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Mitigating and adapting to climate change: the role of nature-based solutions in sustaining vegetation health in the Isiukhu River Basin

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NbS are increasingly recognized for their ability to bolster ecosystem resilience and alleviate climate change impacts. This study evaluated the relationship between these solutions and vegetation health in the River Isiukhu Basin, using the NDVI to assess their effectiveness in addressing climate challenges. Focusing on the period from 1990 to 2023, the research analysed shifts in NDVI alongside temperature and precipitation patterns in the basin, while evaluating how NbS such as afforestation acted as moderating factors. Four key afforestation projects were instrumental in the region. Data on NDVI were sourced from Google Earth Engine and ArcGIS Pro 3.2, while precipitation and temperature information were obtained from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) and TERRACLIMATE, respectively. The interactions among NbS, NDVI, temperature, and precipitation were analysed using Pearson correlation at a 95% confidence level. Findings revealed that afforestation NbS significantly impacted vegetation health and climate conditions. Notably, NDVI in the Isiukhu basin increased by 39.86% from 1990 to 2023, coinciding with a 22.8% rise in precipitation (an increase of 428.53 mm) and a 7.33% increase in mean annual temperature (1.48 °C). A strong positive correlation was identified between NDVI and precipitation (r = 0.6105, p = 0.000), while the relationship between NDVI and mean annual temperature was negative and non-significant (r = –0.006539, p = 0.9737). Therefore, sustaining vegetation health through NbS is not only an ecological necessity but also a strategic policy pathway for mitigating climate change impacts, enhancing sustainable landscape management, and securing long-term ecosystem services in climate-vulnerable Isiukhu River Basin.

KEYWORDS

climate change, nature based solutions (NbS), precipitation, temperature, vegetation health

1 Introduction

Nature Based Solutions (NbS) refer to human actions that protect, restore and sustainably manage ecosystems to address environmental and societal challenges, including climate change, water security, food security, biodiversity loss and human health (Kibii et al., 2025). While the idea of working with nature is not new, communities have long practiced nature-based stewardship by combining indigenous and modern innovative ecological wisdom to offer inclusive and sustainable solutions to this challenges. In the context of accelerating global environmental change, ecosystems worldwide are under increasing pressure from both anthropogenic and climatic drivers. River basins, which are critical hotspots of biodiversity and socio-economic development, have increasingly become hotspots of environmental degradation (Meraj et al., 2018). Changes in vegetation cover resulting from land-use change, deforestation, and climate variability intensify ecosystem stress, undermining ecological integrity and threatening the livelihoods of communities that depend on these systems (Foley et al., 2005; Garai et al., 2022; Singh et al., 2024). Consequently, innovative strategies such as NbS are increasingly recognized as essential tools for sustaining and restoring natural habitats under changing climatic conditions.

Globally, climate change remains one of the most pressing environmental challenges, exerting profound impacts on ecosystems that are heavily dependent on natural resources for ecological services and livelihoods (Guha and Govil, 2020; Lata and Gosh, 2022). Vegetation health plays a critical role in regulating ecosystem functions, including carbon sequestration, soil stabilization, hydrological regulation, and microclimate moderation (United Nations, 2019; Ramakreshnan and Aghamohammadi, 2023). Empirical studies have demonstrated strong linkages between vegetation health and climatic variables such as temperature and precipitation, though the nature and strength of these relationships vary across space and time and are often influenced by human activities (Hissan et al., 2024). In tropical environments, several studies have reported a generally negative relationship between vegetation indices such as NDVI and temperature, underscoring the vulnerability of tropical vegetation to warming trends (Yue et al., 2007).

Despite the potential of NbS to mitigate climate change impacts, limited research has been conducted in the Afrotropical region, particularly in the context of vegetation health (Mård et al., 2017; Keesstra et al., 2018). Much of existing literature has focused on global or continental scales, with limited attention on small tropical river basins where climate-ecosystem–human interactions are most pronounced (Mård et al., 2017; Debele et al., 2023). Furthermore, many studies have examined climate attributes and vegetation dynamics in isolation, rather than explicitly analysing how they interact to mitigate climate change impacts (Carlson and Ripley, 1997; Raymondi et al., 2013; Huang et al., 2021). These gaps are particularly evident in the Afrotropical region, where empirical evidence on the effectiveness of NbS in sustaining vegetation health remains scarce (Mård et al., 2017). Understanding the interaction between NbS and vegetation health is critical for informing mitigation and adaptation strategies that are both effective and sustainable (Pettorelli et al. 2005). In view of the fact that future climate warming could also influence climatic shifts in varying landscapes such as river basins, it is necessary to investigate the linkages between NbS, vegetation health and climatic changes, an issue that has been much less explored, thus becoming a significant gap that this study intend to fill. In the River Isiukhu Basin, where human activities and climate pressures intersect, assessing the effectiveness of NbS such as afforestation in enhancing vegetation health is particularly important.

Nature-based solutions offer a promising framework for addressing these climate change challenges by harnessing the power of natural processes to enhance vegetation health, restore ecosystems, and improve resilience to climate impacts (IUCN, 2016; Seddon et al., 2020; Hobbie and Grimm, 2020). These solutions, which include practices such as afforestation, reforestation, agroforestry, and sustainable land use, seek to mitigate climate change by promoting vegetation health, improving biodiversity, and enhancing the capacity of ecosystems to adapt to environmental changes. NbS are often praised for their ability to go beyond short-term transformations, contributing to long-term climate change mitigation, biodiversity conservation and systemic change. However, there is very little research about their potentials in improving the river basins' vegetation health (Greksa et al., 2024).

At the local scale, River Isiukhu Basin, situated within the Kakamega Forest ecosystem, represents a vital ecological and hydrological landscape in western Kenya. The basin faces multiple challenges, including deforestation, soil erosion, land-use change, and increasing climate variability (Tela et al., 2025). These pressures have heightened the basin's vulnerability to altered rainfall patterns and rising temperatures, and extreme weather events (Gogoi et al., 2019; Singh et al., 2024; Ahmad et al 2024). Such changes threaten biodiversity, water resources, and vegetation health, thereby undermining ecosystem services and the livelihoods of communities that depend on the basin's natural resources. In the River Isiukhu Basin, where human activities and climate pressures intersect, assessing the effectiveness of NbS, particularly afforestation, in enhancing vegetation health is both timely and necessary for informing locally grounded, evidence-based climate mitigation and adaptation strategies. Therefore, this study assessed the roles of nature-based solutions on vegetation health in the Isiukhu River Basin in the face of the changing climatic conditions using the Normalized Difference Vegetation Index (NDVI) as a proxy for vegetation health. Through the lens of NbS, we examined how these approaches not only safeguard vegetation health but also empower local communities, fostering a more sustainable and resilient future for the region. Specifically, the study sought to answer the following research questions:

1 What afforestation NbS projects are implemented in the river Isiukhu basin, and how are they utilized by residents?
2 What are the relationship between NbS and vegetation health in the river Isiukhu basin.
3 To what extent has the identified afforestation NbS projects contributed to climatic variabilities in the river Isiukhu basin.

Theoretically, the study findings advance interaction between ecosystem-climate interaction in tropical context, while practically informing evidence based policies and land management strategies by identifying locally based climate change mitigation strategies.

