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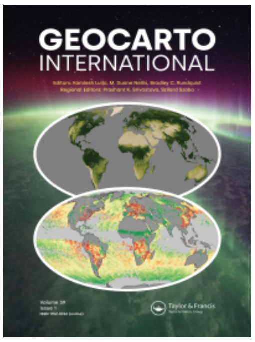

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Effects of vegetation composition changes on surface runoff and land degradation in Sahelian Watersheds

Elias Nkiaka[a,b], Moctar Dembélé[c], Roland Yonaba[d], Axel Belemtougri[d], Tazen Fowé[d], Aigbedion Imuwahen Priscilla[e] and Harouna Karambiri[d]

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ABSTRACT

The relationship between vegetation composition and surface runoff remains unstudied in the Sahel – a region with unique hydrological characteristics compounded by land degradation. This study investigates the effects of vegetation composition changes on runoff and land degradation trends in 45 Sahelian watersheds over two decades (2001–2020). Vegetation composition was assessed using vegetation continuous fields (VCFs) including tree canopy cover (TC), short vegetation cover (SV) and bare ground cover (BG) while vegetation cover was measured using the normalized difference vegetation index (NDVI). The analysis revealed significant increasing trends in annual NDVI across most watersheds, accompanied by gains in TC (mean = 1%) and SV (mean = 3%), and a decline in BG (mean = –6%) – indicating a reversal in land degradation. Results also showed that runoff is extremely sensitive to changes in vegetation composition parameters. These findings offer valuable insights for ecological restoration through the strategic selection of tree species to regulate surface runoff effectively.

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Desertification; runoff sensitivity; vegetation continuous fields; elasticity concept; Great Green Wall

1. Introduction

Understanding the factors affecting surface runoff generation is crucial for sustainable water resources management in arid regions such as the Sahel where surface runoff is extremely sensitive to climate and land cover conditions (Wendling et al. 2019; Yonaba et al. 2021; Bennour et al. 2023). For example, it is widely documented that during the Sahelian droughts that lasted from the 1970s to the 1990s, surface runoff increased significantly in the Sahel despite a decline in rainfall and extensive land degradation, which has been described as the 'Sahel hydrological paradox' (Favreau et al. 2009; Descroix et al. 2012; Gal et al. 2017; Grippa et al. 2017). In recent decades, the Sahel has witnessed significant increasing trends in annual rainfall (Biasutti 2019) and vegetation cover (Dardel et al. 2014; Souverijns et al. 2020; Jiang et al. 2023) which may have contributed to a decline in land degradation (Yang et al. 2022; Yan et al. 2024). However, increasing vegetation cover in the Sahel may not have led to a corresponding decline in surface runoff as anticipated or observed elsewhere (Buechel et al. 2022; Shi et al. 2024).

In fact, numerous field and modelling studies have reported that the runoff coefficient is still increasing in several Sahelian watersheds despite the widespread increase in vegetation cover. This phenomenon has been described as the second 'Sahel hydrological paradox' observed from the year 2000 onwards (Descroix et al. 2018; Gbohoui et al. 2021; Yonaba et al. 2021). Nevertheless, most of the studies investigating the effects of vegetation change on surface runoff in the Sahel have focused mostly on vegetation cover measured using the normalized difference vegetation index (NDVI) (Dardel et al. 2014; Gbohoui et al. 2021; Yonaba et al. 2021; Nkiaka et al. 2024a). Meanwhile, the effects of changes in vegetation composition

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on surface runoff are still poorly understood which is an important knowledge gap in Sahelian hydrology. Considering the unique hydrological behaviour of the Sahel – characterized by anomalous surface runoff increases during the drought period and under recent increases in vegetation cover, it is crucially important to understand how changes in vegetation composition affects surface runoff. Such information may be useful for implementing ecosystem restoration such as the ongoing Great Green Wall Initiative (GGWI) and for regional water resources utilization and planning.

Furthermore, most studies evaluating vegetation changes in the Sahel and other drylands have mostly adopted NDVI as a proxy for vegetation cover (Dardel et al. 2014; Jiang et al. 2023; Mallick et al. 2025). However, NDVI estimates may be less informative than direct assessment of vegetation composition as it primarily measures vegetation greenness and density without distinguishing between different vegetation types, especially on complex processes such as surface runoff and land degradation. Furthermore, NDVI estimates may be strongly influenced by environmental factors such as soil moisture and atmospheric conditions. On the other hand, several studies investigating land degradation trends in the Sahel have used different sets of variables such as a combination of NDVI and soil moisture (Ibrahim et al. 2015), albedo-modified soil-adjusted vegetation index (Yang et al. 2022) and moisture-responded net primary productivity estimates (Yan et al. 2024). To our knowledge, no study has assessed long-term changes in vegetation composition in the Sahel to determine the dominant vegetation types, nor used VCFs to evaluate land degradation trends in the region. These are important knowledge gaps in vegetation and land degradation monitoring in the Sahel. In fact, many studies have demonstrated that VCFs can be used to evaluate changes in land degradation in both drylands and forested regions (Gao et al. 2016; Song et al. 2018; Leng et al. 2020).

Vegetation composition in the context of this study refers to the proportion of different vegetation types including tree canopy cover (TC), short vegetation cover (SV) and bare ground cover (BG) measured using vegetation continuous fields (VCFs). The effects of vegetation composition on surface runoff cannot be overemphasized given that such changes can lead to distinct hydrological behaviour in watersheds (Luo et al. 2020; Chen et al. 2021; Tan et al. 2023; Nkiaka and Okafor 2024). Such differences in hydrological behaviour have been attributed to differences in root water uptake by different vegetation types which influence actual evapotranspiration, infiltration rates, water retention and vegetation structure which also affects rainfall interception by canopy among different vegetation types (Iroumé et al. 2021; Skhosana et al. 2023; Hidayat et al. 2024). Vegetation indices have also widely been used to assess land degradation (Badapalli et al. 2024).

Different techniques have been used to study the effects of vegetation change on surface runoff in the Sahel including field studies and hydrological modelling (Wendling et al. 2019; Yonaba et al. 2021). Other studies have adopted data-driven analytical techniques such as elasticity models and statistical methods (Gbohoui et al. 2021; Nkiaka et al. 2024a). Despite the plethora of methods available, hydrological models remain the most widely used for impact assessments in hydrology because of their ability to explain physical processes to some extent (Addor and Melsen 2019). However, hydrological models have some limitations such as huge input data needed for constraining the models, thereby limiting their application in poorly gauged watersheds (Nkiaka et al. 2018). On the other hand, analytical methods do not need calibration because of their simple model structure and do not also require much input data to produce results that are useful in most hydrological applications (Hasan et al. 2018; Zhang et al. 2023b). However, one of the limitations of this method remains the assumption that the watershed remains under hydrological steady-state conditions for a long period without significant changes in climate and land surface conditions. Despite this limitation, analytical methods are increasingly being used to study the effects of climate and vegetation changes on different components of the hydrological cycle (Hasan et al. 2018; Nkiaka and Okafor 2024; Zhang et al. 2023a; Nkiaka et al. 2024b). Numerous case studies suggest that analytical methods are well suited for understanding the effects of changes in vegetation composition and cover on surface runoff and as such, the same approach is adopted in this study. Furthermore, several studies evaluating land degradation reversal in the Sahel have adopted different methods such as albedo-modified soil-adjusted vegetation index (Yang et al. 2022), moisture-responded net primary productivity (Yan et al. 2024) and Markov models (Edwin et al. 2024). To our knowledge, no study has used VCFs to assess land degradation reversal in the Sahel even though VCFs have been reported to be a good proxy for monitoring land degradation (Leng et al. 2020). In the context of this study land degradation is characterized by a decline in TC and SV and an increase in BG. In the summary, the important knowledge gaps the present study intends to address are to (1) evaluate changes in vegetation composition and their effects on surface runoff in the Sahel and (2) assess land degradation trends in the region using VCFs.

