Change Detection and Dynamics of Dom Palm (Hyphaene thebaica) Forests of Dryland in Northern Sudan

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Abstract: Dryland forests dominated by Dom palm (*Hyphaene thebaica*) in northern Sudan are increasingly threatened by human activities, climate variability, and invasive species. This study aimed to evaluate long-term forest dynamics, identify degradation drivers, and assess community-based management approaches in Umbashim, Helgi, and Gaili forest reserves. Multi-temporal satellite imagery from 1988 to 2025, combined with field observations and household surveys, was used to analyze land cover changes, species composition, and local perceptions. Results revealed clear differences in forests conditions among sites: Umbashim maintained high ecological stability, with over 68% of Dom palm cover retained through natural regeneration and community protection; In contrary, Gaili showed severe degradation, with Mesquite (*Prosopis* spp.) replacing more than 40% of Dom palm cover due to weak governance and overharvesting; Helgi exhibited a transitional state, with native and invasive species coexisting under moderate recovery. Climate analysis indicated substantial interannual rainfall variability and sustained increases in minimum and maximum temperatures, intensifying stress on native vegetation and limiting regeneration. Communities highlighted livelihood-oriented strategies, including handicraft development, local associations, and participatory forest management, as essential for sustainable recovery. The study underscores the need for integrated ecological and socio-economic interventions to enhance resilience, control invasives, and ensure the long-term sustainability of Dom palm forests in Sudan's dryland ecosystems.

Keyword: *Dom palm (Hyphaene thebaica), Dryland Forest dynamics, Land cover change, Invasive species (Prosopis spp.), Climate variability, Community-based forest management, Forest restoration and resilience, Google Earth Engine (GEE).*

Forest ecosystems in drylands, particularly in Sudan, play a critical role in supporting the livelihoods of millions by providing a wide range of products and services [1–3]. However, these ecosystems are increasingly under threat from various anthropogenic pressures, including deforestation, overgrazing, and unsustainable land-use practices, urbanization and agricultural expansion [3]. Furthermore, the impacts of climate change, such as rapid warming and drying, are expected to exacerbate these challenges, posing significant risks to Sudan's forests and savanna woodlands [2, 4, 5].

Remote sensing has become an indispensable tool for monitoring land use and land cover (LULC) changes and assessing forest disturbances. This technology offers timely and accurate insights into the interactions between human activities and natural ecosystems, enabling improved resource management [6–9]. Numerous studies have demonstrated the effectiveness of remote sensing in detecting changes in forest cover and understanding the underlying drivers, including infrastructure expansion, agricultural encroachment, and the spread of invasive species [2, 10–13]. When combined with ground-based observations, remote sensing enhances the precision of forest condition assessments, ultimately supporting better-informed management decisions [2, 14–16].

The Dom palm (*Hyphaene thebaica*) is one of eleven species in its genus found in Africa and belongs to the Arecaceae family. It is widely distributed across the Sahel region, extending from Senegal to Egypt and Sudan [17]. This species is a deciduous tree that typically reaches heights of 10–17 meters, with a trunk girth of up to 90 cm. It is easily recognizable by its Y-shaped trunk and dichotomous branching pattern, which contribute to its resilience in harsh environments. The leaves are fan-shaped, measuring 120 × 180 cm, and are arranged in tufts at the ends of the branches, with blades divided into segments approximately 60 cm long. The Dom palm is dioecious, meaning male and female flowers grow on separate trees [18]. In Sudan, Dom palm forests are primarily found along riverbanks, floodplains, and stream banks, often in saline soils. They also occur in stony sites away from water sources [17]. Nearly pure stands of Dom palms can be found in basins along the Atbara River, while other significant populations exist in the saline soils near the Gash River south of Kassala and along the seasonal wadis of the Red Sea Hills. Along the Blue Nile, Dom palms are relatively rare between Khartoum and Bunzoga [19].

Dom palm forests are well adapted to arid and semi-arid environments, thriving in regions where groundwater remains accessible. They are highly drought-tolerant and play a crucial role in stabilizing soil, preventing erosion, and supporting biodiversity. Their unique dichotomous branching pattern enhances light capture efficiency, promoting resilience in extreme climatic conditions. Additionally, these forests provide critical habitats and food sources for various wildlife species, including birds, mammals, and insects, thereby maintaining ecosystem balance. Beyond their ecological significance, Dom palm forests have substantial socio-economic importance for local communities. They provide essential resources such as fruits, fiber, timber, and animal fodder, contributing to livelihoods, construction materials, and traditional crafts. However, these forests are increasingly threatened by deforestation, overgrazing, and climate change, leading to habitat degradation. Furthermore, the invasion of Mesquite (*Prosopis spp*.) and unsustainable forest management practices further exacerbate the decline of Dom palm populations [20–23]. Despite their ecological and economic importance, long-term research on Dom palm forests remains scarce. There is a growing need for comprehensive studies on forest dynamics, conservation strategies, and sustainable management approaches. Addressing these knowledge gaps will be essential to preserving the ecological integrity and socio-economic benefits of Dom palm forests for future generations [24–27].

This study aims to fill this knowledge gap by assessed, mapping forest cover change, and analyze the anthropogenic factors, invasive species, and climate variability causing it in Umbashim, Helgi, and Gaili Forests reserves in Aldamar locality, River Nile State, Sudan, while providing recommendations for sustainable management and long-term monitoring. Also, it seeks to quantify extent and rate of forest degradation over time using spatial analysis techniques, and support evidence-based on making decisions by generating reliable data for planning and policy development in the study area.

1. Material and Methods

2.1. Study Area and Settings

This study was conducted in three Dom palm forest reserves located in Aldamar locality, northern Sudan, which represent typical Dom palm habitats in the semi-arid zones of Sudan. The gazetted areas of these forests are 208.3 hectares for Umbashim, 674.8 hectares for Helgi, and 245.4 hectares for Gaili (Fig. 1). The region's most notable climatic characteristic is its prolonged dry season, which lasts eight months, from November to June. The average annual rainfall varies between 100–150 mm in the southern parts of the state and decreases to 0–25 mm in the northern parts. The mean maximum temperature during summer reaches 47°C, while the mean minimum temperature in winter drops to 8°C [28]. The elevation of the study area ranges from 100 to 600 meters above sea level [29]. The total forested area in the region is approximately 87,675 hectares, distributed across 107 riparian and dryland forests [23]. The River Nile State is classified as an extremely arid region, encompassing true desert and semi-desert zones. The desert landscape dominates the area, except along the Nile banks and watercourses, where temporary herbs and grasses emerge following seasonal rainfall [19, 22, 23].

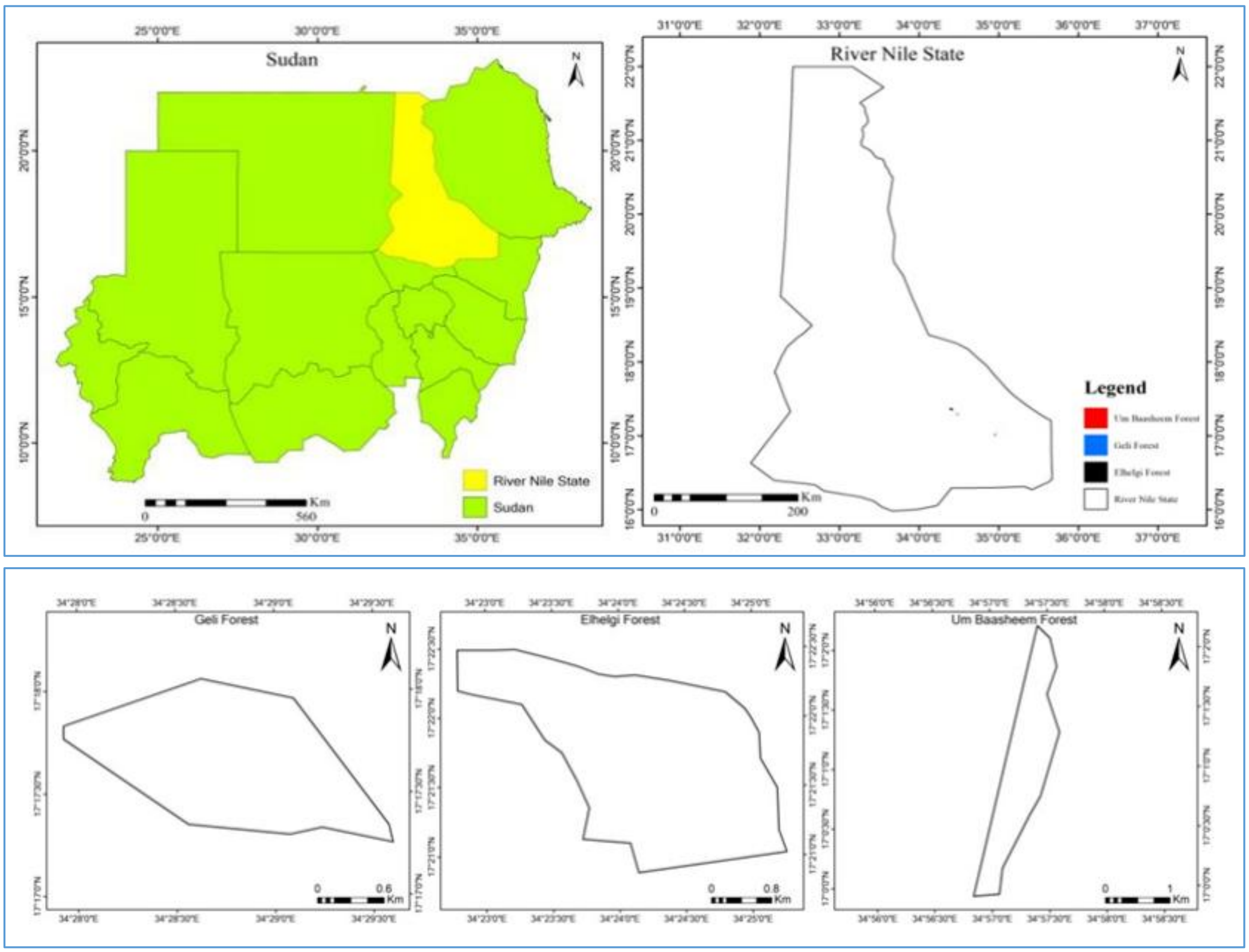

Fig. 1 Map of the Study Area

2.2. Data Collection and Analysis

The study used remotely sensed data to identify changes in land use and land cover (LULC), selecting satellite images from Landsat 5, ETM+ 7, OLI 8, and Sentinel-2. These images were collected cloud-free using Google Earth Engine (GEE). We used four satellite images, each with a spatial resolution of 10 and 30 m. We specifically chose Landsat 5 imagery from 1990, ETM+ 7 imagery from 2002, OLI 8 imagery from 2014, and Setinel-2 imagery from 2025 due to their extensive geographical coverage and temporal availability (***Table 1***). The study employed an integrated approach for data collection and analysis, combining remote sensing data with field-based information on land use activities observed during the research period. A structured questionnaire was designed, incorporating both closed- and open-ended questions, as well as multiple-choice options. All participants provided informed consent prior to participation, and responses were collected anonymously. The questionnaire focused on socio-demographic characteristics and respondents' perceptions regarding various aspects of Dom palm forests, particularly the utilization of their products, such as leaves (Zaaf) and fruit. It also examined the choices made by local communities. In addition, main problems and challenges facing these forests include overharvesting, grazing pressure, land-use changes and drought (Appendix A).

