Characterisation of Vegetation Response to Climate Change: A Review

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Abstract: Climate change extreme events have consequential impacts that influence the responses of vegetation dynamics as well as ecosystem functioning and sustainable human well-being. Therefore, vegetation response to climate change (VRCC) needs to be explored to foster specific-organised management programmes towards ecological conservation and targeted restoration policy to various climate extreme threats. This review aimed to explore the existing literature to characterise VRCC and to identify solutions and techniques fundamental in designing strategies for targeted effective adaptation and mitigation to achieve sustainable planning outcomes. Accordingly, this review emphasised recent theoretical and practical research on the vegetation-climate responses and their related impacts in the wake of climate change and its debilitating impacts on vegetation. Consequently, this study proposes the Information-based model (IBM), needed to examine Factors–forms of Impacts–Solutions (Techniques)–Risks assessment to identify and provide insights about VRCC in a given region. In conclusion, two enablers of adaptive indicators and the novel systems-based serve as a key policy formulation for sustainability in strengthening the goals of global involvement of local and sub-national governments and institutions in the effective management of vegetation and ecosystem protection.

Keywords: climate change; Information-Based Model (IBM); risk assessment; sustainable planning outcomes; vegetation dynamics

1. Introduction

Climate extremes and their impacts on vegetation dynamics have been of great concern to the ecosystem and environmental conservation and the policy-decision makers [1,2]. 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 [3–5]. For instance, the negative consequences attributed to natural hazards associated with climate extremes have been estimated to be billions of dollars across the globe [6]. Accordingly, vegetation dynamics are influenced caused by several factors including climate change, environmental and climatic components among others [7]. These can expend considerable impact on the water balance by evapotranspiration, interception and development strategy [8] which has the potential to lead to vegetation degradation in a wide variety of ecosystems and biodiversity [9]. Understanding the interdependence between vegetation and climate change is needed to investigate the dynamics of vegetation which may offer an opportunity to characterise vegetation response to climate change (VRC) encompassing all the three key vegetation indicator responses. These include the sensitivity effect of vegetation response, the sensitivity effect on vegetation productivity and their distribution, given the prominence...
of climate variability and change [10,11]. The impacts of climate change on vegetation dynamics vary across various countries around the globe based on timing, region and climate zone [12]. In recent years, the global impact of climate change on natural vegetation has caused more than 60,000 fatalities and a loss of USD 1.2 trillion, amounting to 1.6% of the global Gross Domestic Product (GDP) [13]. Global climate change has given rise to shifts in the distribution of plant species, water dearth, reduced agricultural yields and the drastic decline of vegetation. This presents numerous threats from natural and human disturbances of various types in frequency and severity, leading to damage to food security, and sustainable living [14]. Owing to the growing concerns and awareness about vegetation dynamics and its response to climate changes in recent time, few studies have assessed and identified the linkage between changes in climatic parameters and vegetation variability with extreme climate events and other environment-related degradation on the terrestrial ecosystem [15,16].

Studies on vegetation dynamics have become one of the focal issues in global change [17,18]. Currently, most studies have focused on issues of vegetation response to specific climate parameters, e.g., temperature and precipitation [18,19], drought stress [20], time-lag effects and sensitivity [21,22], leaf phenology and net primary production (NPP) [23,24], growing trends [25], landscape dynamics [26], seasonal warming and atmospheric Carbon dioxide (CO$_2$) [27,28]. These studies noted that the impacts of other indicators such as relative humidity (RH), solar radiation, soil moisture, and wind speed among others are scantily quantified. This, therefore, has received little attention at multiple time scales, placing limited emphasis on a micro-scale, thus offering generalised results which created a need for a review on the characterisation of VRCC. There is a need to explore VRCC to foster specific-organised management programmes towards ecological conservation and targeted restoration policy to various climate extreme threats. Therefore, a detailed review of large-scale vegetation dynamics and their response to climate change on terrestrial ecosystems is needed. Environment-related degradation reported by a recent ecological study revealed that if a sustainable planning system is not implemented to address the resultant climate change impacts, communities, institutions and cities may continue to live under impending risk and unavoidable occurrences [29,30]. Consequently, the sought-for-broader focus on extreme climate events, and forms of impacts considering measures needed to address these risks over the years. The magnitude of impacts of climate change on vegetation dynamics in the face of degradation or drought events highlights corporate strategies in risk assessment and sustainable planning outcomes. The resilience and recovery phase of extreme climate-related impacts on vegetation dynamics banking on the enablers of adaptive indicators of impact assessment and adaptive management will stand the test of time [31,32]. Studies have shown that vegetation dynamics in the Global South are vulnerable to climate change and variability as established by the global climate-vegetation assessments [33,34]. Studies have reported that global climate change is changing and is projected to experience unprecedented increased warming both natural and other human disturbances [27,32].

