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# Spatial analysis of drought vulnerability in cocoa agroforestry systems across the Ghana-Togo border

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## ABSTRACT

Extreme events like droughts frequently affect West Africa, known as the world's centre for cocoa production. In Ghana and Togo, these extreme events negatively affect water supplies and agricultural land productivity, especially for cocoa. This study aims to create a cocoa drought vulnerability map that offers a clearer perspective of drought effects over the transboundary territory between Ghana and Togo, where substantial amounts of cocoa are produced. The vulnerability map used 16 criteria categorised under three (3) vulnerability components Exposure [4], Sensitivity [6], and Adaptive Capacity [6]. The study used the Intergovernmental Panel on Climate Change (IPCC) vulnerability framework and the Analytical Hierarchy Process (AHP) to normalise the criteria. Results showed that over 70% of the cocoa cultivation area in the study area is moderately to highly vulnerable to drought, while less than 30% is classified as very low and low. The most susceptible areas are located on the Togolese side, extending from the central to the northern region, compared to Ghana. These findings are relevant to support drought resilience strategies in the cocoa sector aiming to prioritise interventions and maximise cocoa productivity per drought vulnerability category zone.

## ARTICLE HISTORY

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Extreme Events;  
Agroforestry Systems;  
Cacao; Spatial Vulnerability;  
Climate Change

## 1. Introduction

Drought is one of the climate hazards that has become more frequent and intense since the 1970s in Africa (Ahmadalipour and Moradkhani 2018). These extreme events are a major cause of terrestrial ecosystem instability and have a significant

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impact on food security and sustainable development. They are also more likely to be abnormal, unexpected, unpredictable, and sensitive to climate change (Liu et al. 2018; Stocker et al. 2013). Furthermore, the earth system models predict that the likelihood of a worldwide drought will rise in the twenty-first century (Ahmadalipour et al. 2019; Dai 2011; Diasso and Abiodun 2018). Thus, responding to and mitigating the effects of drought becomes a pressing scientific concern.

Drought negatively affects different sectors, but its impact on agriculture is most noticeable and direct in African nations that still rely on rainfed systems. Statistics show that economic loss from all disasters caused by natural hazards accounts for 85% in the case of global meteorological catastrophes, and more than 50% in the case of all meteorological disasters due to drought (EM-DAT, 2023). Between 1850 and 1900, the global surface temperature rose by 1.09 °C, and this trend is expected to continue into the twenty-first century (IPCC 2022). As temperatures rise, there is a greater chance that extreme weather events will occur simultaneously in several places, which puts the world's food supply chain at serious risk and intensifies food insecurity. In West Africa, drought causes water shortages that directly impact crop growth, productivity, livestock health, and market stability, ultimately threatening food security and livelihoods. This underscores the urgent need for adaptive strategies to enhance resilience in agriculture and related sectors (Diasso and Abiodun 2018; Gautier et al. 2016).

Drought events are increasingly frequent in sub-Saharan Africa, primarily attributed to the region's hydroclimatic variability and geographical location (Gebrechorkos et al. 2022; Kasei et al. 2010; Traore et al. 2014). They manifest through an increase in dry days (Klutse et al. 2018; Sylla et al. 2018). Several major droughts have been reported in the past decades with the period 1982–1983, and 2015–2016 being the most severe (Abdulai 2017; Dai 2011). Ghana (the world's second-largest cocoa producer) and Togo (the world's fifteenth-largest cocoa producer) have not been exempted from significant drought events in the past. Recently these countries have been suffering from a drought related to El Niño Southern Oscillation (ENSO) (Abdulai 2017; Amoatey and Sulaiman 2020; Yiran et al. 2017). These drought events negatively affected crop production especially cocoa yield, which remains a great source of revenue for rural as well as urban communities. The resulting negative impacts caused by drought are a source of severe socio-ecological and economic imbalance such as a reduction of the Gross Domestic Product (GDP) for countries involved in cocoa production and processing. To develop effective policies addressing drought vulnerability, information about the causes, influencing variables, and spatial patterns of vulnerability are required. Regardless of the gap between Ghana's and Togo's position as a global cocoa producers, these countries share some similarities in socio-economic and ecological characteristics; therefore, understanding the shared risks and opportunities in these areas can foster regional cooperation and the development of joint adaptation strategies, ultimately leading to more resilient and sustainable management of shared resources under changing climatic conditions. A vulnerability map in this situation may help manage the drought (Zhang et al. 2020).

The cocoa production sector has garnered attention from scholars at the national, regional, and international levels, driven by a keen interest in the produced

commodities. Several studies have been conducted to investigate the impact of climate change on cocoa production in West Africa (Abdulai et al. 2018; Asare et al. 2017; Bunn, Fernández Kolb, et al. 2019; Schroth et al. 2016). These studies have identified various constraints, including reducing the cocoa growing area, yield losses, and spreading pest and fungal diseases rapidly. Recommendations have also been provided based on the research outcomes, some of which include incremental, systemic, and transformational adaptation efforts with good agricultural practices (Bunn et al. 2019; Schroth et al. 2017). Despite the plethora of studies conducted, very little is known about spatial drought vulnerability in cocoa production regions (Dabanli 2018; Mainali and Pricope 2019; Mohammed et al. 2018; Zhang et al. 2015). Therefore, this study aims to assess and map the drought vulnerability of cocoa agroforestry systems in the transboundary region between Ghana and Togo to inform effective management strategies and enhance resilience against climate change. Since drought is a complex phenomenon and several criteria influence its severity, multi-criteria-based approaches are highly useful for generating detailed drought vulnerability information. The specific objective of this study is to analyze the spatial distribution of drought-prone areas within cocoa agroforestry systems using geospatial techniques and climatic data. The main question addressed in this study is: how does the vulnerability to drought vary across the transboundary area between Ghana and Togo? Studies have demonstrated that understanding drought vulnerability can significantly enhance the resilience of exposed systems to climate change, enabling better adaptation strategies. It also helps with efficient resource allocation, better policy development, community awareness and preparedness, and sustainability in agricultural practices. Drought vulnerability assessment is also one of the three key pillars for drought risk reduction (UNDRR 2019). This research, by identifying critical drought-prone areas across the Ghana-Togo border aids in targeted interventions and sustainable agricultural practices.

## 2. Material and methods

### 2.1. Study area

The study area covers the Southern part of the Atakora Mountains, southwest of Togo sharing the border with Ghana, [Figure 1](#). Ghana and Togo rank 2<sup>nd</sup> and 15<sup>th</sup> position of cocoa-producing countries worldwide, respectively, and substantially support West African cocoa production (Merem et al. 2020).