Considering the above, the objectives of this study are to (1) evaluate changes in vegetation composition across the Sahel over two decades (2001–2020), and how this relates to land degradation, and (2) quantify the effects of changes in vegetation composition on surface runoff in the Sahel over the period (2001–2020). Unlike previous studies in the region that focused on small experimental watersheds, the present study leverages the availability of a wide range of high-resolution and long-term remote sensing and water resources reanalysis runoff data to conduct analysis that cover the whole Sahelian belt. The shapefiles used to delineate the watersheds were obtained from HydroSHEDS (Lehner and Grill 2013).

2. Methods

2.1. Study area

The Sahelian belt stretches west-east from the Atlantic Ocean to the Red Sea with a length of about 8000 km, covering more than three million square kilometres. It is located between latitude 10°–20° *N* crossing many countries with a population exceeding 200 million inhabitants (Figure 1). The Sahel is one of the worlds' largest water-limited environments and ranked amongst the most fragile ecosystems in the world (Ghins et al. 2022). The Sahel is remarkable due to a mega drought that affected the region from the 1970s to mid-1990s attracting media coverage due to the humanitarian crisis that ensued from the drought. Lake Chad located in the Sahel is also famous due to its desiccation from 25,000 km^2 in the

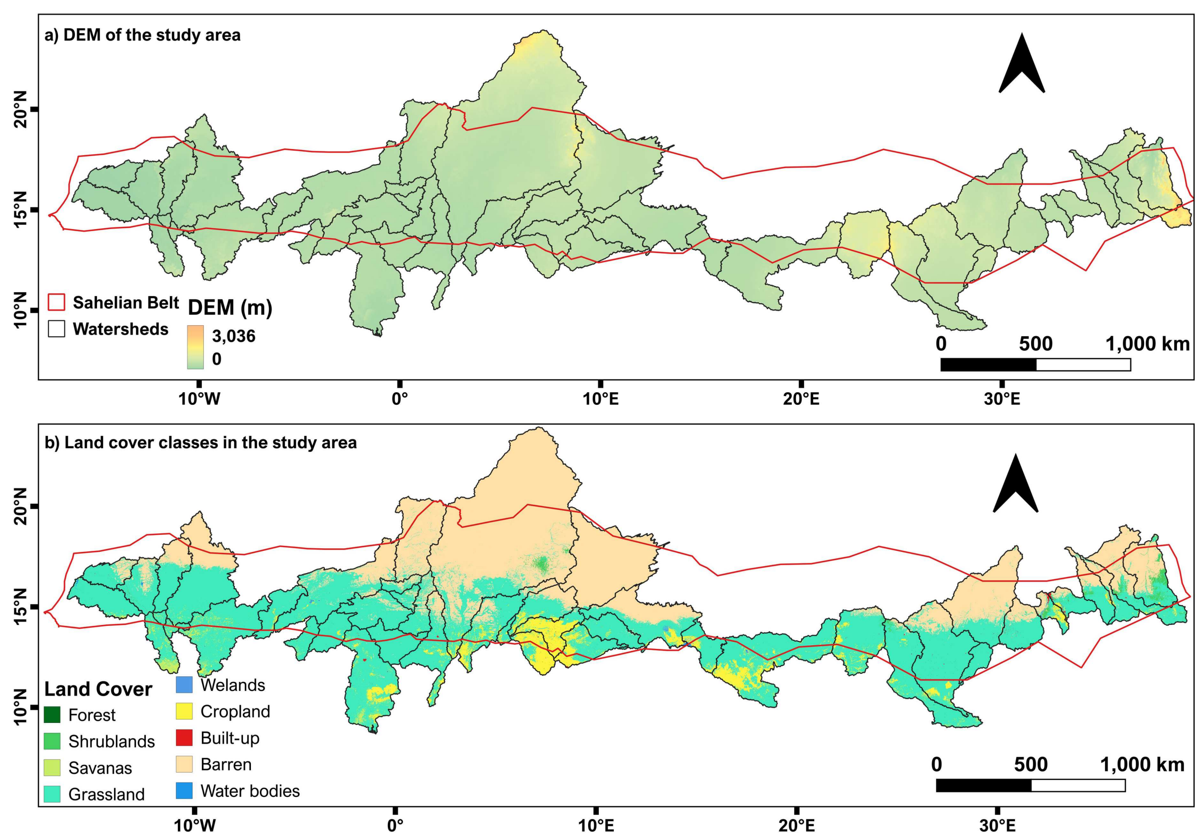

Figure 1. Digital elevation model (a) and land cover map (b) of the study area. The DEM data were obtained from the Shuttle Radar Topographic Mission (SRTM) at 90 m spatial resolution. The land cover dataset for 2020 was obtained from the MODIS Terra + Aqua Combined Land Cover product. The primary land cover scheme identifies 17 classes defined by the International Geosphere Biosphere Programme (IGBP) classification.

early 1960s to less than 4000 km^2 in early 2000s as a result of climate change and unsustainable water management (Gao et al. 2011; Wine 2022). The topography of the Sahel is mostly flat with altitude ranging from 200 to 400 m in elevation. However, there are some isolated plateaus and mountains located within the Sahelian belt. The region has a unimodal rainfall regime that is strongly variable. Precipitation data obtained from Climate Hazards InfraRed Precipitation with Station data (CHIRPS) over a period of four decades (1982–2021) show that annual rainfall varies from 71 to 200 mm/year in the north to about 700–1000 mm/year in the south (Nkiaka et al. 2024b). Rainfall in the Sahel generally lasts from June to September while the rest of the months are dry. According to Köppen climate classification, the region has a tropical semi-arid climate that is hot, sunny and windy with mean annual temperature ranging from 22 to 36 °C throughout the region. The livelihoods of most Sahelian people depends on rainfed agriculture and animal husbandry, thereby making them extremely vulnerable to climate vagaries.

