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A geo-spatial analysis of precipitation distribution and its impacts on vegetation in Rwanda

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Abstract

Rwanda is home to a diverse and picturesque landscape that encompasses a range of ecosystems, including rainforests, savannas, and agricultural regions. The intricate relationship between rainfall patterns and vegetation types shapes these varied landscapes, which are crucial for supporting biodiversity and agricultural productivity across the country. Our comprehensive geospatial analysis employs advanced geographical information systems (GIS) techniques and remote sensing data to assess spatial and temporal variations in precipitation across distinct regions of the country. Utilizing historical precipitation data and satellite-derived vegetation indices, our analysis spans extensive periods, incorporating annual and monthly rainfall records from 1990 to 2020 and MODIS/Terra Vegetation Indices spanning 2000 to 2020. Advanced remote sensing methodologies are employed to investigate the correlations between precipitation patterns and vegetation dynamics. The study reveals discernible spatial variations in Rwanda's precipitation distribution, elucidating marked seasonal fluctuations. Identified regions experiencing notable changes in precipitation levels exhibit a direct impact on vegetation health and density. Recorded annual rainfall data illustrates variations across different years, indicating fluctuating levels such as 1160.1 mm (1990), 1078.2 mm (2000), 1402.4 mm (2010), and 1391.1 mm (2020). Corroborating NDVI imagery demonstrates increased vegetation cover in 2010 and 2020, aligning with higher recorded rainfall during these years. The research underscores the significance of these findings in understanding the intricate interplay between precipitation distribution and vegetation dynamics and offers actionable insights essential for sustainable land management, optimized resource allocation, and the formulation of resilience-building strategies. These insights are particularly crucial in the context of adapting to and mitigating the effects of climate change.

1. Introduction

Rainfall is a critical determinant of vegetation distribution globally, with high precipitation levels often characterizing dense forests and lower rainfall areas featuring grasslands, deserts, and arid landscapes (Kalisa et al., 2019; Shaw et al., 2023). Adequate rainfall is crucial for plant growth and photosynthesis, enabling vegetation to thrive. Precipitation patterns are vital for regulating ecosystem functions such as nutrient cycling, soil moisture, and hydrological processes. Changes in rainfall can significantly impact these functions, leading to potential adverse effects on the health and stability of ecosystems globally. Therefore, it is essential to monitor and comprehend precipitation patterns and their potential changes to safeguard the environment and promote sustainable development (Kirchmeier-Young & Zhang, 2020).

Rainfall patterns play a crucial role in shaping the diverse ecosystems of Africa, which include various biomes such as tropical rainforests, savannas, and deserts. The precipitation levels exert a direct influence on these biomes, with rainfall variation being a significant determinant of their distribution. Regions with sufficient precipitation are conducive to thriving lush rainforests, while arid and semi-arid areas sustain savannas or deserts due to limited rainfall (Mountjoy & Embleton, 2023). Beyond shaping the continent's ecosystems, rainfall plays a critical role in supporting agricultural activities across Africa. Seasonal rainfall patterns dictate planting and harvest cycles, and farmers rely heavily on these patterns for successful crop yields. However, changes in rainfall patterns, especially prolonged droughts or erratic rainfall, have significant implications for food security, livelihoods, and the overall well-being of communities reliant on agriculture (Algur et al., 2021; Shahzad et al., 2019).

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Rwanda, located in the central region of East Africa, boasts an impressive range of landscapes that owe their distinctiveness to the complex interplay between precipitation patterns and their profound effects on vegetation (de Dieu Ndayisenga & Mupenzi, 2020; Kuradusenge et al., 2021; Siebert et al., 2019). This small, landlocked country is blessed with a remarkable geographical mosaic and varied topography, which results in a tapestry of climatic zones that give rise to a diverse array of ecosystems. From the lush expanses of dense rainforests to the vast stretches of grassy savannas, Rwanda's topographical diversity creates an environment that nurtures a multitude of habitats, each uniquely shaped by the prevailing rainfall patterns. The rich variation in vegetation cover is intricately intertwined with the distribution of rainfall across the country, exerting a powerful influence not only on Rwanda's ecological richness and biodiversity but also on its socio-economic landscape. Agriculture is the cornerstone of Rwanda's economy, and the interdependence between rainfall and vegetation profoundly influences agricultural practices, determining planting seasons, crop choices, and overall productivity (de Dieu Ndayisenga & Mupenzi, 2020; Maue, 2021; Siebert et al., 2019). As such, the fluctuations in rainfall and resulting alterations in vegetation significantly shape the socio-economic fabric of the nation, affecting livelihoods, food security, and the overall well-being of its populace.

