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Does Land-Use Policy Moderate Impacts of Climate Anomalies on LULC Change in Dry-Lands? An Empirical Enquiry into Drivers and Moderators of LULC Change in Southern Ethiopia

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Abstract: The study set out to understand drivers of Land-Use Land Cover (LULC) changes in dry-land areas and investigate factors helping mitigate the adverse impacts of climate anomalies on LULC changes. By employing a mixed-methods design, it combined LULC data with socioeconomic and climatic data, to analyze the pattern of LULC changes and its socioeconomic and climatic driving forces along with moderating factors. It was found that rangeland decreased by 764 km^2 (13% of total area) between 1986 and 2015. The results from the Seemingly Unrelated time series regression models confirmed preliminary evidence that climate variability, as well as adaptive land-use policies lacking components of sustainability increase the likelihood of degradation and contraction of rangelands. We also found an indication from the qualitative data that a widening power gap between the customary and statutory governance system reinforces unsustainable land use by obscuring the values of the customary land governance system. However, those policies encompassing economic and natural resource development objectives abate adverse effects of climate variability on land degradation and shrinkage of rangelands. The results suggest that a land governance system with natural resource development objectives fitting to the local context could be an effective policy instrument to lessen the adverse effects of climate anomalies on LULC changes. Although this study focused on analyzing the LULC changes and its drivers in dry-land area, the findings may well have a bearing on the formulation and implementation of effective adaptation and sustainable land-use policies.

Keywords: climate change; drivers; LULC; moderators; pastoralism; policy; sustainable

1. Introduction

The last few decades have seen a growing interest in the understanding of socioeconomic and biophysical drivers of Land-Use Land Cover (LULC) change, along with its societal implications [1–3]. In particular, the growing impacts of climate variability coupled with the recognition of land-use change in the global climate discussions, and the Sustainable Development Goals, have renewed interest in the subject [4,5]. In pastoral areas where livelihoods are primarily based on the productivity of rangelands, a change in land-use and land cover affects all ecosystem services that rangelands provide [6]. Despite pastoralists' dependence on rangelands for their livelihood and climate change's adverse effects on natural resources, little is known about (i) how the local climate variability affects pastoral land uses, and (ii) how the adverse effects could be mitigated. A better understanding of these factors would help identify and nurture land-use policies that promote climate resilient livelihood and curb maladaptive practices.

Though there are studies linking land-use change to climate variability, knowledge in a dryland pastoral context is scarce [3,5,7–11]. Most of the existing LULC studies (i) address the process of change, and its drivers in isolation, (ii) focus on external actors and drivers where attention to local biophysical (climatic) and socioeconomic factors is quite limited [12–14]. Due to the scarcity of comprehensive studies, establishing systematic links between LULC change and its drivers falls short of constituting an empirical basis for comparison or establishing a general relation [1,9,11,15].

A few studies have been undertaken in the pastoral land-use context intending to unpack the link between LULC change and its drivers. First, these studies focus on specific classes of LULC (e.g., changes in cropland, forestland, or expansion of an exotics vegetation), which depicts an incomplete human-environment relation in the pastoral context [4,7,8,16,17]. However, for pastoral communities, who rely on livestock, which is reliant on rangeland productivity, different components of rangelands (i.e., grassland, shrublands, wetlands, and forestlands) have an interconnected and equivalent importance for rearing diverse species of livestock [8,18]. It goes without saying that rearing diverse livestock species is a common climate adaptation strategy among pastoral communities [19,20]. Second, even if literature recognizes the critical role played by adaptation policies in inducing or mitigating climate variabilities' adverse effects on LULC changes, the empirical evidence about policies' direct and indirect effect on land-use change is scarce, which hampers the possibility of evidence-based interventions [21–23].

For this reason, this study puts particular emphasis on these aspects, and combines spatiotemporal data with socioeconomic and climatic data, to analyze the pattern of LULC changes and its socioeconomic and climatic driving forces. Additionally, the role of policies intended to help the locals adapt to the changes and their interaction with the other driving forces in mitigating the adverse impacts of climate variability on LULC changes is studied. This is crucial in assessing the context in which adaptation is occurring, and in developing strategies that would help achieve effective and timely solutions, adequate for local socio-environmental conditions. For this purpose and to test the hypotheses generated, information such as interannual and intra-annual rainfall anomalies, socioeconomic, and LULC data for the period from 1986 to 2015 is used.

Against this backdrop, an illustrative case study region in Ethiopia where many aspects are relevant far beyond its scope—not least the methodology and the question—are looked at. Building upon, and comparing this case with literature on the impacts of climate variability on pasture degradation, farming area, settlement, and the role of adaptation policies in moderating these changes, the study premises the relevance of a comprehensive understanding of the role of an adaptive land governance system in building the adaptive capacity of users [7,8,13,24,25].

1.1. Overarching Framework of LULC Change and Its Drivers

This section presents the overarching framework of LULC change with a brief review of the literature focusing on its local scale drivers and moderating factors, understood here as factors affecting the direction and/or strength of the relation between LULC and its drivers. Finally, it establishes the conceptual basis for deriving and testing the hypotheses.

1.1.1. LULC and Adaptation to Climate Variability

The process and outcome of adaptation to climate change depends largely on the way resources are managed, which in turn contributes to LULC changes [26,27]. As such, land cover encapsulates the type of vegetation covering the land, while land-use shows how people use the land [1]. "...land use changes occurring at various spatial levels, and within various time periods are the material expressions of environmental and human interactions which are mediated by land . . . " [28] (p. 15). In fact, impact of the changes and human responses to these changes do not occur evenly across time and space [15,29]. Therefore, understanding what has really changed, how the changes constrain livelihoods, as well as how land users have been responding to changes requires a historical and contextual analysis. As such, LULC change analysis traces what has actually occurred, both in relation to the cover and use of land. It analyzes the role of direct and indirect effects of inextricably interrelated human and environmental drivers of LULC change.

Changes in the LULC are outcomes of interconnected factors [15,30]. While the changes in LULC affect the climate, the variability in climate also influences LULC changes. The high interdependencies in human-environment systems make it more difficult to identify the main drivers of land-use and land cover changes [31]. A large number of studies has been conducted both regarding impacts of LULC on climate variability (e.g., [1,2]), and impacts of climate variability on LULC changes [1,2,8,10]. Regarding the former, LULC affects the climate by changing the composition of atmospheric gases [32], while climate variability affects LULC changes in two main ways: Firstly, by affecting land cover directly through its effects on the growth and composition of land cover/vegetation [15,30,33]. Secondly (indirectly), the change in the vegetation, coupled with other impacts of climate variability, in turn, require users to adjust the way they use land [25,31,34–36].

Different theories from different disciplines such as sociology, economics, social psychology, and political ecology have been used to explain drivers of LULC change [1,15,28]. Despite variation in the theory informing the studies, LULC changes and its drivers are usually modeled by one of the three models mentioned below. Ref. [35] defines LULC models as tools that support the analysis of the causes and consequences of land-use changes to better understand the functioning of the land-use system and to support land-use planning and policy. The models are different in the way they integrate the link between contextual driving forces (such as socioeconomic and biophysical factors, actors and policies) and their interactions [36]. According to [32], the aim of a particular study of LULC change dictates which model is appropriate, based on the assumption of how driving forces, actors and policies, and their interaction affect LULC changes. For example, model 1 specifically focuses on the analysis of driving forces, whereas model 2 focuses on actors who are exposed to these driving forces. The third model—as in this study—assumes driving forces, actors, and their interaction drives LULC changes [36].