2 Materials and methods

2.1 The study area

The River Isiukhu Basin is the catchment area that drains into the River Isiukhu (Figure 1). The Isiukhu River is located in Kakamega County, Kenya. It flows through a region characterized by lush green landscapes and rich biodiversity, typical of the Western Highlands of Kenya (Figure 1).

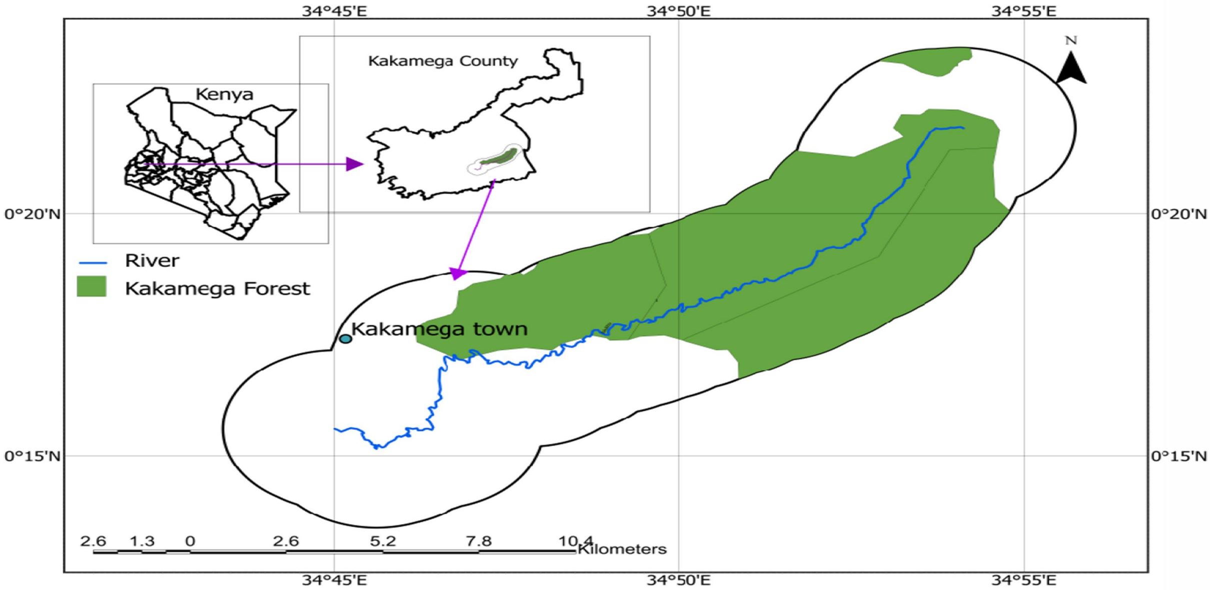

FIGURE 1
Study area.

River Isiukhu originates from the Nandi Escarpment and flows through the Kakamega Forest and empties its water into the river Nzoia which drains in Lake Victoria, the second largest fresh water lake in world. This basin is part of the larger Nzoia River catchment, which ultimately drains into Lake Victoria. The River Isiukhu Basin plays a crucial ecological role, particularly as it flows through the Kakamega Forest, the last remnant of the Guineo-Congolian rainforest in Kenya. The basin supports a variety of ecosystems and provides vital water resources for local communities and wildlife. The latitudinal extent of the basin is 0° 15′–0° 25’ North while longitudinal extent of the basin is 34° 40′–34° 50′ East of the equator. The river basin covers approximately 683 km^2. The upper and middle section of the river basin is covered by dense forest (Kakamega forest and North Nandi Forest) while the lower section is urbanised and dominated by agricultural surfaces. The river basin experiences typical equatorial climate associated with high rainfall (2,000 mm per annum) and high temperatures (26 °C). The rainfall is bimodal with long rains experienced between March and May and short rains from August to October. From the end of December to February is usually a dry season (Onyando et al., 2016). The study area is situated on underlying basaltic rocks and is characterised by undulating terrain. The soils are deep, well drained and heavily leached fertile clay-loamy soils (Seswa, 2016). The basin elevation ranges between 1,240 and 2,000 meters above sea level. General land cover within the river basin varies in relation to natural forest, grassland, agriculture and urban settlement. Despite this river basin being a significant biodiversity hotspot and a source of livelihood, it has become a hotspot of degradation (Tela, 2023). The river’s course is shaped by the hilly terrain, with several tributaries feeding into it, contributing to its volume. The basin is predominantly agricultural, with local communities engaging in farming activities. The river basin also supports various ecosystems, providing habitat for aquatic and terrestrial wildlife.

2.2 Data collection and analysis

2.2.1 Data on nature-based solutions

The paper adopted a theory-informed, qualitative case study design to examine the available NbS in River Isiukhu basin for climate mitigation and sustaining vegetation health. The data on prevailing NbS within the river basin was obtained through field surveys, Key Informant Interviews and content analysis. Literature review was done to establish the available NbS in Kakamega County. The analysis further established the NbS that majorly focus on River Isiukhu basin. Based on the research findings, a field study was carried out to the area of study to establish whether indeed this NbS existed.

Field surveys majorly targeted NbS project managers and community opinion leaders to assess how residents of this region understand and engage with NbS projects. Given the focus on complex social dynamics aspect of the study, qualitative methods were selected as they allow for a richer, more informed understanding of community members’ and project members perspectives on NbS. Semi-structured interviews were conducted with three NbS project leaders and six community members (three women, three men). These nine participants were sufficient since they provided context rich insights that complemented climate and remote sensed datasets, making the sample size adequate for capturing the dominant narratives relevant to the study aims. All the key informants were selected purposively based on immense knowledge of the study area, their active engagement with the various NbS projects and their availability at the time of data collection.

The interviews took place in the month of August and September, 2024. The interview session sought to establish the available NbS in the study area, the activities carried out by the NbS and the community perception on the effect of NbS on vegetation health and climatic conditions of the region. Qualitative data from this study was analyzed using content, thematic and narrative analysis methods (Kiger and

Varpio, 2020). This analysis allowed for the extraction of dominant and relevant themes and information related to NbS, as expressed by community members and NbS project leaders.

The data was categorized according to the four themes which included: the year of establishment, key activities that the NbS initiative engages in, the influence of NbS on vegetation health and, the influence of NbS on regional climatic conditions. Subsequently, the comparison of key findings allowed for drawing conclusions regarding commonalities and differences. A potential limitation of the study is the different data collection methods that ranged from field survey and use of online geodata portal. However, these variations enhanced the quality of the data collected. The study adopted a consistent analytical framework, that facilitated robust cross-site data collection and analysis.

2.2.2 Data on normalized difference vegetation index

To establish variations in vegetation health, satellite images from the United States Geological Survey (USGS) website were collected and analysed for the years running from 1990 to 2023. A median of one image derived for the each selected years was used. Landsat 4 images were derived for the year 1990 to 2003 using google earth Engine. For 2004 to 2013, Landsat 5 imageries were used. For 2013 to 2023, Landsat 8 images were used. 1990 image (when there was no NbS) was selected for comparison analysis. The images underwent pre-processing which included cloud removal, clipping and compositing based on the area of study using Google Earth Engine and ArcGIS Pro. Image analysis involved selecting one image which was a median of the available images for the whole year. The selected imaged had a cloud cover of less than 5%. For accuracy assessment, positional accuracy assessment was conducted by using error matrices producers, users, and kappa accuracies. Forty (40) ground control points (GCP) were determined for the satellite images. The GCP was selected based on various land use classification where points were collected. Barren land, sand was represented by very low NDVI values of less than 0.1. Sparse vegetation such as shrubs and grassland had moderate NDVI values ranging from (0.2 to 0.59). High NDVI values (approximately 0.6–0.9) corresponded to dense vegetation such as forests or crops at their peak growth such as tea plantations. According to accuracy assessment, the image of 2023 and 2013 years had higher RF test accuracy value (93%) and (87%) with Kappa Index of 0.89 and 0.82, respectively. On the other hand, the images of 2003 and 1990 years had lowest RF test accuracy value (83%) and (79%) with Kappa Index of 0.78 and 0.71, respectively. The values were found to be acceptable.

