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Research article

Community wellbeing moderates drought adaptation in South African rangelands

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ABSTRACT

Climate change is triggering diverse responses from communities across environmental and socioeconomic contexts. In African rangelands, selling livestock is critical for adapting to changes in environmental conditions. As these decisions further affect environmental and community wellbeing, identifying where, when, and how livestock sales are expected to respond to particular climatic shifts is important for delineating the total impact of climate change and responding accordingly. Scattered evidence suggests that socioeconomic wellbeing moderates how communities use cattle sales in response to precipitation. However, this has not been quantified as a generalizable trend across spatial and temporal scales. This study examines the relationship between socioeconomic wellbeing (using a standard deprivation index), precipitation, and monthly cattle slaughtering across South Africa from 2015 to 2022. We find that in better-off provinces (−1 standard deviation of deprivation), expected cattle slaughtering declined from 73,296 (90 % CI: 38,430–130,709) under the highest observed precipitation, to 57,897 (90 % CI: 30,431–103,378) in response to the lowest observed precipitation. In contrast, worse-off provinces (+1 standard deviation), increased expected cattle slaughtering from 10,306 (90 % CI: 5916–19,753) under high precipitation, to 19,966 (90 % CI: 11,437–38,245) after low precipitation. We further investigate this dynamic using a novel statistical disaggregation procedure, showing similar effects at a 16-km scale for the year 2020 and producing high-resolution estimates of where slaughtering was most likely given socioeconomic and environmental conditions. Our findings show that poorer communities are more likely to sell cattle in response to drought, a practice that can erode long-term resilience and deepen inequities.

1. Introduction

The global land area and human population annually exposed to extreme weather events will continue increasing into the next century (Fischer and Knutti, 2015; Lange et al., 2020; Laufkötter et al., 2020; Zscheischler et al., 2020). As highlighted by the Intergovernmental Panel on Climate Change (2023), supporting individuals, communities, and regions to sustainably adapt to these changes is an urgent priority for all levels of government. While we possess sophisticated systems for monitoring weather patterns (Ebert-Uphoff and Hilburn, 2023; Hao et al., 2019) and concurrent land cover changes (Pringle et al., 2021; Scanlon et al., 2023), tracking human behavioral responses to these processes remains challenging, especially at scale (Walawalkar et al., 2023). As a result, generalized insights on how specific groups (e.g., socioeconomic, occupational) are likely to respond to particular changes in weather (e.g., drought) remain underdeveloped (Ireland, 2010; Rodriguez Solorzano, 2016). Advancing these "middle-range theories' of climate change adaptation, which use data to identify broad, context-specific patterns, can guide targeted interventions promoting equitable and sustainable adaptation at scale (Arteaga et al., 2023; Meyfroidt et al., 2018).

Climate change adaptation through land use change (e.g.,

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deforestation, changes in agriculture or grazing) is particularly important to understand as a general phenomenon, as it further affects greenhouse gases, earth surface reflectance, biodiversity, and human wellbeing (Beckage et al., 2022; Geng et al., 2023). Complex relationships between climate and land use are evident across contexts, but the effects are especially marked amongst small-scale subsistence producers who utilize land (e.g., for agriculture and grazing) to meet daily needs (Benabderrazik et al., 2022; Fedele et al., 2021; Pienkowski et al., 2024; Wells et al., 2024). For example, small-holder farms are more likely to expand crop area to buffer dry periods than are commercial operations in wealthy countries (Zaveri et al., 2020). African pastoralists are among the groups most directly affected by and pressured to adapt to changing weather patterns, and thus present an important context to understand where and when interventions supporting climate adaptation can be most effective (Murray-Tortarolo and Jaramillo, 2020; Thornton et al., 2009).

Recurrent and worsening droughts and floods (Johnston et al., 2024; Pomposi et al., 2018; Trancoso et al., 2024) are exacerbating poverty and livestock health issues in African rangelands (Barrett et al., 2020; Emediegwu et al., 2022; Sloat et al., 2018). Namely, increasing temperatures and precipitation variability negatively affect cattle populations by decreasing forage and water availability and increasing erosion and the incidence of disease (Johnston et al., 2024; Lacetera, 2019; Onyeneke et al., 2023; Vaiknoras, 2024). Limited livelihood alternatives and continued landscape fragmentation also mean that many African pastoralists have a bounded set of adaptive strategies available to respond to changes in weather and forage (Callahan, 2025; Nozières et al., 2011; Reid et al., 2014). One common response among smallholders coping with the short-term impacts of drought is selling cattle to generate additional income (Bahta and Myeki, 2021).

As tenure insecurity and habitat fragmentation limit the long-distance seasonal movement of livestock, accessible markets have become essential in African rangelands, and in South Africa in particular (Boone, 2007; Hobbs et al., 2008; Nketiah and Ntuli, 2024). Markets contribute to reducing the ecological vulnerability of pastoralists by facilitating cattle destocking and restocking in response to local forage conditions (Tessema et al., 2014). During prolonged droughts, livestock can be sold for cash or animal feed, serving as a form of insurance against weather risks (Ouédraogo et al., 2021). However, drought-induced cattle sales are economically disadvantageous, resulting in income loss and disruption of stock planning. The value of cattle declines sharply during droughts because of reduced animal weights, increased disease risk, and because markets become saturated as many people attempt to offload cattle simultaneously (Kimaro et al., 2018).