1.1.2. Local Drivers and Mediators of LULC Change in Pastoral Areas

Though global, regional or national economic, political, social and climatic changes affect LULC, this paper focuses on interconnected local drivers of LULC change in dryland pastoral context. Mainly because of nonlinearity of the interactions between human and environmental drivers, coupled with a shortage of data, the feasibility of broader-scale land-use studies is limited, particularly in the context of developing countries. Moreover, most impacts of changes are felt locally, necessitating a more targeted local scale analysis in order to come up with evidence-based policy inputs [5]. Therefore, the prime focus of the investigation is in the middle (white) rectangle in Figure 1, which deals with how local socioeconomic and biophysical drivers, the adaptation policy and their interactions affect LULC changes. Details of these components with a brief review of literature on local drivers of LULC change and how gaps in the literature informed the hypotheses, are presented below. While the socioeconomic drivers of LULC have been investigated relatively better in dryland contexts, the role of biophysical drivers such as rainfall, and its interaction with policy has rarely been investigated [4,37,38]. Therefore, in this study, controlling for the effects of socioeconomic drivers (presuming that their effects are relatively better understood) hypotheses are derived to test (or analyze) the role of climatic and policy factors along with their interactive effects on LULC.

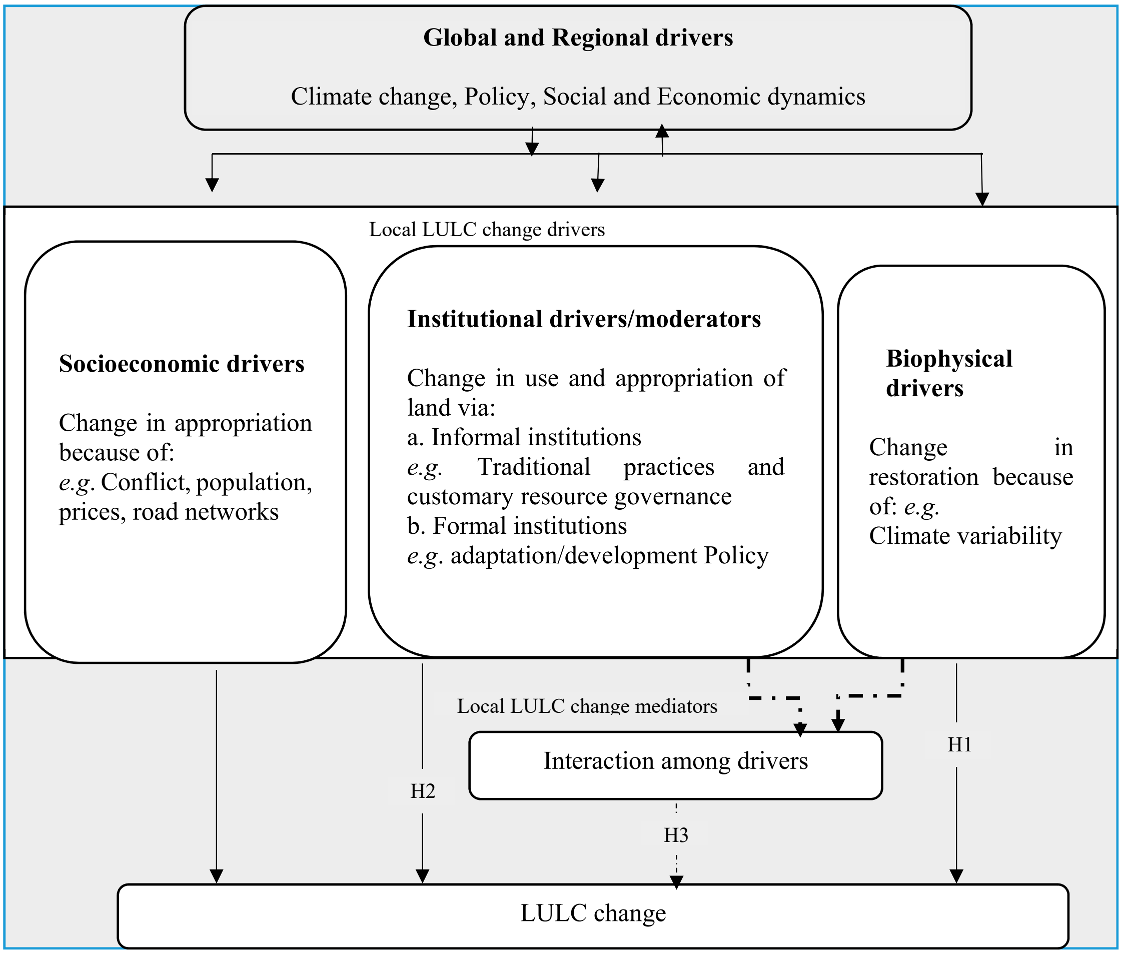

Figure 1. Schematic representation of drivers of Land-Use Land Cover (LULC) changes at the district level.

A. **Socioeconomic** literature engaging with LULC change presents how changes in socioeconomic variables induce LULC changes. Studies in this cluster use different socioeconomic variables to explain, for instance, how prices of agricultural or forest products affect users' land allocative decisions [25,39,40]. Ref. [1] discusses how population and economic growth in an area shapes LULC changes through spurring construction of commercial and residential buildings and increasing the value of land. Furthermore, these factors drive the expansion of markets, and hence, expanding the local crop production and consumption system [5,41,42]. All these effects are interrelated with infrastructure like roads, which are broadly linked with natural resource degradation in two ways: firstly, it induces new settlements, and secondly, it intensifies extraction of natural resources such as forests [1]. Studies explaining LULC changes from economic perspectives recognize the role of the dominant economic activity of the land users under consideration. For pastoral communities, composition and number of livestock influence and are influenced by how households use land, and respond to climatic anomalies [30]. The livestock population also directly affects rangelands' carrying capacity, which is also influenced by the blockage of mobility routes [17,43]. Conflict is the main cause of corridor blockage that commonly affects the strategic use of resources by blocking access to some or all groups, thereby increasing pressures on other accessible resources [44]. This, in turn, leads to overuse and degradation, besides triggering further conflicts [42].

B. **Biophysically** oriented studies contend that climate variability affects LULC patterns through altered precipitation patterns, temperatures (particularly night temperatures), and changes in availability of nutrients which affect land cover, and then land-use [4,10,33]. However, the evidence is not conclusive yet whether pastoralism or the pastoral socioecological system, which is by definition an adaptation to ecological changes, is significantly affected by local climate variability, though it is worth mentioning that the vegetation in the area has adapted to the aridity and erraticism of rainfall [45]. Over the years, many studies have emerged, sparking a notable debate among scholars and practitioners whether it is climate variability (or its interaction with other dynamics) that significantly affects LULC change in pastoral areas [46]. Ref. [47] asks if pastoralism itself is an adaptation to the erraticity and aridity, then what level of climate change is the system unable to tolerate? Therefore, it is vital to identify not only the main driver but also its factors which could lesson adverse impacts of climate variability on LULC changes [48]. For example, from a biophysical perspective, for rainfall variability to have a direct, adverse effect on pastoral livelihood, it is at least expected to adversely affect the size and productivity of rangelands (which could mean an expansion of bare lands and/or non-range land uses). This is because pastoral livelihood is based on livestock, which in turn relies on the productivity of rangelands. With this background, in order to establish the link between climate variability and LULC changes in dryland pastoral context, the following hypothesis is derived:

Hypothesis 1 (H1): *A unit increase in negative rainfall anomalies (rainfall deviations from its long-term average) drives the likelihood of LULC change towards non-range land uses (e.g., expanding lands, settlement), and bare lands.*

C. **Institutional** drivers: besides the potential drivers mentioned above, various studies imply that institutions also determine the pattern of LULC change [49,50]. These institutions are broadly categorized as: informal institutions—e.g., traditional practices and norms, and formal institutions—e.g., adaptation policies affecting governance of land-use, and property rights that affect LULC changes by shaping the behavior of actors to act in a particular way [51,52]. Adaptive land-use policies which shape activities and priorities of actors, and set in place control and monitoring mechanisms for policy implementation are expected to moderate the effect of climate anomalies on LULC change [28]. Even if existing studies recognize the critical role played by policies in affecting LULC changes, the empirical evidence about policies' direct and indirect effect on LULC is scarce [21,53], which is why this study focuses on their role. Additionally, less is known whether and how policies could offset adverse effects of climate variability on LULC changes. For these reasons, this study puts particular emphasis on analyzing the role of policies in shaping the pattern of LULC.