Hence, comprehending the crucial interplay between precipitation distribution and vegetation dynamics in Rwanda holds significant importance. Mainly, Rwanda's ecosystems are home to a wealth of biodiversity that requires meticulous conservation efforts, necessitating a detailed analysis of how these ecosystems respond to changing rainfall dynamics (Gatwaza & Wang, 2021; Maue, 2021). This study is an extensive geospatial investigation that utilizes advanced technology such as GIS and remote sensing data to examine the patterns of precipitation distribution across various regions of Rwanda. Additionally, this analysis aims to clarify the consequential impacts of these precipitation patterns on the vegetative cover, delineating how differing rainfall regimes influence the composition, health, and resilience of vegetation in different ecological zones. By delving into the intricacies of precipitation-vegetation relationships, this research not only contributes to the scientific understanding of Rwanda's ecosystem dynamics but also aims to provide actionable insights. These insights will inform targeted strategies for sustainable land management, resource allocation, and ecosystem preservation, ultimately enhancing Rwanda's resilience to the challenges posed by a changing climate.

2. Method

2.1. Description of the Study Area

Rwanda has five administrative provinces and 30 districts (Figure 1). Rwanda, a landlocked country located in East-Central Africa, is situated between latitudes 1.4484° S and 2.6842° S and longitudes 29.2842° E and 30.7413° E (Figure 2). It shares borders with Uganda to the north, Tanzania to the east, Burundi to the south, and the Democratic Republic of Congo to the west. Rwanda is known for its varied topography, including rolling hills, lush valleys, and numerous lakes, with its capital city, Kigali, positioned in the central part of the country. As of my last knowledge update in the last population census in 2022, Rwanda had an estimated population of around 13.2 million people, making it one of Africa's most densely populated nations (NISR, 2023).