NDVI was selected to determine the vegetation health because of its ability to quickly delineate vegetation and vegetative stress thus making it of great significance in commercial agriculture and land-use studies (Huang et al., 2021). Research has shown that NDVI is effective to differentiate savannah, dense forest, non-forest and agricultural fields and to determine evergreen forest versus seasonal forest types (Pettorelli et al. 2005). NDVI uses light reflectance in near-infrared (NIR) and visible wavelengths to determine vegetation viability and health. The images were taking after every 10 years as a mechanism to identify vegetation health in different periods based on different NbS that were taken at that time. NDVI for 1990 and 2003 used Landsat 4 while NDVI for 2013 and 2023 used Landsat 8. NDVI was derived using the following formula:

NDVI = (NIR − RED).

(NIR + RED)

Where NIR = Near-Infrared reflectance; Red = Red reflectance.

For 1990 and 2003 imageries:

NIR = Band 4.

RED = Band 3.

As for the imageries for 2013 and 2023:

NIR = Band 5.

RED=Band 4.

NDVI values range from −1 to +1. Healthy vegetation typically has values between 0.2 and 0.8, while barren land and water bodies have lower values.

NDVI is a popular satellite-based index used for monitoring vegetation health over large areas (Kumar et al., 2021) and is widely used remote sensing metric in various fields such as forestry, ecology, agriculture as well as monitoring and tracking vegetation conditions over time. Comparative studies of prolonged-time series of NDVI can give helpful evidence for tracking region vegetation health in relation to NbS intervention. The NDVI in this study was delivered as a single band product with values ranging from −1 to +1, with bare soil having a value around zero, and plants having a positive value (Lillesand et al., 2015).

2.3 Climatic data collection

Data on precipitation was collected from Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS). CHIRPS provides reliable weather data for conducting environmental assessments, especially in the context of Sub Saharan Africa, where weather station coverage is poor and with incidences of missing data (Kiprotich et al., 2021; Sacré Regis et al., 2020). Temperature data was collected from TERRACLIMATE.[1] Time series Climate data was collected for the years ranging from 1990 to 2023. The data was downloaded and analysed into mean annual precipitation, mean monthly temperature and mean annual temperature for the stated period of time based on the introduction of NbS in the study area. Pearson correlation was used to determine the strength of relationship between NDVI and climate variables. Non-parametric Mann–Kendall linear regression trend test was used to visually detect these relationships. Negative value indicates decreasing trend while positive value indicates an increasing trend.

3 Results

3.1 Nature based solutions in the study area

The major four afforestation NbS projects recorded in the basin were the Plantation Establishment and Livelihood Improvement Scheme (PELIS), Muliru Farmers Conservation Group, Kakamega Natural Forest Catchment Conservation Organization (KANFCCO) and EMAUA. PELIS was established after enactment of the forest act (2005) (Agevi et al., 2016). PELIS, which is a synonymous project to

1 https://developers.google.com/earth-engine/datasets/catalog/IDAHO_EPSCOR_TERRACLIMATE

the famous 'shamba system', was adopted by the Kenyan government in effort to protect and conserve forest ecosystems such as Kakamega forest. Through this system, the local community are allowed to grow crops under agroforestry in degraded regions within the forest. The farmers are allowed to tend their crops even as they watch over the tree seedling. Once the crops are harvested, it is expected that the trees are left to grow as a rehabilitation strategy within the deforested region.

EMAUA (*Emaua,* in the native Ateso language, is a wild plant) project, is a Swiss-Kenyan non-profit making organisation that was founded in 2015 with the objective of planting one million indigenous trees per year by 2025 and preserve native biodiversity (Figure 2). EMAUA partners with community-based organisations in Kakamega and Busia counties to plant indigenous trees in protected areas like Kakamega forest to enhance biodiversity. Other roles include sensitising locals on importance of protecting indigenous trees, promoting economic stability, self-reliance and sufficiency of local communities through promoting organic farming and planting native seedlings in tree nurseries, encouraging use of energy saving stoves to reduce deforestation, protecting vulnerable, threatened and endangered tree species through collaborating with Kenya Forest Service and Kenya Wildlife Service.

Muliru Farmers Conservation Group was founded in 1997 (Akala, 2021). This is a community-based organization located near Kakamega Forest in western Kenya. The group generates income through the commercial afforestation, agroforestry and selling of herbal medicinal products. The enterprise reduces pressure on the Kakamega Forest by offering an alternative to the exploitation of forest resources, while the commercialization of the medicinal plant has heightened local appreciation of the value of the forest's biodiversity. A portion of the enterprise's revenues are invested in forest conservation and biodiversity research while conserving the Kakamega forest. The organization is investing in mitigating the effects of climate change and enhancing community livelihoods.

Kakamega Natural Forest Catchment Conservation Organization (KANFCCO) (Akala, 2021) is an afforestation NbS in the River Isiukhu watershed that is involved in environmental activities and conservation of genetic resources within the Kakamega region. The organization promotes the growing of the much-exploited medicinal *Mondia whytei* as a strategy to reduce its overexploitation in Kakamega forest. *Mondia whitei* is an herbal medicine with various medicinal values such as treating infertility and increasing fertility.

3.2 NDVI trends in the river basin

NDVI values from 1990 to 2023 were established to show the changes in vegetation health within the river basin (Figure 3). Results show that there was a general increase in vegetation health index in the river basin over a 33-year period. Some of the years that recorded very low NDVI were 1990, 2000, 2009, and 2019 with 0.4428, 0.4727, 0.4732, and 0.506, respectively. On the contrary, the highest NDVI of 0.6468 was recorded in the year 2021.

At decadal context, NDVI maps for 1990, 2003, 2013, and 2023 revealed mean NDVI of 0.4428, 0.535, 0.62, and 0.6193, respectively (Figure 4). NDVI in Isiukhu basin increased by 20.84% between 1990 to 2003 and 15.89% between 2003 and 2013. In general, the NDVI of the region increased by 39.9% between 1990 and 2023.

3.3 Precipitation and temperature trends in the river basin

The overall precipitation within Isiukhu basin increased by 22.8% (428.53 mm) between 1990 and 2023 at decadal levels (Figure 5). Precipitation increased minimally by 0.45% between 1990 and 2003, 13.7% between 2003–2013 and 7.5% between 2013 and 2023. Over this period, the highest precipitation was recorded in 2020 with 3032.46 mm while the lowest precipitation was recorded in 1993 with 1590.1 mm.

