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Research Article

Impact of Climate Change Vulnerability on Forest and Range Species in North Darfur States, Sudan

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Abstract

The methods for assessing climate change vulnerability in Africa are not designed to be easily modified. Finding the appropriate methods for assessing climate change risk is one of the most difficult steps in Africa as general and in Sudan in particular. Therefore, this study was conducted in three localities in North Darfur State (NDS) during 2019 with aim to asses' climate change vulnerability by using the NDVI and Aridity Index (AI) and to study the impact of climate change on forestry and range species. Three methods were used (1) Remote sensing method (2) Focus group discussion and (3) Key informant interview (KII). According to MODIST and LAND SAT-8 data about 57.1% of locality of Kalamendo was classified as highly vulnerable to climate change, 42.7% as moderate vulnerable and 0.2% as slight vulnerable. In El Koma locality about 59.2% from the locality area was classified as highly vulnerable 40.5% as moderate vulnerable and 0.03 are classified as slightly vulnerable. In Mellit locality 99.1% of the locality is classified as highly vulnerable, 07% as moderately vulnerable and the rest of locality as slightly vulnerable. It was observed that Mellit locality is highly affected by climate change vulnerability. The results from focus group discussion (FGD) and key informant interview showed that the forest cover and range conditions were highly deteriorated an affected by climate change. The targeted localities experienced drought spells during the periods 64, 72, 75, 85 and 1992 which lead to crop failure, death of livestock and massive people displacement. According to FGD and KII the coping strategies during the drought and famine period include; use of seeds of grasses and tree species as famine foods, selling assets; displacement of local communities to the nearest towns and reduce food consumption. Therefore, the study recommended using alternatives for energy and building materials sources. This includes solar energy and stabilized soil blocks. Furthermore, capacity building of communities on sustainable forests management, establishment of villages' nurseries and, establishment of community/private forests and improve stove (Azza, Elsurur and easy avi-stoves) to minimize dependency on the traditional stove/three stone stove. The recommendations for improvement of range condition in NDS include adoption of water harvesting techniques, equal distribution of water point, rehabilitating of range land by reseedings of perennials palatable range species, opening of the fire lines, range improvement by broadcasting of seeds to enrich the soil seeds banks and improvement of the poor animal genetic stocks.

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Keywords

Climate Change, NDVI, Vulnerability, North Darfur, Kalamendo, El Koma, Mellit Localities

1. Introduction

Least developed countries (LDCs) like Sudan are particularly vulnerable to climate change because of the overwhelming dependence of their economies on natural resources, and their low adaptive capacity. Most land in Sudan is quite sensitive to changes in temperature and precipitation. Food security is mainly determined by rainfall, with more than 70% of Sudan's people directly dependent on climate sensitive resources for their livelihoods. Forested areas have already been degraded, with forest cover falling from between 36 to 43% of the country's total area in 1958, to 19% in 1990 [22, 23].

Climate variability and climate change are likely to intensify the desertification of arable areas. It also predicts that the humid agro-climatic zones are likely to shift southward, rendering areas of the north increasingly unsuitable for agriculture. In addition, crop production is predicted to decline substantially for both millet and sorghum, because of decreasing rainfall and increasing variability in its distribution [13]. The areas suitable for arable land, as well as the important gum Arabic belt, are also expected to decrease in size, with negative impacts for both local incomes and food security [13].

Climate change is expected to affect Sudan's water resources through reduced groundwater recharge brought about by decreased precipitation and/or increased temperatures and evaporation. It has been shown that soil moisture is also likely to decline under future climate change. When coupled with increased water consumption, population growth and high rainfall variability, these effects mean that the country could face a serious water crisis [17, 18, 20].

Darfur remains an epicenter of large scale protracted displacement, where most IDPs are unable to meet their basic needs independently. The scale and long-term nature of displacement, which has not been matched by economic opportunities, has exposed displaced people to hardship and uncertainty about their future, which in turn puts additional strains on the limited resources available. The long-term effects of protracted displacement have disrupted and limited access and availability of basic public services such as health and WASH, especially in IDPs camps and resettlements. Among displaced people, women and children are the most vulnerable and at risk of being exposed to communicable diseases, malnutrition, and violence during travel necessary for water and wood collection. According to the Sudan HNO (2018), an estimated 537,833 IDPs, 8,078 returnees, and 278,118 residents are in acute need of humanitarian assistance in South Darfur State (SDS), one of the most populous states of North Sudan with about 30% of the population living in IDPs camps and hard-to-reach areas. The war caused the failures of the life system everywhere in Darfur. Most of the time, people could not produce, trade, migrate for work, or move their livestock around in search of grazing and water [12]. The conflict destroyed people's livelihoods [25, 26].

Climate of Sudan can be classified into seven zones using an index based on the ratio of rainfall to temperatures [1]. Aridity index is more appropriate to use for classification of Sudan compared to other indices, and that Sudan can be classified into hyper-arid, arid, semi-arid, sub-humid and humid zones [8].

The aridity index (AI) is a crucial metric for understanding the climatic conditions of an area, particularly in arid and semi-arid regions. It is defined as the ratio of annual precipitation to potential evapo-transpiration (PET), providing insight into the dryness of the environment [1, 2]. The AI is calculated using the UNEP aridity index formula, which helps in classifying the degree of aridity experienced in various geographic areas [1]. Arid zones are typically characterized by excessive heat and variable precipitation patterns, which significantly affect local ecosystems and human activities [3]. The aridity index serves as a key indicator for evaluating climate-related challenges, including water scarcity and desertification, impacting both agricultural productivity and biodiversity in these regions [14, 15]. Understanding the AI is particularly important for developing adaptive strategies in response to climate variability and changes.

Over the past decades, Sudan has seen large-scale environmental degradation. The growth of the population and the lack of alternative fuel sources for cooking have led to deforestation. This has been particularly severe in Darfur, where a combination of displacement, lack of other livelihoods opportunities for the poor and urbanization (which came with an escalating demand for burnt bricks, which production also depends on wood to fire up the 'brick ovens') proved devastating for natural forest areas, which have already been badly affected by the 1984 drought. In the east of Sudan, a similar process happened in the late 1980s when the area saw an influx of refugees from nearby Ethiopia and Eritrea. In Gedaref, the spread of large-scale mechanized agriculture from the 1970s onwards also contributed to this pattern. The reduction in tree cover has had many impacts, among which is a reduction of groundwater recharge and an increase in severity of flash floods [24].

Generally, there is many climatic and non-climatic factors contributing to North Darfur vulnerability such as severe poverty levels, lack of income diversity, lack of agricultural inputs, mismanagement of resources, over-cultivation of land, fragile land or water resources, poor soil fertility, deforestation, conflict over natural resources, poor extension services, displacement of communities, Poor sanitation or health services. The objectives of this paper is to study the climate change vulnerability in three localities in North Darfur State by using the NDVI and Aridity Index (AI) and the effect of climate change vulnerability on forest tree species and range conditions.