The portion of Ghana included in the study area covers one agroecological zone (semi-deciduous forest zone) and is located between latitude 4.5° N and longitude 1.3° E. Administratively, the Ghanaian portion covers the Volta and Oti regions with 1150 to 1300 mm  $y^{-1}$  as the annual precipitation and 23 to 31 degrees C annual range of mean temperature, [Figure 2](#). The Togolese side extends from Ghana's humid and semi-humid forest zone and covers the entire area of the fourth agroecological zone named "Ecological Zone IV" (Ern 1979). The annual total rainfall and mean temperature cover a range of 1200 to 1800 mm  $y^{-1}$  and 21 to 28 degrees C, respectively. The geological structural unit is the Atakora, consisting of epimetamorphic formations. Pedologically, the area is characterized by a gradual evolution of soils, predominantly

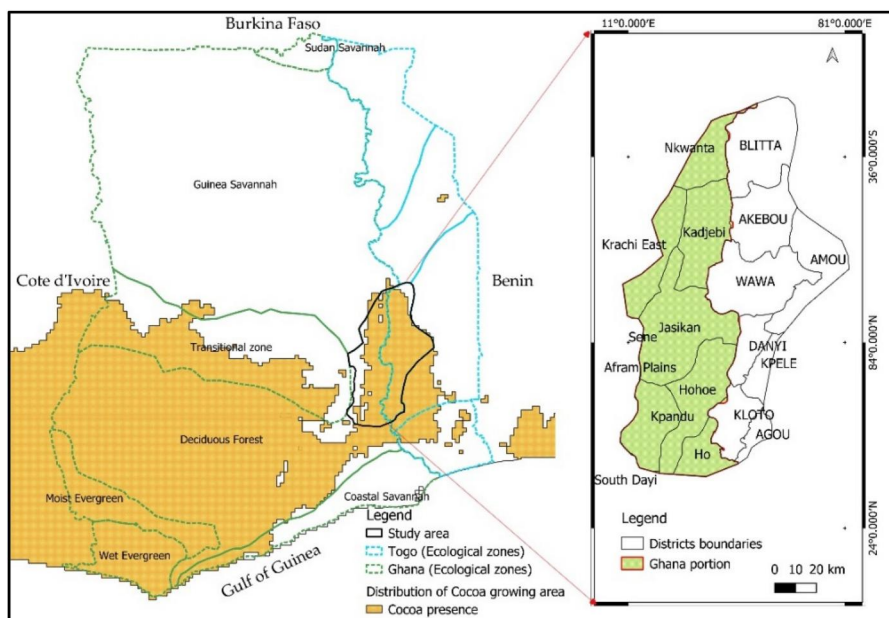


Figure 1. Study area.

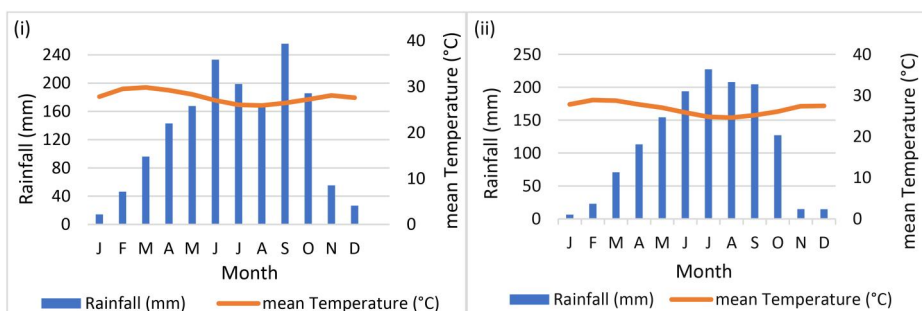
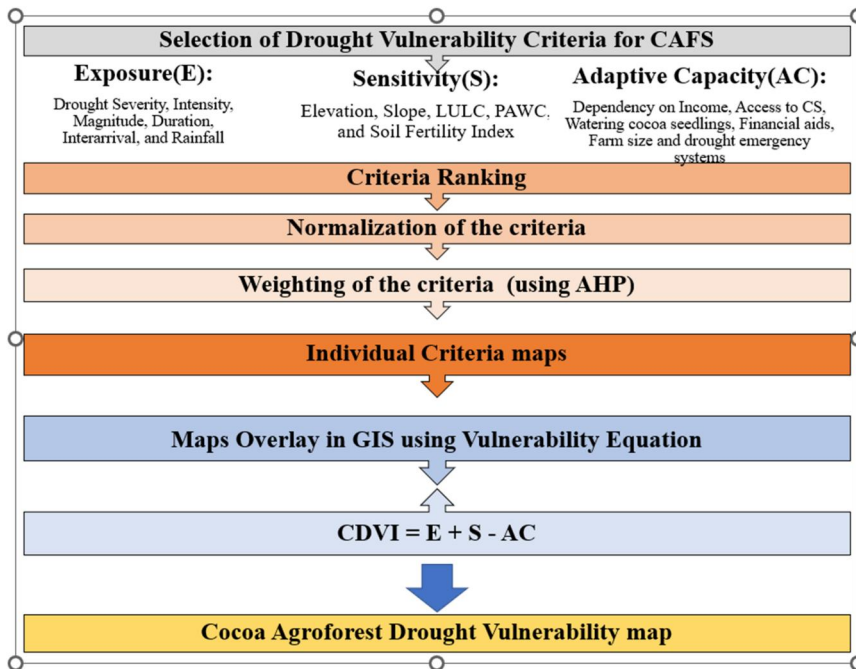


Figure 2. Ombrothermal curve of the study area (i-Ghana side) (ii-Togo side) 1981–2020.

ferrallitic and tropical ferruginous soils. However, substantial land and ecosystem degradation is observed due to human activities, with some forest fragments exhibiting high plant diversity in remote and challenging-to-access locations (Kossi et al. 2019). The study area experiences a transitional sub-equatorial climate with four seasons: a ‘major rainy season’ from March to July, followed by a ‘minor dry season’ in August. This is succeeded by a ‘major dry season’ from November to February, preceded by a two-month ‘minor rainy season’ from September to October (Papadakis 1966).