Both theoretical and empirical case studies have shown that drought-induced cattle sales can create poverty traps for African pastoralists; technically speaking, this dynamic is driven by richer households' capacity to smooth assets while poorer households are more likely to smooth consumption (Carter and Lybbert, 2012). An early study of 37 Tanzanian households found that while wealthy households maintained their herds during droughts, poorer households faced cyclic and worsening poverty brought on by forced sale of animals (Sieff, 1999). Panel data from 55 Ethiopian pastoralist households similarly showed that precipitation shocks reinforced wealth inequality (Lybbert et al., 2004). While this localized evidence indicates that wellbeing differentiates pastoralists' adaptive responses to drought within communities, the salience of these patterns has not been comprehensively demonstrated between communities, at the country scale and throughout time.

In this manuscript, we ask whether community wellbeing reliably moderates the rate of South African cattle sales in response to changes in precipitation at multiple temporal and spatial scales. To answer this, we analyze monthly cattle slaughtering data from all South African provinces from 2015 to 2022. These data provide significant variation in both socioeconomic wellbeing and precipitation conditions. Socioeconomic variation is owed in part to interconnected historical and ecological processes such as forced resettlement under apartheid (Mani et al., 2021). Precipitation variation in these data is characterized by two recorded droughts in 2015/2016 and 2019/2020, both linked to El Niño events which affect global atmospheric circulation and reduce precipitation in the December to February rainy season by up to 80 % (Alemaw, 2022; Kimutai et al., 2024). We first quantify how community wellbeing influences cattle sales in response to precipitation changes, finding that wellbeing is strongly determinative of provincial-level response. We then employ spatial disaggregation methods (Arambepola et al., 2022) to confirm a similar effect within a single year and at a 16-km spatial resolution. We further use this method to identify within-province locations where cattle sales are most probable in a single year, based on the identified important environmental and socioeconomic variables. This study advances our understanding of how precipitation variability interacts with socioeconomic factors to shape rangeland use and offers a framework for identifying targeted interventions to support climate resilience at scale.

2. Methods

2.1. Data collection

2.1.1. Cattle sales

We obtained information on the outcome of interest—cattle sales—using curated cattle slaughtering statistics, which were used as a proxy, as there are no comprehensive records of formal and informal sales across South Africa (Fig. 1). These data include slaughtered cattle that were produced by both small-scale communal grazing associations, as well as large-scale commercial operations. An important assumption of using cattle slaughtering as a proxy for cattle sales across both formal and informal markets is that sales and slaughtering statistics are normally (unbiased) correlated in their response to the socioeconomic and biophysical variables of interest. This assumption was interrogated and determined to be reasonable during personal communications with experts from regenerative grazing organizations operating in South Africa (Meat Naturally and Conservation South Africa). Another key assumption of using these data is that cattle are slaughtered in the province where they are produced. While this is not always true, the large geographic size of provinces in South Africa and high associated travel costs lead most cattle to be slaughtered in the closest available facility. We return to these assumptions in the discussion.

Slaughtering statistics for all South African provinces (Fig. 1) were obtained from the Red Meat Abattoir Association, the largest independent organization representing all official abattoirs nationwide. Data were collected at the provincial level and for every month from January 2015 to December 2022. We did not evaluate available data on smaller livestock species, such as goats, sheep, and pigs, as they have more nuanced sale pressures. These small stock are kept and sold as a stepping stone to buying cattle in some places and are generally viewed as less of a long-term investment. Moreover, a higher proportion of cattle are sold through formal abattoirs than are small stock, for which recorded slaughters may be as low as 0.5 % (Qekwana and Oguttu, 2014). Hence, including the slaughtering statistics for these animals would introduce additional measurement error to our statistical models likely to obscure, rather than delineate, the mechanisms of interest.

2.1.2. Environmental and socioeconomic drivers of cattle sales

We identified and collected data that would enable us to isolate the effects of the two main predictors of interest: precipitation and community wellbeing. Potential covariates were identified by reviewing published literature where they were recognized as drivers of cattle sales, through the ethnographic experience of our team, and through personal communications with experts (Emediegwu et al., 2022; Godde et al., 2019; Lunde and Lindtjørn, 2013; Zscheischler et al., 2020). We then constructed a directed acyclic graph, or causal model (Fig. S1), to display the assumed relationships between variables, allowing for the identification of confounders that would require conditioning when