2. Material and Methods

2.1. Study Area

North Darfur state situated between (12°N-16°N, 22°E-27.5°E). The state occupies more than half the territory of the Greater Darfur region. The state is bordered to the northeast by the Northern State, to the east by North Kordofan, and to the southeast by West Kordofan. To the south are East Darfur, South Darfur, and Central Darfur, while West Darfur is to the southwest. The state consists of 18 localities: Al Fashir, El Malha, Mellit, Sarf Omra, Alseraf, Kebkabiya, Kutum, Alkoma, Um Kedada, Kalamando, Altewasha, El Lait, Alwaha, Um Barou, Karnoi, El Tina, Dar El Salam and Tawila [25]. The study was conducted in three localities in North Darfur (Kaleimendo, Mellit and ElKoma localities) Figure 1.

North Darfur is characterized by its great diversity in climate and geography. One-third of it is of desert climate in the north, which gradually changes into poor and medium savanna, and eventually into rich savanna, the latter characterized by forests and mountains. The region experiences an arid to semi-arid climate, with annual rainfall ranging from 152 mm in the north to 430 mm in the south, about 85% of which falls in August and September. Temperatures vary between 42℃ (max) and 11℃ (min) [13]. Darfur still made a substantial contribution to foreign currency earnings of Sudan from the export of cash crops and livestock.

Nevertheless, the local people in Darfur rural areas learn from past events and current situations about the frequency and the likely consequences of various shocks. Thus, the local people tend to reshape their livelihood systems to buffer against potential catastrophic happenings. They prepare themselves with all means at their disposal and with any external opportunity available.

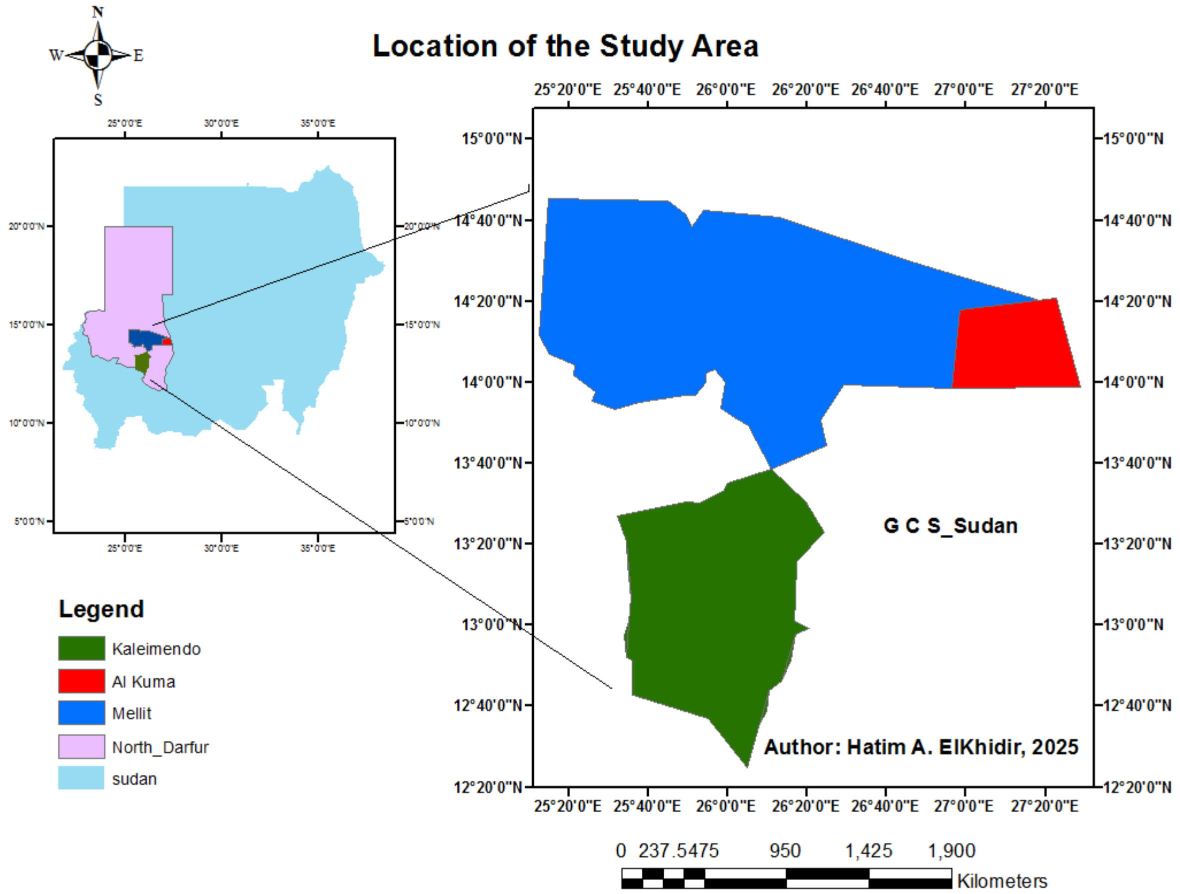

Figure 1. Location of the Study area.

3. Methods

For vulnerability assessment and adaptation planning eleven scenes from Land SAT 8 OLI were used (Table 1) for producing land use and land cover maps (LULC). Eleven scenes of LANDSAT_8 OLI_TIRS with the following specification that used in LULC determination classes with the following specification for the study area.

Table 1. *Land sat images that used in LULC determination classes for the study area.*

SN	Path	Row	Bands	Date of acquisition
2	P177	R050	Band1 - band7	12/23/2018
3	P177	R051	Band1 - band7	12/23/2018
4	P177	R052	Band1 - band7	12/23/2018
5	P178	R050	Band1 - band7	12/21/2018
6	P178	R051	Band1 - band7	12/21/2018
7	P178	R052	Band1 - band7	12/21/2018
8	P178	R053	Band1 - band7	12/21/2018
9	P179	R050	Band1 - band7	12/28/2018
10	P179	R051	Band1 - band7	12/28/2018
11	P180	R051	Band1 - band7	12/19/2018

MODIS data were downloaded to cover the study area for the period 1/1/2008 to 31/12/2019. Products downloaded include Normalized Difference Vegetation Index (NDVI), 250 m resolution and Land Surface temperature (LST), 1000 m resolution (re-sampled to 250 m) to calculate drought index.

The NDVI algorithm subtracts the red reflectance values from the near-infrared and divides it by the sum of near-infrared and red bands.

$$\mathrm{NDVI} = \frac{(\mathrm{NIR} - \mathrm{Red})}{(\mathrm{NIR} + \mathrm{Red})}$$

Theoretically, NDVI values are represented as a ratio ranging in value from -1 to 1 but in practice extreme negative values represent water, values around zero represent bare soil and values over 6 represent dense green vegetation.

Calculation of Drought Index features vulnerability of farmers to dry spells and mapping of drought is done through calculating Vegetation Condition Index (VCI), Temperature Condition Index (TCI) and Vegetation Health Index (VHI).

