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The synergetic effect of drought and land use changes on Ethiopian Rift Valley Northwestern Escarpment livelihood systems

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Received: 14 May 2024 / Accepted: 3 February 2025
Published online: 18 February 2025

Abstract
Climate change has significantly impacted smallholder farmers in developing countries, where most livelihoods rely on rain-fed agricultural systems. The Northwestern Escarpment of the Ethiopian Rift Valley (NEERV) is among Ethiopia's most drought-vulnerable areas and is highly affected by land use and land cover change (LULCC). This study aimed to analyze the synergistic impacts of drought and LULCC in the three major livelihood zones (LZs) of NEERV between 1983 and 2019. The study used socioeconomic, climatic, and earth observation datasets. Utilizing a mix of socioeconomic, climatic, and earth observation datasets, this paper investigated the combined effects of these factors on three major livelihood zones: Alagie-Ofla (ALOFLZ), Tsirare catchment (TCLZ), and Raya Valley (RVLZ). The analysis revealed significant rainfall variability, with annual fluctuations between 31 and 50% and seasonal variations ranging from 39 to 99%. This variability has contributed to frequent drought occurrences, with intervals of approximately 2.13 years in ALOFLZ, 2.2 years in TCLZ, and 2.13 years in RVLZ. There has been a notable increase in cultivated and built-up areas across all zones. The study found that drought and LULCC have severely impacted agricultural productivity and local ecosystems, with the most pronounced effects observed in RVLZ, TCLZ, and ALOFLZ. The findings highlight a critical need for integrated approaches to manage and monitor the synergistic impacts of drought and LULCC. The study underscores the importance of enhancing drought and LULCC monitoring systems to improve resilience and adaptability in vulnerable regions. The research contributes to a deeper understanding of how these intertwined factors exacerbate environmental and socioeconomic challenges, offering valuable insights into policy and management strategies for mitigating their effects. Recommendations include enhancing the current drought and LULCC monitoring systems to improve predictions and mitigation efforts, thus bolstering resilience and adaptability among affected communities.

Keywords Climate variability · Drought · LULCC · Combined effects · Livelihood system

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s44274-025-00193-y.

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1 Introduction

Precipitation shortages and increasing temperatures have significantly impacted smallholder farmers in developing countries due to climate change, where most livelihoods depend on rainfed agricultural systems [1–3]. Drought is one of the costliest disasters that affects almost every corner of the world, even the wettest and most humid areas [4, 5]. The situation is worsening in developing countries [6]. Endemic drought has impacted many countries, while others experience drought regularly [7]. Economically, drought has the highest impact on all-natural tragedies, with billions of dollars in annual losses. The Center for Research on Epidemiology Disasters (CRED) and United Nations Disaster Risk Reduction (UNDRR) reported that from 2000 to 2019, nearly 7348 major disaster events occurred, resulting in the loss of 1.23 million lives, affecting about 4.2 billion people and the consequences of US$ 2.97 trillion in economic losses globally. Also, frequent droughts result in crop failure, livestock loss, and human loss in different parts of Ethiopia [8]. The country has been exposed to drought due to climate variability and low resilience. Drought is becoming a risk for farmers in Northern Ethiopia due to frequent crop failures [8]. The TCLZ, RVLZ, and ALOFLZ are most vulnerable to climate variability, frequent drought impacts, and uncertainty in northern Ethiopia. These LZs are vulnerable to severe climate events and have limited capacity to adapt to low-risk agricultural activities and increase crop productivity [9].

In the last three decades, the worldwide population has grown substantially and become a significant driver of changing land cover and global change processes [10]. Human activities negatively influence smallholders by reducing land productivity, changing weather systems, intensifying environmental degradation, enhancing desertification, and causing biodiversity loss in East Africa [11]. Equally, Ethiopia's long-term biological production has been severely affected by the LULCC [12]. Particularly in the northern regions of Ethiopia, decades of land exploitation have severely lowered soil productive capacity and weakened its ability to endure climatic extremes [13]. In the NEERV, centuries of unrelenting land exploitation have resulted in severe environmental alterations and degradations [14]. The cropland's expansion in parts of the NEERV (RVLZ) comes at the expense of natural vegetation and grasslands. As a result, while drought and LULCC have an impact, their combination on the system of livelihoods in the hotspot area is significant [15]. Drought and LULCC have long been regarded as one of Ethiopia's most serious food security threats [16]. Changes in land use and cover and drought frequency in Ethiopia imply other hazards that are likely to have much more significant influences on the livelihood strategies of the community [17]. The synergetic impact of land use, cover, and drought is not a simple sum of each impact, it has a more significant synergetic effect on the systems of the community's livelihood due to their feedback effects [18].

Drought can be caused by factors other than a lack of precipitation [19]. It is determined by biophysical and management such as land use management and drought-coping strategies [20]. Changes in natural vegetation and land cover are important factors causing drought [21]. Changes influence the characteristics of regional atmospheric circulation and large-scale external moisture fluxes in vegetation types and covers [22]. Biogeophysical feedback mechanisms that provide feedback to them and prolong drought conditions could cause these changes. In contrast, drought significantly affects critical ecological functions, and the crucial issue of global environmental change and its changes are cumulatively significant drivers of global climate change [23]. One or more of these factors could cause a shortage of rainfall [24].

Several synergy studies on climate policy are concerned with the performance of single systems (mitigation or adaptations) aimed at reducing climate impact with multiple regulatory levels [25–28]. The studies reviewed are appreciated for their scholarly contributions to the identified priority areas. However, the reviewed studies did not analyze the synergetic effects of drought and land use and cover modification on livelihood systems. These reviewed studies did not address the synergistic effects of drought and changes in land use and cover on livelihood systems. The study is also notable for employing a diverse set of data, including meteorological data, Landsat images, ground surveys, socioeconomic data, reports, and reviews of scientific works (Fig. 2). In addition, unlike most researchers, the focus was on livelihood systems rather than agroecological zones. As a result, policymakers will find this outcome valuable for planning synergistic solutions for livelihood system management. Also, this empirical evidence of the synergistic implications of drought and LULCC on livelihood systems is expected to contribute to the body of scientific knowledge. Knowing the magnitude or direction of the synergetic drought and the LULCC on community livelihood systems is necessary [29]. However, knowing the exact synergistic impacts of drought and LULCC on the livelihood system of the local community, it is difficult to synthesize measurable outcomes using an empirical formula. There are no standard ways to define the interactions between drought, LULCC, and livelihood systems. Drought, LULCC, and livelihood systems have various dimensions, interconnections (synergy), and biophysical and social circumstances that are not always similar. However, understanding synergy is essential for lowering operating costs and producing effective results [30].

This study investigated the effects of drought and LULCCs on livelihood systems in three different LZs of the NEERV. LZs are areas that have been grouped based on geographic similarities where households broadly share similar livelihood patterns, such as income sources and market opportunities, as well as demographic patterns rather than administrative boundaries. Because social, geographical, and technological inputs influence individual and group perceptions and decisions, livelihood zones are essential in encompassing these aspects under one umbrella. Therefore, this research hypothesized that the synergistic impacts of the LULCC and drought on the livelihood system have more significant consequences than independently or the sum of their results.

2 Materials and methods

2.1 Study area

The three livelihood zones of the study area are located in the Ethiopian Rift Valley's northwest escarpment between 12° 15′0" and 13° 00′0" N and 39° 15′0"–40° 15′00" E (Fig. 1). The research area covers 3809 km^2. The climate conditions of the study area are semi-arid and subhumid. The study area's topography ranges from − 231 to 4534 m above sea level (m.a.s.l.). According to the Ethiopian agroclimatic zone characterization, the dry Kola ranges from 500 to 1500 m.a.s.l., dry Woinadega (1500–2300 m.a.s.l.), dry Dega (2300–3200 m.a.s.l.), and high Dega (above 3200 m.a.s.l.). The RVLZ has

