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TECHNICAL REPORT

Refugee Settlement-Environmental Degradation Nexus in Kassala, El Gedaref, and White Nile States, Sudan

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Front cover photo: Agricultural landscape in northern highlands of Ethiopia (*photo:* Wolde Mekuria).
Back cover photo: Degraded landscape in northern highlands of Ethiopia (*photo:* Wolde Mekuria)

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Acronyms and Abbreviations

1OAO	One-Out All-Out
ASF	Alaska Satellite Facility
CHIRPS v3	Climate Hazards Center InfraRed Precipitation with Station version 3
DEM	Digital Elevation Model
DRC	Danish Refugee Council
ESA	Eastern and Southern Africa
FAO	Food and Agriculture Organization
IOM	International Organization for Migration
ISIM	Institute for the Study of International Migration
ISRIC	International Soil Reference and Information Centre
IUCN	International Union for Conservation of Nature
LC	Land Cover
LDN	Land Degradation Neutrality
LP	Land Productivity
LULC	Land Use and Land Cover
MAR	Mean Annual Rainfall
Max	Maximum
Min	Minimum
NRC	Norwegian Refugee Council
NDVI	Normalized Difference Vegetation Index
NTFP	Non-Timber Forest Products
OCHA	Office for the Coordination of Humanitarian Affairs
RCMRD	Regional Centre for Mapping of Resources for Development
RSF	Rapid Support Forces
SAF	Sudanese Armed Forces
SDG	Sustainable Development Goal
SEPAL	System for Earth Observation Data Access, Processing and Analysis for Land Monitoring
SOC	Soil Organic Carbon
SSA	Sub-Saharan Africa
UN	United Nations
UNCCD	United Nations Convention to Combat Desertification
UNEP	United Nations Environment Programme
UNHCR	United Nations High Commissioner for Refugees
WUE	Water Use Efficiency

Summary

Sudan hosts some of Africa's largest and longest-running refugee populations within environmentally fragile dryland ecosystems already affected by climate variability, land degradation, and conflict. This study examined the nexus between refugee settlements and environmental degradation around 19 refugee camps in Kassala, El Gedaref, and White Nile States and synthesized the implications for community and environmental resilience, refugee settlement siting, and sustainable refugee-hosting strategies.

The study combined satellite-based geospatial analysis with a land degradation neutrality framework. Refugee camps were categorized into three groups based on age: long-established camps (established before 1990 in Kassala), established camps (established during 2011–2019 in White Nile), and recently established camps (established from 2020 onwards in El Gedaref). Environmental changes were assessed across four concentric buffer zones extending from camp centers (0–10 km, 10–20 km, 20–30 km, and 30–50 km). The analysis evaluated long-term changes in land use, vegetation cover, soil condition, and land degradation patterns between 1978 and 2025.

The study reveals a strong and consistent spatial and temporal association between refugee settlements, land-use change, and environmental degradation. These patterns indicate a close association rather than establishing that refugee settlements alone caused the observed changes, as the analysis did not include a counterfactual or control landscape.

- Farmland expansion and settlement growth were the dominant land-use changes across all camps, often replacing shrublands, grasslands, forests, and water-associated ecosystems.
- Long-established camps exhibited the largest cumulative environmental changes, consistent with decades of resource extraction, agricultural expansion, and settlement growth.
- Recently established camps showed the highest annual rates of change, suggesting that environmental degradation can accelerate rapidly in the years following camp establishment.
- Environmental changes were not confined to areas immediately surrounding camps. Instead, the observed degradation patterns extended progressively from inner zones to outer and peripheral landscapes, indicating that land-use change and degradation were distributed across entire camp–host landscapes rather than isolated locations.
- Land degradation neutrality assessments showed a consistent increase in degraded land and a decline in stable and improved land across all settlement categories and

buffer zones, indicating a persistent movement away from sustainable land management pathways.

The findings suggest that refugee settlements should be viewed as components of broader socio-ecological landscapes rather than stand-alone humanitarian sites. Environmental pressures associated with refugee hosting extend far beyond camp boundaries through processes that plausibly include fuelwood collection, grazing, cultivation, infrastructure development, and host-community responses.

The observed conversion of natural vegetation to agricultural and settlement land can reduce ecosystem services that are critical for both refugees and host communities, including fuelwood supply, grazing resources, soil protection, biodiversity conservation, water regulation, and climate resilience. As degradation intensifies, communities may become increasingly vulnerable to droughts, floods, resource scarcity, and conflict over natural resources.

The results also highlight two distinct management priorities. Long-established camps require landscape restoration and rehabilitation interventions to address accumulated land degradation, while newer settlements require preventive measures to reduce the risk of rapid degradation in the early stages of establishment. Integrating environmental management into refugee planning from the outset is therefore essential for maintaining ecosystem resilience and supporting long-term human well-being.

Although based on refugee-hosting areas in Sudan, the findings are highly relevant to refugee settlements across the Horn of Africa, the Sahel, and other dryland regions where displacement, climate stress, and environmental fragility intersect. The study highlights that environmental outcomes are shaped not only by refugee presence but also by governance systems, resource management practices, livelihood opportunities, and pre-existing ecological conditions.

The camp-age and buffer-zone approach provides a practical framework for assessing environmental change and planning interventions in refugee-hosting landscapes elsewhere. More broadly, the findings contribute to global efforts to achieve Land Degradation Neutrality (SDG 15.3) while strengthening the links between environmental sustainability, humanitarian action, and community resilience.

Based on the key findings, we suggest the following recommendations tailored to a specific stakeholder. Because landscape degradation in refugee-hosting areas is shaped by multiple

interacting drivers, the recommendations below should be coordinated with wider policy domains. Livelihood and employment/economic policies, agricultural policies, land tenure, and climate policies all influence resource-use decisions and can create unintended consequences for landscape degradation; landscape management and restoration interventions are therefore most effective when aligned with these broader policy frameworks rather than pursued in isolation.

Humanitarian Agencies

- Integrate environmental safeguards into camp planning from the earliest stages.
- Promote alternative energy sources, fuel-efficient technologies, woodlots, and waste management systems.
- Apply preventive environmental measures in recently established camps and restoration-focused interventions in long-established camps.

Government Authorities and Environmental Agencies

- Institutionalize environmental screening before camp establishment.
- Develop and enforce buffer-based land-use planning and natural resource governance systems.
- Integrate refugee settlements into broader landscape restoration and watershed management programs.

Development Partners and Donors

- Invest in large-scale nature-based solutions, including agroforestry, assisted natural regeneration, soil and water conservation, and community fuelwood systems.
- Support long-term restoration of degraded landscapes around protracted refugee settlements.

Host Communities and Refugees

- Participate in joint resource management, restoration activities, and sustainable land-use planning.
- Promote sustainable grazing, biomass use, and community-based conservation initiatives.

Researchers and Monitoring Institutions

- Establish integrated socio-ecological monitoring systems combining remote sensing, field assessments, livelihood studies, and governance analysis.
- Develop early-warning systems to identify emerging degradation hotspots and guide timely interventions.

1. Introduction

Global forced displacement has grown at a concerning pace in recent years (Cavanagh, 2025), reaching an estimated 117.8 million people by the end of 2025 (UNHCR, 2026a). Africa shoulders a disproportionate share of this burden, hosting roughly 36% of the world's refugees[1], a majority of whom reside in Sub-Saharan Africa (Laird et al., 2022). The Eastern and Southern Africa (ESA) region in particular comprises one of the world's most complex and protracted displacement landscapes, characterized by intricate cross-border flows driven by conflict, drought, and food insecurity. By mid-year 2025, about 16.7 million people were internally displaced in the ESA, and another 6.3 million were refugees, underscoring the scale of forced migration in this region (UNHCR, 2026a).

Within this region, Sudan stands as a critical example. Even before the outbreak of war between the Rapid Support Forces and Sudanese Armed Forces in April 2023, it was Africa's second-largest refugee-hosting country, sheltering over 1 million refugees from neighboring states such as South Sudan, Eritrea, Ethiopia, Syria, and the Central African Republic. Since the onset of the conflict between Rapid Support Forces (RSF) and Sudanese Armed Forces (SAF) in 2023, Sudan's internally displaced population has surged to the highest globally. By 2025, more than 1.7 million people had been newly displaced inside the country, and over 331,587 had fled to neighbors (NRC, 2026), bringing Sudan's total internal displacement to approximately 13 million by the close of 2025[2].

Traditionally, armed conflict and political repression have been the dominant drivers of forced displacement globally and in Africa (Betts et al., 2019; Hiraide, 2023). However, environmental stressors, notably climate change and natural disasters (drought and flood), are now emerging as prominent drivers, often interacting with conflict as "threat multipliers" that exacerbate instability and migration pressures (Terry and Rai, 2023). Over the past decades, weather-related disasters alone have triggered approximately 250 million internal displacements worldwide, underscoring the profound impact of environmental hazards on human mobility (UNHCR, 2025a). Looking ahead, climate projections indicate that up to 200 million people could be displaced by climate-related factors by 2055 (Hirsch et al., 2026). East Africa and the Sahel embody this synergy of conflict and climate drivers: they are beset by a confluence of violence, prolonged drought, and land degradation, making them among the world's most acute displacement hotspots (Chetto et al., 2024).

Closely intertwined with these displacement dynamics is the ecological character of the regions that host refugees, which are themselves often fragile. Refugee-hosting areas in low- and middle-income countries are typically arid or semi-arid landscapes marked by extreme heat, scarce and variable rainfall, high evapotranspiration, and fragile soils (UNHCR, 2025a). These regions are frequently remote and politically marginal, with limited infrastructure and governance capacities (Ouni and Mraihi, 2025). Even before any influx of refugees, such locals endure chronic stress and high exposure to climate risks, exacerbated by recurrent

[1] https://www.nrc.no/global-figures (Accessed on July 23, 2026)

[2] https://www.unhcr.org/europe/emergencies/sudan-emergency (Accessed on July 23, 2026)

droughts and extreme weather events (PreventionWeb, 2025; UNHCR, 2026a). In the Horn of Africa, these pressures are further intensified. For instance, heavy flooding in Sudan's El Gedaref state has already caused significant infrastructure damage in local refugee camps (Ahmed et al., 2021). Globally, an estimated three-quarters of refugees live in these climate-stressed contexts (UNHCR, 2026a). In Sub-Saharan Africa's protracted displacement situations, refugee camps often evolve into long-term, multi-generational settlements dependent on humanitarian aid (Verwimp and Maystadt, 2015), straining already limited natural resources such as water, rangeland, and fuelwood, and pushing local ecosystems toward degradation thresholds (PreventionWeb, 2025).

These fragile conditions, when compounded by large-scale refugee influxes, create a complex refugee settlements environmental degradation nexus wherein displacement and environmental degradation become mutually reinforcing (Bernard et al., 2020; Dutta, 2024). This nexus operates through interlinked pathways: degradation and climate stress can drive displacement, the arrival of large refugee populations could increase pressures on local environments, and displaced populations are themselves disproportionately vulnerable to environmental hazards (Bose, 2024). In host areas, sudden population influxes could increase competition for land and natural resources, especially water, wood and arable land, contributing to deforestation, water stress, land degradation, and pollution (ISIM, 2019). Among these pressures, deforestation is often the most visible consequence, largely due to refugees' and host communities' reliance on fuelwood for cooking and shelter (Bildirici, 2022). Globally, an estimated 20–25 million trees are felled annually around refugee camps, primarily to meet energy needs, contributing to accelerated soil erosion, biodiversity loss, and hydrological disruptions (UNHCR, 2024a). Meanwhile, intense water uses and inadequate sanitation in crowded settlements can affect water supplies and contribute to scarcity and contamination (Yasmin et al., 2022; Yohannes et al., 2025). Mounting resource scarcities can aggravate tensions between refugees and host communities (Laird et al., 2022). International policy frameworks such as the Global Compact on Refugees have begun highlighting environmental sustainability, yet implementation remains limited (UN, 2018; UNHCR, 2025b), reflecting the challenges of addressing environmental concerns amid acute humanitarian crises.

A growing body of empirical evidence from Sub-Saharan Africa (SSA) corroborates the environmental toll of long-term refugee presence, linking protracted camps to cumulative land-use and land-cover (LULC) changes over time. Studies in several countries document extensive vegetation clearance and agricultural expansion around settlements, often reaching several kilometers beyond camp boundaries (Salemi, 2021; Mekuria et al., 2024). These impacts are compounded by limited livelihood options and governance in many host regions, which reinforce dependence on natural resources and heighten the risk of resource-based disputes (Laird et al., 2022; Bertinelli et al., 2025). However, the literature remains inconclusive: a large-scale analysis across 49 countries found no consistent deforestation signal from refugee inflows and even observed a slight increase in vegetation greenness in some cases, suggesting that local conditions such as effective resource management or external interventions can significantly influence outcomes (Maystadt et al., 2020). Additionally, in certain settings, refugee presence has contributed to local economic

development and infrastructure improvements (Kumssa and Jones, 2014), underscoring the context-dependent nature of refugee–environment interactions.

In Sudan, these dynamics are especially acute, making it a critical case for understanding the refugee–environment degradation nexus. The country's predominantly arid climate, highly climate-sensitive agriculture, and persistent conflicts have made Sudan's landscapes particularly vulnerable to environmental stress and degradation (Ali, 2024). Refugee influxes over the years have contributed to deforestation, groundwater depletion, and land degradation: earlier assessments recorded woodlands cleared up to 10 km around camps, alongside conversions of farmland and natural vegetation into bare ground and settlements in Sudan's major refugee-hosting areas (ReliefWeb/UNEP, 2007; Ahmed et al., 2024). The ongoing conflict since 2023 has further increased dependence on fuelwood and charcoal as coping mechanisms, driving even greater forest loss and raising the risk of resource-based violence (Sudan War Monitor, 2024; Singh, 2025). Coupled with weak environmental governance and regulation (Ali, 2024), this has entrenched a dangerous feedback loop wherein ecological degradation, conflict, and displacement feed into one another, deepening vulnerability for both refugees and host communities (IOM, 2024).

In light of these trends and unresolved questions, a focused investigation of the refugee settlement–environmental degradation nexus in Sudan is urgently needed. Existing literature has documented major local environmental impacts of refugee presence in some contexts but also revealed inconsistent patterns and a lack of context-specific evidence for Eastern and Southern Sudan. A better understanding of how large refugee settlements and host environments interact is crucial for informing policies and interventions that mitigate degradation and enhance resilience for both ecosystems and communities in climate-stressed, disaster-prone settings. Accordingly, the present study aims to (i) assess the nexus between refugee settlements and environmental degradation surrounding camps in Sudan's Kassala, El Gedaref, and White Nile states, and (ii) synthesize the implications of these findings for environmental and community resilience to natural disasters.

2. Materials and Methods

2.1. Study Area

The study focused on 19 refugee settlements present in Kassala, El Gedaref, and White Nile states of Sudan, the three largest refugee-hosting states located in eastern and southeastern Sudan (Figure 1). By mid-2026[3]White Nile hosted the largest refugee population (410,538 refugees) in nine refugee camps, Kassala accommodated 111,060 refugees in seven refugee camps, and El Gedaref was home to 59,933 refugees in three refugee camps (UNHCR, 2026b). The refugee camps represent different establishment periods ranging from long-established camps (established before 1990) in Kassala to established camps (established during 2011 - 2019) in White Nile and recently established camps (established from 2020 onwards) in El Gedaref (Table 1). The refugee settlements are situated within a

[3] https://data.unhcr.org/en/country/sdn (Accessed on June 23, 2026)

semi-arid to arid climate characterized by erratic rainfall, high climatic variability, and recurrent drought and floods (Somorin et al., 2026). Local livelihoods depend largely on rain-fed agriculture, livestock production, casual labor, and cross-border trade, and most households rely heavily on biomass energy sources (Somorin et al., 2026).