In the past three decades, Ethiopian governments have put in place different pastoral development policies to lessen adverse effects of climate variability and improve the livelihood conditions of the people. Broadly, these policies possess three distinguishing attributes or approaches, which can also be ordered in relation to particular periods of time they were enacted. In earlier times (i.e., before the mid-1990s) pastoral adaptive land-use policy prioritized settled-mixed farming (referred hereby as a pro-settlement approach) which aims to settle pastoralists mainly around water bodies to improve their adaptive capacity, and hence their socio-economic development. This approach has been criticized for a lack of focus on the sustainable use of natural resources and poor market linkage.

After some unsuccessful experiences, post the mid-1990s, the focus switched towards enhancing marketed offtake of livestock (referred in this study as a pro-commercialization approach). In this policy era, activities enhancing commercial offtake were prioritized even if settlements were being undertaken [51–53]. This approach also suffered from poor market linkage and the lack of a policy direction on development (or conservation) of local natural resources as a means to adapt to the impacts of climate change. More recently (after mid 2000s), the policy focus has taken a more diversified approach by comprising four main components: livelihood diversification, participatory natural resource development, commercialization, and institutional capacity building (this approach is referred to in this study as a pro-diversification approach) [54,55]. For example, there was a national campaign to involve locals in soil and water management practices in each village, besides area specific activities such as the enclosure of protected areas. The focus on pastoral areas was on the development of rangelands, including water resources.

However, these policies have contradicting effects and their effects on LULC are not conclusively proven [16], which therefore require further investigation to understand their role in driving LULC and moderating the impacts of climate variability on LULC. Moreover, the role of introducing natural resources development component to the policy on LULC is not known, mainly in regard to whether it affects some classes of land or has a holistic effect. Thus, the following hypothesis addresses the effects of the most recent policy and how it moderates effects of climate variability on LULC.

Hypothesis 2 (H2): *As compared to the pro-settlement approach, the pro-diversification approach increases non-range land uses and decreases rangeland size.*

Hypothesis 3 (H3): *As compared to the pro-settlement approach, the pro-diversification approach influences LULC changes, and reduces the effect of an increase in negative rainfall anomalies on the rangeland size (i.e., the pro-diversification approach mitigates the effects of climate variability on LULC).*

Legend: the solid arrows show the driving forces while the dashed arrows show how interaction between driving forces could confound the drivers' effect on LULC change; H1, H2, and H3 are depictions of the hypotheses to be tested; Source: Adapted from [1].

2. Materials and Methods

The following section presents description of the study area, together with how the data were collected and analyzed to test the hypotheses derived in the previous section.

2.1. Study Setting

Southern Ethiopia, particularly the Hamer district, has witnessed enormous socio-environmental changes in recent decades. Analyzing the changes occurring across places and time is important for a comprehensive and accurate understanding of how adverse effects of climate variability on LULC could be mitigated. As shown in Figure 2, located at the Southern border of Ethiopia and occupied by small indigenous tribes, the arid subtropical district of Hamer is situated in the Great East African Rift valley between Omo and Weito river basins covering an area of 5696 km^2. By the virtue of its location and topography, Hamer receives bi-annual rainfall: "*Belg*" rains during mid-February-April and "*Kiremt*" rains during June-September (Ethiopia's main "*Meher*" crop growing season [56]. Annual average rainfall (ranging from 350 mm in the southern lowlands to 838 mm around the northeastern plateaus) is becoming more erratic [56].

Recently, there were socioeconomic and environmental changes inducing crop production and other off-farm activities, though livestock rearing is the dominant form of livelihood [39,56]. People also clear bushes to cultivate crops or use flood retreats for crop production by the Omo and Weito rivers [57]. As a result of all these, the district has experienced massive vegetation change [7]. As part of government's policy direction, infrastructure development and the expansion of social facilities like schools, livestock clinics, and human health posts have expanded by more than 200% during the study period [56]. The district is an illustrative example of an area simultaneously experiencing climate variability as well as socioeconomic and LULC changes, which makes it a typical case to study the drivers of LULC change and its moderating factors.

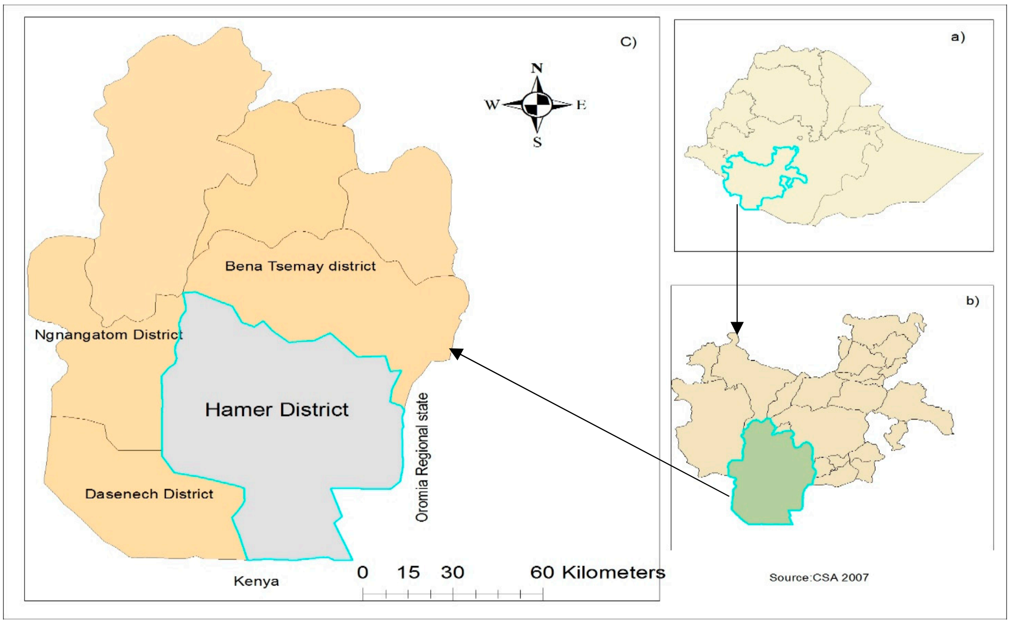

Figure 2. Location of the study area in reference to the Country, Region, and Zone. (**a**) depicts the Southern Nations Nationalities Peoples (SNNP) regional state in reference to Ethiopia; (**b**) location of the South Omo zone in reference to the SNNPR state; (**c**) Hamer district in reference to other districts in the South Omo zone.

2.2. Research Design

After investigating the pattern of LULC change in the district, using a mixed-methods design, which combines at least one qualitative and one quantitative method, two sets of relationships were examined: (i) the role of climate variability and pastoral adaptation policy in explaining the LULC changes. (ii) Whether the pastoral adaptation policies could lessen adverse effects of climate variability on LULC. The study attempted to remedy some of the limitations in relation to the previous studies, by examining the relationship between climate and LULC changes. Firstly, a comprehensive approach (i.e., an approach which takes into account the dynamics in the dominant land classes) was used, rather than focusing on a single land class (e.g., farmland). This is mainly because of pastoralists' dependence on diverse livestock species, which rely on arrays of vegetation rather than on a single vegetation type to cope with the aridity and unpredictability of the environment [19]. Secondly, following the suggestion of [11,31], the land-use data presenting LULC changes was explained using qualitative information along with time-series socioeconomic and climate data. Third, using the interaction terms between rainfall anomalies and policy factors, the hypotheses that the pro-diversification policy (i.e., the policy with a natural resource development components) curbs adverse effects of climate variability on LULC changes was empirically evaluated.