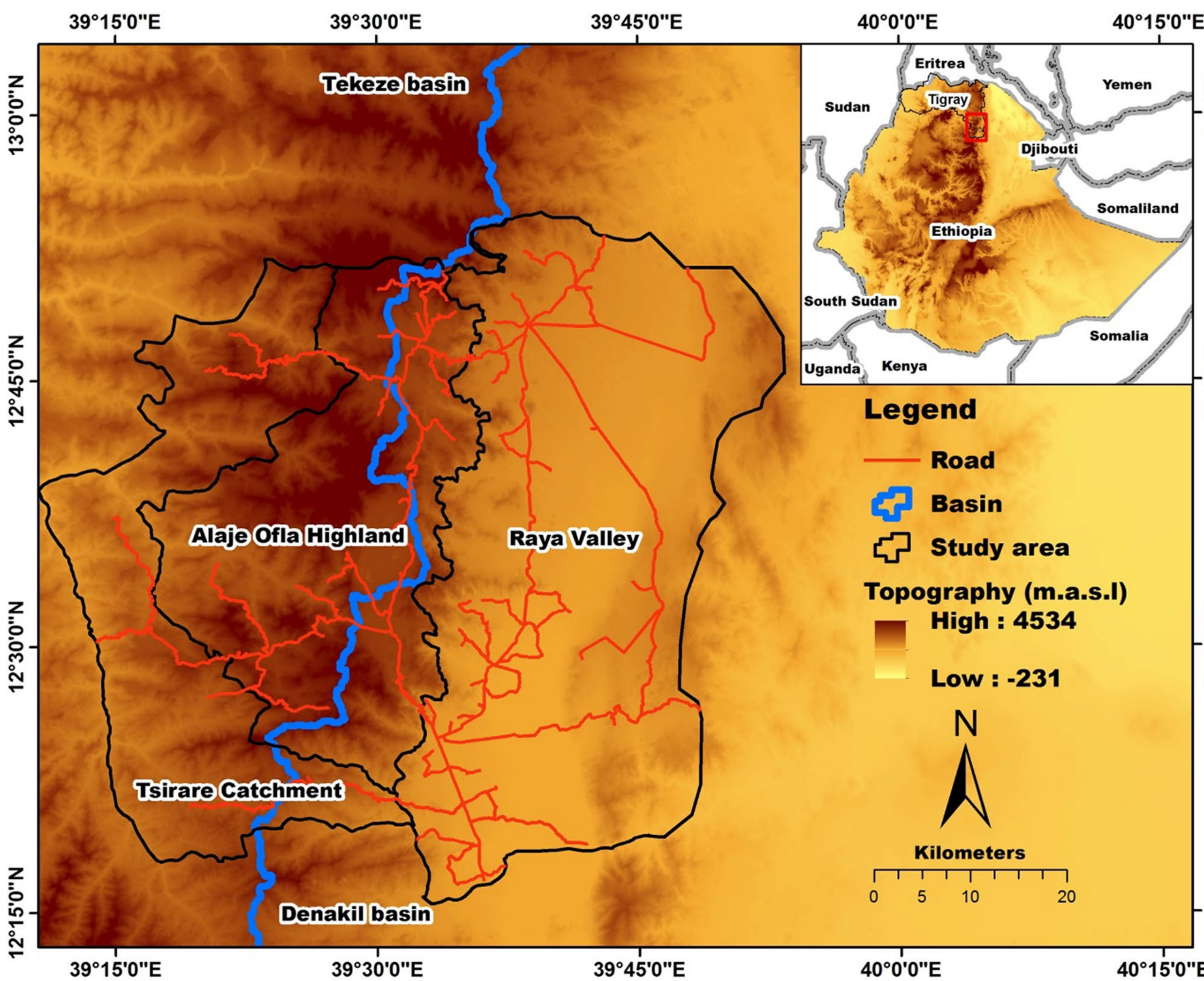

Fig. 1 The location of the study livelihood zones

dry Kola and dry Woinadega agroclimatic zones. The ALOFLZ has high dega and dry dega agroclimatic zones, respectively. However, the TCLZ has only a dry Woinadega agroclimatic zone. The mean annual maximum temperature of the study area ranges from 22.1 °C in ALOFLZ to 27.9 °C in RVLZ, while the mean minimum temperature ranges from 9.8 °C in ALOFLZ to 13.5 °C in RVALZ. The study area receives bimodal rainfall, which is relatively higher in July and August. The Belg (short rainy season) runs from March to May, while the Kiremt (long rainy season) runs from June to August. Rainfall amounts vary with altitude. The RVLZ, ALOFLZ, and TCLZ receive 164–972, between 126 and 1037 and 119–932 mm of rain annually, respectively [31]. See the summary of the biophysical and socioeconomic characteristics of the study livelihood zones in Supplementary file 1 Appendix 1.

3 Data collection

This study applied four different datasets in the three livelihood zones of the study area to analyze the synergistic impacts of drought and LULC change on livelihood systems (Fig. 2). The key factors are seasonal metrological drought and LULC change, with climate variability trends and their characteristics and the drought vulnerability index as subfactors.

3.1 Climate data

This study collected the CHIRPS and ENACTS data sets at 4 km by 4 km pixel sizes from the Ethiopian National Meteorological Agency from 1983 to 2016. The data dealt with the conditions and trends of climate variability, drought events, and their magnitudes in each LZ. The collected data sets were free of missing values to compute the rainfall and temperature trends.

3.2 Satellite data

Landsat images were applied to detect and analyze the LULCC in the study area. Cloud-free Landsat images for 1985, 2000, 2010, and 2019 were used from the USGS Landsat archives (http://earthexplorer.usgs.gov/) between December and February. In addition, 270 ground control points (GCPs) were collected from the field using the handheld Global Positioning System (GPS). The GCPs were used for image classification and accuracy assessment.

3.3 Socioeconomic data

A purposive sampling system was used to select representative LZs. Each LZ had eight kebele (small administrative units), which were picked randomly. Two from ALOFLZ Kebeles and three from TCLZ and RVLZ were chosen based on the number of households in each LZ. Based on the 2020 population estimates, about 384 household heads from ALOFLZ (n = 108), TCLZ (n = 120), and RVLZ (n = 155) were selected using simple random sampling methods for semi-structured interviews. Sampling households was calculated using the Cochran [32] formula (Eqs. 1 and 2) with a maximum variability of 50% (p = 0.5) and a 95% confidence level with ± 5% precision. Eight trained enumerators administered the survey from each of the sampled kebeles. The following equations are used to calculate the sample size:

$$n_0 = \frac{Z^2 pq}{e^2} \tag{1}$$

where n_0 is the sample extent, Z is the selected vital value of the wanted confidence level, p is the valued proportion of an attribute present in the population, q = 1-q = 1-p, and e is the desired level of precision. The following proportional formula is used to determine the sample size distribution to the total household size for each kebele:

$$n_i = n^* \frac{N_i}{\sum N_i} \tag{2}$$

where n_i is the sample size of surveyed i^{th} kebele, n is the sample size of i^{th} kebele, and N is the total household number of i^{th} kebele.

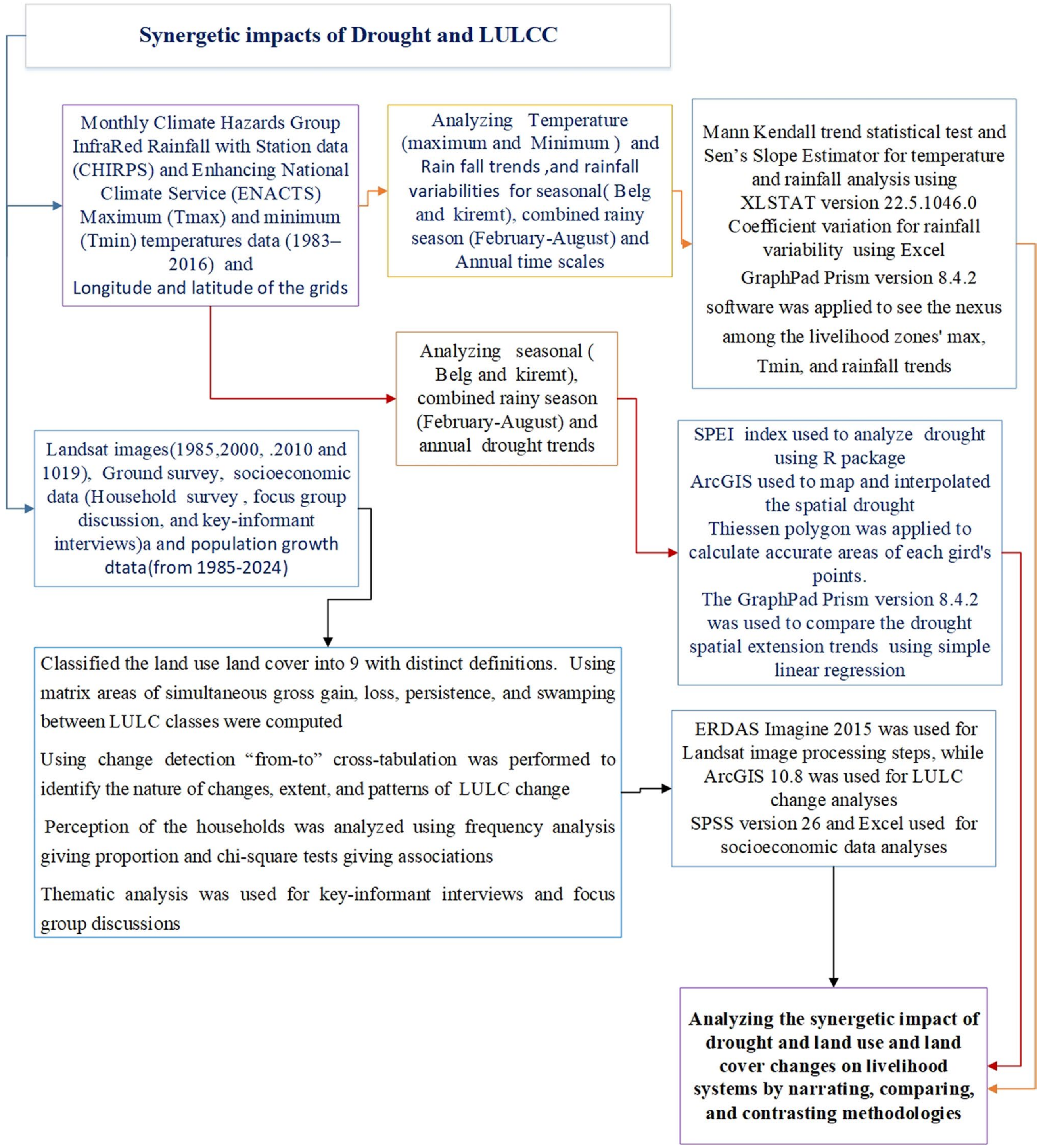

Fig. 2 Methods and data sets to examine the synergetic impact of drought and LULCC on livelihood systems

Field observations were also conducted to assess the characteristics of the LZs and examine the people's livelihood systems. Four focus group discussions with 12 participants in each group were conducted with the sampled kebeles. The participants were diverse in age, sex, profession, community representatives, experts, and livelihood zone. On the thematic topic of crops, livestock, natural resources, land use, early warning, and food security, 24 key informants were interviewed. Further, to see the population pressure in the study livelihood zones, population data were obtained from the Central Statistical Authority of Ethiopia and quadrupled during the study periods.

4 Data processing, analysis, and interpretation

4.1 Climate data

Mann–Kendall trend statistical test was used to examine the seasonal (Belg and Kiremt) and annual climate variability trends from 1983 to 2016 using Eqs. 3–6 [33]. Sen's slope was also applied to assess the linear trends of seasonal rainfall and temperature in the study area using non-parametric techniques in XLSTAT version 22.5.1046.0 from 1983 to 2016 (Eq. 7). In addition, GraphPad Prism version 8.4.2 software was used to compare temperature maximum (Tmax), temperature minimum (Tmin), and rainfall trends across each livelihood zone. Also, the standard deviation (SD) was converted to a percentage of the mean yields to estimate coefficient t variation (CV) using Eq. 8 [34]. Furthermore, the Inverse Distance Weighting (IDW) method was employed for interpolation techniques to map the spatial patterns of rainfall variability in the study area. After that, the SPEI (Standardized Precipitation Evapotranspiration Index), one of the widely used meteorological drought indexes, was applied to assess the condition of drought incidence in the research area at 3, 6, and 12-month time scales using Eq. 9 following [35]. SPEI is widely used to estimate water balances and measure droughts worldwide [29]. Precipitations, minimum and maximum temperatures, and longitude and latitude data were used to run the PET using the Hargreaves (Hg) Equation with the R program. Furthermore, the Thiessen polygon was employed to calculate the exact areas of each meteorological data at the gird point, and the GraphPad Prism version 8.4.2 software was used to compare the condition of drought trends in the three LZs of the study area.

$$S = \sum_{k=1}^{n-1} \sum_{J=k+1}^{n} \operatorname{sgn}\left(X_{j\_}X_i\right) \tag{3}$$

$$\operatorname{sgn}\left(X_{j\_}X_k\right) = \begin{cases} 1\ if\left(X_{j\_}X_k\right) > 0 \\ 0\ if\left(X_{j\_}X_k\right) = 0 \\ 1\ if\left(X_{j\_}X_k\right) < 0 \end{cases} \tag{4}$$