## 2.2. Cocoa drought vulnerability assessment

Drought vulnerability refers to the degree to which a system is susceptible to being damaged by drought and incapable of coping with its adverse effects. For mapping



**Figure 3.** Methodological flowchart of the cocoa agroforest drought vulnerability assessment.

the drought vulnerability of a Cocoa Agroforest System (CAFS), the IPCC's definition was applied, whereby the vulnerability is a function of three (3) components: Exposure, Sensitivity, and Adaptive Capacity (IPCC 2022). The methodology used for the drought vulnerability assessment of CAFS is summarised in Figure 3.

In the present study, Exposure describes the degree of drought to which the CAFS is exposed and Sensitivity refers to the tendency of CAFS at risk (physical and social) to experience damage. Adaptive Capacity (AC) refers to the ability of CAFS to adjust to the potential damage of drought, seize opportunities, or respond to consequences. The drought vulnerability mapping requires various factors including climatic, bio-physical, and socio-economic variables from primary and secondary data sources (UNDRR 2019).

### 2.2.1. Selection of vulnerability criteria

A non-exhaustive list of 23 variables influencing drought in the agricultural field has been selected from the literature (Baik et al. 2019; Hoque et al. 2021; Ortega-Gaucin et al. 2018; Wu et al. 2017). However, the availability of some criteria has become critical due to the sparse data in the study area and generally at the regional level. Thus, 16 dynamic variables for the vulnerability components were selected based on their availability and also their relevance in cocoa fields, Table 1.

### 2.2.2. Data collection and processing

This process involves collecting the required information to assess the value of each of the 16 indicators used for the drought vulnerability analysis and this session is

**Table 1.** Selected variables used in the drought vulnerability assessment and their various weight.

VA comp.	Criteria/ Subcomponent	Data description	Data source	Weight
Exposure	Drought duration	Average time of a drought event that has a severity that is equal to or greater than a threshold	Computed by authors	0.32
	Drought severity	Standardised Precipitation Evaporation Index at 18-month scale	Computed by authors	0.21
	Drought interarrival time	The period between two consecutive droughts	Computed by authors	0.09
	Cocoa distribution	Cocoa potential growing areas	CHIRPS	–
Sensitivity	LULC	Landsat8 images 2020	Processed by authors 0.15	0.15
	Elevation	Height of a geographic point above a fixed reference point, often the mean sea level		
	Slope	Rate of change of elevation for each digital elevation model (DEM) cell	USGS Earth Explorer/ ASTER	0.05
	PAWC	Size of a soil that stores rainwater and supplies for plants	Computed by authors	0.3
	RWC	Relative Water Content of the plant	Estimated by authors	0.15
	Soil Fertility Index	Soil Fertility status of the study area	Computed by authors	0.30
Adaptive capacity	Dependency of farmers to CAFS	Different socio-economic Categories of activities	Survey	0.43
	Watering facilities	Irrigation	Survey	0.3
	Access to agroclimatic information	Availability of agroclimatic information to farmers	Survey	0.10
	Farm size	Average size of cocoa farm	Survey	0.07
	Drought Emergency Responses	Availability of response packages for drought disaster	Survey	0
	Financial aids	Availability of Technical assistance to farmers	Survey	0.10

organised per each vulnerability component as described earlier (section 2.2). The observation period for climate-related data is 40 years spanning from 1981 to 2020.

**2.2.2.1. Exposure.** The exposure component includes rainfall-related parameters and the cocoa distribution data. Important climatological information on dryness (or, conversely wetness) of a system or an area can be obtained from rainfall amounts and their derivatives. Therefore, (i) drought duration, (ii) severity, and (iii) interarrival time were selected as essential metrics in the drought exposure analysis, as they directly affect the extent of exposure to drought-related stresses. Additionally, the (iv) cocoa distribution has been mapped to limit the analysis to cocoa land use. For instance, drought duration reflects how long a system is under water deficit conditions. Longer droughts can cause prolonged stress, leading to depletion of soil moisture, reduced groundwater levels, and prolonged physiological stress on crops and ecosystems (Mishra and Singh 2010). Drought severity measures the intensity of water deficit during a drought period, usually expressed as the magnitude of

**Table 2.** SPEI classes.

SPEI value	Moisture level
+2.0 and greater	Extremely wet
+1.5 to 1.99	Very wet
+1 to 1.49	Moderately wet
-0.99 to 0.99	Near Normal
-1.49 to -1.0	Moderately dry
-1.99 to -1.5	Severely dry
Less to -2.0	Extremely dry

precipitation anomalies or moisture deficits (Wilhite et al. 2014), while the inter-arrival time between consecutive drought events reflects the recovery period available to a system before the next drought (Le et al. 2019). The threshold considered for the drought features analysis was based on the moisture content requirement for cocoa cultivation and they were computed using the Standardized Precipitation Evaporation Index at 18 month-scale (SPEI18) (Vicente-Serrano et al. 2012). SPEI estimation incorporates temperature and expresses the difference between precipitation (P) and potential evapotranspiration (PET) to produce an adjusted log-logistic distribution, and can be calculated using Equation 1.

$$D_i = P_i - PET_i \quad (1)$$

where  $i$  is the time steps.

The SPEI time series range from positive to negative values which correspond respectively to the wet and dry conditions grouped in seven classes Table 2. According to Tan et al. (2015), the threshold value used to determine the drought condition is  $-1$ , ( $SPEI \leq -1$ ). The drought features have been computed using the run theory (Le et al. 2019; Yevjevich, 1967). The rainfall dataset from Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS) and the Temperature dataset from ERA5-Land (ECMWF ReAnalysis 5<sup>th</sup> version for surface variables) were the main input variables for drought calculation. CHIRPS dataset is a quasi-global rainfall dataset covering  $50^\circ$  S to  $50^\circ$  N and spanning from 1981 to the near present with high-resolution satellite imagery with *in-situ* station data to create gridded rainfall time series suitable for trend analysis and seasonal drought monitoring of  $0.05^\circ \times 0.05^\circ$  '<http://chg.geog.ucsb.edu/data/chirps>'. Substantial studies in West Africa have successfully used CHIRPS data and have confirmed its performance regarding other satellite products commonly used such as Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN), Rainfall Estimate (RFE), and Tropical Rainfall Measuring Mission (TRMM), (Atiah et al. 2020; Dembélé and Zwart 2016). As for the temperature, ERA5 is a new climate reanalysis dataset for the fifth (5<sup>th</sup>) phase from the European Centre for Medium-Range Weather Forecasts (ECMWF). The observed period spans from 1981 to 2020 in a manner to fit the availability of the different remotely sensed data of use. Overall exposure map was obtained as a result of the intersection between drought features and the cocoa distribution map.

