Appraising Forest Degradation Dynamics (1988-2018) in Umfakarin Natural Forest Reserve, Sudan, Using Multi-Temporal Landsat Imagery

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Abstract

Sudan, recognized as a forest degradation and deforestation hotspot, has experienced significant forest loss in recent decades. The Umfakarin Natural Forest Reserve (UNFR) is undergoing rapid forest degradation driven by increasing human land-use pressure within a conflict-affected dryland environment. This study assessed long-term land use/land cover dynamics (LULC) and mapped forest degradation in the UNFR. Landsat satellite imagery from 1988, 2002, and 2018 were analyzed using maximum-likelihood supervised classification, transition matrix analysis, and supported by GNSS field-based verification. The classification results revealed marked LULC changes over the study periods, where tree cover reached its peak in 2002 at 32.13%, compared to 19.89% in 1988 and the marked decline by 18.43% in 2018, indicating fluctuating forest conditions. Mixed vegetation increased sharply by 2018 (22.54%) relative to 1988 (16.08%) and 2002 (5.43%), while agricultural land expanded significantly in 2018 (31.96%), exceeding levels observed in 1988 and 2002. Bare land showed a gradual decrease throughout the study period. Matrix analysis revealed rapid transitions across all LULC categories. Forest degradation in UNFR was primarily driven by illegal tree cutting, agricultural expansion, overgrazing, and settlement growth, remaining forest patches are increasingly fragmented and confined to interior areas and seasonal watercourses, indicating progressive forest degradation. Ineffective protection and management strategies have failed to prevent forest loss. This study provides the first spatially explicit, long-term assessment of forest degradation patterns within UNFR and demonstrates the effectiveness of integrating remote sensing and field data for monitoring dryland forests under socio-political and environmental stress. The study emphasizes the urgent need for effective conservation measures, the promotion of alternative livelihoods, formal delineation of reserve boundaries, and the active involvement of local communities to achieve long-term sustainability.

Keywords: Conservation Strategy, Forest Degradation, LANDSAT, LULC Change, Sudan Drylands

1. Introduction

Forests are essential for maintaining ecological balance, promoting biodiversity, and sustaining the livelihoods of millions of people worldwide. They cover approximately 30.8% of the Earth's terrestrial surface and support a wide variety of plant and animal species [1] and [2]. In addition to their biodiversity value, forests play a critical role in carbon sequestration, climate regulation, and the provision of numerous ecosystem services that are vital to human well-being. Africa's forests account for about 21.8% of the global forest area, with countries such as Sudan depending heavily on these ecosystems for environmental stability and the livelihoods of rural communities [2] and [3].

However, Sudan's forest resources are undergoing a rapid and continuous decline [3]. According to the Food and Agriculture Organization (FAO) [4], forest cover in Sudan decreased from 23.57 million hectares in 1990 to 19.21 million hectares by 2015, where FAO recent report indicates that the forest cover area declined to 9.6 % for the period (2023-2025) of the country's total land area [5]. This reduction is primarily driven by anthropogenic factors, including agricultural expansion, wood harvesting, overgrazing, and infrastructure development. These pressures contribute not only to deforestation but also to forest degradation, characterized by the progressive loss of tree canopy cover, biomass, biodiversity, and overall ecological integrity [6] and [7].

Forest degradation differs from deforestation in that it does not involve the complete removal of tree cover. Rather, it refers to the deterioration of forest quality due to factors such as selective logging, grazing, fuelwood collection, and encroachment [8] and [9]. Detecting and quantifying forest degradation presents greater challenges than monitoring deforestation, as it requires finer-scale analyses and more sensitive indicators to capture subtle changes in forest structure and composition [8][10] and [11]. This complexity is particularly pronounced in dryland regions such as South Kordofan, Sudan, where ecological data are scarce and conventional forest monitoring is hindered by limited financial and technical resources [12].

There is broad consensus within the scientific community that timely and accurate information on land use and land cover (LULC) changes is critical for effective and sustainable forest management [13] and [14]. Remote sensing technologies offer valuable tools for monitoring forest dynamics over time and across extensive spatial extents. Multi-temporal satellite imagery, such as data provided by the Landsat program, has proven effective for detecting, mapping, and analyzing forest degradation processes [15] and [16]. When combined with Geographic Information Systems (GIS) and ground-based field observations, satellite-derived data enable evidence-based decision-making and inform policy interventions aimed at forest conservation and sustainable resource management [17] and [18].

Previous studies have employed remote sensing techniques to assess forest change and degradation across various regions of Africa [12][19] and [20]. However, research focusing on Sudan remains limited, particularly in areas such as South Kordofan, where forest ecosystems are increasingly threatened [7]. The Umfakarin Natural Forest Reserve (UNFR) in north-eastern South Kordofan State is undergoing significant ecological transformations driven by the expansion of agricultural activities, intensive grazing, and extensive wood extraction. Gaining a comprehensive understanding of the dynamics and underlying drivers of forest degradation in this region is essential for the development of effective conservation and sustainable management strategies. Although forest cover in South Kordofan has declined markedly over time, the UNFR remains the only national reserved forest in Al-Abbasiyah locality and has experienced noticeable changes in vegetation cover. It forms the frontline adjacent to the sandy zones of North Kordofan, where desert encroachment is advancing southward, and serves as a protective shelter belt for Al-Abbasiyah town and its surrounding villages. UNFR is the largest forest in the locality, located within Sudan's great gum belt, while the remaining forests are mainly small, scattered state-reserved areas, except in mountainous regions in the southern part of the locality. Furthermore, it contains highly valuable tree species, dominated by *Acacia seyal* (Talha), which in some regions in Sudan is mainly managed for firewood and charcoal production, and recently became the second most economically important Gum-Arabic producing tree species in Sudan and contributes substantially to the national economy [21] and [22]. Recently, due to the conflict in South Kordofan that caused population displacement, as well as drought and lack of rainfall, local communities have increasingly relied on forest resources for their livelihoods, leading to considerable changes in the forest. Therefore, such forests require critical assessment and urgent scientific investigation.

During the periods 1983–1985 and 1988, Sudan experienced one of the most severe famines in its history, driven by prolonged drought that led to widespread crop failure and food shortages, particularly in Kordofan and Darfur [23][24] and [25]. These environmental stresses and food crises contributed to increased pressure on forest resources through overexploitation. In addition, ongoing environmental variability and land degradation have intensified human pressure on forest cover during the last decade [26]. This study conducts a multi-temporal analysis of forest degradation in the UNFR using Landsat satellite imagery from 1988, 2002, and 2018 to classify land use and land cover (LULC) types within the UNFR, analyze and compare the spatial extent and distribution of LULC classes across the study periods, assess temporal changes in

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forest cover and identify dominant trends of forest loss, and generate baseline information to inform sustainable forest management, conservation strategies, and land-use policy formulation. Supervised classification techniques, ground-truthing, and GIS-based change detection methods are employed to quantify forest cover changes over the past three decades. The research evaluates the effectiveness of existing conservation measures and offers recommendations to enhance forest management practices and strengthen community involvement. By assessing forest degradation within a vulnerable dryland ecosystem, this study contributes to advancing sustainable land management and improving forest monitoring approaches in arid regions. Moreover, it demonstrates the applicability of remote sensing technologies in informing conservation strategies within data-deficient and conflict-affected contexts such as Sudan.