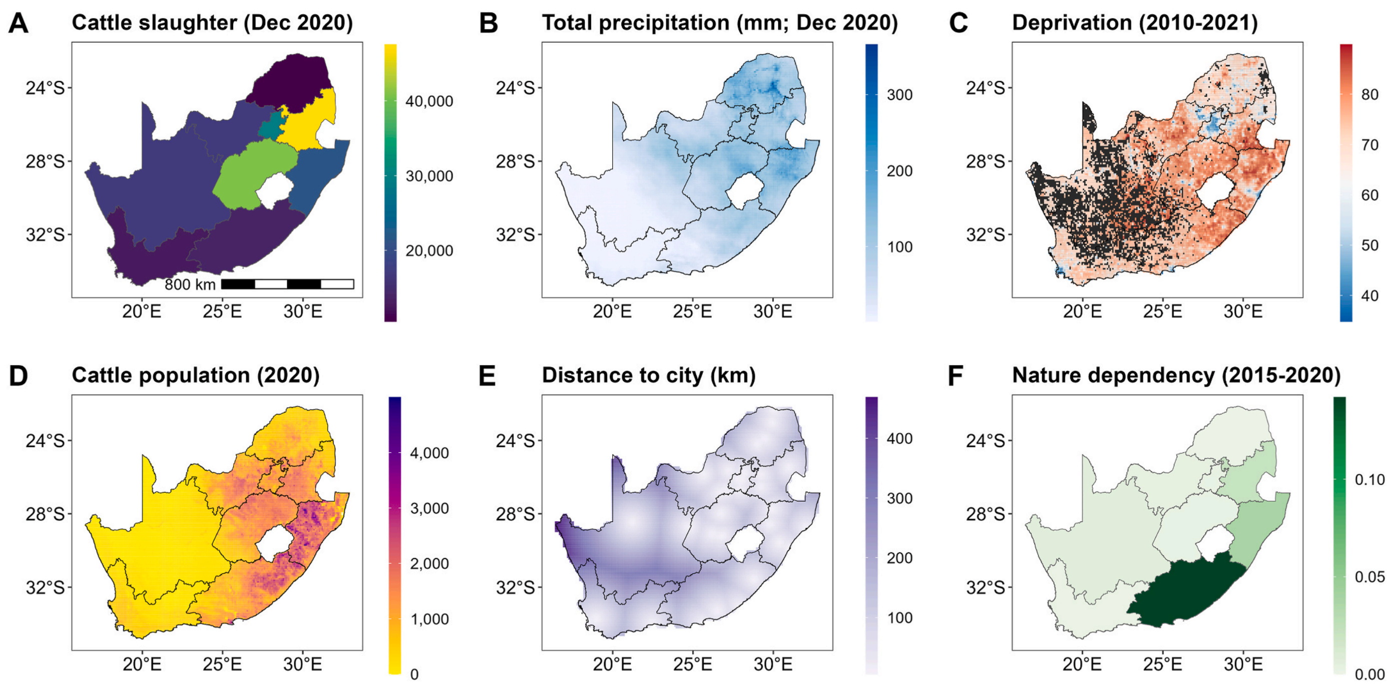

Fig. 1. Illustrative visualization of data used in the study for one month, December 2020. Panel A (response variable) shows the total number of recorded cattle slaughters in each province for the given month. Panel B (predictor of interest) shows the cumulative monthly precipitation in each 0.25-degree grid for the given month. Panel C (predictor of interest) shows the 1-km Global Gridded Relative Deprivation Index value, taken as static across the timeseries; dark grey shows 'NA' values where no human population data are available. Panels D, E, & F respectively show cattle population, distance to city, and proportion of the population dependent on nature (control variables). Panels D, E, & F are also taken as static across the timeseries and were obtained at the 5-arc minute resolution for both gridded products and provincial level for nature dependency. The color bars adjacent to each map show the ranges of values for each variable.

estimating the effects of interest (Biggs et al., 2011; McElreath, 2020). Specifically, while many socioeconomic and ecological factors (e.g., temperature) might affect the rate of cattle sales in a given place and time, these will only bias the coefficient estimates of interest—and hence need to be controlled for—if they affect both a predictor of interest and cattle sales simultaneously (Arif and MacNeil, 2023). The resulting list of control variables includes: cattle population, distance to urban centers, proportion of human population dependent on nature, and month of the year (Fig. 1). All data are described along with links to their sources in the supplemental material (S2).

Historical precipitation data were gathered as daily total values from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) database at the 0.25-degree resolution (Funk et al., 2015). We summed these values across each province for each month in 2015–2022 to yield total monthly precipitation, which has been shown to more strongly explain variance in forage quality compared to other metrics such as intra- and interannual variation (Godde et al., 2019). As forage, and thus pastoral decision-making, does not instantaneously respond to rainfall, we used a 'rolling sum' to calculate the total past rainfall for each province over the past 12 months (Gutiérrez et al., 2020; Wu et al., 2022). A 12-month interval was selected because the effects of rainfall on pasture growth and livestock productivity often manifest with a one-year lag, influencing forage availability and reproductive performance in the following year (Emediegwu and Ubabukoh, 2023).

Community wellbeing was measured using the Global Gridded Relative Deprivation Index (hereafter "deprivation") available from the United States National Aeronautics and Space Administration Socioeconomic Data and Applications Center. These data are relative values ranging from 0 to 100, where 100 is the highest observed level of deprivation. Deprivation is calculated using the subnational Human Development Index, infant mortality, and child dependency, and remotely sensed data products measuring built-up areas, and nighttime lights, with input data covering 2010 through 2021 (CIESIN, 2022). Deprivation data are available as 1-km pixels and was considered as static throughout the study period. We calculated the median value for deprivation for each province.

We obtained gridded estimates of cattle populations from the Gridded Livestock of the World data product (Robinson et al., 2014) available from the Food and Agriculture Organization (Table S2). This product contains estimates of cattle population at the 5-arc minute resolution for both 2015 and 2020 (Fig. 1). We summed these estimates across pixels to obtain a total estimated cattle population for each province.

Distance to urban centers was calculated at the pixel level across each province by measuring the Euclidean distance to a town or city included in the Humanitarian OpenStreetMap 'populated places' database (Table S2). We summarized these values across each province by calculating the median pixel value. Finally, we obtained estimates of the proportion of the population in each province directly dependent on nature for their basic needs (at least three out of: housing materials, water, energy, or occupation) from Fedele et al. (2021). These data are a composite estimate, derived from inputs from 2015 to 2020 and available at the province level. We standardized all covariates to have a mean of 0 and a standard deviation of 0.5, improving the numerical stability and allowing for the direct comparison of coefficient estimates (Gelman et al., 2008).