2.2. Data

2.2.1. Surface runoff

Due to the scarcity of in situ runoff data in the Sahel, this study adopted runoff data from FLDAS-Noah water resources reanalysis (WRR). FLDAS-Noah is a custom instance of the NASA Land Information System (McNally et al. 2017). Noah is a land surface model (LSM), and the latest version of Noah used in FLDAS has a spatial resolution of 0.1° at monthly timescale. Runoff data from FLDAS-Noah have been validated in several basins in West Africa including the Sahel (Nkiaka et al. 2022). Compared to other products, outputs from FLDAS-Noah were proven to outperform other WRR runoff products in the region in terms of simulating water balance components (Nkiaka et al. 2022). In addition, runoff estimates from FLDAS-Noah have been used to monitor water availability in Africa (McNally et al. 2019) and the Sahel (Nkiaka et al. 2024c). Several studies have also used outputs from WRR products to evaluate the impact of climate variability and land cover change on different water balance components including evapotranspiration (Wang et al. 2021) and surface runoff (Liu et al. 2017; Tan et al. 2023). The numerous case studies suggest that runoff data from FLDAS-Noah can be applied in new and innovative ways to enhance our understanding of hydrological processes in data-scarce regions.

2.2.2. Vegetation cover

NDVI data are used as a proxy for vegetation cover change from 2001 to 2020. NDVI is used to measure vegetation greenness with higher scores indicating better vegetation vigour. NDVI data are obtained from Moderate Resolution Imaging Spectroradiometer (MODIS) MODIS/MOD13Q1.061 at a temporal resolution of 16 days and 250 m spatial resolution (Didan 2021). MODIS NDVI data have been used in several studies in the Sahel and proven to be suitable proxy for monitoring changes in vegetation cover in the region (Sacande et al. 2021; Yang et al. 2022; Nkiaka et al. 2024b).

2.2.3. Vegetation composition

Vegetation continuous fields (VCFs) are widely used to quantify vegetation composition as a proportion of the landscape. Unlike discrete land cover classifications, continuous variables provide a more nuanced representation of a mix of trees, herbaceous vegetation and non-vegetated surfaces (DiMiceli et al. 2021). Derived from MODIS/MOD44B.061 at a spatial resolution of 250 m, VCFs offer annual data on fractional vegetation cover, including tree cover (TC), short vegetation (SV) and bare ground (BG). MOD44B.061 specifically estimates 'Percent Tree Cover' within each pixel as a continuous value ranging from 0 to 100. Fractional vegetation cover, as described by DiMiceli et al. (2021), reflects the horizontal density and spatial arrangement of green vegetation projected onto the ground. Tree cover is defined as the percentage of canopy cover where trees exceed a height of 5 m. Previous studies have utilized VCFs to examine the influence of vegetation composition on hydrological processes, including surface runoff (Chen et al. 2021; Tan et al. 2023; Nkiaka and Okafor 2024). VCFs data have also been used to understand the factors influencing agricultural expansion and land degradation in global drylands (Leng et al. 2020). MOD44B.061 VCFs are used in this study to investigate the effects of changes in vegetation composition

Table 1. Summary of datasets used in the study.

Dataset	Data type	Spatial resolution	Temporal resolution	Period used	Reference
FLDAS-Noah	Surface runoff	0.1°	Monthly	2001–2020	McNally et al. (2017)
NDVI	Vegetation cover	250 m	16-day	2001–2020	Didan (2021)
MODIS VCF	Vegetation composition	250 m	Annual	2001–2020	DiMiceli et al. (2021)
Landsat VCF	Forest cover change	30 m	5-yearly	2000–2015	Sexton et al. (2013)
HydroSheds	Watershed shapefiles	–	–	–	Lehner and Grill (2013)
Digital elevation model	Topography	90 m	–	–	(Rabus et al. 2003)
MODIS Terra + Aqua	Land Cover Type 1: Annual (IGBP) classification	500 m	yearly	2020	(Friedl and Sulla-Menashe 2022)

IGBP: International Geosphere-Biosphere Programme.

on surface runoff and land degradation in the Sahel from 2001 to 2020. To ascertain the quality of VCFs data, we validated MOD44B.061 TC using independent Landsat VCF (TC) data derived from Landsat 5 Thematic Mapper (TM) and Landsat 7 Enhanced Thematic Mapper Plus (ETM+) (Sexton et al. 2013). Table 1 summarizes the characteristics of all the datasets used in the present study.

2.3. Methods

2.3.1. Estimating changes in vegetation cover and composition

The non-parametric Mann–Kendall test and Sen's slope estimator were respectively used for trend analysis and to quantify trend magnitude and significance at the 5% level. Trend analyses are conducted over two decades (2001–2020) using the NDVI. The Mann–Kendall trend test was performed in Python open-source software using the pyMannKendall package (Hussain and Mahmud 2019).

Considering the strong year-to-year variation in VCFs estimates, the trend test was not used to estimate changes in VCFs in the present study. Instead, we adopted an approach that consisted of estimating the mean VCFs for first five years (2001–2005) and the last five years (2016–2020). The difference between the two time periods was then used to establish the change in VCFs over the period of our study (2001–2020). A similar technique has been used in other studies to assess changes in vegetation composition (Chen et al. 2021; Hirvonen et al. 2022).

Finally, MODIS TC data are validated against TC data from global forest cover change (GFCC) over different time horizons (2000, 2005, 2010 and 2015). These time horizons were chosen to correspond to the period when GFCC data were available. Given the strong year-to-year variation in MODIS VCFs as highlighted above, mean TC from MODIS for the year 2000 was estimated as the mean of the years 2001–2002, mean TC for the year 2005 was the estimated as mean of the years 2004–2006, mean TC for the year 2010 was estimate as the mean of the years 2009–2011 and mean TC for the year 2015 was the estimated as mean of the years 2014–2015. These mean estimates for the target years were then compared with TC data from GFCC. All statistical analyses were also performed in Python open-source software using the SciPy package (Virtanen et al. 2020).

2.3.2. Quantifying the effects of vegetation composition on surface runoff

The study assessed the effects of changes in vegetation cover and composition on surface runoff using the elasticity concept. The elasticity concept is sometimes used as an alternative to hydrological models in impact studies to estimate how much a relative change in one variable (climate or vegetation) will affects runoff (Zhang et al. 2022). The concept has been widely used to investigate the impact of climatic and vegetation changes on surface runoff (Gbohoui et al. 2021; Zhang et al. 2022; Nkiaka and Okafor 2024). Given the availability of several elasticity models, this study adopts the non-parametric elasticity model proposed by Zheng et al. (2009) due to its ability to overcome the limitations of short data series. The model is expressed as:

$$\varepsilon = \frac{\bar{X}}{Q} \cdot \frac{\sum (X_i - \bar{X})(Q_i - \bar{Q})}{\sum (X_i - \bar{X})^2} = \rho_{X,Q} \cdot C_Q / C_X \quad (1)$$

where Q_i is the annual runoff, and Xi represents the annual vegetation parameter (NDVI, TC, SV, and BG) and $\bar{X}$ and $\bar{Q}$ represent the mean vegetation and runoff variables respectively. $\rho_{X,Q}$ represent the correlation coefficient between the vegetation parameter and runoff and C_X and C_Q represent the coefficients of variation of the vegetation parameter and surface runoff, respectively. Analyses are conducted at an annual timescale using data spatially averaged over each watershed. Statistical analyses were also performed in Python open-source software using the SciPy package (Virtanen et al. 2020). Figures 2, 5, 6 and 7 are produced in Python open-source software using the SciPy package (Virtanen et al. 2020) while Figures 3, 4 and 8 are also produced in the Python open-source software using the GeoPandas package (da Silveira 2024).

