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(Research Article)

Indicators of Vegetation cover Deterioration in Sahel region, Using Remote Sensing, and local ecological knowledge (LEK), case study of Kordofan, Sudan

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Abstract

The Sahel region of Sudan is a highly vulnerable ecosystem that faces significant pressures from climate change, land degradation, and human activities. Monitoring changes in vegetation cover is essential for understanding the extent of these pressures and for informing effective mitigation and adaptation strategies. Satellite-based remote sensing approaches provide a cost-efficient means of collecting information on the world's forests and repeatedly surveying large or inaccessible forest areas. However, it may not always be possible to ground-truth associated findings using direct ecological field surveys conducted by trained forest scientists. Local ecological knowledge (LEK) is an alternative form of data that can be used to complement, interpret, and verify information from satellite data. In this study, we integrated remote sensing and LEK data to measure indicators of vegetation cover and understand patterns and drivers of forest cover change. LEK reports often concurred with or provided key information to enable the interpretation of satellite data. This reveals that between 1975 and 2000, North Kordofan experienced high, but uneven, rates of deforestation. There was a pronounced shift in the study area deforestation in the mid-1980s, coinciding with a period of extreme drought and famine, and associated with the clearance of trees in areas as an economic and fuel resource, as well as the conversion of forest to agricultural cropland. Threats increase the vulnerability of the study area's socio-ecological systems to future environmental change and are an obstacle to the recovery of threatened species across the Sahel zone. This research reviews key indicators used to assess changes in vegetation cover in the Sudanese Sahel, in Sudan, North Kordofan State - Al Dodyia and Umm Seimema area, focusing on remote sensing-based, and the role of ground-based surveys and local ecological knowledge (LEK) in validating remote sensing data and providing valuable insights into the drivers and indicators vegetation change.

Keyword: Vegetation Cover; Sahel Zone; Remote sensing; Local ecological knowledge (LEK)

1. Introduction

The Sahel region of Sudan is characterized by a semi-arid climate, highly variable rainfall, and a reliance on rain-fed agriculture and pastoralism. It serves as a critical transition zone between the arid Sahara Desert to the north and the more humid savanna to the south. This geographical positioning makes the region particularly vulnerable to the impacts of climate change, especially desertification and land degradation. (Jiao et al., 2021; Zhang et al., 2022). These changes are evident in altered vegetation cover, which affects livelihoods, biodiversity, and ecosystem services. Vegetation cover in this area serves as a crucial indicator of ecological health and reflects the interactions between humans and their environment, as well as broader climate dynamics. (Brandt et al., 2015; Leroux et al., 2017; Pausata et al., 2020, Jiao et al., 2021; Zhang et al., 2022).

Vegetation provides a variety of ecosystem services, including the provision of building materials and fuel resources, the purification of ground and surface water, and the regulation of soil erosion. These services directly benefit human

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economies and societies, particularly some of the world's most vulnerable communities. Recently, forests have gained increased recognition for their potential to act as carbon sinks and mitigate the impacts of natural disasters (Zhang et al., 2022). However, global forest cover continues to decline, with an estimated 81.7 million hectares lost between 1960 and 2019 (UNDP, 2003).

Vegetation cover in the Sahel region of Sudan serves as a crucial indicator of ecological stability, supporting livelihoods and acting as a buffer against climatic extremes. In recent decades, the Sahel has become a focal point for intensive research due to its vulnerability to fluctuations in precipitation, anthropogenic pressures, and broader climatic shifts (Pausata et al., 2020; Jiao et al., 2021; Zhang et al., 2022). Understanding the indicators of changes in vegetation cover is essential for sustainable land management (Connolly et.al, 2016), early warning systems for environmental degradation, and effective policy formulation. While substantial research has addressed mathematical and computational indicators in other fields, such as coding theory and language decipherment, emerging quantitative, statistical, and algorithmic methodologies can provide innovative approaches to monitoring ecological signals (Leroux et al., 2017; Pausata et al., 2020; Jiao et al., 2021).

