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Effect of vegetative cover on rainfall pattern: A comprehensive review

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Abstract

Vegetation plays a pivotal role in modulating climate systems, particularly influencing local and regional rainfall patterns through biophysical and biogeochemical processes. The interaction between vegetative cover and rainfall is governed by complex feedback mechanisms involving evapotranspiration, surface albedo, energy fluxes, and atmospheric moisture recycling. This review synthesizes the current understanding of how vegetation affects rainfall dynamics, with a specific focus on methodologies used for detecting and analyzing these relationships. Tools such as remote sensing-especially vegetation indices like the Normalized Difference Vegetation Index (NDVI)-alongside satellite and ground-based rainfall datasets, provide robust means for monitoring and evaluating vegetation-rainfall interactions. Statistical approaches including correlation analysis, Mann-Kendall trend tests, and spatio-temporal overlays are frequently applied to detect trends and relationships. The review also explores key factors influencing this relationship, such as irrigation practices, soil type, topography, groundwater availability, and climatic oscillations like ENSO, which can either amplify or suppress vegetative response to rainfall. In arid and semi-arid regions, including parts of Western Rajasthan, these interactions are particularly critical, where vegetation not only responds to rainfall variability but can also alter local microclimates and precipitation regimes. Findings suggest that sustainable vegetation management can potentially enhance regional rainfall through improved land-atmosphere coupling. The paper concludes with recommendations for integrated land use planning and identifies future research needs, including the development of high-resolution models and long-term observational networks to better understand and predict vegetation-rainfall feedbacks under changing climate scenarios.

Keywords: Vegetation-climate interaction, Rainfall patterns, Evapotranspiration, NDVI, Remote sensing

1. Introduction

Rainfall plays a fundamental role in determining crop growth and yield, making it a vital climatic factor in agricultural systems. Its influence is particularly significant in rainfed regions, where crop planning, irrigation scheduling, and food security are highly dependent on the temporal and spatial variability of precipitation. Fluctuations in rainfall patterns can severely impact crop productivity and rural livelihoods, especially in ecologically fragile zones where adaptive capacity is limited.

Land Use and Land Cover (LULC) represents the spatial manifestation of human-environment interactions, encompassing a range of activities such as urban development, agriculture, conservation, recreation, and habitat preservation. LULC patterns are shaped by socio-economic dynamics, demographic trends, and the effects of climate change. LULC identification is a critical component of sustainability research, particularly for evaluating global, regional, and local environmental changes [3]. Over the last century, human-induced pressures on land have increased substantially and continue to evolve dynamically [4]. The availability of accurate and up-to-date LULC maps is indispensable for effective environmental monitoring, sustainable development planning, forest degradation assessment, and natural resource management [1, 2].

Vegetation growth and survival are directly influenced by water availability, with precipitation acting as the primary source of water input in arid regions [6]. Although groundwater serves as a critical buffer supporting vegetation in dryland ecosystems, rainfall remains the dominant driver of hydrological replenishment and plant water uptake. The inherently erratic and uneven distribution of rainfall in arid zones contributes to significant spatiotemporal variability in vegetation patterns [5]. Due to delays in surface runoff, infiltration, and subsurface redistribution, there may be phase differences between precipitation events and actual vegetation response. Therefore, to understand the ecological impact of rainfall in arid and semi-arid landscapes, it is essential to conduct spatially and temporally resolved analyses of the relationship between rainfall variability and vegetative cover.

1.1 Importance of rainfall variability in ecological and hydrological systems

The majority of hydrological processes depend on rainfall, and changes in its spatiotemporal distribution and properties can have a significant effect on ecosystems, agriculture, and the management of water resources [7, 8]. The 20th century has seen a substantial change in rainfall patterns worldwide [9]. The river ecosystem is disturbed, biodiversity is lost, and floods and droughts occur more frequently as a result of changes in the spatiotemporal patterns of rainfall [10]. Anthropogenic factors have caused rainfall-induced hazards to increase in frequency and severity over the past few