2.2. *Timeseries analysis*

To estimate the primary effect of interest—the effect of precipitation on cattle slaughtering conditional on community wellbeing—we modelled counts of cattle slaughter (*Slaughter*) as a Poisson distributed outcome for each province (p) in every month (t) from January 2015–December 2020 using a Bayesian hierarchical statistical model. We controlled for differential numbers of cattle in each province by including an offset term $log(Cattle_p)$, transforming the discrete counts into a slaughtering rate in each province and each month. We used the cattle population estimates for 2015 as the provincial cattle population estimate for the entire time series to maintain consistency across rate calculations. We allow for varying intercepts (i.e., base rates of slaughtering) for each province by estimating the parameter $\beta 0_p$ in addition to the global intercept α0, accounting for baseline differences in slaughtering rates across provinces resulting from culture, government policy, etc.

We assumed the total precipitation for the past 12 months in each province ($Precip_{pt}$) to have a multiplicative interaction with the provincial median deprivation ($Deprivation_p$), with an estimated slope coefficient of β1. We also estimate the independent effect of the previous 12-month cumulative precipitation (referred to below as "past rainfall") for each province ($\beta 2$). We estimate an independent effect of deprivation as β3, allowing for community wellbeing to affect cattle slaughter irrespective of precipitation. We include the two quantitative control variables, proportion of human population dependent on nature ($NatDepend_p$) and distance to major urban centers ($DistCities_p$), with slope coefficients estimated by parameters $\beta 4$ and $\beta 5$, respectively. Finally, the month of the year is included as a binary effect with slope estimates of $\beta 6$ through $\beta 17$ for January to December, to yield the equation

$$Slaughter_{pt} \sim \text{Poisson}\left(\mu_{pt}\right)$$

$$\log\left(\mu_{pt}\right) = \alpha 0 + \beta 0_p + \beta 1 \cdot Precip_{pt} \cdot Deprivation_p + \beta 2 \cdot Precip_{pt} + \beta 3 \cdot Deprivation_p + \beta 4 \cdot NatDepend_p + \beta 5 \cdot DistCities_p + \beta 6 \cdot January + \ldots + \beta 17 \cdot December + log\left(Cattle_p\right)$$

$$\beta 0_p \sim \text{Cauchy}(0, \sigma), \tag{1}$$

which we use to isolate β1, the primary effect of interest.

We specified weakly regularizing priors for all parameters as recommended by Gelman et al. (2008) for producing conservative coefficient estimates, while allowing for complete sampling of the parameter space. We considered any parameters for which the inner 0.9 quantile of posterior draws (i.e., credible interval (CI)) were entirely positive or negative to have a credible effect on cattle slaughtering. In a Bayesian context, this indicates at least a 0.95 probability of a credible effect, given the data.

In interpreting and communicating the effect size of the primary parameter of interest—β1—we calculated the conditional effect, or the expected change in cattle slaughtering, given variability in past rainfall and community wellbeing when all other variables are held constant. In calculating the conditional effects of both community wellbeing and past rainfall, we hold each control variable constant at the observed mean value. In calculating the conditional effect of past rainfall, we hold the deprivation value (community wellbeing) constant at the mean, one standard deviation below the mean, and one standard deviation above the mean, estimating the expected cattle slaughter for each deprivation level across the observed range of past rainfall (Fig. 2A). This range of deprivation values correspond closely to the observed range of median deprivation values across all provinces. Across the continuous range of deprivation values, we calculated the estimated effect of past rainfall on cattle slaughtering, allowing us to identify if and where in this range the effect of rainfall changes sign (±) and where in this range, that effect is statistically credible (Fig. 2B).

We implemented all timeseries analyses using the probabilistic programming language STAN (Stan Development Team, 2024), accessed through the 'brms' package in R (Bürkner, 2017; R Core Team, 2023). We considered this statistical model to be stable based on observed $\widehat{R}$ values equal to one for all parameters and the adequate mixing of Markov chains (Fig. S3A) (Gelman et al., 2020). We performed a posterior predictive check, shown in Fig. S3B, showing that this model reliably reproduced the observed data using the estimated coefficient values. All data and code used in this analysis are available in the supplemental material of this manuscript (S5).

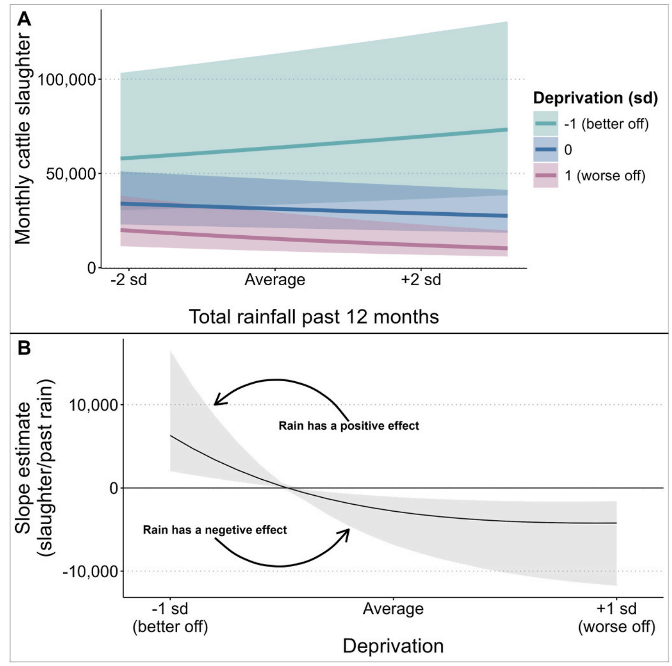

Fig. 2. Conditional effects of provincial-level deprivation and past precipitation (12 months) on monthly cattle slaughtering across all South African provinces from 2015 to 2022. Panel A shows median predicted monthly cattle slaughter as a function of total provincial rainfall, mediated by levels of deprivation. Colors show varying deprivation levels, including −1 standard deviation, average deprivation, and +1 standard deviation. The shaded areas around each line represent the 90 % credible intervals (CI). Panel B shows the interaction effect of deprivation on the relationship between past rainfall and cattle slaughter, displaying the slope estimate of past precipitation as a function of deprivation. The shaded area shows the 90 % CI.