The environmental change on vegetation cover in the Sahel region is complex, marked by both greening trends and localized degradation. Remote sensing technologies play a crucial role in monitoring these changes, offering valuable data for conservation efforts (Herrmann & Sop, 2016; Brandt et. al, 2015). The Sahel region of Sudan has experienced significant declines in woody vegetation, particularly in large trees, which are essential for biodiversity and ecosystem stability (Herrmann & Sop, 2016; Horion et al., 2014). Field studies indicate a shift toward drought-tolerant species, highlighting the need for nuanced interpretations of satellite data (Herrmann & Sop, 2016). Earth observation technologies, such as NDVI analysis, enable the assessment of changes in tree cover and vegetation health over time (Horion et al., 2014; Brandt et. al, 2015). High-resolution imagery can identify areas of degradation and inform targeted conservation strategies, such as agroforestry initiatives that have successfully rehabilitated degraded lands (Herrmann & Sop, 2016; Nguyen, 2015).

While remote sensing provides crucial insights into vegetation dynamics, it is essential to incorporate ground-truthing to fully understand the ecological implications of these changes. This integrated approach can enhance conservation strategies, ensuring they are aligned with both satellite observations and local ecological conditions (Haq et.al, 2023).

The integration of LEK with remote sensing presents untapped potential for evaluating land degradation. (Haq et.al, 2023). Numerous studies in the Sudanese Sahel have utilized NDVI to map land cover changes, assess the impacts of drought on vegetation, and monitor the effectiveness of restoration efforts (Wu et al., 2020).

This paper aims to explore the key indicators used to assess changes in vegetation cover in Kordofan. It delineates and critically reviews the indicators of vegetation cover changes in the Sahel region of Sudan. By employing Ecological Local Knowledge (ELK) alongside computational statistical analysis, the research integrates perspectives from both the natural and computational sciences.

The Environmental changes, particularly increases in temperature and variability in precipitation, significantly impact vegetation cover in the Sahel. Remote sensing technologies, such as Landsat imagery, can effectively monitor changes in the Normalized Difference Vegetation Index (NDVI), thereby informing conservation strategies and enhancing our understanding of vegetation dynamics in fragile ecosystems (Wu et al., 2020).

According to El Smani (1982), environmental degradation refers to a temporary or permanent disturbance of the ecology in a specific area. Such disturbances may arise from physical factors, various climatic influences, or human activities, such as the overexploitation of natural resources, which can push ecosystems beyond their equilibrium limits. Abu Sin (1991) argued that degradation signifies a decline in environmental quality, encompassing depletion of resources, loss of biodiversity, changes in vegetation cover, fluctuations in rainfall, the disappearance of depressions and khors, and a reduction in land productivity. Between 1973 and 2001, North Kordofan experienced significant shifts in vegetation cover, transitioning from woodlands to agricultural land, which indicates increased desertification (Dafalla et al., 2014). The region's fragile ecosystem is highly vulnerable to desertification, exacerbated by climate change and land-use pressures, resulting in a decline in vegetation cover (Khiry et al., 2007).

While advanced remote sensing technologies provide valuable insights into vegetation dynamics, they also highlight the need for ground-truthing to validate satellite observations and understand local ecological changes more comprehensively (Herrmann et al, 2014).