2. Study Area and Methodology

2.1 Study Area

The Umfakarin Natural Forest Reserve (UNFR) is situated in the north-eastern part of South Kordofan State, Sudan, between latitudes 12°29′12″ and 12°35′N and longitudes 31°17′31″ and 31°20″E. The reserve covers approximately 2,748 hectares and lies 44 km north of Al-Abbasiyah town "Figure 1". Formerly part of the Al-Abbasiyah Forest Division and Rashad Forest Circle. UNFR was officially designated as a protected area in 1993 under Gazette No. 8. The reserve is bordered by four villages; Umfakarin, Alhafirah, Alhafirah Dardig, and Awlad Rahal, which collectively support a population of approximately 3,688 individuals, primarily engaged in subsistence farming and livestock herding. UNFR is considered the most important forested area in the local region and occupies a strategic position along the advancing southern margin of desertification from North Kordofan. It functions as a critical shelterbelt, mitigating sand encroachment and providing environmental protection for the surrounding areas. As the only national forest reserve and the largest forest within the locality, UNFR is located within Sudan's great gum belt and supports tree species of high economic significance , notably *Acacia seyal* (Talha), *Acacia Senegal* (Hashab), and *Acacia mellifera* (Kitir) which are the most important gum-producing species in Sudan for (Talha and Hashab) beside the importance of the use as charcoal and fuel wood for (Talha and Kitir) which contributes substantially to the national economy.

The region is characterized by low-rainfall woodland savanna, with annual precipitation ranging from 350 to 900 mm, concentrated during a rainy season extending from May to September (approximately 4 to 5 months), and often accompanied by seasonal flooding.

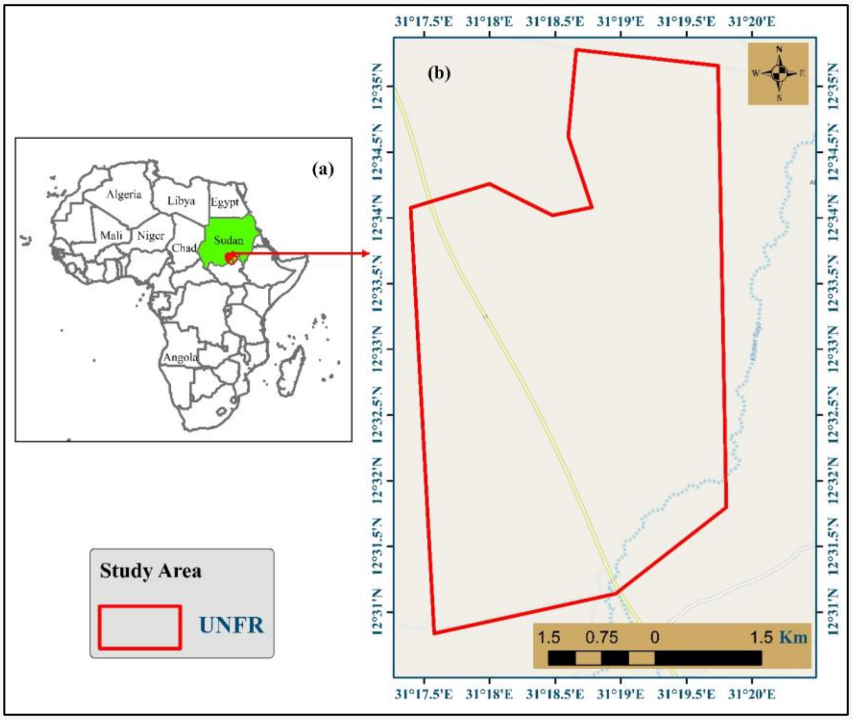

Figure 1: Umfakarin Natural Forest Reserved (UNFR)

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Mean temperatures typically range between 30°C and 35°C. The prevailing soil types are clay plains and sandy clay, locally known as *Gardud*, which are non-cracking in nature. The topography of UNFR consists of gently undulating terrain traversed by several seasonal streams; however, the reserve lacks clearly defined physical boundaries. The vegetation is progressively degrading, characterized by sparse stands of Acacia species intermixed with other woody plants. The dominant tree species include *Acacia seyal* and *Acacia mellifera*, with additional representation of *Acacia senegal* and *Balanites aegyptiaca*.

2.2 Data Collection and Analysis

This study employed remotely sensed data to assess changes in land use and land cover (LULC). Cloud-free satellite imagery was selected from Landsat 5 (1988), ETM+ (2002), and OLI 8 (2018), each providing a spatial resolution of 30 meters (Table 1). The images used in this study were Landsat terrain-corrected products, no further radiometric or atmospheric correction was needed. The images which were freely acquired from the United States Geological Survey (USGS) Earth-Explorer platform (http://earthexplorer.usgs.gov). All images used in the analysis were free of cloud cover to ensure accurate classification results and to avoid the distortion of atmospheric correction. Visual enhancement (brightness and contrast) adjustments were applied solely to improve visual interpretation of selected images. Due to the seasonal selection of images, no radiometric or atmospheric normalization was performed. An integrated approach was adopted, combining remote sensing data with field-based observations of land use activities recorded within the research data collection. The temporal remote sensing analysis with field-based observations is valuable for assessing vegetation cover changes and quantification of deforestation and forest degradation especially of drylands in sub-Saharan African countries as addressed by [27] and [28].

To complement the remote sensing analysis, a structured questionnaire was developed to collect information regarding the perceived importance of the forest and to identify the primary drivers of forest degradation and deforestation. The questionnaire included a combination of closed-ended, open-ended, and multiple-choice questions. It addressed social and demographic characteristics, community dependence on forest resources, and respondents' perceptions of the causes and consequences of forest degradation. This integrated methodological framework could generate better understanding and an authentic representation of all forest aspects, and it may provide a robust result as seen on the study of [29].

Satellite image analysis was conducted using ERDAS Imagine 2014 and ArcGIS 10.7. The analysis included calculating the extent of LULC changes, transition percentages, and land cover conversions. Pre-processing steps involved visual enhancement, layer stacking, and merging relevant spectral bands (Bands 1, 2, 3, and 4 for Landsat TM 5 and ETM+; Bands 2, 3, 4, and 5 for Landsat OLI 8) into composite single-layer files. Sub-scenes corresponding to the study area were clipped from each image to facilitate detailed analysis and to ensure consistency across time-series imagery.