Figure 2 shows the datasets and different methodological steps used in the present study.

3. Results

3.1. Validating MODIS TC using Landsat TC

TC estimates from MOD13A1 V6 VCFS are validated with TC estimates from GFCC over the different time horizons (2000, 2005, 2010 and 2015). Analysis shows statistically significant correlations (r) between the two set of independent TC datasets with correlation values ranging from 0.75 to 0.85 for all the time horizons (Figure 3a–d). The strong correlations values between the two independent datasets lend credibility to MODIS VCFs estimates.

3.2. Mean annual vegetation cover and vegetation composition

Figure 4 shows the long-term mean vegetation cover and composition across the Sahelian belt. It can be observed that from 2001 to 2020, NDVI scores range from 0.09 to 0.33 across the study area with higher values obtained around the southern fringes of the Sahel where mean annual rainfall is relatively higher compared to the northern parts with lower annual rainfall (Figure 4a). Mean TC in the Sahel range from 0% to 8.76% suggesting that TC is not the dominant vegetation type in the region (Figure 4b). Analysis shows that SV is the dominant vegetation type ranging from 0.24% to 86% which reflects the characteristics of the Sahel as an area dominated by shrubs, grass and other vegetation including crops (Figure 4c). Most of the SV occurs mostly around southern fringes of the Sahel (Figure 4c). The percentage of the BG cover ranges from 9% to 100% with BG dominating central and northern portions of the study area (Figure 4d). The percentage of BG in the southern fringes of the Sahel is substantially lower which corresponds to the high percentage of SV in this part of the study area.

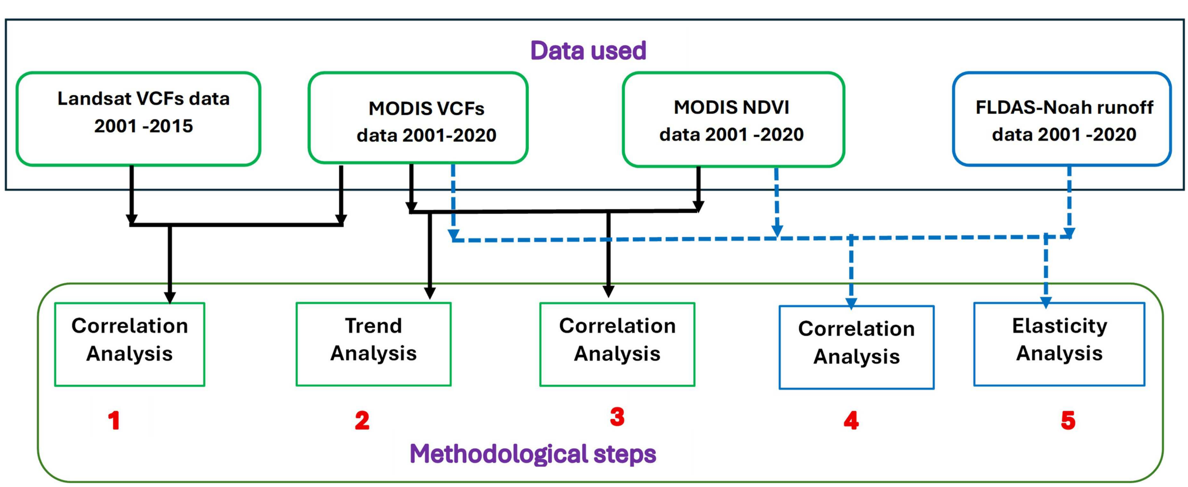

Figure 2. Flowchart outlining the datasets methodological steps used in the study. The number in red show the different methodological steps adopted in the study.

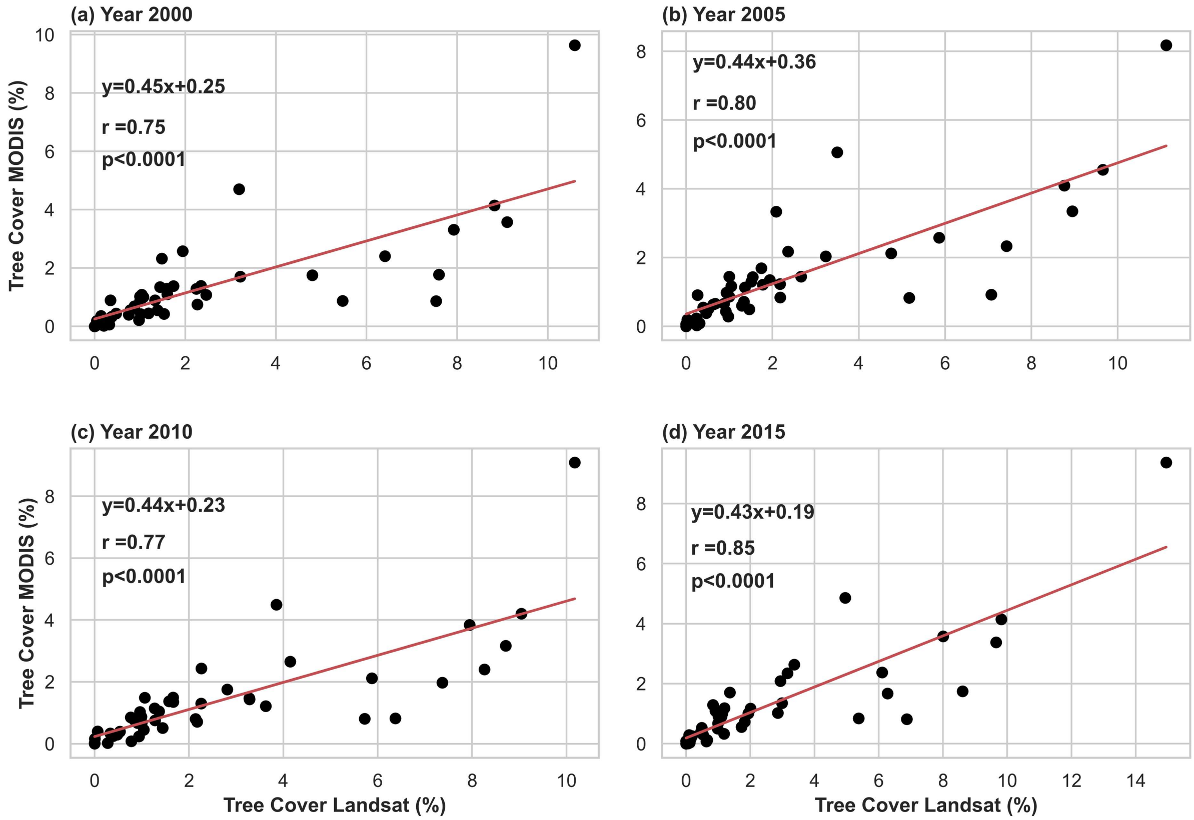

Figure 3. Relationship between tree cover estimates from MOD13A1 V6 and Landsat 5 TM and Landsat 7 ETM+.