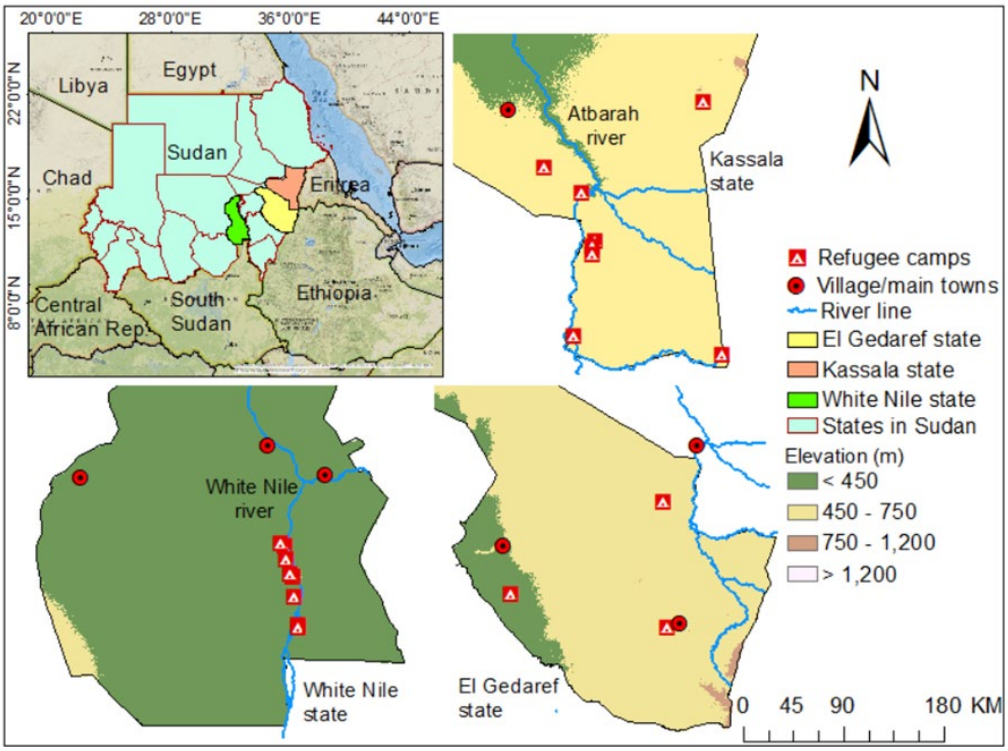


Figure 1. Location of refugee camps in Kassala, El Gedaref and White Nile states (Source: Authors creation using data from OCHA (https://data.humdata.org/dataset/sudan-administrativeboundaries-2) and UNHCR (https://data.humdata.org/dataset/unhcr-refugee-camps)

Table 1. Years of establishment, refugee population and key natural resources in the surrounding areas of refugee camps

Locality	Camps	Year of establishment	Population[4], [5]	Natural resources in the surrounding areas	References
			Kassala state		
Reifi Khashm Elgirba	Girba	1989	7,486	Atbara River, agricultural land, sparse woodland, shrublands, and dryland acacia forest patches	UNHCR, 2024b; FAO, 2023
	Kilo-26	1978	9,843		UNHCR, 2024b; Ethar Relief, 2024[6]
Reifi Wad Elhilaiw	Abuda	1981	2,418	Communal grazing land, near Setit and the Khors River, Bushland providing non-timber forest products, the Atbara River, Shrubland, and Rangeland ecosystems dominated by Acacia.	UNHCR, 2024b
	Shagarab 1	1985	39,985		Raut, 2020[7]
	Shagarab 2	1985	13,329		UNHCR, 2024b
	Shagarab 3	1985	6,363		UNHCR, 2024b
Reifi Kassla	Wad Sharife	1983	18,432	Near Khor Abna and seasonal wet areas, agricultural and rangelands	IOM, 2024[8]; ReliefWeb, 2024[9]
			El Gedaref State		
Al Mafaza	Tunaydba	2021	23,072	Seasonal streams (khors) and shallow groundwater, acacia-dominated woodland and bushland, grazing land, and rainfed farmland.	Osman and Yassin, 2024; UNHCR, 2023[10]
Al Fashaga	Um Gargour	2021	11,636	Productive farmland, close to Atbara River tributaries, bushland providing fodder and biomass, rich beekeeping potential (acacia belts)	OCHA, 2022[11]
Galabat Ash-Shargiah	Um Rakuba	2020	19,189	Grasslands and small patches of woodland, water from seasonal rivers/khors, Wildlife and forest patches offering NTFP.	DRC, 2023[12]
			White Nile state		
Aj Jabalain	Al Alagaya	2014	38,632	Seasonal streams (khors), agricultural and grazing land, limited groundwater wells	UNHCR, 2022
	Al Jameya	2018	11,986	Nearby grazing and rainfed plots	OCHA, 2022[11]; UNHCR, 2025a
	Khor Alwarel	2016	37,942	Rainfed agricultural land and rangelands, proximity to seasonal water courses	UNHCR, 2024b
	Um Sangour	2015	36,255	Water sources (stream) in the rainy season, local firewood supply	UNHCR, 2023[13]
As Salam / Ar Rawat	Jouri	2014	11,737	Rangelands and some arable plots	DRC, 2023[12]
	Al Redis 1	2014	11,615	Rangelands and some arable plots	UNHCR, 2024b
	Al Redis 2	2015	27,095	Located near seasonal floodplain and grazing areas, camp water points	UNHCR, 2024b
	El Kashafa	2014	13,363	Floodplain/rangeland, local biomass sources, camp water points	UNHCR, 2022
	Dabat Bosin	2014	27,356	Grazing and agricultural lands, shallow groundwater wells/boreholes serving the camp	UNHCR, 2022

Source: Authors' creation

[4] https://data2.unhcr.org/en/country/sdn (Accessed on April 05, 2026)
[5] https://data.unhcr.org/en/documents/download/92034? (Accessed on April 05, 2026)
[6] https://www.etharrelief.org/kilo26floodsappeal (Accessed on April 10, 2026)
[7] https://doi.org/10.13140/RG.2.2.11417.85603 (Accessed on April 12, 2026)
[8] https://mailchi.mp/iom/dtm-sudan-flash-alert-heavy-rains-and-flooding-in-reifi-aroma-aroma-town-kassala-update-001?e=c095dde85b (Accessed on April 15, 2026)
[9] https://reliefweb.int/report/sudan/sudan-humanitarian-impact-heavy-rains-and-flooding-flash-update-no-1-28-july-2024-enar (Accessed on April 15, 2026)
[10] https://data.unhcr.org/en/documents/details/103401 (Accessed on April 15, 2026)
[11] https://www.unocha.org/publications/report/sudan/ocha-sudan-gedaref-state-profile-march-2023 (Accessed on April 15, 2026)
[12] https://drc.ngo/resources/news/hope-amidst-conflict-for-ethiopian-refugees-in-um-rakuba-camp-sudan/ (Accessed on April 15, 2026)
[13] https://www.unhcr.org/news/stories/sudan-conflict-rages-health-crisis-hits-displacement-camps (Accessed on April 15, 2026)

2.2. Study Approach

We employed a combination of camp age and a concentric buffer-based approach to assess the temporal and spatial nexus between refugee settlements and environmental degradation. First, refugee camps were grouped into three categories: long-established (established before 1990), established (established during 2011 - 2019), and recently established (established from 2020 onwards) settlements. Then, four concentric buffer zones were delineated around each settlement: 0-10 km (hereinafter referred to as the inner zone), 10-20 km (intermediate zone), 20-30 km (outer zone), and 30-50 km (peripheral zone). An exclusion procedure was applied to avoid spatial overlap among the four buffer zones using the multiple ring buffer tool in ArcGIS 10.8. The overall approach used in this study enabled the analysis of LULC change and land degradation neutrality (LDN) among settlements of different ages and across the four buffer zones to support informed environmental management and restoration. The LULC and LDN maps were prepared using ArcGIS 10.8.

2.3. Data Sources

Data for biophysical characterizations of refugee sites were derived and collected from various geospatial datasets and sources (Table 2).

Table 2. Key features of the datasets and sources

Data type	Data source	Resolution	Sources	Uses or applications
Digital Elevation Model (DEM)	Alaska Satellite Facility (ASF)	12.5 m	https://search.asf.alaska.edu/#/	Used to calculate slope and assess altitude ranges
SoilGrids	International Soil Reference and Information Centre (ISRIC)	250 m	https://soilgrids.org/	Used to assess soil organic carbon loss (SOC)
Long-term (1981–2025) mean annual rainfall (MAR)	Climate Hazards Group InfraRed Precipitation with Station (CHIRPS v3)	5 km	https://data.chc.ucsb.edu/products/CHIRPS/v3.0/	Used to estimate the minimum and maximum MAR
Agroecological zones	Regional Centre for Mapping of Resources for Development (RCMRD)	-	https://gmesgeoportal.rcmrd.org/datasets/rcmrd::agro-ecological-zones-dataset/about	Defined in terms of climate, landform and soils, and/or land cover
Landsat 4, 5, 7, and 8	System for Earth Observation Data Access, Processing and Analysis for Land Monitoring (SEPAL) and Google Earth Engine	30 m	https://sepal.io; https://earthengine.google.com/	Used to assess land use/land cover (LULC) dynamics

Source: Authors' creation

2.4. Data Analysis

The study employed geospatial analysis to investigate the nexus between refugee settlements and environmental degradation. The sub-sections below present detailed procedures used in the study.

Land use and land cover analysis

The LULC classification was performed using a hybrid classification approach that combined unsupervised and supervised classification in ArcGIS 10.8 and ERDAS IMAGINE 16. Unsupervised classification was performed using the Iterative Self-Organizing Data Analysis Technique Algorithm to cluster pixels into spectrally similar groups (Girma et al., 2022). Because on-ground accessibility to the study area was limited during the study period, field-based ground truthing was not feasible; consequently, reference data for both class labeling and accuracy assessment were derived from visual interpretation of high-resolution Google Earth imagery, complemented by other freely available high-resolution satellite imagery, an approach widely adopted in remote sensing studies as a reliable alternative to field verification when direct site access is constrained (Xiong et al., 2017). Accordingly, a total of 210 reference points, 140 training samples and 70 independent validation points were generated through systematic visual interpretation of Google Earth imagery, with samples distributed across all land-cover classes.

Using Google Earth observations, we assigned spectral clusters to seven predefined land cover classes: water bodies, forestlands, farmlands, bare land, settlement areas, grasslands, and shrublands. Training signatures were drawn for each of the predefined classes and used as input for a maximum likelihood classifier (supervised classification) (Kafy et al., 2021). Before change detection, we evaluated classification accuracy using overall accuracy, user accuracy, producer accuracy, and the kappa coefficient (Dey et al., 2021). The overall classification accuracy and kappa coefficient exceeded 70% and 0.68, respectively (Table 3). These values fall within the "substantial" to "perfect" agreement categories, indicating that the classified maps are sufficiently reliable for the subsequent analyses. Finally, change detection was assessed over different time periods between 1978 and 2025 to characterize the direction, magnitude, and spatial patterns of LULC dynamics.

Table 3. Accuracy assessment of the land-use and land-cover classification.

Year	LULC Class														OA (%)	Kappa coefficient
	Waterbody		Forestland		Farmland		Bare land		Settlement area		Grassland		Shrubland			
	PA (%)	UA (%)	PA (%)	UA (%)	PA (%)	UA (%)	PA (%)	UA (%)	PA (%)	UA (%)	PA (%)	UA (%)	PA (%)	UA (%)		
1985	75.4	69.8	65.7	70.3	76.1	77.0	68.9	65.8	70.0	72.7	65.0	71.6	70.4	65.3	70.4	0.68
1989	77.2	72.0	67.9	71.5	78.0	75.4	70.5	66.0	67.9	71.8	74.2	72.9	70.9	67.6	71.9	0.75
2014	81.0	73.4	71.0	70.9	80.4	79.6	79.6	71.2	73.5	75.0	81.4	79.4	69.7	76.4	80.2	0.80
2015	84.1	77.3	74.2	75.4	82.6	82.1	81.4	73.9	79.9	77.3	85.9	83.5	73.8	80.8	80.9	0.79
2016	82.9	79.5	78.9	82.7	85.1	85.4	85.0	74.5	82.5	80.1	85.2	85.7	79.0	79.2	81.6	0.82
2018	85.0	81.0	79.6	86.4	82.3	86.1	87.3	75.9	86.7	87.0	87.1	88.0	80.7	80.6	84.0	0.87
2020	91.6	90.0	80.2	86.0	76.5	86.7	89.0	89.4	88.9	91.5	89.1	90.4	85.7	84.7	85.9	0.84
2021	94.2	93.7	77.1	89.7	78.8	80.0	91.8	90.0	90.6	93.3	92.4	91.0	74.2	87.0	86.3	0.85
2025	96.7	97.1	78.8	90.0	85.5	86.7	93.6	94.7	95.3	96.7	96.6	93.3	75.9	83.9	87.4	0.91

Note: Kappa values < 0 refer to no agreement, 0–0.2 - slight agreement, 0.2–0.41 - poor agreement, 0.41–0.60 - moderate agreement, 0.60–0.80 - substantial agreement, and 0.81–1.0 - perfect agreement. Source: Authors creation

Land degradation neutrality assessment

Land degradation neutrality was assessed following the Good Practice Guidance using three spatially explicit sub-indicators: land productivity (LP), land cover (LC), and soil organic carbon (SOC), implemented in Trends.Earth (Teich et al., 2025). Detailed procedures for assessing LP, LC, and SOC are described in our previous publication (Mekuria and Girma, 2025). Briefly, LP trends were derived from time-series NDVI data from the Advanced Very-High-Resolution Radiometer and Terra Moderate Resolution Imaging Spectroradiometer Vegetation Indices, with the Water Use Efficiency (WUE) correlation method applied to minimize climate and seasonal variability (Schillaci et al., 2023; Mekuria et al., 2026). LC changes were determined using a custom LULC map (Section 2.4.1) together with the land cover transition matrix and degradation typology generated in Trends.Earth (Mekuria and Girma, 2025). Changes in SOC were assessed using land-use conversion coefficients recommended by the Intergovernmental Panel on Climate Change and the United Nations Convention to Combat Desertification (Yuan et al., 2022), where losses exceeding 10% indicate degradation and gains exceeding 10% indicate improvement (Sims et al., 2021).

Finally, the LP, LC and SOC were combined using the 'one-out all-out' (1OAO) rule to determine the extent of degraded land and create an LDN indicator map (Schillaci et al., 2023). The 1OAO rule implies that if any one of the indicators shows degradation (reduction or negative change), the overall assessment classifies the land as degraded regardless of positive trends in other indicators (Sims et al., 2021; Schillaci et al., 2023).

3. Results

3.1. Biophysical Characteristics

Table 4 summarizes the mean annual rainfall (mm), agroecology, and topographic conditions within a 0–50 km radius of the refugee camps in the three states. The results indicated differences in key biophysical characteristics among the investigated refugee camps. Mean annual rainfall varies significantly across the refugee settlement areas, with some areas receiving very low amounts (e.g., 180 mm in Wad Sharife) while others experience relatively higher precipitation (e.g., 660 mm in Tunaydba). Most camps are situated within semi-arid agroecological zones, while a few fall in arid regions, and some span both semi-arid and arid conditions. Overall, the terrain is predominantly flat, with very gentle slopes dominating the landscape. The gentle slope class represents the second largest category, while moderate to very steep slope classes cover relatively small areas across the camps except Wad Sharife (Table 4).