Xj and Xk are the successive data values in time series j and k (j > k), and n is the number of data points. When the number of observations is more than 10 (n ≥ 10), the statistics' S' is approximately normally distributed with a mean and variances as follows [33]

$$Vas(S) = \frac{n(n-1)(2n+5)(x+a)^n = \sum_{t=1}^{m}\left(t_{i\_}1\right)\left(2t_i+5\right)}{18} \tag{5}$$

where m is the number of tied groups, n is the number of observations, and tj is the number of remarks in the ith sample time series. When the sample size is n > 10, the standard normal test ZKM is calculated using Eq. 6.

$$Z_{KM} = \begin{cases} \frac{S-1}{\sigma}\ ifS > 0 \\ 0 ifS = 0 \\ \frac{S-1}{\sigma}\ ifS < 0 \end{cases} \tag{6}$$

Using the Z_{KM} value at a 5% significance level and XLSTAT version 22.5.1046.0, the study computed the Tmax, Tmin, and rainfall trends of the three LZ over the study years. Positive (increasing) or negative (decreasing) values indicate the direction of the trends. Based on the 5% significance level, if the Z_KM value is ≤ α = 0.05, the H1 hypothesis will be accepted, but if the Z_{KM} value is ≥ α = 0.05, H_1 will be rejected instead of H_0 being accepted. The Sen's slope estimator of the N-pair data was computed following [36].

$$Q_i = \frac{X_{j\_}X_k}{j-k} \tag{7}$$

where X_j and X_k are data at time j and k (j > k), and the median of these N values of Q_i is Sen's slope estimator.

Standard deviation (SD) is also converted to a percentage of the mean yield to see coefficient variation (CV) with Eq. 8. Further, Arc GIS with inverse distance weighting for the measured time scales was employed to map the spatial rainfall variability trends during the study year (Belg, Kiremt, and annual).

$$CV = \frac{SD}{Mean} \times 100 \tag{8}$$

If the CV is less than 20% (less variable), from 20 to 30% (moderately variable), and more than 30% indicates high variability of rainfall [36].

$$SPEI = P - PET \tag{9}$$

where P is the monthly average rainfall, and PET is the potential monthly evapotranspiration [35].

4.2 Land use and land cover change data

In this study, errors (e.g., geometric, radiometric, atmospheric) were corrected in the downloaded Landsat images. For instance, the geometric distortions of the images were corrected using the Adindan Zone 37 of the Universal Transverse Mercator (UTM). The images were also enhanced to their original pixel sizes (i.e., 30 m) into 15 m by 15 m using the wavelet resolution merge. The band 8 panchromatic of the Landsat image 8 Operational Land Imager (OLI) was used in this case. After that, adequate signatures were created for each land use/cover class using the ground control points supported by the visual image interpretation techniques. A pixel-based image (supervised) classification using the maximum likelihood technique was applied to map each land use or cover class of the study area based on ground truths. Unlike an unsupervised classification system, supervised classification provides more accurate class definitions [37]. In the study area, based on personal observation and earlier research [14] and [38], nine land use and cover types were identified, which are barren land (BL), built-up area (BA), cultivated land (CL), floodplain (FP), grasslands (GL), shrub/bushland (SBL), water body (WB), forestlands (FL), and wetland (WL). The accuracy of each land use and cover type was assessed using 135 ground control points (50% of the total) to quantify post-classification errors and ensure the representativeness of the classified land use and cover types. The classified land use/cover reliability based on pixel-to-pixel comparison was validated using kappa coefficient statistics, producer, user, and overall accuracy for 1985, 2000, 2010, and 2019. The nature of changes, extent, and patterns of one land use/cover transition to other types were identified using change detection "from-to" cross-tabulation from the succeeding three eras (1985–2000, 2000–2010, and 2010–2019) and over study periods (1985–2019) using Eqs. 10, 11, and 12 following [14].

The following Equation mathematically analyzes this study's producer, user, and total accuracy.

$$\text{The overall accuracy} = \frac{\text{Number of correct points(Value)}}{\text{Total number of points (Value)}} \times 100 \tag{10}$$

$$\text{Users accuracy} = \frac{\text{Number of correctly identified in a given map class)}}{\text{A number claimed to be in that map class)}} \times 100 \tag{11}$$

$$\text{Producers accuracy} = \frac{\text{Number of correctly identified in a given map class)}}{\text{The number actually in that reference class)}} \times 100 \tag{12}$$

In addition, for each LULC, the kappa coefficient was calculated to compare the precision of the categorized findings. The kappa coefficient data for the LULC eras (1985–2019) were evaluated and interpreted in the following [14]:

$$K = \frac{N\sum_{i=1}^{r} x_{ii} - \sum_{i=1}^{r}\left(x_i - X_{x+i}\right)}{N^2 - \sum_{i=1}^{r}\left(x_{ii} - X_{x+i}\right)} \tag{13}$$

where r is the number of rows and columns in the error matrix, N is the total number of observations (pixels), x_{ii} is the observation in row i and column i, x + i is the marginal total of row i and x + i is the marginal total of column i. A Kappa coefficient equal to 1 shows perfect agreement, whereas a value near zero indicates that the bargain is no better than what would be expected by chance.

Equations 14–17 were used to compute the scale of change (MC), percentage of change (PC), and annual rate change (ARC) for each land-use category and each study period following [39]:

$$\text{MC} = \textit{Area of the final year} - \textit{area of the intial year} \quad (14)$$

$$\text{PC} = \frac{\textit{Area of the final year} - \textit{area of the intial year}}{\textit{area of the year intial}} \times 100 \quad (15)$$

$$\text{ARC}\left(Km^2.year^{-1}\right) = \frac{\textit{Area of the final year} - \textit{area of the intial year}}{\textit{Number of the year of time period}} \times 100 \quad (16)$$

$$\text{ARC}(\%) = \frac{\textit{Area of the final year} - \textit{area of the intial year}}{\textit{Area of the year intial X Number of the year of time period}} \times 100 \quad (17)$$

4.3 Socioeconomic data

SPSS version 26 was used to investigate households' perceptions through frequency analysis tools to know the extent of the synergetic impacts of drought and changes in land use and cover on their livelihood strategies. Chi-square tests are also used to evaluate associations. Thematic analysis was used for key informants and focus group discussions. Population data from the Central Statistical Agency (CSA) of Ethiopia based on the census (1984, 1994, and 2007) and district offices (2017) were also gathered in the study region to see the population pressure on the community resource base in the study livelihood zones. Following [40], the population numbers for 1985, 2000, 2010, 2019, and 2024 were extrapolated using the nearest census data and annual growth rates (Eq. 18). Available emergence and safety net beneficiaries were collected further from the Tigray Agricultural Office to see the synergetic impacts of drought and LULCC on community food security. The study used all the results to integrate and analyze the synergetic impact on the livelihood system with narration, comparing, and contrasting methods. The results are presented in text, graphs, charts, and maps.

$$P_2 = P_1 e^{rt} \quad (18)$$

where P_1 and P_2 are the total populations at Time 1 and 2, respectively, e is the exponential population constant, t is the number of years between census enumerations, and r is the yearly population growth rate.

5 Results

5.1 Annual climate variability and drought trends

Figures 3, 4, 5a shows that annual Tmin showed a statistically significant trend in all LZs (from 0.32 °C in ALOFLZ to 0.27 °C in RVLZ). The TCLZ (Fig. 4b) and RVLZ (Fig. 5b) recorded the statistical significance of annual Tmax (0.32 °C and 0.42 °C), respectively. In addition, this study discovered significant and severe yearly rainfall variability, ranging from 32–35% to 31–50% at the livelihood zone and grid levels, respectively (Figs. 3, 4, 5c). This finding revealed that rainfall variability trends were positively related to temperature trends in the study areas. TCLZ had more yearly spatial rainfall at the grid and livelihood zone levels, followed by ALOFLZ and RVLZ. However, the annual rainfall of the study livelihood zones did not indicate any significant positive or negative change trends during the study periods (Figs. 3, 4, 5d). As a result, from 1984 to 2016, the increasing temperature trends combined with declining rainfall trends, high rainfall variability, and anthropogenic factors (e.g., LULCC) were the consequences of fourteen mild to severe drought years in all LZs (Figs. 3, 4, 5e). Drought was revisited annually with 2.13, 2.2, and 2.13 interval years in ALOFLZ, TCLZ, and RVLZ, respectively. Once drought occurred, it lasted 1.5, 1.9, and 1.7 years in ALOFLZ, TCLZ, and RVLZ. From 1984 to 1998, ALOFLZ and TCLZ experienced more severe yearly droughts than RVLZ (Fig. 9a).

Figure 4 illustrates the temporal trends of Tmax and Tmin, along with rainfall, variability, drought frequencies, and magnitudes in the TCLZ. The study disclosed a statistically significant increase in annual Tmax of 0.32 °C in the TCLZ. This finding indicates a positive correlation between rainfall variability and temperature trends in the study area. The

