Vegetation Dynamics and Climate Change

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Climate extremes and their impacts on vegetation dynamics have been of great concern to the ecosystem and environmental conservation and the policy-decision makers. Of great concern now is that climate change impacts on vegetation dynamics have influenced the global terrestrial ecosystem adversely, thus making ecosystems vulnerability one of the current issues in ecological studies. For instance, the negative consequences attributed to natural hazards associated with climate extremes have been estimated to be billions of dollars across the globe. Accordingly, vegetation dynamics are influenced by several factors including climate change, environmental and climatic components among others. These can expend considerable impact on the water balance by evapotranspiration, interception and development strategy which has the potential to lead to vegetation degradation in a wide variety of ecosystems and biodiversity.

Vegetation Dynamics
Climate Change
Information-Based Model
Risk assessment
Vegetation distribution

1. Global Vegetation Response to Climate Change Impacts

Global vegetation response in the terrestrial ecosystem is considerably impacted by incoming climate variability and change [1][2]. Owing to the spatial variance of ecosystems, the responses of vegetation dynamics to climate change vary significantly with the different spatial patterns and sensitivity effects to global climate change [3][4]. This presents a feedback mechanism in vegetation-climate interactive effects. Of great concern now, is that climate change can significantly impede vegetation activities [5]. Studies showed that El Niño–Southern Oscillation (ENSO) influences the dynamics of vegetation in Africa [6][7], while certain regions tend to experience significant vegetation enhancement or suppression which depends on the ENSO phase [8][9][10]. An individual ENSO event can cause a variety of changes in vegetation intensity [11]. The magnitude and timing of the response of vegetation intensity to climate forcing may vary between different vegetation types and classification which depend on high spatial coverage and long-time series [7][12] to counter the reliance on ENSO episodes. Conversely, the interaction between the changes in air temperature and precipitation may influence the distribution of plants and vegetation vigour, thus temperature changes can impede the length of the growing season. Studies have reported that a warming climate may significantly enhance the process of respiration in vegetation, evapotranspiration, and increase the deficit of soil moisture which can influence vegetation growth [13][14]. Climate change impacts on natural and human activities may determine the immediate cause of the observed pattern in vegetation growth as a result of the interaction between climate change and the responses of vegetation dynamics [15][16][17]. Studies show that increasing global temperatures have a significant impact on the responses of vegetation, rising sea levels, and the environment [17][18]. Accordingly, air temperature exerts the highest influence on changes in the inter-annual variability of vegetation vigour after solar radiation and sunlight and precipitation change [19]. Conversely, in the Southern Hemisphere, the decline in precipitation is likely to have contributed to the drying trends and the resultant observed vegetation activity in the semi-arid regions such as southern-coastal Chile, southern Africa and south-eastern Australia [20][21]. Consequently, affecting certain structural characteristics of the world vegetation types and their associated functions in the earth-atmospheric system functioning, which are determined by the vegetation sensitivity response effect, productivity and distribution of plant species [1][13][22]. In general, global vegetation coverage has been noted to have undergone significant transformation, affecting species dynamics and grassland conditions [23][24]. The world's vegetation types including the native vegetation such as forests, grasslands and shrublands are adversely affected by land, topography and soil (land cover change, drainage and erosion potentials and decreased cohesion of residual plant) in response to environmental factors [25][26]. The understanding of these factors on vegetation dynamics and related effects affords the adoption of targeted effective mitigation measures to ensure biodiversity sustainability including vegetation conservation.