**2.2.2.2. Sensitivity.** The sensitivity of the CAFS to drought conditions is categorised into (i) land use land cover (LULC), (ii) slope, (iii) elevation, (iv) soil fertility status,

(v) potential available water capacity (PAWC), and (vi) relative water content for the landscape. LULC is an important criterion for assessing agricultural drought vulnerability in terms of sensitivity because it constitutes a driving force behind water demand (Xu et al. 2020). Landsat8 (30 m spatial resolution) scenes of 2020 (193/054 and 193/055, Path/Row) were therefore acquired from the United States Geological Survey (USGS) database. Supervised classification techniques with random forest algorithm were used to classify the images, considering water, grassland, farmland, build-up, cocoa AFS, bare land, and forest as major classes. Accuracy assessment of classified images using the Kappa index resulted in 0.92 (see Table 3). Elevation and Slope of an area play an important role in agricultural vulnerability leading to severe drought in high elevation and steep slopes, whereas lower vulnerability has prevailed in regions with low elevation and gentle slopes (Pandey et al. 2012). A digital elevation model (DEM, 30 m resolution) was acquired from the USGS to produce the spatial layer. The soil water content from field capacity to wilting point is defined as the PAWC. And it implies the “bucket” size of the soil that stores rainwater and supplies for plants. A soil with a smaller PAWC will fill up with less rainfall compared to a soil with a larger PAWC. In a longer dry spell, plants grown in soil with larger PAWC would have a better chance to survive than with a smaller PAWC (Wu et al. 2017). Therefore, in this study, PAWC has been used as a criterion for assessing the susceptibility of a cocoa production area to drought. The relative water content (RWC) of the plant, in addition inform on the amount of water hold by a plant compared to its fully turgid state. Another important factor of influence of cocoa yielding is the soil fertility status. The Cocoa Soil Fertility Index (CSFI) was computed through soil chemical properties analyzed at the laboratory with standard methods from collected soil samples in the study area during a field survey (Kongor et al. 2019).

**2.2.2.3. Adaptive capacity.** Drought vulnerability does not only rely on a natural phenomenon but also on socio-economic characteristics (Naumann et al. 2014); therefore its evaluation requires consideration of local specific factors. In this study, factors like (i) cocoa watering schemes, (ii) income diversity, (iii) farm size, (iv) access to financial aid, and (v) climate information including (vi) drought emergency systems have been considered and collected from 420 cocoa farmers in the study area. These criteria are essential indicators in drought adaptive capacity analysis as they collectively determine a system’s ability to cope with, recover from, and adapt to drought impacts. Efficient watering schemes enhance water use during dry periods, while diverse income sources reduce reliance on rainfall-dependent agriculture, ensuring livelihood stability (Adet et al. 2024). Farm size influences resource availability and management options, with larger farms often having more capacity to adopt adaptive measures (Lobell et al. 2008). Access to financial aid provides critical economic buffers, enabling investments in resilience strategies and quicker recovery from losses (Owusu et al. 2022). Lastly, agroclimatic information and drought emergency systems empower proactive decision-making, allowing farmers to prepare for and respond effectively to drought events (Tham-Agyekum et al. 2024). Together, these factors provide a comprehensive framework for assessing and

**Table 3.** Description and accuracy of the four classes considered in the study.

LULC classes	Description	Accuracy (%)	
		Producer	User
Waterbodies	Waterbody surfaces such as reservoirs, ponds, lagoons, and river	90.4	86.3
Grassland	Vegetation is composed of tree savannahs, shrubs, and grasslands. Generally, tree height is lower than 5 m	74.2	77.0
Farmland	Areas dominated by crop production such as cereal crops and vegetable	93.0	95.6
Build-Up	Industrial, commercial services, residential, communications, transportation, commercial and industrial, mixed urban or built-up land, built-up land or other urban land	80.1	84.3
Cocoa AFS	Cocoa Plantations and Cocoa Agroforestry including coffee AFS	75.2	79.1
Bareland	Land with no occupations including road networks	73.8	79.2
Forest	Areas dominated by tree clusters resulting from natural regeneration or planting; Woodland or protected areas with trees height higher than 5 m	76.4	76.7
Overall Accuracy (%)			82.1
Kappa Coefficient (%)			0.81

enhancing drought resilience. The Likert scale of five (5) levels has been used to appraise the factors: (1) being the worst situation while (5) being the best.

Thematic layers of all selected criteria of the vulnerability components were therefore prepared using GIS. They were transformed into raster format with a spatial resolution of  $30\text{ m} \times 30\text{ m}$  for supporting a raster-based analysis. The layers have been first normalized, and then weighted before being integrated into the drought vulnerability map.

### 2.2.3. Normalisation of drought vulnerability criteria layers

The normalisation constitutes an important step to integrate all criteria uniformly and facilitates the application of the spatial multi-criteria decision-making approach; since criteria have been measured using different scales. All spatial maps were normalized using Equations 2 and 3 according to the variable contribution to the drought phenomenon. When the indicator has a direct functional (positive) relationship with drought, Equation 2 was used while when it has an inverse functional (negative) relationship, Equation 3 was used.

$$np = \frac{n - n_{\min}}{n_{\max} - n_{\min}} \quad (2)$$

$$nn = \frac{n_{\max} - n}{n_{\max} - n_{\min}} \quad (3)$$

where  $np$  and  $nn$  specify the normalized value of the criteria in positive and negative relationship cases respectively,  $n_{\min}$  and  $n_{\max}$  refer to the minimum and maximum values of each criterion, respectively and  $n$  indicates the cell value of the criterion.

### 2.2.4. Weighting the criteria using AHP

Weighting aims to give values of each basic map (criterion layers) according to their contribution to drought vulnerability. The Analytical Hierarchy Process (AHP), developed by Saaty (1980), was used to overcome subjectivity in decision-making (Lyu et al. 2020). The AHP method follows five-step (Saaty 2008):

**Step 1:** Choose the criteria linked to the drought vulnerability assessments

**Step 2:** Apply the pairwise comparison and prepare the matrix following the opinions of six experts

**Step 3:** Aggregate pairwise comparison matrixes, and synthesize the judgments to develop a set of overall priorities for the hierarchy

**Step 4:** Calculate the consistency ratio (CR) to justify the consistency of experts' opinions in pairwise matrices

**Step 5:** Transform the pairwise matrix criteria weights into linguistic variables

The expert's choice of opinions relied on their experience in drought research, factors liable for droughts, and their influence on the study site. Experts were selected from academic, governmental, and non-governmental research institutions. These experts provided their opinions considering the relative importance of each selected criterion.