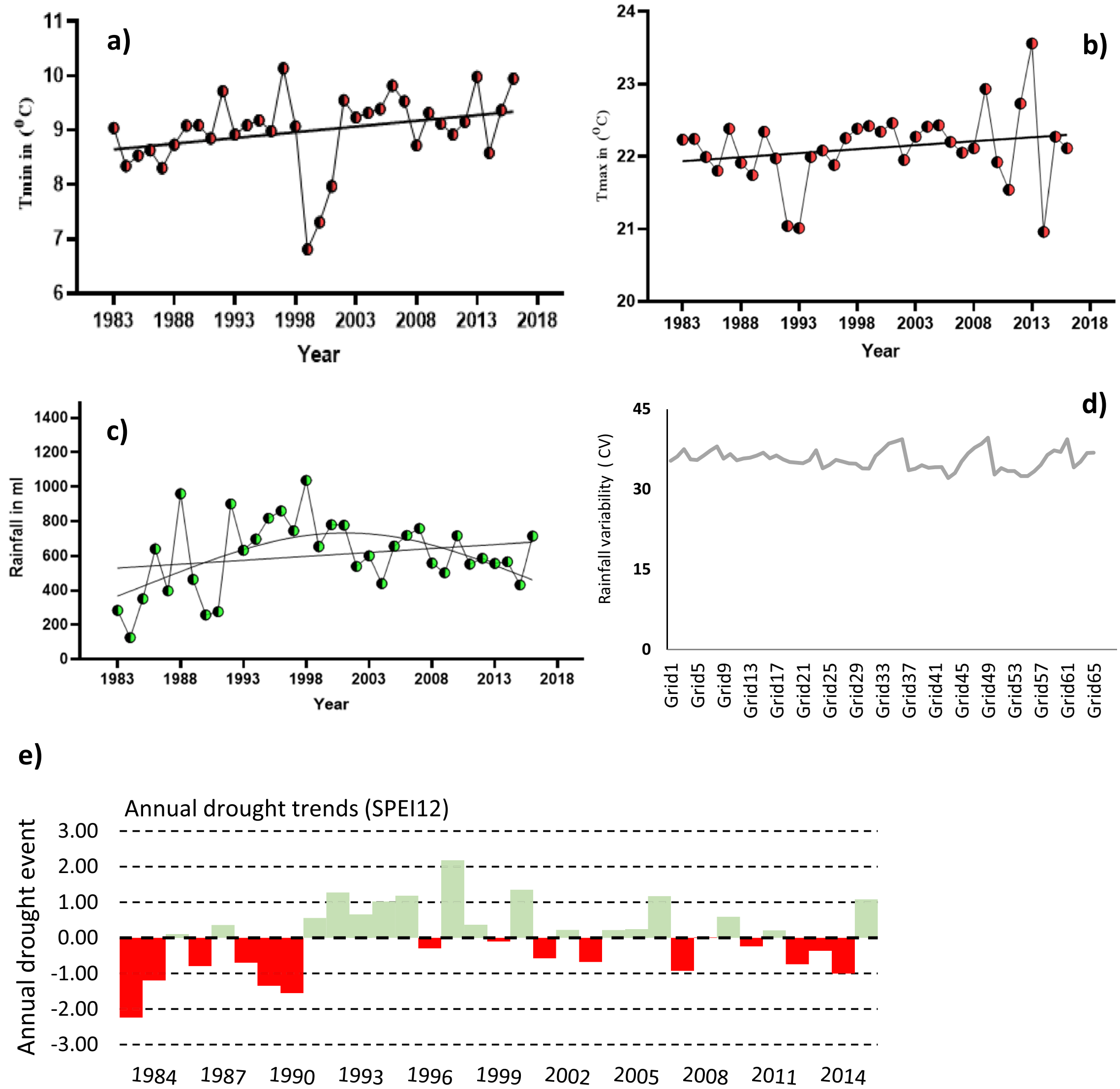

Fig. 3 Trends of Annual Tmin (**a**), Tmax (**b**), rainfall (**c**), and rainfall variability (**d**) and drought frequency and magnitude (**e**) in ALOFLZ from 1983–2016

TCLZ experienced more spatial variability in annual rainfall at the grid and livelihood zone levels. Drought events were reviewed annually, occurring every 2.2 years in the TCLZ and lasting an average of 1.9 years. Notably, from 1984 to 1998, the TCLZ experienced more severe and frequent droughts.

In addition, in the RVLZ, Fig. 5b shows a significant increase in annual Tmax of 0.42 °C. However, there were no significant positive or negative trends in annual rainfall during the study period. Droughts were observed every 2.13 years on average and lasted about 1.7 years.

5.2 Belg season climate variability and drought trends

Seasonally, the Belg Tmax increased significantly (from 0.30 to 0.43 °C) in all LZs [31]. Tmin, on the other hand, showed a nonsignificant positive trend in all LZs during this season. Rainfall in the Belg season showed declining trends, which is the foundation for farming and a source of moisture for local ecosystems. Subsequently, the significantly increased temperature in Belg associated with decreasing rainfall trends resulted in extreme rainfall variabilities recorded from 64 to 70% at livelihood zones and 57–99% at grid levels across all LZs (Fig. 6a). The rainfall variability in the Belg is more severe than in Kiremt (Fig. 6b) and on annual time scales (Fig. 3). The TCLZ had relatively higher Belg rainfall variability, followed by RVLZ and ALOFLZ [31]. Drought is prevalent in all livelihood zones due to rising temperatures, falling rainfall

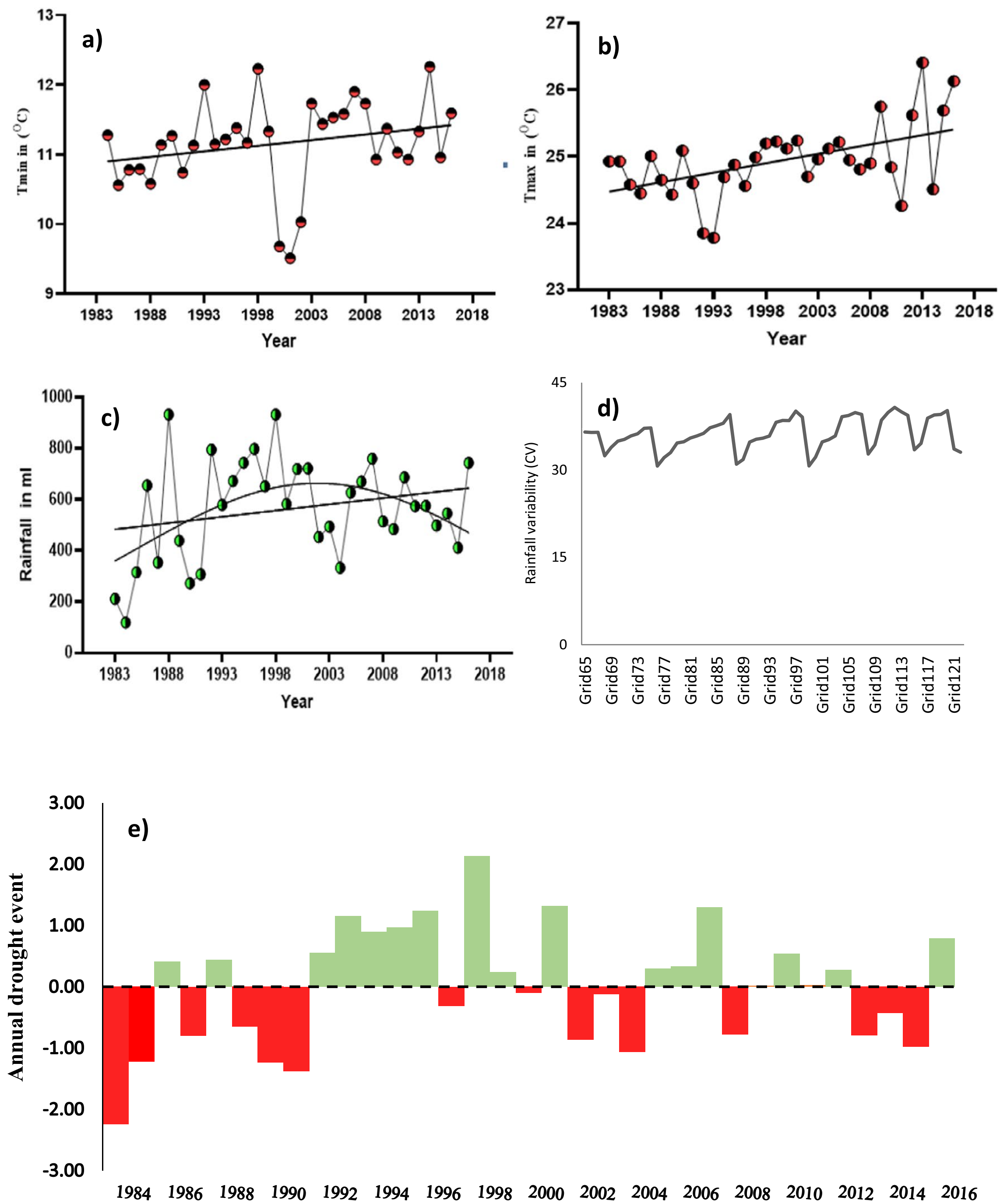

Fig. 4 Trends of Annual Tmin (**a**), Tmax (**b**), rainfall (**c**), and rainfall variability (**d**) and drought frequencies and magnitude (**e**) in TCLZ 1983–2016

in spatial and temporal patterns, extreme rainfall variability, and human-caused consequences. Over the study years, drought trends in the Belg have consistently increased in all LZs, both temporally and spatially, with a slight difference between livelihood zones (Fig. 6c and d). From 1998 to 2004 and 2012 to 2016, the Belg drought persisted for seven and five years. There have been 18 mild to severe Belg droughts during the study years in the three LZs. Since 1998, drought occurrences have become more common in this season across each LZ. The frequencies of periodic drought for Belg had increased with 1.82, 1.77, and 1.6 interval years in ALOFLZ, TCLZ, and RVLZ, respectively. The drought in ALOFLZ, TCLZ, and RVLZ lasted 1.4, 2, and 1.8 years during the Belg season.