3.1. Drought Index and Vulnerability Calculation

The vulnerability of the study area to drought was assessed using the Vegetation Health Index (VHI) framework, a widely used method for monitoring drought and vegetation stress from satellite data. The VHI integrates vegetation vigor and thermal conditions and is derived from two sub-indices: the Vegetation Condition Index (VCI) and the Temperature Condition Index (TCI), calculated as follows:

3.2. Vegetation Condition Index (VCI)

The VCI compares the current NDVI to range of values observed in the same period in previous years. The VCI is expressed in % and gives an idea where the observed value is situated between the extreme value (minimum and maximum in previous years. Lower and higher values indicate bad and good vegetation state conditions, respectively. VCI varies from 0 for extremely unfavorable condition, to 100 for optimizing the formula:

$$\mathrm{VCI} = \frac{\mathrm{NDVI} - \mathrm{NDVImin}}{\mathrm{NDVImax} - \mathrm{NDVImin}} * 100 \tag{1}$$

3.3. Temperature Condition Index (TCI)

This index reflects thermal stress on vegetation. It compares the current Land Surface Temperature (LST) to its long-term range. Higher temperatures typically indicate increased water stress, so lower TCI values correspond to poorer vegetation conditions. The TCI is calculated as:

$$\mathrm{TCI} = \frac{\mathrm{LST} - \mathrm{LSTmax}}{\mathrm{LSTmax} - \mathrm{LSTmin}} * 100 \tag{2}$$

3.4. Vegetation Health Index (VHI)

The VHI combines the VCI and TCI into a single comprehensive index for estimating vegetation health and drought conditions. It provides a balanced measure of both vegetation health and thermal stress. The VHI is calculated as:

$$VHI = \frac{VCI+TCI}{2} \quad (3)$$

3.5. Vulnerability Classification

The resulting VHI values were used to classify the region's vulnerability to climate change, based on established drought severity thresholds. The terms used in this study (e.g., "High vulnerability") correspond directly to drought classes, as detailed in the (Table 2) below.

Table 2. Vulnerability Classification.

Vulnerability Class	Drought Class	VHI Range (%)
Very High Vulnerable	Extreme Drought	0-20
High Vulnerable	Severe Drought	21-40
Moderate Vulnerable	Moderate Drought	41-60
Slight Vulnerable	Slight Drought	61-80
Non-vulnerable	No Drought	81-100

Focus group discussion (FGD) with the beneficiaries in the targeted localities in each locality more than three focus group discussions were established with aim to identify communities perception towards the impact of climate change vulnerability on forest cover and range condition beside the past event and the copping mechanism with climate change and their suggestion for important intervention to improve the current situation. Key informant interview (KII). The objective of the KII isto collect information from the local authorities about the situation of the natural resources management, the past intervention and the gaps in (NRM) and their suggestion to fill these gaps.

4. Results and Discussion

4.1. Rainfall Distribution in the Study Area

Figures 2 & 3 shows the variability in rainfall in El-Fashir the capital of North Darfur Sate during the period 1960-2006. The study area is characterized with average annual rainfall: 195 mm/yr and Average maximum temperature of 35 ℃ during the summer season and average minimum temperature of 18 ℃during the winter season. The rainfall is erratic and show uneven distribution from year to year and from place to place. The erratic and uneven distribution of the rainfall leads to a series of improper adaptive coping strategies. For example, livestock overgrazing, over cultivation and deforestation is degrading land quality. According to [19, 20, 27] water tables have fallen rapidly in some areas including by 10 meters around El Fasher since 2007. According to NPA report 2013 Climate projections suggest that crop failure due to inadequate or highly variable rainfall could reach as high as 70% by 2050 in North Darfur [14].

North Darfur is already experiencing a downward trend in rainfall, effecting its limited sorghum and millet production. This results are line with the finding with [4] who stated that rainfall is one of the utmost important and governing factors in the planning and operation strategies of any agricultural program for any given area, a comprehensive knowledge of the trend and persistence in rainfall of the area is of great importance because of economic implications of the rain sensitive operations and since it plays vital role of any agricultural and nonagricultural program. Topography, vegetation type, and precipitation characteristics (quantity, frequency, and distribution) all have a major impact on the spatial patterns of the interaction between precipitation and vegetation.

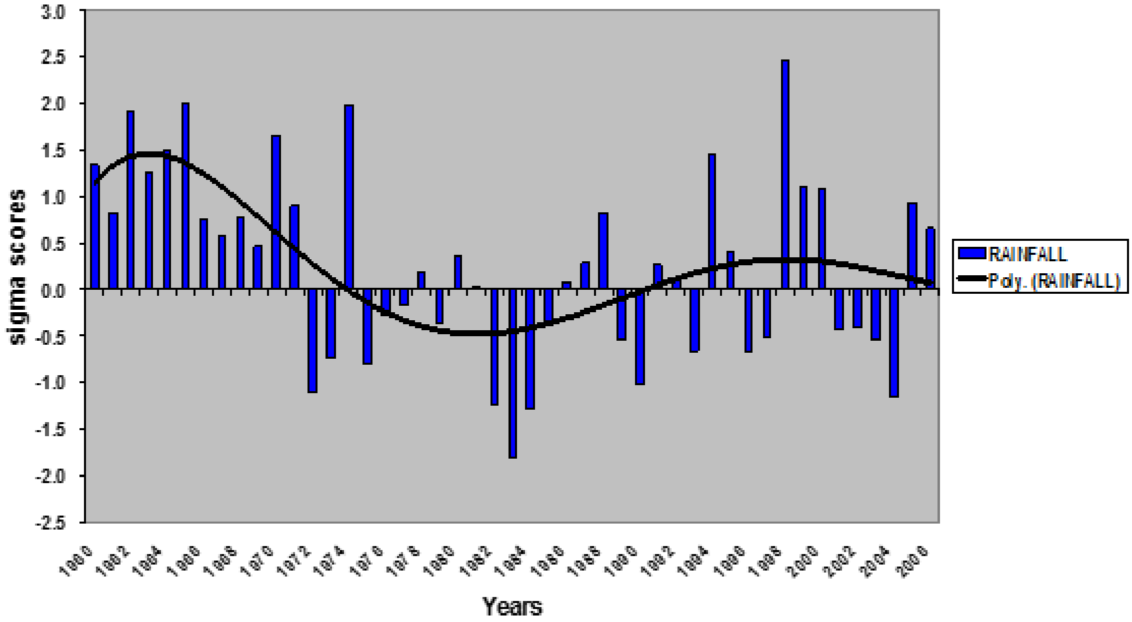

Figure 2. Annual Rainfall anomalies and trend at El- Fashir Station for the period (1960- 2006).

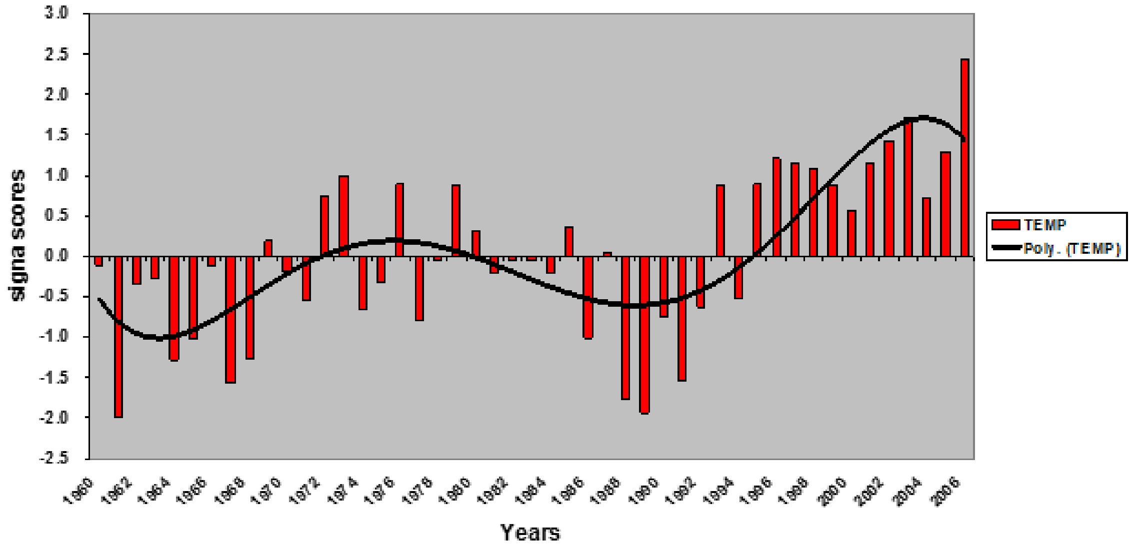

Figure 3. Annual Temperature anomalies and trend at El- Fashir Station for the period (1960- 2006).