Supervised image classification was conducted using ground control points collected with a GNSS device (Garmin GPS-MAP 65s), which was used for navigation and for acquiring reference data to support training and validation of the 2018–2021 Landsat image classifications for assessing forest degradation in the study area. Signature analysis refers to the examination of the spectral characteristics of training samples for each LULC class prior to classification. In this study, spectral signatures were analyzed to evaluate mean reflectance values, variance, and overlap among classes across the selected Landsat bands, ensuring that training samples were representative and spectrally separable before applying the maximum likelihood classifier.

The maximum likelihood classifier was used because of its proven effectiveness in arid and semi-arid environments and its capacity to account for class variability, which is particularly important in dryland landscapes characterized by high spectral heterogeneity and spectral overlap among land-cover classes [29]. Ground reference points for field surveys were randomly assigned and spatially distributed using ArcMap v.10.2 prior to ground truth data collection. Each point represented a circular sampling plot used for field verification of LULC classes. A total of 100 ground truth data were collected during the field surveys conducted between 2018 and 2021 and covered all land-cover classes within the study area, thereby improving the reliability of the processes of training sample selection and classification accuracy assessment. Classification accuracy was assessed using field-collected ground truth data, high-resolution Google Earth imagery, and existing knowledge of the study area. Accuracy assessment involved calculating user accuracy, producer accuracy, overall accuracy, and Kappa coefficients constructing an error matrix for land cover classification "Figure 2".

Table 1: Landsat imagery used for forest cover change detection

Satellite/Sensor	Path/ Row	Acquisition date	Spatial resolution	Cloud cover (%)
Landsat 5 TM	174/51	22 December 1988	30 m	0
Landsat 7 ETM+	174/51	21 December 2002	30 m	0
Landsat 8 OLI	174/51	07 January 2018	30 m	0

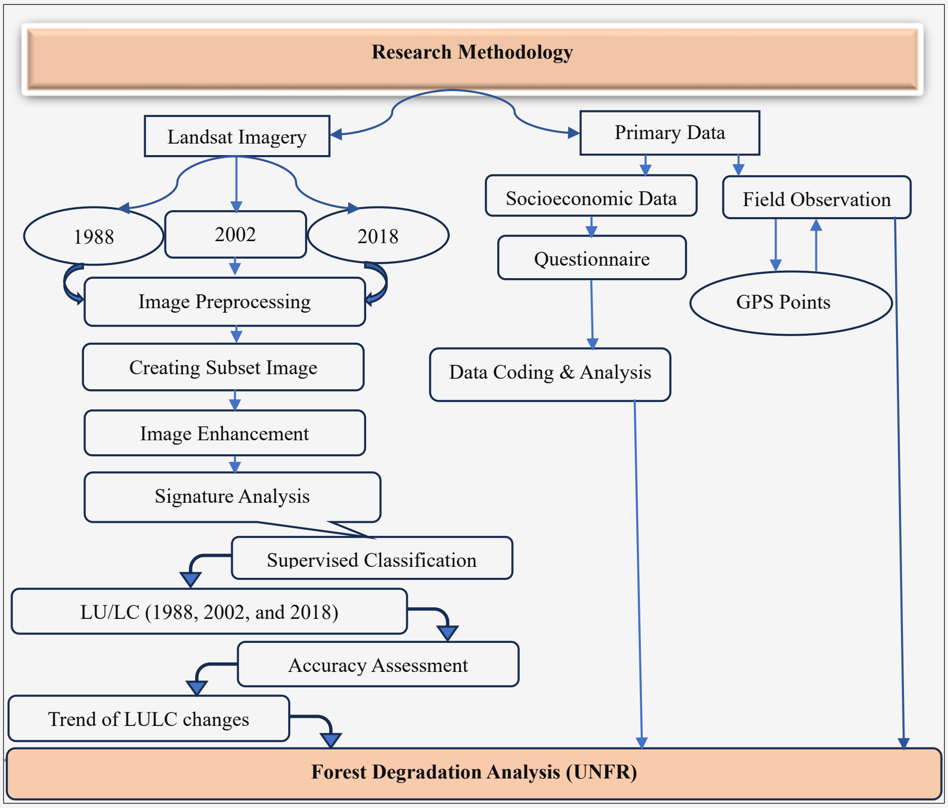

Figure 2: Forest degradation schematic

2.3 Socio-Economic Data

Social survey data were collected using a structured questionnaire administered to residents of villages surrounding UNFR. The questionnaire focused on the history of the forest and patterns of forest use to identify the key drivers of vegetation cover change during the study period. Interviews were conducted in three villages, targeting household heads to assess the extent of community interaction with the forest, types of activities carried out within it, and relevant socio-economic characteristics. Population data were obtained from the Ministry of Health, The Expanded Immunization Program, Al-Abbasiyah Office (Feb 2020). The populations of the surveyed villages were 1,285 in Umfakarin, 725 in Awlad Rahal, and 1,678 in Alhafera (Umdam/Dardig). The total population was calculated, and proportional random sampling approach was applied to allocate respondents to each village based on population size. A total of 97 respondents were selected for the survey. The questionnaire was pre-tested to ensure clarity and reliability. Both close-ended and Open-ended responses were used. Open-ended responses were coded into thematic categories and both analyzed using descriptive statistics in SPSS v24. These categories include building materials collection, fuelwood, charcoal production, agricultural expansion, overgrazing, and settlement growth. Frequencies and relative importance of these activities were calculated and used to rank dominant human pressures on forest resources. These ranked drivers were then systematically compared with the spatial and temporal patterns of forest cover change derived from Landsat imagery, allowing socio-economic factors to be evaluated as explanatory variables rather than descriptive information.

3. Results and Discussion

3.1 Land Use/Land Cover (LULC) Results for 2018

Supervised classification of the Landsat OLI 2018 imagery identified four primary LULC categories within the UNFR: tree cover, mixed vegetation, agricultural land, and bare land, "Figure 3"; "Table 2". Tree cover occupied a relatively limited portion of the area, reflecting a substantial decline in dense tree cover. Mixed vegetation represented a moderate share of the reserve. Agricultural land was the dominant land-use category, indicating increasing pressure from farming activities on the forest area. Bare land, corresponding to highly degraded areas with minimal vegetation cover, constituted a considerable portion of the area. Collectively, agricultural land and bare land covered more than half of the reserve, reflecting extensive landscape alteration and ongoing forest degradation. These LULC classes were defined based on ecological characteristics and dominant land cover composition. Classification was performed using a supervised maximum likelihood approach, in which representative training samples were selected for each class based on field observations, high-resolution Google Earth imagery, and expert knowledge of the study area. Tree Cover was characterized by relatively dense woody vegetation with semi-continuous canopy cover, exhibiting higher near-infrared reflectance. In contrast, Mixed Vegetation represented areas with sparse tree cover interspersed with shrubs, grasses, or bare soil, resulting in more heterogeneous spectral responses. Agriculture was differentiated from Mixed Vegetation based on its distinct spatial patterns, including field boundaries and seasonal spectral variability associated with cultivation practices, as well as lower vegetation persistence across years. This distribution underscores the intensifying anthropogenic impacts, particularly due to land clearing for agriculture, wood extraction, and livestock grazing [30]. The relatively low proportion of intact tree cover emphasizes the urgent need for effective conservation, restoration, and sustainable land management interventions [6].