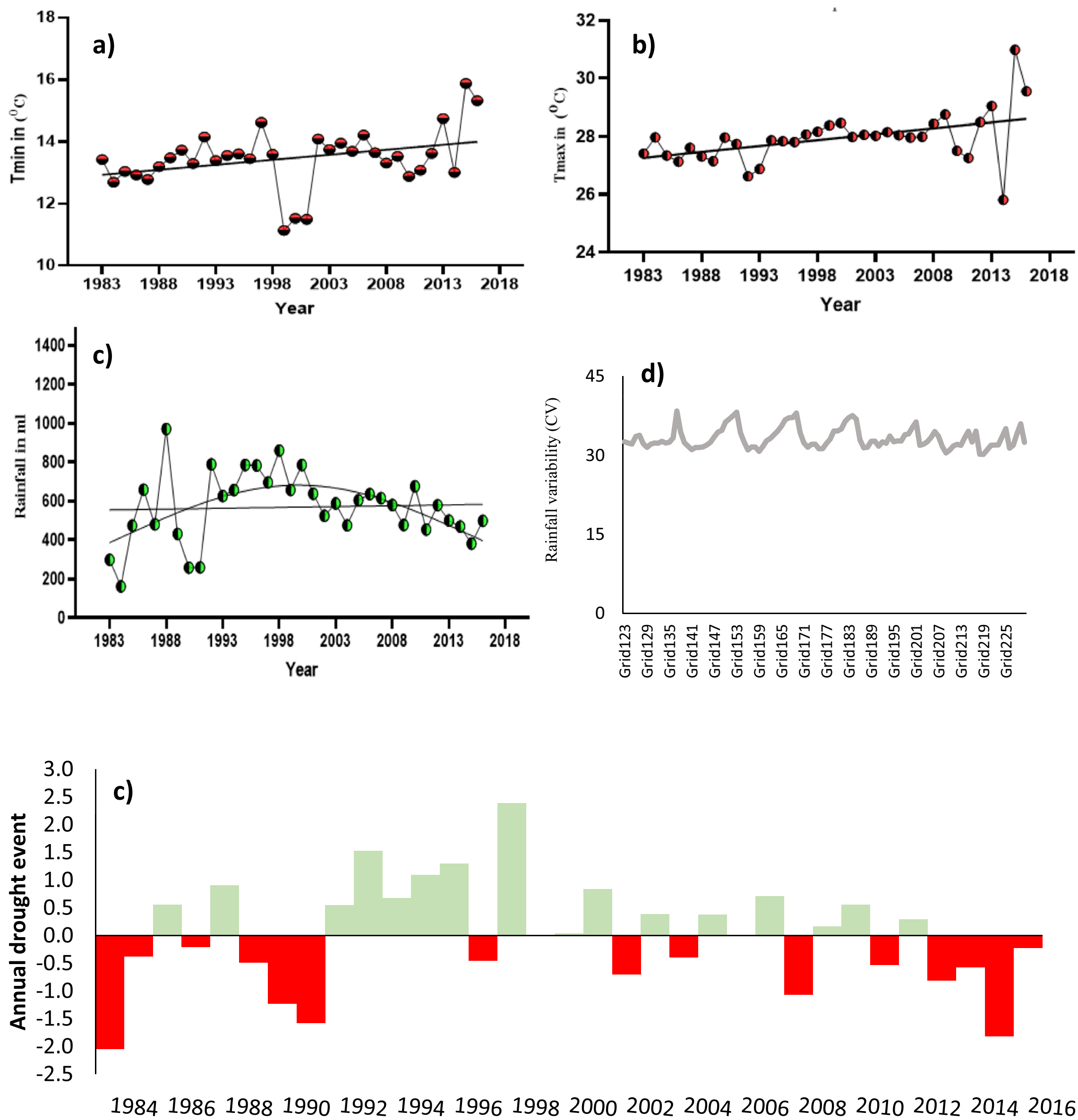

Fig. 5 Trends of Annual Tmin (**a**), Tmax (**b**), rainfall (**c**), and rainfall variability (**d**) and drought frequencies and magnitude (**e**) in RVLZ from 1983–2016

5.3 Kiremt season climate variability and drought trends

The Tmax demonstrated nonsignificant positive trends in TCLZ and RVLZ in the Kiremt rainy season. However, the Tmax in ALOFLZ displays negative but not statistically significant trends during the season. On the other hand, the study discovered statistically significant positive rainfall changes in RVLZ and TCLZ during the Kiremt rainy season. Despite increasing rainfall trends in RVLZ and TCLZ, the authors found extreme rainfall variability in all livelihood zones studied (44.34–49.81%) at livelihood zones and 39.34–49.81% at grid levels [31]. These contradicting trends of increasing temperature, increasing rainfall, and increasing rainfall variability indicate that the rainfall was concentrated for a month or weeks rather than properly distributed temporally and spatially during this rainy season. As a result, while the total amount of rain does not guarantee drought occurrence, rainfall consistent with temporal and spatial distribution is critical for drought incidences. Over the study years (1983–2016), the combined effects of maximum temperature, uneven temporal and spatial rainfall distribution trends, extreme rainfall variability, and other anthropogenic factors were the consequences of twelve mild to highly severe droughts in the Kiremt season

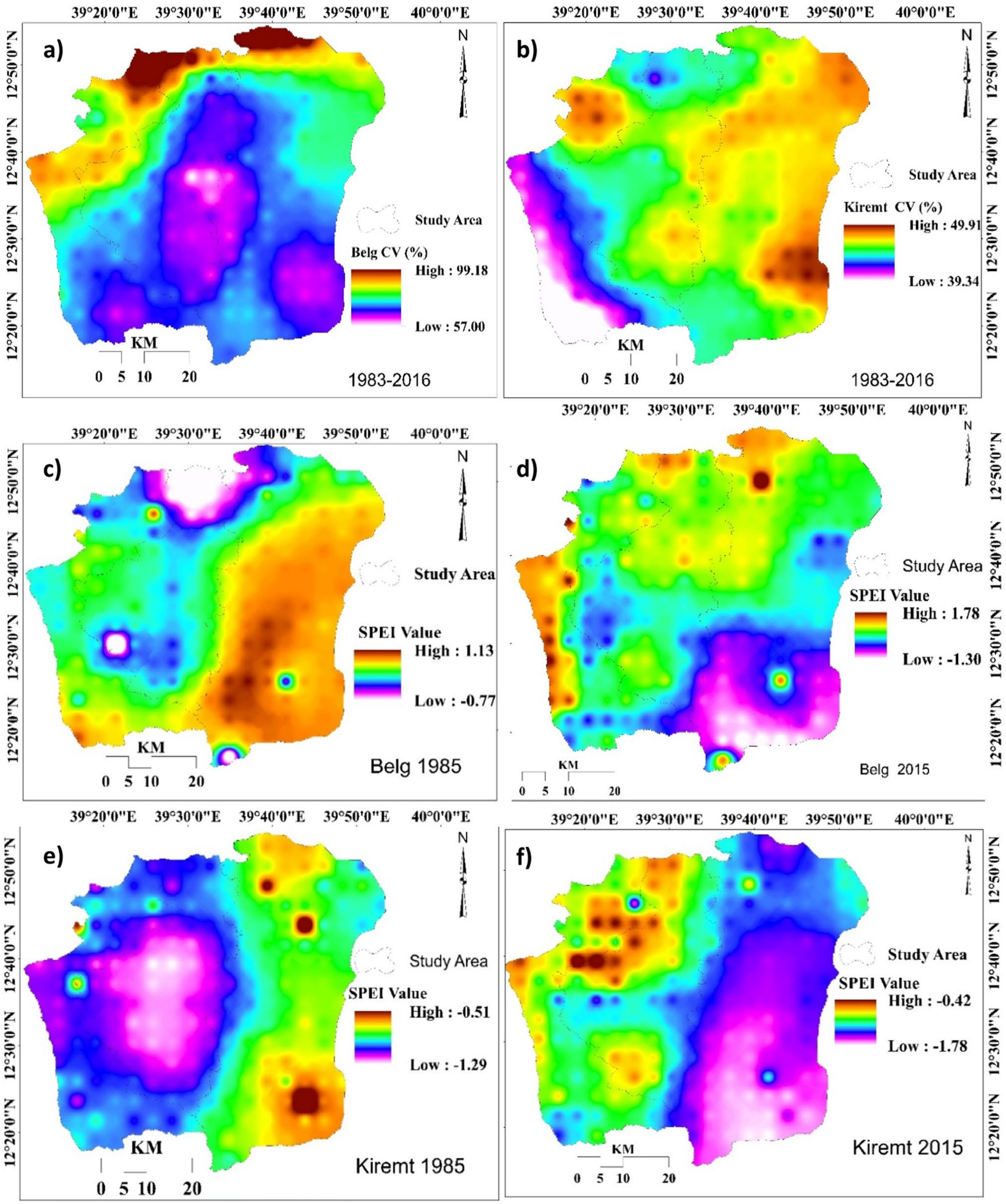

Fig. 6 Trends in rainfall variability Belg (**a**), Kiremt (**b**) from 1983–2016 and spatial drought comparison between 1985 (**c** & **e**) and 206 (**d** & **f**) for Belg and Kiremt rainy seasons, respectively

across all LZs [41]. Between 1983 and 1993, high drought severity, persistence, and frequent events in all LZs. Over the study years, drought in the Kiremt season was revisited with 2.36, 2.27, and 2.54 intervals in ALOFLZ, TCLZ, and RVLZ, respectively. The drought lasted 1.3, 1.4, and 1.5 years in ALOFLZ, TCLZ, and RVLZ, respectively, once it started in the Kiremt season throughout the research years. There were yearly Kiremt, Belg, or both-season droughts in grids or livelihood zone levels. Extreme drought frequency decreased in the Kiremt season, whereas moderate to mild drought frequency increased in all livelihood zones (Fig. 6e and f). Even though droughts decreased from 2001 to 2016, seven wet Kiremt seasons were recorded with SPEI values below 0.5, indicating mild wetness [31]. For agricultural purposes, this precipitation value was too low. Drought incidences in this season were becoming locally fragmented, even at village levels.

5.4 Land use and land cover change trends

The identified land use and cover accuracy was 90% with an overall kappa coefficient of 0.88. The land use and cover types of the study area revealed an increasing trend in cultivated land (Fig. 7d) and built-up area (Fig. 7c) areas in all LZs and flood plains (Fig. 7h). From the total gain of 177.10, 159.19, and 372.34 km^2 of cultivated land, about 171.21 km^2 (97%), 150.83 km^2(95%), and 364.36 km^2 (98%) of the area were derived from natural resources (SBL, FL, and GL) conversions in ALOFLZ, TCLZ, and RVLZ, respectively. Similarly, from the net gain of 22.81, 17.47, and 42.49 km^2 of built-up area, about 14.12 km^2 (62%), 12.44 km^2 (71%), and 18.38 km^2 (43%) of it were derived from the conversion of the natural resource areas in ALOFLZ, TCLZ, and RVLZ, respectively. Flood plains also derived about 4.77, 12.62, and 30.17 km^2 from 1985 to 2019 in ALOFLZ, TCLZ, and RVLZ, respectively. TCLZ gained 5.14 and 7.46 km^2 FP, while RVLZ gained 19.31 and 18.56 km^2 FP from the natural areas and CL, respectively. Similarly, all LZs significantly reduced shrub and bushland covers (Fig. 7e). In addition, grassland (Fig. 7f) in RVLZ and ALOFLZ has decreased dramatically. Over the study period of 34 years (1985–2019), 257.51 km2 in ALOFLZ, 182.15 km2 in TCLZ, and 483.59 km2 in RVLZ of natural area (SBL, GL, and FL) were changed into other LULC types, respectively (Figs. 7e, f and g). The results show that 82%, 72%, and 77% of RVLZ, ALOFLZ, and TCLZ changed between classified LULC types. Except for wetlands and water bodies, all LULCC and population trends are presented in Fig. 7. These trends indicated no climaxes or stabilization of LULC types within the study years in all LZs.