decades [11]. The changing characteristics of the global precipitation is also a concern for agriculture and water management sector. With increasing concerns about intensification of climate change, it is essential to understand the nature and variability of rainfall and its changing patterns at different spatiotemporal scales.
Particularly for tropical nations like India, whose economy, agriculture, and food security are largely reliant on the start and course of the monsoon rainfall, the effects of these changes are profound [12]. It is widely acknowledged that historical climatic variables analyzed at the continental or regional scale are not very helpful for planning at the local or river basin scale [13]. Therefore, it is crucial to have a deeper understanding of rainfall trends, distribution, and changes at the regional or basin scales, especially when it comes to managing water resources and developing adaptive farming and agriculture strategies.

1.2 Significance of vegetation in modifying rainfall

Variations in precipitation over time and space affect vegetation productivity. Plant communities are geographically vulnerable to environmental changes that modify vegetation at all scales, similar to most biological systems. These are processes that operate independently of plant processes, such as germination, growth, and death, and they have exogenous effects on the vegetation community. Such events can quickly and permanently change the composition and structure of vegetation across large areas. As a common and recurring feature of long-term system dynamics, few ecosystems are entirely free from some form of disturbance [14]. Abrupt changes, like wildfires, strong winds, landslides, floods, and avalanches, are generally considered disturbances.
Abrupt changes, such as landslides, floods, avalanches, wildfires, and strong winds, are generally regarded as disturbances. Climate-driven vegetation mortality is happening all over the world, so it's critical to understand vegetation dynamics and how it responds to climate change. Additionally, this knowledge will support the development of the habit of recognizing improved environmental management and forecasting the growth of vegetation in the future [15].

2. Vegetation and Rainfall Dynamics

Vegetation is one element of the environment that is extremely vulnerable to changes in the climate, despite its significance in preserving environmental balance [16]. Both the growing season and the overall amount of vegetation cover are influenced by vegetation dynamics, and both are significantly impacted by climatic variability [17]. The amount of net radiation available for warming the ground and the lower environment, as well as for vanishing water, is determined by the amount of vegetation that affects the arrived surface albedo [18]. Air humidity, convection processes, wind speed, and drizzle are all influenced by vegetation, and these factors together determine how much rainfall an area experience. However, it is commonly known that adequate rainfall is required for plants to grow healthily. Vegetation growth may be greatly impacted by changing rainfall and temperature patterns brought on by climate change [19].
In many parts of the world, the NDVI's temporal trend has been regarded as a popular and extensively used vegetation index that is highly effective for tracking the dynamics and conditions of vegetation [20]. Because the vegetation cover in arid and semi-arid regions is highly sensitive to the amount, duration, and frequency of rainfall, rainfall is a critical factor that regulates dynamic changes in vegetation growth in those regions [21]. Previous research has shown that changes in rainfall over time and space are consistent with changes in the NDVI in arid regions [22].
In the world's tropical regions, it is important to examine how rainfall and vegetation interact. Heavy rainfall is a defining feature of this climate zone and is thought to be a key determinant of vegetation growth. However, in areas where human interference is more prevalent, this relationship may alter. The tropical region is undergoing major changes as a result of growing populations and human-caused environmental effects. Therefore, understanding the rainfall-vegetation pattern and how they interact is important for researching the tropical region's vulnerable conditions.
Through a number of interrelated processes, vegetation has a major impact on regional and local precipitation patterns. By affecting evapotranspiration, which in turn affects atmospheric moisture and cloud formation, it has an impact on rainfall and the water cycle. Regional rainfall patterns and water availability may change as a result of changes in vegetation cover, such as afforestation or deforestation.
As a link between the atmosphere, soil, and water, vegetation is essential to terrestrial ecosystems. It is also vital for material and energy exchange, biochemical cycling, and the regulation of the climate system on land surfaces [23]. Another crucial metric for tracking local ecological conditions is vegetation [24]. The health and environmental carrying capacity of terrestrial ecosystems are impacted by vegetation, which is extremely sensitive to environmental factors like precipitation, altitude, and human activity. Additionally, vegetation is susceptible to changes in the environment [25]. Rainfall is the primary factor that propels plants from a drought-tolerant state to an active growth state [26], and water is one of the most limiting factors in arid and semi-arid ecosystems [27]. In order to create adaptation plans to deal with future climate change, which is essential for the sustainable management and preservation of terrestrial ecosystems, more quantification of the effects of precipitation changes on vegetation in arid and water-scarce areas is required [28].