Table 1 Landsat 5 TM, ETM+ 7, OLI 8, and Sentinel-2 Data Used for Forest Cover Analysis

Satellite/Sensor	Acquisition Date (01.01 – 31.12)	Spectral Bands	Resolution (m)
Landsat 5 TM	1990	1, 2, 3, 4, 5, 7	30
Landsat 7 ETM+	2002	1, 2, 3, 4, 5, 7	30
Landsat 8 OLI	2014	2, 3, 4, 5, 6, 7	15/30
Sentinel-2	2025	2, 3, 4, 5, 8, 11, 12	10/20

for data analysis, the study employed Google Earth Engine (GEE), a powerful cloud-based geospatial platform, to access, preprocess, and analyze multi-temporal satellite imagery, ArcGIS Pro 3.5, and Microsoft Excel 2019 for the analysis and processing of satellite images. We used tools to calculate the areas of LULC changes, along with their percentages and transitions. Before processing the images, they were adjusted, the geometry and atmosphere were fixed, the layers were stacked, and the composite bands tool was used to merge spectral bands (1, 2, 3, 4, 5, and 7 for Landsat TM 5 and ETM+ 7, 2, 3, 4, 5, and 6 for OLI 8, and 2, 3, 4, 5, 8, 11, 12 for Sentinel-2) into a single-layer file. We clipped sub-scenes to the three forests for further analysis.

The study applied Random Forest classifier to classify forest cover from the acquired Landsat 5 1990, Landsat 7 ETM+ 2002, OLI 8 2014, and Sentinel-2 2025 images. The accuracy of each classified image was systematically evaluated using ground truth data, Google Earth imagery, and prior knowledge of the study area. The assessment involved calculating user accuracy, producer accuracy, overall accuracy, and Kappa coefficients, alongside the generation of an error matrix for the land cover classification (Fig. 2). The results demonstrated that the overall accuracy and Kappa coefficients for all classified images exceeded 85%, indicating a high level of classification reliability. SPSS Version 24 was used to analyze socio-demographic data, with emphasis on examining managerial and socio-economic factors influencing the collection of Dom palm leaves (Zaaf), as well as anthropogenic factors and natural disturbances affecting Dom palm forests.

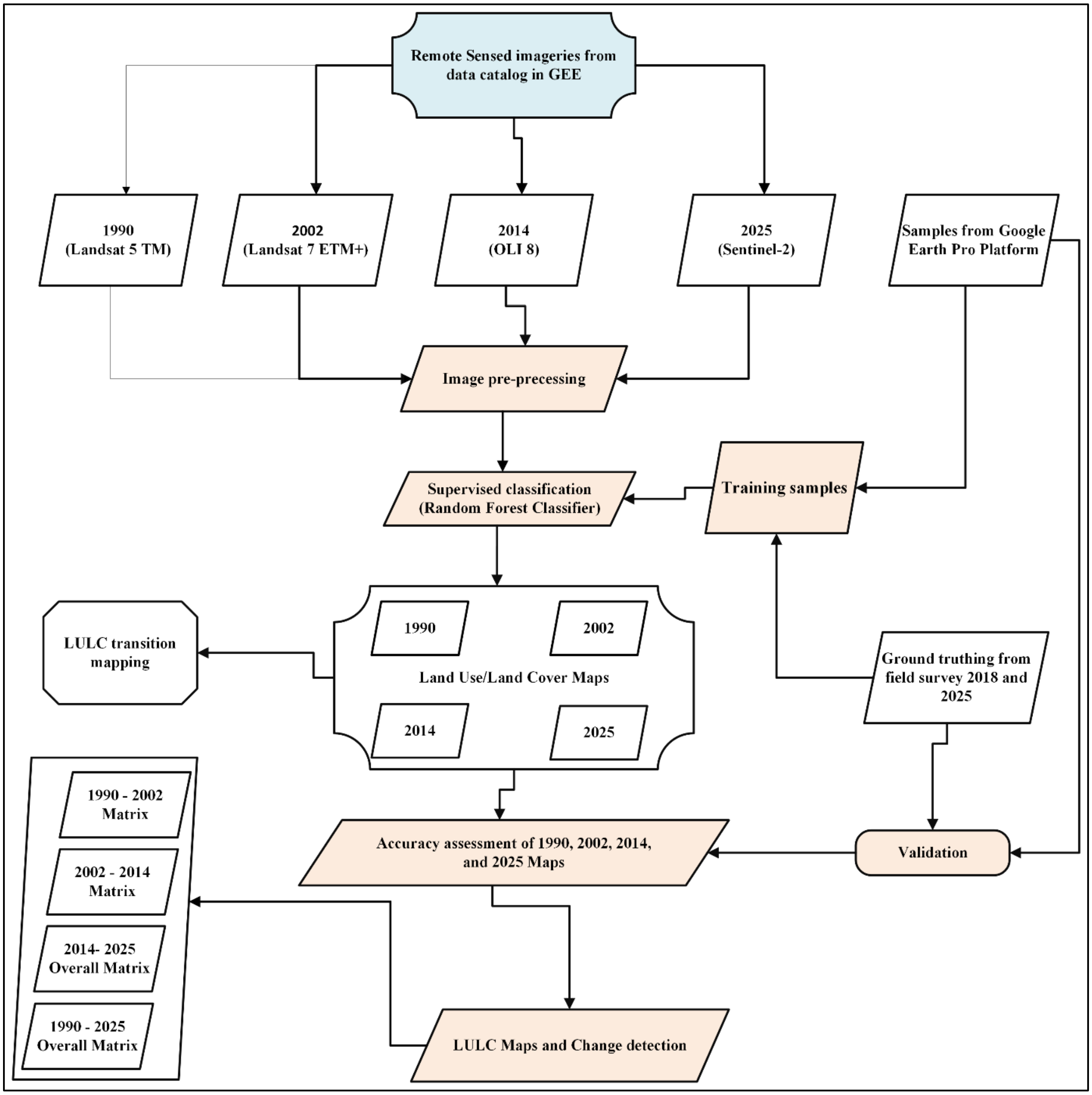

Fig. 2 Schematic workflow for data collection and analysis.

2. Results and Discussion

3.1. Forest Cover (FC) results in 2025

Gaili Forest is dominated by Mesquite trees (*Prosopis spp*.), occupying the largest area of 32.56% followed by other species 31.03%. Dom palm, represent 26.25%, while water body occupies the smallest area 10.15%. In Helgi Forest, Mesquite (*Prosopis* spp.) leads with 31.28%, demonstrating its adaptability, followed by Dom palm with 26.57%, indicating relative stability. Helgi forest, mixed trees contribute 23.23%, while the bareland accounts for 18.93%. In Umbashim Forest, Dom palm at low density dominates with 38.70%, followed by Dom (HD) with 30.23%, while other species and Sedir (*Ziziphus spina-christi*) accumulate contribute with 31.06% (Fig. 3 and Table 2).

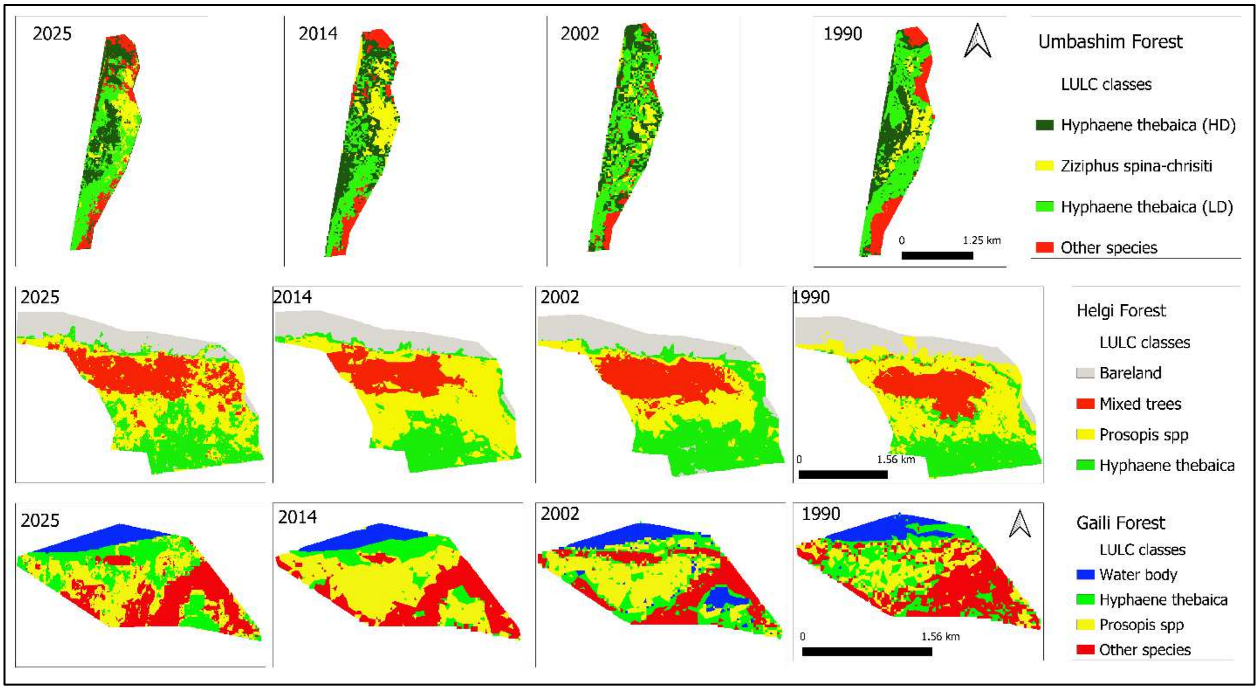

Fig. 3 Distribution of Forest Cover Classes in Umbashim, Helgi, and Gaili Forest Reserves for 1990-2025.