2.3. Data Collection

The study conducted a time series analysis of annual characteristics of Hamer district's LULC change for a period of 30 years, between 1986 and 2015. Based on the model requirement, data sets quantifying LULC changes, socioeconomic, and climate variables influencing LULC changes were collected. The Geographic Information System (GIS) used to represent LULC change was collected by spatiotemporal analysis of remotely sensed imagery data for the years 1986, 2000, and 2015. For the in-between observations, data were derived from a previous study conducted in the area [7] and data from the regional mapping authority [56]. These data were also compared with data generated through interpolation. A land cover classification was applied [58] to the Landsat data. Before classifying the Landsat TM images, a land-use ground reconnaissance was carried out in order to understand the land-use situation of the area, and collect ground truth points. Based on that, the LULC characteristics in the district were divided into eight classes: cropland, shrubland, forestland, grassland, riverine vegetation and wetland, urban land and settlements, and barren land (definition of the land classes are presented in Table A1 (in Appendix A)).

Landsat imagery acquired on 21/12/2015, was used to understand the LULC change in Hamer district and in addition to the FGDs, KIIs and secondary information used in this study. For this analysis, Landsat TM (Path169/Rows 56 and 57) images for 1986, and 2010, as well as ETM images were acquired in 2015. All the images have a spatial resolution of 30 m and were taken in December. The reconnaissance study was undertaken in the December–January window of 2015–2016. After geo-referencing and standardization of the images, following the nearest-neighbor resampling algorithm, images were projected into a UTM WGS-84 (zone-37) coordinate system.

ArchGIS 10.3 software was used to process, classify and quantify image information, and images were classified based on 428 reference (ground truth) points collected during the ground reconnaissance, of which 214 and 214 were used for classification and for assessment accuracy, respectively. After confirming that the overall classification accuracy is above 85%, the size of each of the eighth LULC classes was documented for further analysis. Afterwards during the FGD and KIIs discussion, the data and maps generated in this process were discussed and validated.

Then, five Focus Group Discussions (FGD) composed of elderly men and women, and experts were held in Dimeka, Turmi, Besheda, and Arbore villages to collect socioeconomic data on the pattern of change and its drivers where participants were presented with LULC maps, and statistics to get their views on the changes. Additionally, six Key Informant Interviews (KIIs) with experts from government and Non-Government Organizations (NGOs) were held. The discussions were also used to construct variables about the effects of adaptation policies, and elicit explanations from elders and experts.

In order to analyze the drivers and moderating factors of LULC change, secondary annual data on climate and socioeconomics was collected for the 1986–2015 period from the Ethiopian National Meteorological Agency, and the Ethiopian Central Statistical Authority (ECSA), respectively. Additionally, data were also collected from South Omo Zone Department of Economic Development office to supplement and validate the ECSA. Furthermore, a set of geo-referenced conflict data was obtained from the Uppsala Conflict Data Program (The data from Uppsala Conflict Data Program was brought for discussion during the FGDs for its reliability.) [59] for the same period, since conflicts are among the main "social" factors affecting land-use in pastoral areas [44]. The district is the unit of observation.

2.4. Data Analysis

Qualitative and quantitative data were combined in testing the hypotheses, and explaining the result. Thematic content of the qualitative data was analyzed guided by the hypotheses, to understand the locals' perspective on the social and environmental dynamics, encompassing historical events and trends in land-use land-cover change. To describe the changes on LULC classes, descriptive statistical analysis such as mean and percentage changes were used. The quantitative data concerning LULC changes was analyzed using Seemingly Unrelated Regression (SUR) model [60]. Since a decline in one of the land classes could mean an increase in the other, the time series SUR yields better estimators when the error terms of the equations are correlated, albeit the errors are assumed to be homoscedastic and linearly independent within each equation (see [60] for detailed model specifications). Additionally, to decide whether a structural time series SUR or simple SUR model fits the data, the autocorrelation function (AFC) for testing seasonality and stationarity of LULC classes was used, which turned out to imply the absence of seasonality and nonstationarity (weak-sense stationarity).

Following [60], a standard SUR model can be presented as a model comprising of M multiple regression equations of the form;

$$Yt_i = \sum_{j=1}^{ki} Xt_{ij}\beta_{ij} + \mathcal{E}tit = 1,\ 2, \ldots,\ \mathrm{T};\ \mathrm{I} = 1,\ 2, \ldots, \mathrm{M};\ \mathrm{j} = 1,\ 2, \ldots, \mathrm{ki} \quad (1)$$

where Yt_i is the tth observation on the ith dependent variable, which was explained by the ith regression equation, Xt_{ij} is the tth observation on jth explanatory variable appearing in the ith equation, β_{ij} is the coefficient associated with X_{tij} at each observation, and εti is the tth value of the random error component associated with ith equation of the model.

The SUR Equations (1)–(3) below imply that the use or conversion of one category of land is dependent on the others. The Breusch-Pagan test confirmed that the error terms of the Equations (1)–(3) are correlated, and hence that time-series SUR estimates are better than the ordinary least squares estimators or the ARIMA model. In order to see the role of the explanatory variables and their interactions, four different models were analyzed. The first model only scrutinized the role of climate variables on LULC changes. Then the second model presented what happens to the relationship between climate variables and LULC changes when socioeconomic changes are also considered. Controlling for the effects of the socioeconomic variables, in model three effects of the policies were analyzed. The fourth model was used to analyze the directional and magnitudinal effects of the three policies (i.e., pro-settlement, pro-commercialization, and pro-diversification) directions on the relationship between climate and LULC change (i.e., a moderation effect). Further, to select the most important variables for analyzing climate-policy interaction, marginal effects of predictors were estimated by applying Lindeman-Merenda-Gold's procedure, as suggested by [61].

2.4.1. Outcome Variables

Based on a theoretical and literature-based evaluation along with close scrutiny of pastoral livelihood activities, LULC changes as dependent outcome variables have been specified as follows: aggregation of grassland, shrubland, forestland, wetland, and riverine vegetation were categorized as rangelands (Range). Whereas cropland, settlements and urban built up areas were classified as non-range land uses (NonRange) and degraded areas as Bare lands (BareLand). The dependent variables on the left-hand side of the equation are changes in the size of LULC in the district.

$$Range = \alpha 1 + \beta 1 Climate + \delta 1 S - Economic + \theta 1 Policy + \mu 1 t \quad (2)$$

$$\mathrm{NonRange} = \alpha 2 + \beta 2\mathrm{Climate} + \delta 2\mathrm{S} - \mathrm{Economic} + \theta 2\mathrm{Policy} + \mu 2\mathrm{t} \quad (3)$$

$$\mathrm{BareLand} = \alpha 3 + \beta 3\mathrm{Climate} + \delta 3\mathrm{S} - \mathrm{Economict} + \theta 3\mathrm{Policy} + \mu 3\mathrm{t} \quad (4)$$

2.4.2. Explanatory Variables

The right-hand side of the equations represents the independent variables, "Climate" comprises various specifications of rainfall variability that could influence LULC, while "Policy" represents a pastoral adaptation policy variable, and "S-Economic" stands for a set of socioeconomic variables. μ_{it} captures the unobserved factors in each equation that may affect LULC changes (see Table 1). Time 't' includes the observations between 1986 and 2015. The coefficients β_i and δ_i represent the amount of increase or decrease in the respective dependent variables (e.g., bare land size), due to a unit increase in specified climate and socioeconomic variables, respectively. The coefficient of the categorical variable, Policy (i.e., θ_i), expresses changes in the respective dependent variable because of change in policy towards pro-commercialization or pro-diversification approach as compared to the pro-settlement approach which serves as the reference (A reference category is one of the categories in the variable; when comparing the changes within a variable, it is used as a baseline or point of reference.) category. The explanatory variables were selected based on the adopted model of LULC drivers, literature and empirical knowledge as well as data availability. A brief description of the variables, which were categorized as Climatic, Socioeconomic, and Policy variables are shown on Table 1 along with their specification and measurements.

Table 1. Summary of variables used in the Seemingly Unrelated Regression model.