2.3. Spatial disaggregation

The cattle slaughtering data used in the timeseries analysis are available only at the provincial scale. While these data are highly resolved temporally, allowing us to identify trends in adaptive responses to precipitation over time at the aggregate level, they are too spatially coarse to inform targeted interventions for individual communities. Here, we used the parameter estimates derived from the timeseries analysis as prior information to spatially disaggregate these provincial slaughtering data and estimate the effect of interest at a finer spatial resolution. We demonstrate this disaggregation for 2020, the year for which the most recent gridded estimates of cattle populations were available.

In summarizing cattle slaughtering at the yearly resolution, we summed the reported slaughtering values for each province for the year 2020. We summarized precipitation data by calculating the cumulative rainfall in each pixel from January to December of 2019. We spatially aligned all covariates, upscaling to approximately a 16-km resolution, to create a more realistic scale of decision-making. While pastoralist mobility is highly variable across contexts (Coppolillo, 2000; Turner and Schlecht, 2019), 16-km captures the upper range of daily foraging radius of communal cattle herds, limiting the likelihood of pseudo-precision in our projections of cattle sales locations (Hendricks et al., 2005; Liao et al., 2017). We upscaled by taking the sum of cattle populations and performing a bilinear interpolation for all predictors. We do not include the proportion of the population dependent on nature for their wellbeing as a predictor, as these data are only available at the provincial level (Fedele et al., 2021).

We implemented a Bayesian spatial disaggregation regression as introduced by Arambepola et al. (2022) to model the number of cattle slaughtering for each province (p), as a Poisson distribution, as in the timeseries analysis. For each of the 9 provinces (p), deterministic cattle slaughtering counts (y_p) were modelled as the weighted sum of the pixel-level predictions (mu_{pj}) multiplied by the total number of cattle (a) reported in each pixel (j) to yield the equation

$$Slaughter_p \sim \text{Poisson}\left(y_p\right)$$

$$y_p = \sum_{j=1}^{N_p} a_{pj} \cdot mu_{pj}, \tag{2}$$

where Np is the total number of pixels in province p.

Within each province, the number of cattle slaughtered (mu) per pixel (j) was modelled as

$$\log\left(mu_{pj}\right) = \beta0 + \beta1 \cdot Precip_{pj} \cdot Deprivation_{pj} + \beta2 \cdot Precip_{pj} + \beta3 \cdot Deprivation_{pj} + \beta4 \cdot DistCities_{pj} + GP_{pj} + u_{pj}, \tag{3}$$

where β0 is the global intercept, β1 is the slope coefficient estimate for the interaction of the cumulative rainfall from 2019 and the deprivation value for each 16-km pixel. The independent effects of 2019 rainfall and deprivation are estimated by coefficients β2 and β3, respectively. The estimated slope coefficient for the effect of distance to urban center on cattle slaughtering is estimated by β4. Statistical noise is accounted for at the pixel-level with the terms GP_{pj}, which is a Gaussian random field, and u_{pj} which accounts for independent random noise ("iid" effect).

We fit this statistical model using a Bayesian approximation framework, specifically through the integrated nested Laplace approximation (INLA), which allows for efficient estimation of approximately Gaussian spatial processes (Lindgren and Rue, 2015). Thus, our model assumed and approximated continuous space across the study area. Another required assumption of the model is the estimation of the aggregated response data as a weighted sum of all counts within each polygon (i.e., 16-km pixels within each province) (Nandi et al., 2023).

We used weakly informative priors for each coefficient, informed by the coefficient estimates from the timeseries model (shown in Fig. S4A). All slope coefficients were estimated using a normally distributed prior distribution with a mean of −0.5 and a standard deviation of 0.5. This centered all coefficients near the observed slope value from the timeseries model, while allowing enough variance to identify null or positive effects, should they be supported by the data. We assessed the within-sample predictive capacity of this model, as shown in the supplemental material (Fig. S3C), to identify that the estimated coefficients were capable of adequately reproducing the observed data. Coefficient values for this model are reported at the 95 % CI, as INLA is a Bayesian approximation and the interpretation of a 90 % CI as indicating a 95 % probability of a true effect does not hold in this approximated framework as in the true Bayesian implementation of the timeseries model.

3. Results

3.1. Timeseries analysis

The standardized coefficient estimates from the timeseries regression model (Equation (1)) strongly indicate that community wellbeing moderates the use of cattle slaughtering as an adaptive response to changes in precipitation at the provincial level across South Africa. Specifically, the estimated effect of the interaction of deprivation and past precipitation was negative in each of 20,000 draws from the posterior distribution, indicating a 1.0 probability that the interaction coefficient is negative, based on our data. This effect can be seen visually in Fig. S4A, as the 90 % CI does not overlap the zero line. Our data also show credible negative independent effects of community wellbeing and past precipitation on cattle slaughtering at the provincial level across the timeseries. The proportion of posterior draws that estimated the effects of deprivation and the past 12 months of precipitation as negative were 1.0 and 0.99, respectively (Fig. S4A).