1.1. Climate-Related Vegetation Interactions

According to the literature, scientific models are more significant in analysing climate-vegetation interactions and permit simulation of biogeochemical mechanisms. For instance, vegetation and terrestrial ecosystem services thus permit increases for the potential carbon dioxide (CO_2) which may serve as the justification for predicting vegetation response to variability and change [27]. A study identified climate-related vegetation models such as the dynamic global vegetation model (DGVM) to be evident on crop yields, and to predict weather impacts and other important events on agriculture [28]. The processed-based model validates how climate change may alter crop yields and has shown to be a good indicator for agriculture, climate and the economy [29][30]. The experimental outcomes on the effect of climate change on terrestrial ecosystems and their functions on vegetation dynamics revealed a significant increase in rising air temperatures owing to a global warming climate [22][31]. Vegetation dynamics have been shown to have a fairly slow response to temperature and rainfall conditions; as the higher level of latent heat is found with a more vegetated area [32], while the sensible heat exchange was more prominent with a more sparsely vegetated region [33]. Nevertheless, oftentimes more than the immediate resultant effects of climate variability and change, the indirect aspects may upset the diversity of life and terrestrial ecosystem. Studies revealed the response lag as the period before the reaction to a perturbation is evident and occurs due to changes in vegetation and geomorphic temporal response [16][34]. Climate change-induced vegetation shifts may be related to climatic perturbation (i.e., the imposed perturbation on energy earth balance). Climate-vegetation interaction can be perturbed by human activities through deforestation, and natural extremes or surface disturbance [35][36]. Human-made forcings are the result of aerosols and gases from fossil fuel or anthropogenic activities, changes in land use, such as the transformation of the forest into agricultural land, loss of habitat, and other intense disturbances among others. Accordingly, the global land-use changes have transformed farmlands, grazing fields, human settlements, and urban area at the expense of natural vegetation with resultant land degradation, deforestation and loss of biodiversity [25][36]. The evaluation of vegetation dynamics and its increasing trends due to climatic and environmental conditions including rainfall, temperature, land, topography and soils play a key role in better understanding the vegetation stress and its related effects [37][38][39]. The natural response of land is the response of vegetation, soils and human-induced environmental changes, leading to the increasing atmospheric concentration (CO_2), nitrogen deposition, and climate change [40]. Changes in vegetation coverage and biomass may lead to an alteration in the earth-atmosphere processes and climate dynamics [22]. Studies show that temperatures were found to be the major limiting factor for vegetation growth at high latitudes in the Northern Hemisphere [41] and Western Europe [42], while in Central Asia, South America and Southern Africa [43][29], declining precipitation and rising temperatures were correlated with a decline in vegetation vigour. Ref. [44] reveal that vegetation vigour will continue to decline under temperature and rainfall conditions especially in the arid or semi-arid region. The interconnections between climatic conditions and terrestrial ecosystems offer some insight into the status of vegetation [45]. Vegetation dynamics have undergone extreme climate change events both in Asia and Europe with agricultural drought hazards, landslides, heat-wave, increased risk and intensity of wildfires, and flooding, among others, including in Africa [13][46]. Vegetation growth is highly unstable and susceptible to drastic changes such as climate change [47]. Therefore, understanding the responses of vegetation to climate change and the precision of different types is important to guide decision-making on climate change impacts especially in the area of vegetation and forest resource management. This is fundamental in adopting targeted adaptation and mitigation strategies to improve resilience to climate change effects, for example, drought occurrences especially on rangeland vegetation which experiences additional pressure from overgrazing. The grazing pressure on vegetation is often altered in rangelands particularly in dense grassland where much of the primary production is being removed compared to open arid vegetation [48][49].

1.2. Socio-Economic Scenarios of Climate Change on Vegetation Dynamics

Vegetation dynamics are strongly influenced by global climate change, including complete seasonal cycles in the estimation of climate change associated with shifts in vegetation [50]. Consequently, socio-economic challenges that many low-income communities in the world such as Liberia, Somalia, Zimbabwe and other African countries experience are from the extreme weather and climate events related to the changing climate, with the resultant adverse effects on the ecosystem and human well-being [51]. Extreme climate events such as torrential rain, drought, wildfires and heat-waves are reported to threaten forest ecosystems and sustainable livelihoods, resulting in limited food and water supply, and forces families from their homes and pushes people into poverty in the low-income countries [52][53]. Studies have shown that the Arctic, small islands, South East Asia, and Western Europe including Africa are considered regions most susceptible to climate change and variability [54]. This present resultant multiple environmental changes, geographical location and low adaptive capacity [55]. Recurrent extreme climatic events are worsened to bring about socioeconomic losses and limit the capacity of local communities and individual resilience to cope and adapt to these potential challenges that might be induced by future climate change [56]. Climate change will adversely affect the socio-economic sectors such as forest management, water resources, agriculture, and human settlements as well as ecological systems [57]. Consequently, this poses several climate threats and risks in areas across the globe in which both rural and urban livelihood is built, particularly in Africa [58]. Developing countries such as China, Brazil, India and Somalia, whose population is vulnerable to extreme climate events, are at risk of natural human disturbances causing both socio-economic and climatic impact on the environment [59][60][61]. Even in developed countries, the significance of vegetation response to the pattern of land use and intense human activities have gained attention with livelihood activities susceptible to incoming climate change and variability [62]). Studies have reported that most countries are affected by climate change; in the magnitude of extreme heat or cold events with some confidence level of increased socio-economic impacts on vegetation and terrestrial ecosystem as well as human settlement [63][61].