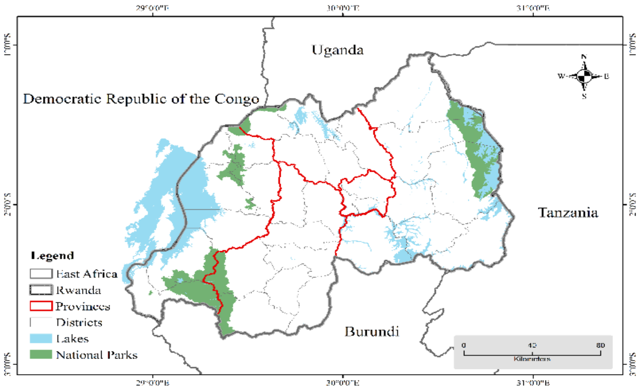

Figure 1. Administrative map of Rwanda

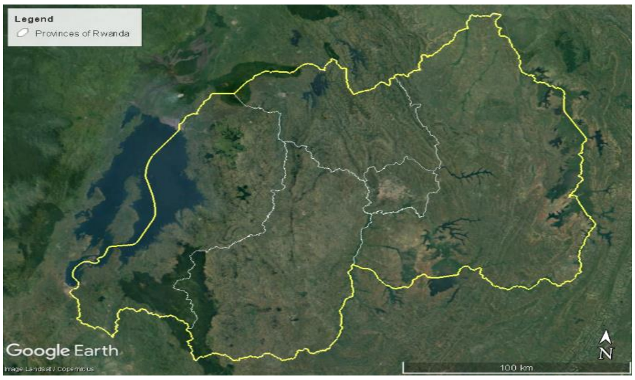

Figure 2. Google Earth Image of Rwanda

2.2. Topography

Rwanda is a stunning country located in Central/Eastern Africa, situated on a raised terrain that elevates approximately 1,200 meters above sea level. This beautiful country is characterized by its hilly topography with the majestic Virunga Mountains being the highest points. These mountains are located on the border with the Democratic Republic of the Congo, making for a breathtaking view. Standing tall at 4,507 meters, Mount Karisimbi is the highest mountain in Rwanda. Interestingly, the highest point in Rwanda is situated in the north, while the lowest is located in the west. It is worth noting that Rwanda's elevation ranges between 4507 and 900 meters above sea level, as depicted by Figure 3 and its mathematical results.

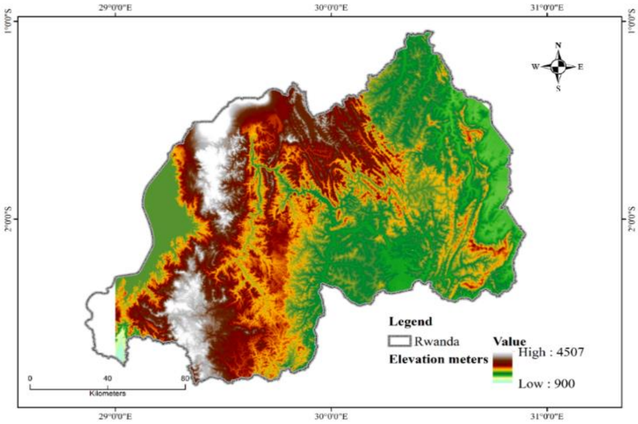

Figure 3. Topographic map of Rwanda

2.3. Data set

2.3.1. Data source

The primary focus of this investigation revolved around the detection of the normalized difference vegetation index (NDVI), a crucial indicator of vegetation health and distribution. The study area's vegetation dynamics were analyzed using MODIS-NDVI data, which had a resolution of 250 meters and were derived from MOD13Q1 (Table 2). The NASA Land Processes Distributed Active Archive Center provided the MOD13Q1 Terra vegetation index data from 2000 to 2020. Furthermore, Precipitation data from 1990 to 2020 were meticulously collected from the WorldClim web platform (Table 1). Due to the high prevalence of cloud cover in Landsat images, we transitioned to using MODIS NDVI data, which are available starting from the year 2000. As a result, we refrained from correlating rainfall data with NDVI prior to this year.

This supplementary information enriched the analysis by providing insights into how climatic factors may have influenced the observed changes in NDVI. To enhance the spatial context of the research, shapefiles and DEM were downloaded from two sources: DIVA-GIS and the Rwanda Spatial Data Hub (RSDH). These datasets, encompassing a broad spectrum of geographical attributes, bolstered the analytical rigor and facilitated a holistic perspective on the factors influencing the observed changes. Moreover, to ensure the accuracy and reliability of the gathered data, an additional layer of meteorological information was obtained directly from Mateo-Rwanda. This direct collaboration with local meteorological authorities validated the findings and improved the outcomes' precision.

Table 1. Data type and source

Data owner	Data type	Link
NASA	MODIS/Terra Vegetation Indices 16-Day L3 Global 250m (2000, 2010, & 2020)	https://ladsweb.modaps.eosdis.nasa.gov/
WorldClim	Monthly total precipitation (mm) with 10 minutes (~340 km^2) resolution (1990, 2000, 2010, & 2020)	https://worldclim.org/data/monthlywth.html
Government of Rwanda & DIVA-GIS	Spatial data: Boundary and DEM	https://www.diva-gis.org/gdata https://geodata.rw/portal/apps/sites/#/nsdi
METEO-Rwanda	Monthly Rainfall and Temperature data	https://meteorwanda.gov.rw/index.php?id=2