3.2. Change Detection in Forest Cover

The land cover dynamics of Helgi, Gali, and Umbashim forests from 1990 to 2025 reveal contrasting patterns of native vegetation persistence, invasive expansion, and structural change in Sudanese dryland ecosystems (Fig. 3 and Table 2). Multi-decadal satellite monitoring is widely recognized as essential for detecting long-term ecological shifts, degradation pathways, and recovery processes in dryland forests [30, 31]. These temporal variations further emphasize the influence of disturbance regimes, invasive pressure, and management effectiveness on forest stability [32, 33].

In Helgi Forest, Bare land remained relatively stable, decreasing slightly from 19.94% in 1990 to 18.93% in 2025, consistent with evidence that abiotic surfaces often change slowly compared with vegetation classes in drylands [34, 35]. Mixed tree cover increased markedly from 16.36% to 23.23%, suggesting gradual regeneration and structural diversification, which aligns with studies highlighting the utility of dense Sentinel-2 time series for detecting woodland expansion [36, 37]. Prosopis spp. remained dominant, fluctuating from 38.82% in 1990 to 23.82% in 2002, then rising to 31.28% by 2025. This reflects the opportunistic behavior of invasive woody species under disturbed conditions [38, 39]. Dom palm increased to 34.02% in 2002 before declining to 26.57% in 2025, indicating resilience but vulnerability to invasive competition [40, 41].

Gaili Forest experienced the strongest invasive expansion, with Prosopis increasing from 24.32% in 1990 to 45.23% in 2014, then declining to 32.56% in 2025. Such dominance is typical where disturbance reduces native cover [30, 32]. Dom palm declined sharply to 16.62% in 2014, reflecting biodiversity loss and compositional simplification in degraded dry ecosystems [33, 35]. Its recovery by 2025 suggests some regeneration detectable through multi-temporal Sentinel imagery [42, 43].

Umbashim Forest showed the strongest native persistence. Low-density Dom palm remained dominant, reaching 44.83% in 2002 and sustaining 38.70% in 2025, while high-density Dom palm peaked at 37.42% in 2014. This stability supports findings that protected or community-managed forests maintain stronger regeneration capacity [31, 37]. *Ziziphus spina-christi* increased to 19.07% in 2014, reflecting internal turnover shaped by climatic and land-use pressures [44, 45].

Overall, Sudanese dryland forests follow divergent pathways, from native stability (Umbashim) to transitional competition (Helgi) and invasive dominance (Gali). These results highlight the importance of long-term satellite monitoring and machine learning classification frameworks for sustainable forest management and biodiversity conservation [30, 31, 46].

Table 2 Forest Composition and Area Distribution in Helgi, Gaili, and Umbashim Forests during 1990 – 2025.

Helgi Forest	**Class name**	**1990**		**2002**		**2014**		**2025**	
		Area(ha)	**%**	**Area(ha)**	**%**	**Area(ha)**	**%**	**Area(ha)**	**%**
	Bareland	143.69	19.94	150.76	20.92	140.68	19.52	136.38	18.93
	Mixed trees	117.91	16.36	153.04	21.24	121.4	16.86	167.35	23.23
	Prosopis spp	279.72	38.82	171.64	23.82	301.63	41.86	225.38	31.28
	Hyphaene thebaica	179.21	24.87	245.09	34.02	156.77	21.76	191.42	26.57
	Total	**720.53**		**720.53**		**720.53**		**720.53**	
Gaili Forest	Water body	27.79	11.24	34.13	13.80	24.30	9.83	25.10	10.15
	Hyphaene thebaica	63.96	25.86	58.37	23.60	41.11	16.62	64.92	26.25
	Prosopis spp	60.14	24.32	87.90	35.55	111.85	45.23	80.53	32.56
	Other species	95.40	38.58	66.89	27.05	70.03	28.32	76.74	31.03
	Total	**247.29**		**247.29**		**247.29**		**247.29**	
Umbashim Forest	Hyphaene thebaica (HD)	78.33	28.23	94.68	34.13	103.82	37.42	83.88	30.23
	ZIziphus spina-chrisiti	33.36	12.03	32.95	11.88	52.91	19.07	41.21	14.85
	Hyphaene thebaica (LD)	114.34	41.21	124.39	44.83	81.35	29.32	107.38	38.70
	Other species	51.42	18.53	25.42	9.16	39.37	14.19	44.98	16.21
	Total	**277.45**		**277.45**		**277.45**		**277.45**	

3.3. Forest Cover trajectory matrix

The forest cover trajectory matrices for Umbashim, Gaili, and Helgi forests reveal distinct long-term vegetation dynamics shaped by ecological resilience, disturbance regimes, and management effectiveness over a 35-year period (Fig. 4 and Table 3). Umbashim consistently exhibited the highest stability and internal regeneration of native vegetation. Between 1990 and 2002, high-density Dom palm retained 12.06% of its original cover, while low-density Dom palm persisted at 23.01%, with 10.97% transitioning into high-density Dom stands, indicating natural densification. This trend continued through 2002–2014, with high-density retention rising to 14.82% and low-density Dom maintaining 18.69%. By 2014–2025, high-density Dom remained relatively stable at 16.22%, and low-density Dom retained 18.18%, resulting in cumulative native Dom persistence of 68.72% over the entire period (Fig. 4 and Table 3a). These patterns confirm that community protection and restricted forest access have effectively supported ecological resilience and minimized vegetation loss [35, 47, 48].

In contrast, Gaili Forest experienced severe degradation and Mesquite (*Prosopis spp.*) dominance. During 1990–2002, Mesquite retained 15.16% of its cover while gaining 9.62% and 8.58% from Dom palm and other species, respectively. Expansion accelerated in 2002–2014, with Mesquite retaining 17.31% and acquiring an additional 12.56% from Dom palm. By 2014–2025, Mesquite became the dominant class at 24.75%, while Dom palm stability fell to 10.36% (Fig. 4 and Table 3b). These transitions reflect the combined effects of weak governance, heavy extraction, and open-canopy conditions that facilitated opportunistic invasive proliferation [30, 33, 38, 39].

Helgi Forest displayed an intermediate trajectory, with both persistent native vegetation and ongoing invasive transitions. Between 1990–2002, Dom palm retained 20.29%, while Mesquite retained 16.47% and gained from Dom and mixed tree classes. Unlike Gaili, Helgi also showed reverse transitions, with 5.80% of Mesquite converting to mixed vegetation and 14.84% to Dom palm by 2002–2014, indicating partial recovery from targeted management. By 2014–2025, Mesquite reached 23.69% stable cover, but native classes remained resilient at 15.77% (Fig. 4 and Table 3c), highlighting a transitional equilibrium influenced by localized intervention and ecological resistance [44, 45, 49].

Overall, these matrices demonstrate the value of multi-temporal satellite analyses using Landsat and Sentinel archives for assessing forest stability, degradation, and invasive dynamics. Umbashim illustrates resilience under community management, Gaili shows the consequences of weak governance and invasive dominance, and Helgi reflects intermediate, partially managed conditions. These findings reinforce the role of trajectory-based monitoring for guiding sustainable dryland forest management in Sudan [31, 34, 36, 37].

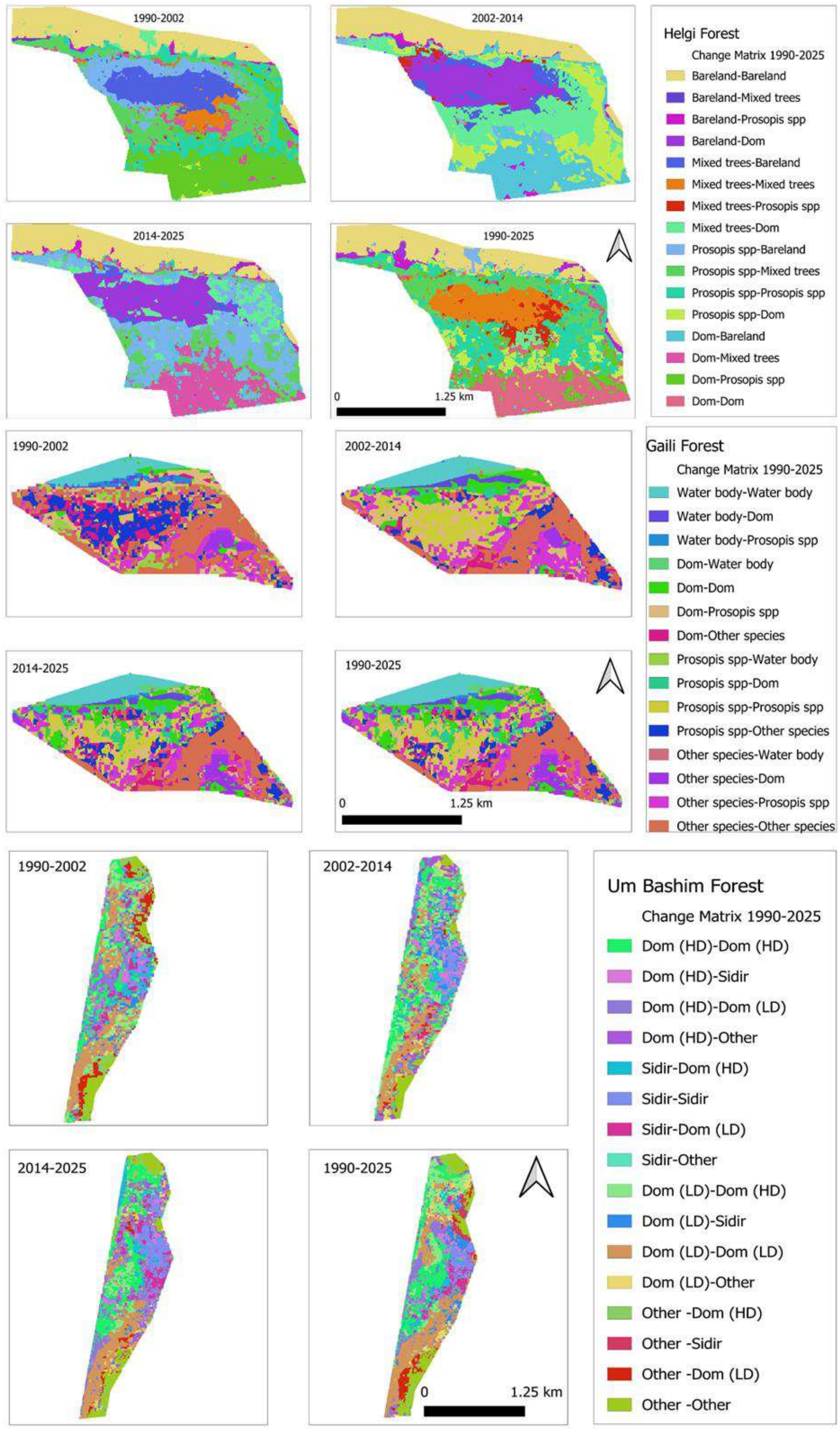

Fig. 4 Forest Cover trajectory Matrix in Helgi, Gaili, Umbashim Forest Reserve 1990-2025.