The rating is considered true if the consistency ratio, CR (Equation 4) is equal to or less than 0.1.

$$CR = \frac{\text{Consistency Index}}{\text{Random Index}} \quad (4)$$

where the random index (RI) calculation is based on the matrix order (n) developed by Saaty and Shang (1996). Moreover, the consistency index (CI) was obtained using Equation 5.

$$CI = \frac{(\lambda_{\max} - n)}{(n - 1)} \quad (5)$$

where,  $\lambda_{\max}$  and n present the largest eigenvalue and order of a matrix, respectively.

### 2.2.5. Overall drought vulnerability analysis

The output vulnerability map uses the ranking scheme values from 1–5, where 1 represents extremely low vulnerability, and 5, extremely high vulnerability, (IPCC 2022).

The Cocoa Drought Vulnerability Index (CDVI) was calculated using Equation 6.

$$CDVI = E + S - AC \quad (6)$$

where E, S, and AC denote respectively the Exposure, Sensitivity, and Adaptive Capacity. All the components have been obtained by using Equation 7.

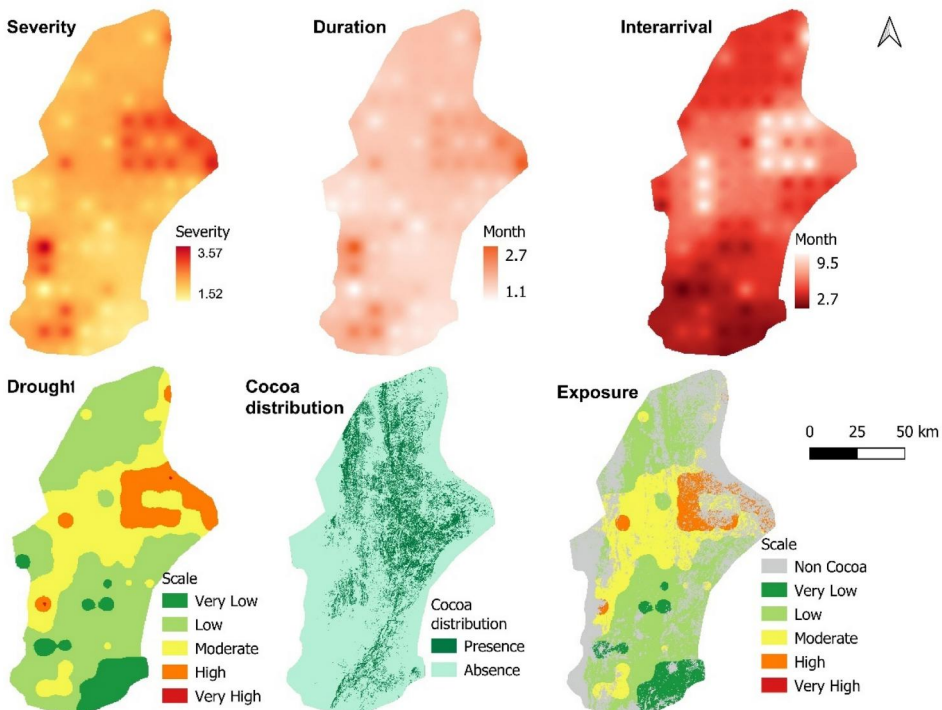
$$C = (C_1 \times wC_1) + (C_2 \times wC_2) + (C_3 \times wC_3) + (C_n \times wC_n) \quad (7)$$

where  $C$  represents the component (Exposure, Sensitivity, or Adaptive Capacity),  $C_1 \dots C_n$ , is the criteria of the components, and  $w$  is the weight of the criteria.

### 3. Results

#### 3.1. Spatial characteristics of CAFS exposure to drought

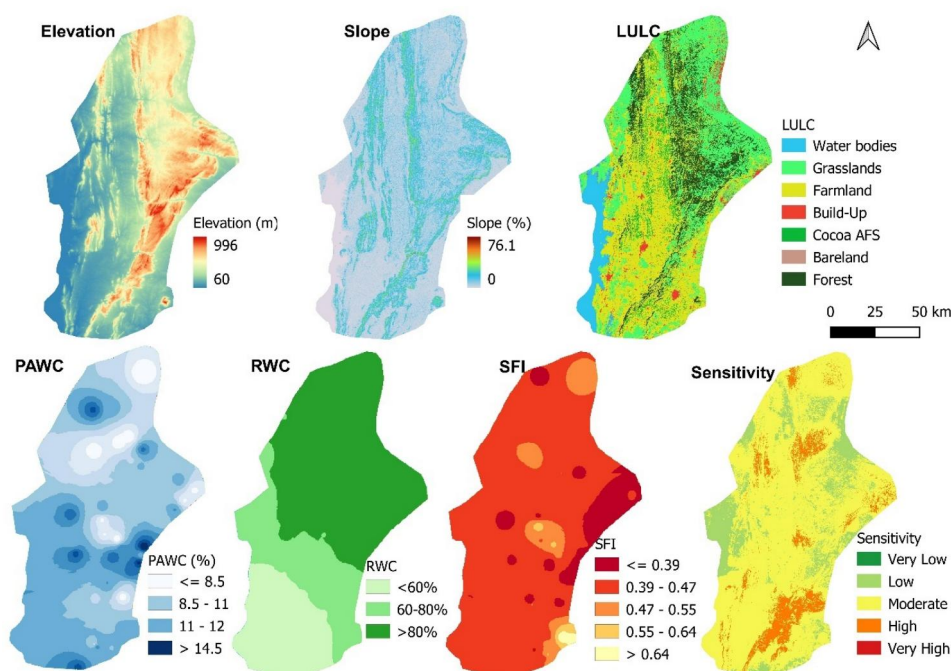
The spatial extents of drought exposure in the study area are illustrated in Figure 4. The drought severity, duration, the characteristics that are positively correlated to drought vulnerability, were mainly high in the southwest part of Ghana and the northern area of Togo. Overall, the mean drought duration in the area is less than three (3) months, revealing the area suffers from short-term drought rather than long-term drought. However, a low drought interarrival ( $<3$  months) is observed in a high proportion (more than 50% of the area coverage) and mainly in the southwest of the study area. This result revealed that the area suffers from frequent droughts that may affect cocoa growth and impede the system from recovering from subsequent drought effect. The longest interarrival drought observed is 9.5 months, which means that droughts occur every ten (10) months or once a year in a particular location considering our observed period. This is critical for perennial crops like cocoa, which can record such events in their memories and affect the plant physiology and productivity. The drought hazard is more pronounced in the northern and