Table 2. MODIS/Terra vegetation indices

Year	Resolution	Date	Name
2000	250m	25/06/2000	MOD13Q1.A2000177.h21v09.061.2020048031344.hdf MOD13Q1.A2000177.h20v09.061.2020048031104.hdf
2010	250m	26/06/2010	MOD13Q1.A2010177.h20v09.061.2021168170801.hdf MOD13Q1.A2010177.h21v09.061.2021168180554.hdf
2022	250m	11/07/2020	MOD13Q1.A2020193.h21v09.061.2020340134419.hdf MOD13Q1.A2020193.h20v09.061.2020340134512.hdf

2.3.2. Data processing

2.3.2.1. Normalized difference vegetation index

NDVI is a widely utilized metric for assessing the vitality and density of plant cover through the analysis of light reflection across distinct spectral ranges. Its values are derived by analyzing the spectral data acquired by satellite sensors like Landsat, which capture information across various electromagnetic spectrum bands. The calculation of NDVI for each image followed a prescribed equation (Dehling & Sinsch, 2023). Typically, NDVI is computed utilizing a specific formula (Equation 1). However, our research employed NDVI data with a resolution of 250 meters. The ArcGIS project tool (Geoprocessing tool that projects spatial data from one coordinate system to another) combined and adjusted the NDVI data for 16-day composites (Yuan et al., 2019). The mosaics for each 16-day composite were transformed from a sinusoidal projection to ITRF_2005, a widely adopted projection in Rwanda. Finally, on each day, two images were downloaded, one for 35 and 36. Mosaic to New Raster tool (Geoprocessing tool that mosaics multiple raster datasets into a new raster dataset) was used to merge two images for each year, and Extract By Mask (Geoprocessing tool that extracts the cells of a raster corresponding to the area defined by a mask) was used to extract only NDVI map of Rwanda.

Raster Calculator and Image*0.0001 formula were used to put an image in the range between -1 to 1 values.

$$Landsat\ NDVI = (NIR - RED)/(NIR + RED) \quad (1)$$

where *NIR* is near-infrared reflectance, and *RED* is red reflectance.

NDVI values start from -1 to +1, with elevated positive values signifying robust and more densely vegetated areas. Furthermore, researchers used average annual and monthly rainfall data in this article. This helped us to create Excel graphs illustrating how monthly rainfall changes. These graphs make it simple to spot any patterns or connections between agriculture and rainfall.

2.3.2.2. Annually and monthly rainfall

The study conducted a comprehensive analysis of the influence of rainfall on agriculture in Rwanda using annual and monthly rainfall data spanning from 1990 to 2020 (Figure 4). The data was acquired from the WorldClim website and was accurately processed to integrate with ArcGIS 10.8.2. To ensure accuracy, 320 weather stations situated across Rwanda were utilized as sampling points within the Spatial Analyst tool. In addition to the global climate data, the localized information was also incorporated into the analysis to produce a detailed and accurate assessment of climate change patterns in the region. The Inverse Distance Weighting (IDW) interpolation method was applied to extrapolate data points, facilitating the creation of continuous raster layers that depict rainfall's spatial and temporal trends.

The study's integrated approach combines global climate data with locally collected information to provide a comprehensive understanding of climate change patterns in the region. By using a combination of global and local data, the study provides a detailed and accurate assessment of the impact of rainfall on agriculture in Rwanda. This information is critical to better-informed decision-making and mitigation efforts aimed at addressing the challenges posed by climate variability and change.