The four-season periods in the study area [December–January–February (DJF), March–April–May (MAM), June–July–August (JJA) and September–October–November (SON)] all recorded variations in the amount of precipitation (Figure 6). Lowest amount of rainfall was recorded in the DJF season. The highest amount of precipitation was recorded in the MAM period except for the years 1992, 2007, 2008, 2011, and 2014 where the highest amount of precipitation was recorded in the JJA season. In 2012 and 2019, the highest amount of precipitation was recorded during the SON season.

FIGURE 2
EMAUA afforestation project in river Isiukhu Basin.

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FIGURE 3
Trends in NDVI values for Isiukhu River Basin 1990–2023.

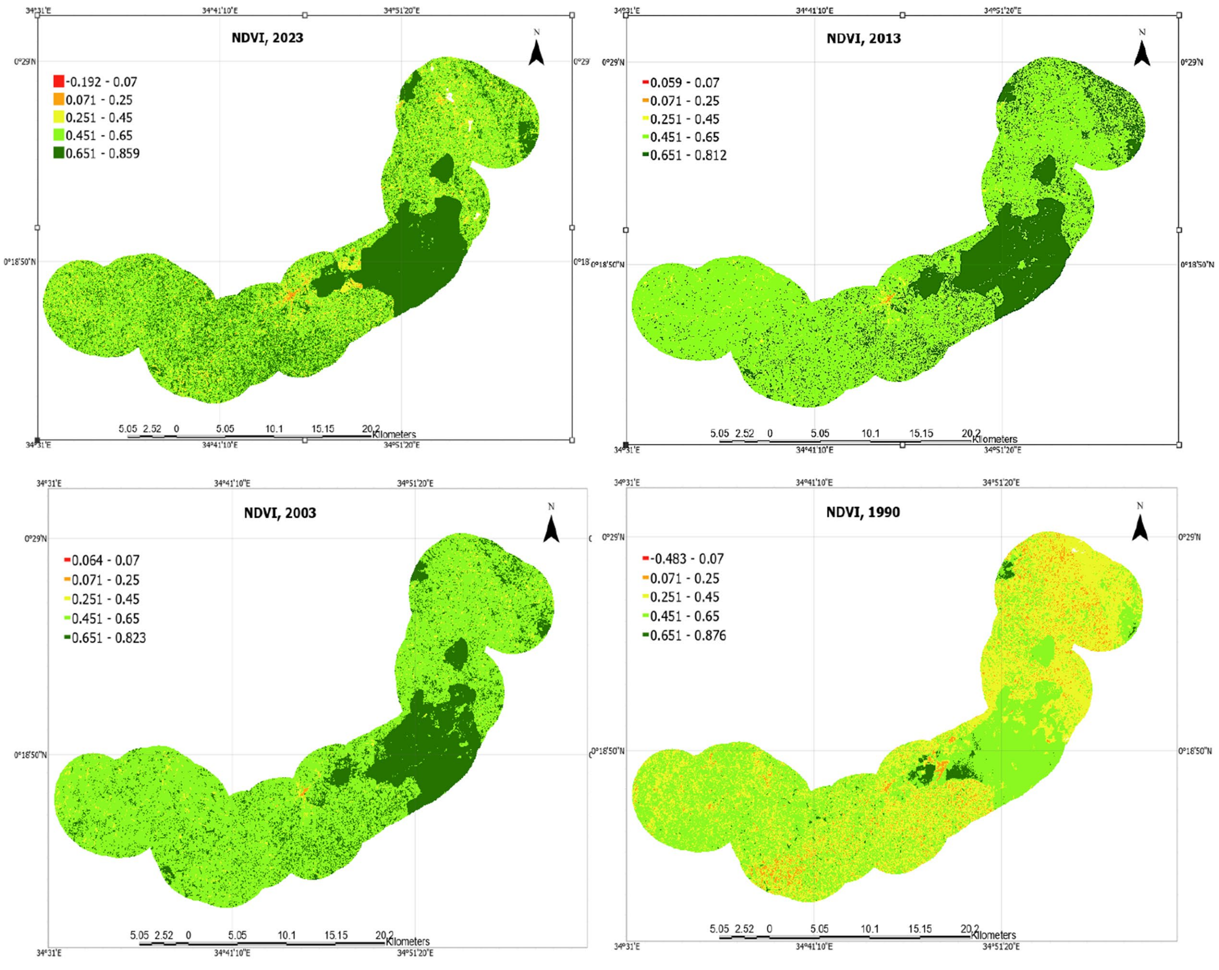

FIGURE 4
NDVI status from 1990 to 2023.

Variations were also noted in the maximum and minimum temperature in the entire basin from 1990 to 2023 (Figure 7). Mean annual temperature increased by 7.33% (1.48 °C) between 1990 and 2023, which is consistent with global warming trend (Alemayehu et al., 2023). Furthermore, the basin recorded a mean annual temperature range of 1.47 °C. At decadal level, the mean temperature increased by 6.09% (1.23 °C) between 1990 and 2003, decreased by 2.71% (0.58 °C) between 2003 and 2013 and increased by 3.98% (0.83 °C) between 2013 and 2023. Over this period, the highest mean maximum temperature recorded in 2023 was 29.73 °C followed by 2009 with 29.717 °C and 2019 with 29.67 °C. The lowest mean maximum temperature was recorded in 1992 with 28.102 °C, followed by 1990 and 1994 with 28.14 °C and 28.16 °C, respectively.

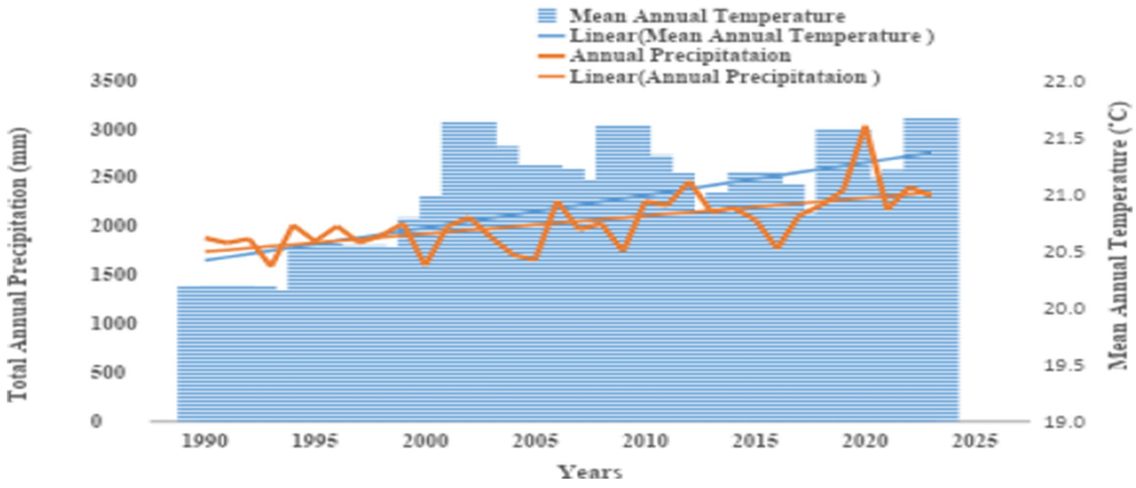

FIGURE 5
Precipitation and temperature trends 1990–2023.