**Figure 4.** Drought exposure maps (severity, duration, interarrival, drought hazard, cocoa distribution, and resultant exposure respectively)

**Table 4.** Cocoa drought vulnerability statistics

Classes	Exposure		Sensitivity		Adaptive Capacity		CDVA	
	Area (ha)	Area (%)	Area (ha)	Area(%)	Area (ha)	Area (%)	Area (ha)	Area (%)
Very Low	69590	9.55	0	0.0	39792.1	5.46	36940	5.07
Low	375100	51.47	614.6	0.1	423453	58.11	153600	21.1
Moderate	228600	31.37	624500	85.7	228352	31.34	347300	47.71
High	55340	7.59	103500	14.2	37107	5.09	166800	22.92
Very High	124.6	0.02	0	0.0	0	0	23250	3.2

**Figure 5.** Drought sensitivity maps (Elevation, Slope, LULC, PAWC, RWC, CSFI, and integrated map of sensitivity respectively)

southwestern of the study area. The integrated Exposure map is divided into five (5) classes very low, low, moderate, high, and very high with a percentage of 9.55%, 51.48%, 31.37%, 7.59%, and 0.02% respectively, Table 4. Overall, the largest portion of the cocoa growing exposure to drought is low (51%), while about 40% is significantly exposed to drought.

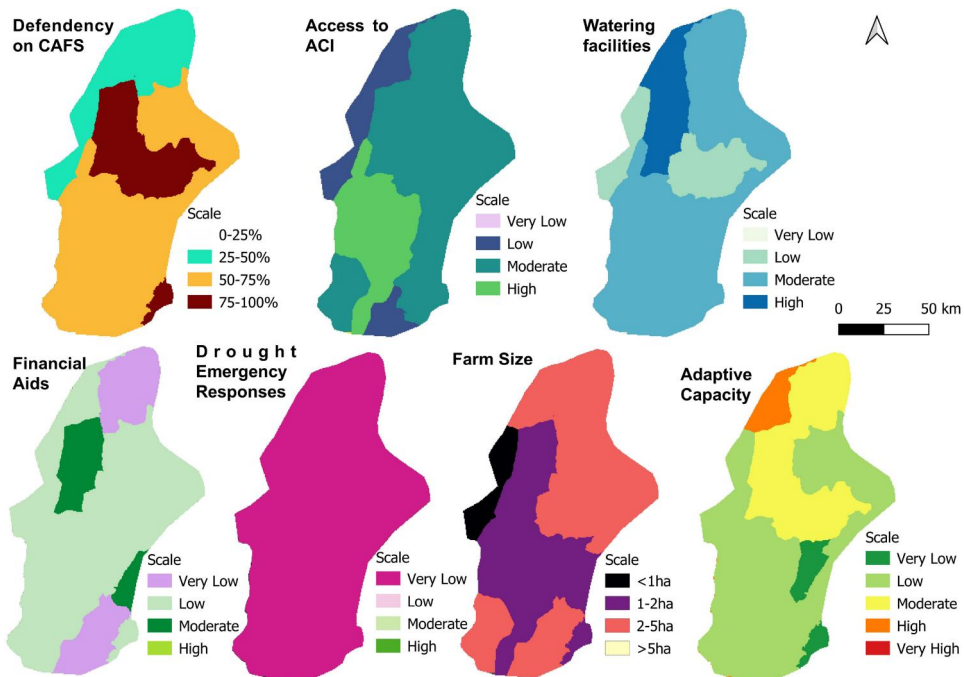
### 3.2. Spatial characteristics of CAFS drought sensitivity

Overall, six (6) criteria contributed to assessing the drought sensitivity, and the results are summarized in Figure 5. The Elevation and the Slope are quite low in the majority of the study area. However, high elevations (900 m and above) and steep slopes (around 70%) are also present in some small areas. These areas were mainly found in the mountainous part and in Togo in particular. The LULC is dominated by

farmland, forest land, and cocoa cultivation. The PAWC of the area, assessed from 30 cm soil depth, is generally low; only some sporadic areas have high water holding capacity, a situation which is critical for cocoa production. The Cocoa Soil Fertility Index across the study area is very low (0.31) and only a very small portion is above 70% (0.72) considering a scale of 0–1, which was located on the Togo side. Such information needs to be taken into account considering ongoing land degradation and unsustainable practices that are impoverishing the soils. About 85.7% (624,500 ha) of the study area is moderately sensible to drought events and constitutes the dominating compared to the other four categories of sensitivity classes (Figure 5). These areas are dispersed across the study area. In contrast, areas that are highly sensitive to drought are located in the southern and some clusters of the northern paths. Overall, the study area is denoted as sensitive to drought.

### 3.3. Spatial characteristics of CAFS' adaptive capacity to drought

The spatial distribution of cocoa farmers' adaptive capacity to drought in the study area is shown in Figure 6. No area has been classified under the "very high" adaptation capacity class. High adaptive capacities of cocoa farmers to droughts were denoted for only one northern district (Nkwanta). Moderate adaptive capacity is denoted for cocoa farmers living in the Krachi district (Ghana region), and Wawa district (Togo region). Nine (9) districts out of the 15 had low adaptive capacity two (2) districts (Danyes and Agou in Togo regions) had a very low adaptive capacity.



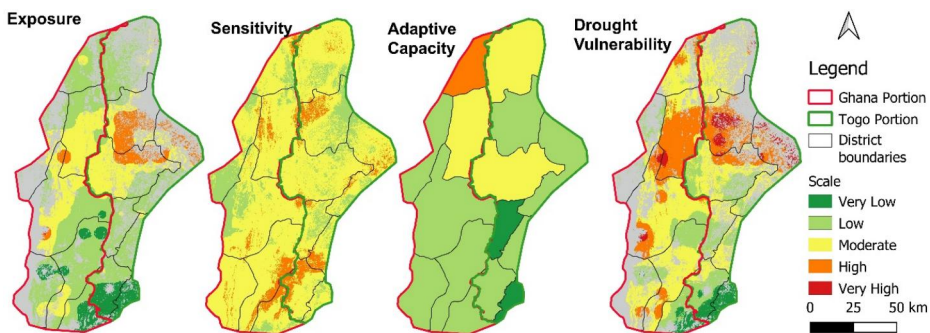
**Figure 6.** Adaptive capacity maps to drought (dependency on CAFS, access to agroclimatic information, watering facilities, financial aids, farm size, drought emergency responses, and integrated map of adaptive capacity to drought).