3. Methods and Tools for Analysis

To examine the influence of rainfall patterns on vegetative cover, a combination of geospatial technologies, statistical tools, and remote sensing methodologies are widely employed. These approaches enable the spatio-temporal assessment of vegetation dynamics and their correlation with climatic variables, particularly precipitation.

Remote Sensing and Vegetation Indices

Satellite imagery from platforms such as Landsat, Sentinel, and MODIS has become fundamental in monitoring vegetation change over time. Among various vegetation indices, the Normalized Difference Vegetation Index (NDVI) is the most widely used, as it quantifies vegetation greenness and vigor using red and near-infrared reflectance.

Multi-temporal NDVI datasets allow for the detection of vegetation trends and land cover transitions through techniques like vegetation index differencing and image classification. These datasets can be integrated and processed using Geographic Information System (GIS) platforms such as ArcGIS and QGIS, which facilitate spatial visualization and overlay analysis with rainfall data.

Rainfall Data and Trend Analysis

Rainfall data can be obtained from traditional rain gauge networks as well as satellite-based sources like the Tropical Rainfall Measuring Mission (TRMM) and the Global Precipitation Measurement (GPM). These sources provide both point-based and gridded estimates of rainfall across spatial and temporal scales. Statistical techniques such as the Mann-Kendall trend test, Sen's slope estimator, and Detrended Fluctuation Analysis (DFA) are employed to identify and quantify trends in precipitation datasets. These analyses can be used in conjunction with NDVI to assess how temporal rainfall variability corresponds with vegetative response.

Statistical and Predictive Modeling Approaches

The relationship between precipitation and vegetative cover can be further explored through correlation analysis and regression modeling. Time series analysis methods, including Auto-Regressive Integrated Moving Average (ARIMA) models, are useful in exploring temporal dependencies between rainfall and NDVI trends. Furthermore, land change modeling tools such as IDRISI Selva enable predictive simulations of land cover dynamics based on historical LULC patterns and future climatic scenarios.

3.1 Use of NDVI and remote sensing in vegetation monitoring

A deeper comprehension of the Earth's environment can be gained with the help of Multi-Spectral Remote Sensing images [29]. It is the science and art of gathering data about certain objects, regions, or phenomena-such as vegetation, land cover classification, urban areas, agricultural land, and water resources-and extracting features in the form of spectral, spatial, and temporal information without actually coming into contact with the objects [30].

Land cover classification, soil moisture measurement, forest type classification, vegetation liquid water content measurement, snow mapping, sea ice type classification, and oceanography are just a few of the many application areas for remote sensing data [30]. Essentially, integrating spectral and spatial features of the objects are carried by the multispectral remote sensing images [31]. To prevent natural disasters like floods, this article uses a multispectral image of the Vellore district to determine the percentage of versatile features, such as vegetation, hilly areas, water bodies, open areas, scrub areas, agricultural areas, thick forests, and thin forests, that are presented in the image. These features are then made publicly available for additional analysis.

The 7-band data, known as LANDSAT images, is used by the National Aeronautics and Space Administration of the United States (NASA) to extract features [32]. Tools for image analysis using various algorithms and mathematical indices are provided by digital image processing of satellite data. Reflectance characteristics serve as the basis for features, and indices have been developed to draw attention to the image's salient features [33]. On a remote sensing scene, vegetation-bearing areas can be highlighted using a variety of indices. One popular and extensively used index is the NDVI [34]. It is a significant vegetation index that is frequently used in studies on climate change and the environment worldwide [34]. The difference between the measured canopy reflectance in the red and near-infrared bands, respectively, is used to compute the NDVI [35].