Table 3a Forest Cover trajectory Matrix in Umbashim Forest Reserve 1990-2025

Class name	HT (HD)	ZS	HT (LD)	OS	Total
1990-2002					
HT (HD)	12.06	4.34	12.76	4.86	34.02
ZS	4.17	3.33	3.94	0.57	12.01
HT (LD)	10.97	4.46	23.01	6.30	44.74
OS	0.90	0.08	1.49	6.76	9.23
Total	**28.10**	**12.22**	**41.19**	**18.49**	**100.00**
2002-2014					
HT (HD)	14.82	4.08	17.28	1.17	37.34
ZS	7.14	5.44	6.34	0.18	19.10
HT (LD)	6.87	2.08	18.69	1.78	29.42
OS	5.21	0.35	2.52	6.06	14.13
Total	**34.05**	**11.94**	**44.82**	**9.19**	**100.00**
2014-2025					
HT (HD)	16.22	3.81	6.71	3.22	29.97
ZS	4.05	9.12	1.72	0.13	15.02
HT (LD)	13.00	5.58	18.18	1.98	38.74
OS	4.01	0.66	2.77	8.83	16.28
Total	**37.28**	**19.18**	**29.39**	**14.15**	**100.00**
1990-2025					
HT (HD)	14.39	3.26	9.94	2.38	29.97
ZS	3.22	4.54	4.94	2.31	15.01
HT (LD)	8.86	4.13	22.19	3.58	38.75
OS	1.68	0.26	4.08	10.25	16.27
Total	**28.15**	**12.18**	**41.16**	**18.52**	**100.00**

Table 3b Forest Cover trajectory Matrix in Gaili Forest Reserve 1990-2025

Class name	WB	HT	P spp	OS	Total
1990-2002					
WB	7.97	2.09	0.16	3.64	13.86
HT	1.08	8.85	4.38	9.24	23.55
P spp	2.25	9.62	15.16	8.58	35.61
OS	0.03	5.30	4.61	17.04	26.98
Total	**11.33**	**25.86**	**24.31**	**38.50**	**100.00**
2002-2014					
WB	8.37	1.33	0.04	0.10	9.85
HT	2.81	7.92	2.44	3.53	16.70
P spp	0.08	12.56	17.31	15.30	45.24
OS	0.00	4.05	4.57	19.60	28.22
Total	**11.26**	**25.86**	**24.35**	**38.53**	**100.00**
2014-2025					

WB	9.59	0.49	0.07	0.00	10.16
HT	0.24	11.60	12.11	2.25	26.20
P spp	0.11	3.25	24.75	4.45	32.57
OS	0.00	1.34	8.36	21.37	31.07
Total	**9.94**	**16.69**	**45.29**	**28.08**	**100.00**
			1990-2025		
WB	8.79	1.14	0.10	0.14	10.16
HT	2.08	10.36	6.20	7.58	26.22
P spp	0.47	8.98	12.45	10.71	32.61
OS	0.00	5.43	5.67	19.90	31.01
Total	**11.34**	**25.90**	**24.43**	**38.33**	**100.00**

Table 3c Forest Cover trajectory Matrix in Helgi Forest Reserve 1990-2025

			1990-2002		
Class name	**BL**	**MT**	**P spp**	**HT**	**Total**
BL	18.71	0.03	1.74	0.45	20.93
MT	0	12.58	8.14	0.55	21.26
P spp	0.26	3.56	16.47	3.56	23.84
HT	0.96	0.25	12.46	20.29	33.97
Total	**19.93**	**16.42**	**38.81**	**24.85**	**100.00**
			2002-2014		
BL	19.15	0.00	0.00	0.38	19.54
MT	0	15.38	1.42	0.09	16.89
P spp	0.21	5.80	20.96	14.84	41.81
HT	1.59	0.08	1.40	18.70	21.77
Total	**20.95**	**21.26**	**23.78**	**34.00**	**100.00**
			2014-2025		
BL	18.15	0.00	0.11	0.58	18.83
MT	0.00	14.59	8.46	0.24	23.28
P spp	0.27	2.19	23.69	5.16	31.31
HT	1.08	0.11	9.61	15.77	26.57
Total	**19.50**	**16.89**	**41.86**	**21.75**	**100.00**
			1990-2025		
BL	17.05	0.04	1.60	0.12	18.82
MT	0.06	11.40	10.74	1.12	23.32
P spp	1.35	3.65	18.66	7.67	31.32
HT	1.47	1.32	7.83	15.92	26.54
Total	**19.92**	**16.42**	**38.83**	**24.83**	**100.00**

3.4. Climate Trends and Implications for Forests

Climate data from 1980/1981 to 2025 reveal strong interannual rainfall variability alongside a pronounced warming trend in both minimum (Tmin) and maximum (Tmax) temperatures (Fig. 5). Annual precipitation fluctuated markedly, with wet peaks in the late 1980s and early 2000s. Multi-period trend analyses (1981–2025, 1991–2025, 2001–2025) indicate a moderate long-term increase, though variability dominates, consistent with Sahelian patterns where shifts in extremes outweigh directional change [50, 51, 52]. Irregular rainfall reduces soil moisture, intensifies drought stress, and limits regeneration of native species like Dom palm (Hyphaene thebaica) under growing land-use pressures [53–58].

Tmin increased steadily since 1980, accelerating after 2000, reflecting warmer nights that heighten plant respiratory losses and physiological stress [59–65]. Tmax rose from ~43°C to 46°C, especially after the mid-1990s, accelerating evapotranspiration, reducing seedling survival, and favoring drought-tolerant invasives like Prosopis spp. [52, 59, 66, 67].

Together, rising temperatures and rainfall variability threaten forest productivity, interacting with land degradation to increase vulnerability in unmanaged areas like Gaili, while community-managed forests like Umbashim show greater resilience [53, 54, 56]. Integrating climate-resilient strategies is essential to ensure long-term Dom palm persistence.

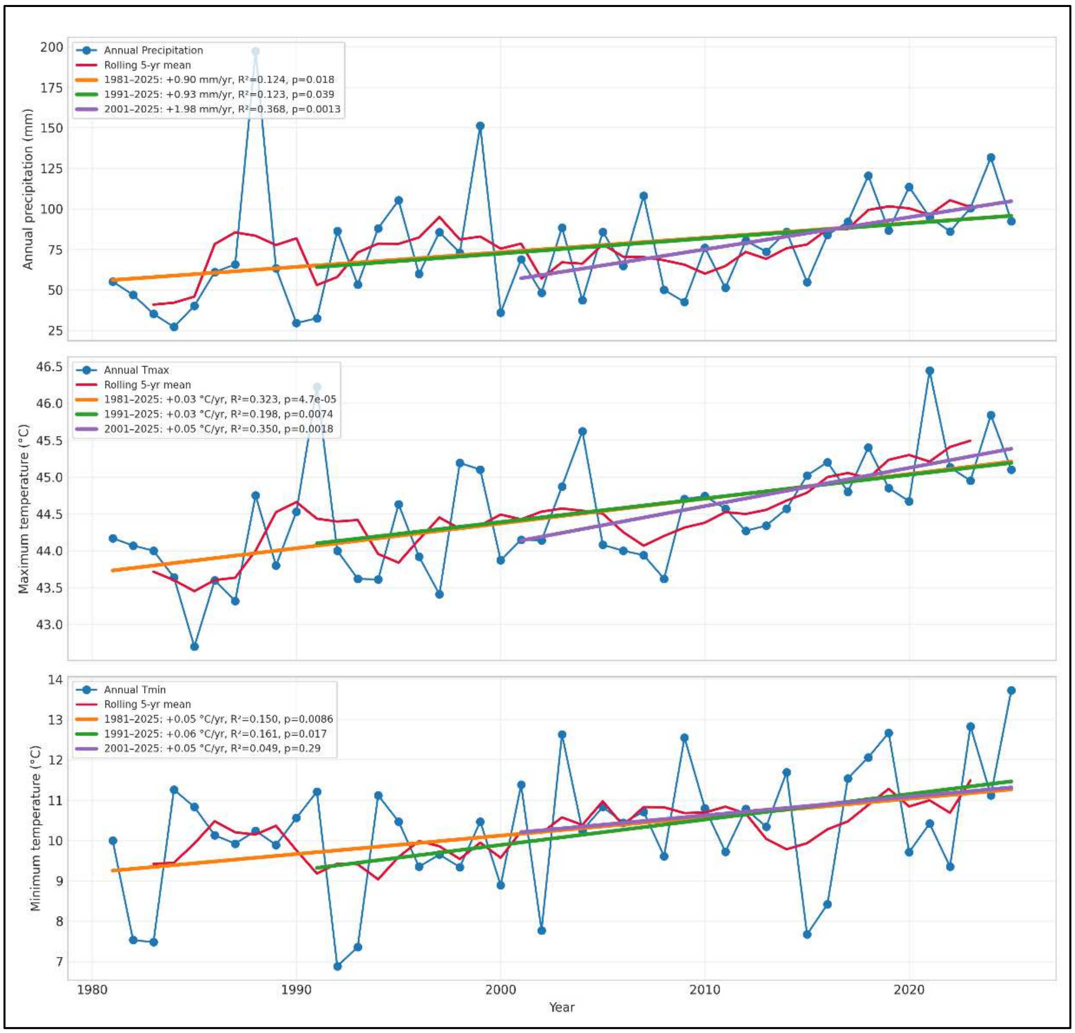

Fig. 5 Temporal Dynamics of Precipitation and Temperature (1981–2025) Including 5-Year Smoothing and Multi-Period Trend Estimates.