Table 4. Biophysical characteristics of areas surrounding the refugee camps (50 km radius)

State	Refugee camp	Mean annual rainfall (mm)		Area covered under each agroecology (ha)		Area covered under each slope class (ha)				
		Min	Max	Semiarid	Arid	0-5%	5-15%	15-30%	30-45%	>45%
Kassala	Abuda	422	654	764619	20779	680055	104460	866	16	1
	Girba	231	480	175481	609917	679306	104993	1006	71	22
	Kilo 26	213	463	79779	705619	703592	80109	1405	229	63
	Shagarab 1	274	535	398791	386607	685072	99441	819.7	65	0.3
	Shagarab 2	289	543	424981	360417	707130	78070	193	4	0.3
	Shagarab 3	306	545	465119	320279	740401	44846.7	145	5	0.3
	Wad Sharife	180	396	0	520691	436540	74457	3854	2464	3376
El Gedaref	Tunaydba	389	660	591522	0	534050	55071	1199	1008	194
	Um Gargour	377	585	716823	68575	690372	94938	54	14	20
	Um Rakuba	607	851	785398	0	725518	58262	1352	196	70
White Nile	Al Alagaya	333	478	608822	0	576547	31910	252	55	58
	Al Redis 1	331	473	708264	0	644286	63136	724	60	58
	Al Redis 2	329	473	720686	0	676234	43998	336	60	58
	Al Jameya	314	456	760831	0	657454	102263	948	108	58
	El Kashafa	333	473	678212	0	632048	45255	624	218	67
	Jouri	333	478	613234	0	538268	74596	257	55	58
	Khor Alwarel	318	456	759999	0	703224	56072	588	57	58
	Um Sangour	326	473	746348	0	646018	99348	846	78	58

Source: Authors' creation

Note: Al Redis 1 and Dabat Bosin have identical coordinates in the UNHCR[14] dataset and are treated as a single point in the spatial analysis

3.2. Land Use and Land Cover Dynamics of the Buffer Zones Around Refugee Camps

LULC change exhibits strong spatial and temporal differentiation across buffer zones and settlement age categories, reflecting both cumulative and expanding human pressure (Figures 2–13).

Variation across settlement categories within the inner buffer zone

In the inner buffer zone (0–10 km), LULC change is most pronounced in the long-established camps in Kassala, where prolonged occupation has led to substantial landscape transformation (Figure 2; Figure 3). Shrublands decline by 17–53%, farmland expands by 26–59%, and settlement areas increase markedly, accompanied by losses in grassland, forest, and waterbodies. Established camps in White Nile show similar but less intense changes, with moderate grassland decline (0.5–56%) and farmland expansion (1–42%). In contrast, recently established camps in El Gedaref exhibit relatively limited, spatially heterogeneous changes, although early signs of vegetation loss and settlement expansion are evident. However, annual rates of change in LULC suggest that recently established camps experience the fastest ongoing changes, despite smaller cumulative impacts (Figure 4).

[14] https://data.humdata.org/dataset/80b8342a-ca82-4fa2-aa00-d806d4d925bd (Accessed on September 27, 2025)

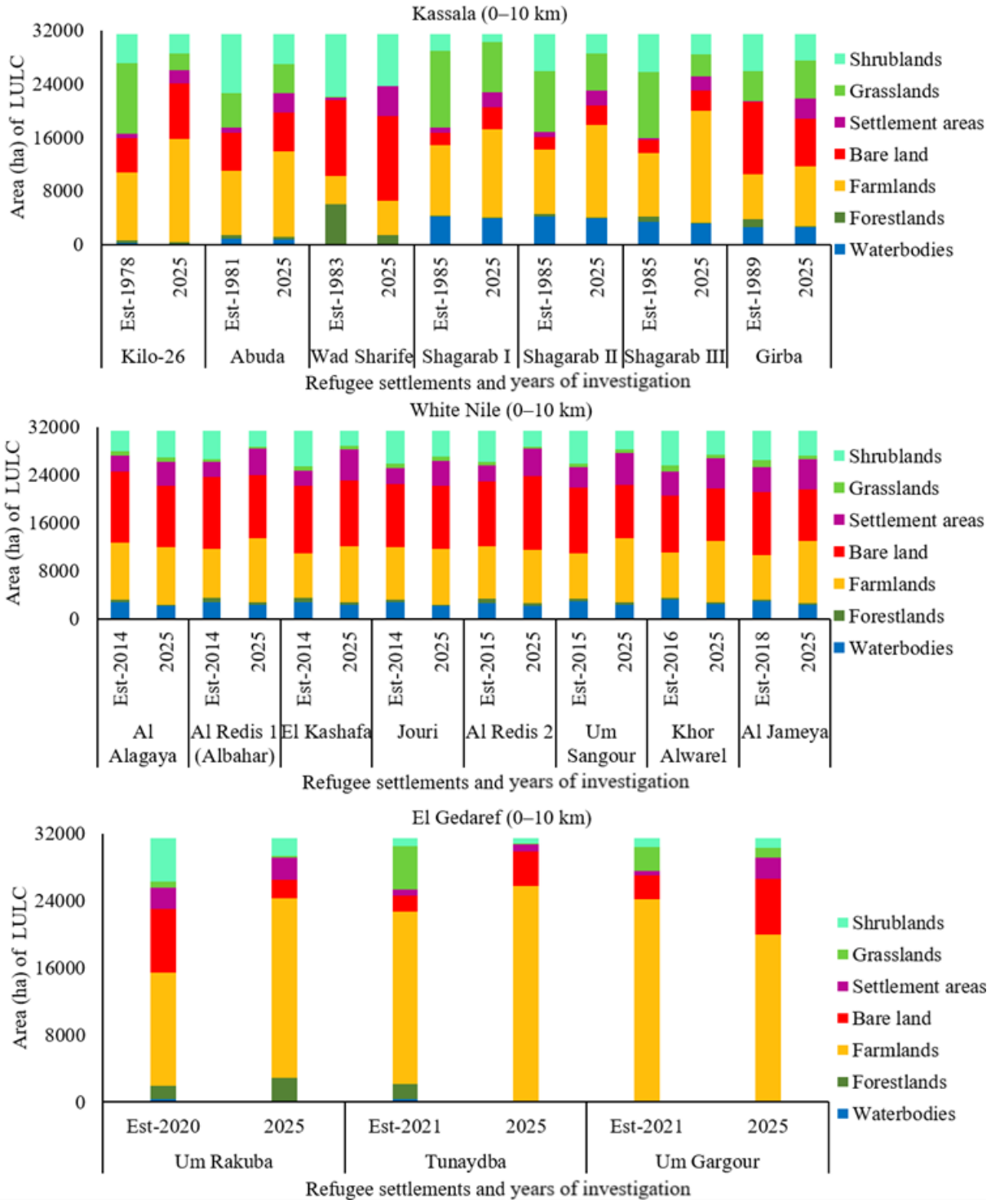


Figure 2. Changes in land-use and land-cover classes in the inner buffer zone (0–10 km radius). Est refers to the year of establishment of the refugee camps and LULC refers to land use and land cover. *Source:* Authors' creation.

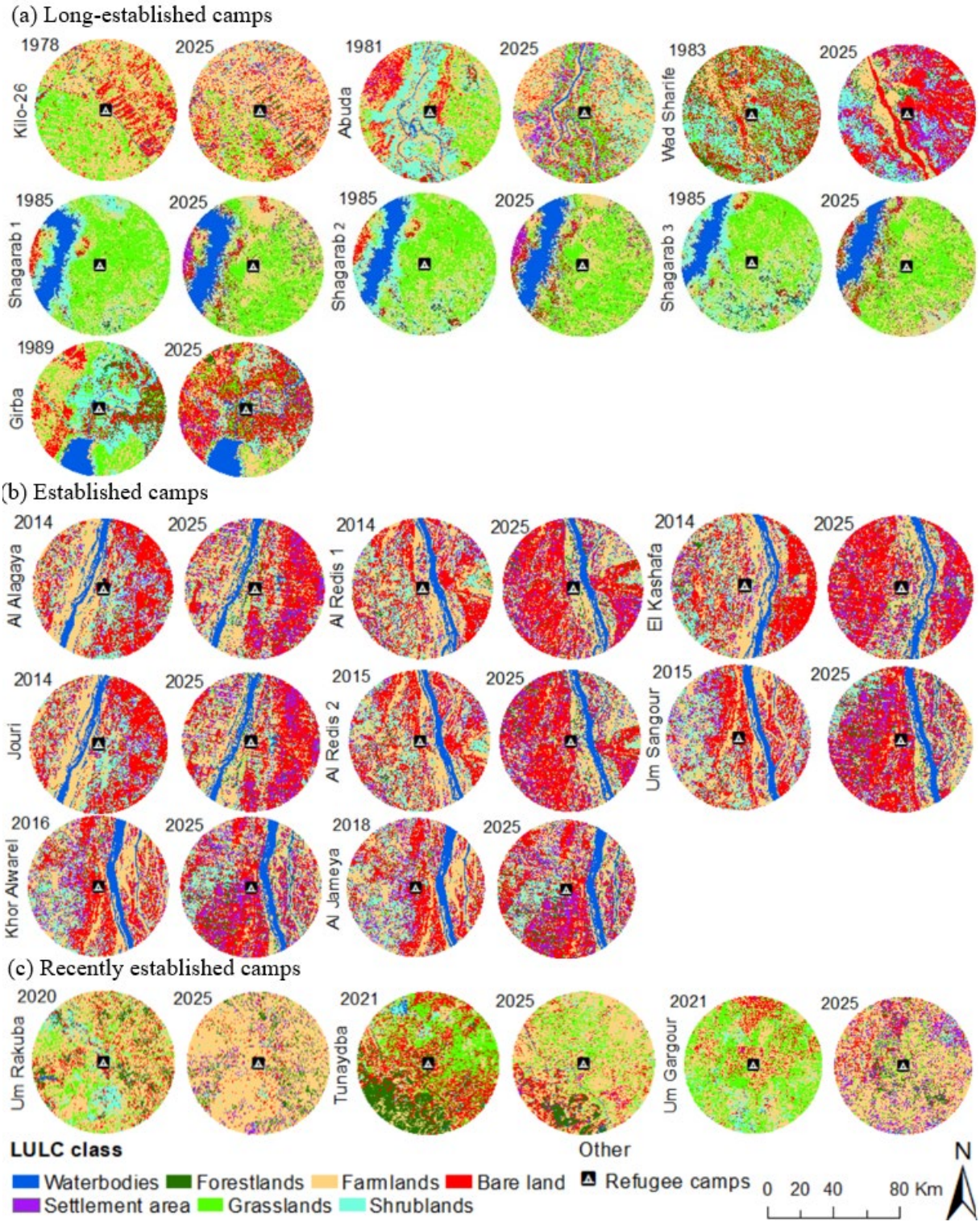


Figure 3. Land-use and land-cover classes in the inner buffer zone (0–10 km) of refugee camps. *Source:* Authors' creation.

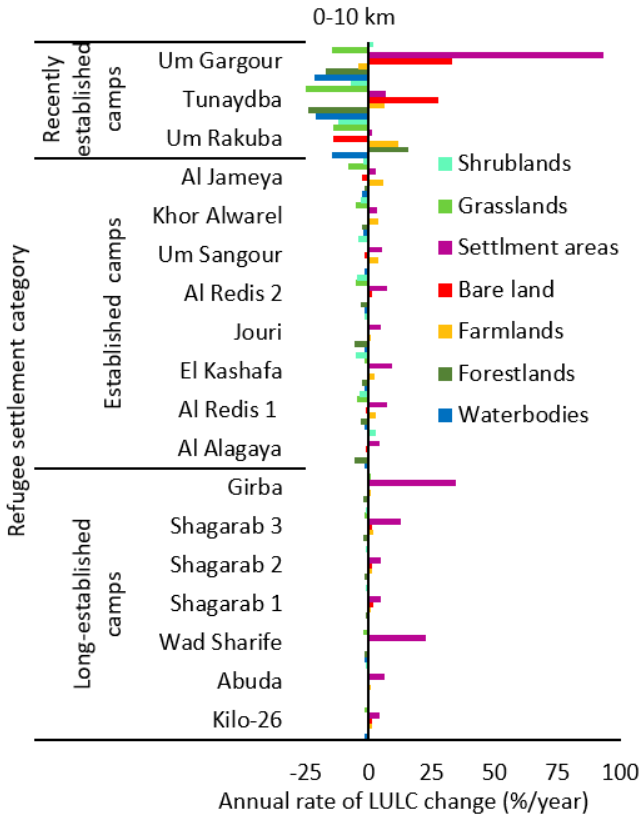


Figure 4. Annual rate of land-use and land-cover (LULC) change in the inner buffer zone (0–10 km) of refugee camps.
Source: Authors' creation

Variation across settlement categories within the intermediate buffer zone

In the intermediate buffer zone (10–20 km), LULC change intensifies and becomes more spatially extensive (Figure 5; Figure 6). The long-established camps show the greatest transformations, including substantial farmland expansion (e.g., +150% in Wad Sharife) and extensive settlement growth (often exceeding +1,200%), along with sharp declines in forest and grassland (up to −76% and −99%). Established camps follow similar trajectories but at lower magnitudes of farmland expansion (+50% in Al Alagaya) and settlement growth (e.g., +96% in Jouri). Similarly, recently established camps show increasing farmland and settlement expansion (up to +62% and +85% in Um Gargour), coupled with continued vegetation loss (grassland down to −95%). In the intermediate buffer zone, the annual rate of change in settlement area is substantially greater in the old camps (Figure 7). However, similar to the inner zone, the decline of natural ecosystems is higher in recently established camps.

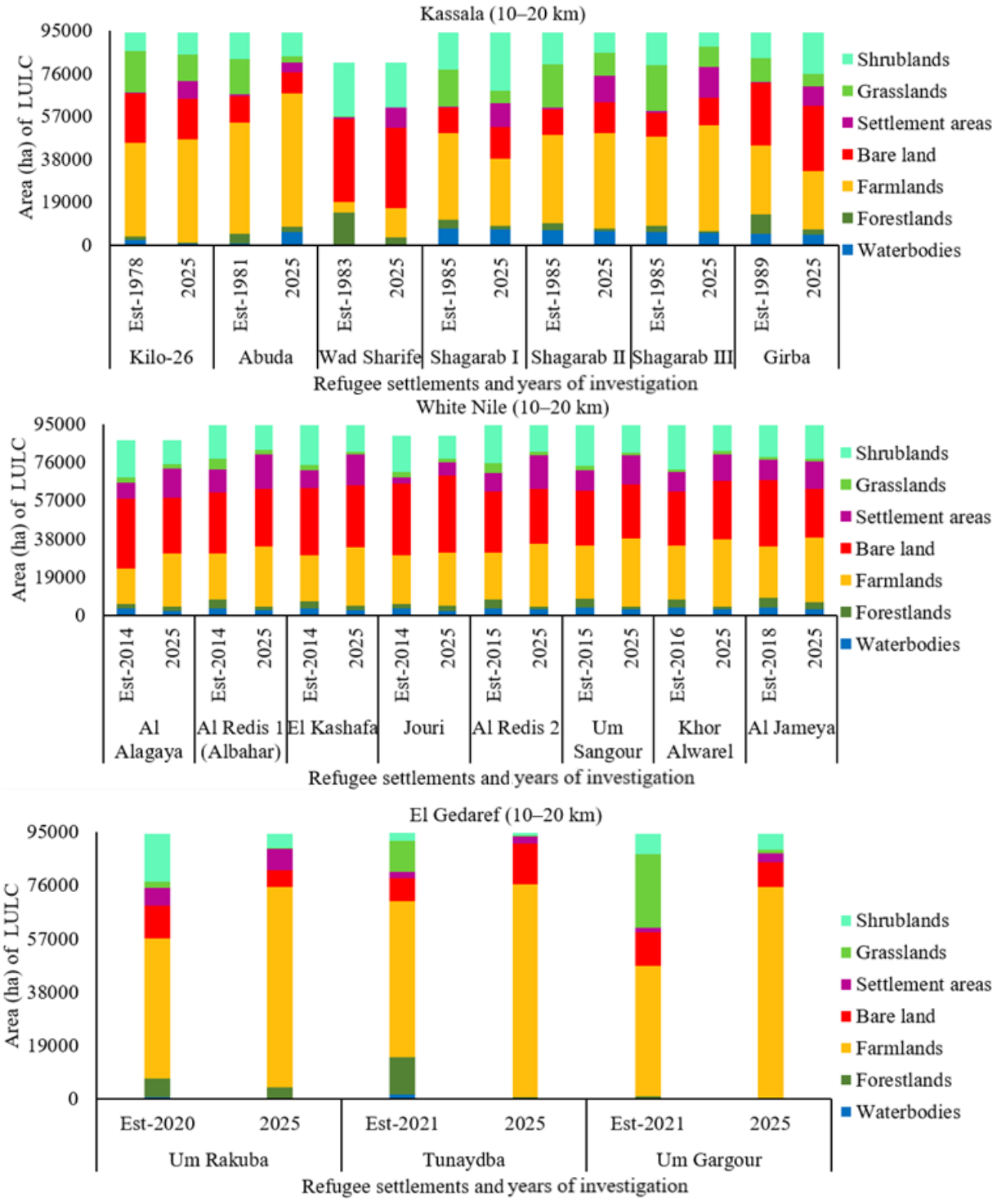


Figure 5. Changes in land-use and land-cover classes in the intermediate buffer zone (10–20 km radius). See Figure 2 for other details.
Source: Authors' creation