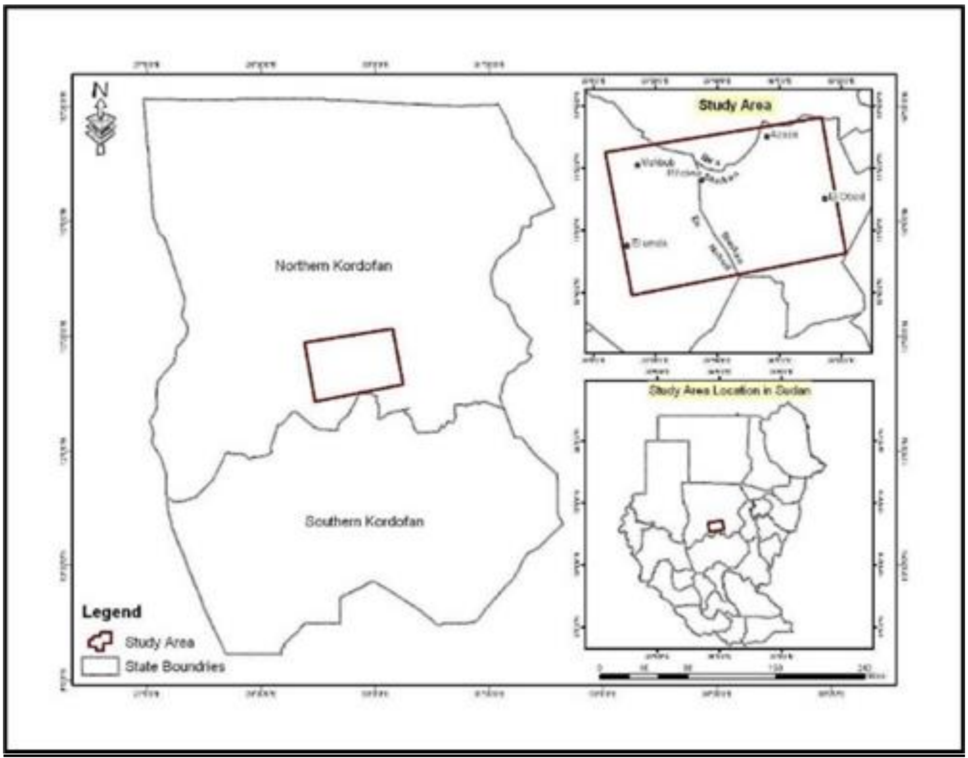
2. Materials and Methods

2.1. Geographical location:

We constrained our analysis to Northern Kordofan, the study area lies about 60 km west of El Obeid, the capital town of Northern Kordofan State. Administratively the study area is a part of El Khuwei administrative area, in Abo Zabad locality (West Kordofan State), and Abo Haraz administrative area, in Shiekan locality (Northern Kordofan State), it lies between latitudes 13º, 2'-13º, 3' N and longitudes 29º-30º E. It lies in a savanna with low rainfall, it typical Sahelian zone (Figure 1).