These results do not favour the potential impact of the drought that is being experienced by the cocoa region as highlighted above. The results showed that northern districts have a low dependency (<50% of household incomes) on cocoa activities incomes compared to the remaining area, mainly because of dryer conditions, they have diverse income sources to cover financial gaps. The remaining proportion relies significantly on cocoa farming as their principal activity (50–75%) for their income. The investigation on the availability and access of cocoa farmers to agroclimatic information showed that 80% of the farmers have low access; however, such information are assumed to offer knowledge and guidance for farmer decisions in adopting drought smart adaptation strategies. The watering facilities were low in the study area and this condition is not favourable for sustainable irrigation planning for cocoa. Moderate financial aid was only denoted 20% of the study area coverage, revealing non-adequate. The cocoa farm size usually for the cocoa farmers is equally divided between low (1–2 ha) and moderate classes (2–5 ha).

### 3.4. Cocoa drought vulnerability status

While individual maps depicting components of drought vulnerability can provide insights, consolidating them into an index, namely the Cocoa Drought Vulnerability Index (CDVI) may yield more comprehensive information. The CDVI obtained is categorized into five classes, and expressed in proportion [Table 4](#). The majority of assessed areas fall within the moderate to very high vulnerability range, encompassing over 70% of the cocoa cultivation area, with 23% classified as highly vulnerable. This outcome underscores the urgency of implementing drought mitigation and adaptation measures for sustainable cocoa production in the study area. The spatial distribution of the CDVI is depicted in [Figure 7](#).

In detail, the findings revealed that only 3.2% of the territory exhibits very high vulnerability, with 23% being highly vulnerable to drought. Moreover, 48% have a moderate vulnerability, while 21% show low vulnerability, and 5% display very low vulnerability. Regions with high to very high vulnerability to drought are predominantly situated in the southern parts and some portions of the southern parts, notably in the Danyes, Krachi, and Hohoe districts. These areas exhibit characteristics such as extremely high exposure, sensitivity, and low adaptive capacity, implying potential



**Figure 7.** Spatial distribution of the drought vulnerability of CAFS (components and integrated drought vulnerability maps).

damages from drought occurrences. Factors contributing to their vulnerability include high variability and low annual rainfall, the absence of irrigation and financial facilities, low soil PAWC, and limited coping capacity during and after drought events. Moderately vulnerable areas constitute the largest proportion of the area coverage. Low and very low vulnerability areas are concentrated in the southwestern and northern parts, primarily falling where cocoa production is missing (over the Volta Lake) and in the northern region where cocoa growth is unavailable.

## 4. Discussion

There is scientific evidence that drought intensity in Sub-Saharan Africa significantly increased over the past four decades (1981–2020), affecting crop production, especially cocoa crop and its dependent communities (Ajayi and Ilori 2020; Läderach et al. 2013). Several studies predicted that such events will be more severe and frequent in the future climate change scenario (Ahmadalipour et al. 2019; Diasso and Abiodun 2018). Therefore, an integrated vulnerability map was key to envisaging which areas are affected the most by drought occurrences.

### 4.1. Drivers of cocoa drought vulnerability: implications for adaptation strategies

The drought vulnerability analysis revealed that, indeed cocoa cultivation area considered in the present study is subjected to drought. However, the intensity varies spatially. Roughly, the low vulnerable areas coincide with mountainous areas covered by some patches of forest land. In these areas, rainfall is more abundant and ranges from 1600 to 1800 mm  $y^{-1}$ . This abundance of rainfall when unevenly distributed across seasons might rather become a favourable factor for cocoa disease (black pod disease) (Cilas and Bastide 2020; Lass and Wood 1985). Moreover, mountainous areas are generally unfavourable for cocoa farming due to rugged landscapes and steep slopes which become harsh for cocoa trees when experiencing drought, especially during the establishment phase. The moderate vulnerability cut across the study area. In these areas, rainfall amount is still tolerable, however, its distribution across the area is problematic. Another factor contributing to the vulnerability of CAFS to drought in the study area is the low fertility of the soil, compounded by the socio-economic characteristics of cocoa farmers. This issue was underscored in some studies indicating that soil fertility in cocoa farming lands is generally low, not only in Ghana but also across West Africa (Kongor et al. 2019; Quaye et al. 2021). Furthermore, limited water availability, limited access to climate information and services, small farm sizes, and a high dependency of farmers on cocoa cultivation exacerbate the situation. Therefore, addressing socio-economic factors is crucial in mitigating drought vulnerability in these agricultural systems.

The results, overall, showed that a great proportion of the cocoa farmland (72%) is vulnerable to drought in the study area. This outcome is supported by some studies that have been carried out in the framework of climate change and have concluded that drought events will become more frequent in the context of global climate change (Ajayi and Ilori 2020; Dai 2011). Consequently, drought disasters will be a

continual challenge for ecology in the future, especially for cocoa production; if adequate strategies are not put in place. Some authors have specifically researched the putative impacts of climate change in West Africa and concluded that negative impacts on cocoa production may be related to the dry season precipitation (Schroth et al. 2016) and temperatures (Anim-Kwapong and Frimpong 2008), or growing season evapotranspiration (Läderach et al. 2013). The extent of suitable areas for cocoa production and yields were found to reduce as a result of projected future conditions in these studies (Attiogbé et al. 2022; Gateau-Rey et al. 2018). Drying out could lead to a significant decline in the West African regions suitable for cocoa farming (65% of world production), instead of a 2 °C rise in temperature by 2050, which seems less harmful to the cocoa tree (Schroth et al. 2016). Drying climate would therefore arise from an increase in evapotranspiration brought by a rise in temperature that is not counterbalanced by a minor decrease in annual rainfall. The amount of land suitable for cocoa production would decrease as a result of this drying out because it will be difficult to create new fields since young plants die frequently, and suitable land becomes scarce. Abdulai (2017), highlights that cocoa production is suffering from drought, especially in the dry region which constitutes the northern portion of our study area. The far northern portion of our study area per our analysis, showed low vulnerability because it is losing its potentiality for cocoa growth. Bunn et al. (2019) found that climate change could reduce the available area for cocoa production in the north due to a shift of the northern transition to the Savanna zone, a land cover type that does not favour cocoa production. Even though Jagoret et al. (2012) have demonstrated in Cameroon that degraded savannah land can be restored by cocoa agro-forest, it is a time-consuming process and may compromise food availability and the well-being of cocoa-dependent livelihoods. Therefore, knowing how to effectively minimize or reduce the yield losses caused by drought is particularly important.