Natural resources in the livelihood zone are stressed due to rapid population growth. The focus group discussions (FGD) and key informant interviews (KII) revealed that the population of all studied LZs expanded significantly over the study years. Pressures from population growth and population density (Fig. 7a and b) in ALOFLZ and TCLZ came from the expansion of the population, according to the FGD participants and KII findings. The RVLZ, on the other hand, was being squeezed by both internal population growth and surrounding immigrants (Fig. 7a and b). According to the KII perspective, another cause of LULCC was rapid settlement expansion and infrastructure development in recent years. The findings of the spatial data (Fig. 7c and d) back up the viewpoints of FGD participants and KII on settlement expansion. The findings of the spatial data confirm the perspectives of FGD participants and KII on settlement expansion. The rapid growth of BA came at the expense of natural resource areas. Farmland is expanding in all LZs, according to KIIs and all four focus group discussion results. KII reports show thousands of hectares of cultivated land have been converted in the RVLZ's northern parts. RVLZ investors evicted and dispossessed farmers from their farmland and settlements without providing adequate compensation or alternative farmland.

According to the FGD, there is no appropriate land management. Further, severe problems with grazing lands affected livestock sectors, aggravated climate change, disrupted rainfall patterns, and brought conflicting interests, affecting fuelwood resources and forest ecosystems. There were issues with land redistribution in the sloppy area in ALOFLZ and TCLZ. Moreover, FGD participants in all LZs examined how land distribution for youth influences local climatic patterns and has implications such as deforestation, grazing land shrinkage, and land degradation. Participants are concerned that future droughts will be more frequent and severe. They are worried that it will have long-term effects on their area's agroclimatic zone and the soil fertility of their farmlands.

5.5 Consistency and interaction between climate variability, drought, and LULCC

The results show consistency among temperature trends, rainfall variability, drought occurrences, LULCC trends, and drought vulnerability patterns of each LZ. The study found that temperatures rose and rainfall was erratic, with varying seasonal and annual timescales. All LZs showed significant and nonsignificant Tmin and Tmax trends at measured time scales. However, yearly rainfall trends did not indicate substantial positive or negative changes. This research revealed that rainfall in all LZs and grid-wise levels was erratic and varied in seasonal and annual time. In addition, all LZs experienced significant and severe seasonal and yearly rainfall fluctuations. Based on these contradictory findings (rising

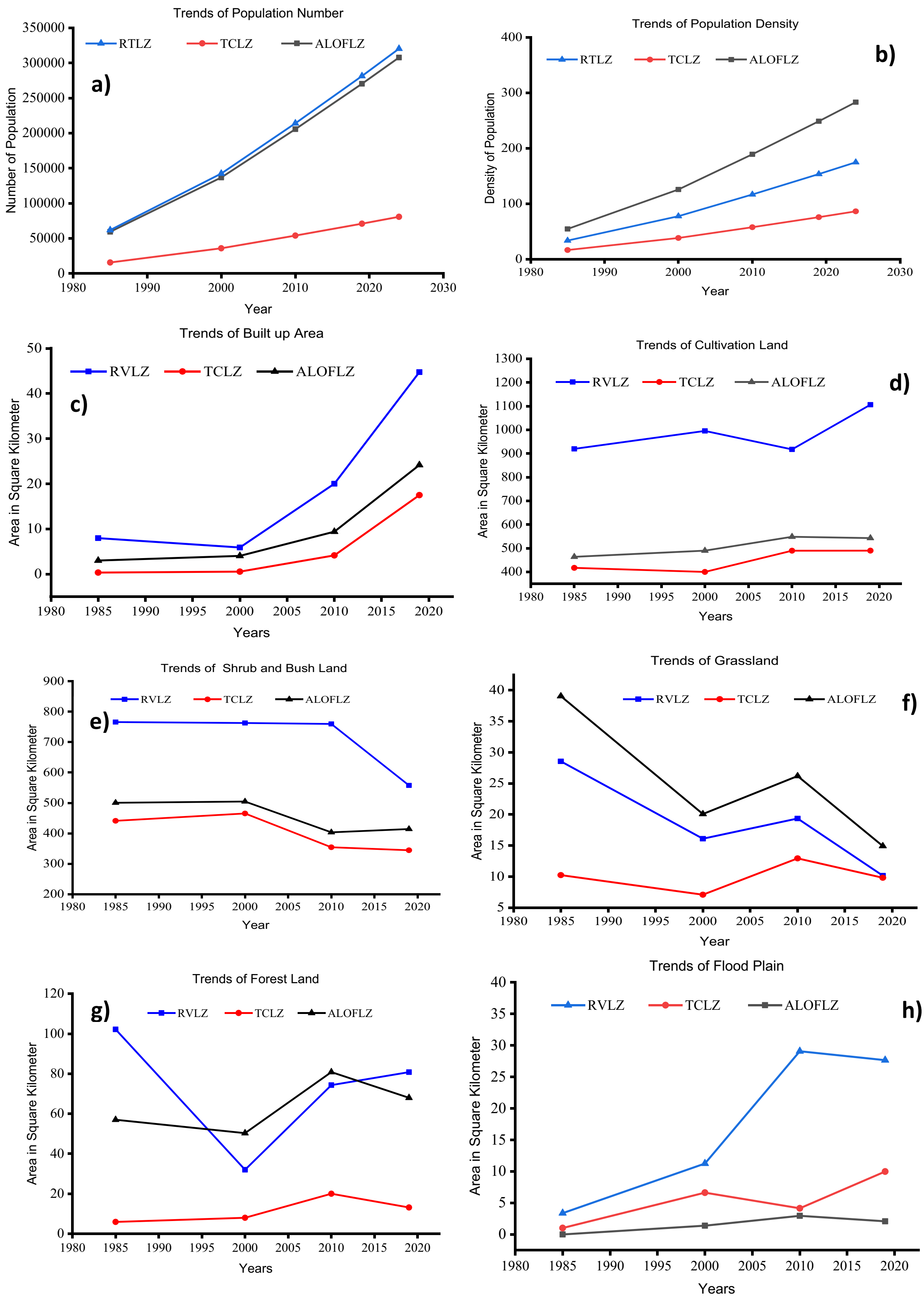

Fig. 7 Population growth trends from 1985 to2024 (**a** & **b**) and LULC change trends from 1985 to 2019: Built up area (**c**) Cultivation land (**d**), Shrub and bushland (**e**), grassland (**f**), Forest land (**g**) and Flood plain (**h**)

temperature, rising Kiremt rainfall (RVLZ), and rising rainfall variability), heavy rain was concentrated for months or weeks instead of being spread evenly across time and space through the LZs. Climate variability sensitivity in LZs was asked of the surveyed households. The RVLZ, ALOFLZ, and TLCZ household respondents (99.3%, 80.4%, and 82.6%) perceived temperature is warming in their area, respectively.

The respondents also claimed that the rainy season's distribution, intensity, and starting and ending times had changed. According to surveyed households, key informants' interviews, and FGD participants, the Belg rain season began in mid-February and ended in late May in previous decades. The Kiremt rain began in mid-June and lasted until early September. However, recent rainfall has become fragmented, late-onset, early-terminate, and partially distributed across small-scale areas. In the last ten years, the Belg rain has arrived at the end of April, while the Kiremt (summer) rain has begun at the end of July, particularly in RVLZ and TCLZ. Furthermore, intraseasonal and annual rainfall variability trends varied spatially between and within LZs. Seasonal temperature increases and high rainfall fluctuations have resulted in frequent droughts.

This study examined the changes in LULC in three livelihood zones in drought-prone areas. In all LZs, the LULCC was caused by several factors, including population growth due to a lack of substitute income sources and fuelwood needs for household use, as well as the need for land for farming and settlement, changes in local climate patterns, and frequent droughts. However, the overall LULCC detection analysis revealed that RVLZs shifted more quickly than ALOFLZs and TCLZs. Because of this, RVLZ has more significant ecosystem disruptions than ALOFLZ and TCLZ. Rainfall variability and drought occurrences were compared with LULCC in 1985 and 2019 (Fig. 9). In 1985, the natural vegetation cover in RVLZ was healthier, and drought intensities and geographical distribution were better (Fig. 8a and b). However, significantly diminished natural vegetation trends were observed when comparing the 2019 maps (Fig. 8d) to the 1985 maps in RVLZ (Fig. 8b). The maps indicated that drought effects (Fig. 8c) and LULCC (Fig. 8d) had feedback loops. No LULC types reached a climax within the research years or stabilized LZs. Therefore, the ecosystem service cannot support natural ecosystem cycles and human needs there is no climax and stabilized ecosystem. A continuously disrupted ecosystem was exposed to drought hazards that resulted in local climate system disturbances and affected the agricultural productivity of LZs in the study. The results show that all the study's LZs are highly vulnerable to drought impacts due to their incredible exposition levels, susceptibility, and inadequate adaptive capacity. The RVLZ is more susceptible to drought than the TCLZ and ALOFLZ (Fig. 9a). As presented in Fig. 9b, annually from 2000 to 2018, about 31% (56764) in RVLZ, 9% (15322) in ALOFLZ, and 56% (24705) in TCLZ of the population were emergency beneficiaries since they were more vulnerable to drought.

Similarly, from 2005 to 2019, annually, about 43% (92299) in RVLZ, 24% (50676) in ALOFLZ, and 39% (21311) in TCLZ of the total population were safety net program beneficiaries because of less resilience (Fig. 9c). This result coincides with climate variability trends, drought frequencies, LULCC trends, and the drought vulnerability of the study livelihood zones. TCLZ has less adaptive capacity than RVLZ and ALOFLZ. The emergency beneficiaries flow more through RVLZ. On the other hand, RVLZ experienced high levels of climate variability, which led to more instances of drought, high levels of LULCC disturbance, and more drought-vulnerable areas (Fig. 9a). The synergy impacts followed about 62% of the RVLZ population, who are food insured and waiting for relief support from emergency and safety net programs every year for the past twenty years. Respondents between and within LZs had different perspectives on the magnitude of drought and the impact of LULCC on water resources. Due to increased rainfall coverage during good wet seasons before 2000, RVLZ respondents showed they had comparatively low water stress. However, TCLZ and ALOLZ respondents perceived that they experienced severe water stress in a similar study period. The LZs' history of drought and LULCC trends support their perception. Furthermore, since 2000, respondents in RVLZ have faced high water stress on their farmlands. However, water stress becomes moderate in ALOFLZ.