The use of NDVI for vegetation monitoring [36, 37], crop cover assessment [38], drought monitoring [39, 40], and agricultural drought assessment at the national [41, 42] and international [43] levels has been documented by numerous researchers. In the field of remote sensing, the vegetation index (VI) is a straightforward and useful measurement parameter that is used to show the earth's surface vegetation covers and crop growth status [43].

3.2 Rainfall data sources: satellite and station-based

Precipitation data is a crucial input for hydrological studies involving flood forecasting and rainfall-runoff modeling. Precipitation data has historically been gathered and made available by ground-based meteorological gauging stations. Estimates are spatially interpolated for area coverage in order to represent rainfall fields that are spatially distributed. Space-born estimates are an alternative to in-situ estimates. Every source has unique benefits and drawbacks. For example, space-born estimates use images with pixel sizes of 1 km2 or larger (>25 km2) to provide spatial coverage. Although it is the only source of dense precipitation coverage in mountainous regions, its spatial resolution is low when compared to in-situ observations, which are regarded as point measurements [44]. Missing data from various sources, like blockage, which is particularly relevant during strong storms, is frequently present in the spatial coverage of spaceborne estimates (like radar) [45].

Satellite-based rainfall estimates are not always accurate [46, 47], and it has been agreed that estimates need to be corrected. Rain gauges are used to compare observations to in-situ measurements, which are regarded as the "true" estimate, in order to evaluate the accuracy and dependability of satellite-based estimates [47, 48]. However, stations in areas like remote and mountainous terrain are not evenly distributed, and rain gauge networks frequently have low densities. Furthermore, rainfall time series are frequently lacking or subject to inaccurate estimations brought on by inadequate maintenance. Research on evaluating the accuracy of Satellite Rainfall Estimates (SREs) has increased as a result of the unreliability of time series, which can impede hydrological assessments and modeling studies. Given the lack of data in areas with inadequate measurement, it's critical to determine whether SREs can serve as an additional or replacement source of data.

3.3 Statistical methods

The majority of earlier studies on precipitation trend analysis in India concluded that there was no discernible national trend [49]. Nonetheless, there has been a notable upward trend at the regional level and a downward trend at the local or river basin level [50, 51]. It highlights the necessity of trend analysis at relatively small scales because the impact of climate variability is anticipated to be significantly more detrimental in small river basins and over brief periods [52]. As a result, this study uses rainfall time series spanning 34 years to analyze precipitation at the regional (district) level. Two conventional tests, the Mann-Kendall (MK) test in conjunction with the Sen's Slope estimator and the Spearman Rank-Order Correlation (SROC) test, have been used for trend analysis. Furthermore, this study also uses an emerging trend test called the "Innovative Trend (IT) test" [53], which has drawn the interest of a small number of hydrologists in recent years [54, 55].

Ecohydrological research is still very interested in the connection between precipitation and vegetation cover in arid regions [57]. An ecosystem's structure and composition are determined by its vegetation. Additionally, it shields inhabitants from desertification and maintains the stability of an ecosystem in arid regions. However, water availability has a direct impact on vegetation growth and survival [56]. While it is generally acknowledged that in arid regions, groundwater support is necessary for plant growth and distribution, precipitation serves as the regional source of water input. Significant spatial heterogeneity in natural water resources results from the generally uneven distribution of precipitation in arid regions [58]. There may be spatiotemporal phase differences between precipitation and plant water availability because water flow and redistribution at a basin scale take time. In order to comprehend how precipitation affects vegetation in arid regions, it is crucial to conduct a spatial analysis of the relationship between precipitation and vegetation cover across various time scales.

4. Factors Affecting Vegetation-Rainfall Relationship

Understanding the complex interplay between vegetative cover and rainfall requires consideration of several modulating factors that mediate or obscure their direct interactions. While vegetation can influence local to regional rainfall patterns through evapotranspiration and surface energy balance, these effects are strongly conditioned by anthropogenic and environmental variables such as irrigation, soil characteristics, topography, groundwater dynamics, and broader climate oscillations.