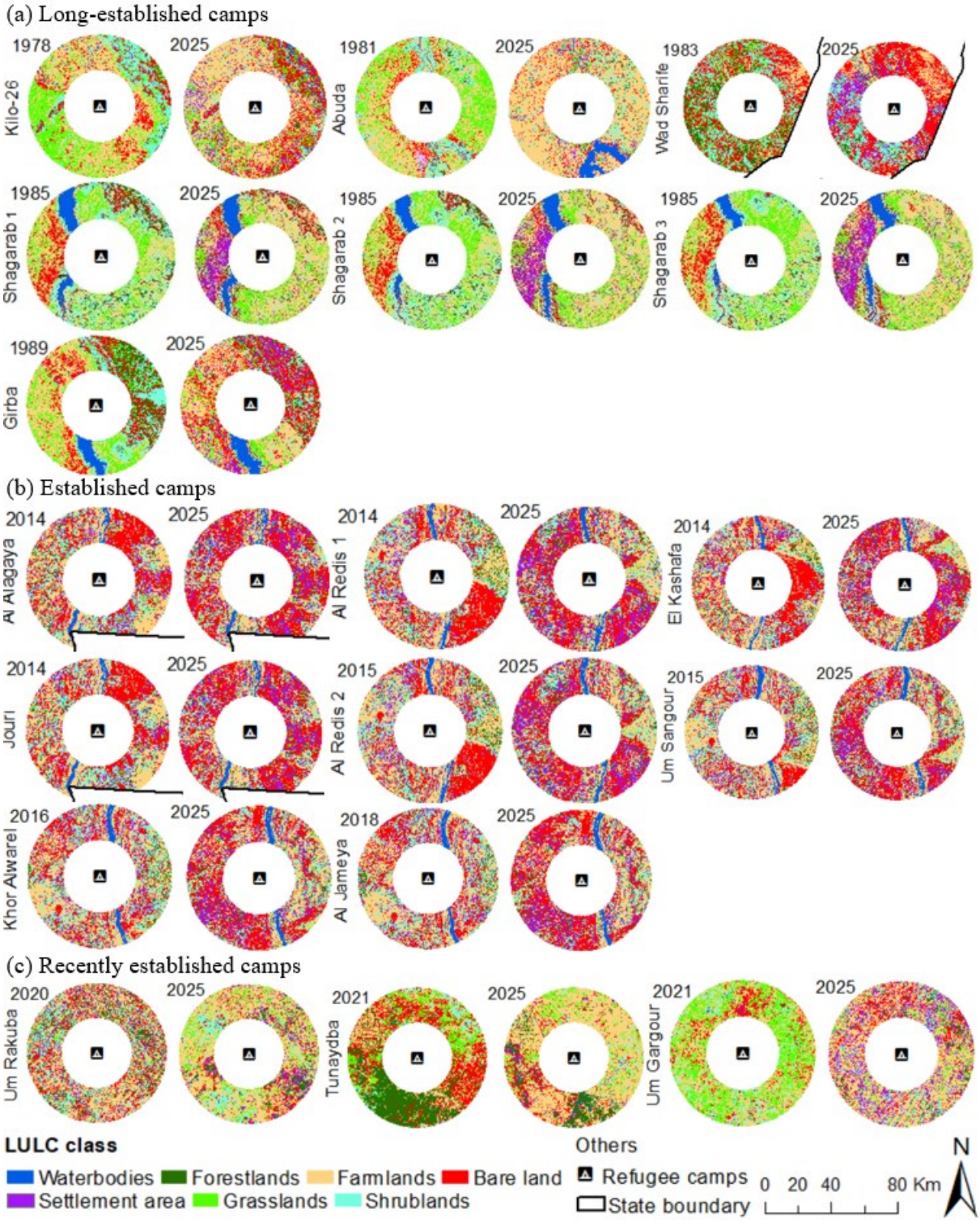


Figure 6. Land-use and land-cover classes in the intermediate buffer zone (10–20 km) of refugee camps. Clipping buffer zones to the respective state boundaries resulted in incomplete rings where buffer areas extended outside the state boundaries.

Source: Authors' creation

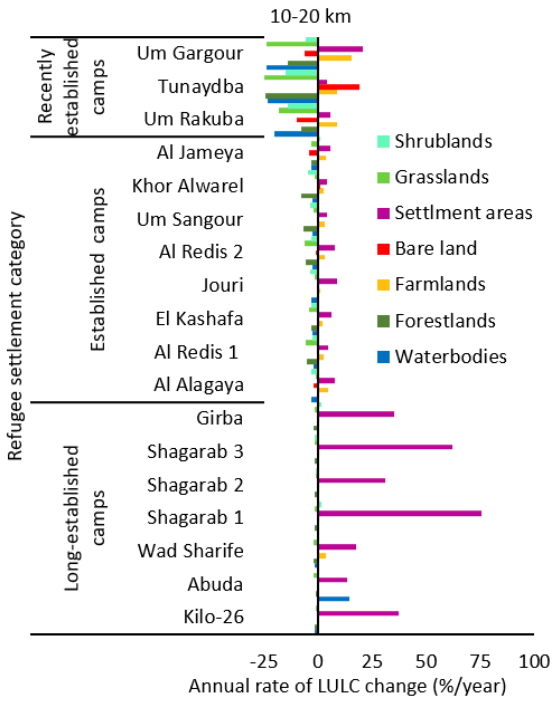


Figure 7. Annual rate of land-use and land-cover (LULC) change in the intermediate buffer zone (10–20 km) of refugee camps.
Source: Authors' creation

Variation across settlement categories within the outer buffer zone

In the outer buffer zone (20–30 km), LULC dynamics reflect landscape-scale transformation across all settlement categories (Figure 8; Figure 9). The long-established camps again show the greatest cumulative impacts, including widespread farmland expansion (up to +101%), severe vegetation loss (up to −85% forest, −52% shrub and −95% grassland), and substantial settlement growth (up to +3,745%). Established camps exhibit similar but attenuated patterns of farmland expansion (up to +80%), settlement growth (up to +88%) and vegetation loss (up to −67% forest, −44% shrub and −81% grassland). Likewise, recently established camps show expansion of built-up areas (+99%) and declining natural vegetation (forest up to −95%, shrub –85% and grassland –97%) alongside smaller absolute changes but consistent increases in farmland (up to +45%). These patterns indicate strong negative vegetation changes around recently established camps, and strong and consistent increases in settlement areas around old refugee camps (Figure 10).

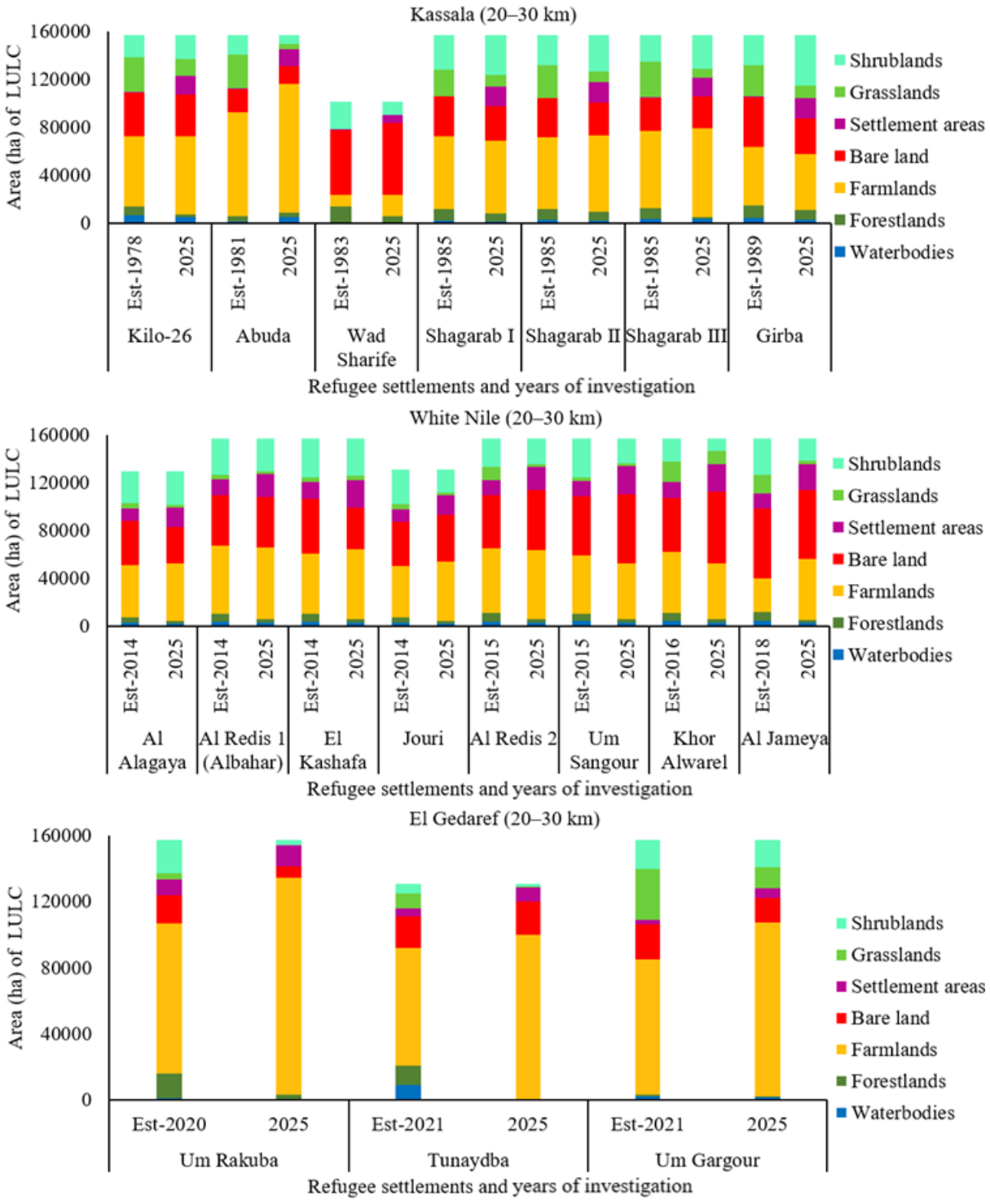


Figure 8. Changes in land-use and land-cover classes in the outer buffer zone (20–30 km radius). See Figure 2 for other details.
Source: Authors' creation

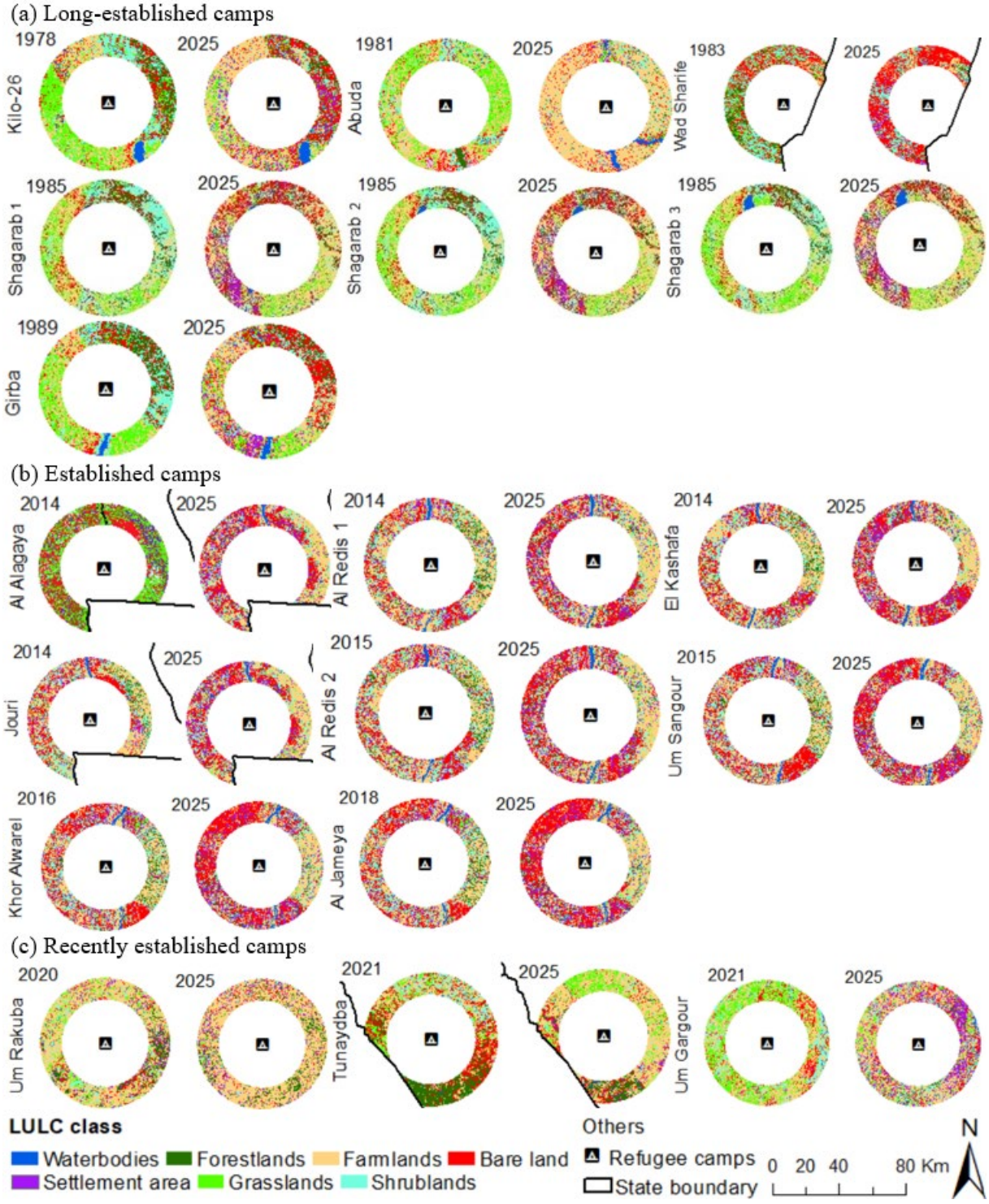


Figure 9. Land-use and land-cover classes in the outer buffer zone (20–30km) of refugee camps. See Figure 6 for other details.
Source: Authors' creation

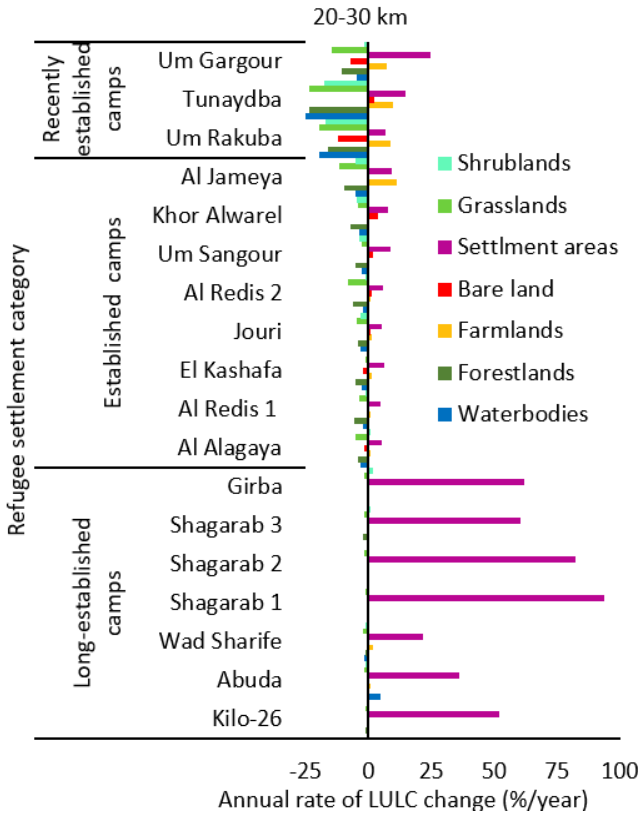


Figure 10. Annual rate of land-use and land-cover (LULC) change in the outer buffer zone (20–30km) of refugee camps.
Source: Authors' creation

Variation across settlement categories within the peripheral buffer zone

In the peripheral buffer zone (30–50 km), LULC change reaches its widest spatial extent (Figure 11; Figure 12). The long-established camps demonstrate the largest absolute transformations, including farmland increases of 20–53% and settlement expansion of 774–2,923%, combined with broad declines in forest, grassland, and shrubland. Established camps show moderate increases in farmland (3–11%) and settlements (67–104%), while recently established camps exhibit smaller but still notable increases (farmland 14–35%; settlements 23–92%). Across all categories, natural vegetation declines and settlement area expansion persist (Figure 13), indicating outward diffusion of land conversion processes.