Category	Variables	Variable Description	Type and Measurement
Dependent variable	Rangeland	Combination of grassland, shrub, forest, wetland, and riverine vegetation	
	Non-Range land uses	Cropland, settlement, and urban built-ups	
	Bare land	Degraded land size	
Independent variable			
Climate anomalies	AnNeg/Anpos	Interannual negative/positive rainfall anomalies, respectively	[1] Scale, index
	MehNeg/BelgNeg	Interannual rainfall negative anomalies in *Meher* and *Belg* crop production seasons, respectively	Scale, index
	ANR^2	Extreme values of Interannual negative rainfall anomalies (Square of the negative anomalies)	Scale, index
	AnP^2	Extreme values of Interannual positive rainfall anomalies (Square of the positive anomalies)	Scale, index
Socioeconomic	Population $_{log}$	Population growth rate	Scale, %
	Livestock	Number of livestock in tropical livestock value	Scale, index
	Road	All-weather road network length in kilometers	Scale, number
	Maize prices	Average prices of main food crop, Maize in Birr	Scale, real price
	HConflict	Number of incidents of non-state conflict within Hamer	Scale, number
	Nconflict	Number of incidents of non-state conflict in the neighbouring districts,	Scale, number
Policy	Adaptive land-use policy	The policies named based on their prime target (0 = pro-settlement (1986–1994), 1 = pro-commercialization (1994–2005) and 2 = pro-diversification (2006–2015)	Nominal, number

NB: These are variables used in the main model, selected after accounting for multicollinearity and other specification tests (e.g., Table A2). The log function of population variable is used to minimize the multicollinearity problem. [1] A variable has one of four different levels of measurement: Nominal (e.g., 1 = Yes or F = Female), Ordinal (e.g., 1 = High, 2 = Moderate), Interval (e.g., 1986–2015), or Ratio (e.g., −0.64). Interval and Ratio levels of measurement are also called Scale. While indexes are calculated or composite statistic, numbers are the raw values or representations of them [59].

Climate drivers: to evaluate the first hypothesis that when holding other variabilities at their mean, rainfall anomalies then instigate LULC change, various specifications of rainfall anomalies were used. Precipitation and temperature anomalies are the predominant indicators of climatology deviations from the long-term average [33]. The anomaly-based index helps to take into account effects that may not come from lower average rainfall but from a widening of the standard deviation as weather extremes become more frequent. The specification of rainfall anomaly follows [62].

$$\text{Observations of} = \frac{\text{Observations of climatological variables} - \text{Long} - \text{term mean climatological variables}}{\text{Standard deviation of long} - \text{term mean climatological variables}} \tag{5}$$

The drylands' climate is dominated by intra-annual and interannual climate anomalies [5]. However, counting on the interannual rainfall anomalies may disguise the adverse effects of rain coming in the wrong seasons [33]. Then, in order to account for this problem, anomalies for the two farming seasons of *Meher,* and *Belg*, as well as extreme anomalies, were calculated. Both negative and positive deviations from normal rainfall patterns can change land-use decisions: higher negative anomalies decrease the availability of water for farming and pasture for livestock. A positive anomaly can also interfere with the crop's vegetation system and in extreme cases may cause flooding [24,33]. Apart from analyzing how the results change with different rainfall anomalies, the effects of interannual temperature anomalies were used to check the robustness of the model.

Socioeconomic drivers: though different socioeconomic factors are suggested in the literature to drive LULC (e.g., [1,14,25], for their relevance in the pastoral context and data availability, an annual data of population, livestock, prices of food crops, conflict within and in the neighboring districts, and the road network were considered for the 1986–2015 period. Population data was also converted to a population growth rate to minimize the multicollinearity issue with other variables. Following the literature-based justifications in Section 1.1.1. Local drivers and mediators of LULC change in pastoral areas, the socioeconomic variables were controlled in the regression model.

Policy factors: to evaluate the second hypothesis, which is, pastoral adaptive land-use policies drive as well as moderate rainfall anomalies' effects on LULC, the policy variable with three categories representing the attributes of policies were analyzed. Pastoral adaptive land-use policies (Section 1.1.2. Local drivers and mediators of LULC change in pastoral areas) were used as a categorical variable with three categories (0 = pro-settlement (which was the dominant adaptation discourse mainly before mid-1990s but the settlement aspect remains in its successors), 1 = pro-commercialization (1994–2005), and 2 = pro-diversification (2006–2015).

3. Results

This section presents results of the quantitative and qualitative analysis combined with a discussion in following two subsections. The first subsection presents the general social, economic, and climatic changes in Hamer district along with the LULC changes during the period 1986–2015. The second subsection presents result and discussion of the hypothesis tests on drivers and moderating factors of LULC change.

3.1. Description of LULC Changes and Socioeconomic Changes in Hamer

In the last three decades, the Hamer district has experienced massive socioeconomic and climatic changes, as well as LULC changes. Table 2 shows the main changes in land cover, and land uses in the study area. In 1986, rangelands (combinations of grass, wetlands, riverine vegetation, shrub, and forestlands) made 84% of the land classes, where grass and shrublands were covering more than 60% of the land. This high percentage of rangeland and its diverse composition has allowed the tribes in Hamer to rely on different livestock species ranging from sheep and goats to camels to secure their livelihoods against seasonal climate variabilities and other hazards. During this observation, bare land, and cropland accounted for 655 km^2 (12%), and 230 km^2 (4% of the land area), respectively. Whereas, non–rangeland uses like settlement and crop production accounted for a tiny proportion of the land classes. The pattern of LULC distribution in the year 2000 underwent changes. In this period, cropland increased from covering 230 km^2 (4% of the total land) to 872 km^2 (11% of the total land), and transitions were apparent within the rangeland components. A similar trend continued in 2015, where the general transitions of LULC change was from rangeland to non-rangeland uses and bare lands.

Table 2. Land-use land cover change in the Hamer district during 1986–2015.

LULC Type	[a] LULC Size						[b] Relative Change		[C] Total Relative Change	
	1986		2000		2015		1986–2000	2000–2015	1986–2015	
	km^2	%	km^2	%	km^2	%	%	%	km^2	%
Wetland	343	6	351	6	364	6	2	4	21	6
Riverine Vegetation	472	8	429	8	408	7	−9	−5	−64	−14
Forestland	545	10	502	9	409	7	−8	−19	−136	−25
Shrub land	1448	25	1359	24	1345	24	−6	−1	−103	−7
Grassland	2001	35	1766	31	1519	27	−12	−14	−482	−24
Cropland	230	4	598	11	872	15	160	46	642	279
Bare land	655	12	688	12	769	13	5	12	114	17
Settlement	2	0	3	0	10	0	126	233	8	536
Category										
Rangelands	4809	84	4407	77	4045	71	−8	−8	−764	−16
Non-range	232	4	601	11	882	11	160	47	418	280
Total	5696	100	5696	100	5696	100				

[a] LULC size (%) is calculated by using the formula: (the size of the specific LULC type/Total land)) × 100. [b] Relative change is calculated by using the formula: ((target year-base year)/base year)) × 100. [C] Total relative change is calculated by using the formula: ((target year-base year)/base year)) ×100.

Between 1986 and 2015, wetlands maintained their consistency in magnitude (Though seasonal shrinkage of Chew Bahir is the main factor for shrinkage of wetlands, irrigation discharges/water loggings on the banks of Weito and Omo river created pockets of wetlands (Source: FGD)). whilst built-up and settlement areas expanded by 8 km^2, a 536% increase which makes up about 0.1% of the total land (since the initial values were very small for settlement and urban buildups, the trends cannot be shown in Table 2 below with a compatible scale). Similarly, the land area covered with forest declined over the study period. Generally, the comparative LULC analysis in the study period shows that the rangelands that are bases of pastoral livelihood contracted by 764 km^2, which is a change of 16% that accounts for 13% of the total land. In the same period, the size of bare land increased by 17% (an expansion of 114 km^2), whereas the average corresponding increase in non-range land-use (cropland, and urban built ups and settlement) was 650 km^2 (a relative change of 280%), which is about 11% of the total land.

