DOCTORAL (PhD) DISSERTATION

University of Sopron

Roth Gyula Doctoral School of Forestry and Game Management

Geospatial Assessment of Vegetation Recovery, Climate Variability, and Ecosystem Services in Conflict-Displaced Landscapes

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1 Background

1.1 Conflict Background

The Darfur region of western Sudan has been a focal point of conflict and humanitarian crises since the early 2000s. Driven primarily by ethnic tensions, political marginalization, and competition over scarce resources, the conflict has displaced millions and caused profound environmental degradation (N. Solomon et al., 2018a). Often described as the "first genocide of the twenty-first century," the Darfur conflict since 2003 has led to mass displacement, with hundreds of thousands seeking refuge within Sudan and neighboring Chad (Behrends, 2024).

The roots of this violence are deeply embedded in socio-political dynamics, notably the deliberate targeting of essential resources, such as food and water, as tools of war and displacement (Hagan & Kaiser, 2011). Janjaweed militias, supported by elements of the Sudanese government, have been implicated in systematic attacks on civilian populations, contributing to the displacement of approximately 2.7 million individuals (Birech, 2009). The resulting sociopolitical instability has amplified vulnerabilities, leading to unsustainable resource management practices, as displaced communities increasingly depend on the overexploitation of local natural environments (Young & Ismail, 2019).

1.2 Impact on Internally Displaced Persons (IDPs)

IDPs in Darfur remain among the most vulnerable groups globally, facing acute protection gaps due to the absence of binding international legal frameworks (Islam, 2006). Unlike refugees, IDPs lack safeguards enshrined in international refugee law, leaving their welfare largely contingent on national capacity and political will.

Conflict-induced displacement has directly accelerated environmental degradation across Darfur. Extensive research has indicated that warfare-driven land cover changes contribute to increased desertification, deforestation, and soil erosion (Brendan, 2008). Violence frequently results in the destruction of agricultural fields and the decimation of livestock populations, undermining food security and altering local ecological equilibria (FAO, 2023). Remote sensing analyses have captured significant shifts in land use patterns, highlighting the conversion of former agricultural zones into barren or scrubland ecosystems (Kyrpychova et al., 2024).

As of 2024, Sudan is home to one of the world's largest IDP populations, exceeding 10.4 million people which is exacerbated by the resurgence of conflict and environmental stresses (ACAP, 2023; OCHA, 2024). The current displacement crisis, claiming more than 5,000 lives, has heightened anthropogenic pressure around IDP camps, with dense population concentrations accelerating vegetation loss and resource depletion (Hagenlocher et al., 2012). Persistent droughts, rainfall variability, and socioeconomic instability are critical global hotspots for land degradation and the environment (Akasha, 2013; Almulhim et al., 2024; Hardt & Brief, 2019; Kranz et al., 2015; Younis et al., 2022). Furthermore, the degradation of natural resources exacerbates competition among displaced and host communities, reinforcing cycles of violence and undermining efforts toward durable peace (OCHA, 2023; N. Solomon et al., 2018b; Xie et al., 2024). Thus, understanding the dynamic interplay between vegetation loss, climate variability, and conflict-induced displacement is essential for effective humanitarian and environmental interventions.

Despite international efforts, including the Juba Peace Agreement, durable peace remains elusive. The international community’s response has been criticized as insufficient, with peacekeeping missions operating below authorized capacities and financial resources often falling short (Barltrop, 2010; Foerstel, 2010; Samah, 2022). Geopolitical considerations, including the strategic interests of international actors such as China, further complicate this situation (Foerstel, 2010).

1.3 Prospects for Peace and Reconciliation

Resolving Darfur conflict requires an integrated approach that balances justice, reconciliation, and sustainable development. Traditional conflict resolution mechanisms, that emphasize community-based dialogue and trust-building, have been proposed to facilitate the voluntary return or local integration of displaced people (Birech, 2009). However, persistent insecurity continues to impede these initiatives.

Recent escalations, notably the April 2023 conflict between the Sudanese Armed Forces (SAF) and Rapid Support Forces (RSF), have further displaced more than eight million individuals internally, alongside 3.9 million refugees seeking safety abroad (USCRI, 2025). This unprecedented displacement underscores the urgent need for durable solutions that incorporate the perspectives of the affected populations. Studies indicate that many IDPs express a preference for local resettlement over returning to their places of origin, reflecting the complex considerations of security, livelihoods, and social cohesion (Yagub, 2019). Therefore, a comprehensive peace framework must consider not only political settlements but also environmental recovery and livelihood restoration as foundational pillars for long-term stability.