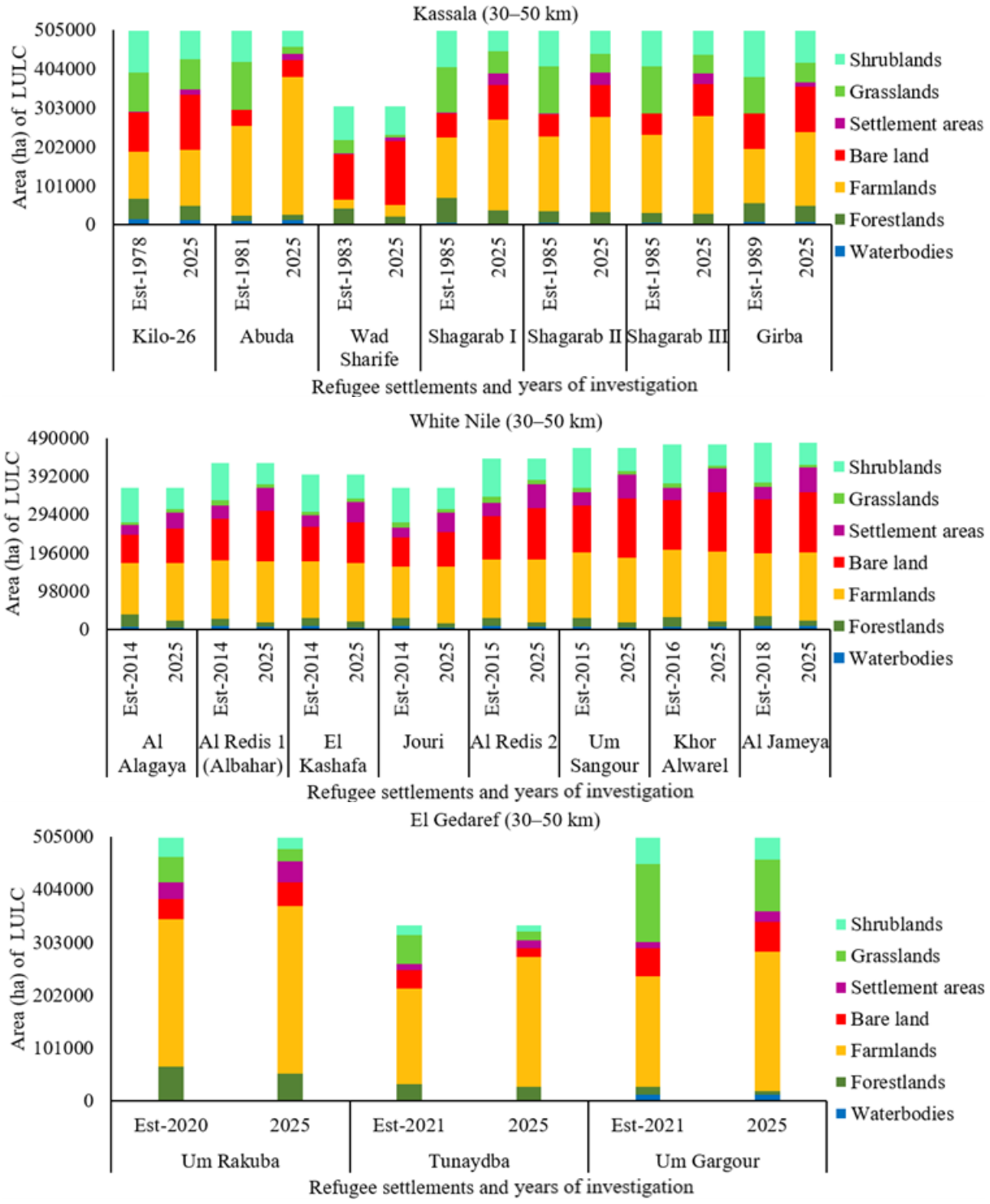


Figure 11. Changes in land-use and land-cover classes in the peripheral buffer zone (30–50 km radius). See Figure 2 for other details.
Source: Authors' creation

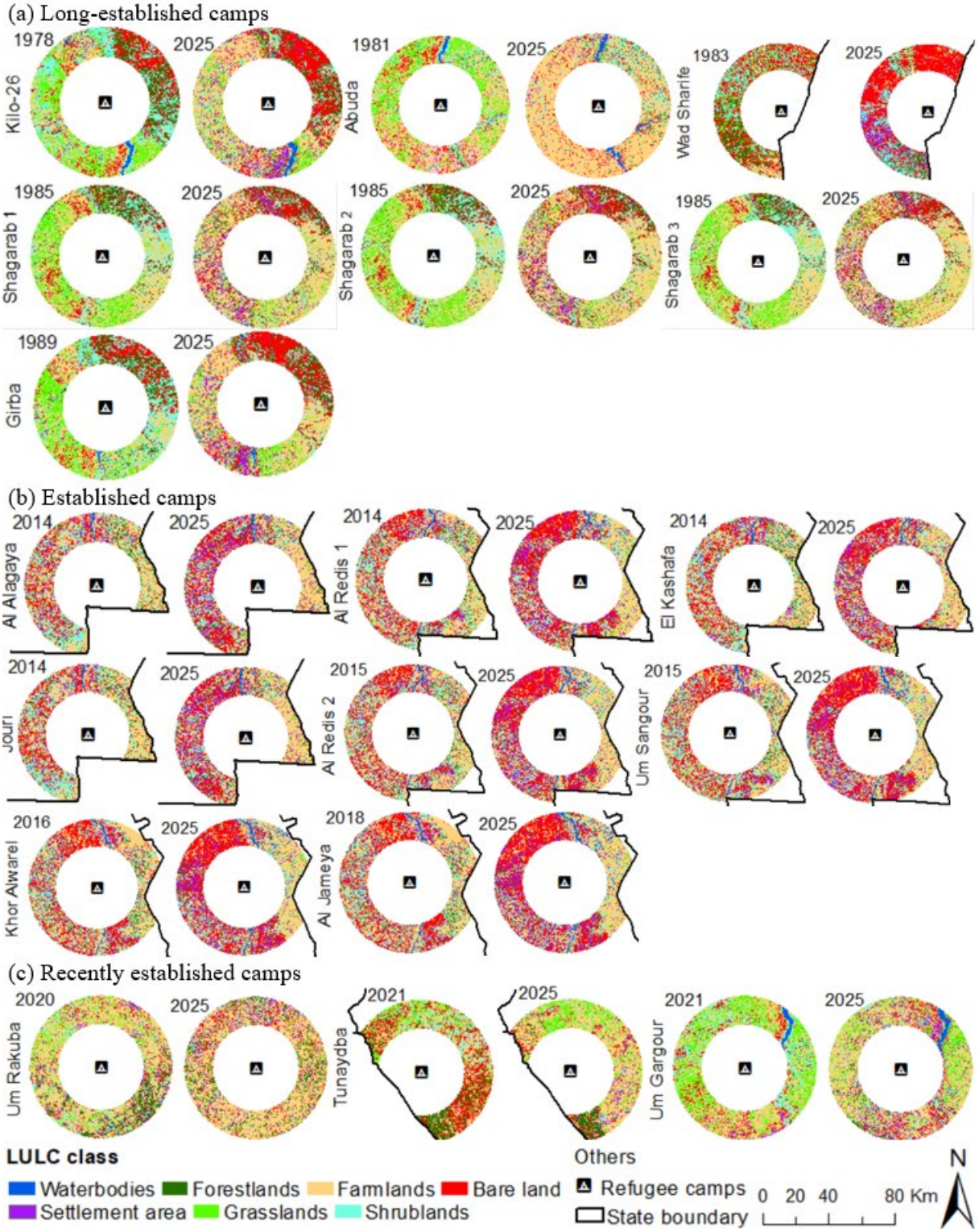


Figure 12. Land-use and land-cover classes in the peripheral buffer zone (30–50km) of refugee camps. See Figure 6 for other details.
Source: Authors' creation

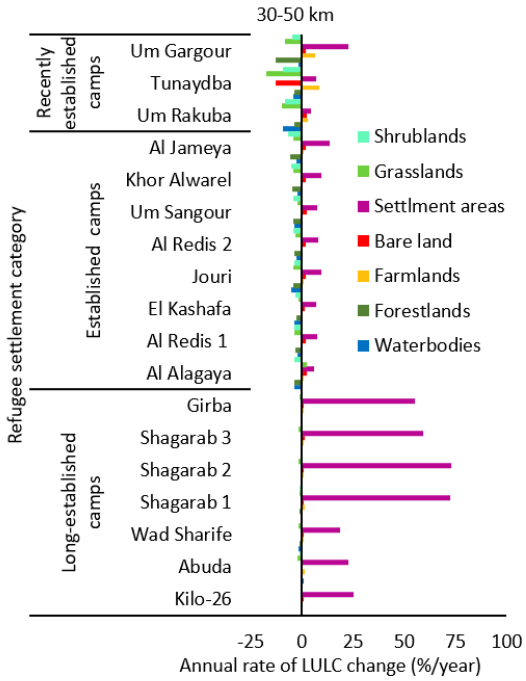


Figure 13. Annual rate of land-use and land-cover (LULC) change in the peripheral buffer zone (30–50km) of refugee camps.
Source: Authors' creation

3.3. Land Degradation Neutrality of the Buffer Zones Around Refugee Camps

The LDN analysis reveals a consistent and reinforcing pattern of increasing degraded land and declining stable and improved land across all buffers and settlement categories (Figures 14–25).

Variation across settlement categories within the inner buffer zone

In the inner buffer zone (0–10 km), degradation is most pronounced in the long-established camps (Figure 14; Figure 15), where degraded land expands substantially (e.g., +49% in Abuda camp) and improved land declines sharply (−56%). Established camps and recently established camps show smaller absolute increases in degraded land (approximately 10–11%) but follow the same directional trend, with declining stable and improved areas. Annual rates of change in LDN indicate that recently established camps experience the fastest increases in degradation, reaching up to 15% per year (Figure 16).

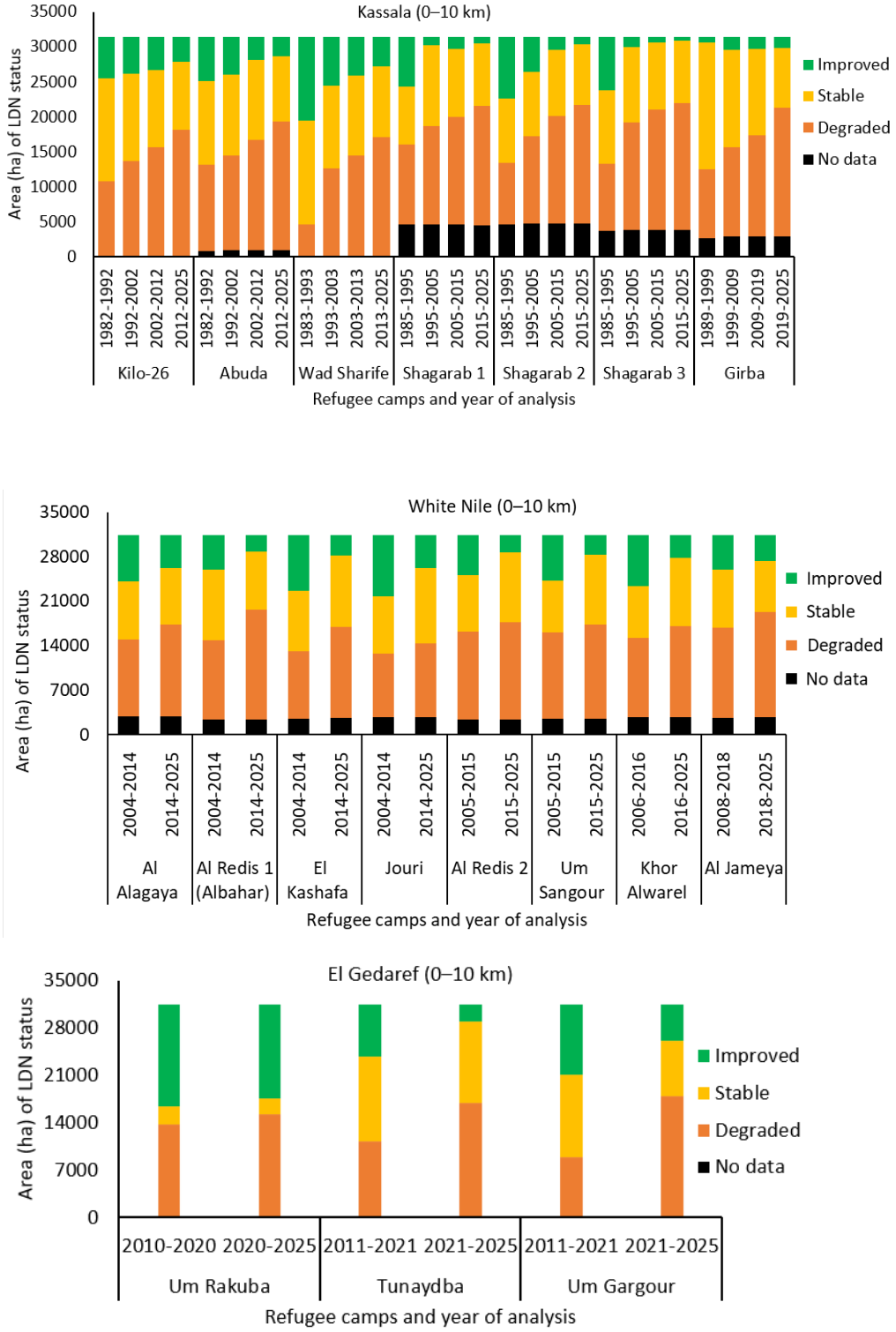


Figure 14. Land degradation neutrality in the inner zone (0–10 km). LDN refers to land degradation neutrality.
Source: Authors' creation