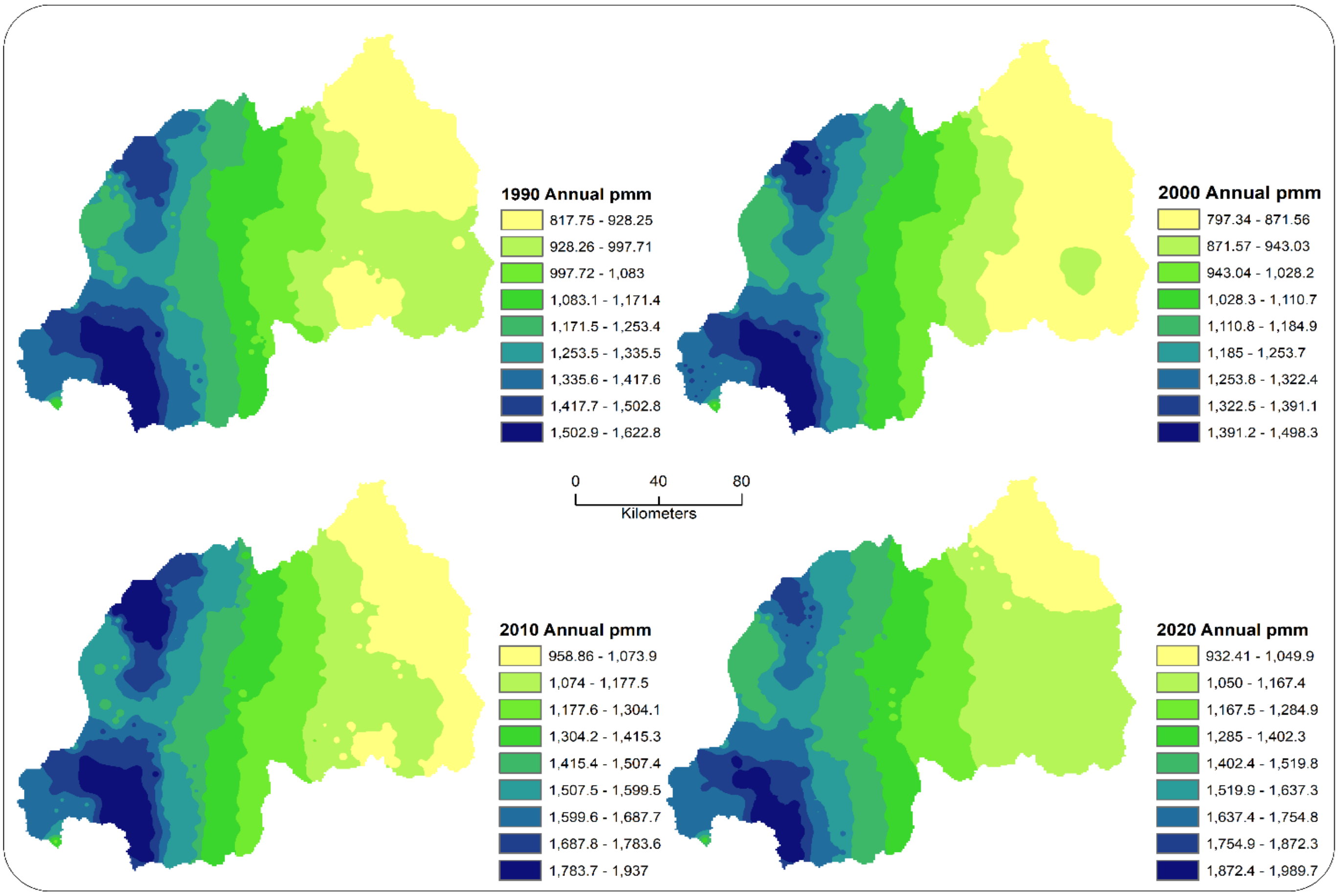

Figure 4: Rainfall change from 1990 to 2020

3. Results and discussion

3.1. Rainfall variability and vulnerability

The significance of precipitation as a climatic factor for agriculture cannot be overstated, and with climate change, precipitation patterns are changing globally. In some regions, precipitation is becoming less frequent but more intense; in others, it is becoming more variable and unpredictable. These changes considerably impact crop yields, water availability, and pest and disease pressure. Figure 4 illustrates alterations in rainfall patterns across various years, highlighting spatial variations. The eastern part of Rwanda consistently experiences a rainfall shortage, adversely affecting neighboring provinces. On a nationwide scale, in 1990, precipitation levels ranged from 817.75 to 1,622.8 mm, while in 2000, they varied between 797.34 and 1,498.3 mm. In 2010, rainfall spanned from 958.86 to 1,937 mm; in 2020, it ranged from 932.41 to 1,989.7 mm.

Figure 4 shows that the rainfall distribution in Rwanda varies from east to west, with the western regions receiving more rainfall than the eastern regions. This is due to the country's topography, with the western regions being higher in elevation and receiving more precipitation from the Congo Basin. The rainfall also varies yearly, with some years being wetter than others.