1.3. Terrestrial Vegetation Responses to Future Climate Change

The pattern of weather and climate has been altered by global climate change around the world, causing degradation or drought in some regions and floods in others [64]. The frequency and intensity of these events are projected to increase as a result of global climate change. Future climate change impacts on vegetation and ecosystem conservation, sustainable livelihood and rural economies of poor societies in developing nations, especially among the local rural smallholder farmers. Appropriate mitigation and adaptation strategies to improve climate resilience and recovery should be put in place to empower communities and institutions to adapt, innovate and thrive [52][65]. Uncertainties in terrestrial vegetation responses to future climate change and biotic features provide key insights into the precise mechanisms associated with different spatial and socio-economic impacts. The risk from these uncertainties of future climate change requires strategies to respond to climate issues based on local knowledge of coping with uncertainty and systems spanning a wide range of spatiotemporal scales of model projections [66]. Climate change is projected to adversely impact biodiversity, environment and human settlement with associated impacts on agriculture and natural resources to survive the effects of extreme climate events [67]. The development of programmes in developing nations will alleviate hunger and poverty where limited water resources and increasing competition and conflict over natural resources determine their existence [68].

2. Vegetation Biodiversity Vulnerability to Future Climate Change

Vegetation biodiversity is vulnerable to changing climate with complexity in the hierarchy and high influence in diversity [66][69]. Consequently, global warming has brought several detrimental effects on environmental components including vegetation and ecosystem, making their vulnerability one of the current research hotspots in ecological studies [22][69]. Vegetation biodiversity vulnerability may be considered as exposure to contingencies, stress, and challenges in coping with the resultant climatic conditions which are determined by its location, extent and its biodiversity, and the number of linkages within the food cycle [70][71]. The magnitude and nature of stressors are determined relative to vulnerability such that, the assessment is restrained by uncertainties in the drivers of change such as climatic, physical and environmental, and other forms of threats. A recent meta-analysis established that the negative impacts of vegetation loss and fragmentation have been unduly severe in regions with high temperatures in the warmest month and decreasing rainfall, and the impacts varied across vegetation types [72]. A better understanding of the multidimensional vegetation biodiversity vulnerability to rapid climate change and other threats is needed concerning the socio-economic consequences of biodiversity loss and ecosystem services [73]. The inadequate observations of multifaceted systems under rapidly changing climate; the socio-economic and environmental change are the cause of the deficiencies spurred by key changes in species adaptive capacity, the role of species range movement, vegetation dynamics, and its response to climate change and variability [74][75]. Vegetation community to ecosystem vulnerability and landscape dynamics and their interaction with the changing climate and other threats cannot be overemphasised; therefore, these vulnerabilities are multifaceted and across a wide range of spatial and temporal scales. VRCC impacts on vegetation biodiversity vulnerability are amplified by the limited capacity to shift into suitable climates due to the near-relationship to certain ecological formations and the fragmentation of the landscape by agriculture and other land uses [26][76]. This is projected to significantly impact societal well-being if degradation of biodiversity results in a decline in the quantity and resilience of ecosystem service provision. Understanding how biodiversity is linked to vegetation is crucial for designing more sustainable environmental policy formulation and landscape planning. The significance of regressions in biodiversity and the consequences for vegetation and ecosystem services are increasingly projected for future climate scenarios. For instance, the over-exploitation of land use for agriculture and other purposes has led to drastic declines in vegetation biodiversity through rapid urbanisation, wildfire, high population growth and infrastructure development associated with changing patterns of land use [57]. The effects of declining vegetation with biodiversity and ecosystem degradation will be exacerbated by climate change, with consequences especially for human well-being and societies in the absence of effective management and planning outcomes. The complexity within these levels includes composition among elements, structure, and their functions of genetic through eco-regional diversity which contributes to the preservation of species diversity [77][78]. The key aspects of the vulnerability of biodiversity to climate change are considered from the ecology of species and their genetics through community and ecosystem dynamics and the states of species and their landscapes [79][80]. The corresponding challenges in integrating vegetation biodiversity vulnerability to changing climatic conditions in natural resource management and planning are inherently both important and challenging.