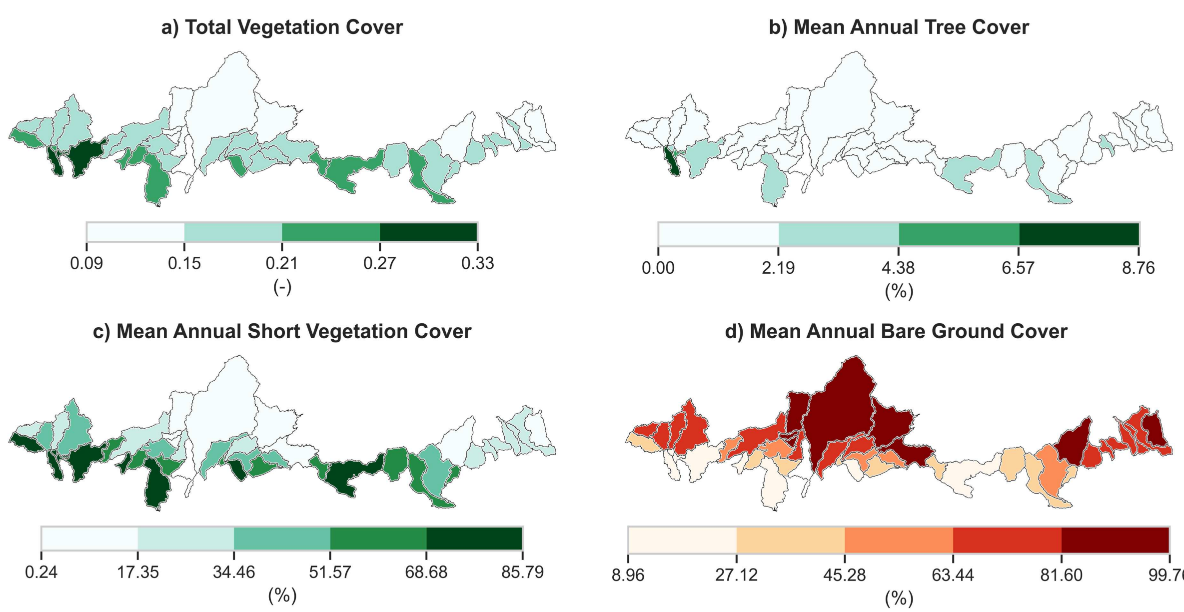

Figure 4. Mean annual vegetation cover and vegetation continuous fields (VCFs) from 2000 to 2020 (a) NDVI, (b) tree cover, (c) short vegetation and (d) bare ground.

3.3. Change in vegetation cover and composition

Figure 5 shows the changes in vegetation cover and composition measured using NDVI and VCFs respectively. NDVI shows statistically significant increasing trends in all the watersheds from 2001 to 2020 (Figure 5a). Meanwhile from 2001 to 2020, TC shows marginal gains in most watersheds with a mean of about 1% (Figure 5b). Similarly, SV shows substantial gains in several watersheds ranging from 1% to 8% and a marginal decline in some watersheds around the central Sahel (Figure 5c). Analysis also shows a decline in BG across most watersheds notwithstanding marginal gains some areas (Figure 5d). However, the decline in BG is higher than other VCFs with a mean of (−6%) (Figure 5d). Most watersheds that witnessed a decline in BG also witness corresponding gains in TC and SV suggesting that a decline in BG is mostly driven by gains in SV and TC. Moreover, watersheds with significant increases in NDVI also witnessed substantial gains in SV which suggests that the increase in NDVI in the Sahel may be dominated by gains in SV.

3.4. Relationship between vegetation cover and composition

Figure 6 shows the relationship between mean NDVI and mean VCFs. It can be observed that there are statistically significant correlations between NDVI and all the VCFs with correlation (r) values ranging

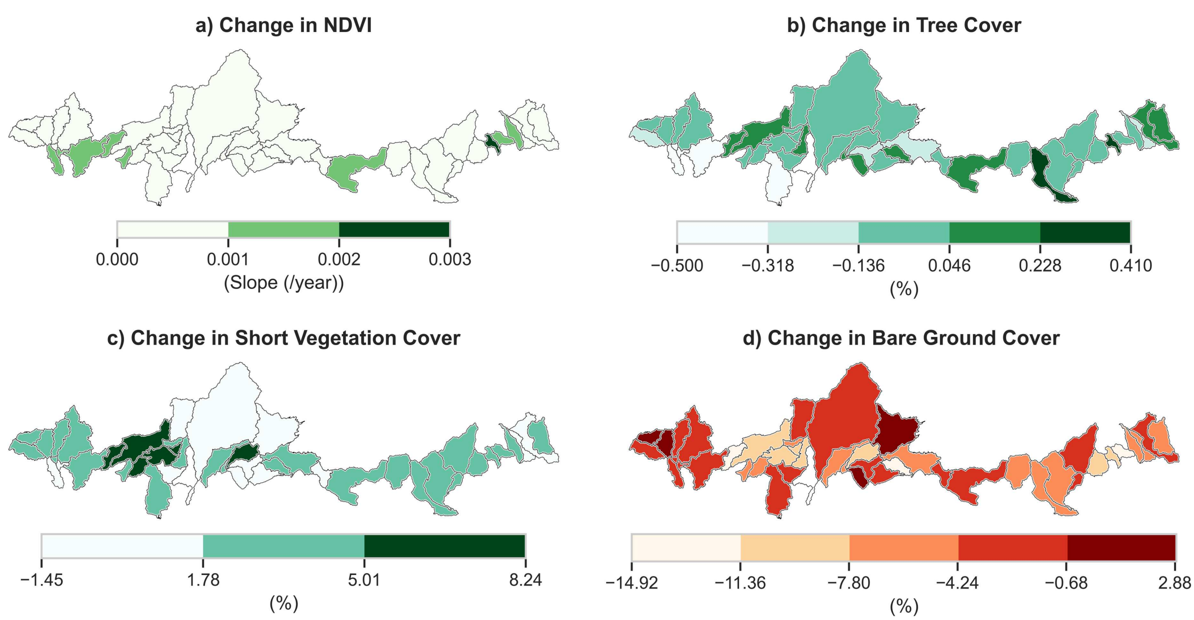

Figure 5. Change in vegetation cover (NDVI) and vegetation composition from 2001 to 2020.