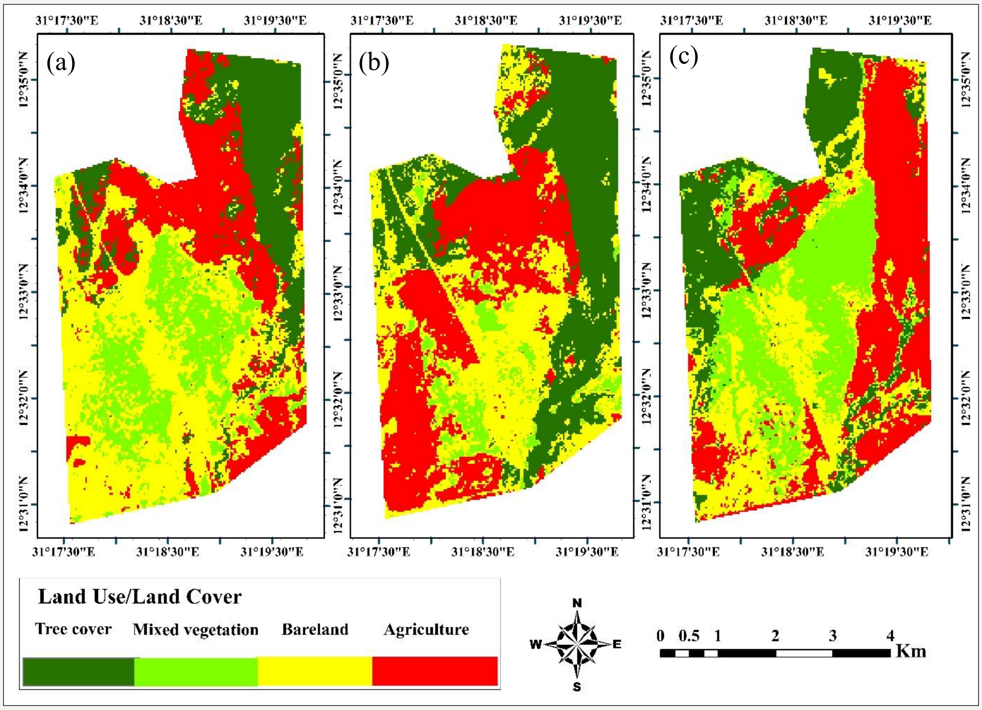

Figure 3: Land use/land cover of UNFR (a) 1988, (b) 2002, and (c) 2018

Table 2: Area and percentages of land use/cover (LULC) categories in the Umfakarin Natural Forest Reserve (UNFR) for 1988, 2002, and 2018

Class	1988		2002		2018	
	Area(ha)	**%**	**Area(ha)**	**%**	**Area(ha)**	**%**
Tree cover	546.57	19.89	883.08	32.13	506.43	18.42
Mixed vegetation	441.81	16.08	149.13	5.43	619.38	22.54
Bareland	1091.16	39.70	872.19	31.74	744.12	27.08
Agriculture	668.70	24.33	843.84	30.70	878.31	31.96
Total	2748.24	100.00	2748.24	100	2748.24	100.00

3.2 Land Use and Land Cover (LULC) Dynamics in UNFR (1988-2018)

The observed LULC changes in UNFR indicate a noticeable conversion of forested areas into agricultural land and other classes, shaped by both natural processes and anthropogenic activities. These changes have profound implications for ecological processes, resource management, and sustainable development [7][31] and [32]. Understanding LULC dynamics is critical for establishing baseline conditions and for monitoring environmental changes over time. In this study, substantial LULC changes were observed across the three time periods analyzed (1988, 2002, and 2018), as illustrated in “Figure 3” and summarized in “Table 2”. These changes were primarily driven by human activities such as agricultural expansion, wood harvesting, and grazing, along with broader environmental influences. Analysis of land cover dynamics over the study period indicates a clear transformation of the forest reserve. Tree cover exhibited a temporary recovery during the early period, followed by a pronounced decline in the later years by 13.71% reflecting increasing deforestation pressure. Mixed vegetation expanded over time, largely replacing dense tree cover and signaling noticeable forest degradation. Agricultural land consistently expanded by 7.63% during overall study period, underscoring sustained human pressure on forest resources, while bare land declined by 12.63%, indicating localized vegetation encroachment, land rehabilitation or shifts in land use practices. Overall, the observed changes highlight a transition from relatively intact forest cover toward more fragmented and human-dominated land use patterns.

These dynamics illustrate a transition from dense tree cover to a fragmented landscape dominated by degraded vegetation and agricultural fields, highlighting the need for integrated land management strategies to address forest loss and ecosystem degradation. The results showed that overall accuracy and Kappa coefficients for all classified images exceeded 85%, indicating high classification reliability.

Additionally, from the ground observation as well as the information exhibited satellite images in Figure 3, it illustrates a pronounced spatial reorganization of LULC classes across the reserve over the study period. Agricultural expansion is concentrated along the forest margins, indicating progressive encroachment from surrounding villages. Tree cover is increasingly confined to interior patches and areas associated with seasonal watercourses, while mixed vegetation occupies transitional zones between dense trees and cultivated lands. Bare land is primarily distributed in highly disturbed peripheral zones and along the transportation corridor, reflecting localized degradation and land-use intensification. The clearly visible national transportation corridor that traverses the reserve, linking major regional cities and the capital, which has facilitated access and intensified land use within the forest.

Having a simple rate of change analysis further substantiates the observed LULC dynamics. Tree cover increased at an average rate of approximately 0.87% annually between 1988 and 2002 but subsequently declined at a comparable annual rate of about 0.86% from 2002 to 2018, indicating a pronounced shift from forest recovery to accelerated degradation. During the period 1988-2002, large portions of the study area experienced relatively lower population density and limited agricultural expansion compared to the subsequent years. In addition, informal community protection of forest patches and reduced accessibility to some parts of the reserve may have facilitated natural regrowth of vegetation. Although detailed historical forestry program records are limited, local knowledge indicates that tree cutting intensity was lower during this period, which may have contributed to the observed recovery. Over the full study period, mixed vegetation expanded gradually (0.22% annually), suggesting replacement of dense forest by transitional vegetation types. Agricultural land increased steadily at an average rate of approximately 0.25% annually, reflecting sustained anthropogenic pressure, while bare land decreased at an annual rate of about 0.42%, likely due to localized vegetation encroachment or land-use changes.