We used the estimated coefficient values and associated uncertainties from the timeseries regression to calculate the expected conditional effect of changes in rainfall across different deprivation levels on reported cattle slaughters, given a mean value of all other predictors (Fig. 2). In less deprived areas (−1 standard deviation), an increase in 12-month provincial cumulative rainfall from the lowest to the highest observed values resulted in a median expected increase in cattle slaughtering from 57,897 cattle (90 % CI: 30,431–103,378) to 73,296 (90 % CI: 38,430–130,709). Conversely, in areas with average deprivation, increased rainfall was associated with a decrease in expected slaughtering, from 34,013 cattle (90 % CI: 22,957–51,121) to 27,503 (90 % CI: 18,556–41,303). This decline was also observed in highly deprived areas (+1 standard deviation), where the expected slaughter fell by nearly half, from 19,966 cattle (90 % CI 11,437-38,245) to 10,306 (90 % CI 5916-19,753) as rainfall increased across the observed range (Fig. 2A).

The credibility of the interaction coefficient of deprivation and past (12-month) precipitation indicates that, given our data, provincial deprivation moderated the effect of rainfall on cattle slaughter from 2015 to 2022 across South Africa. We show this as a change in the estimated slope value for the effect of past precipitation on cattle slaughter across deprivation values ranging from −1 standard deviation to +1 standard deviation away from the mean in Fig. 2B. These values are conditional on an average value of all other covariates, including the month with the closest to average precipitation (October). A positive effect of rainfall on cattle slaughter was observed only in better-off (less deprived) provinces, with an estimated increase of 6301 cattle (90 % CI: 2025–16,496) slaughtered as 12-month cumulative rainfall increased from −2 standard deviations to the average value. This trend was reversed in both average and worse-off communities. In areas with average and higher (+1 standard deviation) deprivation, rainfall was associated with a negative effect, reducing expected slaughtering by an estimated 2780 cattle (90 % CI: −6836 to −1070) and 4213 cattle (90 % CI: −11,745 to −1594), respectively with every +2 standard deviations in 12-month cumulative precipitation.

3.2. Spatial disaggregation

The standardized coefficient estimates from the disaggregation regression (Equations (2) and (3)) showed that the spatial distribution of cattle slaughtered in 2020 was likely driven by similar factors as identified at the provincial level from 2015 to 2022 in the timeseries model. The primary difference in interpretation is that coefficients from the disaggregation regression reflect within-year effects at a spatial resolution of approximately 16 km (Fig. S4B). Deprivation showed the strongest effect on cattle slaughtering (credible at a 95 % interval), while the interaction of cumulative precipitation in 2019 and deprivation also showed credible yet weaker effects. The independent effect of past precipitation was not credible at the 95 % level.

We used the coefficient values from the disaggregation regression to produce a spatially explicit cattle slaughtering estimates across South Africa in 2020 (Fig. 3). The disaggregated map (Fig. 3B) shows localized patterns not visible in the Red Meat Abattoir Association provincial data (Fig. 3A), with the highest expected cattle slaughtering occurring near urban centers. For instance, hotspots were identified around Pretoria and Johannesburg in Gauteng province. In contrast, lower slaughtering rates were predicted across most of the country, particularly in the western regions.

4. Discussion

This study demonstrates that economic wellbeing is determinative of how South African pastoral communities use cattle sales to cope with drought, confirming previous localized insights and anecdotal evidence as a robust, generalized rule. We examined highly temporally and

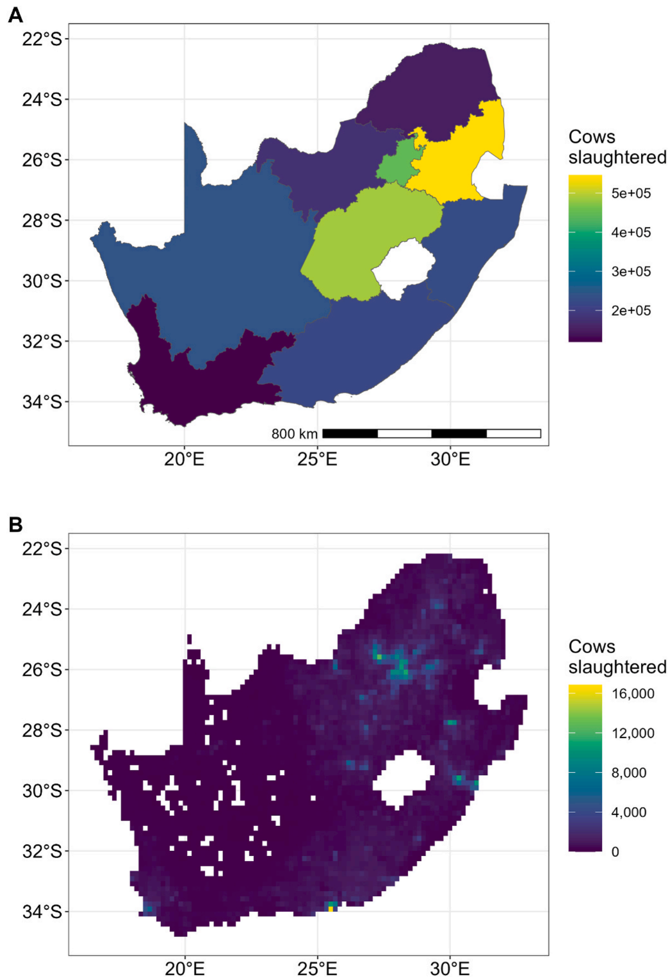

Fig. 3. *Provincial cattle slaughter data from 2020 across South Africa and resulting disaggregated expectations. Panel A shows the aggregated cattle slaughter by administrative regions from Red Meat Abattoir Association for 2020. Panel B shows the mean expected cattle slaughter for 2020 at a spatial resolution of approximately* 16-km, *as predicted by the disaggregation regression. The color bars next to each map display the range of cattle slaughtered, with higher concentrations indicated by warmer colors, yellow and green. White areas within maps denote regions with missing data or administrative exclusions.*

spatially resolved datasets, indicating that community wellbeing reliably moderates the use of cattle sales in response to changes in precipitation across both space and time. We detected evidence of this trend at the provincial scale over eight years and within a single year (2020) across 16-km grids covering the country.