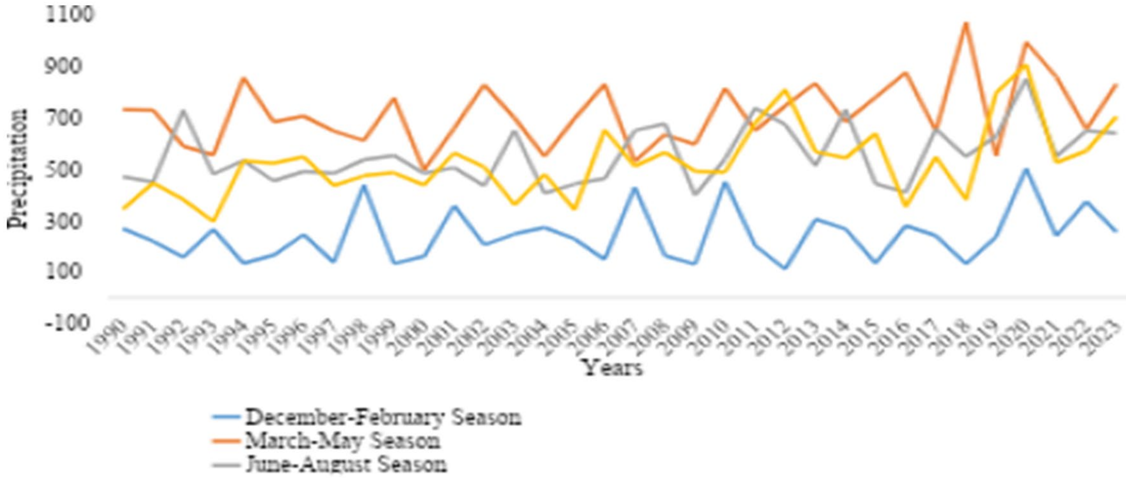

FIGURE 6
Precipitation trends in different seasons from 1990 to 2023.

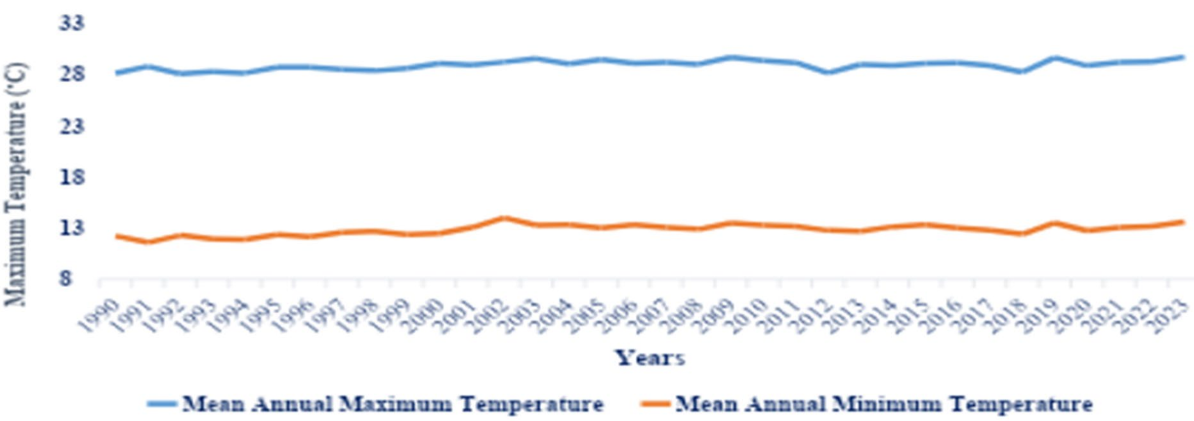

FIGURE 7
Minimum and maximum temperature trends from 1990 to 2023.

3.4 The Nexus between the NDVI, climate variability and the nature-based solutions

For this study, the period 1990–2023 was divided into two parts: (a) 1990–1996 (no afforestation NbS project in the study area), (b) 1997–2023 [PELIS, Muliru Farmers Conservation Group, Kakamega Natural Forest Catchment Conservation Organization (KANFCCO), and EMAUA]. Over the period with NbS, the study area experienced a 16.98% increase in NDVI which translated to a 0.7% annual increase in precipitation (Figures 8, 9).

For the period of no NbS, the study established a 5.56% (100 mm) increase in precipitation between the 6 years (Figure 9). This translated to a 0.92% annual increase in precipitation. After the introduction of NbS, the region recorded a 33.3% (600 mm) increase in precipitation translating to 1.28% per annual increase (Figure 9). Increases were also recorded in temperatures with a 0.28 °C (1.39%) increase in temperatures over the period with no NbS. This translated to an annual increase in temperatures of 0.047 °C (0.232%). After the introduction of NbS, the region recorded an increase in temperature of 0.3 °C (1.44%) for the 26-year period. This translated to a 0.012 °C (0.06%) per annum increase in temperature (Figure 9).

Figure 10 shows vegetation health in relation to the establishment of the NbS in the river Isiukhu basin. The study established that before the introduction of NbS projects (1990–1996), the vegetation health of the study area had an NDVI of 0.529. With the introduction of Muliru Farmers Conservation Group (1997–2004), the NDVI increased to 0.548. The NDVI value increased further to 0.55 between (2005–2011) a season when PELIS was the introduced in the region. Between 2012 and 2014, the NDVI value increased even further to 0.6. A slight decline was recorded between (2015 and 2023) with the region recording an NDVI of 0.569. The results of this study reveal that the highest mean NDVI was achieved with introduction of KANFCCO and EMAUA projects.

Precipitation increased over time with introduction of various NbS projects in the river basin. The increases were also noted in different seasons as shown in Figure 11. During the season DJF, 207.58 mm of mean precipitation was recorded for the period 1990–1996. Precipitation increased to 243.75 mm during 1997–2004 period and 250.367 mm during the 2005–2011 period. A slight decline of 27.53 mm was recorded in the 2012–2015 period. An increase realized in the 2015–2023 period, recording 266 mm. MAM recorded increases for all the five periods with amount of precipitation increasing from 692.97 mm in 1990–1996 to 807.17 mm in 2015–2023 period. During SON, the region recorded 438.5 mm in the 1990–1996, 468.24 mm in the 1997–2004, 532.9 mm in the 2005–2011 and a further increase to 639.86 mm in 2012–2014 periods. A small decline was recorded in 2015–2023 period of 602.51 mm.

With reference to temperature, there was an increase in mean maximum temperature between the various seasons with respect to introduction of NbS (Figure 12). The mean temperature for 1990–1996 was 20.25° C. This value increased to 20.94° C during the 1997–2004 period. The mean temperature further increased to 21.24° C in the 2005–2011 period. A decline in mean maximum temperature was recorded in the 2012–2014 period of 20.77° C. There was an increase in the 2015–2023 period to 21.09° C (Figure 12). Results clearly show that except for 2012–2014 season, NbS did not positively influence temperatures of the river basin.

3.5 Relationship between vegetation health and climate variability

There was a significant positive association between NDVI, which is a proxy of vegetation health, and precipitation ($r = 0.6105$, $p = 0.00056$). The four different precipitation periods positively associated significantly with NDVI as a result of introduction of different afforestation NbS projects in Isiukhu River Basin ($r = 0.9692$, $p = 0.0065$). Specifically, December to February, March to May, June to August and September to November seasons had positive association with NDVI ($r = 0.4363$, $p = 0.4627$; $r = 0.8182$, $p = 0.09044$; $r = 0.9388$, $p = 0.01799$ and r = 0.9752, $p = 0.004661$), respectively. A negative non-significant association occurred between NDVI, an indicator of vegetation health and mean annual temperature ($r = -0.006539$, $p = 0.9737$).