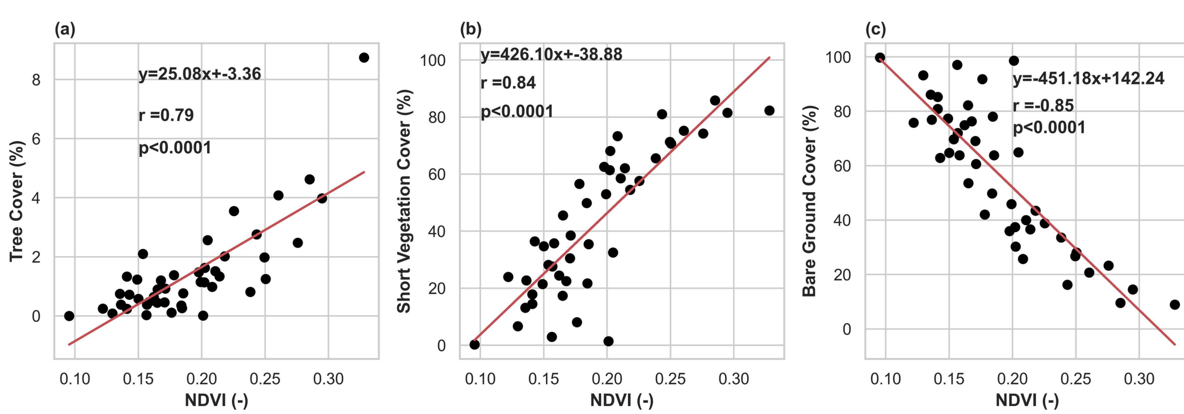

Figure 6. Relationship between vegetation cover (NDVI) and vegetation composition (VCFs).

from 0.79 to 0.85. Analysis also revealed that whilst an increase in TC and SV both lead to a corresponding increase in NDVI (Figure 6a and b), an increase in NDVI leads to a decline in BG as the growth of vegetation leads to a decline in land degradation (Figure 6c). This is reflected by the statistically significant negative correlation (−0.85) between NDVI and BG (Figure 6c).

3.5. Attribution of runoff change

Before calculating the elasticity coefficients, scatter plots are created to show the relationship between surface runoff and the different vegetation parameters (NDVI, TC, SV, BG). Analyses show statistically significant correlations between surface runoff and the different vegetation parameters (Figure 7a–d). Analyses further revealed that as the percentage of BG declines, surface runoff increases as indicated by the negative correlation (−0.75) between surface runoff and BG (Figure 7d).

The box plots in Figure 8 display the elasticity coefficients of the different vegetation parameters on surface runoff. Analyses show that NDVI, TC and SV produce mostly positive elasticity coefficients on surface runoff while BG produce negative elasticity coefficients. Elasticity coefficients of the vegetation parameters range from −0.03 to 7.07, −0.76 to 3.06, −10.12 to 18.19 and −14.65 to −0.26 with corresponding mean elasticities of 1.45, 0.24, 7.34 and −2.56 for NDVI, TC, SV and BG, respectively. Among the vegetation parameters, SV has the highest mean positive elasticity coefficient and widest spread while TC has the lowest mean positive elasticity coefficient with the least spread. The elasticity coefficients suggest that a 10% increase in NDVI, TC and SV may lead to an increase in surface runoff by about 15%, 2.4% and 73%, respectively, while a 10% increase in BG may lead to a decline in surface runoff by 25%. The results suggest that SV has the strongest positive influence on surface runoff while BG has the strongest negative influence on surface runoff.

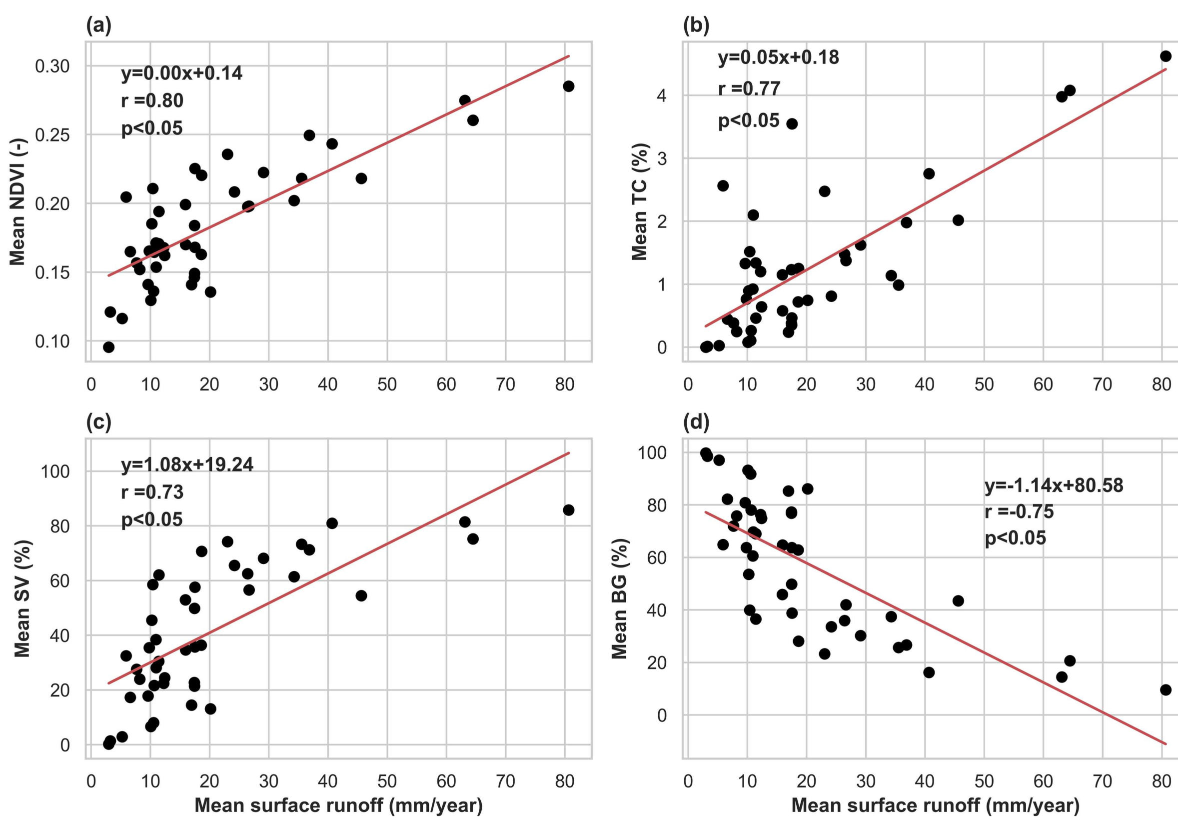

Figure 7. Scatter plot showing the relationship between surface runoff and the vegetation parameters (a) vegetation cover, (b) Tree canopy cover, (c) short vegetation cover and (d) bare ground cover.