Maps-based analysis shows that the country's western regions consistently receive more rainfall than the eastern regions. In all four years, the annual rainfall in the western regions is above 1,500 mm, while the annual rainfall in the eastern regions is below 1,000 mm. The variability of rainfall from east to west can also be seen in the image. For example, in 1990, the annual rainfall in the western regions was significantly higher than in the eastern regions. However, in 2020, the annual rainfall in the western regions was only slightly higher than in the eastern regions.

3.2. Correlation between rainfall variability and NDVI

The rainfall variability from year to year can significantly impact agriculture and water resources in Rwanda. For example, if there is a drought in the western regions, it can lead to crop failure and water shortages. The rainfall distribution in Rwanda is more variable in the eastern and western regions. This is because the eastern regions are more exposed to the prevailing winds, which can bring in moisture and dry air. Consequently, this rainfall variability is affecting crops and other plants; this means that the increase in rainfall leads to more farming activities carried on the ground so that people can live sustainably. These are shown in the following NDVI images: 2000, 2010, and 2020 (Figure 5).

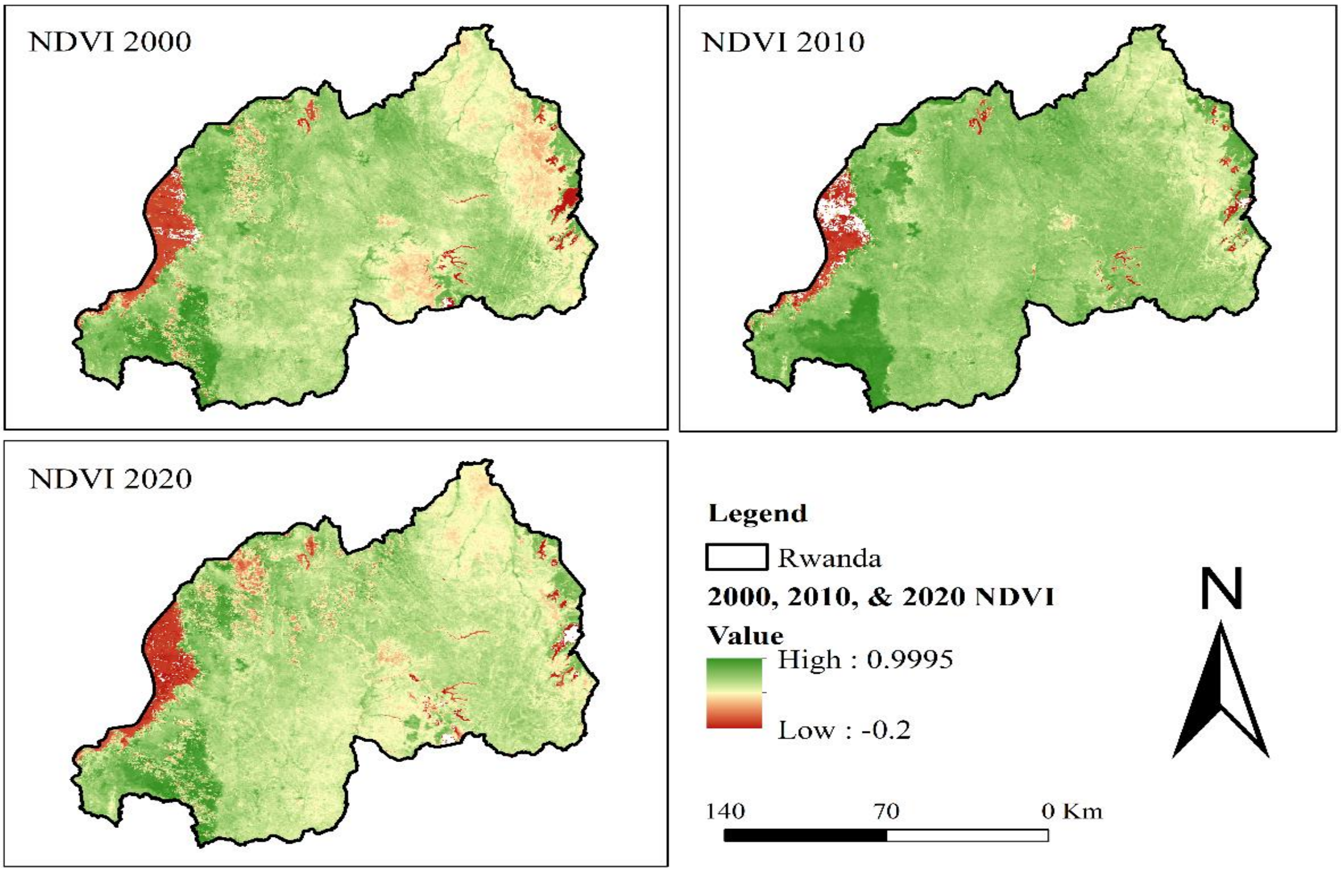

Figure 5: NDVI variation from 2000 to 2020

NDVI is a satellite-derived index that measures the amount of green vegetation on the Earth's surface. NDVI can be used to assess the health and productivity of crops. Climate change can cause changes in NDVI by affecting photosynthesis, evapotranspiration, and other plant physiological processes. High NDVI values indicate dense vegetation, while low NDVI values indicate sparse vegetation or no vegetation. The NDVI of Rwanda has decreased over the past 20 years. This is consistent with the fact that