4.2. Land Use and Land Cover in North Darfur State

The results of land use and land cover in Kalamando locality in NDS are shown in Table 3 and Figure 4. The satellite images showed that 58% of the land is grassland, 28.9% is cropland, 8.2% is shrub land and 1.5% is woodland. The vulnerability assessment for the same locality (Table 6 & Figure 7) shows that 57.1% of the locality areas were classified as highly vulnerable 42.7% were classified as moderate vulnerable and 0. 2% of the area is classified as slight vulnerable.

For ElKoma locality the land use/land cover map (Figure 5 and Table 3) shows that 59.3% of the area is grassland, 30.7% cropping land, 5.1%of the area is shrub land and 1.5% is woody land. However, for Mellit locality the land use/land cover map (Figure 6 and Table 3) shows that 69.6% of the area is grassland, 16.0% cropping land, 8.2%of the area is shrub land and 2.6% is woody land.

Around the world, remote sensing is utilised to study the venerability of climate change using vegetation indices and LULCC. The NDVI is inversely related to temperature and proportional to precipitation [6]. Over the past three decades, temperature has grown dramatically while precipitation has decreased negligibly. Generally speaking, NDVI values continuously decline from autumn to winter and progressively increase from spring to the rainy season, which is consistent with this study's findings [21].

Numerous researches have focused on the NDVI and LULCC as indicators of climate change in Africa. The dynamic of NDVI in response to climate and LCC change is examined by [11]. The study has shown that NDVI is a useful tool for assessing the effects of climate change on the region of Northwest Algeria. They also find that the rate of change of NDVI varies between land cover types and regions, with resilience in forests and grasslands. According to NDVI, these changes have a big impact on vegetation dynamics. Strong correlations between vegetation indices including NDVI and climate variables were found in the study of vegetation-climate relationships. They have a negative association with minimum precipitation and a positive correlation with temperature and maximum precipitation.