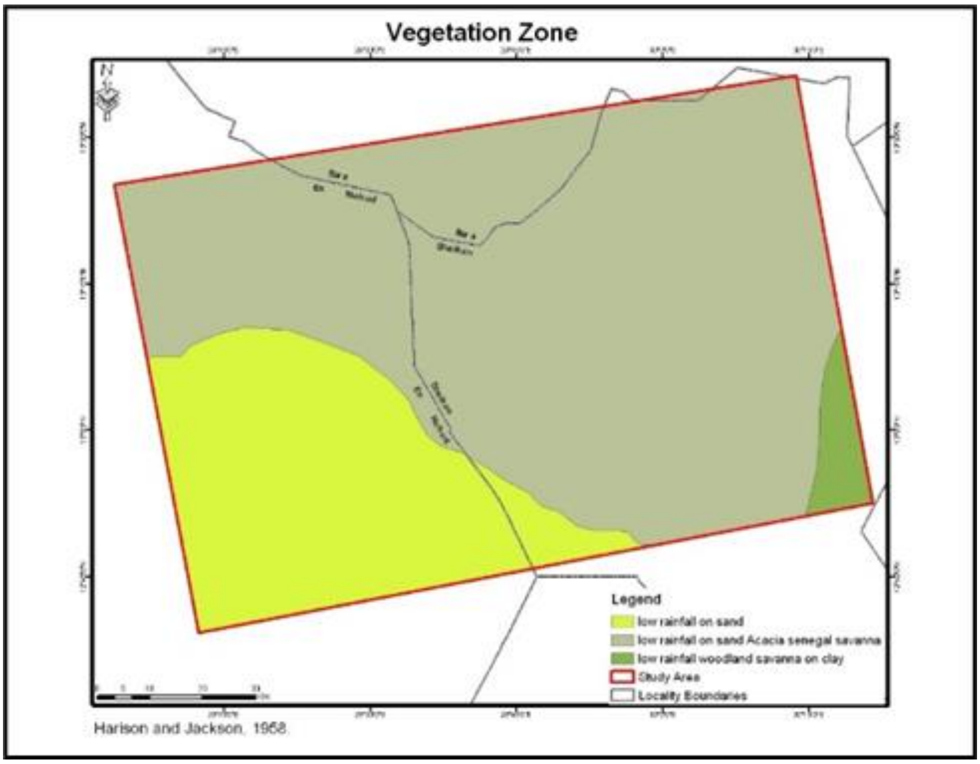
Vegetation cover is a special ecosystem component due to its role in soil stabilization and primary production. Rainfall plays a vital role in the distribution of the vegetation cover in the study area. There is a strong relation between the availability and the distribution of rainfall and vegetation density and type, and according to Figure 2, the vegetation cover can be distinguished as rich in both quantity and quality. The study area lie in Low rainfall savannah belt, Figure 2, the north and eastern part covered by low rainfall on sand Acacia Senegal Savanna zone, the western part covered by low rainfall on sand with main species are Marakh *"Lepatadenisa spartium"*, and Arad *"Acacia etabica"*, Lao'at "*Acacia nubica* ", Habeil *"Combrefum"*, Hegleig *"Balanites aegyptica"*, Arad *"Acaia etabica"* Darot *"Terminalia brownie"*, Sunot *"Acacia nilotic"*, Hashab *"Acacia sensgal"*, Humeid "*Sclerocarijal birrea"*, Sahab, *"Anogeissus lucarbus"* with very few Tabaldi *"Adansonia digitats"*.

The dominant grass species include Haskanit *"Cenchrus biflours"*, Bogil *"Blepnaris linzriifolia"*, Shelini: "*Zornia diphella"*, Difra *"Echinochloa colonam"*, and Snna Makka" *Cassia italica"*.



Source: Sudan Survey Department (2010)

Figure 1 Location of the study area



Source: Harrison and Jackson, 1958.

Figure 2 Vegetation Zone of Study Area

2.2. Data development

The methodology adopted in the field was conducted in-depth qualitative interviews with local producers (farmers and agro-pastoralists) in the area. A total of two local communities were selected, namely Umm Semaima and ELDodyia. To measure and assess vegetation cover, we have identified data from four major sources: published maps, which include topographic, geological, vegetation, soil, agro-ecological, drainage, land cover types, and contour maps; and remotely sensed data.

2.2.1. Remote Sensing-Based Vegetation Indices

Remote sensing technologies provide a cost-effective and spatially comprehensive method for monitoring vegetation cover across extensive areas. Several vegetation indices derived from satellite imagery are commonly employed in the Sahel to evaluate vegetation dynamics. (Shi et.al 2022).

The study used imageries from different satellites (Landsat and ASTER) and multi-temporal dates (MSS 1972, TM 1985, and ETM+ 2000) acquired in the dry season. Table 1 lists the source of each image, including year of capture and spatial resolution (m).

Table 1 Spatial Characteristics of Satellite Images

Satellite	Sensor	Bands	Date of Acquisition	Spatial resolution
Landsat	MSS	NIR, R, G(4,3,2)	1972	60m
Landsat	TM	NIR, R, G(4,3,2)	1985	30m
Landsat	ETM+	NIR, R, G(4,3,2)	2000	15m

Source: Remote Sensing Authority, Khartoum

2.2.2. Ground-Based Surveys and Local Ecological Knowledge (LEK)

While remote sensing offers a comprehensive overview, ground-based surveys and the integration of local ecological knowledge (LEK) are crucial for validating remote sensing data and achieving a deeper understanding of the factors driving vegetation changes and their impacts.