1.4 Climate Change and Environmental Stressors

Climate change has emerged as a fundamental driver exacerbating existing vulnerabilities in conflict-affected regions. It has profound impacts on ecosystems, agriculture, water availability, and human health, particularly in developing countries that already have socio-economic and institutional weaknesses (Füssel, 2009; Kikstra et al., 2022; S. Solomon et al., 2007).

Africa, particularly the Sahel region, is on the frontline of climate change. Rising temperatures, declining precipitation, frequent droughts, and increasing desertification are projected to intensify, and the Intergovernmental Panel on Climate Change (IPCC) forecasts that temperature increases in the Sahel will exceed global averages (Osman et al., 2021; Yvonne et al., 2020).

Sudan's exposure to these climatic risks is compounded by endemic poverty, weak governance structures, limited adaptive capacities, and ongoing conflicts (Hamadalnel et al., 2022). These challenges significantly constrain the resilience of the local populations and ecosystems. Recent studies have demonstrated that strategic land management interventions and shifts in precipitation patterns can support vegetation regeneration and ecological restoration in degraded landscapes (Elhag & Walker, 2009; Nzabarinda et al., 2021). Therefore, understanding the interconnectedness between climate variability, land use changes, and ecological recovery is critical for designing integrated approaches for building resilience, sustainable development, and post-conflict reconstruction.

2 Research objectives

1. To quantify and analyze land use and land cover (LULC) changes in Darfur using multi-sensor remote sensing data.

2. To evaluate the spatial and temporal dynamics of vegetation cover using the NDVI/EVI time-series and their relationships with climate trends.

3. To assess the impact of IDPs on vegetation dynamics and land use transitions using spatial overlays.

4. To analyze drought patterns and their influence on vegetation and ecosystem resilience using Standardized Precipitation Evapotranspiration Index (SPEI-6 and SPEI-12) timescales.

5. To forecast future land cover changes under business-as-usual (BAU) scenarios using CA-Markov modeling.

6. Estimate ecosystem service values (ESVs) across different LULC classes and evaluate the impact of LULC changes on service provisioning.

3. Research Methods

In this study a multidisciplinary design was employed (Figure 1), incorporating remote sensing technologies, machine learning algorithms, ecosystem service valuation, spatial simulation, and climate forecasting to deliver a comprehensive ecological assessment of the region between 1981 and 2034. Key methodological highlights include:

- High-resolution remote sensing datasets (MODIS, Sentinel-2, PlanetScope, and ESRI LULC) were used to analyze vegetation dynamics and land degradation across scales.

- Deployment of CA-Markov modeling to simulate future LULC changes under a BAU scenario.

- Application of NDVI, EVI, and SPEI to track vegetation-climate interactions and drought trends over time.

- Valuation of ESVs using benefit transfer methods to capture the economic implications of land cover transitions.

- Integration of climate forecasting tools (ARIMA and ETS) to project future rainfall and temperature dynamics.

- Spatial pattern and fragmentation analyses were performed using landscape metrics (LPI, Patch Density, Edge Density) to assess ecological stability and connectivity.

- Sensitivity analysis and model validation techniques were applied to ensure the accuracy and robustness of the models and findings.