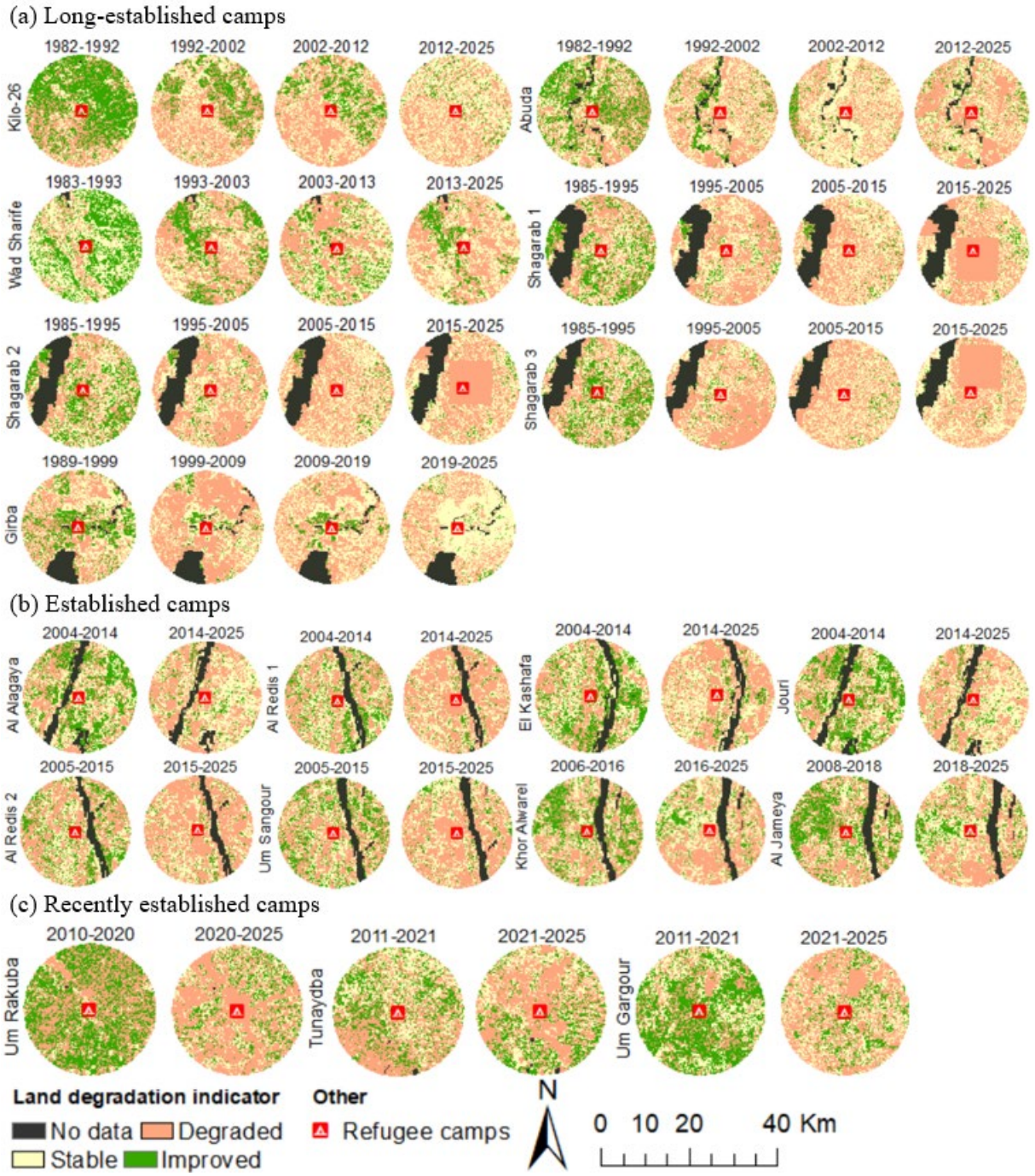


Figure 15. Land degradation status in the inner buffer zone (0–10 km) of refugee camps.
Source: Authors' creation

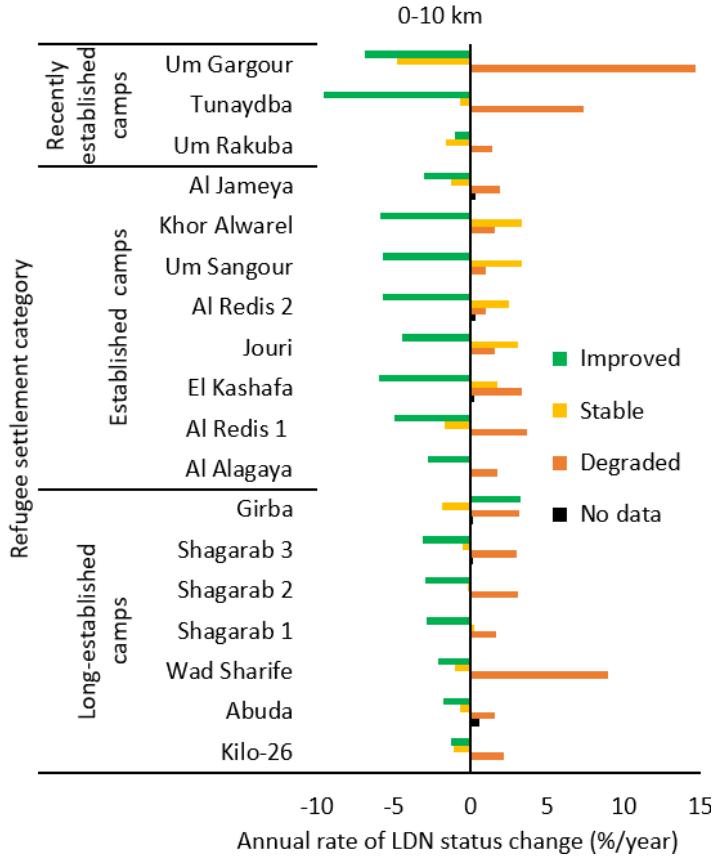


Figure 16. Annual rate of change in land degradation status in the inner zone (0–10 km). LDN refers to land degradation neutrality.
Source: Authors' creation

Variation across settlement categories within the intermediate buffer zone

In the intermediate buffer zone (10–20 km), degradation intensifies across all settlement types (Figure 17; Figure 18). The long-established camps show large increases in degraded land (e.g., +13,435 ha in Abuda) and substantial declines in stable and improved land. Established camps and recently established camps exhibit similar but smaller-scale changes, with consistent expansion of degraded land and contraction of improved land. Annual degradation rates remain high (0.5–5.8% per year), particularly in recently established camps (Figure 19).

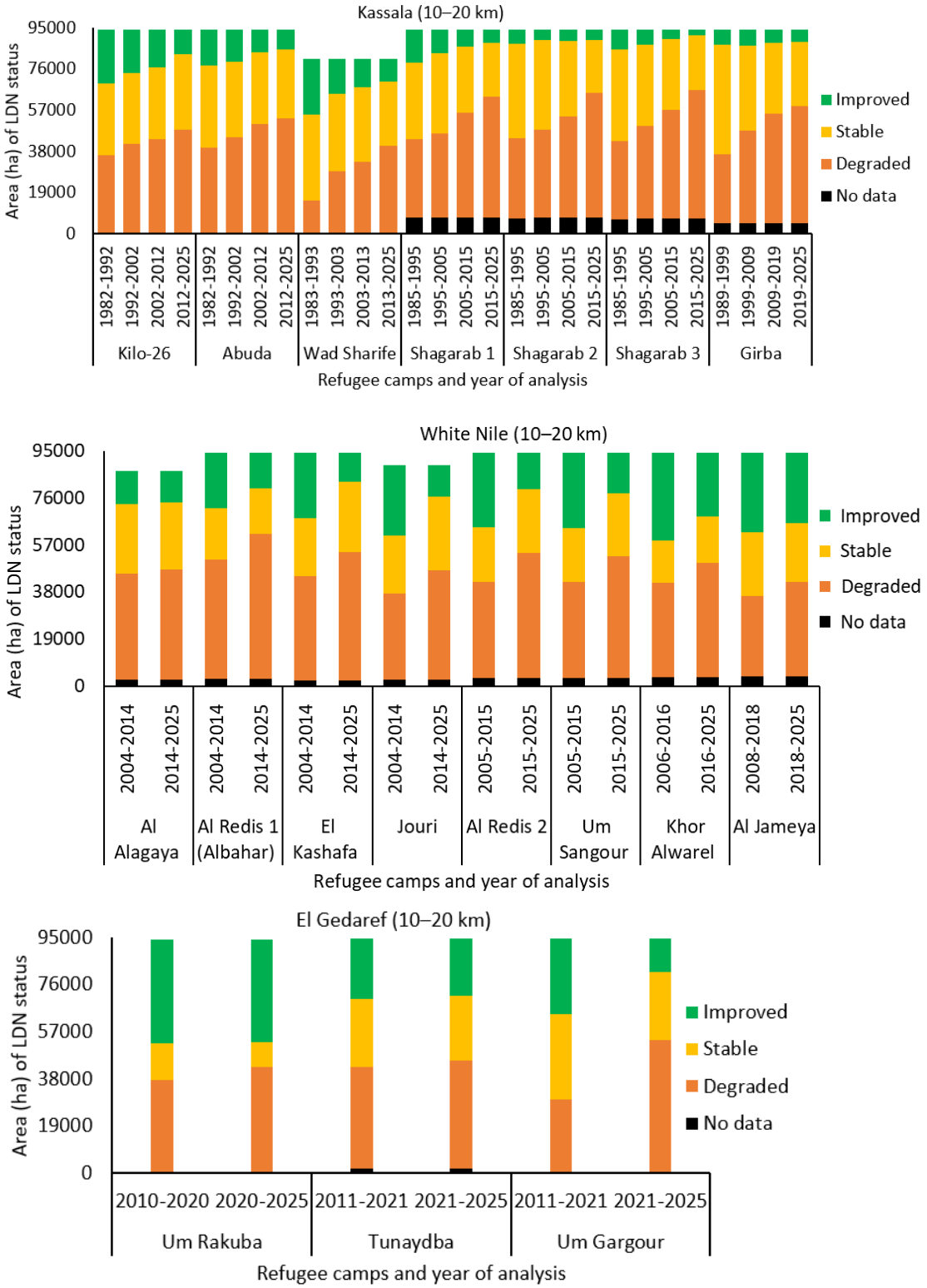


Figure 17. Land degradation neutrality in the intermediate buffer zone (10–20 km). LDN refers to land degradation neutrality.

Source: Authors' creation



Figure 18. Land degradation status in the intermediate buffer zone (10–20 km) of refugee camps. Clipping buffer zones to the respective state boundaries resulted in incomplete rings where buffer areas extended outside the state boundaries.

Source: Authors' creation

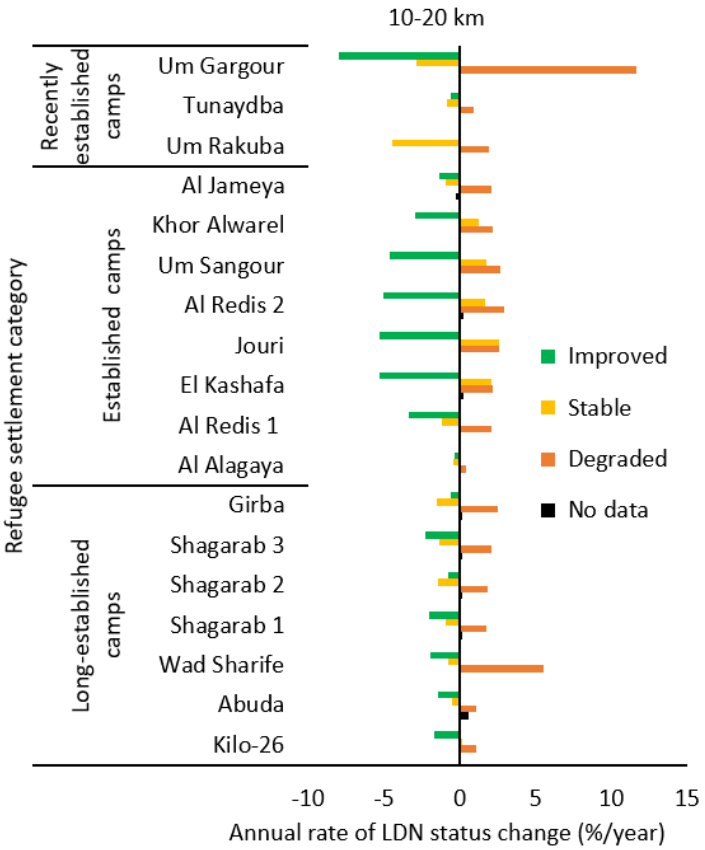


Figure 19. Annual rate of change in land degradation status in the intermediate zone (10–20 km). LDN refers to land degradation neutrality.
Source: Authors' creation

Variation across settlement categories within the outer buffer zone

In the outer buffer zone (20–30 km), degraded land becomes dominant (Figure 20; Figure 21). The long-established camps show large absolute increases (e.g., +45% in Abuda), while established camps and recently established camps continue to experience steady growth in degraded land and declining stable and improved areas. The annual rates of change in LDN indicate that old settlements experience the highest increases in degradation, reaching up to 6% per year (Figure 22). This buffer reflects the consolidation of degradation across broader landscapes.

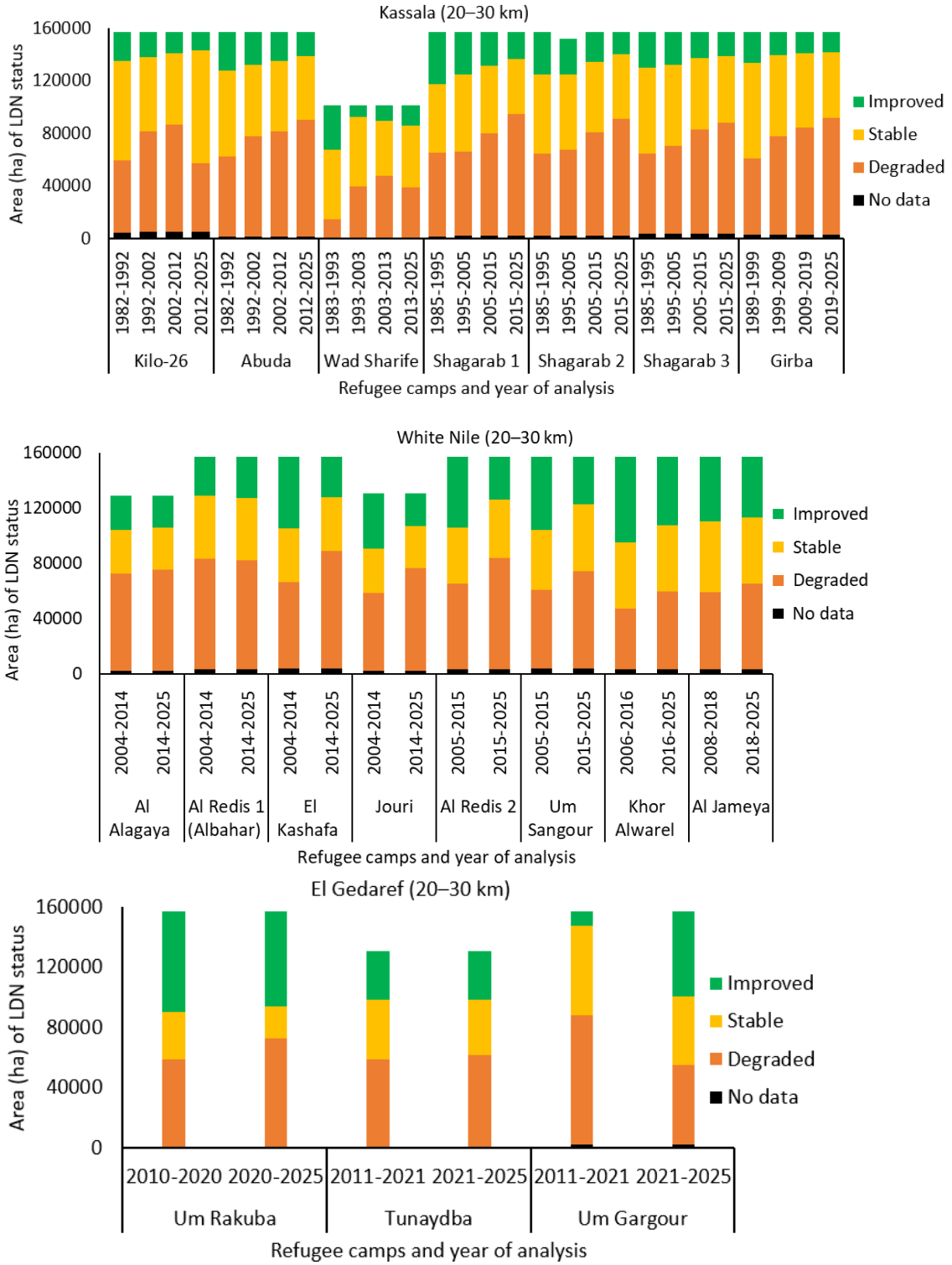


Figure 20. Land degradation neutrality in the outer zone (20–30 km). LDN refers to land degradation neutrality.
Source: Authors' creation