3.5. Impact of Invasive Species

The spread of Mesquite (Prosopis spp.) is a major ecological threat to Dom palm (*Hyphaene thebaica*) forests. Land cover transition analysis revealed extensive displacement of native vegetation, particularly in

Gaili and Helgi Forests. Approximately 41.8% of Dom palm in Gaili and 35.1% in Helgi were replaced by Mesquite (Tables 4B and 4C). This aligns with broader evidence that Prosopis is one of the most aggressive woody invaders in arid and semi-arid ecosystems, owing to rapid growth, high drought tolerance, and deep rooting [68–70]. Fig. 3 highlights spatial dominance in disturbed areas, consistent with studies showing that invasive expansion accelerates under heavy land-use pressure and forest degradation [56, 71, 72].

In Gaili and Helgi, Dom palm loss corresponded with increased human activity, harvesting, and weak enforcement. Mesquite rapidly colonizes exposed soils, suppresses native regeneration through shading, and competes for groundwater [67, 70, 73]. Similar patterns across the Sahel and East Africa show Prosopis reduces biodiversity, simplifies forest structure, and weakens resilience under climatic stress [69, 71, 74]. These transitions indicate that unmanaged drylands are highly vulnerable to invasive dominance when native species' competitive capacity is reduced [56, 58, 68].

In contrast, Umbashim Forest experienced minimal Mesquite intrusion due to stronger community governance, restricted access, and awareness of Dom palm's value. This supports findings that community-managed dryland forests exhibit higher ecological stability and reduced invasion risk [70, 71, 74]. Local interventions in Helgi also demonstrate that mechanical removal can partially restore Dom palm, though long-term suppression requires sustained management to prevent reinvasion [68, 69, 72].

Overall, unchecked Mesquite expansion threatens the sustainability of Sudan's Dom palm forests. Open-access forests with weak governance are particularly vulnerable, whereas community management enhances native persistence. Integrated strategies combining community participation, systematic Prosopis removal, and Dom palm restoration are essential to prevent further degradation and support ecosystem resilience under climate stress [56, 58, 67].

3.6. Anthropogenic Pressures and Community Drivers

Human activities are primary drivers of Dom palm (*Hyphaene thebaica*) forest degradation across the study area, consistent with evidence that anthropogenic pressures dominate dryland vegetation loss globally. Socioeconomic surveys indicate that 91% of households rely on forest biomass for traditional house construction, maintaining continuous extraction pressure on Dom palm and associated native species. Fig. 6 shows that dwellings built from palm and wood remain predominant, while alternative materials are rarely used. Similar patterns of dependence on woody biomass for housing and fuel have been documented in Sudan and East Africa, where forest products fulfill essential livelihood needs [75–77]. Such extraction depletes standing trees and limits regeneration, particularly when harvest rates exceed natural recruitment. Extensive livestock grazing further contributes to forest decline, as livestock consume or trample seedlings, reducing regeneration and altering species composition. Field studies confirm that overgrazing reduces seedling survival, increases soil compaction, and degrades dryland ecosystems [78–80]. Livestock impacts are intensified under climatic stress, resulting in persistent recruitment failure.

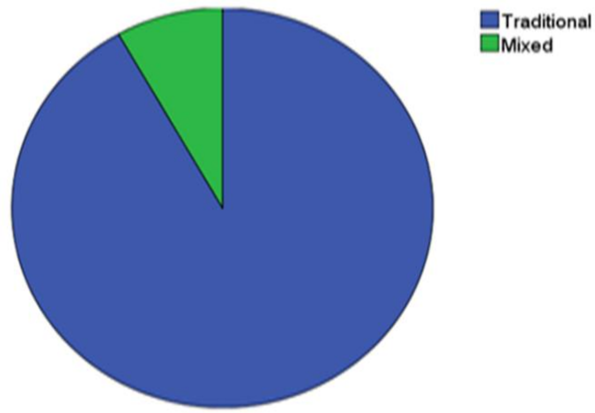

Fig. 6 Types of Residences of Respondents in the Study Area.

Community perceptions support these trends. Fig. 7 indicates that respondents identify declining rainfall, drought, overharvesting, grazing, and Mesquite (*Prosopis spp.*) spread as major causes of Dom palm degradation. Ethnobotanical studies further show that all parts of Dom palm have commercial and domestic value, amplifying extraction pressure [81–83]. Climate variability exacerbates these impacts: rising temperatures and fluctuating rainfall reduce soil moisture, increase mortality of young plants, and favor drought-tolerant Mesquite, which has displaced substantial Dom palm in Gaili and Helgi [58, 69, 67, 84].

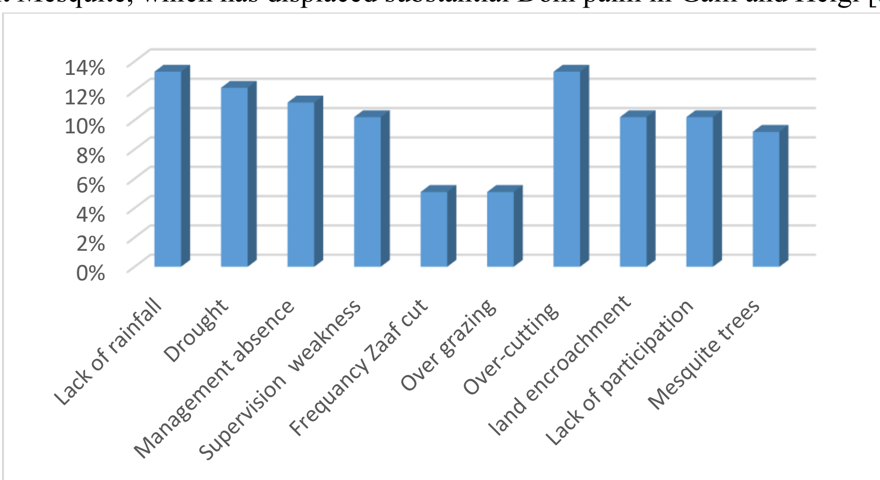

Fig. 7 Reason of degradation of Dom Forest

Weak governance and the absence of structured restoration programs further compound degradation, limiting enforcement of sustainable use [85–87]. In contrast, Umbashim Forest benefits from restricted access and active community management, resulting in lower degradation and higher vegetation resilience, highlighting the positive role of participatory governance [75, 86, 88].

Overall, Dom palm forest degradation is driven by a reinforcing cycle of human extraction, overgrazing, invasive spread, climate stress, and weak governance. Effective mitigation requires integrated strategies combining community-based management, sustainable harvesting, livelihood alternatives, and adaptive climate measures to ensure long-term forest resilience.

3.7. Management Interventions and Development Opportunities

Dom palm (*Hyphaene thebaica*) forests in the study area face substantial ecological pressure, yet local communities possess valuable knowledge and practical strategies for improving forest conditions and safeguarding remaining resources. Survey responses revealed strong awareness among respondents regarding the drivers of degradation and potential opportunities for forest rehabilitation. As shown in (Fig. 8), top-priority development strategies included expanding the Zaaf handicraft industry, forming production associations, improving financial support, and strengthening local markets. These strategies align with evidence that enhancing the economic value of non-timber forest products incentivizes conservation by shifting resource use from subsistence extraction to sustainable, livelihood-based production [86, 89, 90]. Similar studies across African drylands demonstrate that livelihood diversification linked to forest products reduces pressure on standing vegetation while supporting household resilience [75, 81, 83].

Participatory management also emerged as central for sustaining forest health. In Umbashim Forest, where communities actively monitor and protect resources, vegetation cover is more stable and invasive spread is limited. This supports literature showing that community-based governance improves compliance, strengthens stewardship, and enhances ecological outcomes compared with top-down approaches [86, 88, 90]. Locally grounded decision-making further increases long-term sustainability by adapting management to social and environmental realities [91–93].

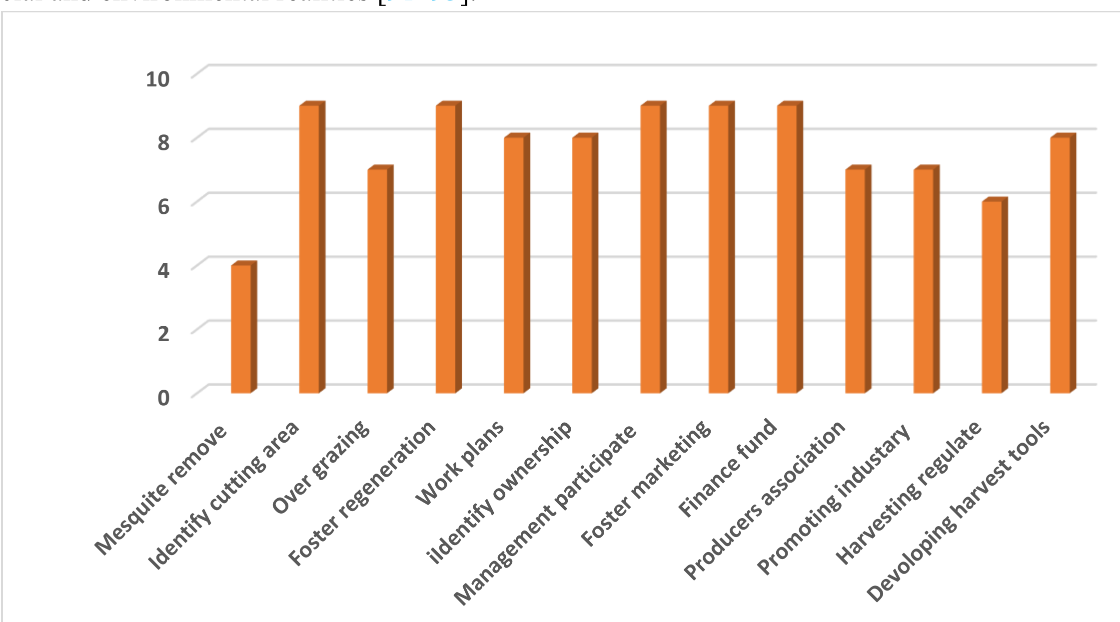

Fig. 8 Suggestions of improve and development of Dom palm forests

A smaller portion of respondents emphasized direct ecological measures, including grazing control, regulated cutting, and enhanced natural regeneration. While ranked lower than economic initiatives, these actions remain critical, as overgrazing and continuous harvesting reduce seedling survival and hinder recruitment [78–80]. Figure 10 shows that selective Mesquite removal, particularly near riverbanks, has enabled partial Dom palm recovery, consistent with evidence that sustained invasive control supports native vegetation restoration [67, 69, 71, 73, 74, 84].