Ground-Based Surveys: Field surveys involve direct observation and measurement of vegetation characteristics, such as species composition, biomass, plant height, and ground cover. These surveys provide valuable data for calibrating and validating remote sensing. Furthermore, ground surveys can identify species-specific responses to environmental changes that may not be detectable through remote sensing alone (Herrmann et al, 2014).

Local Ecological Knowledge (LEK): Indigenous communities in the Sahel possess a wealth of knowledge about local ecosystems, including changes in vegetation cover, species distribution, and the impact of environmental stressors (Tengö et al. 2017). LEK can provide context, identify indicator species, and offer insights into the social and economic consequences of changes in vegetation. LEK can enhance vegetation monitoring efforts, improving the accuracy, relevance, and sustainability of assessment programs (Tengö et al, 2021).

3. Result and Discussion

The vegetation in the study area shows distinct intra-annual seasonal variation. This research investigates vegetation changes based on the analysis of satellite images from the years 1972, 1985, and 2000 (Figure 6), along with Local Ecological Knowledge (LEK) gathered through field observations and interviews with local farmers, pastoralists, and agro-pastoralists in the selected sample villages. This study builds upon earlier work in the area, primarily by Harrison and Jackson (1958), Al Samani (1984), and Al Mahi (1986).

In the study area, there are changes in vegetation cover, whether in types, density, or both. According to the field survey, the dominant species is Usher (*Calotropis procera*). The trees in the study area are primarily located around water points and settlements, largely due to the concentration of animals. This distribution serves as an indicator of soil degradation (Figure 3). The replacement of Usher (*Calotropis procera*) with more valuable tree species in the study area signifies progressive ecological succession. However, this process may be reversed by retrogressive succession due to new environmental factors.

According to Table 2, the primary tree species that have disappeared are Abanos (*Dalbergia melanoxylon*), Darot (Terminalia brownie), Kadad (*Dichrostachys glomeruti*), Sahab (*Anogeissus leiocarpus*), Subag (Terminalia sp.), and Tabaldi (*Adansonia digitata*). Figure 4 shows the decline of Tabaldi (*Adansonia digitata*) in Abo Goud village, located near El Obeid. According to respondents, 92% believe there is no new generation of Tabaldi (*Adansonia digitata*) due to climate change, as it requires wet weather.

Another piece of evidence for changes in vegetation cover is the disappearance of native grass. The main species that have vanished are Shillini *(Zornia diphella)*, Bogheil *(Blepheris libarijoli*), and Difra (*Echinochloa colona*), which are recognized by 98% of the total respondents. Table 4 shows the main types of grass species that emerged in the study area. 95% of respondents viewed changes in vegetation as a result of decreased rainfall, deforestation, and overgrazing (Figure 5). The natural forest and low woodland savannah appear only along wadis and depressions, as seen in the case of “Buried depression of El Dodyia and near Abo Haraz.”

Figure 3 Usher Tree replaced value trees in the study area

Table 2 Evidence of vegetation Cover from Field and Literature (Trees)

Old Trees	Percentage of respondents %	Newly grown Trees	Percentage of respondents %
Abanos *(Dalbergia melanoxylon*)	100	Usher *(Calotropis procera*)	100
Darot *(Terminalia brownie*	92	Markh *(L. pyrotechnica)*	98
Kadad *(Dichrostachys glomeruti)*	88	Laot *(Acacia nubica)*	89
Sahab (*Anogeissus leiocarpus)*	98	Haraz *(Acacia albida)*	65
Subag *(Terminalia sp)*	98	Layon *(Lannea humilis)*	65
Tabaldi *(Adansonia digitata*)	74	Sarih *(Maerua crossifolia)*	44
Kitir(*Acacia mellifra)*	96	Arad *Acacia etabica)*	78