Studies have shown that the impacts of climate change and extreme weather events on the sensitivity and rate of vegetation response to climatic variations operate over a scope of spatiotemporal scales [22,35]. Extreme events have far prominent impacts in the short interval compared to gradual changes in rainfall and temperature [36]. It is crucial to differentiate the changes attributed to climate change from other climatic factors. Remote sensing (RS) and Geographic information system (GIS) are recently widely used as innovative tools in vegetation mapping based on multi-time series analyses to enhance change detection and monitoring [37,38]. Investigating the in-depth details and linkage between the pattern of vegetation dynamics and its response to different factors is important. More so, evidence-based empirical research of the observed, experimental and remote sensing and GIS is yet lacking in the inputs of specific-organised management programmes [39,40]. Henceforth, the information-based model (IBM) is proposed to answer evolving questions from vegetation-climate responses and their related impacts. The significance of this re-
views lies in exploring the linkage between long-term vegetation dynamics and its response to climate change on terrestrial ecosystems. Therefore, this review aimed to explore the existing literature to identify solutions and techniques fundamental in designing strategies for targeted effective adaptation and mitigation to achieve sustainable planning outcomes. The outcomes of this study will help to improve resilience by providing strategic adaptation and associated policy formulation to mitigate the damage of natural and human-induced impacts on vegetation dynamics.

1.1. Global Vegetation Response to Climate Change Impacts

Global vegetation response in the terrestrial ecosystem is considerably impacted by incoming climate variability and change [22,41]. 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 [42,43]. This presents a feedback mechanism in vegetation-climate interactive effects. Of great concern now, is that climate change can significantly impede vegetation activities [44]. Studies showed that El Niño–Southern Oscillation (ENSO) influences the dynamics of vegetation in Africa [45,46], while certain regions tend to experience significant vegetation enhancement or suppression which depends on the ENSO phase [47–49]. An individual ENSO event can cause a variety of changes in vegetation intensity [50]. 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 [46,51] 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 [52,53]. 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 [54–56]. Studies show that increasing global temperatures have a significant impact on the responses of vegetation, rising sea levels, and the environment [56,57]. 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 [11]. 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 [58,59]. 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 [22,52,60]. In general, global vegetation coverage has been noted to have undergone significant transformation, affecting species dynamics and grassland conditions [61,62]. 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 [63,64]. 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.

1.1.1. 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 (CO₂) which may serve as the justification for predicting vegetation response to variability and change [65]. 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 [27]. 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 [66,67]. 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 [60,68]. 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 [69], while the sensible heat exchange was more prominent with a more sparsely vegetated region [70]. 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 [55,71]. 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 [72,73]. 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 [63,73]. 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 [7,74,75]. 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 [76]. Changes in vegetation coverage and biomass may lead to an alteration in the earth-atmosphere processes and climate dynamics [60]. Studies show that temperatures were found to be the major limiting factor for vegetation growth at high latitudes in the Northern Hemisphere [77] and Western Europe [78], while in Central Asia, South America and Southern Africa [32,66], declining precipitation and rising temperatures were correlated with a decline in vegetation vigour. Ref. [79] 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 [80]. 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 [52,81]. Vegetation growth is highly unstable and susceptible to drastic changes such as climate change [82]. 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 [83,84].