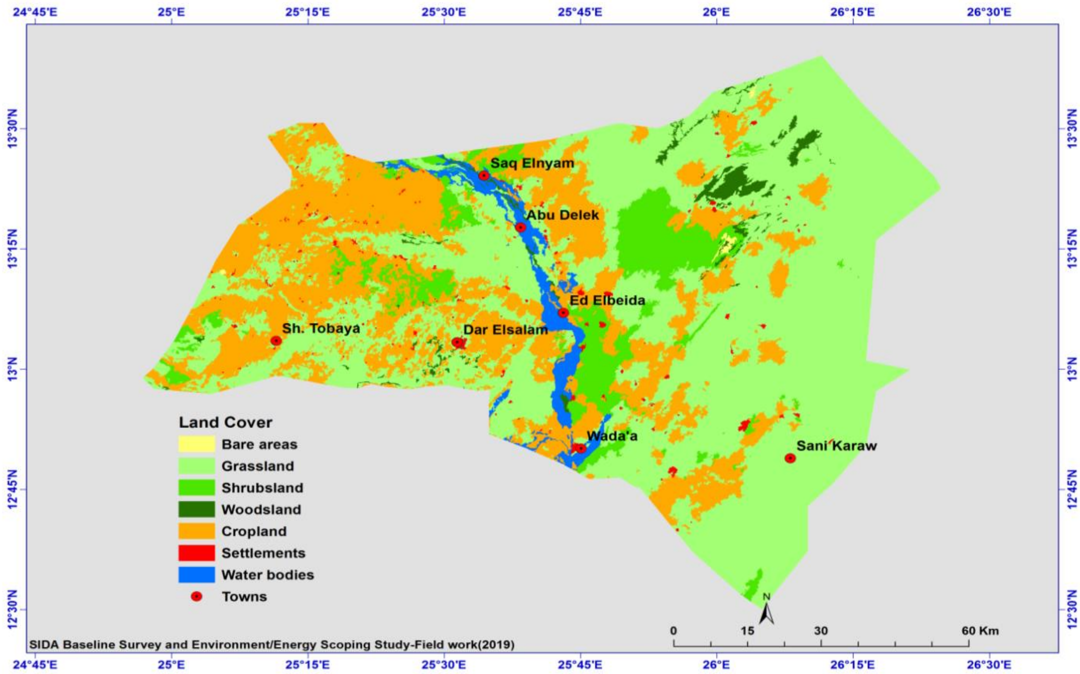

Figure 4. *Land Use/Cover of Kelemendo locality.*

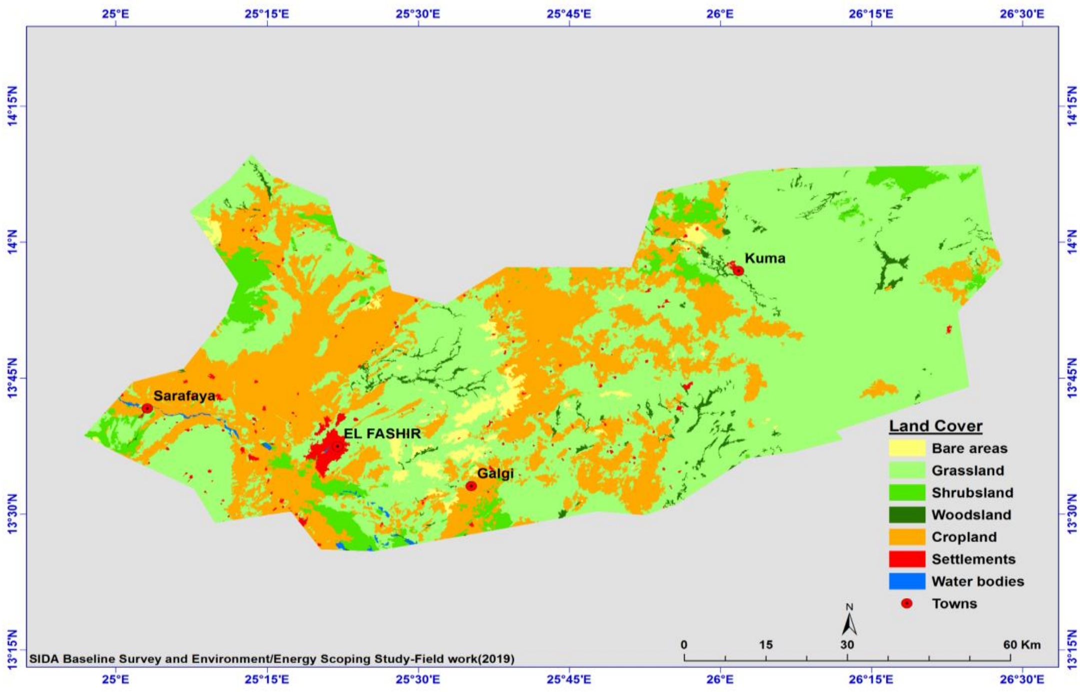

Figure 5. *Land Use/Cover of ElKoma locality.*

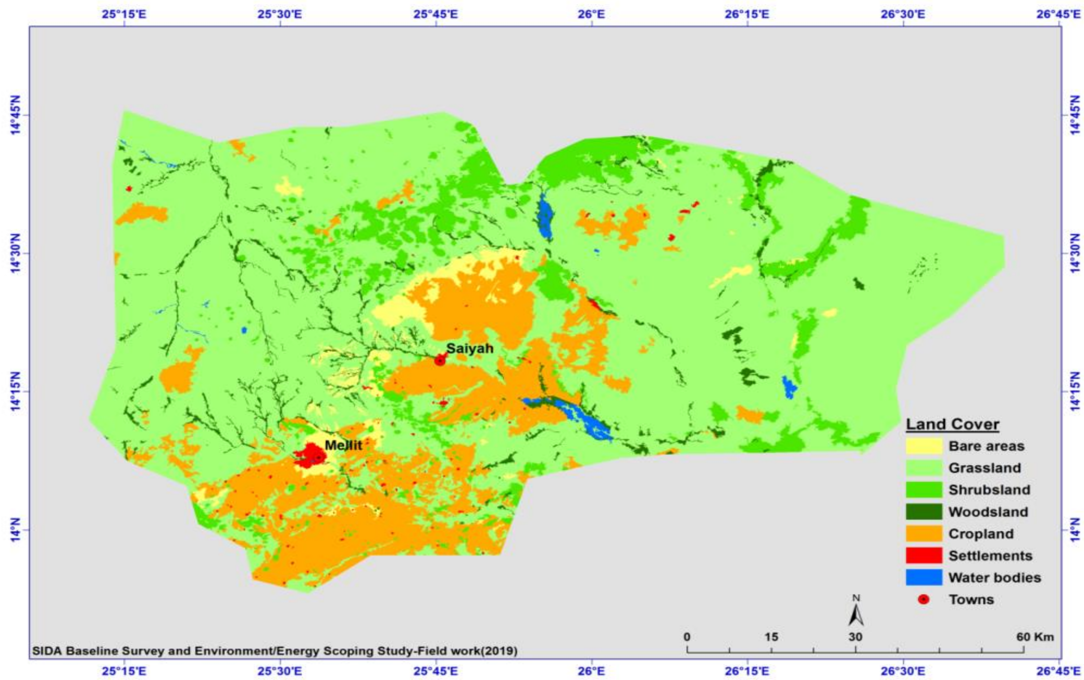

Figure 6. Land Use/Cover of Mellit locality.

Table 3. Land use and land cover in Kalamendo, El Koma and Mellit localities in North Darfur State.

Localities	Land use	Area (Ha)	Area (%)
	Bare areas	1,183.9	0.1%
	Cropland	299,453.2	28.9%
	Grassland	600,787.5	58.0%
Kelemendo locality	Settlements	6,505.8	0.6%
	Shrubs land	84,537.2	8.2%
	Water bodies	26,887.7	2.6%
	Woodland	15,955.1	1.5%
Total area		1,035,310.4	
	Bare areas	17,287.8	2.1%
	Cropland	253,925.3	30.7%
	Grassland	489,628.1	59.3%
Kuma locality	Settlements	8,411.0	1.0%
	Shrubs land	42,459.6	5.1%
	Water bodies	1,548.1	0.2%
	Woodland	12,686.0	1.5%
Total area		825,945.7	
	Bare areas	27,230.8	2.7%
	Cropland	163,428.1	16.0%
	Grassland	710,418.7	69.6%
Mellit locality	Settlements	4,163.6	0.4%

Localities	Land use	Area (Ha)	Area (%)
	Shrubland	83,819.6	8.2%
	Water bodies	5,021.7	0.5%
	Woodland	26,291.7	2.6%
Total area		1,020,374.2	

4.3. Impact of Climate Vulnerability on Forest Tree Cover and Range Conditions

Climate change and increased climate variability have both direct and indirect effects on forests and forest-dependent people. According to the finding from the FGD and KII the forest cover in the targeted localities was deteriorated due to many factors these factors include (1) drought and desertification (2) illicit tree cutting (3) over grazing, (4) Expansion of rainfed farming into forest and grazing land (5) tribe conflict and displacements and (6) poor extension services. The main tree species in the targited area are Heglig *(Balanites aegyptiaca*), Sidir (*Ziziphgus spine-christia), Haraz (Fidiherbia albida)*, Seyal (Acacia *tortilis)*, Arad (*Albizia amara*) and Tondob *(Capparis dicudiua)*. The results showed that there is about 11 community and unreserved forest and about 9 nurseries in the targeted localities (Tables 4 & 5).

The palatable range species in the targeted localities are decreasing compared with the previous years due to low and erratic rainfall and significant increases in human and animal population. The main animal types in the targeted localities are goats, cattle, camels and sheep. The main constrains for range improvement can be summarized as follow (1) Lack of fodder during the dry season (2) lack of proper distribution of water point (3) fire outbreak (4) speared of invader species especially noxious and toxic ones. The consultants recommendations to improve range and animal production in NDS project area include (1) rehabilitation of range land by seeds broadcasting of palatable species (2) capacity building in conflict resolution (3) opening of animal routes (4) opening of fire lines to protect range land from seasonal fires (5) improvement of poor animal genetic stock (6) Provide new water sources for animals and redistribution of water points and (7) planting of fodder trees.

The study concluded that, large area integrated localities were converted from rangeland into crops production lands, as a result many problems such as rangeland degradation, and conflict between farmers and herders have intensified. Gradual change of plants species, emergence of new plants species such as *Prosopis chelenisis*, Cassia tore *Colotropis procera* were dominant and covered a vast area of range lands. In general most of the range lands were changed converted into cultivated land.

Planning for conservation requires an understanding of how forest and range land dynamics and climatic extremes interact. The decline in vegetation health, specifically a 45.4% decline in the normalised difference vegetation index (NDVI) and a 55.1% increase in the bare soil index (BSI), highlights the compounding effects of deforestation, agricultural expansion, and climate-induced stresses like unpredictable rainfall and rising temperatures, according to Terry (Otieno *et al*., 2025) study in the Mount Kenya forest. This emphasises how urgent it is to address the causes of deforestation and methods for climate adaption.