3.3 Land Use/Land Cover Change Trajectories

LULC change reflects a complex interplay of interdependent processes driven by human activities and environmental dynamics [7][33] and [34]. Understanding these transitions requires analyzing the succession of different land cover types over time, a task effectively facilitated by remote sensing data [7] and [35]. In the UNFR, substantial LULC changes have occurred over recent decades, reflecting significant transformations across both spatial and temporal scales. The LULC transition matrices, “Table 3”and corresponding maps, “Figure 4” illustrate the evolution of the landscape into a dynamic mosaic of land use categories. These analytical tools are essential for detecting patterns of natural resource depletion in semi-arid environments [17][18] and [36], as well as for interpreting land use transition pathways and their driving forces [37] and [38].

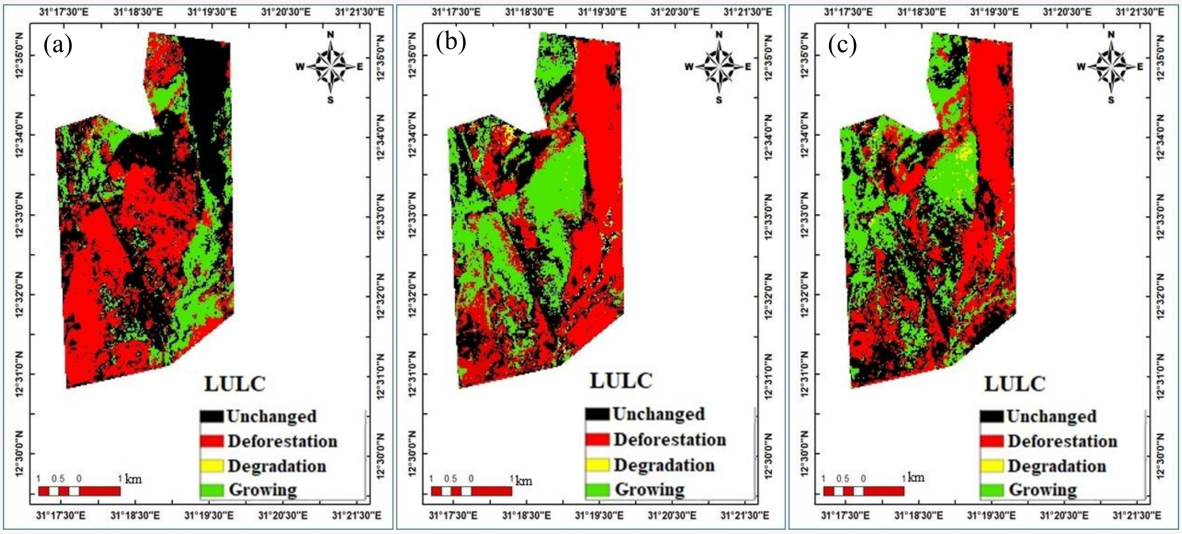

Figure 4: Land use/land cover change trajectories in UNFR:
(a) 1988 -2002, (b) 2002 – 2018, and (c) 1988 -2018

Table 3: Land use/land cover (LULC) transition matrices in UNFR between 1988 and 2018 (in hectares). Rows represent the land cover class at the start of the period; columns represent the land cover class at the end

Period	From / To	Tree cover	Mixed vegetation	Agriculture	Bareland	Start Area
1988-2002	**Tree cover**	455.9	1.6	39.0	50.1	546.6
	Mixed vegetation	16.4	89.1	138.8	197.6	441.8
	Agriculture	230.2	8.9	260.1	169.5	668.7
	Bareland	180.6	49.5	406.0	455.1	1091.2
	End Area	883.1	149.1	843.8	872.2	2748.2
2002-2018	**Tree cover**	229.1	29.7	506.7	117.5	883.1
	Mixed vegetation	7.7	50.6	10.1	80.7	149.1
	Agriculture	95.4	295.7	198.0	254.7	843.8
	Bareland	174.2	243.4	163.5	291.2	872.2
	End Area	506.4	619.4	878.3	744.1	2748.2
1988-2018	**Tree cover**	150.3	28.4	322.1	45.7	546.6
	Mixed vegetation	10.9	210.7	44.4	175.9	441.8
	Agriculture	165.7	119.3	252.0	131.8	668.7
	Bareland	179.6	261.0	259.8	390.8	1091.2
	End Area	506.4	619.4	878.3	744.1	2748.2

Analysis of transitions across the periods 1988–2002, 2002–2018, and the full period of 1988–2018 reveals distinct trends of deforestation, forest regeneration, and land use shifts. Between 1988 and 2002, tree cover expanded significantly. Approximately most of the tree cover that existed in 1988 remained intact by 2002, while a few amounts were lost, mainly due to conversion to agricultural and bare land. During this period, substantial forest regeneration occurred. Tree cover extended into previously non-forested areas, reclaiming a considerable area of forest land that had been under agriculture, similarly wide area from bare land, and small area from mixed vegetation. These gains resulted in a net increase in the forest area, with total tree cover rising by 61.9% compared to its 1988 extent.

In contrast, the period from 2002 to 2018 witnessed a sharp decline in tree cover. Only a quarter of the tree cover present in 2002 persisted by 2018, indicating a loss of most of forest land. Most of this loss resulted from conversions to agriculture and bare land, with a smaller proportion transitioning to mixed vegetation. Although some regeneration took place, equivalent to the recorded degraded area, it was insufficient to compensate for the extensive deforestation. These trends underscore the increasing vulnerability of forest ecosystems due to growing land-use pressures.

Over the full 30-year period (1988–2018), almost a quarter of the original tree cover area persisted. Approximately two-thirds were lost, and converted to agriculture, bare land, and mixed vegetation. While forest regeneration remained a considerable amount of the original 1988 forest area, the net loss over the period stood at 6.2%. However, this modest figure masked the extensive turnover in land cover and reflected the dynamic nature of landscape transformations over time.

Other land use categories also experienced considerable change. By 2018, only a few amounts of the mixed vegetation that was recorded in 1988 remained unchanged; the majority had transitioned to other land cover types. Similarly, bare land retained less than half of its 1988 extent but underwent several transitions that contributed to both forest regeneration and agricultural expansion. These findings reflected the complexity of land-use dynamics and highlighted the significant impact of human activities on forest landscapes. Agricultural land exhibited both expansion and contraction across the study periods, reflecting the fluctuating pressures and demands on land resources. These transition patterns, as captured in the LULC transition matrices, offer valuable insights into the broader landscape dynamics and the multiple land use pressures shaping the evolution of the UNFR.

Consequently, as illustrated in Figure 4, it reveals that healthy trees between 1988 and 2002 were spatially concentrated along seasonal drainage lines and in interior portions of the reserve that were less accessible to human activities. In contrast, forest loss after 2002 shows a pronounced peripheral and linear spatial pattern, with major transitions to agriculture and bare land occurring along the reserve boundaries and in areas adjacent to settlement zones. These patterns indicate that accessibility strongly structured the direction and intensity of forest cover transitions. Regenerated forest patches are increasingly fragmented and confined to hydrologically favorable areas, whereas conversion to agricultural and degraded land dominates easily accessible and road-adjacent zones.