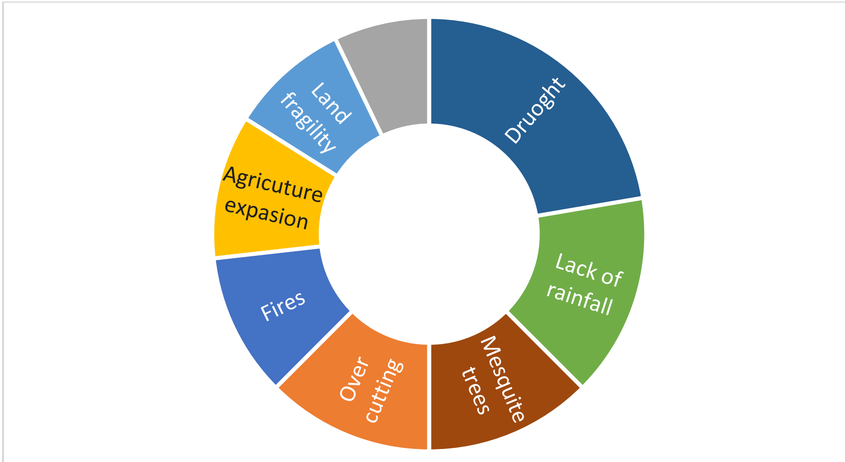

Fig. 9 Problem facing Dom palm forest

Community expectations were cautiously optimistic. Fig. 10 shows that while many respondents recognized ongoing degradation, they believed improvement is possible with proper interventions. Integrating livelihood-oriented initiatives with ecological management, including Mesquite control, grazing regulation, and regeneration enhancement, provides the most practical strategy for restoring Dom palm forest resilience under combined climatic and anthropogenic pressures [58, 79, 84, 89].

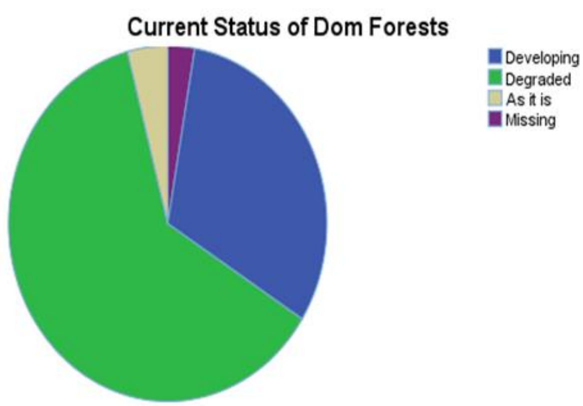

Fig. 10 Status of Dom Palm Forests.

4. Conclusion and Future Research Directions

The long-term assessment of Dom palm (*Hyphaene thebaica*) forests in Umbashim, Gaili, and Helgi demonstrates that ecological outcomes are strongly shaped by the interaction of anthropogenic pressures, invasive species, climate variability, and local governance. Umbashim Forest maintained high stability and internal regeneration, reflecting the effectiveness of community protection and restricted access. In contrast, Gaili Forest exhibited severe degradation and dominance by invasive Prosopis species, driven by weak governance, excessive extraction, and climate stress. Helgi Forest displayed intermediate dynamics, with both persistence of native vegetation and partial recovery following targeted management interventions.

These findings underscore the critical need for integrated management strategies combining ecological restoration and livelihood support. Recommended measures include systematic Prosopis control, regulation of grazing and harvesting intensity, promotion of Dom palm regeneration, and development of alternative income sources, such as handicraft production and market strengthening, to reduce pressure on forest resources. Community-based participatory governance should be prioritized, as it enhances compliance, ecological stewardship, and long-term resilience. Future research should focus on refining species-level monitoring using high-resolution multi-sensor satellite data, assessing the effectiveness of restoration interventions over time, and modeling climate–human interaction impacts on dryland forest dynamics. Additionally, studies exploring the socioeconomic feasibility of sustainable livelihood programs linked to forest conservation would provide actionable guidance for policymakers. Integrating ecological, climatic, and social dimensions offers the most promising pathway for sustaining Dom palm forests in Sudan's dryland ecosystems under ongoing environmental and anthropogenic pressures.

Finding:

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CRediT authorship contribution statement:

Hashim A. Abdelkarim: Conceptualization, Methodology, Data Curation, Writing – Original Draft, Writing – Review & Editing. **Emad H. E. Yasin**: Data Curation, Methodology, Software, Visualization, Formal Analysis, Writing – Original Draft, Writing – Review & Editing. **Yousif E. Yagoub**: Writing – Review & Editing. **Adrienn Horvath**: Supervision, Writing – Review & Editing. **Dafa-Alla M. D. Ahmed**: Supervision, Writing – Review & Editing.

Declarations:

Ethics approval and Consent to participate

This study involving human participants was reviewed and approved by the Research Ethics Committee of the Faculty of Forestry, University of Khartoum, Sudan (Approval date: 15 June 2025). The research was conducted in accordance with the ethical standards and institutional guidelines for research involving human participants. Verbal informed consent was obtained from all participants prior to data collection, and the procedure for verbal consent was approved by the Ethics Committee. No vulnerable groups were included in the study. No biological materials were collected. All questionnaire responses were anonymized, and no identifiable personal data were recorded. Data were stored securely and used solely for academic research purposes.

Consent to publish

All authors have read and approved the final manuscript and agree to its submission and publication.

Informed consent

Informed consent was obtained from all individual participants included in the study. No personally identifiable information is presented in this manuscript.

Competing interests

The authors declare that they have no competing interests.

Data availability: All data generated or analyzed during this study will be made available on request from corresponding author.

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Appendix A. Survey Questions for Assessing the Status and Management of Dom Forests

General Information

Name (Optional)	
Village	
Forest name and Area	

Section A: Household Characteristics

1. **Type of Housing**

☐ Traditional

☐ Modern

☐ Mixed (Traditional and Modern)

☐ Other: ___________________________

Section B: Institutional and Technical Status of Dom Forests

2. **What privileges are granted to local communities in the Dom forests?**
(Select all that apply)

☐ Grazing livestock

☐ Passage / access through the forest

☐ Collection of fruits and seeds

☐ Cutting Dom leaves (fronds)

☐ Collection of fallen firewood

☐ Other: ___________________________

3. **What is the current condition of the Dom forests?**

☐ Improving / Well developed

☐ Degraded

☐ Stable / Unchanged

☐ Do not know

4. **If the forest is degraded, what are the causes of degradation?**
(Select all that apply)

☐ Lack of rainfall

☐ Drought

☐ Absence of forest management

☐ Weak supervision or monitoring

☐ Repeated leaf cutting

☐ Overgrazing

☐ Excessive cutting of trees

☐ Land encroachment

☐ Lack of community participation

☐ Spread of mesquite trees

☐ Other: ___________________________

5. **Do you observe natural regeneration of Dom trees?**

☐ Yes

☐ No

6. **If regeneration is limited, what are the possible causes?**
(Select all that apply)
☐ Grazing
☐ Drought
☐ Fire
☐ Land fragility or poor soil conditions
☐ Agricultural expansion
☐ Spread of mesquite trees
☐ Lack of rainfall
☐ Other: ___________________________

7. **What are the main problems facing Dom forests in the study area?**
(Select all that apply)
☐ Overgrazing
☐ Drought
☐ Excessive fruit and seed collection
☐ Leaf cutting
☐ Failure to leave seed trees (mother trees)
☐ Other: ___________________________

8. **What are your suggestions for improving the management and development of Dom forests?**
(Select all that apply)
☐ Regulation of harvesting
☐ Identification of specific areas for cutting
☐ Removal of mesquite trees
☐ Development of Doum-based industries
☐ Establishment of producer associations
☐ Creation of financial support funds
☐ Promotion of marketing systems
☐ Strengthening participatory forest management
☐ Clarification of forest ownership
☐ Implementation of forest management plans
☐ Promotion of natural regeneration
☐ Regulation of grazing
☐ Development of improved cutting tools
☐ Other: ___________________________

References

1. Agustino S, Mataya B, Senelwa K, & Achigan-Dako GE. Non-wood forest products and services for socio-economic development: A compendium for technical and professional forestry education. African Forest Forum. 2011.
2. Yasin EH, Kamil OH, & Mulyana B. Multi-temporal satellite images analysis for assessing and mapping deforestation in Um Hataba Forest, South Kordofan, Sudan. J Sylva Indones. 2022;5:81–92. https://doi.org/10.32734/jsi.v5i01.7504