The percentages did not add up to 100% due to the multiple responses

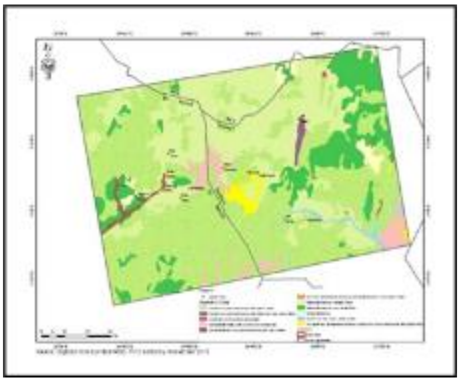
The total area of vegetation cover, considering all its types and density, has decreased from 5426.427300 km^2 in 1972 to 5160.947400 km^2 in 2000. The area of closed trees with closed to open shrubs has decreased from 4.058600 km^2 to 0.750600 km^2 between 1972 and 2000.

Figure 4 Tabaldi (*Adansonia digitata*)

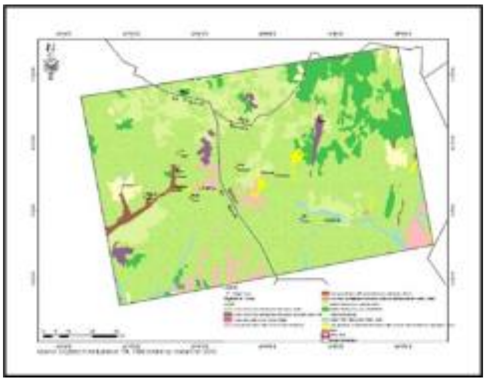
Figure 5 over Grazing

3.1. Usher Tree replaced the value trees in the study area

On the other hand, open general shrubs with closed to open herbaceous cover have increased from 327.817000km^2 in 1972 to 380.752300km^2 in 1985 and to 480.987900km^2 in 2000, reflecting the main change in the type and density of vegetation cover in the study area (Figure 6). This is supported by the respondents, who stated that 83.8% of households reported deterioration in vegetation cover, approximately 71.2% attributed this deterioration to cutting, and 13.3% stated it was due to a reduction in rainfall amount. Table 3 shows evidence of vegetation Cover changes from according to respondents.



(a)



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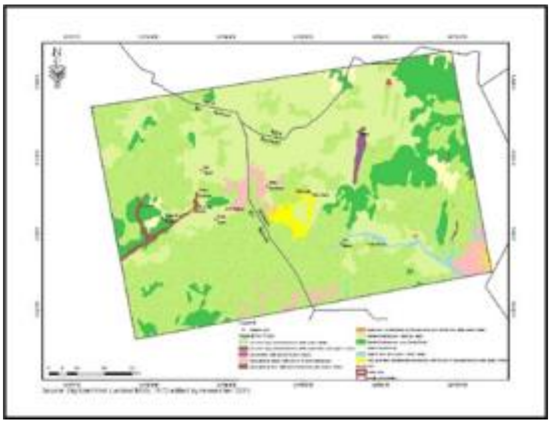

(d)

Figure 6 Landsat images of Vegetation cover of the Study Area, years 1972, 1985, 2000, 2010

Table 3 Evidence of vegetation Cover from Field and Literature (Grasses)

Old Grasses	**Percentage of respondents %**	**Newly grown Grasses**	**Percentage of respondents %**
Sillini*(Zornia diphella)*	98	Haskanit *(*Cenchrus biflorous)	93
Bogheil *(Blepheris libarijoli*	98	Tees Borakhis *(Andropogon gayanus)*	100
Difra *(Echinochloa colona),*	98	Bennu *(Eragrofic tremulu)*	98
Argassy *(Chrozophora spp)*	75	*Tibra*	64
Halfa()	80	Gatgat *(Crotalaria spp)*	
Hantoot *(Ipomeas pp)*	88	Gaw *(Artistida spp)*	65
Darisa *(Tribulus terrestris)*	95	Boda *(Striga hermonthica)*	35