1.1.2. 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 [85]. 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 [86]. 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 [87,88]. 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 [89]. This present resultant multiple environmental changes, geographical location and low adaptive capacity [90]. 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 [91]. Climate change will adversely affect the socio-economic sectors such as forest management, water resources, agriculture, and human settlements as well as ecological systems [92]. 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 [93]. 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 [94–96]. 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 [97]). 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 [35,96].

1.1.3. 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 [98]. 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 [87,99]. 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 [100]. 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 [101]. 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 [102].

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 [100,103]. 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 [60,103]. 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 [104,105]. 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 [106]. 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 [107]. 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 [108,109]. 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 [64,110]. 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 [92]. 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 [111,112]. 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 [30,113]. 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 [66], Australia [114], Europe [78], Asia [32] and Southern Africa [115], 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 [116]. 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 [117,118]. 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 [119,120]. 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 [121,122].
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 [17,123]. Studies have shown a significant relationship between the terrestrial ecosystem and climatic variation [45,124,125]. 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 [11,126]. 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 [45,126]. 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 [10,83,127]. 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 [104,128]. 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 [45,129].

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 [100]. 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 [130]. Climate change variations have been considered to pose major threats to the terrestrial ecosystem and sustainable human settlement [131]. 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 [132]. 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 [26]. 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 [133,134]. 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 [47,48,135]. 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 [35]. A recent study used precipitation and temperature to assess the impact of climate factors on vegetation dynamics over East Africa from 1982 to 2015 [48]. 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 [136]. 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 [52,115]; however, some showed a negative correlation [136,137]. 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 [9,125,138,139].

The information in Table 2 shows the types of climatic parameters used as well as their temporal reference. The findings established in the various literature highlighted the relationship between vegetation dynamics and forms of extreme climate events; including agricultural drought hazard, floods and heat-waves among others, which have thus, greatly impacted the global terrestrial ecosystem. Although the results varied based on location and climatic zone, in general, most studies have reported that there exists a positive correlation between the response of vegetation and different environmental factors such as temperature, drought impact, land-use change, soil moisture, precipitation, variability and environmental changes, among others. Some reported a negative relationship, i.e., increasing temperature response and vegetation parameters with decreased precipitation over species transformation affecting ecosystem dynamics. Consequently, vegetation dynamics and its response to climate change are critical challenges for ecological conservation and restoration policy.