The Mann–Kendall test in Figure 13 detected trends in distribution of vegetation health (NDVI), precipitation and temperature in the basin. In generally, NDVI showed a positive increasing trend in the entire basin. However, Mann–Kandall Tau correlation was more strong in areas where afforestation NbS was practised (Figure 13). Mean temperature showed an increasing trend in the entire basin, with areas practising afforestation NbS showing a

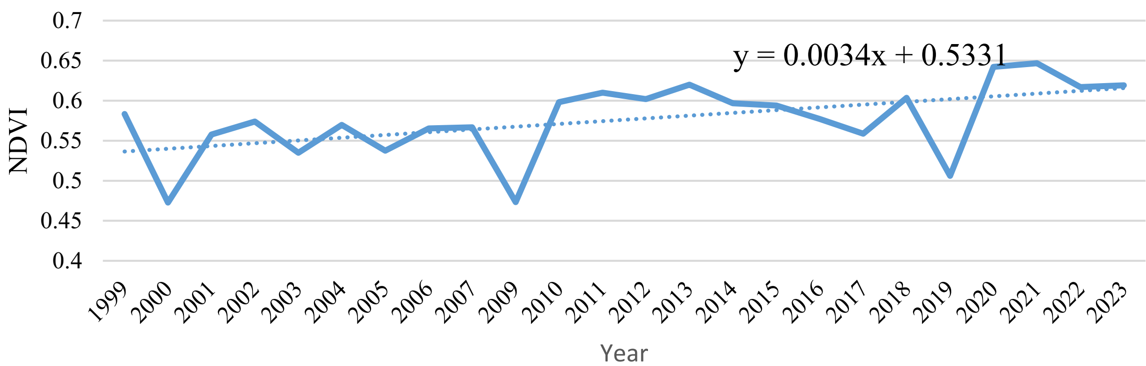

FIGURE 8
Trends in NDVI after the introduction of NbS.

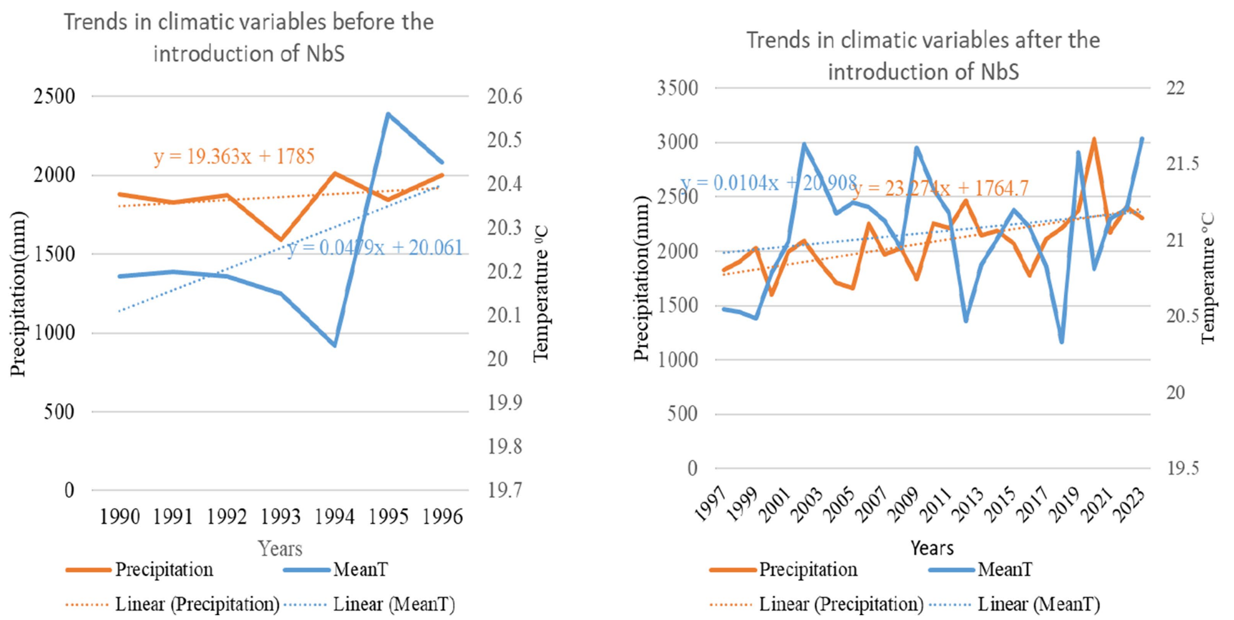

FIGURE 9
Trends in climatic variables before and after the introduction of NbS.

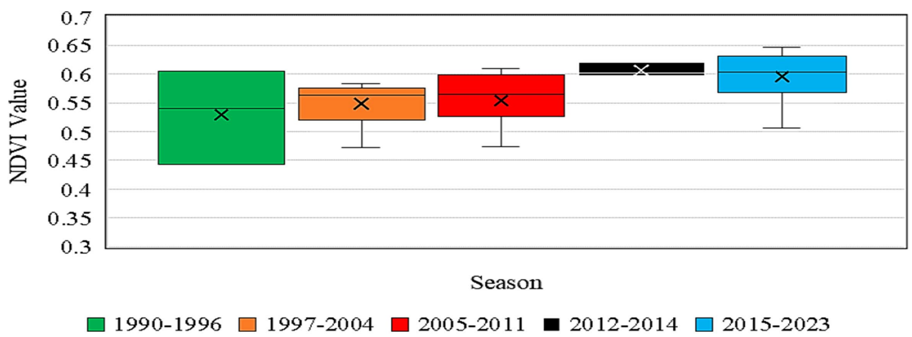

FIGURE 10
Distribution of NDVI in relation to establishment of NbS.

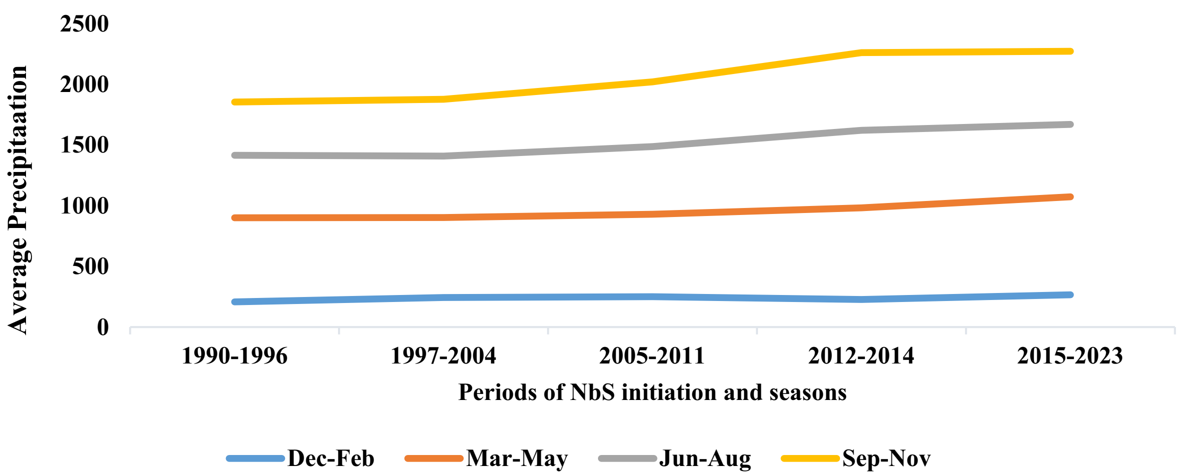

FIGURE 11
Precipitation patterns in relation to establishment of NbS.

