil erosion on tea production (Ananda et al., 2001), although they do not elicit the sort of state-conditional expectations data we gathered.

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