6 Discussions

The analysis revealed that the temperature is warming, and the rainfall has shown high irregularities and various seasonal and annual timescales. The temperature data revealed a clear warming trend across all livelihood zones. Respondents from the RVLZ, AOLZ, and TLCZ acknowledged the increasing temperatures, which aligns with the findings from various studies across Ethiopia [34, 42, 43]. Statistical analyses confirmed that minimum temperatures had increased significantly across all zones, with maximum temperatures showing a statistically significant rise in the RVLZ and TCLZ. These trends are consistent with global rising temperatures due to climate change, as reported by numerous studies [42–44]. This

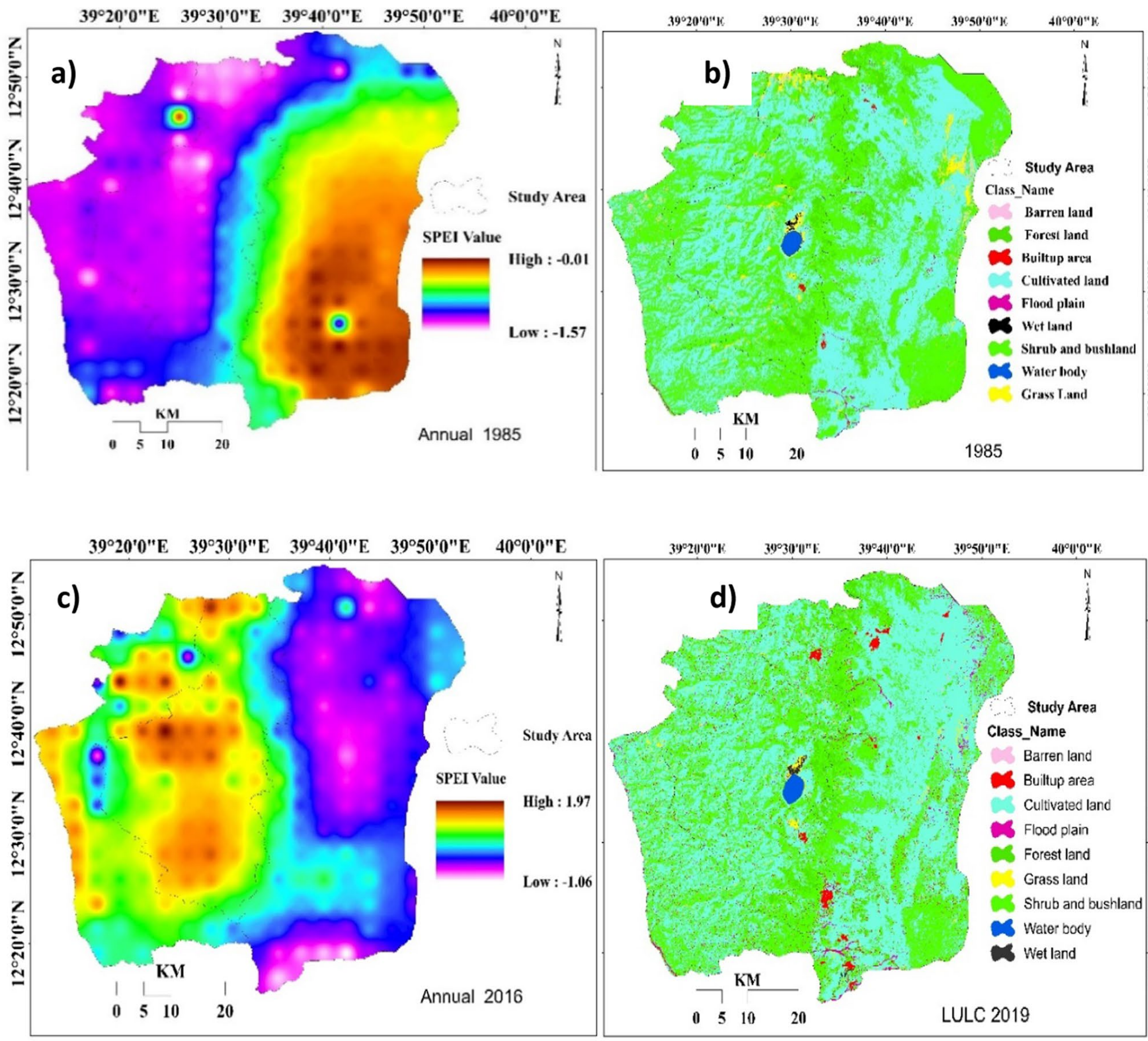

Fig. 8 Drought in 1985 (**a**) & 2016 (**c**) and LULCC in 1985 (**b**) & in 2019 (**d**) trends

warming is critical, as higher temperatures can exacerbate drought conditions by increasing evaporation rates, thus reducing the availability of water resources for agriculture and other livelihoods.

Rainfall variability, characterized by irregularities in different seasons and years, was observed. The Belg (spring) and Kiremt (main) rainy seasons, particularly for agricultural production, have been significantly affected by temperature changes. The seasonal onset, intensity, and duration of rainfall have become increasingly unpredictable, with respondents noting shifts in the timing of rainfall events. For instance, the Belg rains, which traditionally began in mid-February and ended in late May, have shown signs of delay and shortening over recent decades. Similarly, the Kiremt rains, which typically began in mid-June and ended in early September, are now characterized by increased variability and erratic distribution. Respondents observed that this inconsistency in rainfall timing and intensity has disrupted agricultural cycles, particularly those reliant on rainfed systems. These findings align with the results of [44], who also reported increasing trends in Kiremt rainfall, although studies by [42, 45, 46] have pointed to a reduction in Kiremt rainfall in other parts of Ethiopia. The Belg rainfall has shown a consistent decline across all three study zones, with annual rainfall trends decreasing in RVLZ and ALOFLZ but showing slight increases in TCLZ. This observation mirrors the findings from several studies that highlighted declining Belg rainfall in parts of Ethiopia [42, 45–48]. However, contrary studies, such as that by Geremew et al. [49], report an increase in annual rainfall trends in regions like Northwest Ethiopia, which aligns with

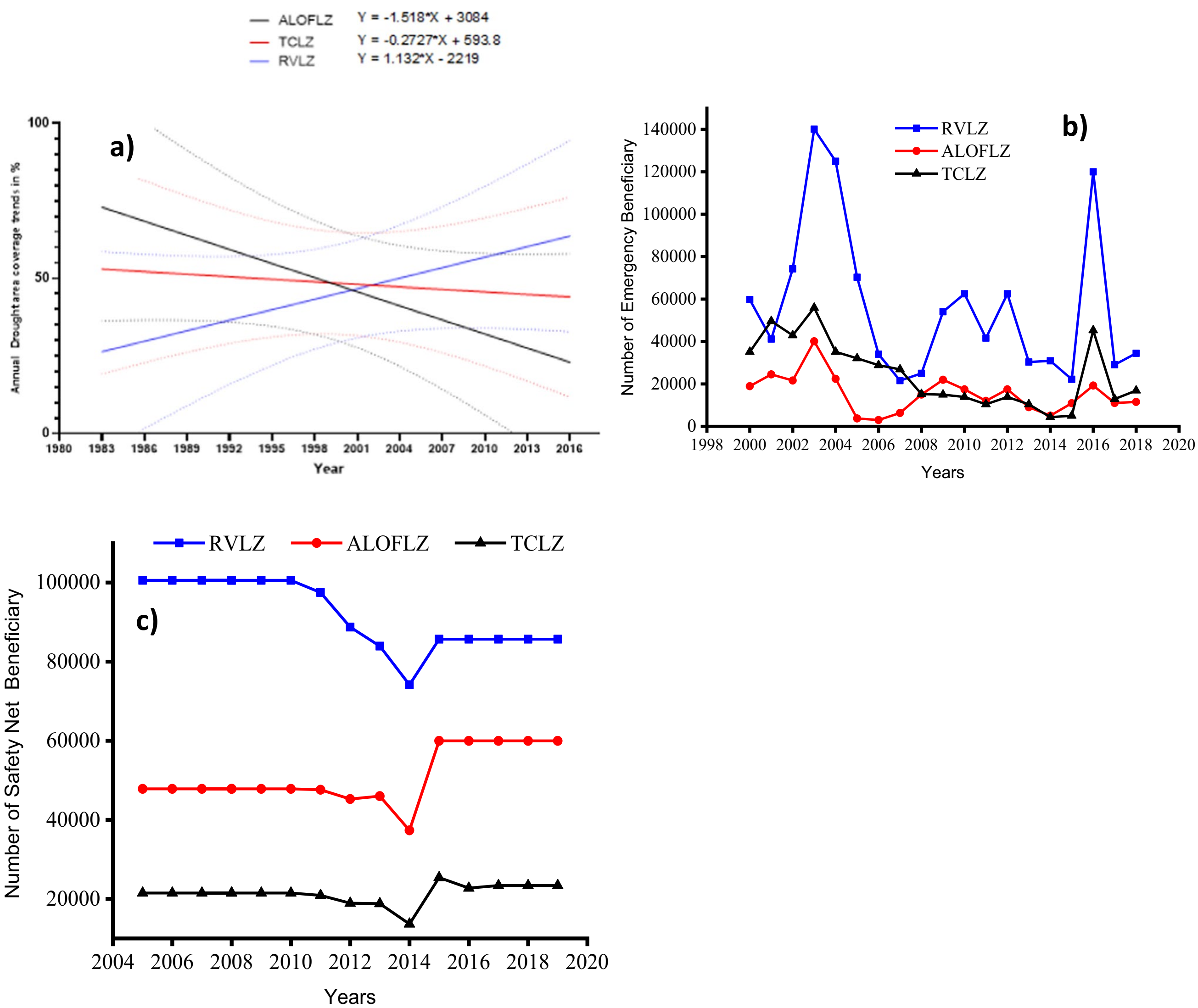

Fig. 9 Annual spatial drought trends from 1984 to 2016 (**a**), number of emergency beneficiaries from 2000 to 2018 (**b**), number of safety net beneficiaries from 2005 to 2019 (**c**)

trends observed in TCLZ and ALOFLZ. Rainfall variability within the LZs was higher during the Belg season than during the Kiremt season, with annual variability influencing agricultural production and water resource management. This study also showed the rainfall was highly irregular and varied in seasonal and annual time scales in all LZs and grid-wise levels. The Belg rainfall variability was higher than Kiremt, and yearly variability in all livelihood zones. The current findings are strengthened by [43, 47, 50–52] reports that rainfall variability is extremely high in their study area.