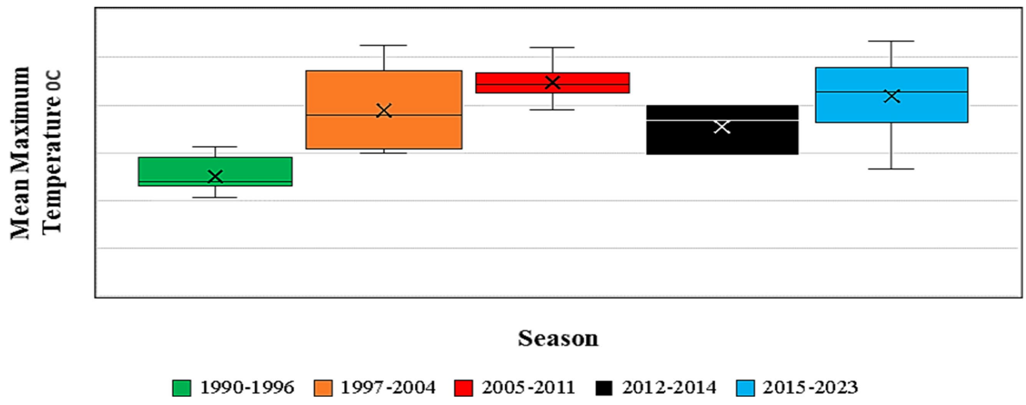

FIGURE 12
Mean maximum temperature in relation to introduction of NbS.

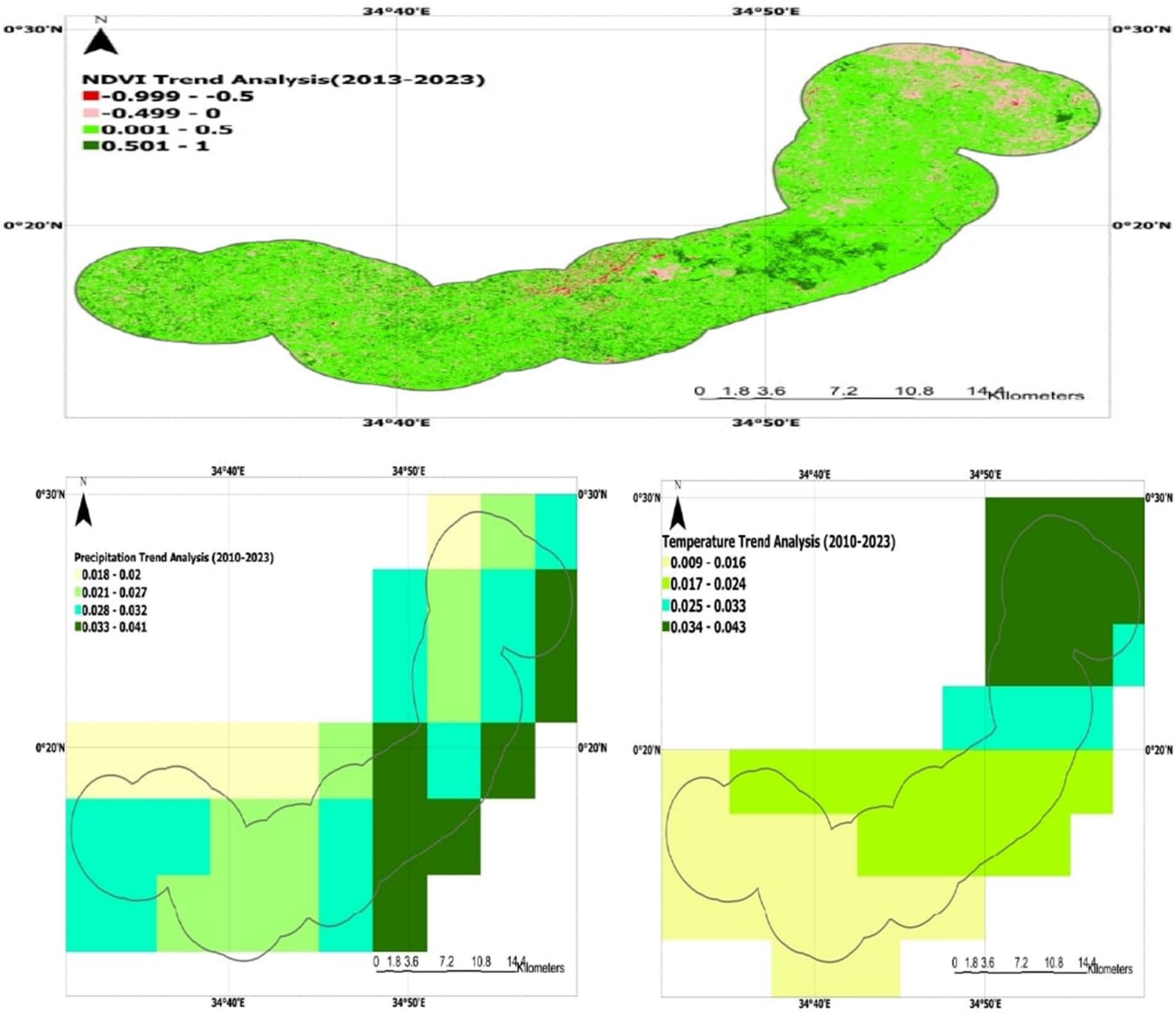

FIGURE 13
Mann–Kendall trend detection test for NDVI and climate variability in Isiukhu Basin.

slow increase in temperature, signifying the buffering and shading effects of trees on temperature.

4 Discussion

Four major afforestation NbS projects were initiated in river Isiukhu basin. The establishment of these projects in the Isiukhu River Basin coincided with a 39.9% increase in NDVI between 1990 and 2023, indicating a substantial improvement in vegetation health through restoration of canopy cover. This trend demonstrates that afforestation, a core NbS strategy in this basin, has been instrumental in restoring vegetation structure and enhancing overall ecosystem productivity in the basin. The NDVI increase suggests also a substantial improvement in vegetation health due to sustained management actions such as tree planting, riparian rehabilitation, and forest protection led by NbS actors (Lillesand et al., 2015). Similar outcomes have been recorded in China's Loess Plateau where large scale afforestation programmes led to marked improvements in vegetation cover and ecosystem stability (Wu et al., 2021). China's "Grain for Green" afforestation and restoration project has reported significant positive NDVI trends following tree-based rehabilitation efforts, confirming the strong relationship between targeted afforestation and vegetation recovery (Li et al., 2025). Studies such as Sun et al. (2021) likewise show that afforestation enhances photosynthetic activity, ground cover stability, and resilience to climate variability.