Overall, the LULC changes observed in UNFR between 1988 and 2018 reflect a highly dynamic and evolving landscape shaped by competing forces of degradation and regeneration. Though certain periods demonstrated encouraging signs of forest recovery, these gains were ultimately offset by extensive deforestation and the continued expansion of agricultural land. The findings underscore the urgent need for integrated land use planning and inclusive, community-based forest management strategies to secure the long-term sustainability of forest ecosystems in Sudan's semi-arid regions. The gain/loss analysis revealed clear land use/land cover (LULC) transformations in the study area between 1988 and 2018. During 1988–2002, tree cover increased by approximately 427 km² and agriculture expanded by nearly 584 km², while mixed vegetation declined by over 350 km², and bareland also experienced notable losses outlined in "Figure 5". These patterns reflect widespread conversion of natural and barren land into productive uses, consistent with recent multi-decadal LULC studies that report agricultural expansion at the expense of forests and shrublands in Africa and Asia [7][39][40][41] and [42].

In the second period (2002–2018), tree cover suffered a major reduction exceeding 650 km², whereas mixed vegetation recorded the highest gain (~569 km²), suggesting vegetation regeneration or transitions from degraded lands. Over the full 30-year period, agriculture had the largest net increase (+210 km²) and bareland the greatest net loss (−347 km²), highlighting a long-term shift toward cultivated and vegetated landscapes. Similar trajectories have been documented in recent remote sensing studies, showing that forest decline often coincides with regrowth in secondary vegetation, while agricultural expansion dominates landscape change globally [43][42][41][7] and [39]. These findings confirm that the study area has undergone complex, human-driven LULC transitions, with significant implications for ecosystem stability, land management, and sustainable development.

3.4 Drivers of Forest Degradation in UNFR

The socio-economic survey and remote sensing analysis reveal that UNFR is subject to continuous pressures from both environmental and anthropogenic factors. Local communities depend heavily on forest resources for fuel, construction materials, fodder, and non-wood forest products, contributing to widespread deforestation and forest degradation. Among environmental drivers, most respondents identified insufficient rainfall and drought as key factors weakening forest ecosystems. Soil erosion and other minor factors were also reported as contributing to forest degradation.

Human-induced pressures emerged as the dominant threat to forest integrity. Illegal tree cutting, reported by 85 of 97 household surveyed (88% of respondents), was identified as the primary driver of forest loss, driven largely by demand for firewood and charcoal production. Most fuelwood harvesting occurs directly from natural forests, accelerating resource depletion. Settlement expansion and overgrazing are also considered as significant contributors, converting forested land into residential areas and grazing fields. Additionally, shifting cultivation exacerbates degradation by clearing forest patches for temporary agricultural use.

Other contributing threats include forest fires, road construction, and unclassified factors. Although these have a comparatively smaller impact than the primary drivers, they nonetheless contribute to the overall degradation of the forest ecosystem. The cumulative effects of these pressures are particularly pronounced in areas near urban centers, where demand for forest products is high and enforcement of protection measures is often weak "Figure 6". These statistical findings were derived from descriptive analysis of the social survey data, in which interview respondents identified illegal tree cutting as being reported significantly more often than other contributing factors.

In the other hand, the relationship between questionnaire findings and remote sensing results was examined through qualitative approach. Spatial patterns of vegetation change derived from Landsat imagery were compared with reported land-use practices, forest utilization activities, and perceived drivers of change identified through the questionnaire survey. Convergences between observed vegetation loss and dominant human activities reported by respondents were used to interpret the underlying causes of land-cover change. Despite visible signs of degradation and the advancing threat of desertification, pressure on both natural and planted forests continues to escalate. This situation underscores the urgent need for integrated forest management strategies that address both environmental and socio-economic drivers of deforestation. Priority should be given to promoting sustainable energy alternatives, implementing community-based forest governance models, and launching public awareness campaigns aimed at reducing local dependence on forest resources. These measures are critical to ensure the long-term conservation and sustainability of forest landscapes in Sudan's semi-arid regions [7][31] and [44].

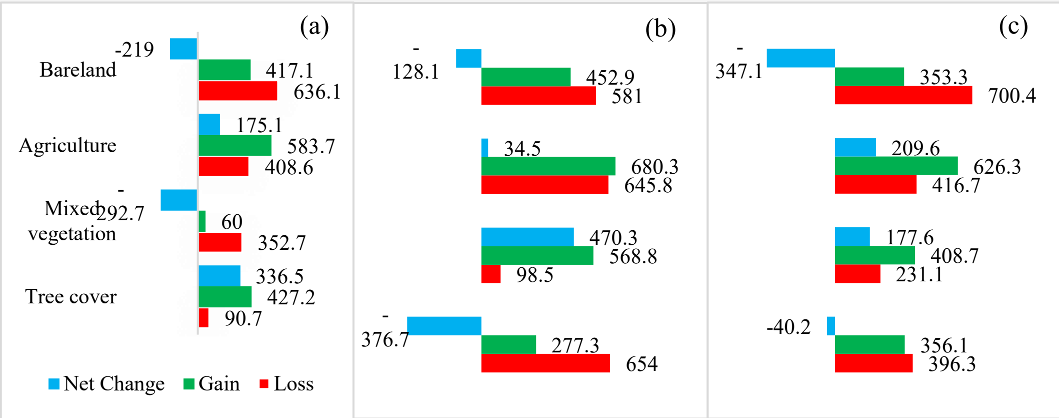

Figure 5: Gain and Loss Patterns of Land Use/Land Cover Classes in UNFR: (a) 1988-2002; (b) 2002-2018; (c) 1988-2018

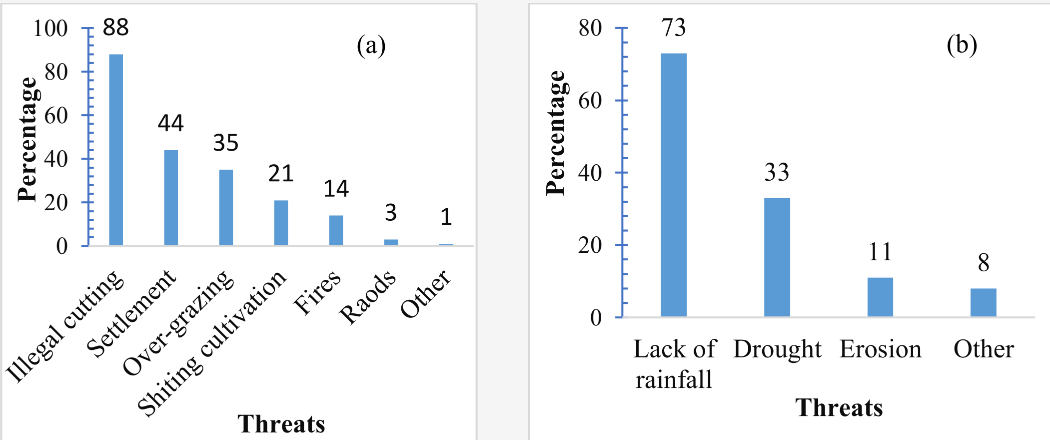

Figure 6: Summary of major drivers of forest degradation and deforestation in UNFR, categorized as: (a) anthropogenic factors and (b) environmental factors