The percentages did not add up to 100% due to the multiple responses

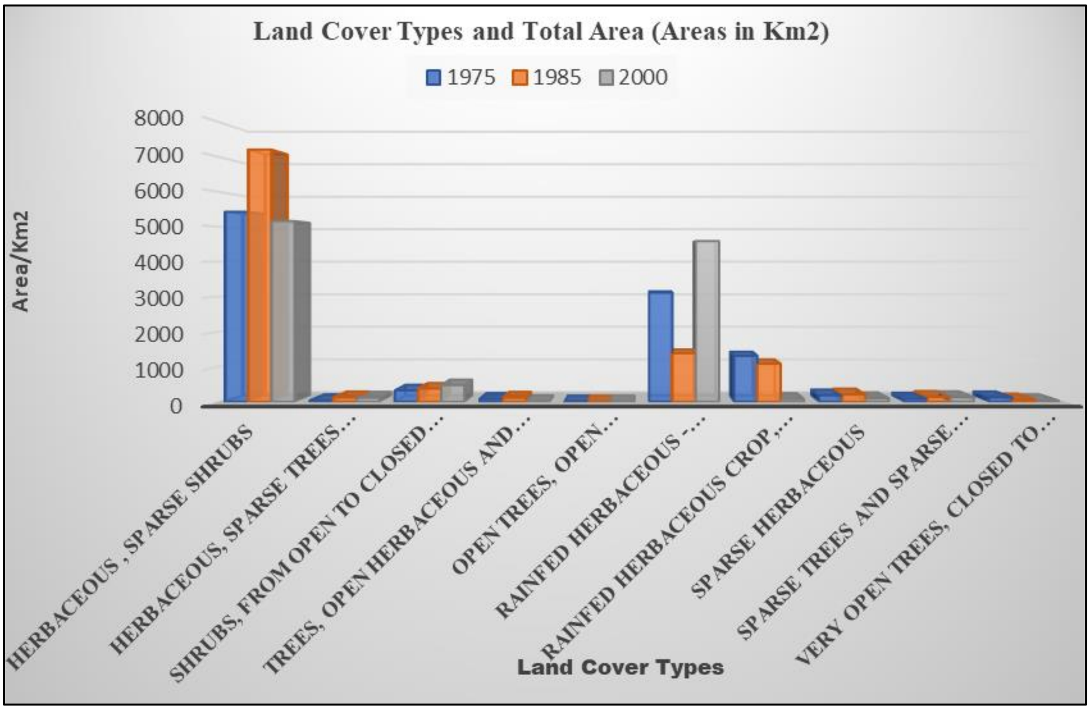

Figure 7 Land Cover Types and Total Area (Areas in Km²)

The period from 1972 to 1984 shows intense clearance of natural vegetation due to the expansion of cash crop cultivation, mainly groundnuts. The cultivation area reached 3,118.65 km², and the high profit encouraged many farmers to clear new areas of their natural vegetation.

Moreover, opening new areas has a double benefit: gaining new fertile agricultural land and, at the same time, selling the harvested wood at the local market as firewood and/or building materials.

Woody materials are still the primary building material in all villages, as indicated by 87.4% of respondents who use woody materials for construction purposes, while only 2.1% of the total sample size uses mud and iron in their houses.

4. Conclusion

Monitoring vegetation cover changes is essential to understand the impacts of climate change and anthropogenic activities on the fragile ecosystems of the Sudanese Sahel. Remote sensing-based vegetation indices, combined with ground-based surveys and local ecological knowledge, provide valuable tools for assessing vegetation dynamics and informing sustainable land management practices. Addressing the challenges associated with data availability, scale issues, and the integration of LEK is crucial for improving the accuracy, relevance, and sustainability of monitoring efforts. By investing in these areas, we can better understand the drivers and impacts of vegetation changes in the Sudanese Sahel and develop effective strategies to build resilience and promote sustainable livelihoods.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare no conflict of interest.

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