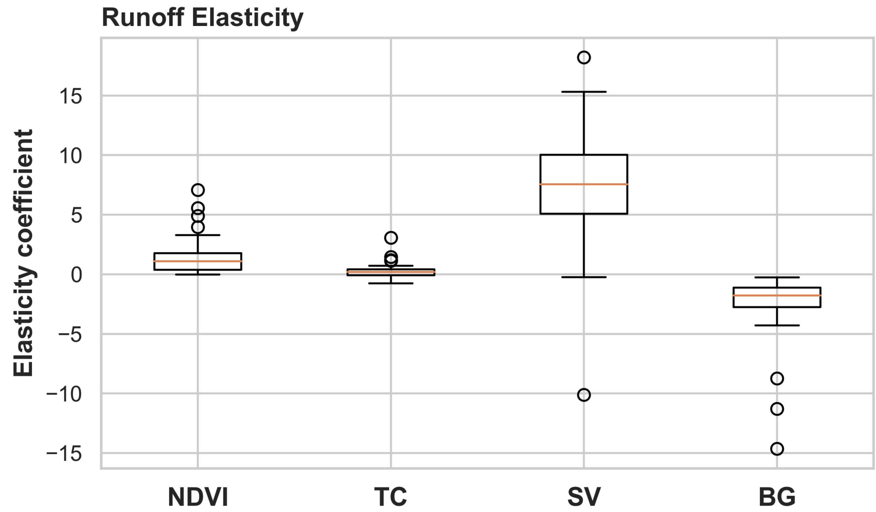

Figure 8. Elasticity coefficients of vegetation cover and composition. Elasticity coefficient relates to how much a change in vegetation cover (NDVI), tree canopy cover (TC), short vegetation cover (SV) and bare ground cover (BG) would affect surface runoff generation.

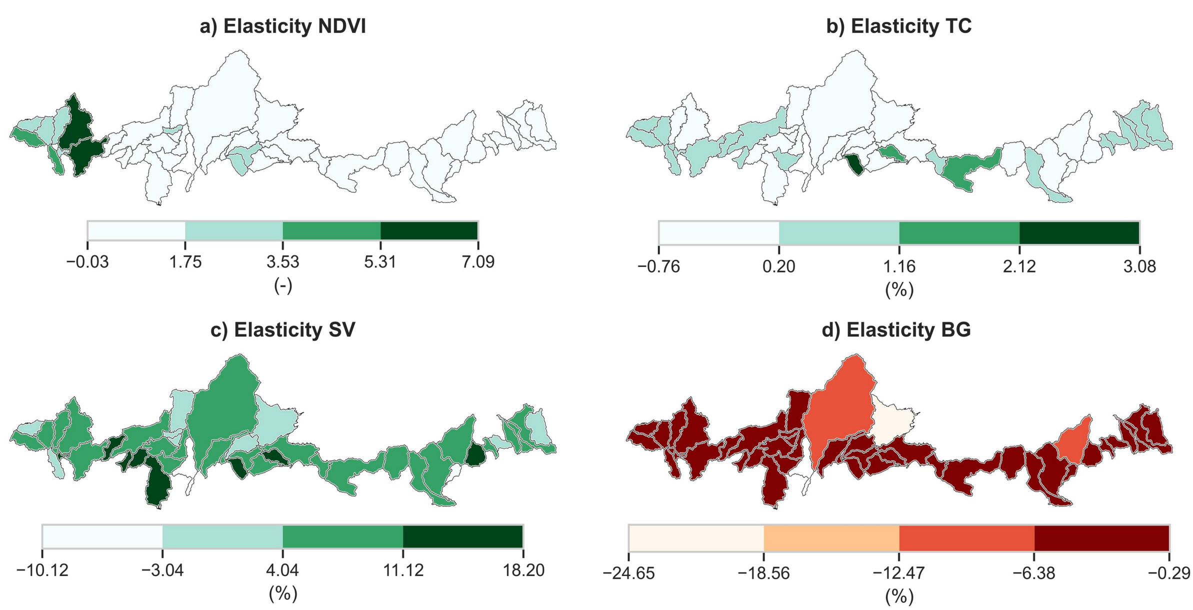

Figure 9. Spatial variability of elasticity coefficients across the watersheds.

Figure 9 shows the spatial variation in elasticity coefficients across the watersheds. It can be observed that a change in NDVI will lead to positive albeit low elasticity coefficients in most watersheds in the central and eastern Sahel compared to the western Sahel with higher elasticity coefficients (Figure 9a). The spatial variability in TC elasticity coefficients is not as strong as those of other vegetation parameters (Figure 9b). In contrast, SV elasticity coefficients strongly vary spatially with mostly positive elasticity coefficients across the watersheds (Figure 9c). The elasticity coefficients of BG are quasi-uniform across the study area except in a few watersheds with exceptional high elasticity coefficients (Figure 9d).

4. Discussion

4.1. Assessing changes in vegetation cover and composition

NDVI shows increasing trends across the Sahel which is consistent with results from previous studies in the region and this increase has largely been attributed to increasing precipitation in the region (Dardel et al. 2014; Souverijns et al. 2020).

Results also show changes in composition across the Sahel with varying order of magnitudes among the different VCFs. However, gains in TC occur only in 19 watersheds and are quite marginal with a mean of just about 1% over the period of analysis. On the other hand, analyses show larger gains in SV across 43 out of 45 watersheds with a mean annual increase of about 3% over the period of analysis. The increase in SV is consistent with similar gains observed in other dryland regions of the world (Leng et al. 2020). Marginal increases in TC along with a substantial increase in SV are consistent with increasing trends in vegetation cover observed across the Sahel and have been widely reported (Souverijns et al. 2020; Sacande et al. 2021). Increasing SV in the Sahel may also be attributed to agricultural expansion and ecosystem restoration initiatives such as the GGWI that is currently under implementation. The GGWI aims to restore about 100 million hectares of degraded land through reforestation across the Sahel. Results also revealed that increasing vegetation cover in the Sahel is dominated by SV (shrubs and grass) which reflects the fact that SV is the dominant vegetation type in the region (Gebremedhn et al. 2023).

Results also show a substantial decline in BG in 42 out of 45 watersheds with an average decline of about −6% per year over the period of analysis. The results are consistent with those from several studies in the region reporting a decline in land degradation over the same period of analysis using the albedo-modified soil-adjusted vegetation index (Yang et al. 2022) and moisture-responded net primary productivity estimates (Yan et al. 2024). Results are also consistent with those of a recent study using Markov models and revealed a decline in BG in parts of the Sahel (Edwin et al. 2024). Another study in the region has also shown unexpectedly large count of trees in the West African Sahel (Brandt et al. 2020). Results from this study show that the decline in land degradation may be stronger around parts of the central and eastern Sahel. Nevertheless, there are areas where land degradation is still occurring at a mean rate of about 1.33% which is also consistent with results from other studies in the region (Yang et al. 2022; Yan et al. 2024). Whilst the desertification and land degradation narrative in the Sahel continues to dominate academic (Trichon et al. 2018) and international development discourses (Gangneron et al. 2022), our analyses show a decline in BG in most watersheds at least to some extent. This does not also discount the fact that land degradation is still taking place in the Sahel as equally revealed by our analyses study. Results from this study also revealed that VCFs may be used to monitor changes in land degradation as reported in several other studies (Gao et al. 2016; Song et al. 2018; Leng et al. 2020).