The Isiukhu Basin experienced increased total precipitation over the study period. Furthermore, there was a remarkable increase in precipitation during the period of implementation of NbS initiatives. Although year-to-year and seasonal variability precipitation remained high, the underlying trend points toward a gradual intensification of rainfall over the past three decades. This general increase can be attributed to the location of the basin in the equatorial zone as well as convectional rains due increase in evapotranspiration resulting from increase in vegetation health over the same period. Similar precipitation-vegetation health feedbacks have been reported globally, including in the India and central Africa where forested and reforested landscapes have been shown to increase atmospheric humidity and rainfall intensity (Duku and Hein, 2021; Gupta et al., 2024). Vegetation restoration through afforestation, such as those implemented in the Isiukhu Basin, can locally reinforce moisture recycling through enhanced evapotranspiration, which may help sustain convective rainfall (Huebner, 2020).

The Isiukhu River Basin experienced a notable rise in mean annual temperature of 1.48 ° cover the study period, accompanied by pronounced variability in the decadal trend. This warming trend is consistent with global and regional analyses showing accelerated temperature have been increasing across Sub -Saharan Africa since the 1990s, driven largely by anthropogenic greenhouse gases (Alemayehu et al., 2023). Similar magnitudes of warming have been reported in East African highland and basin systems, where increases of 0.8 to 1.5 °C over the past three to four decades have been documented (Gebrechorkos et al., 2023). Furthermore, general increase in local temperature over time may also point to urban heat island effects as a result of increasing urbanisation within Kakamega urban centre in the basin as well as expansion of bare surface areas due to increased land degradation (Berger et al., 2017; Lata and Gosh, 2022). While afforestation and greening may provide local cooling through shading and evapotranspiration, such biophysical effects rarely offset broader greenhouse-gas-driven warming at the basin scale (Rohatyn et al., 2023). This reinforces the need and urgency of integrating NbS with climate-resilient land and water management on a bigger national, regional and continental scale.

However, there was a notable moderation and slow increase of temperature during the NbS period and in areas practising NbS compared to period with no NbS project as well as areas with no NbS. While temperatures increased under both periods, consistent with global warming trajectories, the annual rate of warming slowed substantially after NbS implementation, from 0.047 °C annually in the pre-NbS period to only 0.012 °C annually during the NbS period. This attenuation of warming is consistent with the surface energy balance framework, whereby vegetated surfaces promote evaporative cooling, reduce sensible heat flux, and provide shading that lowers surface temperatures (Shipra et al., 2024). Comparable findings have been reported in reforested regions of Brazil and Mediterranean Europe, where forest expansion has been linked to localized micro- and meso-climatic cooling (Patrício et al., 2025; Sofiadis et al., 2022).

The positive significant correlation between NDVI and precipitation indicated that increased rainfall had positively influenced vegetation health. Higher precipitation supports plant growth, improves soil moisture, and enhances ecosystem productivity, contributing to the effectiveness of afforestation NbS efforts. This suggests that regions with increased precipitation have benefited the most from these solutions. Furthermore, a positive correlation between NDVI and precipitation point to good vegetation health and greenness in the area which are depended much on precipitation, implying that the healthier the vegetation, the more rainfall due to high evapotranspiration. Similar results have been reported in western Kenya. Similar results have been reported in other regions of the world where a strong temporal relationship between NDVI and rainfall occurred, and that precipitation patterns were determined by vegetation phenology (Dagnachew et al., 2020; Garai et al., 2022; Alemayehu et al., 2023). Many other studies have also investigated the association between NDVI and rainfall on both global and regional scales with the aim to unlock the close linkage between them (Martiny et al., 2006; Jammes et al., 2006). The NbS activities such as afforestation and other sustainable management practices might have led to increased NDVI, resulting in increased rainfall in the river basin (Borner et al., 2009). Results of this study clearly demonstrate that climatic variables and anthropogenic activities can significantly influence positively the vegetation cover and general ecosystem health (McAlpine et al., 2007; Raymondi et al., 2013).

However, a negative non-significant correlation occurred between NDVI and mean annual temperature. This suggests that rising temperatures over the study period did not significantly affect vegetation health in the River Isiukhu Basin. While temperature increases of 1.48 °C were recorded, the lack of a significant correlation indicates that, under current climate conditions, vegetation health was more sensitive to changes in precipitation than temperature. This could be due to the moderating effects of afforestation NbS projects, which may have buffered vegetation from the adverse effects of temperature rise. Forest cover, for instance, can reduce surface temperatures, increase humidity, and maintain soil moisture, thereby offsetting some of the negative impacts of higher temperatures.

The qualitative interviews with nine participants was vital in explaining and contextualising the quantitative findings from the NDVI and climate datasets. While the remote-sensing data showed long-term trends in vegetation health and climate variability, the interviews provided local explanations for these patterns, particularly the role of afforestation NbS in driving the observed 39.86% increase in NDVI. Participants described how tree-planting, riparian protection, and community involvement strengthened vegetation recovery, helping interpret the strong positive association between NDVI and precipitation. Their perspectives also clarified why vegetation remained relatively resilient to rising temperatures, highlighting the buffering role of increased tree cover. Therefore, the qualitative data did not aim for statistical generalisation but were used to deepen and validate the quantitative results, offering a comprehensive understanding of how NbS influence vegetation health in the Isiukhu River Basin.

Therefore, study demonstrates that NbS projects, particularly afforestation, have had a positive influence on both vegetation health and climate conditions in the basin. The increase in NDVI, despite rising temperatures, suggests that NbS can enhance ecosystem resilience to climate change by improving the capacity of ecosystems to adapt to environmental stressors. The significant correlation between NDVI and precipitation further underscores the role of NbS in managing water resources, reducing soil erosion, and enhancing the basin's ability to retain and distribute water, a critical function in climate adaptation strategies. Main limitation of the study is that there was much focus on correlation based relationships and or association rather than direct causality between afforestation NbS, vegetation health, and climate variability. While the study focused on afforestation projects, quantitative data on tree species composition and survival rates were not covered. Future studies should examine how different afforestation tree species and their survival rates influence climate.

5 Conclusion

The study's findings highlight the success of Nature-Based Solutions in enhancing vegetation health and mitigating some of the negative impacts of climate change in the River Isiukhu Basin. While precipitation had a stronger influence on vegetation health than temperature, NbS interventions have helped stabilize the ecosystem in the face of changing climatic conditions. These results support the broader adoption of NbS as a viable strategy for climate change mitigation and adaptation, particularly in ecosystems vulnerable to both anthropogenic pressures and environmental change. This research offers evidence based NbS strategies that can be integrated into Kenya's national and county climate action plans and beyond since interventions such as riparian restoration, afforestation and agroforestry improve vegetation health (NDVI) and mitigate climate change impacts. The study offers valuable contributions to the existing body of knowledge by contextualising global afforestation climate change mitigation strategy within a sub-Saharan region, a highly vulnerable region to climate variability and water stress. The study supports social-ecological and inclusive interventions strategies for climate change mitigation at basin scale level.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

ST: Formal analysis, Methodology, Writing – review & editing, Investigation, Writing – original draft, Conceptualization. NM: Writing – original draft, Formal analysis, Writing – review & editing, Software, Investigation, Project administration, Methodology, Validation. MT: Visualization, Formal analysis, Project administration, Data curation, Writing – review & editing, Methodology, Validation, Software, Investigation, Writing – original draft, Supervision, Resources.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that Generative AI was not used in the creation of this manuscript.

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