3. Dafa-Alla DM, Gibreel HH, Siddig AAH, Yagoub YE, Abdelkarim HA, Saeed KHT, & Abuelbashar AI. Exploring trees diversity and ecological value of mountain forests in the Blue Nile Region of Sudan. Open J Ecol. 2024;14:245–56. https://doi.org/10.4236/oje.2024.143015
4. Gauthier S, Bernier P, Kuuluvainen T, Shvidenko AZ, & Schepaschenko DG. Boreal forest health and global change. Science. 2015;349:819–22. https://doi.org/10.1126/science.aaa9092
5. Kidane YO, Hoffmann S, Jaeschke A, Beloiu M, & Beierkuhnlein C. Ericaceous vegetation of the Bale Mountains of Ethiopia will prevail in the face of climate change. Sci Rep. 2022;12:1858. https://doi.org/10.1038/s41598-022-05846-z
6. Lu D, Mausel P, Brondizio E, & Moran E. Change detection techniques. Int J Remote Sens. 2004;25:2365–401. https://doi.org/10.1080/0143116031000139863
7. Ali A, Khalid A, Butt MA, Mehmood R, Mahmood SA, Sami J, et al. Towards a remote sensing and GIS-based technique to study population and urban growth: a case study of Multan. Adv Remote Sens. 2018;7:245–58. https://doi.org/10.4236/ars.2018.73017
8. Jiang J, Xing Y, Wei W, Yan E, Xiang J, & Mo D. DSNUNet: an improved forest change detection network by combining Sentinel-1 and Sentinel-2 images. Remote Sens. 2022;14:5046. https://doi.org/10.3390/rs14195046
9. Khan I, Javed T, Khan A, Lei H, Muhammad I, Ali I, & Huo X. Impact assessment of land use change on surface temperature and agricultural productivity in Peshawar-Pakistan. Environ Sci Pollut Res. 2019;26:33076–85. https://doi.org/10.1007/s11356-019-06448-5
10. Zhu S, Jing W, Kang P, Emam M, & Li C. Data augmentation and few-shot change detection in forest remote sensing. IEEE J Sel Top Appl Earth Obs Remote Sens. 2023;16:5919–34. https://doi.org/10.1109/JSTARS.2023.3285389
11. Chaudhary S, & Pandey AC. Multiple indices-based drought analysis by using long term climatic variables over a part of Koel River basin, India. Spat Inf Res. 2020;28:273–85. https://doi.org/10.1007/s41324-019-00287-9
12. Hu Y, Raza A, Syed NR, Acharki S, Ray RL, Hussain S, et al. Land use/land cover change detection and NDVI estimation in Pakistan's Southern Punjab Province. Sustainability. 2023;15:3572. https://doi.org/10.3390/su15043572
13. Jamali A. Improving land use land cover mapping of a neural network with three optimizers of multi-verse optimizer, genetic algorithm, and derivative-free function. Egypt J Remote Sens Space Sci. 2021;24:373–90. https://doi.org/10.1016/j.ejrs.2020.07.001
14. Bullock EL, Healey SP, Yang Z, Houborg R, Gorelick N, Tang X, & Andrianirina C. Timeliness in forest change monitoring: a new assessment framework demonstrated using Sentinel-1 and a continuous change detection algorithm. Remote Sens Environ. 2022;276:113043. https://doi.org/10.1016/j.rse.2022.113043
15. Khatami R, Mountrakis G, & Stehman SV. A meta-analysis of remote sensing research on supervised pixel-based land-cover image classification processes: general guidelines for practitioners and future research. Remote Sens Environ. 2016;177:89–100. https://doi.org/10.1016/j.rse.2016.02.028
16. Rahman MT. Detection of land use/land cover changes and urban sprawl in Al-Khobar, Saudi Arabia: an analysis of multi-temporal remote sensing data. ISPRS Int J Geo-Inf. 2016;5:15. https://doi.org/10.3390/ijgi5020015
17. Vogt K. Common trees and shrubs of dryland Sudan: a field workers guide to the identification, propagation and uses. SOS Sahel International (UK). 1995.

18. Orwa C, Mutua A, Kindt R, Jamnadass R, & Simons A. Agroforestry database: a tree species reference and selection guide version 4.0. World Agroforestry Centre. 2009.
19. Badi KH, Ahmed AEH, & Bayoumi AAMS. Dom (Hyphaene thebaica) forests. Forest Department, Khartoum, Sudan. 1989;11–119.
20. Juffe-Bignoli D, Burgess ND, Bingham H, Belle EMS, De Lima MG, Deguignet M, et al. Protected planet report 2018. IUCN. 2018.
21. Abdelmagid TDM, Mohamed TAE, & Adil MAD. Equalizing Gum Codal Term (a Code E414) of Acacia senegal (L) with Acacia seyal (Del.), and its impact on gum production and exportation. J Appl Ind Sci. 2014;2:144–51.
22. Abdelkarim HA. Analysis of contribution of Hyphaene thebaica L. Mart. (Dom) forests to the local economies in Ad-Damar Locality, River Nile State, Sudan. MSc dissertation. University of Khartoum, Sudan. 2019.
23. Abdelkarim HA, Ahmed MDA, Yagoub YE, & Siddig AAH. Composition, structure and regeneration status of Hyphaene thebaica (L.) Mart. natural forests in dry lands of Sudan. Agric For J. 2021;5:82–88. https://doi.org/10.5281/zenodo.5803385
24. Ge Z. The hidden order of Turing patterns in arid and semi-arid vegetation ecosystems. Proc Natl Acad Sci USA. 2023;120:e2306514120. https://doi.org/10.1073/pnas.2306514120
25. Rajasugunasekar D, Patel AK, Devi KB, Singh A, Selvam P, & Chandra A. An integrative review for the role of forests in combating climate change and promoting sustainable development. Int J Environ Clim Change. 2023;13:4331–41. https://doi.org/10.9734/ijecc/2023/v13i113614
26. Jardim AMDRF, de Morais JEF, de Souza LSB, de Carvalho Lopes D, da Silva MV, Pandorfi H, et al. A systematic review of energy and mass fluxes, and biogeochemical processes in seasonally dry tropical forests and cactus ecosystems. J South Am Earth Sci. 2023;126:104330. https://doi.org/10.1016/j.jsames.2023.104330
27. Musa FI, & Sahoo UK. Role of sustainable forest management in poverty reduction and livelihood improvement in Sudan: a review. Int J Ecol Environ Sci. 2023;49:449–56. https://doi.org/10.55863/ijees.2023.3036
28. Abass RSEB, Abd Alla MYM, & El-Eragi AMEH. Spatial risk analysis of water borne diseases (bovine leptospirosis) in the River Nile State–Sudan. J Geogr Inf Syst. 2014;6:1–10. https://doi.org/10.4236/jgis.2014.61001
29. Abdalla MS, & Elkhalifa KF. Trees and shrubs species at lower Atbara basin. In Tropentag 2010: World Food System, a contribution from Europe, Zurich, Switzerland. 2010.
30. Fassnacht FE, Latifi H, Sterenczak K, Modzelewska A, Lefsky M, Waser LT, Straub C, & Ghosh A. Review of studies on tree species classification from remotely sensed data. Remote Sens Environ. 2016;186:64–87. https://doi.org/10.1016/j.rse.2016.08.013
31. Senf C, & Seidl R. Mapping the forest disturbance regimes of Europe. Nat Sustain. 2021a;4:63–70. https://doi.org/10.1038/s41893-020-00609-y
32. Senf C, Buras A, Zang CS, Rammig A, & Seidl R. Excess forest mortality is consistently linked to drought across Europe. Nat Commun. 2020;11:6200. https://doi.org/10.1038/s41467-020-19924-1
33. Reinosch E, Backa J, Adler P, Deutscher J, Eisnecker P, Hoffmann K, et al. Detailed validation of large-scale Sentinel-2 forest disturbance maps across Germany. Forestry. 2024;cpae038. https://doi.org/10.1093/forestry/cpae038
34. Walsh SJ. Coniferous tree species mapping using LANDSAT data. Remote Sens Environ. 1980;9:11–26. https://doi.org/10.1016/0034-4257(80)90044-9

35. Thonfeld F, Gessner U, Holzwarth S, Kriese J, da Ponte E, Huth J, & Kuenzer C. Assessment of canopy cover loss after drought years. Remote Sens. 2022;14:562. https://doi.org/10.3390/rs14030562
36. Hemmerling J, Pflugmacher D, & Hostert P. Mapping temperate forest tree species using dense Sentinel-2 time series. Remote Sens Environ. 2021;267:112743. https://doi.org/10.1016/j.rse.2021.112743
37. Blickensdörfer L, Oehmichen K, Pflugmacher D, Kleinschmit B, & Hostert P. National tree species mapping using Sentinel-1/2 time series and German National Forest Inventory data. Remote Sens Environ. 2024;304:114069. https://doi.org/10.1016/j.rse.2024.114069
38. Illarionova S, Trekin A, Ignatiev V, & Oseledets I. Tree species mapping on Sentinel-2 imagery with weakly supervised classification. Forests. 2021;12:1413. https://doi.org/10.3390/f12101413
39. Bolyn C, Lejeune P, Michez A, & Latte N. Mapping tree species proportions from satellite imagery using spectral spatial deep learning. Remote Sens Environ. 2022;280:113205. https://doi.org/10.1016/j.rse.2022.113205
40. Persson M, Lindberg E, & Reese H. Tree species classification with multi-temporal Sentinel-2 data. Remote Sens. 2018;10:1794. https://doi.org/10.3390/rs10111794
41. Immitzer M, Neuwirth M, Böck S, Brenner H, & Atzberger C. Optimal input features for tree species classification based on multi-temporal Sentinel-2 data. Remote Sens. 2019;11:2599. https://doi.org/10.3390/rs11212599
42. Grabska-Szwagrzyk E, Tiede D, Sudmanns M, & Kozak J. Map of forest tree species for Poland based on Sentinel-2 data. Earth Syst Sci Data. 2024;16:2877–91. https://doi.org/10.5194/essd-16-2877-2024
43. Verhulst M, Heremans S, Blaschko MB, & Somers B. Temporal transferability of tree species classification with Sentinel-2 time series. Remote Sens. 2024;16:2653. https://doi.org/10.3390/rs16142653
44. Meyer H, & Pebesma E. Predicting into unknown space? Estimating the area of applicability of spatial prediction models. Methods Ecol Evol. 2021;12:1620–33. https://doi.org/10.1111/2041-210X.13650
45. Axelsson A, Lindberg E, Reese H, & Olsson H. Tree species classification using Sentinel-2 imagery and Bayesian inference. Int J Appl Earth Obs Geoinf. 2021;100:102318. https://doi.org/10.1016/j.jag.2021.102318
46. Freudenberg M, Schnell S, & Magdon P. Sentinel-2 machine learning dataset for tree species classification in Germany. Open Agrar Data Set. 2024. https://doi.org/10.3220/DATA20240402122351-0
47. Senf C, & Seidl R. Persistent impacts of the 2018 drought on forest disturbance regimes in Europe. Biogeosciences. 2021b;18:5223–30. https://doi.org/10.5194/bg-18-5223-2021
48. Holzwarth S, Thonfeld F, Kacic P, Abdullahi S, Asam S, Coleman K, et al. Earth-observation based monitoring of forests in Germany. Remote Sens. 2023;15:4234. https://doi.org/10.3390/rs15174234
49. Plakman V, Janssen T, Brouwer N, & Veraverbeke S. Mapping species at an individual-tree scale using Sentinel-2 and ALS data. Remote Sens. 2020;12:3710. https://doi.org/10.3390/rs12223710
50. Nicholson SE. The West African Sahel: A review of recent studies on rainfall variability. ISRN Meteorol. 2013;2013:453521. https://doi.org/10.1155/2013/453521