Table 4: Accuracy assessment of classified map of 2018

Class Name	Tree Cover	Mixed Vegetatio	Bareland	Agriculture	Total	UA %
Tree Cover	18	2	0	0	20	90.0
Mixed Vegetation	1	22	0	2	25	88.0
Bareland	0	1	30	2	33	90.9
Agriculture	0	1	1	20	22	90.9
Total	19	26	31	24	100	
PA %	94.7	84.6	96.8	83.3		
OA %						89.9
Kappa %						86.5

Table 5: accuracy assessment of classified map 2002

Class Name	Tree Cover	Mixed Vegetation	Bareland	Agriculture	Total	UA %
Tree Cover	17	2	0	1	20	85.0
Mixed Vegetation	2	21	1	1	25	84.0
Bareland	0	1	29	3	33	87.9
Agriculture	0	2	2	18	22	81.8
Total	19	26	32	23	100	
PA %	89.5	80.8	90.6	78.3		
OA %						88.8
Kappa %						84.2

Table 6: Accuracy assessment of classified map of 1988

Class Name	Tree Cover	Mixed Vegetation	Bareland	Agriculture	Total	UA %
Tree Cover	15	3	1	1	20	75.0
Mixed Vegetation	2	20	1	2	25	80.0
Bareland	1	2	28	2	33	84.8
Agriculture	1	2	3	16	22	72.7
Total	19	27	33	21	100	
PA %	78.9	74.1	84.8	76.2		
OA %						85.0
Kappa %						80.1

3.5 Accuracy Assessment of Classified Images

The accuracy assessment confusion matrices of the classified maps for 2018, 2002, and 1998 are illustrated in Tables 4 to 6, respectively. The overall accuracies of the classified maps were 89.9%, 88.8%, and 85%, with corresponding Kappa values of 86.6%, 84.2%, and 80.1% respectively. It is worth noting that these Kappa values indicate an acceptable level of classification accuracy. The classification accuracy varied among the three study years, reflecting differences in sensor characteristics, image quality, and landscape heterogeneity. Inspection of the confusion matrices indicates that most classification errors occur between the "Tree Cover" and "Mixed Vegetation" classes, as well as between "Mixed Vegetation" and "Agricultural Land." This confusion reflects the spectral similarity of sparse woody vegetation, fallow fields, and cultivated plots in semi-arid environments. Consequently, some transitions involving mixed vegetation may be overestimated, while subtle degradation of dense forest into sparsely vegetated formations may be partially underestimated. However, misclassification between tree cover and bare land was minimal, suggesting that the major deforestation trends and conversion to degraded land reported in this study are robust and not artifacts of classification error.

4. Discussion

This study revealed noticeable LULC changes in the UNFR over the 30-year period from 1988 to 2018. The most notable trends include a substantial reduction in tree cover, a steady expansion of agricultural land, and a marked increase in mixed vegetation cover, indicating progressive forest degradation rather than complete deforestation. The temporary increase in tree cover observed between 1988 and 2002 may be attributed to periods of natural regeneration or small-scale afforestation efforts, consistent with patterns reported in other semi-arid regions of Sub-Saharan Africa [7][12] and [31]. Consequently, this temporary increment in tree cover

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coincided with a period of low land-use pressure which was especially notable after the region recovered from a prolonged drought in the late 1980s, as documented by [23] and [24]. Local knowledge indicates that access to interior forest areas was limited during this period, and population density and agricultural expansion were lower compared to later years. Parts of South Kordofan also experienced intermittent population displacement and reduced settlement activity in the 1990s, which may have lessened extraction pressure and facilitated natural forest regeneration, particularly along seasonal drainage lines. Despite the formal gazetting of the reserve in 1993, enforcement capacity was limited, so the observed recovery is more likely due to reduced human pressure rather than structured conservation management.

However, this gain was not sustained; from 2002 to 2018, tree cover experienced a sharp decline, reflecting intensified anthropogenic pressures, including unsustainable agricultural expansion, illegal tree cutting, overgrazing, and settlement growth. Similar drivers have been widely recognized in studies of dryland forest ecosystems where competing demands for land and forest resources lead to rapid landscape transformations [45] and [46]. Additionally, the pronounced forest loss between 2002 and 2018 corresponds to a period of intensified socio-political instability and livelihood stress in South Kordofan. Conflict-related displacement, return migration, and weakening of institutional control increased dependence on forest resources for fuelwood, charcoal production, and agricultural expansion as reported by [47] and [48]. These processes likely amplified encroachment along road corridors and settlement margins, as observed in the spatial patterns of forest conversion. Armed conflict in South Kordofan has greatly changed how forests are used and managed, turning protected forest areas into important survival resources for local communities. Insecurity has weakened forest monitoring and law enforcement, allowing widespread tree cutting, higher fire risk, reduced natural regeneration, and fragmentation of forest patches. These pressures have accelerated the conversion of dense forest into degraded shrubland and increased forest degradation in UNFR.

The period of rapid forest loss from 2002 to 2018 aligns with increased conflict in South Kordofan after the separation of South Sudan in 2011. This conflict escalated between the Government of Sudan and the Sudan People's Liberation Movement, North (SPLM-N), the correlation is consistent with the evaluation of the war's impact discussed in reference [49]. This conflict weakened governance, displaced populations, and increased livelihood pressures on forest resources. In the other hand, long-standing tensions between farmers and pastoralists in South Kordofan have further intensified pressure on forest resources. Increasing competition over land, water, and grazing routes has led to local conflicts, particularly in areas surrounding forest reserves as stated in [50]. As agricultural expansion and livestock movements increasingly overlap, forest areas are often cleared to establish new farms, temporary settlements, or grazing access points. These processes not only accelerate forest conversion but also promote repeated disturbance through fuelwood collection, charcoal production, and uncontrolled grazing. Such dynamics likely contribute to the fragmentation and degradation patterns observed in UNFR, particularly along forest margins and transportation routes, and may exacerbate future forest loss in the absence of integrated land-use planning and conflict-sensitive resource management strategies.

The increase in mixed vegetation, particularly after 2002, suggests forest degradation processes where selective logging and grazing reduce tree density but leave degraded secondary vegetation in place. This pattern aligns with previous research highlighting that forest degradation, while less immediately visible than clear-cutting, poses a significant long-term threat to ecosystem health and resilience [33] and [35]. The recorded decline in tree cover in the whole study period was closely associated with various human-induced activities. Despite the increment of trees in some parts of the forest, agricultural expansion was the dominant drivers of the forest disturbance between 1988 – 2002, where it has been noticed particularly on the forest areas close to the settlements and in line borders with agriculture. However, in the subsequent period in 2002 – 2018, the selective tree logging for fuelwood and intensified grazing have been clearly visible, observed inside the forest which contribute to further forest degradation.