#### ***4.2. Interlinkages between drought exposure, adaptive capacity, and vulnerability for better resilience***

The agricultural drought vulnerability highlighted through the CAFS in this study is the combined result of drought exposure, sensitivity, and adaptive capacity. Mitigating the cocoa drought vulnerability should take into account the mitigation of drought exposure and the increase in the resilience of communities through the strengthening of sensitivity and adaptive capacity indicators.

From the exposure perspective, the resulting exposure is mainly caused by variations in climatic conditions changes in the length of the dry seasons, and the frequency of drought. To improve our ability to detect and monitor drought, efforts need to be made to understand the drivers of regional drought and the long-term variability of drought features of the climate system.

Overall, the sensitivity analysis revealed that both Ghana and Togo sides are sensitive to drought for cocoa production; however, the southwest portion located on Ghana's side has low sensitivity to drought. This is basically due to the great portion covered by Volta Lake, low altitude, and weak slope.

From an adaptive capacity perspective, the current limited human and infrastructural capacity undermines farmers' capabilities to react to the direct and indirect influences of drought and adequate strategies need to be put in place to recover from drought consequences. Some scholars confirmed that it is becoming increasingly difficult for farmers to bounce back from ever-changing, incompatible weather affecting their livelihoods, and many have been forced to adopt other sources of livelihoods and coping mechanisms that only extend the period of vulnerability (Aggarwal et al. 2018; Campbell et al. 2014). This challenge is expected to increase since more than 50% of the study area is experiencing frequent drought and might not have sufficient resources to recover. Agricultural insurance has been recognised as one of the important adaptation measures for farmers to insure crops in case of unexpected crop failure and to increase their resilience (Agbenyo et al. 2022; Panda 2017). However, its adoption by farmers is still low and more needs to be done to improve farmer awareness and knowledge of the insurance scheme (Ali et al., 2020; Owusu et al. 2022). In our area of investigation, no adequate financial aid were available and we have argued that financial schemes designed for agricultural fields have to be explored, tested, and introduced to support farmers for sustainable investments. Recent studies that aimed to promote smart agriculture to limit climate change and related risks impact promoted agroforestry systems (AFSs) as a way to buffer those impacts and reduce deforestation (Luedeling et al. 2014; Schneider et al. 2017), even if an AFSs cannot be an absolute response (Abdulai et al. 2018; Blaser-Hart et al. 2021; Ruf et al. 2015). The role of agroforestry systems in carbon sequestration could be recognised and farmers would receive extra income from carbon payment schemes (Mohammed et al. 2016; Nijmeijer et al. 2019). Drought impacts pollination and pollinators (Toledo-Hernández et al. 2017), and it would be useful to understand all the production components affected, from flowering to mature pods. Diversity of income can help in mitigating drought (Wessel and Quist-Wessel 2015). Only farmers with an off-farm income could improve their farm management system; however, this does not reflect the reality, because it is observed that farmers with the ability to do so, preferred to use the money and resources to enlarge their cocoa farms. Rehabilitation practices and replanting cocoa trees are also widely recommended (Djuideu et al. 2021; Somarriba et al. 2021).

#### **4.3. Limitation and future research**

The complexity and variety of drought severity across several CAFS constitute the limitations of our study. The mapping process may not completely capture the localised microclimatic changes, soil types, and particular management techniques that impact drought resilience at a farmer level. Furthermore, short-term variations or severe drought occurrences may not be sufficiently reflected by the temporal resolution (1981–2020) used in the study, which could cause vulnerability assessments to be oversimplified. The study's conclusions may not apply to other crops and areas since the study focuses on specific characteristics of cocoa agroforestry and cocoa farmers. Moreover, the criteria choice is based on the availability of data in the study area. Thus, research can be designed to capture these issues; for instance, how specific agroforestry architectures with different management practices within cocoa systems

influence drought resilience at a more granular level. This could involve integrating high-resolution remote sensing data, localised climate projections, and detailed soil moisture monitoring to better capture microclimatic and seasonal variations. Additional research must be conducted on the impact of recurring droughts on cocoa yield, quality, and ecosystem services.

## 5. Conclusion

Climate change is increasing the frequency, intensity, extent, and duration of droughts worldwide. To put in place drought smart strategies, vulnerability assessment is one of the first steps among early warning, monitoring systems, and other drought risk mitigation measures. To bridge the gap of earlier studies that focused on limited vulnerability components, either climate indicators or performed without taking into account adaptation capacity or biophysical components, this study proposes a holistic agricultural drought assessment technique, consisting of 16 criteria under the three (3) vulnerability components, Exposure, Sensitivity, and Adaptive Capacity. The cocoa drought vulnerability was obtained with an integrated climate, biophysical as well as socio-economic characteristics of the study area. Overall, a significant portion of the study area (72%) is vulnerable to drought for cocoa production and this is attributable to the higher exposure, and sensitivity coupled with relatively lower adaptive capacity. Moreover, this study provided detailed information on each vulnerability component. For instance, the exposure revealed how drought varies across the study area; the same for the sensitivity variables. Drought adaptation capacity assessment revealed a high dependency of farmers on cocoa farming coupled with a low diversity of incomes, a limited access to climate services, and irrigation facilities. However, it should be noted that vulnerability assessment of climate-related risks is complex and dynamic, thus, it is crucial to consider these dynamics within a community with respect to the time and location of the community. Adaptive strategies play a great advertising role in the drought potential impact (drought exposure and sensitivity), therefore investigating in factors that could enhance or encourage cocoa farmers to invest in drought adaptive and mitigation strategies would help in fighting against drought in the era of climate change. Our study highlights the importance of spatial vulnerability assessment; which will increase farmers' knowledge of their vulnerability categories and incite them to adopt strategies or not to bounce back from drought events. Policy developers could dig into this outcome to plan for successful investments in the cocoa sector.

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No potential conflict of interest was reported by the author(s).

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## Data availability statement

The datasets used in this study can be found at (<http://chg.geog.ucsb.edu/data/chirps>); (<https://cds.climate.copernicus.eu/cdsapp#!/search?type=dataset&text=era5-land>), ERA5land and (<https://earthexplorer.usgs.gov/>). However, further inquiries on the station data and socio-economic data of cocoa farmers surveyed in the study area can be directed to the corresponding author.

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