Table 4. *Forests under process of reservation in targeted localities.*

No	Forest name	Status	Area (feddan)	Locality
1	Um Ganatier	Not reserved	2000	Kalamendo
2	Shawa	Suggested	1500	Kalamendo
3	Um-gandul	Not reserved	3	Mellit
4	Extension of Mellit West	Not reserved	250	Mellit
5	Extension of Mellit East	Not reserved	500	Mellit
6	Wadi Um - mineikhir	Not reserved	430	Mellit
7	Al-iekeirshi	Not reserved	200	Mellit
8	Al-aakhar	Not reserved	450	Mellit

No	Forest name	Status	Area (feddan)	Locality
9	Goz-laban	Not reserved	800	Mellit
10	Sag-elnaam	Community forest	2	Kalamendo
11	Al-kibeir	Community forest	10	Elkoma

Table 5. *Forest nurseries in the project area.*

No	Nursery Name	Type	Production Capacity (seedlings)	Locality
1	Kalameindo	Governmental (FNC)	50,000	Kalamendo
2	Mellit	Governmental (FNC)	50,000	Mellit
3	Sag-elnaam	Village	10,000	Kalamendo
4	Abudelek	Village	10,000	Kalamendo
5	Wadkuta	Village	10,000	Kalamendo
6	Wadaah	Village	10,000	Kalamendo
7	Sanikarow	Village	10,000	Kalamendo
8	Arjune	Village	10,000	El koma
9	Armal	Village	10,000	Mellit

4.4. Vulnerability Classification

The study indicated that over 59.656.9 thousand hectares about 57.1% of locality of Kelemendo was classified as highly vulnerable to climate change, 44.669.4 ha about 42.7% as moderate vulnerable, 197.5 thousand about 0.2% of the area was classified as slight vulnerable while only 104.505.7 ha was classified as non-vulnerable (Figure 7 & Table 6).

In ElKoma locality about 59.2% (488.735.4 ha) was classified as highly vulnerable 40.5% from the total area are classified as moderate vulnerable and 0.03 are classified as slightly vulnerable (Figure 8 & Table 6).

In Mellit locality 99.1% of the locality is classified as highly vulnerable, 07% as moderately vulnerable and the rest of locality as slightly vulnerable. It was observed that Mellit locality in the northern part of the state is highly affected by climate change and rainfall fluctuation (Figure 9 & Table 6).

High climate vulnerability in North Darfur where large areas have high or moderate vulnerability is related to wider climate response patterns in vegetation. The remote sensing informs us that vegetation indices like NDVI strongly correlate with precipitation and temperature anomalies [6, 21]. For example, NDVI would usually decline in dry seasons and under rising temperatures [3, 6], consistent with our findings for current poor vegetation health in dry conditions. The remote tensing literature also reports that various land covers have varying resilience: forest and grassland areas might have more buffering for climate impacts in comparison to crop lands [11].

In North Darfur, however, widespread deforestation and land degradation (reported by stakeholders and historical data) have likely erased such natural buffering [22]. Ecosystem changes emphasize that climate impacts have a direct translation of irregular rain and heat into vegetation stress for this semi-arid system. These systems are experiencing rising pressure from various stressors that increase their susceptibility. Years of low rainfall and rising temperatures already pushed the system closer to climatic Critical thresholds. Official reports show an alarming decline in water levels around El Fasher and propose that, if rainfall variability continues, crop failures will increase to 70% by 2050 [19, 14]. From a resilience perspective, this means the system is moving toward or actually has crossed critical thresholds between regimes of stability [9, 5]. The ecological systems often have “multiple domains of attraction,” separated by thresholds beyond which they can shift into completely different regimes [9]. In this case, recurring droughts combined with land misuse, such as overgrazing and deforestation; threaten to push local agro-pastoral areas into a degraded, desertified condition that is extremely difficult to reverse.The resilience depends on the ability to persist and adapt, whether the changes are expected or sudden, across different pathways and threshold points [5]. The visible decline in vegetation and water in North Darfur, therefore, signals a shrinking “resilience basin” and highlights the urgent need for proactive adaptation to avoid a full regime shift [5, 9].

According to the author of a study conducted in eastern Sudan to assess the effects of climate change on vegetation cover, adaptation techniques like rainwater harvesting and the management of overgrazing and deforestation have the potential to increase vegetation resilience to the changing climate conditions in this arid region. This can be applying on the study area to alleviate the impact of climate change [10].