These results are consistent with our hypothesized mechanism, in which reduced rainfall leads to increased cattle sales in disadvantaged communities as people are forced to sell animals to feed the remainder of the herd. This hypothesis was derived in part from personal communications with experts describing their experiences with this dynamic. A representative from the rangeland restoration social enterprise, Meat Naturally stated, “these farmers [pastoralists] sell out of necessity […], they destock in order to afford the hay for the remaining cattle and to meet the family needs.” This expert continued to note “there will definitely be an increase [in cattle sales from drought], but it might not necessarily increase the farmers’ income because we have seen that when drought comes, the price of animals drops. So, it is just a dynamic to make sure they survive in the business” (Dr E. Masaire, personal communication, July 24, 2024). In contrast, better-off communities and large-scale commercial operations are presumed to be able to buy supplementary feed outright and otherwise support stock health, selling animals only when they are in good physical condition after years of high precipitation (Reid et al., 2014).

Generalized mechanisms, such as those shown here, can refine our thinking about the expected outcomes of changes in climate and the use of interventions. These broadly applicable, context-specific expectations are critical as we attempt to trace the cumulative consequences of climate change through connected environmental and economic systems (e.g., Andrews et al., 2024). In the case of African rice production, for instance, it is expected that future climatic conditions will drive the expansion of production areas, particularly in rainfed agriculture (De Vos et al., 2023). This effect can be offset by increasing rice imports, pointing to targeted policy solutions to limit agricultural expansion resulting from climate change in rainfed versus irrigated lands (Gouel and Laborde, 2021). Land use changes resulting from climate adaptation can be understood as second-order impacts of climate change and thus are instrumental to understanding its cumulative impact (Degroot et al., 2021; Ferner et al., 2018; Sinare et al., 2022). Here, we add to a growing body of evidence (e.g., Zaveri et al., 2020) that these responses are likely differentiated by levels of economic wellbeing and community development in many systems.

4.1. *Climate change adaptation, equity, and interventions*

In pastoral communities, livestock serve as a capital buffer against environmental and other income shocks (Kibona and Yuejie, 2021; Collishaw et al., 2023; Onyeneke et al., 2023). However, pastoral communities in wealthier areas can more strategically utilize this buffer because of larger herds and better access to markets and services. For smallholders, even minor losses can threaten the viability of their entire operation, increasing the risk of herd collapse during prolonged crises (Godde et al., 2019; Collishaw et al., 2023).

As stated by a representative from Conservation South Africa, “many [small-scale pastoralists] either lose their livestock through death or they will try to hang on to their livestock for as long as they possibly can […] it will usually take years, a few seasons of drought before [pastoralists] decide to sell, sometimes it’s already too late because they have experienced so much loss already” (Dr G. Arena, personal communication, July 30, 2024). Hence, while the increased sales shown here by poorer communities in response to drought are a form of adaptation, this season-by-season adaptation may be maladaptive in the long-term, perpetuating preexisting inequities.

Wealthier communities benefit from extensive social networks and cooperatives, providing access to crucial resources like loans, insurance, restocking options, and market information (Borgerhoff Mulder et al., 2010; Collishaw et al., 2023; Kibona and Yuejie, 2021). These networks enhance market participation and improve their ability to navigate weather variability. Wealthier communities and commercial operations are better positioned to make preemptive decisions in the face of expected climate changes in the decades to come. Even with information on future climate and market conditions provided from supportive organizations like Conservation South Africa, small-scale livestock operations may be unable to adapt. As one Conservation South Africa representative noted, “We don’t know of [small-scale pastoralists] that pre-emptively slaughter or sell their livestock because of future extreme events to come. And this is not because they are not thinking about adapting to climate, but rather because it is a bigger financial risk” (Dr G. Arena, personal communication, July 30, 2024).

The differentiated responses to precipitation variability shown here suggest differentiated infrastructure and market intervention strategies to support climate adaptation in better-off and worse-off communities. In poorer areas and for smaller herds, interventions may aim to support herd health and limit the need for suboptimal, drought-induced sales during times of low precipitation. Specific interventions might include supplemental fodder, livestock vaccination, and the introduction of hardier cattle species (Mapiye et al., 2007; Slayi et al., 2023). Drought-induced cattle sales may also be avoided by introducing collaborative coping strategies such as village savings and loans associations (Rass, 2006), or through externally funded cash transfers or insurance programs (Jensen et al., 2017).

During times of high precipitation and especially preceding expected drought conditions (e.g., El Niño), market support efforts may prioritize areas where cattle exist (Fig. 1D) but have little recorded cattle slaughtering (Fig. 3B), suggesting these areas might have unmet market demand. In these areas, mobile abattoirs and on-farm slaughter units can improve access to markets and preserve animal welfare, offsetting the decreasing number of traditional slaughterhouses across South Africa (Astruc and Terlouw, 2023). These mobile units can also help support industry recovery in regions under Foot and Mouth Disease restrictions. Governments and non-profit organizations can provide timely information systems accessible at the community level to inform strategic destocking before drought or before disease outbreaks reach unaffected communities (Bahta et al., 2016).