Spatial Assessment of Local Climate

Globally, studies on vegetation-climate responses and environmental impact postulate that extreme climatic events pose a severe risk in ecosystem services. This is a serious emerging concern across the globe, for example, in the USA [29], Australia [81], Europe [42], Asia [43] and Southern Africa [82], among others. The alteration of the natural environment in urban regions has made the surface temperatures and local air rise a few degrees higher than that of surrounding urban areas [83]. Local microclimate and meteorological variables such as rainfall, wind speed and surface temperature, among others, are often influenced by biophysical and chemical properties of soil ecology, anthropogenic activities and climatic condition in a relatively small area within vegetation canopies present in the environment [84][85]. The difference between the absorptive and reflective abilities of a surface to interact with incoming solar irradiance and associated heterogeneity of their physical characteristics often leads to the modification of climatic variables which may influence the drivers of vegetation coverage in urban settlement [86][87]. The relationship between edaphic factors and local micro-climatic patterns has led to the development of various climatological, geophysical, hydrological indices which have been studied in climate-vegetation interactive effects [88][89].

3. Linkage between Long-Term Vegetation Dynamics and Climate Change

Studies about the linkage between climate change and vegetation dynamics provide a lot of powerful scientific information [90][91]. Studies have shown a significant relationship between the terrestrial ecosystem and climatic variation [6][92][93]. Accordingly, studies characterise three key indicators in vegetation response to climatic variation. The first indicator is the sensitivity effect which refers to the condition of susceptibility for measuring inter-annual climatic disturbances or the degree to which vegetation is responsive to incoming climate variability and change, for example, inter-annual variability in weather and climate [19][94]. The second indicator is the sensitivity effect on vegetation productivity, which is the magnitude, long-term and seasonal variability along gradients of aridity varying from semi-arid to sub-humid conditions [6][94]. This is done to detect and spatially delineate anomalies in vegetation condition, growth and development, in both length and intensity, for example, climate interaction with vegetation structure, biogeochemical cycles and energy fluxes [95][48][96]. The third indicator is the distribution as well as their response to climate change based on the spatial distribution and cover change, associated with terrain characteristics of vegetation types, human activity and changing climate [70][97]. Consequently, spatiotemporal vegetation monitoring and assessment of its dynamics at large scales are vital to design appropriate measures needed to address the multiple threats at different time scales [6][98].

The novel climate approach used for climate change projections could simulate the observed climate at spatiotemporal scales to provide novel space-based solutions in earth observations and to detect and monitor vegetation trends, sensitivity effect, productivity as well as distribution. The ecosystem’s biodiversity is complex in the hierarchy with high influence in diversity including agricultural drought hazard, flood, torrential rainfall and environmental factors [66]. The physical, socio-economic, and infrastructural project are the testaments of the impact of climate change on livelihood and other environment-related effects on vegetation vigour [99]. Climate change variations have been considered to pose major threats to the terrestrial ecosystem and sustainable human settlement [100]. The spatial observation of regional climate on vegetation and plant phenology such as the increasing temperature trend on vegetation dynamics and the emergence of environmental threats to ecosystem functioning has revealed a positive correlation [101]. Global climate change has been reported to reveal the drying and warming trend and thus, will continue to experience unprecedented increased warming climate as a consequence of natural and other human disturbances [102]. The understanding of the long- and short-term natural fluctuations in climate is crucial in tracking the effect of human-induced climate change occurring from year to year and decade to decade on ecosystem dynamics. The natural climate fluctuations in different climates have a direct impact on drivers of ecosystem change such as drought, floods, wildfires and alien invasion, as well as the timing of vegetation greening [103][104]. Studies have revealed that the large-scale inter-annual fluctuations in weather and climate are caused by the changes in the pattern of oceanic circulation and atmospheric pressure in response to global warming [8][9][105]. The responses of vegetation to short-term variation have far prominent impacts in the short interval because of its short-term climate change (e.g., El Niño occurs in cycles and lasts from days to a year), and its causes are of greater significance to human activities compared to the long-term changes in rainfall and temperature trend [63]. A recent study used precipitation and temperature to assess the impact of climate factors on vegetation dynamics over East Africa from 1982 to 2015 [9]. Their results point out that anomalies of NDVI correlate differently with precipitation and temperature during the long and short rainy seasons, which indicates that, the moisture source in each of the seasons influences vegetation dynamics over East Africa. The effect of ENSO on NDVI series is predominant when vegetation is considered in seasons before actual months, suggesting a time lag between them. In general, there is a need to characterise the linkage between long-term temporal vegetation variability and climate change impacts on terrestrial ecosystems. This is because a deeper understanding is needed on key issues of vegetation dynamics to improve our comprehension of vegetation responses to climate change.