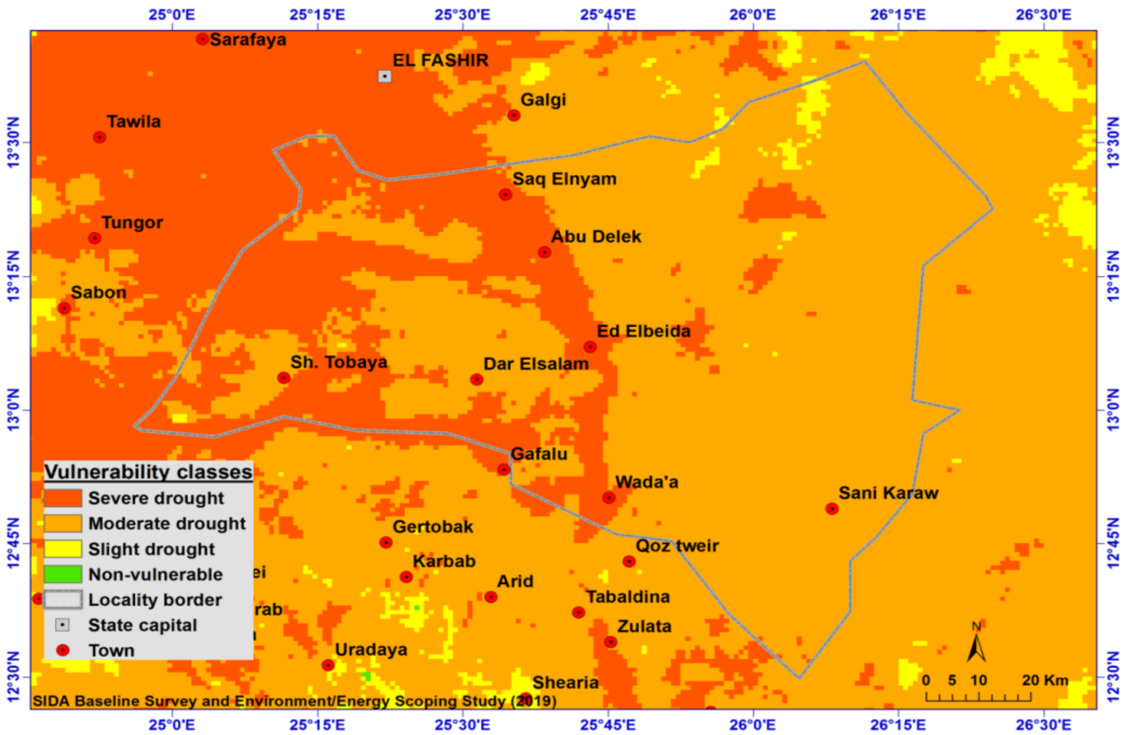

Figure 7. *Vulnerability to climate changes in Kalamendo locality.*

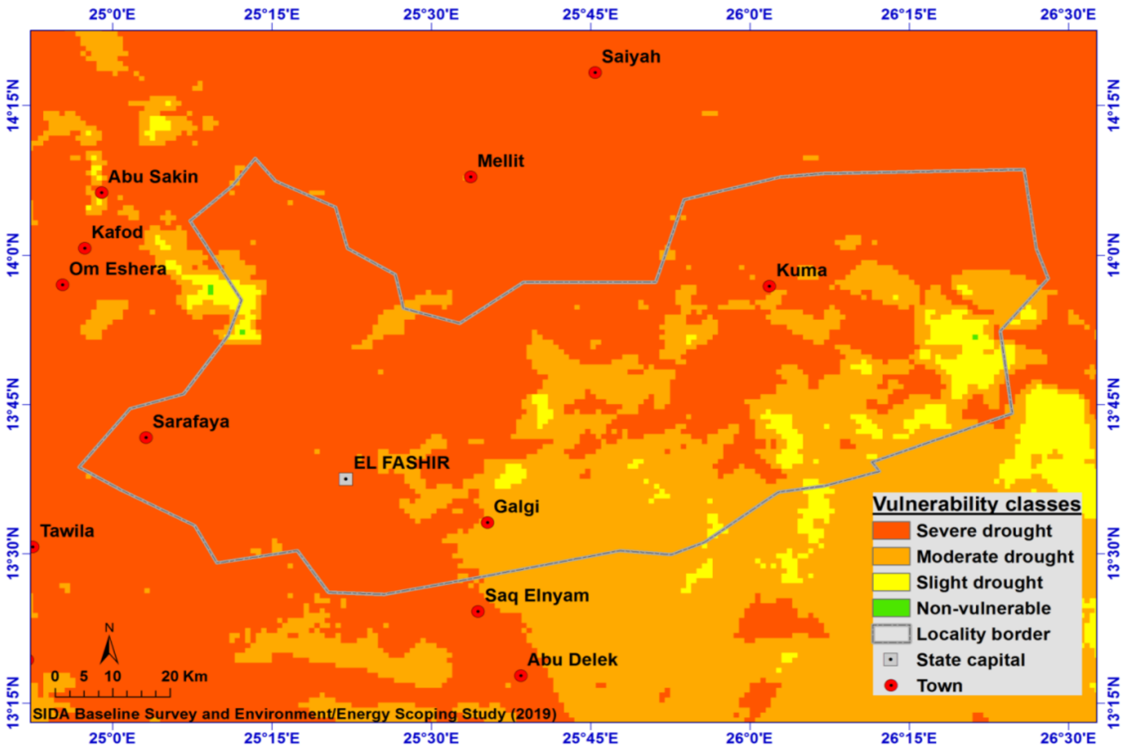

Figure 8. *Vulnerability to climate changes in El Koma locality.*

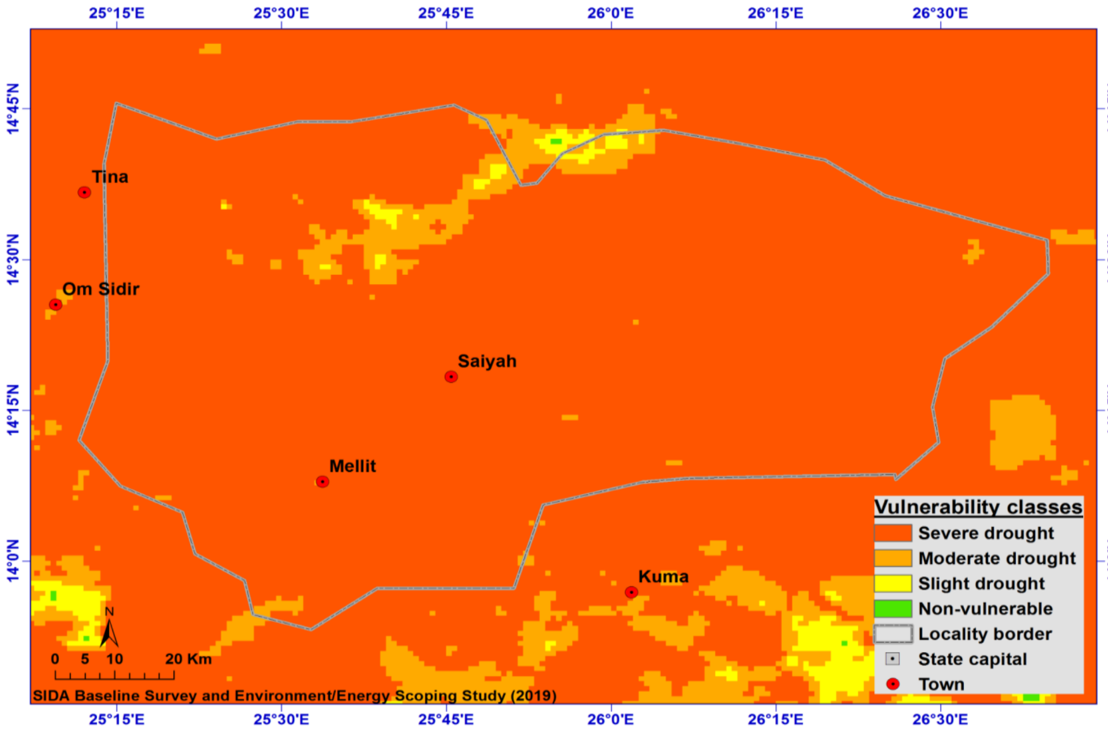

Figure 9. *Vulnerability to climate changes in Mellit locality.*

Table 6. *Vulnerability classes in Kelemendo locality.*

Localities	Vulnerability classes	Area (Ha)	Area (%)
	High vulnerable	59,656.9	57.1%
Kalamendo locality	Moderate vulnerable	44,669.4	42.7%
	Slight vulnerable	179.5	0.2%
	Non-vulnerable	104,505.7	0.0%
	High vulnerable	488,735.4	59.2%
ElKoma locality	Moderate vulnerable	334,435.3	40.5%
	Slight vulnerable	2,770.8	0.3%
	Non-vulnerable	825,945.7	0.0%
	High Vulnerable	1,011,686.0	99.1%
Mellit locality	Moderate Vulnerable	7,535.9	0.7%
	Slight Vulnerable	1,152.3	0.1%
	Non-vulnerable	1,020,374.2	0.1%

4.5. Climatic and Non-climatic Events in the Targeted Localities in North Darfur State

Climate change significantly impacts farming systems, primarily by altering growing conditions, increasing weather extremes, and impacting soil health and water resources. FAO (2020) reported that climate variability and conflicts are major obstacles to eliminating hunger, malnutrition, and chronic food insecurity. Conflicts create immediate and lasting food insecurity by disrupting production, trade, and access to food. These disruptions, exacerbated by environmental factors, can lead to food shortages, resource competition, and increased social grievances. Food security encompasses four dimensions: food availability, food system, food safety and food accessibility.

In the current study, according to the focus group discussion (FGD) and key informant interview with the local communities and community leaders in the targeted localities they stated that " the area experiences successive drought years in 1964, 1972, 1975, 1983, 1985 and 1992 beside the war in 2003, the consequences of all this factors include; shortage of water, shortage of foods, dust storms, bush fires, crop failure, dead of trees, loss of livestock, food gap and famine and death of children and elder people Table 7. The copping strategies adopted by the local communities include; displacement to the bigger cities as IDPs, using of herbs and tree fruits as food during the famine periods and digging ants' houses searching for stored grains (Figures 10 & 11).

These results are in line with the finding of Changes in temperature and rainfall patterns represent a priority threat to food security in Sudan's agriculture-based economy and have caused a shift in the precarious distribution of ecological zones in the productive capacity of rain-fed agriculture. Sudan's First and Second National Communication as well as the NAPA from 2007, have documented how climate change is amplifying and increasing the frequency of many of the climate related hazards already affecting Sudan. An impact of climate change is an increasing frequency of extreme flooding events caused by an increase in intensity of rainfall both during the rainy season (seasonal flooding) and in rainstorms (flash flooding).According to the World Bank's Natural Hotspots Study, Sudan has 29% of its population in areas at relatively high risk from multiple natural hazards.