rainfall in Rwanda has also decreased during this period. The annual rainfall in Rwanda for 1990, 2000, 2010, and 2020 was 1160.1 mm, 1078.2 mm, 1402.4 mm, and 1391.1 mm, respectively. These values show that the annual rainfall in Rwanda can vary significantly from year to year. For example, the rainfall in 2010 and 2020 was significantly higher than in 1990 and 2000. NDVI image shows Rwanda had higher vegetation cover in 2010 and 2020 than in 2000. This is consistent with the recorded rainfall data, which shows that Rwanda had more rainfall in 2010 and 2020 than in 2000. Here is a more detailed comparison of the NDVI image and the rainfall data:

Table 3. Correlation of the NDVI image and the rainfall data

Years	Rainfall (mm)	NDVI level
2000	1078.2	Low
2010	1402.4	Very high
2020	1391.1	High

According to Table 3, there is a positive correlation between NDVI and rainfall. This is because NDVI measures vegetation health, which needs water to grow.

More water is available for vegetation when there is more rainfall, and NDVI is higher. The image shows that the highest NDVI values in Rwanda are found in the western and northwestern parts of the country. These areas also have the highest rainfall. This suggests that these areas are most suitable for agriculture. The eastern and southeastern parts of the country have lower NDVI values and rainfall. This suggests that these areas are less suitable for agriculture. However, some areas in these regions still have higher NDVI values, which suggests that agriculture is still possible but may require more irrigation or other management practices.

3.3. Rainfall variability in both seasons and months

Figure 6 and Figure 7 show the rainfall changes from 2000 to 2020 and rainfall variability and distribution from January to December.

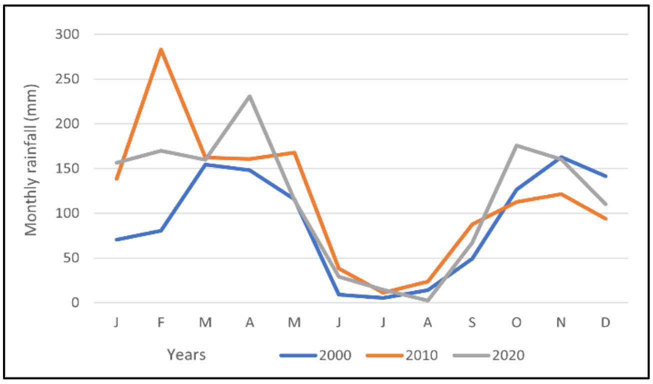

Figure 6: Monthly rainfall distribution and rainfall decreasing trend line (January to December)