Hence, considering the empirical evidence that explains the inputs of organised ecological restoration programmes has drawn little attention [38,111]. Therefore, to fill the gap in the literature, the present study proposes a systematic communication network for risk assessment in planning, implementing, and evaluating information to enhance sustainable planning outcomes, and by extension to address the factors and forms of impacts occasioned by extreme climate events on vegetation dynamics. SDG13 (Climate Action) and SDG15 (Life on Land) were highlighted in line with VRCC to further corroborate the findings presented in the study. Therefore, the proposed information-based model (IBM) was designed to enhance ecological conservation and restoration policy towards VRCC. The model provides information on vegetation dynamics in the wake of climate change and its debilitating impacts on vegetation.
| S/N | Vegetation Indices                                      | Algorithms                                                                 | Remote Sensing (RS) Imagery                  | Findings/Gaps                                                                 | References |
|-----|--------------------------------------------------------|----------------------------------------------------------------------------|---------------------------------------------|--------------------------------------------------------------------------------|------------|
| 1.  | Normalized Difference Vegetation Index (NDVI3g)        | NDVI = \frac{(\text{NIR} - \text{RED})}{(\text{NIR} + \text{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 NDVI and low precipitation was significantly positive. | [34]       |
| 2.  | Enhanced Vegetation Index (EVI)                        | EVI = G \ast \frac{\text{\rho}_{\text{NIR}} - \text{\rho}_{\text{red}}}{\text{\rho}_{\text{NIR}} + \text{\rho}_{\text{red}} + \rho_{\text{blue}} + \text{C}} | 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. | [22]       |
| 3.  | Leaf Water Content Index (LWCI)                        | LWCI = G \ast \frac{\log(1) \ast (\text{\rho}_{\text{NIR}} - \text{\rho}_{\text{SWIR}})}{\log(1) \ast (\text{\rho}_{\text{red}} - \text{\rho}_{\text{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. | [140]      |
| 4.  | Leaf Area Index (LAI)                                  | LAI\_1 = \frac{1}{\lambda} \sum\lambda LAI(\lambda)                       | Moderate Resolution Imaging Spectrometer (MODIS) | The model shows that the vegetation status is 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. | [141]      |
| 5.  | Fraction of Photosynthetically Active Radiation (FPAR)  | FPAR = \frac{\text{\rho}_{\text{PAR}} \ast \text{\rho}_{\text{Other}}} {\text{\rho}_{\text{PAR}} \ast \text{\rho}_{\text{Other}}}                     | 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. | [142]      |
| 6.  | Vegetation Condition Index (VCI)                       | VCI\_1 = \frac{\text{\rho}_{\text{NIR}} - \text{\rho}_{\text{RED}}}{\text{\rho}_{\text{NIR}} + \text{\rho}_{\text{RED}} + 100} | Moderate Resolution Imaging Spectrometer (MODIS) | Findings show that the VCI widely distributed 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. | [143]      |
| 7.  | Temperature Condition Index (TCI)                      | TCI = 100 \ast \frac{\text{NDVI} - \text{NDVI}_{\text{min}}}{\text{NDVI}_{\text{max}} - \text{NDVI}_{\text{min}}} | 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. | [144]      |
| 8.  | Vegetation Health Index (VHI)                          | VHI = \alpha VCI + TCI \ast (1 - \alpha) 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. | [145]      |
| 9.  | Soil-adjusted Vegetation Index (SAVI)                  | SAVI = \frac{(\text{\rho}_{\text{NIR}} - \text{\rho}_{\text{RED}})}{(\text{\rho}_{\text{NIR}} + \text{\rho}_{\text{RED}})} \ast (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 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. | [146]      |
Table 2. Related studies on climate extreme events and their associated impact on vegetation.

| S/N | Forms of Extreme Climate Events | Continent | Country | Duration | Author | Data Source (Models and Climate Variables) | Data |
|-----|---------------------------------|-----------|---------|----------|--------|-------------------------------------------|------|
| 1.  | Agricultural drought hazard and drastic decline of vegetation | Asia      | China   | 1982–2012 (30 years) | [32] | SPEI from AVHRR, seasonal NDVI and Mann-Kendall (MK) Test, Climate data | Meteorological air temperature, precipitation, and evaporation |
| 2.  | Severe flash flooding and intense storm | Asia      | China   | August 2015 | [124] | Climate data (nearest rain gauge), hydrodynamic model, Digital Elevation Model downstream from LiDAR | Field survey numerical hydrodynamic simulation and rainfall |
| 3.  | Flood damage to croplands and grassland | Europe    | Germany and France | 2002–2007 (5 years) | [78] | Evaluation of direct and indirect flood losses and the State of Saxony in Germany | Interviews, 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) | [66] | 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 | [94] | The long-term observational study, National Natural Foundation of China, dust storm from Beijing Weather Station, and Climate data | Drought index, inter-decadal changes, surface temperature anomalies, and precipitation based on a documented record |
| 6.  | Floods, agricultural damage, uprooted vegetation, and landslide/earthquake | Western Asia | Yemen | 1973–2008 (35 years) | [81] | 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) | [147] | 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) | [115] | 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) | [148] | Ministry of Finance and Economic Affairs and Gambian Disaster Management Agency | A multi-modal cross-sectional survey comprising online/electronic survey software and a face-to-face interview |
| 10. | The drastic decline of vegetation and narrow grazing, and shortage of water resources | Africa    | South Africa | 2019 | [149] | Multistage sampling procedure, snowball sampling approach statistical program | A cross-sectional household survey, Simple descriptive statistical tools |
4. Information-Based Model (IBM)

The proposed Information-Based Model (IBM) presents a communication network management programme designed specifically to address the factors and forms of impacts and offer solutions and techniques to deal with threats occasioned by extreme climate events on vegetation dynamics. The major focus of the model is to attain a systematic communication network for risk assessment in planning, implementing and evaluating information to enhance sustainable planning outcomes. The model exerts influence on ecological conservation and restoration policy towards vegetation response to climate change as presented in Figure 1.