The observed expansion of agricultural land underscores the central role of mechanized rainfed farming in driving deforestation in South Kordofan, as reported in previous studies [51] and [52]. This expansion is often fueled by population growth, food security concerns, and limited access to alternative livelihoods. The limited involvement of local communities in forest governance further exacerbates resource depletion and increases the risk of land use conflicts [44] and [53]. As observed in other studies, excluding key stakeholders from decision-making undermines conservation efforts and weakens enforcement of protection measures [54] and [53]. The results of the socio-economic survey show that there is limited local involvement in forest management. While 53% of respondents mentioned their participation in reforestation programs, they did not mention any involvement in actual forest management. Additionally, 46% stated that they did not have a formal role in decision-making, monitoring, or protecting the reserve. The survey respondents identified several barriers to participation, including the lack of benefit-sharing mechanisms, insufficient consultation, and poor communication with forest authorities. In terms of suggestions for improving forest management, respondents highlighted the importance of community-based forest patrols, designated fuelwood harvesting zones, alternative livelihood opportunities like Gum Arabic production and agroforestry, and clearer access rights. These responses indicate that local communities are willing to engage in forest protection if inclusive governance structures and livelihood options are put in place.

Environmental factors such as recurrent droughts, reduced rainfall, and soil erosion also contribute to forest vulnerability. These climatic stressors, combined with human pressures, create a complex socio-ecological system where forest degradation is both a cause and consequence of broader environmental instability [12] and [31].

The spatial patterns of forest degradation observed through remote sensing were further substantiated by socio-economic survey findings, which highlighted the intense dependence of local communities on forest resources. A significant proportion of respondents identified illegal tree cutting, overgrazing, and shifting cultivation as principal anthropogenic drivers [55], consistent with LULC transitions from tree cover to agricultural and mixed vegetation areas. The tree loss identified in this study has direct implications for forest governance and monitoring in UNFR. Deforestation is concentrated along transportation corridors, settlement margins, and accessible forest edges, highlighting priority areas for targeted enforcement, community patrols, and fuelwood regulation. These findings underscore the importance of integrating community-based forest management, controlled charcoal production schemes, and alternative livelihood programs, into regional forest policies [56]. Using multi-temporal Landsat imagery for monitoring can effectively detect gradual degradation and abrupt deforestation, offering a cost-effective approach for routine surveillance of protected dryland forests. Regular remote-sensing-based monitoring can facilitate early-warning systems, guide patrol deployment, and assess the impact of conservation efforts in conflict-affected areas.

The limited community engagement in forest governance revealed in the study likely contributes to persistent unsustainable land-use practices. These findings confirm that forest degradation in the UNFR is not solely an ecological issue but is intricately linked to socio-economic vulnerabilities, including energy poverty, a lack of alternative livelihoods, and weak institutional enforcement. This underscores the importance of aligning forest conservation strategies with local development needs, particularly through participatory approaches that empower local stakeholders and promote sustainable land management solutions. The ineffectiveness of legal protection can be attributed to limited institutional capacity, insufficient enforcement resources, and weak integration of local communities into reserve management frameworks. The absence of clearly defined benefit-sharing mechanisms and alternative livelihood options has further undermined compliance, resulting in continued forest encroachment despite formal protected status.

The findings emphasize the urgent need for integrated land management strategies that address both environmental and socio-economic drivers of forest loss. Conservation efforts should prioritize the promotion of sustainable energy alternatives to reduce dependence on fuelwood, the implementation of community-based governance models, and awareness campaigns aimed at fostering sustainable land use practices. Future research should incorporate higher temporal resolution satellite data, socio-economic assessments, and long-term monitoring to better capture the dynamics of forest degradation and support evidence-based policy interventions.

5. Conclusions

This study reveals notable forest degradation in the UNFR over the past three decades, with a decline in tree cover and expansion of agricultural and degraded lands. Forest loss is concentrated along transportation routes, settlement edges, and accessible forest areas, while remaining tree cover is found in interior areas and seasonal watercourses as outlined within the Satellite images. Accessibility, settlement growth, and unsustainable resource extraction are the drivers' reasons of degradation. The study identifies weaknesses in UNFR management, including undefined boundaries and limited enforcement capacity, leading to settlement encroachment, agricultural expansion, and illegal logging. Conflict-related stress and governance disruption exacerbate these pressures, causing forest fragmentation and conversion to shrubland. Recommendations based on spatial and socio-environmental evidence should be implemented and it involves clearly marking the reserve boundaries and using georeferenced mapping for enforcement, establishing buffer zones and enforcement priorities along the transportation routes, setting up monitoring units with local communities to enhance compliance and protection, introducing regulated fuelwood harvesting zones and promoting alternative energy sources, prioritizing reforestation in interior areas with high regeneration potential, implementing annual Landsat-based monitoring and higher resolution sensors for early detection of encroachment.

Nevertheless, the study's findings have practical implications for policy development, reforestation efforts, and land-use planning to address issues such as overgrazing, shifting cultivation, and environmental disturbances. Integrated forest management strategies are urgently needed to involve communities, regulate agricultural expansion, and address unsustainable wood harvesting practices. This research enhances our understanding of forest degradation in dryland regions and offers a model for monitoring similar environments facing ecological pressures. Implementing these insights into national conservation frameworks can help mitigate forest loss and promote the long-term ecological sustainability of Sudan's forests. Future research should incorporate higher resolution satellite data with more frequent fieldwork, and advanced classification algorithms to improve LULC analysis accuracy. Incorporating socio-economic assessments and expanding ground-truthing efforts will provide a comprehensive understanding of forest degradation drivers and sustainable resource management. Longitudinal studies on forest regeneration and community resilience, aligned with REDD+ frameworks, are recommended to inform evidence-based land management and sustainable forest conservation strategies in dryland regions like Sudan. Overall, the UNFR is a conflict-affected dryland forest experiencing rapid degradation due to accessibility issues. Targeted enforcement, restoration planning, and monitoring efforts are essential to protect forest resources and promote sustainable land management in South Kordofan.

6. Limitations

Although, the study has valuable outcomes, several methodological limitations should be acknowledged. The analysis is based on three Landsat acquisition years over 30 years, limiting the capture of short-term dynamics and interannual variability. The images were acquired during the dry season (temporal resolution) to ensure cloud-free conditions which may hinder the differentiation of vegetation types, overlook short-term changes and the classification accuracy may be influenced by spectral similarities among vegetation types and seasonal variability which may lead to spectral confusion between LULC classes. Socio-economic survey data, while valuable for perceived drivers of forest change, was limited to household heads, it might potentially bias the generalization survey findings. Despite these limitations, the study's approach offers valuable insights and remains cost-effective and replicable for monitoring forest change in data-scarce regions like South Kordofan and provides important information for sustainable forest management and supports baseline data sources for future research within UNFR.

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