The decline of rangeland area has negative repercussions on the pastoral livelihood, which is reliant on the rangelands. The contraction of the rangelands and the changes in the composition of the rangelands does not only affect the number of livestock that a household could herd, but it also affects the compositions of livestock. It is important to note that pastoralists strategically compose their herd to deal with the local climate and range conditions. Besides the shrinkage, the change in vegetation from grasses to browses persuades households to herd more of the browsers (such as goats), leading to herd structure polarization and subsequent risks due to an inability to diversify herd. Therefore, from these findings, it could be understood that Hamer pastoralists' adaptation response to climate variability takes place under a situation where size and composition of rangelands is narrowing, which entails narrowing adaptation options, among other things.

Besides the changes on LULC, the district has also witnessed changes in its local climate and socioeconomic status. Among indicators of climate variability used in this analysis, analysis of interannual climate anomalies show that the district experienced 12 years of below average rainfall (negative interannual rainfall anomalies), and 7 years of above-average rainfall anomalies between 1986 and 2015. As shown on Table 3. rainfall and temperature variabilities have been observed between various years and during the main farming seasons of *Belg* and *Meher*.

Table 3. Descriptive statistics of the socioeconomic and climatic variables.

Variable	Mean	SD	Min	Max	Frequency
Interannual negative rainfall anomalies	−0.62	0.62	−1.8	0	12
Interannual positive rainfall anomalies	0.34	0.63	0	3.05	7
Interseasonal *Meher* negative rainfall anomalies	−0.35	0.36	−1.2	0	11
Interseasonal *Meher* positive rainfall anomalies	0.65	0.79	0	2.6	19
Interseasonal *Belg* negative rainfall anomalies	−0.40	0.61	−1.9	0	18
Interannual positive temperature anomalies	0.35	0.58	0	2.5	24
Square of Interannual negative rainfall anomalies	1.7	1.85	0	6.4	
Square of Interannual positive rainfall anomalies	0.50	1.71	0	3.24	
All-weather Road (in km)	125	41	82	191	
Human Population (in 1000)	47.4	16.9	27.4	75.6	
Livestock Population (in 1000)	245.6	15.6	140.8	573	
Maize price (Birr/quintale)	209.3	202	32	590	
Sorghum price (Birr/quintale)	221	205	35	620	
Conflict within Hamer district	31	22	2	74	
Conflict in the neighboring district	117	75	16	271	

NB: 'Mean' represents the average values, while the 'Standard Deviation (SD)' depicts how the observed values deviate from the mean value. The Minimum (Min) and Maximum (Max) show how low and high the value has been during the observation period. 'Frequency' on the other hand demonstrates the number of times, for example, Interannual rainfall anomalies became negative.

From the socioeconomic perspective, the district has experienced substantial changes. Livestock and human population have grown by 176% and 322%, respectively. In the same period (i.e., 1986–2015), average prices (inflation adjusted) of the main food crops sorghum and maize increased by 1781% and 1744%. With the other factors mentioned above, the expansion of the road network by 136% indicates the economic and social transitions of the district in the last three decades. Apart from these changes, Table 3 also shows that an average of 31 incidents of conflicts within the Hamer district, while 117 have occurred in the neighboring district with whom they are shared rangelands. To understand how these changes affect pastoral livelihoods, further investigation has been made on how these factors affect the three main LULC categories along with climate variability and policy factors, as presented in the next section.

3.2. Determinants of LULC Change in the Hamer District

This subsection presents results from the Seemingly Unrelated Regression (SUR) analysis on the drivers of LULC change, with a focus on the impacts of climate variability and adaptation policies controlling for the effects of changes in the socioeconomic variable. After presenting the key drivers, and factors that could lessen the adverse effects of the main drivers on LULC change, results are discussed backed by the qualitative data and related literature.

3.2.1. Do Rainfall Anomalies Determine LULC Change?

Table 4 shows empirical evidence of the effects of climate variability and socioeconomic drivers of LULCs. Each model introduces a new variable and displays the impact on the LULC changes. When only climate variability indicators are considered (i.e., Model-1), a unit increase in interannual negative rainfall anomaly (i.e., below average annual rainfall) induces contraction of rangelands by 180 km^2 over the study period, and facilitates the expansion of non-range land uses by 126 km^2 (crop production, and settlement) and bare lands by 27 km^2. Increases in positive anomalies (i.e., above average rain during the main crop production season), increase the area of land employed for non-range uses like crop production.

Table 4. Coefficients of Seemingly Unrelated Regression with climate and socioeconomic drivers.

Model-1(Climate Anomalies)				**Model-2 (with Socioeconomic)**		
Variables	**Range Land**	**Non-Range**	**Bare Land**	**Range Land**	**Non-Range**	**Bare Land**
Negative interannual rain anomaly (AnNeg)	−180 **	126 *	27 **	−60 ***	47 ***	9 ***
	(74)	(67)	(11)	(16.2)	(95.1)	(2.8)
Positive interannual rain anomaly (AnPos)				36.5 *	−13 **	−6.3 **
				(10.5)	(6)	(1.8)
Meher positive rain anomaly (MehPos)		89 *			10.5 **	
		(52)			(5.2)	
Maize Price	-	-	-	−0.55 **	0.54 ***	0.08 ***
				(0.13)	(0.07)	(0.02)
Road Network	-	-	-	−2.4 **	1.4 ***	0.4 ***
				(0.66)	(0.37)	(0.11)
Livestock (TLU)	-	-	-		0.00 **	
					(0.07)	
Constants	459	351	690	4728	14	677
Observations	30	30	30	30	30	30
Breusch–Pagan independence test (chi^2)	86.5 ***			37.6 ***		
R^2	0.24	0.22	0.25	0.97	0.98	0.97

NB: Table 3 shows estimation coefficients with standard errors in parentheses; * $p < 0.1$; ** $p < 0.05$; ** $p < 0.05$; *** $p < 0.01$ denote significance at 10%, 5%, and 1% levels, respectively; '-' denotes that the analysis does not apply to this cell, and empty cells represent the insignificant value of the corresponding variable; and only variables with significant values are displayed for brevity.

In Model-2, the effects of changes in specific socioeconomic variables (i.e., expansion of road network, maize price, livestock and incidents of conflict) that might be correlated with both rainfall patterns and LULC changes (Table 4) are controlled. As a result, an increase in interannual positive rainfall anomaly (i.e., above average annual rainfall) induced expansion of rangelands by 36.5 km^2, while reducing the bare land and non-range land uses by 6.3 km^2 and 13 km^2, respectively. The latter result could be an indicator that the rain was coming during the non-crop production season, as the FGD discussants raised.

However, to account for cases where annual rainfall amount is on par but the rain did not come during crop production seasons, seasonal variations in rainfall were analyzed (Model-2). Seasonal variabilities in the form of an increase in positive rainfall anomalies during the main crop production season (*Meher* season) significantly increase the expansion of non-range land uses like crop production. As it was hypothesized, a unit increase in interannual negative rainfall anomaly induces an average rise in the cultivated area and settlement (non-range land uses) by 47 km^2, while contributing to the reduction of rangelands by 60 km^2. An increase in interannual negative rainfall anomalies increases the size of bare lands by 9 km^2.

According to FGDs, the expansion of non-range land uses and degradation in the face of negative interannual rainfall anomaly is explained by the fact that households want to distribute the risk and compensate crop failure due to drought by expanding their farm size and diversifying locations. In Hamer, members of the tribe are rarely prohibited from cultivating in areas, which are not set aside to be sacred or for communal use e.g., mobility corridors, pasture lands. Ref. [8] (p. 110) have come up with a similar finding that pastoralists perceive mixed farming as being more reliable than a pastoral way of life for coping with recurrent drought among Afar pastoralists in Ethiopia. Ref. [21] found that frequent droughts undermined herd rebuilding capacity of the locals, which led to crop production that has eventually contributed to the transformation of grazing areas to croplands in pastoral and agro-pastoral areas of eastern Ethiopia. Therefore, expansion of non-range land use as a result of negative interannual rainfall variability is explained by the inherent need to adapt and facilitated by the existing land tenure system. The findings from this analysis and the previous studies, therefore show that dryland land cover changes as a result of climate variability and mainly as users' attempt to adapt to the changes. Thus, as it was argued, climate variability in the form of rainfall anomaly induces vulnerability of the pastoral livelihood by driving the shrinkage of rangelands.