The information in **Table 1** reveals the techniques used in global vegetation–climate response analysis to highlight the types of indices, algorithms, remote sensing imagery used as well as their findings or gaps filled. The gaps filled in the various studies highlighted their findings with different vegetation indices such as Normalized Difference Vegetation Index (NDVI), Vegetation Condition Index (VCI), Enhanced Vegetation Condition Index (EVI), Vegetation Health Index (VHI) and Leaf Area Index (LAI) among others in contributing to the understanding of vegetation dynamics and their response to climate change. Therefore, these indices are broad spatiotemporal vegetation monitoring and drought indicators and a step toward monitoring global climate change. A recent study has shown that the monthly NDVI, VHI and VCI trends were most considered suitable indices and showed a good signal in the assessment of spatiotemporal changes in vegetation dynamics and drought over South Asia [106]. Nevertheless, their results varied based on topography and climatic condition for different vegetation types and distribution. More so, most studies showed that there exists a positive correlation between the response of vegetation and different climatic parameters such as precipitation and temperature [13][82]; however, some showed a negative correlation [106][107]. The newest GIMMS NDVI3g dataset from AVHRR showed a good surrogate measure in the length of the growing season of the physiologically functioning surface greenness level of a region [108][93][109][110].

Table 1. Techniques used in global vegetation-climate response analysis.

S/N	Vegetation Indices	Algorithms	Remote Sensing (RS) Imagery	Findings/Gaps	References
1.	Normalized Difference Vegetation Index NDVI3g derived from (GIMMS)	$NDVI = (\lambda NIR - \lambda RED)(\lambda NIR + \lambda RED)$	Advanced Very High-Resolution Radiometer NOAA (AVHRR)	Findings show that NDVI significantly increased in most seasons at the regional scale. AVHRR NDVI3g show good quality and the correlation between growing season NVDI and low precipitation was	[111]

S/N	Vegetation Indices	Algorithms	Remote Sensing (RS) Imagery	Findings/Gaps	References
				significantly positive.	
2.	Enhanced Vegetation Index (EVI)	$EVI = G \ast$ $\rho NIR - \rho Red\rho NIR + C1 \ast \rho Red - C2 \ast \rho Blue + L$	Moderate Resolution Imaging Spectrometer (MODIS)	The model performance improved using lags of up to one year and found that a one-month lag provided the best explanatory power for vegetation responses to variability on different timescales.	[1]
3.	Leaf Water Content Index (LWCI)	$LWCI = G x$ $-\log[1 - (NIR - SWR)]-\log[1 - NIR - SWIR]$	Landsat TM	Findings reveal that the model could apply not only to the forest area but also to the agricultural area indicating that the time lag comparison between LWCI and NDVI was significantly observed about a month in the tropical forest while it was barely observed in the temperate deciduous forest.	[112]
4.	Leaf Area Index (LAI)	$\bar{LAI}_{(\tau)} = 1\tau \sum \tau tLAI(\tau)$	Moderate Resolution Imaging	The model shows that the vegetation status is	[113]

S/N	Vegetation Indices	Algorithms	Remote Sensing (RS) Imagery	Findings/Gaps	References
			Spectrometer (MODIS)	positively sustainable and there limited accuracy of LAI for sparsely vegetated arid areas which indicates that the findings require support from detailed fieldwork at a local scale.	
5.	Fraction of Photosynthetically Active Radiation (fAPAR)	FPAR = [PARci − PARcr − (PARgi − PARgr)]PARci	Moderate Resolution Imaging Spectrometer (MODIS)	The model showed higher assessment accuracy up to 16% when compared with FPAR assessment models based on a single vegetation index. Findings show that vegetation productivity is significantly affected by environmental factors; hence, the effect of FPAR cannot be neglected in the satellite-derived FPAR algorithms.	[114]
6.	Vegetation Condition Index (VCI)	VCI_{ijk} = VIijk − VIi,min VIi,max − VIi,min ∗ 100	Moderate Resolution Imaging	Findings show that the VCI widely distributed	[115]

S/N	Vegetation Indices	Algorithms	Remote Sensing (RS) Imagery	Findings/Gaps	References
			Spectrometer (MODIS)	vegetation stress for a long period and enhanced the trend of vegetation activity. Hence, the VCI should be cautiously used in the context of climate warming but may vary with different topography and climatic condition for different vegetation distributions.	
7.	Temperature Condition Index (TCI)	$TCI = 100 \ast (NDVI - NDVImin)(NDVImax - NDVImin)$	Advanced Very High-Resolution Radiometer (AVHRR) sensor of the NOAA satellite	Findings show that the model has the advantage of being independent of the surface type and is available for all regions where a sparse weather-observing network exists. TCI should be jointly used with VCI to reflect the meteorological conditions and drought monitoring.	[116]