![Figure 1. Graphical representation of the information-based model (IBM).](image)

The information-based model (IBM) was designed to provide information dynamics about Factors–Impacts–Solutions (Techniques)–Risks assessment and answers to vegetation and climate-related events. It is as follows:

1. **Factors** should state the influence that contributes to an episode and address a specific case study.
2. **Impact** on biota may spread through these factors which can include climatic, socio-economic, environmental and physical changes.
3. **Solutions** are outlined to address the type and extent of impacts of climate extremes on vegetation dynamics, its widespread, and forms of losses documented.
4. **Risk assessment and answers to climate-related impacts** should be done and offer step by step solutions and techniques to deal with threats occasioned by extreme climate events and other related impacts on vegetation dynamics.

Many studies on climate-related events, without sequence, contribute to the feeling of recurrence of records or documentation in relation to land degradation, human activities and drought events which are information-based and very complex [150–152]. The information in Figure 1 presents changes in climatic parameters such as temperature, precipitation, RH, and solar radiation among others. These, therefore, present interrelated effects on the socio-economic, environmental and physical factors that often lead to the impacts on
vegetation dynamics and its response to climate change. These factors are considered significant determinant factors of the vulnerability of the ecosystem to climate change. The impacts of climate change thus expend considerable impacts on affected biota, which include urban ecosystem, vegetation and forest resource, pastoral rangeland and agriculture because of the multiple benefits derived from it as mankind searches for a sustainable economy. The climatic, socioeconomic, and environmental factors are very complex and thus expend considerable impacts on the functioning of the terrestrial ecosystem [82]. Consequently, these factors have several significant consequential influences on the response of vegetation activities. These factors arise from the climatic, socio-economic, environmental, and physical changes towards resilience and recovery through a systems-based approach. The systems-based approach includes the nature and space-based solutions [45,153], human and problem-based solutions [154,155] and knowledge-based solutions [156], and is pivotal for ecosystem functions and services. Hence, these highlighted factors leading to the impacts require a systems-based approach in our contemporary time that will dictate the standardised set of management steps and its associated objectives. Implementation through the enablers of adaptive indicators in vegetation assessment such as impact assessment and adaptive management for sustainable planning outcomes could be incorporated through the IBM. This can be done through the interconnection between the proposed model and the appraisal of a systems-based approach through effective adaptation and early warning systems intended to predict and provide strategic mitigation and associated policy formulation to mitigate the damage of natural and human-induced impacts on vegetation dynamics. These strategies and development goals are established to promote effective response management for sustainable planning outcomes to tackle the related impacts of climate change threats on vegetation dynamics. The IBM has identified Factors–Impacts–Solutions (Techniques)–Risks assessment and answers to vegetation and climate-related impacts through drivers of vegetation dynamics that influence the response of the ecosystem to climate change using the observational and experimental study with remote sensing and GIS techniques (Figure 1). Remote sensing and GIS techniques provide a multi-time analysis of vegetation health and assess the spatially changing patterns between the vegetation coverage and its response to climatic factors from high-resolution thermal and hyperspectral imagery. The information-based model answers major questions concerned with the resilience and recovery phase of impacts from natural or human-induced impacts towards environmental restoration policy and practice of environmental conservation programmes. Nevertheless, the ecosystem’s biodiversity and the environment mostly account for the magnitude, ranging from type to the nature of the stressor, in the long run, constituting threats at different timing, location and zone, which are the effects of the combined structure of risks.