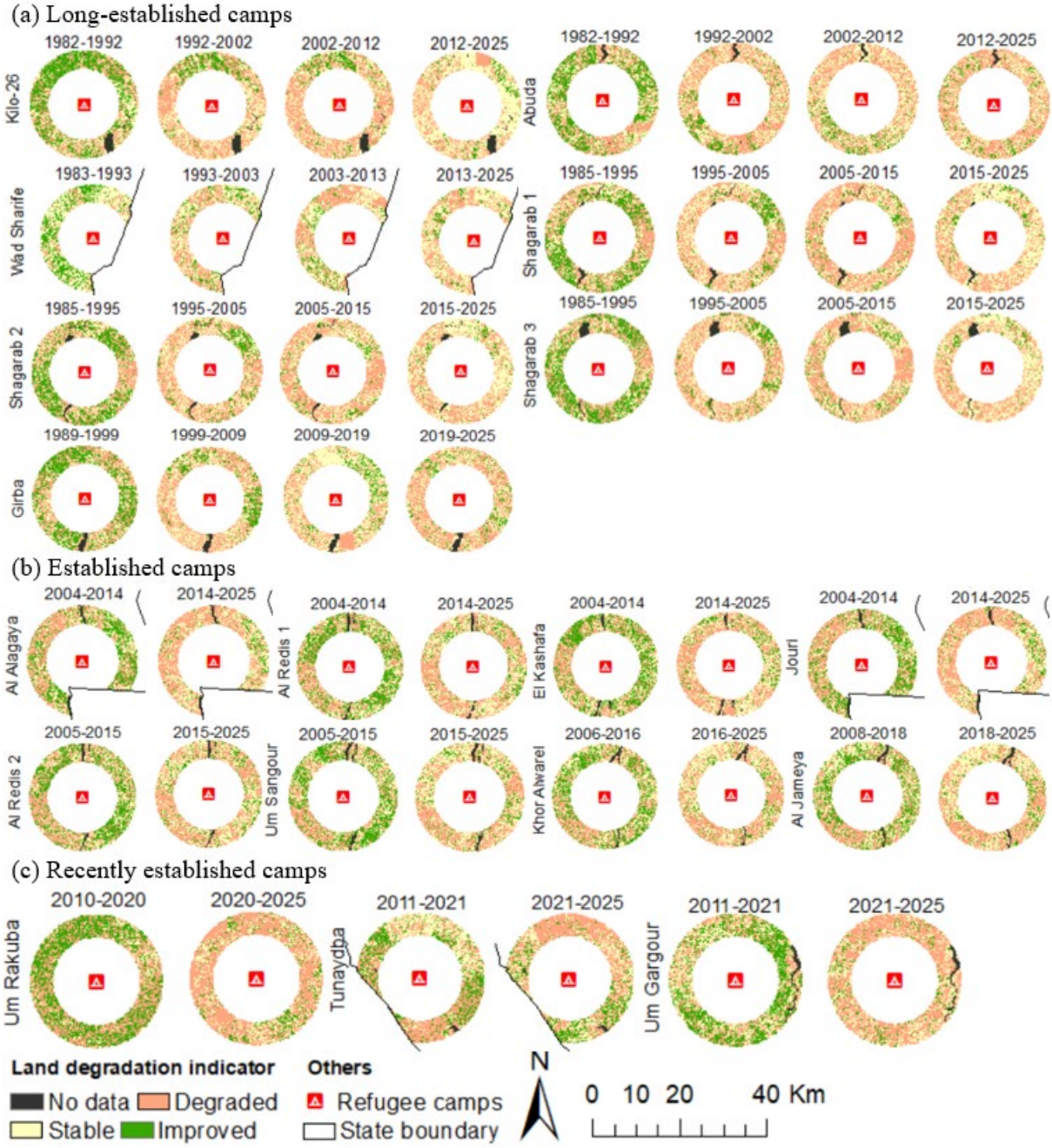


Figure 21. Land degradation status in the outer buffer zone (20–30 km) of refugee camps. See Figure 18 for other details.

Source: Authors' creation

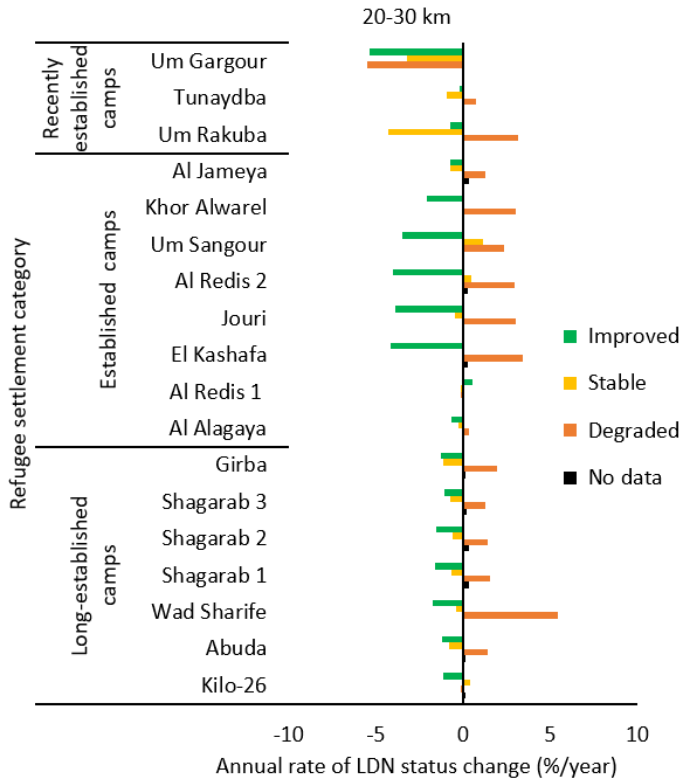


Figure 22. Annual rate of change in land degradation status in the outer zone (20–30 km). LDN refers to land degradation neutrality.
Source: Authors' creation

Variation across settlement categories within the peripheral buffer zone

In the peripheral buffer (30–50 km), the largest absolute extent of degraded land is observed (Figure 23; Figure 24). The long-established camps show massive cumulative increases (e.g., +102,000 ha in Abuda), accompanied by major losses of improved land. Established camps exhibit moderate increases (25–35%), while recently established camps show the highest proportional growth in degraded land (83–136%) and significant declines in improved land (44–74%). These patterns confirm that degradation expands outward and intensifies over time. The annual rate of LDN change in Figure 25 indicates that recently established camps are experiencing the highest rate of degradation (+9% per year) and a substantial decline in improved land (-11% per year).

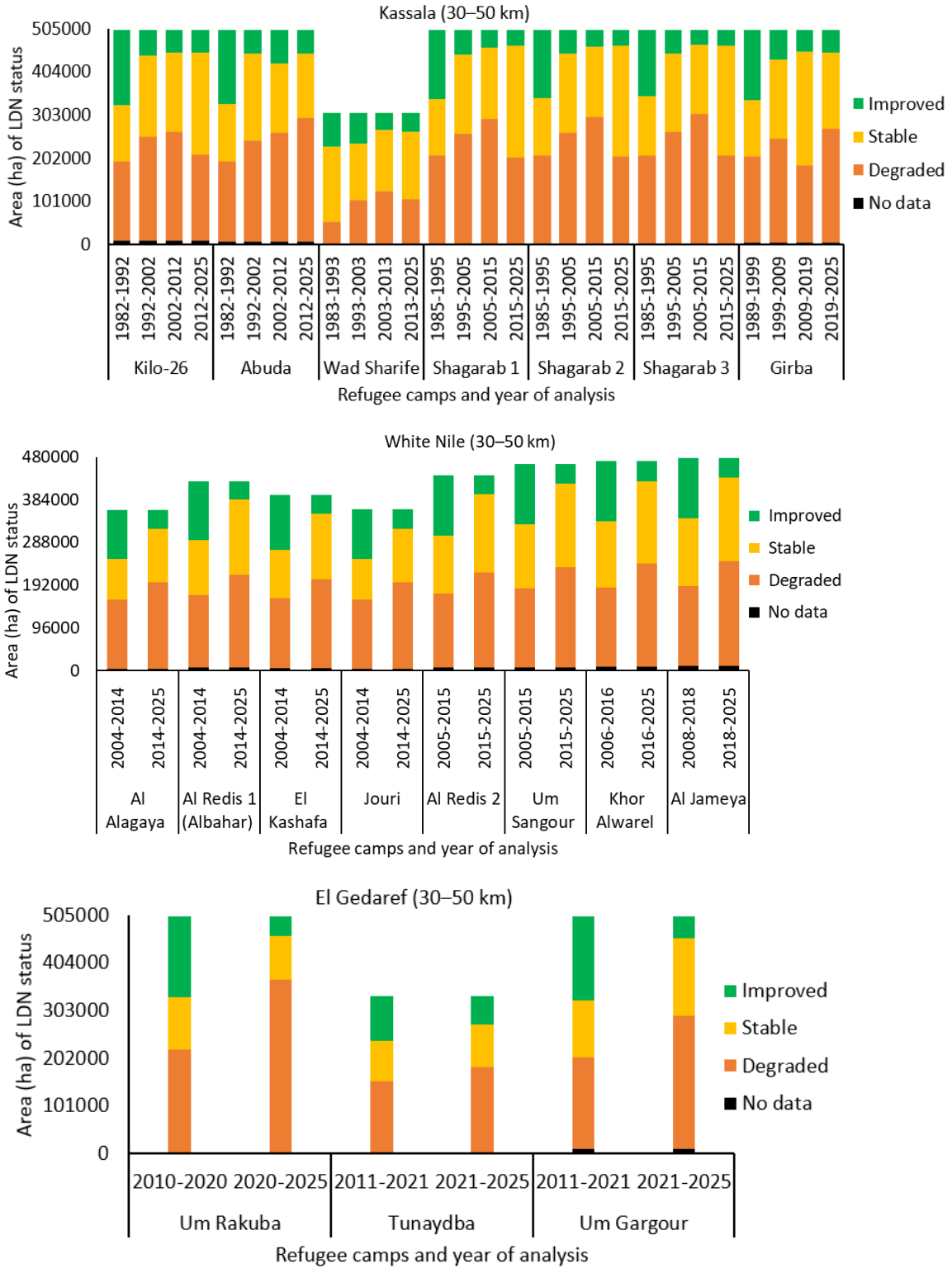


Figure 23. Land degradation neutrality in the peripheral zone (30–50 km). LDN refers to land degradation neutrality.
Source: Authors' creation

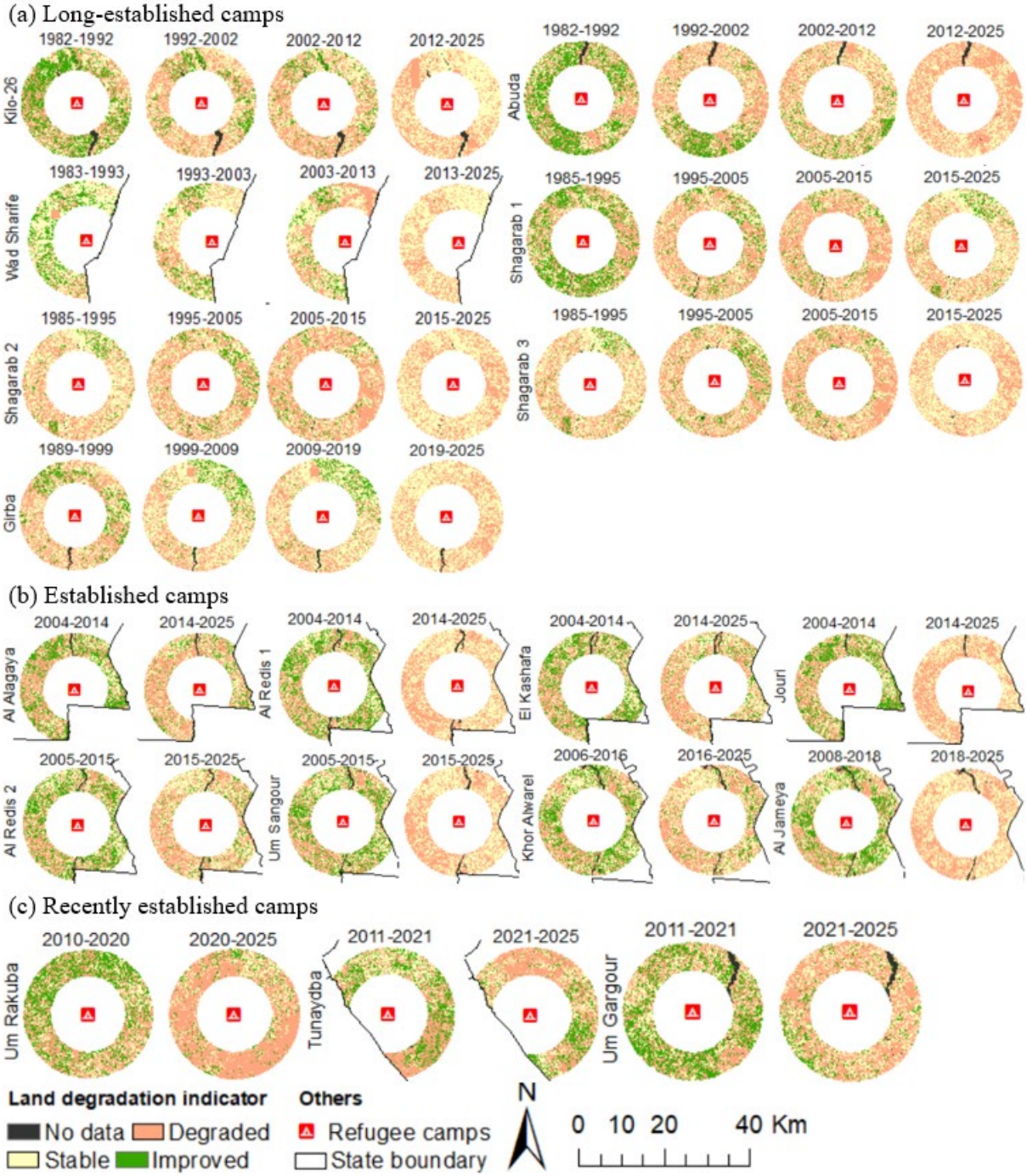


Figure 24. Land degradation status in the peripheral buffer zone (30–50 km) of refugee camps. See Figure 18 for other details.
Source: Authors' creation

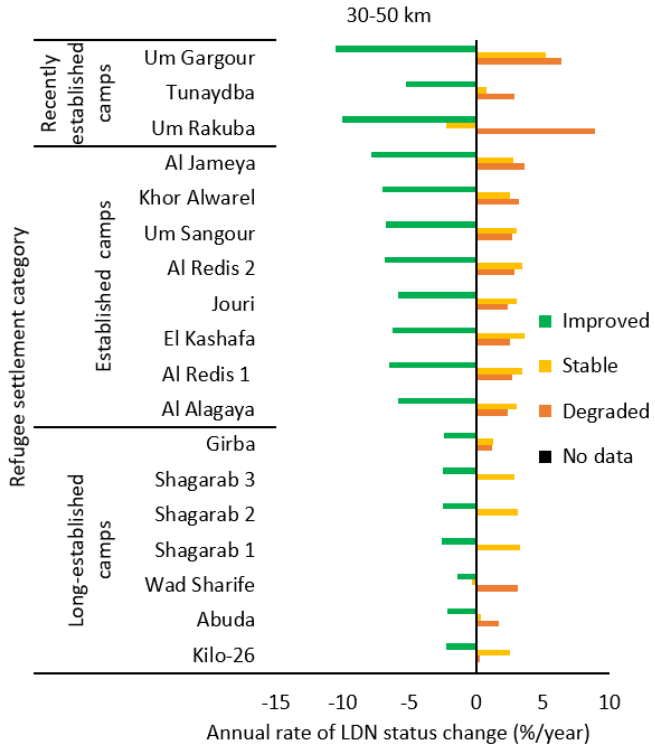


Figure 25. Annual rate of change in land degradation status in the peripheral zone (30–50 km). LDN refers to land degradation neutrality.
Source: Authors' creation

3.4. Integrated Insight

Integrating LULC and LDN reveals a tightly coupled nexus in which land conversion processes directly drive land degradation outcomes. Across all buffers and settlement categories, farmland expansion and settlement growth consistently replace natural vegetation and water resources, resulting in increased degraded land and declining stable and improved land (Figures 14–25). Two consistent patterns emerge: (i) temporal effect (settlement age): long-established camps exhibit the largest cumulative degradation, while recently established camps show the fastest rates of change; (ii) spatial effect (distance): both LULC transformation and land degradation expand outward from camp centers, increasing in spatial extent from inner to peripheral buffers. Together, these patterns indicate a progressive and spatially expanding degradation system, driven by sustained land conversion and reinforced over time.