4.2. Quantifying changes in runoff and effects of vegetation composition on hydrology

The effect of changes in VCFs on surface runoff was quantified using the elasticity concept. Analysis shows that surface runoff in the Sahel is sensitive to changes in vegetation cover and composition which is consistent with results from other dryland regions (Tan et al. 2023). The increase in NDVI, TC and SV in the Sahel are expected to produce negative elasticity coefficients as observed in other dryland regions due to enhanced evapotranspiration and therefore lead to a decline in surface runoff (Buechel et al. 2022; Shi et al. 2024). However, our analysis shows that increases in NDVI, TC and SV instead produce positive elasticity coefficients in most watersheds. This corroborates with our initial findings which revealed positive and statistically significant correlations between surface runoff and NDVI, TC and SV (Figure 7). The strong correlations between surface runoff and the vegetation parameters may partly be attributed to the 'Sahel hydrological paradox' which has been characterized by anomalous increases in runoff coefficient and surface runoff despite the increase in vegetation cover (Wendling et al. 2019; Gbohoui et al. 2021; Yonaba et al. 2021). This has been described as the second 'Sahel hydrological paradox'. Different studies conducted in the field have attributed the causes of the second 'Sahel hydrological paradox' to the fact that the re-greening of the Sahel may not have reached a threshold that can enhance soil water infiltration to reduce surface runoff volumes (Descroix et al. 2018). Trichon et al. (2018) have attributed this anomalous increase in surface runoff despite an increase in vegetation cover to the continuous degradation of tiger bush thickets in some areas which may have led to a shift in surface hydrology from sheet to concentrated runoff. Another study has attributed it to the shallow groundwater table in the Sahel which easily gets saturated leading to saturation excess runoff (Mamadou et al. 2015). Other studies have attributed it to land use change caused by reduced soil infiltration capacity leading to infiltration excess runoff (Favreau et al. 2009). The disparate explanations suggest a lack of consensus on the causes of the second 'Sahel hydrological paradox', suggesting that additional research is needed to shed more light on this phenomenon.

Results also revealed that surface runoff is more sensitive to changes in SV than the other vegetation parameters which is consistent with results from other studies (Chen et al. 2021; Tan et al. 2023; Nkiaka and Okafor 2024). The high sensitivity of surface runoff to SV changes may partly be attributed to land management practices that do not favour soil water infiltration thereby leading to high runoff volumes as observed in the field (Ky-Dembele et al. 2024). Analysis also shows that BG produce negative elasticity coefficients on surface runoff suggesting that an increase in BG may lead to a decline in surface runoff which is in-line with results from other studies in dryland regions (Chen et al. 2021; Tan et al. 2023). This behaviour in the Sahel may be attributed to concentrated recharge in gullies bottoms in some watersheds leading to a reduction in surface runoff as observed in the field (Favreau et al. 2009).

Analysis further revealed that changes in vegetation cover and composition affect surface runoff in the Sahel in different ways which is consistent with results from other studies (Chen et al. 2021; Tan et al. 2023). Such differences have been attributed to differences in vegetation structure, composition and morphology which all influence hydrological processes in different ways as revealed by experimental studies (Iroumé et al. 2021; Skhosana et al. 2023; Hidayat et al. 2024). Our analyses have provided new evidence on the intrinsic relationship between vegetation composition and surface runoff in the Sahel which is one of the novelties of this study. Such evidence may be useful in ecosystem restoration initiatives such as the GGWI by guiding the strategic selection of tree species for planting in the different watersheds. Analyses in this study were conducted at an annual timescale which may conceal the effects of changes in vegetation cover and composition on surface runoff at shorter timescales, as such, future studies may seek to focus on such timescales.

4.3. Uncertainty

Whilst this study presents a general picture of the sensitivity of surface runoff to changes in vegetation composition and cover in the Sahel, the results are not void of uncertainties. Firstly, due to a lack of in situ data, the study adopted mostly remote sensing and reanalysis datasets which have been shown to be fraught with uncertainties (Nkiaka et al. 2022). However, the datasets used in the present study contain several grid cells that are averaged over each watershed thereby, contributing to reducing the uncertainties inherent in the data. This implies that our results are not greatly affected by uncertainty issues and thus the conclusions from the study are still valid for the scale of the study region. Nevertheless, more studies are need using in situ runoff data.

Even though, VCFs have been extensively validated across several global locations (DiMiceli et al. 2021), a previous study has reported that TC data from MOD44B needs additional calibration in sparsely vegetated areas because they consistently underestimate woody cover in such areas (Adzhar et al. 2022). To overcome this weakness, the present study validated TC data from MOD44B.061 with GFCC data from Landsat 5 (TM) and Landsat 7 (ETM+) and both datasets show statistically significant correlations for all the time periods thereby lending credence to the MOD44B.061 VCFs. It is therefore, recommended that results from this study should be interpreted with some level of caution.

5. Conclusion

The objectives of the present study were to monitor changes in vegetation composition and its effects on land degradation and surface runoff in the Sahel. Analysis of vegetation cover and composition over the period 2001–2020 shows increasing trends in NDVI and a decline in BG. Whilst the Sahel desertification and land degradation narrative persists in academic and international development discourses, our analysis shows declining trends in land degradation in several watersheds across the Sahel. Analysis further revealed that decomposing vegetation into different parameters using NDVI and VCFs may have different hydrological effects on surface runoff. Additionally, this study suggests that VCFs may be used to monitor land degradation in other dryland regions. Due to a lack of in situ data, the present study used runoff data from a global land surface model, future studies may seek to investigate the effects of vegetation composition on surface runoff in the Sahel using in situ runoff data.

Author contributions

E.N.: Conceptualization, Investigation, Methodology, Writing – Original Draft; M.D.: Methodology, Writing – original draft; R.Y.: Methodology, Writing – original draft, review and editing; A.B.: Methodology, Writing – original draft, review and editing; T.F.: Writing – original draft, review and editing; A.I.P.: Writing – original draft, review and editing; H.K.: Writing – original draft, review and editing. Critical revision for intellectual content and final approval of the version to be published, all the authors. All the authors have agreed to be accountable for all aspects of the work.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

The MODIS NDVI and FLDAS-Noah data are available from Climate Engine Research App. Restrictions apply to the availability of these data, which were used under license for this study. Data are available from https://www.climateengine.org/ with the permission of Climate Engine Research App.

MODIS VCFs data were obtained from https://modis-land.gsfc.nasa.gov/vcc.html using a customized user account.

Landsat VCFs, MODIS Land cover and SRTM topographic data were obtained from Google Earth Engine using a customized users account.

Watershed shapefiles are freely available from https://www.hydrosheds.org/

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