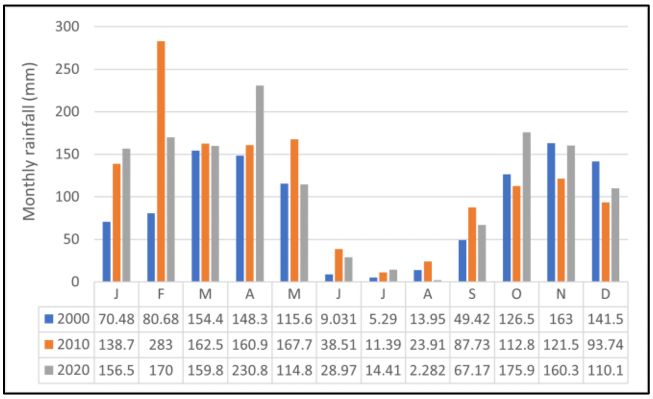

Figure 7: Monthly and Annual rainfall distribution and variation

According to Figures 6 & 7, MAM receives high rainfall, followed by SON, then DJF, and finally JJA. Generally, the country experiences two rainy seasons: a long rainy season from March to May (MAM) and a short rainy season from September to November (SON). During the long rainy season, the country experiences heavy rainfall, especially in the western and northwestern parts, while the eastern and southeastern parts receive less rainfall. The long rainy season is essential for agriculture, providing the necessary moisture for growing crops. The short rainy season is less intense than the long rainy season. During this time, the country experiences moderate rainfall. Also, Rwanda experiences two dry seasons each year, ranging from June to August (JJA) and December to February (DJF) (Muhire et al., 2018). During these times, the country receives very little rainfall. The dry seasons can be challenging for agriculture, as crops can suffer from drought. During the specified timeframe, Rwanda experiences abundant rainfall from September through the end of May, followed by a decline in precipitation from early June to late August. This pattern can negatively impact rain-fed agriculture due to irregular rainfall and droughts, resulting in water scarcity, crop loss, and diminished yields. Additionally, rural households dependent solely on subsistence farming are prone to experiencing reduced income levels, as they cannot generate surplus produce for the market (Ngango & Seungjee, 2021). During the dry season, growing upland crops can be tricky due to their specific water needs. At first, they require 30 millimeters of water each month, but as they grow, this jumps to 120 millimeters. Assuming the soil can hold 50 millimeters of water for every 75 centimeters of depth, we ideally need 100 to 140 millimeters of monthly rainfall to keep the crops healthy. This highlights the difficulty of providing the right amount of water during dry seasons (Oldeman & Suardi, 1977).

4. Conclusion and recommendations

As we observe the patterns in Rwanda, it becomes clear that there is a strong correlation between rainfall and vegetation cover. The gradual decrease in rainfall from the west to the east has a direct impact on the vegetation, with areas that receive higher rainfall boasting denser vegetation cover. This is particularly evident in the national parks and northwestern regions. Research has shown that there is a direct relationship between increased rainfall and augmented vegetation, while reduced rainfall leads to decreased vegetation cover. Moreover, it is evident that areas in the eastern province, which receive lower rainfall, suffer from diminished vegetation. Given the critical role of trees in influencing rainfall patterns, it is recommended that trees be strategically planted in regions with lower rainfall, particularly in the eastern areas. This intervention aims to mitigate the effects of drought and associated negative impacts by potentially influencing local rainfall patterns positively. In summary, this research underscores the pivotal relationship between rainfall and vegetation cover in Rwanda. It emphasizes the need to address areas with lower vegetation cover by implementing tree planting initiatives to combat drought and related adversities while leveraging the interconnection between trees and rainfall to foster a more balanced ecosystem across the country.

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Author contributions

Rosette Ambiance Shema: Conceptualization, Data curation, Writing-Original draft preparation, Methodology, and Software. **Li Lanhai:** Visualization, Investigation, Writing-Reviewing, Editing Validation.

Conflicts of interest

The authors declare no conflicts of interest.

Statement of Research and Publication Ethics

Research and publication ethics were complied with in the study.

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