4.2. Limitations and future research

The data and statistical approaches used in this manuscript are subject to several important limitations. We link records of cattle slaughtering at the provincial level with observed precipitation in each province. Drawing these links assumes that there is no movement of cattle raised in one province to be slaughtered in another; this assumption is likely unmet. However, we speculate that unobserved movement of cattle from poorer (more deprived) to richer provinces to be slaughtered in response to decreases in precipitation would likely lead to more conservative estimates in our statistical analysis, indicating the true effect may be stronger than reported here.

We assess the impact of cumulative precipitation over the past 12 months based on the suggestion of Godde et al. (2019). While total precipitation has been shown to effectively predict forage quality, variability in precipitation has also been shown to affect both vegetation and community adaptation to climate change (Clark et al., 2025; Pisor et al., 2023). Future work might examine cattle sales in response to anomalies or variability in precipitation, rather than the total amount. Moreover, both climate change and livestock management practices can cause changes in the proportion of palatable versus unpalatable vegetation (Hopping et al., 2018). These small-scale changes can lead to local experiences of environmental change that deviate from what is readily observable in the satellite record (Clark et al., 2024); future work may also examine cattle stocking in response to local perceptions of precipitation or vegetation change rather than remote observations (e.g., Clark et al., 2024a,b).

Other limitations in the data include the omission of information on informally sold and slaughtered animals. Poorer and more rural communities are more likely to engage in informal markets than commercial livestock operations, thus potentially biasing our findings toward these operations and away from communal and small-scale pastoralists. Moreover, in using cattle slaughtering statistics as a proxy for cattle sales, we assume an unbiased correlation in their response to precipitation changes. Yet, as wealthier commercial operations are more likely to report slaughtering than small-scale subsistence operations, some variation in our response variable could be driven by differential reporting across richer and poorer communities, rather than actual sales rates. This dynamic would, however, likely lead to the underestimation of cattle slaughter in response to drought in poorer areas, leading to conservative estimates in our reported models. Further research might aim to systematically identify the conditions under which formal and informal cattle sales are expected to show parallel trends.

Furthermore, we were unable to obtain data on disease prevalence (e.g., foot-and-mouth disease), which can limit the formal sale of animals and hence encourage engagement with informal markets. Our data could then also show bias toward areas with a lower burden of disease. As with all regression-based statistical approaches, our parameter estimates depend on the absence of omitted confounding variables (McElreath, 2020). While we used causal diagrams (Fig. S1A and S1B) and expert opinion to attempt to identify all possible confounds, unobserved confounds may still affect the reported parameter estimates. Additional research might take a nested sampling approach to reduce the influence of omitted variable bias (Byrnes and Dee, 2025).

The primary analytical limitation of this manuscript is the disjointed analyses of the high-resolution temporal and spatial data using the timeseries and disaggregation regressions, respectively. A more comprehensive analytic strategy would make use of the monthly timeseries of slaughtering data in the disaggregation framework shown in equations (2) and (3). At the time of writing this manuscript, however, this is not possible using the available ‘disaggregation’ package available in R (Nandi et al., 2023). Future statistical work might usefully expand this mathematical disaggregation framework to include timeseries and panel data.

Future research might also explore additional contexts where community wellbeing is expected to influence resource use in response to climate change. Identifying contexts where these differences take the form of sustainable versus unsustainable resource use might be particularly interesting and actionable. This study does not explicitly consider how climate change may drive individuals to abandon raising livestock entirely. This so-called ‘deagrarianisation’ is widespread in South Africa (Fischer et al., 2024) and may lead to interesting and unexpected social-ecological dynamics as the abandonment of pastoralism opens grazing lands for other pastoralists or special interests (e.g., mining).

5. Conclusions

Documenting the myriads of ways that climate change is affecting people and our environment is critical to mitigate negative outcomes. This includes not only the directly observable impacts, but also the downstream effects of human behavioral responses to these changing conditions. While some localized and experiential evidence is emerging, these processes are not largely understood as general phenomena. In this manuscript, we examine the prevalence of one such process across South Africa over eight years. We show that community wellbeing is strongly associated with how livestock are managed in response to precipitation. In particular, the data indicate that communities with greater wellbeing are likely to respond to decreased precipitation in ways that are more economically sustainable may be less environmentally damaging (i.e., purchasing supplemental fodder rather than overgrazing during drought). This process suggests then that gains can be made for both environmental and community wellbeing by supporting lower income pastoral communities to more strategically respond to ongoing and future climatic changes. Governments and non-profit organizations aiming to achieve these gains may use the generalized trends and spatial identification methods described here to more deliberately deliver interventions to communities where they will be most effective.

CRediT authorship contribution statement

Matt Clark: Writing – original draft, Visualization, Validation, Supervision, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Iacopo Tito Gallizioli:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Olivia Crowe:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Thomas Pienkowski:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Ruan de Wet:** Writing – review & editing, Investigation, Conceptualization. **Anna Jean Haw:** Writing – review & editing, Investigation, Conceptualization. **Morena Mills:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Data and code

All data and code used in this manuscript can be found in the following repository: https://doi.org/10.5281/zenodo.13856118.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.127066.

Data availability

All data and code are provided in a stable repository that is given in the title page of this manuscript under the supplementary material.

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