51. Sultan B, & Gaetani M. Agriculture in West Africa in the twenty-first century. Clim Change. 2016;139:215–32. https://doi.org/10.1007/s10584-016-1664-3
52. Panthou G, Vischel T, Lebel T, Blanchet J, Quantin G, & Ali A. Rainfall intensification in the Sahel. Environ Res Lett. 2018;13:064013. https://doi.org/10.1088/1748-9326/aac334
53. Elagib NA, & Elhag MM. Major climate indicators of ongoing drought in Sudan. J Hydrol. 2011;409:612–25. https://doi.org/10.1016/j.jhydrol.2011.08.047
54. Ahmed K, Shahid S, Nawaz N, & Khan N. Spatiotemporal changes in aridity of Sudan under climate change. Theor Appl Climatol. 2020;140:1267–81. https://doi.org/10.1007/s00704-020-03142-5
55. Alriah MAA, Bi S, Nkunzimana A, Elameen AM, Sarfo I, & Ayugi B. Multiple gridded-based precipitation products' performance in Sudan's different topographical features. Atmos Res. 2022;271:106127. https://doi.org/10.1016/j.atmosres.2022.106127
56. Brandt M, Rasmussen K, Hiernaux P, Herrmann SM, Tucker CJ, Tong X, Tian F, Mertz O, Kergoat L, Mbow C, & Fensholt R. Human population growth offsets climate-driven increase in woody vegetation in sub-Saharan Africa. Nat Ecol Evol. 2020;4:377–85. https://doi.org/10.1038/s41559-020-1125-0
57. Ayugi B, Tan G, Rouyun N, & Ojara M. Evaluation of rainfall and temperature variability over Sudan. Theor Appl Climatol. 2020;141:1585–1602. https://doi.org/10.1007/s00704-020-03261-z
58. Fenta AA, Tsunekawa A, Haregeweyn N, Tsubo M, Yasuda H, & Kawai T. Climate change impacts on dryland vegetation dynamics. Sci Total Environ. 2021;755:142556. https://doi.org/10.1016/j.scitotenv.2020.142556
59. IPCC. Climate change 2021: The physical science basis. Cambridge: Cambridge University Press; 2021. https://doi.org/10.1017/9781009157896
60. Funk C, Harrison L, Shukla S, Husak G, Korecha D, & Magadzire T. Examining the role of warming in recent droughts in the Greater Horn of Africa. Clim Dyn. 2018;50:1–17. https://doi.org/10.1007/s00382-017-3644-x
61. Engdaw MM, Ballinger AP, Hegerl GC, & Steiner AK. Intensification of heat extremes across Africa. Environ Res Lett. 2022;17:044020. https://doi.org/10.1088/1748-9326/ac5a2a
62. Allen CD, Macalady AK, Chenchouni H, Bachelet D, McDowell N, Vennetier M, Kitzberger T, Rigling A, Breshears DD, & Hogg EH. A global overview of drought and heat-induced tree mortality. For Ecol Manage. 2010;259:660–84. https://doi.org/10.1016/j.foreco.2009.09.001
63. Liu YY, van Dijk AIJM, de Jeu RAM, Canadell JG, McCabe MF, Evans JP, & Wang G. Recent reversal in global terrestrial drying trend. Nature. 2013;502:747–51. https://doi.org/10.1038/nature12645
64. Miralles DG, Teuling AJ, van Heerwaarden CC, & Vilà-Guerau de Arellano J. Mega-heatwave temperatures due to combined soil desiccation and atmospheric feedbacks. Nat Geosci. 2014;7:345–9. https://doi.org/10.1038/ngeo2141
65. Vicente-Serrano SM, Beguería S, & López-Moreno JI. A multiscalar drought index sensitive to global warming. J Clim. 2020;33:1–20. https://doi.org/10.1175/JCLI-D-19-0272.1
66. Harrington LJ, & Otto FEL. Reconciling theory with the reality of African heat extremes. Weather Clim Extremes. 2020;28:100254. https://doi.org/10.1016/j.wace.2020.100254
67. D'Odorico P, Bhattachan A, Davis KF, Ravi S, & Runyan CW. Global desertification: Drivers and feedbacks. Adv Water Resour. 2013;51:326–44. https://doi.org/10.1016/j.advwatres.2012.01.013

68. Shiferaw H, Teketay D, Nemomissa S, & Assefa F. Invasive Prosopis juliflora effects on native vegetation in Ethiopia. Biodivers Conserv. 2019;28:1–20. https://doi.org/10.1007/s10531-019-01767-9
69. Wakie TT, EvanGailista PH, Jarnevich CS, & Laituri M. Mapping Prosopis invasion in Ethiopia using remote sensing. Remote Sens. 2016;8:1–20. https://doi.org/10.3390/rs8020156
70. van Klinken RD, Graham J, & Flack LK. Population ecology of Prosopis invasions. Biol Invasions. 2020;22:1–18. https://doi.org/10.1007/s10530-020-02217-5
71. Shackleton RT, Le Maitre DC, van Wilgen BW, & Richardson DM. Prosopis invasions in South Africa: Impacts and management. J Arid Environ. 2014;100–101:1–10. https://doi.org/10.1016/j.jaridenv.2013.10.005
72. Pasiecznik NM, Felker P, Harris PJ, Harsh L, Cruz G, Tewari JC, Cadoret K, & Maldonado LJ. The Prosopis juliflora–Prosopis pallida complex: a monograph. Coventry, UK: HDRA. 2001;172:29–32.
73. Schachtschneider K, & February EC. Impact of Prosopis invasion on groundwater. J Arid Environ. 2013;95:83–91. https://doi.org/10.1016/j.jaridenv.2013.03.012
74. Ilukor J, Rettberg S, Treydte A, & Birner R. To eradicate or not? Prosopis juliflora invasion in Kenya. Ecol Soc. 2016;21:1–15. https://doi.org/10.5751/ES-08235-210202
75. Alemu T, Degefa T, & Mesele D. Household reliance on woody biomass and implications for forest sustainability in the drylands of Ethiopia. Environ Dev. 2018;25:50–60. https://doi.org/10.1016/j.envdev.2017.11.003
76. Awodoyin R, Aiyelari E, & Oluwole S. Wood fuel dependence and its ecological impact in semi-arid West Africa. Energy Sustain Soc. 2020;10:1–12. https://doi.org/10.1186/s13705-020-00267-y
77. Gebremedhin B, La Rovere RL, & Haile F. Dependence on forest products and deforestation: Evidence from the Horn of Africa. For Pol Econ. 2021;128:102481. https://doi.org/10.1016/j.forpol.2021.102481
78. Angassa A, & Oba G. Effects of grazing pressure and bush encroachment on above-ground biomass and soil chemical properties in southern Ethiopia. J Arid Environ. 2008;72:1234–45. https://doi.org/10.1016/j.jaridenv.2007.10.008
79. Mekuria W, Veldkamp E, & de Graaff J. Intensive grazing impacts on vegetation and soils in dryland rangelands. J Arid Environ. 2015;116:45–55. https://doi.org/10.1016/j.jaridenv.2015.01.006
80. Yimer F, Teferi E, & Gebeyhu G. Effects of grazing on soil and vegetation in Eritrea. Environ Monit Assess. 2018;190:296. https://doi.org/10.1007/s10661-018-6649-1
81. Lemenih M, & Teketay D. Utilization and management of Hyphaene thebaica in Ethiopia. For Ecol Manag. 2004;188:305–16. https://doi.org/10.1016/j.foreco.2003.08.001
82. Haile AT, Fiedler S, & Pauw J. Household forest product use and landscape change in northern Ethiopia. Environ Manag. 2019;63:350–63. https://doi.org/10.1007/s00267-019-01161-y
83. Gebreslassie M, Tadesse D, & Gebrekirstos A. Ethnobotanical insights into Hyphaene thebaica use in Ethiopia. J Ethnobiol Ethnomed. 2021;17:74. https://doi.org/10.1186/s13002-021-00493-z
84. van Wilgen BW, & Richardson DM. Challenges and trade-offs in invasive alien plant management. Biol Invasions. 2014;16:115–26. https://doi.org/10.1007/s10530-013-0615-8
85. Ehlers MH, Pauw J, de Vos V, & Sinclair ARE. Governance and dryland forest degradation in southern Africa. Land Use Policy. 2019;87:104073. https://doi.org/10.1016/j.landusepol.2019.104073

86. Chomba S, Sinclair F, Dumaru P, & Munawara S. Community natural resource management and forest outcomes in Tanzania. Ecol Soc. 2016;21:10. https://doi.org/10.5751/ES-08680-210410
87. Tsegaye D, Mekuria W, & Veldkamp E. Governance structures and rangeland condition. Land Use Policy. 2020;99:105034. https://doi.org/10.1016/j.landusepol.2020.105034
88. Tessema YT, Pretzsch J, & Nelde T. Community participation and forest outcomes in dryland Ethiopia. For Pol Econ. 2020;111:102090. https://doi.org/10.1016/j.forpol.2019.102090
89. Shackleton S, Delang CO, & Angelsen A. From subsistence to safety nets: Non-timber forest products and livelihoods. Int For Rev. 2011;13:331–42. https://doi.org/10.1505/146554811798293908
90. Leventon J, Kalaba FK, Dyer JC, & Stringer LC. Delivering community benefits through REDD+: Lessons from participatory forest governance. For Pol Econ. 2017;78:1–9. https://doi.org/10.1016/j.forpol.2016.12.003
91. Reed MS, Vella S, Challies E, de Vente J, Frewer L, Hohenwallner-Ries D, … & van Delden H. Participatory approaches for land restoration. J Environ Manag. 2015;161:1–13. https://doi.org/10.1016/j.jenvman.2015.06.021
92. Mekonnen K, Tadesse W, & Kassa H. Local perceptions of forest change and drivers in Bonga, Ethiopia. For Sci Technol. 2019;15:253–61. https://doi.org/10.1080/21580103.2019.1687331
93. Ruelle ML, & Kassam KAS. Perceptions and realities of dryland forest change in Niger. Ecosyst Health Sustain. 2019;5:1698662. https://doi.org/10.1080/20964129.2019.1698662