On the other hand, the IBM functions with the enablers of adaptive indicators in vegetation assessment to provide strategic mitigation and effective adaptation for consequential loss to ecosystem services. The ripple effects of extreme climate change on all-natural and human-made events such as floods, heat-stroke, drought, invasion of alien plants, etc., and environmental degradation through deforestation, pollution, and land use cover change pose threats to ecological conservation and sustainable livelihood. Consequently, the resultant effects exacerbate loss, causalities, and substantial loss to governments, stakeholders, institutions, and societies. The systems-based approach should be fully incorporated into the management cycle which may be linked to enablers of adaptive indicators for sustainable developmental goals, objectives, and activities of the conservation program, policy, and practice [157,158]. The IBM provides the design of a communication network management programme for risk assessment towards resilience and recovery to the effects of extreme climate-related impacts occasioned by climate change.

4.1. Enablers of Adaptive Indicators in Vegetation Assessments

Monitoring vegetation conditions and assessment are integral in adaptive management and impact assessment processes of its dynamics at large scales [30,159]. Assessment
of ecosystem-based adaptation monitoring and evaluation is vital in assessing the effectiveness and management of natural resources to design appropriate measures needed to address the multiple threats under global climate change [99,160], thus leading to better decision-making processes in sustainable planning outcomes. Impact assessment and adaptive management are considered as a robust management approach in ecosystem conservation and sustainable livelihood in the face of threats posed by climate change, socio-economic, physical, and environmental impacts, and other hazards that trigger them [161]. Impact assessment is a one-time assessment approach of measuring the effectiveness and social significance of impact such as projects, programmes or policy [162]. Meanwhile, adaptive management is an approach for managing natural resources which leads to robust decision-making in the face of uncertainty to reduce the uncertainty over time through system monitoring as mankind searches for a sustainable economy [163].

The flow of IBM supports the enablers of adaptive indicators—impact assessment and adaptive management—in vegetation assessment in planning, implementing, evaluating, monitoring and managing information order of all channels of a communication network to enhance ecosystem management and sustainable planning outcomes, and suggests the model should be operationalised, tested and applied in reality. The comprehension and assessment of the type and extent of impacts and risk assessment are important to mitigate the impacts of these extreme climate events and other environment-related degradation based on records and quantification of historic or past events. The application of IBM will provide measures to implement, plan, monitor, and manage the operations required to enhance the sustainable planning outcomes through impact assessment and adaptive management approach as highlighted in this study. The government, institutions, and communities would be empowered to evaluate the magnitude of impending risks and putting strategic adaptation and effective mitigation plans in place. Incorporating the information-based model through the systems-based approach and enablers of adaptive indicators in vegetation assessments is strategic in strengthening the goals of global involvement of local and sub-national governments in the effective management of ecosystems and the protection of biodiversity. The sustainable goal is to address multiple climate change risks, build resilience and protect biodiversity to improve human settlement and livelihood [12]. The link between the impact assessment and adaptive management is geared towards the activities of the conservation program, policy, and practice aimed at sustainable planning. [53,85,164]. The implementation of impact assessment and adaptive management provides guidance intervention for socio-economic, environmental, and structural response required to enhance sustainable vegetation management, human settlement, and planning outcomes [165]. The enablers of adaptive indicators of vegetation assessment function with the IBM and by extension offer effectiveness in the management of natural resources towards robust decision-making and social significance of impact to mitigate the climate-related risk on the socio-economic, environmental and physical factors, which often leads to the impacts on vegetation dynamics and its response to climate change through the appraisal of the systems-based approach.

Information in Figure 2 was highlighted across various sectors to advance the practices for sustainable ecological conservation and restoration policy towards vegetation response to climate change. The advanced practice of sustainable vegetation and forest resource management emphasised four key basic conglomerates of information associated with policy formulation to mitigate the damage of natural and human-induced impacts on vegetation dynamics. The resilience and recovery phase of extreme climate-related impacts on vegetation dynamics is very important in the wake of climate change and its debilitating impacts in line with sustainable development goals (SDGs) for planning outcomes.
4.1.1. Linkage between Spatial and Temporal Scales

The linkage between long-term temporal vegetation variability and climate change is characterised based on spatial distribution and cover change associated with terrain characteristics of vegetation types, trend detection, human activities and changing climate. The loss of natural vegetation and forest resource to urban expansion or loss of agricultural areas through land use and land cover change may have significant environmental consequences to loss of biodiversity [110]. Vegetation monitoring and assessment of its dynamics at large scales [45] are vital to design appropriate measures needed to address the numerous threats. Hence, the long-term spatiotemporal dynamics analysis thus provides insights into the mechanism of vegetation response to climate change.