As the result in Model-2 shows, socioeconomic changes over the past 30 years have greatly contributed to the LULC change in Hamer district. According to the locals, the increase in crop price (inflation adjusted) has not only incentivized the expansion of crop production, but it also motivated households to look for alternative income sources to match the increase in living expenses. According to the FGD, in such circumstances, the off-farm activity of selling firewood/charcoal, and crop production, which further enhances vegetation clearing, is evolving as an alternative livelihood.

Furthermore, the FGDs and KIIs revealed that households' extensive crop cultivation in or closer to forestlands, is a growing adaptive strategy. The locals' rationale is that forestlands are relatively humid, and the remaining trees serve as a windbreak. These results provide further support for the hypotheses that land-use changes from pasture to crop cultivation and off-farm activities are important climate adaptation strategy among pastoral communities that enhance LULC changes. These outcomes are in line with previous observations of different land-use studies across various places around the world that show that variability in climate variability and subsequent adaptive responses eventually lead to LULC changes [8,17,40].

As it was hypothesized, it is apparent that rainfall variability, particularly negative interannual rainfall anomalies, drive shrinkage of rangelands and expansion of non-rangeland uses and land degradation which further expose land users to impacts of rainfall variability. The result indicates that rainfall deficiency exacerbates the shrinkage of rangelands (i) inducing land-based adaptation activities; (ii) expanding bare land and land degradation. The next section presents how pastoral adaptive land-use policies shape the way pastoralists use land, and mitigate the adverse impact of climate variability on LULC.

3.2.2. Do Policies Moderate Effects of Climate Variabilities on LULC?

Table 5 demonstrations the effects of pastoral adaptive land-use policies in driving LULC change, as well as its role in lessening the effects of climate variability on LULC changes. In Model-3, the effects associated with the policies on LULC changes are presented, after controlling for the socioeconomic and climate variables. As hypothesized, the change in policy towards a pro-diversification policy was positively and significantly associated with the expansion of non-range land uses and bare lands compared to the pro-settlement (reference category), and pro-commercialization approaches. As compared to the pro-settlement approach, during the pro-diversification era a larger rangeland area (116 km^2) than the pro-commercialization (97 km^2) approach has been converted to non-rangeland uses, and bare lands. These results imply that the pro-diversification adaptation policy has more impacts on rangelands' shrinkage than the pro-settlement and pro-commercialization policies.

Table 5. Coefficients of Seemingly Unrelated Regression with policy and interaction effects.

Variables	Model-3 (with Policy)			Model-4 (Rainfall-Policy Interaction)		
	Range	Non-Range	Bare Land	Range	Non-Range	Bare land
Negative interannual rain anomaly (AnNeg)	−52 ***	52.3 ***	7.1 ***	−139 ***		28 ***
	(9.2)	(7.7)	(1.5)	(50.3)		(8.2)
Positive interannual rain anomaly (AnPos)	16.2 ***	−10.8 **	−2.6 ***	18.3 ***	−14 ***	−28 ***
	(6.1)	(5.4)	(1.1)	(58)	(5.8)	(9.5)
Meher positive rain anomaly (MehPos)			−4.1 **	10 **	10 **	1.5 **
			(1.8)	(4.4)	(4.4)	(0.7)
Meher negative rain anomaly (MehNeg)				−23 **	18.7 *	
				(10)	(11.3)	
Policy: Pro-settlement(pro-Stl) Pro-commercialization(Pol-Com)	−97 ***		17.5 ***	−99 ***		19 ***
	(11.2)		(1.9)	(16)		(2.3)
Pro-Diversification(Pol-Div)	−117 ***	75.4 ***	19.6 ***	−243 ***	105 **	41 ***
	(22.4)	(19.3)	(3.7)	(43)	(42.3)	(7.1)
AnNeg * Policy: AnNeg * Pol-com	-	-	-			
AnNeg * Pol-Div	-	-	-	91 * (49)		−21 ** (8.3)
Constants	4890	78	646	4858	73	652
Observations	30	30	30	30	30	30
Breusch–Pagan independence test (chi^2)	32.2 ***			33.7 ***		
R^2	0.98	0.99	0.99	0.98	0.99	0.99

Table 5 shows estimation coefficients with standard errors in parentheses; * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$ denote significance at 10%, 5%, and 1% levels, respectively; '-'denotes that the analysis does not apply to this cell (model), and empty cells represent the insignificant value of the corresponding variable; socioeconomic and other insignificant variables used in the model are not reported for brevity.

According to the KIIs, these results emanate from the specific features of the policies adopted by the government. The policy instruments prior to the pro-diversification approach focused more on linking the (agro) pastoralists to markets and enhancing their marketed offtake, than transitioning them to other livelihood systems. Market-orienting the production system was envisaged to complement and sustain settlement of pastoralists nearby water-bodies. However, infrastructural, cultural, and environmental factors coupled with poor agricultural market performance in the area limited its effectiveness [54,55,63]. As a response to the failures and increasing livelihood hazards in pastoral areas, the pro-diversification approach came up with three components: income diversification, participatory natural resource adaptation, and marketization. As diversifying in the (agro) pastoral context is mostly related to engaging in crop farming and non-farm activities, this policy further enhances vegetation clearing.

Agricultural experts and key informants attribute the recent expansion in crop production to government's high involvement in diversifying pastoral livelihoods, mainly towards off-farm activities and crop production. For example, a minimum of three agricultural extension experts look after the locals' production activities in each village. Similarly, ref. [21] argues that the government's emphasis on training extension officers in pastoral area enhanced crop production in pastoral and agro-pastoral areas of eastern Ethiopia, which eventually contributed to the transformation of grazing areas to croplands. Moreover, evidence from the Office of Agriculture shows that in the last decade alone, farming facilities like irrigation infrastructure have increased by 150%, albeit few are functioning up to date. As a FGD participant indicated, the government is giving incentives for those who want to engage in market-oriented farming:

" ... government is striving to produce 'model farmers' who lead innovation and mobilize others to follow suit. The annual award of best-performing-farmers is creating competition among agro-pastoralists ... and even attracting the nomads to settled life ... " (Participant from Besheda village 22 February 2015).

In contrast to Model-2 (i.e., where no policy effect is considered), inculcation of the policy variable (Model-3) minimized the adverse effects of interannual negative rainfall anomaly on rangeland and bare lands sizes. A positive effect on rangeland (16.2 km^2) was noted when the interannual positive rainfall anomaly increases, whereas non-range land uses and bare land size declined by 10.8 and 2.6 km^2, respectively. The decline in non-range land use, mainly crop production, with an increase in interannual positive rainfall anomaly, could be attributed to rain coming on non-crop production seasons. As the findings of [64] and community perception confirms, the onset and termination time of rain has been changing and becoming more erratic.

The findings confirm the hypothesis that the pro-diversification and pro-commercialization approaches drive non-rangeland uses, implying that the adaptive responses resulting in non-range uses would exacerbate shrinkage and degradation of rangeland, exposing pastoral livelihood to further risks. Similar to this finding, ref. [3] identified the simultaneous occurrence of climatic variability and drastic conversion of natural vegetation areas into agricultural lands in pastoral areas of Eastern Sudan, attributing the changes to the pro-settlement land-use policy of the country.