Local communities in North Darfur have mostly relied on coping mechanisms rather than long-term adaptation. As shown in Table 7, strategies such as migration, eating marginal food sources, or collecting reactive water sourcing from unconventional supplies, are short-term survival responses to extreme drought. Even though these actions help in the current time, they do little to build lasting adaptive capacity and may even become harmful if they reinforce dependence on crisis-driven measures. Resilience theory warns that systems risk being locked into maladaptive regimes in undesirable situations unless deep vulnerabilities are fixed [5]. That is to say, adaptation alone may lock communities into a cycle of vulnerability, particularly when it reinforces short-term coping at the expense of transformative change. Conversely, conscious adaptation practices such as improved water harvesting, agricultural diversification, and sustainable grazing increase resilience. Other dry land data from such regions as dry areas in Sudan suggest that actions such as rainwater collection and control over overgrazing can enhance vegetation resilience under climate stress significantly [1]. Such adaptive measures build adaptive capacity - the ability of actors to adjust to shocks within safe thresholds.

A resilience-based approach also prioritizes the concept of threshold and transformation. As [11] demonstrated, ecosystems could lie in different basins of attraction; transformation refers to converting the system into a considerably new basin when conditions currently prevailing prove unsustainable, transformability as the potential of creating a new system when ecological and societal frameworks make the existing system unsustainable [5]. In North Darfur, if climate variability and overexploitation of resources are not kept in check, a few of the present livelihood systems would have to experience transformation to avoid collapse. For example, if rain fed agriculture continuously fails, societies would have to adopt other livelihoods (e.g. irrigated agriculture wherever feasible, value-added pastoral systems, or income from off-farm livelihoods) in order to remain resilient. This would entail the adoption of new practices and rebuilding institutions.

What really matters is that resilience isn't just about returning to how things were before a crisis. It's about learning, adapting, or even changing the system so it can keep working under new conditions.

Figure 10. *Focus group discussions in Mellit locality.*

Figure 11. *Women participation in the FGD.*

In Darfur, that means staying within key limits like making sure the soil stays fertile and underground water doesn't drop too low. And if those limits are passed, it's better to guide a planned change than to let things fall apart on their own. Past studies have indicated farmers do perceive that climate is changing and taking adaptive management measures to reduce the negative impacts of climate change, smart climate change agriculture like agro forestry and production of bee honey, rangeland and forest catchment areas. Traditional knowledge can help to provide efficient, appropriate and time-tested ways of advising and enabling adaptation to climate change in communities who are feeling the effects of climate changes**.**

Lastly, the study identifies focal interventions to enhance resilience and adaptive capacity in North Darfur. Diversification of livelihoods (already practiced by the vast majority of households in agro-pastoralist or seasonal migration) and investment in sustainable land management (seedling fodder trees, restoration and hydrological enhancement of rangeland ecosystems, safeguarding surviving woodlands) have the potential to lower climate shock exposure. Institutionally, adaptive co-management-proof policies, conflict resolution, and water infrastructure feature prominently. Recommendations of such a nature appeal both to place-based planning (e.g., National Adaptation Plan priorities of Sudan [13] and to the literature on resilience: [5] the value of enhancing diversity, learning, and inclusive governance to enhance resilience. Similarly, Sudan's First National Communication [16] calls for improving water management and agricultural research as a means to construct adaptive capacity. In general, coping means marrying traditional knowledge with innovative adaptation interventions. By intentionally building adaptive capacity and being prepared to transform practices when thresholds are approached, North Darfur's communities can improve their resilience - that is, their ability to sustain livelihood functions and ecosystems in the face of mounting climate variability.

Table 7. *Climatic and non-climatic events in the targeted localities in North Darfur State.*

Years	Events	Impact	Consequences	Coping strategy
1964	No rainfall for 2 years	drought	Dust storm, bush fires, crop failure, dead oftrees	Migration of people to bigger cities and work as workers, Use of famine food
1972	No rains in that year	drought	Shortages in food Shortage in drinking water	Migration, use of tree and herbs fruits and seeds as food
1975	No rainfall for 2 years	drought	Famines, low production, loss of trees cover, loss of livestock	People migrate with their livestock, farmers work as labors in towns, use of seeds of grasses species as grains for food, digging ants house for grains
1983-1985	No rainfall for 3 years	drought	No agricultural production Death of animals Dead of Hashab trees	People migrate with their livestock towards Jebel Marrah, use of grasses seeds as food, digging ants houses for grains
1991-1992	No rainfall for 2 years	drought	Reduction in crop production Food gab Death of some animals	Migration Use of all stores of cereal, even that allocated for cropping

The methods for assessing climate change vulnerability that are now in use in Africa are not designed to be easily modified. Finding the appropriate methods for assessing climate change risk is one of the most difficult steps in the development process. Indicators for ever vulnerability function component. Expert judgement is typically needed, which is not always the case. Therefore, in order to have consistent results for collective adaptation actions, Africa must establish vulnerability assessment methodologies that are easily adaptable to the context of a country or sub-region and adhere to standard mathematical and statistical techniques. The majority of vulnerability assessment techniques for climate change that have been developed thus far have constructed vulnerability indices using the additive approach. Seldom are alternative techniques employed. The majority of the authors used historical indications of sensitivity to create climate change vulnerability indices. And adaptability for the future vulnerability index by presuming that the current situation will continue rather than creating future projections for every indication [7].

5. Conclusion and Recommendation

Most people in North Darfur particularly in the rural areas depend on forests to obtain energy for different purposes such as cooking, lighting, manufacturing of red bricks and also to obtain building poles for construction, this practice led to environmental degradation, therefore the study recommend to use alternatives for energy and building materials sources; This alternative include Solar energy, using of stabilized soil blocks as an alternative for building materials in the rural areas, capacity building of communities on sustainable forests management (awareness & extension training), establishment of nurseries and training of communities on nursery management and tree planting, establishment of community/private forests, shelter belts and planting with multi-purpose trees (gum trees, wild fruit trees, fodder trees, nitrogen-fixation trees …etc, provision of improve stove (*Azza, Elsurur and easy avi-stoves*) to minimize dependency on the traditional stove/three stone stove. The recommendations for improvement of range condition in NDS include adoption of water harvesting techniques. equal distribution of the water point to avoid overstocking and over grazing, rehabilitating of range land by reseedings of perennials palatable range species, medicines and vaccines, opening of the fire lines to protect the range land from wildfire, range improvement by broadcasting of seeds to enrich the soil seeds banks, improvement of the poor animal genetic stocks.

Abbreviations

AI	Aridity Index
ARC	Agricultural Research Corporation
FGD	Focus Group Discussion
HNO	Humanitarian Needs Overview
IDP	Internally Displaced People
KII	Key Informants Interview
LDCs	Least Development Countries
LST	Land Surface Temperature
LULC	Land Use And Land Cover
MODIS	Moderate Resolution Imaging Spectroradiometer
NDVI	Normalized Difference Vegetation Index
NRM	Natural Resources Management
SDS	South Darfur State
TCI	Temperature Condition Index
VCI	Vegetation Condition Index
VHI	Vegetation Health Index

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Conflicts of Interest

The authors declare no conflicts of interest.

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