4.1 Role of Irrigation and Land Management Practices

In semi-arid and arid regions, where rainfall is highly variable and often insufficient to sustain natural vegetation, irrigation plays a pivotal role in maintaining vegetative cover. Human interventions such as canal irrigation, groundwater extraction, and drip irrigation systems artificially support vegetation, thereby disrupting the natural dependency between rainfall and vegetation growth. This anthropogenic decoupling can obscure the natural vegetation-rainfall feedbacks observed in unaltered landscapes. Furthermore, land management practices such as agroforestry, mulching, contour farming, and afforestation programs not only enhance soil moisture retention but also alter evapotranspiration dynamics, potentially influencing localized precipitation regimes. Therefore, irrigation and land-use strategies can act as both mediators and confounders in rainfall-vegetation interactions.

4.2 Influence of Soil Type, Topography, and Groundwater Availability

The capacity of the land surface to retain moisture and support vegetation is highly dependent on soil properties such as texture, porosity, and organic content. Sandy or highly permeable soils, for instance, have low water retention capabilities, limiting vegetation density even under favorable rainfall conditions. Topography further modulates this relationship by influencing runoff, drainage, and microclimatic conditions-elevated areas may receive higher orographic rainfall, while depressions accumulate moisture that sustains vegetation longer. Groundwater availability serves as a crucial buffer in dry periods, especially in areas where deep-rooted vegetation can access sub-surface water. This hydrological subsidy can support vegetation during rainfall deficits, complicating the direct correlation between surface precipitation and vegetative greenness indices.

4.3 Temporal Lags and Climatic Variability

The relationship between vegetation and rainfall is rarely instantaneous. There exists a temporal lag between rainfall occurrence and vegetative response due to physiological growth cycles, soil infiltration, and delayed evapotranspiration feedbacks. Such lags are especially relevant when analyzing satellite-derived indices like NDVI, where vegetation response may follow cumulative rainfall over several weeks or months. Moreover, inter-annual climate variability, driven by large-scale oscillations such as the El Niño-Southern Oscillation (ENSO), can significantly alter both rainfall distribution and vegetation dynamics across regions. During El Niño phases, many tropical and subtropical regions experience suppressed rainfall, leading to vegetation stress, while La Niña phases may result in enhanced precipitation and vegetation growth. These broader climatic patterns introduce variability that can mask or amplify the local-scale vegetation-rainfall coupling, thus requiring consideration in any robust analytical framework.

5. Conclusion

The relationship between vegetative cover and rainfall pattern represents a complex, dynamic interplay of biophysical processes, climate variability, and anthropogenic influences. Vegetation, through mechanisms such as evapotranspiration, albedo modification, and surface roughness, plays a critical role in modulating local and regional precipitation regimes. This review highlights that vegetation not only responds to climatic inputs like rainfall but also actively shapes atmospheric moisture dynamics, particularly in water-limited environments such as arid and semi-arid regions.

Remote sensing tools, especially NDVI, along with ground-based and satellite-derived rainfall datasets, have greatly enhanced our ability to monitor vegetation-rainfall interactions over spatial and temporal scales. Statistical methods, including correlation analysis and non-parametric trend tests like the Mann-Kendall test, offer valuable insights into long-term shifts in these interactions. However, the strength and nature of this relationship are influenced by several factors including irrigation, soil and groundwater conditions, topography, and climatic oscillations such as

ENSO. These variables often introduce spatial and temporal variability, leading to non-linear or delayed vegetation responses to rainfall.

For land managers and climate planners, these findings emphasize the importance of integrating vegetation management strategies within broader water resource and climate resilience frameworks. Protecting and restoring vegetation cover, especially in critical recharge and biodiversity zones, could enhance localized rainfall patterns and support long-term ecological stability. Future research should focus on developing high-resolution, coupled vegetation-climate models, incorporating socio-ecological factors, and conducting long-term observational studies. Such efforts will not only deepen our understanding of vegetation-climate feedbacks but also inform adaptive land-use planning in the face of accelerating climate change.

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