S/N	Vegetation Indices	Algorithms	Remote Sensing (RS) Imagery	Findings/Gaps	References
8.	Vegetation Health Index (VHI)	VHI = αVCI + TCI (1 − α) TCI	Advanced Very High-Resolution Radiometer (AVHRR) sensor of the NOAA satellite	Findings show that the northern ecosystems are characterised by positive correlations, indicating that increasing temperature favourably influence vegetation activity. Hence, the VHI should be undertaken with caution, especially in high-latitude regions where vegetation growth is primarily limited by lower temperatures which are opposite to the low-latitudes, mainly in arid, semi-arid and sub-humid climatic regions.	[117]
9.	Soil-adjusted Vegetation Index (SAVI)	SAVI = (NIR − RED)](NIR + RED + L) ∗ (1 + L)	Satellite Pour l'Observation de la Terre (SPOT-6 and SPOT-7) satellite	The model was found to be an important step toward the development of global models that can describe dynamic soil-vegetation	[118]

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	Climate Events						Climate Variables)
1.	Agricultural drought hazard and drastic decline of vegetation	Asia	China	1982–2012 (30 years)	[43]	SPEI from AVHRR, seasonal NDVI and	Meteorological air temperature, precipitation, and evaporation

S/N	Vegetation Indices	Algorithms	Remote Sensing (RS) Imagery	Findings/Gaps	References
			[92]	systems from remotely sensed data using the most sensitive L-factor value for SAVI. Findings indicate that the SAVI is suitable for distinguishing between the vegetation and non-vegetation areas of mangrove forest.	

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3.	Flood damage to croplands and grassland	Europe	Germany and France	2002–2007 (5 years)	[42]	direct and indirect flood losses and the State of Saxony in Germany	review of flood loss estimation, water depth, inundation duration for cropland, magnitude and flow velocities
4.	Flooding and Agricultural drought	North America	USA	(1985–2005) (20 years)	[29]	Vegetation Condition Index (VCI), Temperature Condition Index (TCI) and NDVI from NOAA AVHRR dataset, Global Vegetation Index (GVI) from global area coverage (GAC) data, and Climate data	Soil moisture, snow cover, precipitation, solar radiation, and air temperature
5.	Drought and floods	Asia	China	1880–1998	[59]	The long-term observational study, National Natural Foundation of	Drought index, inter-decadal changes, surface temperature anomalies, and precipitation based

S/N	Forms of Extreme Climate Events	Continent	Country	Duration	Author	Data Source (Models and Climate Variables)	Data
						China, dust storm from Beijing Weather Station, and Climate data	on a documented record
6.	Floods, agricultural damage, uprooted vegetation, and landslide/earthquake	Western Asia	Yemen	1973–2008 (35 years)	[46]	Global Facility for Disaster Risk Reduction (GFDRR), Wadi Flood protection system and Emergency Events Database	Desk reviews of the data including triangulation and field visits and surveys in the affected areas
7.	Floods, drought, and landslides	South Asia	Colombo, Sri Lanka	2004–2017 (13 years)	[119]	Sri Lanka and Civic Force, Disaster Management Centre, and Ministry of Foreign Affairs of Japan	Questionnaire survey involving quantitative and qualitative questions
8.	Agricultural drought hazard	Africa	South Africa	2015–2017 (2 years)	[82]	Department of Water and Sanitation, Department of Environmental Affairs, MOD13Q1 data from MODIS, Climate data and census data	Vegetation Condition Index (VCI), Standard Precipitation Evapotranspiration Index (SPEI), precipitation and temperature
9.	Torrential rainfall, heat waves, and agricultural drought	Arica	Gambia	2017–2018 (1-year)	[120]	Ministry of Finance and Economic Affairs and Gambian Disaster	A multi-modal cross-sectional survey comprising online/electronic survey software and a face-to-face interview

S/N	Forms of Extreme Climate Events	Continent	Country	Duration	Author	Data Source (Models and Climate Variables)	Data
						Management Agency	
10.	The drastic decline of vegetation and narrow grazing, and shortage of water resources	Africa	South Africa	2019	[121]	Multistage sampling procedure, snowball sampling approach statistical program	A cross-sectional household survey, Simple descriptive statistical tools

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