4.1.2. Communication Network Management

The synergy between communication network management and risk assessment themes was highlighted. The information order of communication network management enhances integrated planning through the implementation of sustainable practice for ecological conservation and restoration policy towards VRCC. Systematic monitoring provides early warning systems in decision-making and policy redesign to support the systems-based approach through standardised management steps and operational response for sustainable planning outcomes. The systems-based approach is crucial in strengthening the goals of global involvement of institutions and government at both local and sub-national levels through effective management of vegetation and ecosystem protection. More so, increased awareness by individual role and government agencies in the effective communication network across different sectors of the economy is very essential, especially at the community level since climate varies greatly at the local level than the regional and global scales which, therefore, has varying influences on vegetation dynamics.
4.1.3. Impact Assessment

The impact assessment to ecosystem vulnerability provides strategic adaptation and effective mitigation to improve the resilient community to the effects of various climatic and anthropogenic factors under the impact of climate change. This in turn would promote the implementation and management of ecological restoration programmes towards VRCC. Impact evaluation and social significance of impacts such as (projects, programme or policy) towards VRCC also have a profound effect on the development of ecological restoration [166]. Drivers of global climate change and other related threats will continue to produce altered disturbance regimes, novel trajectories of change and new spatial patterns in distributional shifts and the ecological response of landscape dynamics [42,167]. Future disturbances will continue to provide valuable opportunities for studying climate-vegetation interactions.

4.1.4. Adaptive Management

Adaptive management is the combined effects of natural resources and robust decision-making through corporate strategies into management cycles for sustainable livelihoods and planning outcomes. As such, farming, urbanisation, wildfires and grazing pressure on vegetation which often altered rangelands are the main challenges for forests and afforestation practices. Human afforestation practices that will enhance different facets of vegetation and ecosystem biodiversity for development goals to strengthen resilience to the effects of climate change are essential. Ecological conservation including vegetation and ecosystem is characterised by the adaptive capacity to climate-induced impacts and other environment-related events to conserve, protect, restore natural resources and promote the sustainable practice and use of the terrestrial ecosystem. Appropriate adaptation and mitigation strategies to enhance climate-resilience and recovery phase of degraded vegetation and forest resource will impact ecosystem functioning and services that are valuable to local communities and institutions to adapt and withstand the test of time [87]. Conversely, the recovery of indigenous vegetation, ecological conservation and restoration policy on VRCC are all interdependent approaches that all culminate into the “systems-based approach”. This, therefore, serves a wide range of co-benefits of climate change mitigation in policy formulation. The overall combination of the systems-based approach forms a vital guide in interventions for sustainable vegetation management and conservation to enhance ecosystem functioning, either now or in the future.

5. Practice for Sustainable Management and Restoration

The sustainable Development Goals (SDGs) is one of the recent frameworks that includes the collection of 17 interlinked goals adopted by the United Nations (UN) General Assembly in 2015, considering the constituted policies for sustainable planning outcomes [168,169]. It is, therefore, challenging to efficiently exploit these global top practices given the constraints that impede strategic adaptation and effective mitigation measures through the development and restoration of biodiversity. With regards to answering the critical questions of how to improve vegetation and forest resource management and planning outcomes. This, therefore, affords the implementation of IBM through the enablers of adaptive indicators and the systems-based approach in vegetation assessment in line with the evolving scholarship of incorporating vegetation dynamics and its response to climate change. To provide elaborate and integrated information to address ecosystem and biodiversity loss under global climate change in line with sustainable development goals (SDGs), this study focused on the indicator framework of SDGs, which includes SDG13 (Climate Action) and SDG15 (Life on Land) respectively. SDG13 (Climate Action) was passed to take urgent actions to intensify resilience and adaptive capacity to combat extreme climate-related events and integrate climate change measures into policies and planning for ecosystem conservation and sustainable human settlements [168], while the SDG15 (Life on Land) was to preserve, restore and promote the sustainable practice and use
of terrestrial ecosystem, and to continually manage forest resources, combat desertification, reverse land degradation and biodiversity loss [168].