The study revealed seasonal and annual droughts have become more frequent, intense, and prolonged. This has resulted in increasing drought vulnerability in all three livelihood zones. Respondents from the RVLZ reported that droughts have become chronic, with severe consequences for food and water security. This result coincides with [39] findings that an increased precipitation pattern had an inverse relationship with drought vulnerability. The findings of key informant interviews (KIIs) and focus group discussions (FGDs) supported this observation, confirming that drought frequency has increased over time, and the persistence of drought periods has worsened, particularly in the RVLZ. This concurs with the studies by [53–57], which have documented similar trends in drought severity and frequency in other drought-prone areas of Ethiopia. One notable finding is that droughts in the RVLZ and TCLZ are becoming increasingly severe and are impacting agricultural productivity, livestock, and household food security. Experts from early warning systems and food security agencies confirmed drought severity has intensified in recent decades. For example, in ALOFLZ, droughts were less frequent 20 years ago, and the spatial extent and severity of droughts have increased significantly, occurring at more frequent intervals of about ten years compared to the more sporadic droughts of the past. The interconnectedness between temperature rise, altered rainfall patterns, and increasing drought frequency exacerbate drought vulnerability and can severely affect agricultural productivity, food security, and overall livelihood sustainability. The irregular rainfall during the Belg and Kiremt seasons underlines the challenge of adapting to climate change. The findings of this study stress the need for targeted adaptation strategies to mitigate the effects of changing climate patterns and LULC on the livelihoods of local communities.

The results revealed significant shifts in land cover, with cultivated land (CL) and built-up areas (BA) increasing at the expense of natural vegetation types, particularly shrublands (SBL) and grasslands (GL). The expansion of farmland and settlements occurred notably from 2000 onwards, with deforestation for agriculture. The expansion of CL was most notable in RVLZ, where farmland expansion has been rapid and driven by population pressure and large-scale agricultural investments. The spatial data supports these observations, highlighting that CL and BA have expanded at the expense of natural vegetation, with detrimental effects on soil erosion and water retention. The shift from natural vegetation to CL has significant implications for soil conservation, biodiversity, and local climate stability, as deforestation and land degradation are key consequences of this transition [43, 58, 59]. In all study zones, SBL decreased significantly over the study period, with a marked reduction in the area covered by bushlands and shrublands. This reduction was particularly pronounced in RVLZ, where the conversion of natural vegetation into farmland and settlements was evident from both satellite data and the perspectives of FGD participants. The expansion of farmland in RVLZ has been driven by both local population pressures and immigrant populations, further intensifying the demand for land and exacerbating the loss of natural vegetation. KIIs and FGDs revealed that settlement expansion, which was minimal before 2000, has increased dramatically in recent years due to population growth and immigration. This trend is consistent with the findings of other studies with rapid urbanization, and land use change in various parts of Ethiopia [43, 58].

The demand for land is increasing each year due to population pressures. Internal population pressures mostly drive land-use change in the ALOFLZ and TCLZ. In all LZs, population pressures from a lack of other revenue sources and family fuelwood demands, inadequate land use procedures, disturbance of local climate patterns, and recurrent droughts were among the LULC change-driving variables [39, 60–62]. The main driver of LULC change in RVLZ was population pressures from residents and immigrants from nearby regions. Large and medium agricultural investors were the primary drivers of LULC change in RVLZ. Communities in RVLZ are left without contingency land for their youths and coming generations. Improved technologies socioeconomic and institutional dynamics, market access, and recurrent drought were the driving forces behind LULCC in Ethiopia's Rift Valley dry lands [40]. This conversion has increased soil erosion, reduced water retention, and diminished biodiversity. The degradation of natural habitats has contributed to the loss of key ecosystem services, such as water regulation, soil fertility maintenance, and habitat for wildlife. This loss of natural vegetation has further intensified drought, reduced water retention capacity, and more frequent and severe land degradation [41, 43].

The combined effects of climate variability and LULC change have affected agricultural productivity and livelihoods. The changes in temperature and rainfall patterns, coupled with the conversion of natural vegetation to cultivated land and settlements, have created an unstable environment for smallholder farmers. The declining availability of grazing lands and soil quality degradation reduced livestock production and crop yields. Livestock experts in RVLZ noted a dramatic decline in cattle numbers, with only 1,000 cattle remaining in a village over 7,000 in 1993/94. In the past, the average household owned more than 40 cattle. Farmers shifted from large ruminants like cattle to small ruminants (sheep, goats) and poultry due to drought, land-use changes, and cactus diseases, which now serve as primary income sources. The number of small ruminants in RVLZ grew significantly, from around 10,000 before 2010 to approximately 100,000 today. In ALOFLZ, although the number of animals is increasing, grazing land is insufficient to support them. In all LZs, there has been a shift in practices, with agricultural residue now being harvested for livestock feed due to the frequent droughts and land-use changes affecting forage availability. This practice, while addressing short-term livestock needs, has negatively impacted soil fertility and farm productivity. According to [64], this shift is harmful to soil health, as the removal of crop residues reduces soil protection from erosion, weakens soil structure, and depletes organic content, ultimately reducing agricultural sustainability. In RVLZ, respondents noted a sharp decline in agricultural productivity, with yields dropping from 80 quintals per hectare to less than 30 quintals due to erratic rainfall, declining soil fertility, and increasing land degradation. The FGD participants further explained that there was now little use of inorganic fertilizers due to the area's limited access to inputs and high moisture scarcity. This decline in productivity is consistent with studies that have shown that land use changes, such as deforestation and conversion to agriculture, result in lower agricultural yields due to soil degradation and loss of organic matter [65]. In contrast, respondents at TCLZ reported mixed views regarding productivity, with some areas experiencing better productivity than others. These differences were attributed to variations in soil quality, land management practices, and exposure to drought [66, 67]. In ALOFLZ, where agricultural inputs and intensive farming techniques were increasingly adopted, respondents observed improvements in yield compared to the past, and concerns about the side effects of chemical fertilizers on soil health were also raised [68].

The combined effects of climate variability, drought, and LULC changes are a vicious cycle of environmental degradation, reduced agricultural productivity, and increased vulnerability in the studied livelihood zones. The impacts of high temperatures, erratic rainfall, and frequent droughts are exacerbated by rapid LULC changes, leading to soil erosion, loss of biodiversity, and reduced ecosystem services. These synergistic effects are destabilizing the local climate system and undermining the resilience of the community's livelihood systems. The study suggests that both environmental and human-induced factors heighten the vulnerability of these livelihood systems. The combined pressures of population growth, settlement expansion, agricultural intensification, and climate variability are causing profound changes to the landscape, leading to increased environmental degradation and reduced livelihood resilience. These findings support previous studies, demonstrating human activities and climate change are the primary drivers of land degradation, desertification, and biodiversity loss in similar regions [41, 63, 64]. Finally, this study has shown that the synergistic effects of drought and LULC change are exacerbating the vulnerability of livelihoods in the study area. These effects have led to a decline in agricultural productivity, and livestock numbers, and the destabilization of local ecosystems. The findings underscore the need for integrated climate change adaptation strategies and sustainable land management practices to mitigate the impacts of these combined stresses. Given the increasing frequency and intensity of droughts and land degradation, policies must address climate variability and land use practices to enhance resilience and ensure food and water security.

7 Conclusions

This study underscores the intricate and compounding effects of drought and land use and land cover (LULC) changes on livelihood systems in three livelihood zones in Ethiopia's Rift Valley's Northwestern Escarpment. The climate variability, drought trends, LULCC, and drought vulnerability were analyzed to investigate the synergistic effects. There are complex interactions between the factors and their collective impact. Hence, all livelihood zones showed significant changes in minimum and maximum temperature trends at measured time scales. Annual rainfall trends did not indicate significant changes in the LZs. However, rainfall trends in the Belg season, the basis for farming, and precipitation for local ecosystems imply diminishing trends. However, during the Kiremt rain season, there were significant changes in RVLZ and TCLZ. On the other hand, all of LZ had significant and severe rainfall variability in Kiremt.

Drought significantly impairs water availability and agricultural productivity. The reduction in soil moisture and river flows observed during drought directly affects crop yields and heightens the risk of food insecurity. Additionally, drought exacerbates the vulnerability of natural habitats, leading to an increased frequency of biodiversity loss. This result provides insight into how climate variability's effects on drought vary temporally and spatially within and across livelihood zones. Climate variability trends were positively related to both spatial and temporal drought history. This interaction made it even more likely for livelihood systems to be affected by drought. This study uncovers seasonal and annual recurrent droughts that vary in intensity, frequency, and duration within and between livelihood zones.

The findings also highlight the significant impacts of LULC changes across three livelihood zones in drought-prone areas. Urbanization and agricultural expansion lead to increased impervious surfaces and reduced natural vegetation, which disrupt local hydrological cycles and exacerbate runoff and soil erosion. The conversion of land for development or intensive agriculture diminishes the landscape's capacity to retain water and regulate temperature, further stressing ecosystems already impacted by drought. These LULC changes contribute to increased drought, revealing a feedback loop and intensifying environmental stress. The changes have long-term ramifications for community livelihood systems that rely on rainfed systems.

The combined effects of drought and LULC changes present a compounded challenge. For instance, areas undergoing deforestation or urban expansion experience heightened soil erosion and reduced water retention during drought. This synergistic effect demonstrates how interactions between drought and LULC changes can create a cascade of environmental and socioeconomic issues, necessitating a more integrated approach to management and policy.

This study provides insight into how the synergistic impacts of drought and LULCC on the livelihood system have more significant effects than independently or the sum of their results. This new approach can be used as input for strategies and policymakers to integrate relevant sectors to reduce the synergetic impacts of drought and LULCC livelihood systems at LZ levels. The study will improve the current drought and LULCC monitoring systems.

This study encountered limitations related to the long-recorded socioeconomic data. These limitations restricted the ability to capture and model the complex interactions between these factors. Future research should address these limitations by developing integrated models to create advanced models that can simulate the interactions between drought and LULC changes across different scales and scenarios to predict their synergistic effects. Conducting regional case studies to undertake detailed case studies in various regions to understand localized impacts and develop targeted management strategies is important. Addressing these areas will provide a more nuanced understanding of the synergistic effects of drought and LULC changes, leading to more effective management and policy solutions. By advancing research and integrating findings, we can better address the multifaceted challenges posed by these intertwined factors and build more resilient ecosystems and communities.

Acknowledgements The investigator expresses gratitude to Addis Ababa University and Aksum University for their monetary contributions, and to the editor and anonymous manuscript reviewers for their insightful comments. We acknowledge the Institute of International Education-Scholars Rescue Fund (IIE-SRF), and Nord University, Faculty of Bioscience and Aquaculture (FBA) for supporting the research stay of Emiru Birhane.

Author contributions "J.N., T.Z., E.G., E.A., S.K., E.B., and P.M. wrote the main manuscript text. J.N. wrote the first draft of the manuscript, and all authors commented on earlier versions. All authors reviewed the manuscript."

Funding Addis Ababa University and Aksum University financially supported this research.

Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate The manuscript has been thoroughly reviewed and approved for submission for publication.

Competing interests The authors declare no competing interests.

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