4. Discussion

4.1. Patterns of LULC transformation around refugee settlements

The observed LULC trajectories indicate that refugee-hosting landscapes in Kassala, White Nile, and El Gedaref are undergoing a transition from semi-natural dryland mosaics toward more intensively used, human-dominated landscapes. The consistent expansion of farmland and settlement areas, together with the contraction of natural vegetation classes, suggests that refugee settlements operate not simply as isolated built-up enclaves, but as catalysts within broader land-use systems (Maystadt et al., 2020; Andualem et al., 2026). This transformation reflects the combined effects of shelter construction, livelihood adaptation, food production needs, biomass extraction and the reorganization of host-community land use around new population and market centres (Ssentongo et al., 2024). In this sense, the camps appear to function as focal points around which land demand is redistributed and intensified rather than as discrete sources of environmental change alone (Laird et al., 2022).

The implication is that environmental degradation in refugee-hosting areas should be understood as a process of landscape restructuring. Farmland expansion may contribute to short-term food and livelihood security, but when it occurs through conversion of shrubland, grassland, forest patches and water-associated habitats, it can reduce habitat continuity, degrade vegetation structure and weaken ecological resilience (Jellason et al., 2022). In dryland systems, where woody vegetation, seasonal grasslands and riparian resources play disproportionate roles in soil protection, fodder supply, microclimate regulation and hydrological functioning, such shifts can create long-term land-use lock-in (Wu et al., 2024; Yu et al., 2024). Once cultivation, settlement infrastructure and access routes become established, the landscape may follow a path of progressive intensification that is difficult to reverse without deliberate restoration and land-use governance (Birhanu et al., 2024)

This interpretation is consistent with wider evidence from African refugee-hosting areas showing that refugee-related vegetation change is often mediated through agricultural expansion rather than through a single pathway of direct biomass removal. Maystadt et al. (2020) and Salemi (2021) found that refugee presence across Africa was linked to increased risk of forest-to-cropland conversion, emphasizing that refugee–environment relationships are context-dependent and shaped by local land-use responses rather than by refugee presence alone.

4.2. Spatial Gradients of Environmental Pressure Across Buffer Zones

The buffer-zone analysis shows that environmental pressure is spatially extensive and diffuses outward from settlement cores into surrounding production and resource-use landscapes. Although the most immediate pressures are expected near camps, the results demonstrate that land conversion and degradation are not confined to the inner zone. Instead, changes extend through intermediate, outer and peripheral buffer zones, indicating that the environmental footprint of refugee settlements is shaped by the spatial range of

resource collection, cultivation, grazing, transport, market exchange and host-community responses (van Blerk et al., 2026).

This outward pattern matters because it challenges conventional planning assumptions that environmental mitigation can focus only on camp boundaries or nearby greenbelts. In practice, camps are embedded in functional landscapes that extend well beyond administrative or humanitarian site limits (Cavanagh, 2025). Fuelwood collection, livestock grazing, seasonal farming, informal settlement expansion and host-community land-use adjustments may all operate at distances far larger than the camp footprint itself (Walelign et al., 2022). Therefore, the relevant unit for environmental planning is not the camp alone, but the broader camp–host landscape. The strongest implication is that buffer-based planning must recognize nested pressure zones: an inner zone where direct settlement-related impacts are concentrated; an intermediate zone where agricultural and resource-use pressures intensify; and an outer/peripheral zone where cumulative land conversion may become visible at the landscape scale.

The finding also has implications for monitoring design. If remote-sensing assessments focus only on narrow buffers, they may underestimate the full environmental footprint of displacement. Conversely, if assessments use only broad administrative units, they may obscure localized gradients of change. A multi-buffer approach, therefore, provides a more policy-relevant way to identify where pressure is emerging, where it is accumulating, and where intervention should be prioritized. Literature from similar dryland refugee-hosting contexts also supports buffer-based assessment, with recent work in Ethiopia recommending that camp planning consider land degradation, erosion risk, water availability, and biodiversity within a defined influence zone before establishment (Mekuria et al., 2025).

4.3. Camp Age and Cumulative Versus Emerging Degradation

Because camp age in this study is closely aligned with geography and state, the contrasts among categories cannot be read as a function of elapsed time alone. They are more plausibly the product of camp age acting together with differences in landscape conditions, in the refugee policies and resources available at the time of establishment, and in host-location socioeconomic and governance contexts. The patterns described below are therefore best understood as suggestive of temporal dynamics rather than as a cleanly isolated effect of settlement age, and the degradation dynamics compared in what follows are offered as an interpretation of observed spatial patterns rather than as a direct causal attribution to age.

The contrast between long-established, established and recently established camps reveals two distinct but related degradation dynamics. Long-established camps show the legacy of cumulative transformation: decades of settlement, cultivation and resource extraction have produced landscapes where degradation is already spatially consolidated. In these cases, the major concern is not only ongoing change, but the persistence of degraded states and

the difficulty of restoring ecosystem function after long-term pressure. Long-establisehd camps, therefore, require interventions that address accumulated ecological debt, including restoration of vegetation cover, rehabilitation of degraded communal lands and long-term governance of resource-use zones.

Recently established camps, by contrast, show why early-stage degradation deserves urgent attention even when absolute transformation remains lower than in long-established camps. The high rates of change around newer settlements indicate that degradation can accelerate soon after camp establishment, particularly where planning, energy provision, livelihood support and environmental safeguards lag behind population arrival (Laird et al., 2022). This pattern implies that the first years after camp establishment are a critical intervention window. If environmental management is delayed until degradation becomes visually obvious or statistically dominant, restoration costs are likely to rise, and ecological recovery options may narrow (Waring, 2024).

This apparent temporal distinction remains important for humanitarian and environmental planning, even if it cannot be fully separated from the geographic and contextual differences noted above. Long-established camps require restorative and corrective measures, whereas recently established camps require preventive and anticipatory measures. In practice, this means environmental screening, energy alternatives, controlled resource-use zones and restoration planning should be integrated from the earliest stages of camp establishment, rather than introduced later as remedial projects (Dutta, 2024; Bildirici, 2026). The findings, therefore, support a shift from reactive environmental management to staged management based on camp age and degradation trajectory.

4.4. Linking LULC Change to LDN and Ecosystem-Service Decline

The combined LULC and LDN results show a tightly coupled relationship between land conversion and declining land condition. The expansion of farmland and settlements at the expense of natural vegetation and water-associated land-cover classes corresponds with increasing degraded land and declining stable and improved land (Mekonnen et al., 2018; Mekuria and Girma, 2025). This indicates that land-cover transformation is not merely a change in land category; it reflects a loss of ecological function and a movement away from the conditions required to maintain LDN (IUCN, 2015).

The implications for ecosystem services are substantial. Provisioning services are affected because the same vegetation and rangeland resources that support fuelwood, fodder, non-timber forest products and local food systems are reduced or fragmented (Petrosillo et al., 2023). Regulating services are affected because vegetation loss and soil exposure can weaken erosion control, infiltration, local water regulation and microclimatic buffering (Wu et al., 2020). Supporting services are affected because changes in vegetation structure and soil condition can reduce habitat quality, nutrient cycling and the regenerative capacity of dryland ecosystems (Quoreshi et al., 2022). These linkages are especially important in refugee-hosting drylands, where livelihoods and ecological resilience depend heavily on sparse but functionally important biomass and seasonal water resources (Wang et al., 2024).

This interpretation aligns with the UNCCD framing of LDN as maintaining or increasing the quantity and quality of land resources needed to support ecosystem functions and services within defined spatial and temporal scales (Orr et al., 2017). In the Sudan case, declining stable and improved land suggests that environmental change around camps is not only a local conservation concern but also a land-system sustainability issue (Mekuria et al., 2026). The results, therefore, connect refugee-hosting landscapes directly to SDG 15.3 and show that humanitarian settlement planning can influence whether dryland regions move toward or away from LDN.

4.5. Drivers of Degradation in Refugee-Hosting Landscapes

The results imply that degradation is driven by interacting proximate and underlying factors. Proximate drivers include farmland expansion, settlement growth, vegetation removal, fuelwood demand, grazing pressure and the conversion of natural land-cover classes into cultivated or built-up areas. These are the direct land-use processes through which environmental pressure becomes visible in remote-sensing indicators. Their repeated occurrence across states, buffers and settlement-age categories indicates that degradation is not an isolated site-specific anomaly but part of a wider land-use response to displacement and resource demand (Ahmed et al., 2024). It is important, however, to be explicit about what these methods can and cannot establish: the remote-sensing analysis identifies spatial associations and land-use and degradation patterns around refugee-hosting landscapes, but it cannot attribute the observed changes specifically to refugees, nor empirically partition the relative contributions of refugee-related pressures, host-community land use, agricultural expansion, market dynamics, conflict and governance conditions. This caution is particularly

important in Sudan's conflict-affected setting, and it keeps the policy message constructive by directing attention to shared resource systems rather than to refugee presence alone.

Underlying drivers include population concentration, limited livelihood options, dependence on biomass energy, weak environmental governance, fragile dryland biophysical conditions and the broader conflict context in Sudan (UN-Habitat, 2022). The introduction of large and often protracted populations into arid and semi-arid landscapes increases demand for land, water, fuel and construction materials. Where formal resource management and environmental regulation are weak, these pressures are more likely to translate into unplanned extraction, agricultural encroachment and degradation feedback (Laird et al., 2022). The draft introduction already identifies Sudan’s refugee-hosting areas as environmentally fragile and governance-constrained, and links conflict, displacement and resource scarcity to reinforcing vulnerability (Ahmed et al., 2024; Ali, 2024)

Building on this caution, a key implication is that refugees should not be framed as the sole agents of degradation. Rather, degradation emerges from the interaction between displaced populations, host-community needs, humanitarian settlement models, market incentives, governance capacity and pre-existing ecological vulnerability (Bose, 2024). This distinction matters because it shifts policy responses away from blaming refugee presence and toward managing shared resource systems (Tafere, 2018). The broader literature supports this caution: continental-scale evidence finds that refugee-related environmental outcomes vary by context and are often mediated through agricultural expansion, governance and local economic conditions rather than by refugee population alone (Dutta, 2024; Bildirici, 2026).

4.6. Broader Implications for Camp Siting, Buffer Planning and Restoration in Refugee-Hosting Drylands

The findings highlight that environmental impacts of refugee settlements are spatially diffuse and extend beyond camp boundaries into wider camp–host landscapes. Land-use change and degradation expand outward across buffer zones, indicating that camps should be planned and managed as part of larger socio-ecological systems rather than isolated sites.

First, environmental screening should precede camp establishment and consider the broader resource-use landscape. Assessments should include vegetation condition, water availability, erosion risk, agricultural pressure, grazing routes, restoration potential and host-community vulnerability. This is critical in fragile drylands where small ecological changes can have large

impacts on stability and livelihoods.

Second, buffer-based management should be institutionalized. Different zones require tailored interventions: inner zones need settlement greening, controlled fuelwood use and waste management; intermediate zones require agroforestry, woodlots, sustainable grazing and regulated expansion; outer and peripheral zones require landscape restoration, watershed management and monitoring of cumulative land conversion. This approach better captures the spatial distribution of environmental pressure.

Third, restoration should start early and align with camp age. Recently established camps require preventive measures such as woodlots, assisted natural regeneration, alternative energy and soil and water conservation. Long-established camps require rehabilitation of degraded lands, restoration of ecological corridors and negotiated land-use planning. Nature-based solutions that combine ecological recovery with livelihood benefits—such as agroforestry and community fuelwood systems—are particularly relevant (Mekuria et al., 2026). These align with LDN principles of avoiding, reducing and reversing degradation (Orr et al., 2017).

The results also show that LULC change and LDN should be interpreted together. While land conversion may reflect livelihood adaptation, it often reduces ecosystem function and resilience. Integrating both indicators helps distinguish adaptive land use from degradation.

These insights extend beyond Sudan to other refugee-hosting drylands with similar characteristics. In particular, they align closely with related IWMI research in the refugee-hosting drylands of Ethiopia's Somali Region, where settlement and farmland expansion similarly replaced forests, shrublands, grasslands and water bodies, soil erosion intensified, and degraded land expanded outward from camp cores—leading to the same recommendation to assess land degradation, erosion risk, water availability and biodiversity within a defined influence zone before camp establishment (Mekuria et al., 2024, 2025). What appears common across both settings is the outward, buffer-wide loss of natural vegetation and ecosystem function around protracted camps; what is more context-specific to Sudan is the pronounced camp-age gradient and the active-conflict setting, whereas the Ethiopian cases unfold in a predominantly pastoral, drought-prone context shaped by rangeland use and invasive species. They underscore the need to integrate environmental safeguards from the outset and to link ecological resilience with human security. At the same time, impacts are context-specific: refugee presence interacts with governance, markets and

local land-use systems in different ways. Rather than assuming a universal refugee–degradation relationship, the findings show that in fragile settings with weak governance, displacement can amplify existing pressures and accelerate movement away from land degradation neutrality.

4.7. Limitations and Need for Integrated Socio-Ecological Monitoring

The analysis provides strong spatial evidence of LULC transformation and LDN decline, but LULC and LDN indicators alone cannot fully explain causality, livelihood decision-making or governance processes. Remote-sensing products capture where land-cover and degradation changes occur, but they do not directly identify who drives specific changes, how land-use decisions are negotiated, how host and refugee communities differ in resource access, or how humanitarian policies shape extraction and cultivation. They also cannot fully capture seasonal resource use, informal tenure arrangements, fuelwood supply chains, local conflict dynamics or the quality of restoration interventions.

Future monitoring should therefore integrate biophysical and socio-economic evidence. At minimum, this would include repeated high-resolution LULC and LDN monitoring, field validation, vegetation and soil condition surveys, household energy-use data, livelihood and land-access assessments, governance mapping, and participatory resource-use mapping with both refugees and host communities. Such an integrated socio-ecological monitoring system would help distinguish proximate land-cover changes from underlying institutional and livelihood drivers, and would allow early warning when recently established camps begin to show accelerating degradation.

The main implication is that environmental audit, safeguards planning, and monitoring should become complementary, routine elements of refugee-settlement planning and management, rather than an occasional post-impact assessment. Environmental audits and a safeguards plan should guide decisions both before settlement establishment or expansion—informing siting and design—and throughout ongoing management, while monitoring tracks change over time. Linking satellite-based indicators with field and governance data would enable more adaptive decisions: where to prioritize restoration, where to regulate land conversion, where energy alternatives are most urgent, and where host-community resource systems need support. In this way, combining audit, safeguards, and monitoring can move beyond

documenting degradation toward enabling prevention, restoration and more resilient refugee-hosting landscapes in Sudan and comparable dryland regions.

5. Conclusion

Overall, the results demonstrate a consistent and reinforcing nexus between LULC change and land degradation across all buffer zones and settlement categories. Farmland expansion and settlement growth emerge as the dominant land transformations, systematically replacing forest, grassland, shrubland, and waterbodies, and strongly associated with the expansion of degraded land. Two key gradients define this nexus: a temporal gradient, in which the magnitude of change increases with settlement age (long-established > established > recently established), and a spatial gradient, in which both land conversion and degradation intensify outward from camp centres (0–10 km to 30–50 km). While the long-established camps exhibit the largest cumulative environmental changes, the most rapid rates of change occur in recently established camps, indicating accelerating early-stage degradation. Across all contexts, stable and improved lands consistently decline, confirming a persistent trajectory away from land degradation neutrality. It should be emphasized, however, that these spatial LULC and LDN patterns indicate strong associations rather than established causation: remote-sensing indicators reveal where land-cover and degradation changes occur but cannot, on their own, identify who drives them or disentangle the underlying livelihood, institutional, governance, and humanitarian-policy processes involved. Attributing causality will therefore require integrating this biophysical evidence with socio-economic and governance data.

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