At the community level, a greater focus is essential on the individual, ecological guidelines for sustainable management and restoration policy and practice by the institution, government and increased awareness and effective communication network across the economy of different sectors. The proposed model provides answers to major questions concerned with the resilient and recovery phase of impacts from natural or human-induced impacts towards environmental restoration policy and practice of an environmental conservation programme. Restoration policy support planners should consider the impacts of extreme events; however, foreseeing these scenarios would make restoration goals more practical. In general, the guiding standards and assessment briefing from the global initiatives further strengthens the IBM for sustainable planning outcomes for better management at the community level towards resilience and recovery to face more of the external force of natural woes. More so, the rural smallholder farmers and immediate communities are distressed from uncontrolled extreme climate events in the Global South facing the ever-growing concerns. Global climate change impacts and dearth in the application of present-day initiatives of this manner necessitate the design of IBM for effective mitigation and strategic adaptation of sustainable planning outcomes.

6. Summary

This study reviewed large-scale vegetation dynamics and their response to climate change. However, two enablers of adaptive indicators in vegetation assessment (impact assessment and adaptive management) were elaborated as steps towards the model application and to enhance sustainable goals of ecological conservation and restoration policy. Vegetation dynamics and its response to climate change aimed at implementing action on the information about the phase of impacts on the ecosystem’s biodiversity and to advance the practice of sustainable management of various extreme climate threats. This captures the broader idea of vegetation dynamics and its response to climate change (see Figure 2). Thus, the effort to integrate the two enablers of adaptive indicators and the novel systems-based approach in practice is crucial, especially where resilience and recovery are related to these terms considering their integration into vegetation dynamics and its response to climate change. The two enablers of adaptive indicators and the novel systems-based serve as a key policy formulation for sustainability in strengthening the goals of global involvement of local and sub-national governments and institutions in the effective management of vegetation and ecosystem protection. Vegetation dynamics and its response to climate change have a wide range of cross-cutting issues and common goals; the first considered issues on climate-related impacts through drivers of vegetation dynamics observation that affects the response of the ecosystem dynamics to extreme climate conditions. Meanwhile, the latter involves dealing with all-natural or human-induced impacts including environmental, socio-economic and physical influences, risk perception and vulnerability of biodiversity, the incidence of climate change, and human response. However, the response of vegetation dynamics deals with the long-term coping mechanism of the inhabitant to changing climatic conditions, including the multiple benefits derived from it. Climate change, on the other hand, is a long-term change in the earth’s climate due to the increase in average atmospheric temperature which specifically results in extreme events. Furthermore, this review proposes that a point of convergence between large-scale vegetation dynamics and its response to climate change in addressing climate-related impacts may bring about a desired common objective in mitigating ecosystem vulnerability and attaining sustainable livelihood in the area of vegetation and forest resource management. The new IBM was designed to enhance the general overview of vegetation-climate responses and their related impacts towards resilience and recovery to the effects of climate change in planning and management of ecosystem functions, ecological conservation, and restoration policy. The relationship between the proposed model and the appraisal of the systems-based approach through enablers of adaptive indicators in planning outcomes for
vegetation and forest resource management suggests that the information-based model (IBM) should be operationalised, tested, and applied in the real world. In conclusion, this study emphasised SDG$_{13}$ and SDG$_{15}$, which are the indicator framework set to review issues relating to climate change impacts and resilience of ecosystem’s biodiversity across the world until the year 2030, and which are a hotspot for researchers to explore in future studies because of its constituted policies and planning. The knowledge of VRCC provides an all-inclusive policy formulation for climate change adaptation and mitigation. This review suggests more studies on the long-term vegetation dynamics considering other key indicator responses such as solar radiation, RH, soil moisture and wind speed to climate change to understand the multiple-scale response precision of different types of land-cover change and the immediate cause of observed trends.

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