However, as compared to the pro-commercialization approaches, during the pro-diversification approaches, the rate of expansion of bare lands and adverse effects of interannual negative rainfall anomalies on LULC has declined (Model-4). As the positive relation between the rainfall-policy interaction term (AnNeg * Pol-Div) indicates, the pro-diversification approach exacerbates the adverse effects of rainfall anomalies on the rangeland size. This result could be related to a high incentive for diversifying income sources coupled with the weakening of the customary land governance system that opened room for vegetation clearance, as people look for affordable adaptation measures. In Hamer, unless the land is a footpath, mobility corridor, or sacred place, where rituals are practised or meetings are carried out, people are rarely prohibited from farming.

According to the interviewees, at present, with declining relevance of customary governance, such as elder's land distribution, people engage in deforestation and cultivation of areas traditionally not allowed for cultivation. Strengthening the interviewees' claim [65] argues, pastoral rangeland management has been weakened by poorly adapted adaptation interventions and inadequate land use policies, referring to the situation of Borena rangeland. Other researchers indicated that squatters expand land cultivation with the increase in the economic values of land, and absence of regulations or enforcement mechanisms banning the squatting [16,41]. This indicates that, in the face of weak formal or informal governance of rangelands, adaptation responses might lead to shrinkage and degradation of rangelands. Emphasizing the importance of land governance for maintaining benefits of the resource also into the future, ref. [22] suggests that such control over land-uses promotes climate resilient adaptation and curbs maladaptive practices.

On the other hand, the negative relation between the rainfall-policy interaction term (AnNeg * Pol-Div) and bare land size shows that the pro-diversification policy significantly reduced the adverse effects of negative rainfall anomalies on the expansion of the bare land size. This could be related to the components of the pro-diversification approach in which developing natural resource in the (agro) pastoral areas is one of the main intervention strategies which has not been a policy priority in the previous adaptation approaches [66]. For example, the last decade has seen a massive work on rangeland adaptation, and soil and water management practices from Federal to *Kebele* (lowest administrative hierarchy) levels. This result implies natural resource adaptation could be an effective adaptation mechanism in dryland pastoral context, as it enhances adaptive capacity. Altogether, results of Model-4 show that recent pastoral adaptation policy components (i.e., income diversification and natural resource adaptation) are important determinants of pastoralists' response to climate variability and subsequent LULC changes.

3.2.3. Robustness Checks

In order to check if the current results hold even if some of the model specifications changed, besides different specifications of the interannual rainfall anomalies, temperature anomalies were also evaluated (Table A3). For this purpose, interannual rainfall anomalies was replaced with interanual temperature anomaly. This confirmed that the result that climate variability drives LULC holds in relation to all categories except non-range land use, which is dominantly crop production. The reason could be that in most areas of rain-fed agriculture, output and production incentives are highly dependent on rain. Additionally, an alternative specification for each land class as a dependent variable rather than pooling land uses classes was also evaluated. However, it did not show any important difference in explaining the linkage between land-use and climate variability.

4. Conclusions and Implications

By coupling a time-series socioeconomic and climate data with LULC data, this paper sought to explain LULC changes, along with whether and how land-use policies moderate rainfall anomalies' adverse effects on rangelands. The data revealed the district has experienced a considerable LULC changes, with a decline in rangeland and expansion of non-range land uses and bare lands. The analysis also shows that socioeconomic and policy factors play an important role both in driving and moderating the LULC changes. Additionally, as the qualitative data indicate weakening of customary land governance have contributed towards unchecked expansion of croplands and deforestation.

The main conclusions drawn from this are: firstly, climate variability constrains pastoral livelihoods by contracting the rangeland size. Secondly, pastoral adaptation policies inclined towards livelihood diversification tend to enhance rangeland shrinkage, whereas the inculcation of the natural resource adaptation objectives in the policy curbs adverse effects of rainfall anomalies on land degradation. This result highlights both the adverse effects of climate variability and the mitigating role of policies that foster natural resources protection on rainfall anomalies' existing and interaction effects. The results are robust to different specifications and suggest that policies strengthening a land governance system with balanced economic and natural resource development objectives could be effective instrument to lessen the adverse effects of climate anomalies on LULC change.

Although the study focused on analyzing the LULC changes, its (climatic and policy) driving and moderating factors, the findings may well have a bearing on the effective formulation and implementation of adaptation and land-use policies. As a future approach, studies with diverse methods considering additional biophysical, socioeconomic, and relevant spatiotemporal factors, will need to complement the results and help to establish even more robust causal links relevant for a sound design of land-use and adaptation policies. In particular, government—as a statutory co-owner of the country's land—should close the loopholes which occurred due to the weakening customary institutions, and inability of statutory land governance system to control land uses, which has opened a way for squatters to unchecked access over the commonly owned or no-man's land. Doing this either by empowering the customary governance system or designing policy instruments that could fit with the local practices, does not only promote sustainable land use and adaptation, but also lessens or avoids conflicts, which is again another problem ruining the adaptive capacity of the pastoralists and adaptation efforts in the area. Emphasizing the importance of land governance for maintaining benefits of the resource into the future as well, ref. [22] suggests that such control over land-uses promotes climate resilient adaptation and curbs maladaptive practices.

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Appendix A

The materials in this section could give supplementary information about the processes used in the production of the information contained in the main manuscript sections. It includes information on the definition of the land classes, specification tests and robustness tests undertaken.

Table A1. Description of dominant land covers classes.

LULC Types	Description
Wetland	Land area that is saturated with water
Riverine vegetation	Vegetation growing on the banks of water bodies
Forests	Areas dominated by natural high forests, which are above 5 m tall.
Shrubland	Areas covered with small trees less than 5 m, and bushes, mainly ranged from closed canopy to open canopy areas.
Grasslands	All areas covered with natural grass and small shrubs dominated by grass.
Croplands	Areas of land prepared for growing agricultural crops. This category includes areas currently under crop and land under preparation.
Bare lands	Areas of land bare of vegetation, due to erosion, overgrazing, or other mis-uses
Settlements and built-ups	Build-ups (houses) in both urban and rural parts.

This table describes the LULC classes discussed in the manuscript based on [67].

Table A2. Test for multicollinearity for the Seemingly Unrelated Regression model.

Variables	VIF	Tolerance
Conflict in Neighborhoods	6.38	0.1568
Conflict in Hamer (incidents)	3.81	0.2625
Interannual negative rainfall	2.92	0.3421
Interannual positive rainfall	8.09	0.1236
Interannual negative *Meher*	1.48	0.6761
Interannual positive rainfall	1.71	0.5857
Interannual negative Belg rain	1.70	0.5880
All-weather Road	3.79	0.2640
Maize price (Real)	12.92	0.0774
Interannual negative rainfall	7.69	0.1300
Livestock (TLU)	5.16	0.1939

The VIF index is calculate to test the multicollinearity between the variables used in the model, and after iteratively testing, the ones with lower than VIF are selected to be included in the model.

Table A3. Coefficients: Seemingly Unrelated Regression validation model.

		Validation Model	
Variables	Range	Non-Range	Bare Land
Interannual negative temperature anomaly	13.1 ***	52.3 ***	7.1 ***
	(31.1)	(7.7)	(1.5)
Policy(pro-Stl) Pro-Commercialization	−97 ***		17.5 ***
(Pol-Com)	(11.2)		(1.9)
Pro-Diversification	−117 ***	75.4 ***	19.6 ***
(Pol-Div)	(22.4)	(19.3)	(3.7)
Constants	4890	78	646
Observations	30	30	30
Breusch–Pagan independence test (chi^2)	32.2 ***		
R^2	0.98	0.99	0.99

*** $p < 0.01$ denote significance at 10%, 5% and 1% levels, respectively.

The table shows how the model would behave when interannual rainfall anomalies are replaced with temperature anomalies. Years of below average temperature are related with expansion of the rangeland, the non-range and bareland sizes. Similarly, as compared to the pro-settlement adaptive land use policy the pro-commercialization and the pro-diversification policies reduce the size of rangelands by 97 and 117 ha.

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