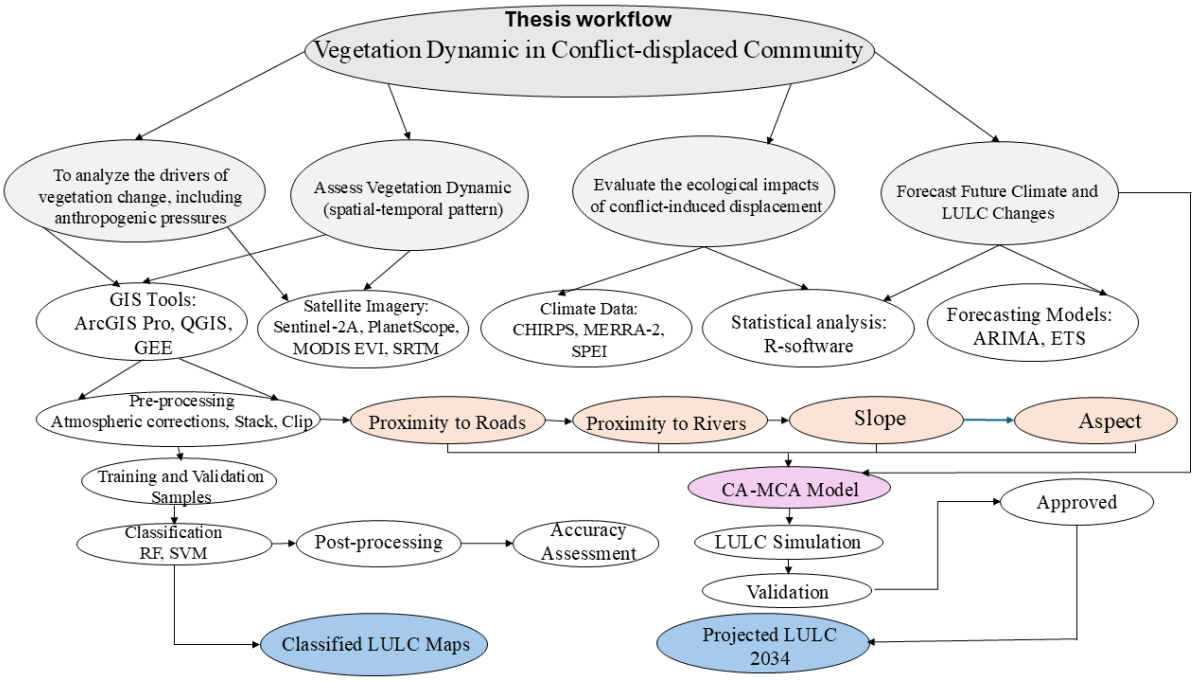

Figure 1. Methodology Framework

4 New Scientific Results

This research introduces several novel scientific contributions to the fields of environmental monitoring, land use dynamics, and post-conflict ecological assessment in arid and semi-arid landscapes. By integrating the spatial, temporal, and socio-ecological dimensions, this study offers innovative methods and context-specific findings that advance current knowledge and inform policy and practice in fragile environments (Figure 2).

1. Multiscale Integration of Remote Sensing Platforms

This is the first study in the region to employ a synergistic integration of MODIS (250 m), Sentinel-2 (10 m), PlanetScope (3 m), and ESRI global land cover datasets to analyze vegetation dynamics and LULC transitions. This multi resolution fusion enabled the detection of both large-scale trends and fine-grained local changes, overcoming the limitations of single-sensor studies. It enhances classification accuracy, facilitates temporal continuity, and provides robust spatial context for ecosystem monitoring in complex socio-ecological settings.

2. First CA-Markov LULC Projection for Central Darfur

This study presents the first spatially explicit LULC simulation for Central Darfur, using the CA-Markov modeling. Forecasts to 2034 indicate the continued expansion of grasslands and forest cover under a business-as-usual scenario, alongside a projected decline in cropland. This predictive modeling offers a valuable planning tool for land managers, conservationists, and policymakers to anticipate ecological outcomes in data-scarce conflict-affected regions.

3. Quantitative Drought-Vegetation Coupling via SPEI and BFAST

By combining SPEI with the BFAST algorithm, this study introduces an innovative method to identify abrupt vegetation responses to climatic shocks. This approach revealed strong temporal alignments between major drought episodes (e.g., 1984, 1990, 2010) and NDVI breakpoints, providing a powerful tool for detecting ecosystem vulnerability and resilience thresholds.

4. New Evidence Linking IDP Dynamics and Vegetation Recovery

This study challenges the prevailing narrative that displacement leads to environmental degradation. Instead, it provides empirical evidence that in post-conflict settings, IDP communities, when supported by improved rainfall, reforestation, and agroecological initiatives, can contribute to vegetation recovery and ecosystem restoration. This finding underscores the potential of conflict-sensitive land use planning and community-based adaptation.

5. First ESV in Conflict-Affected Darfur

This study conducted the first ESV assessment in Darfur using benefit-transfer methods linked to LULC classifications. The results revealed a dual pattern: an increase in regulating services due to forest and grassland gains, and a concurrent decline in provisioning services resulting from cropland reduction. This nuanced insight enhances our understanding of ecological trade-offs and informs integrated land restoration strategies in post-disaster settings.

These novel findings provide essential contributions to the global literature on land degradation neutrality, environmental resilience in post-conflict zones, and the application of Earth observation technologies to humanitarian landscapes. They also established a methodological foundation for future research in similarly fragile contexts across Africa and beyond.

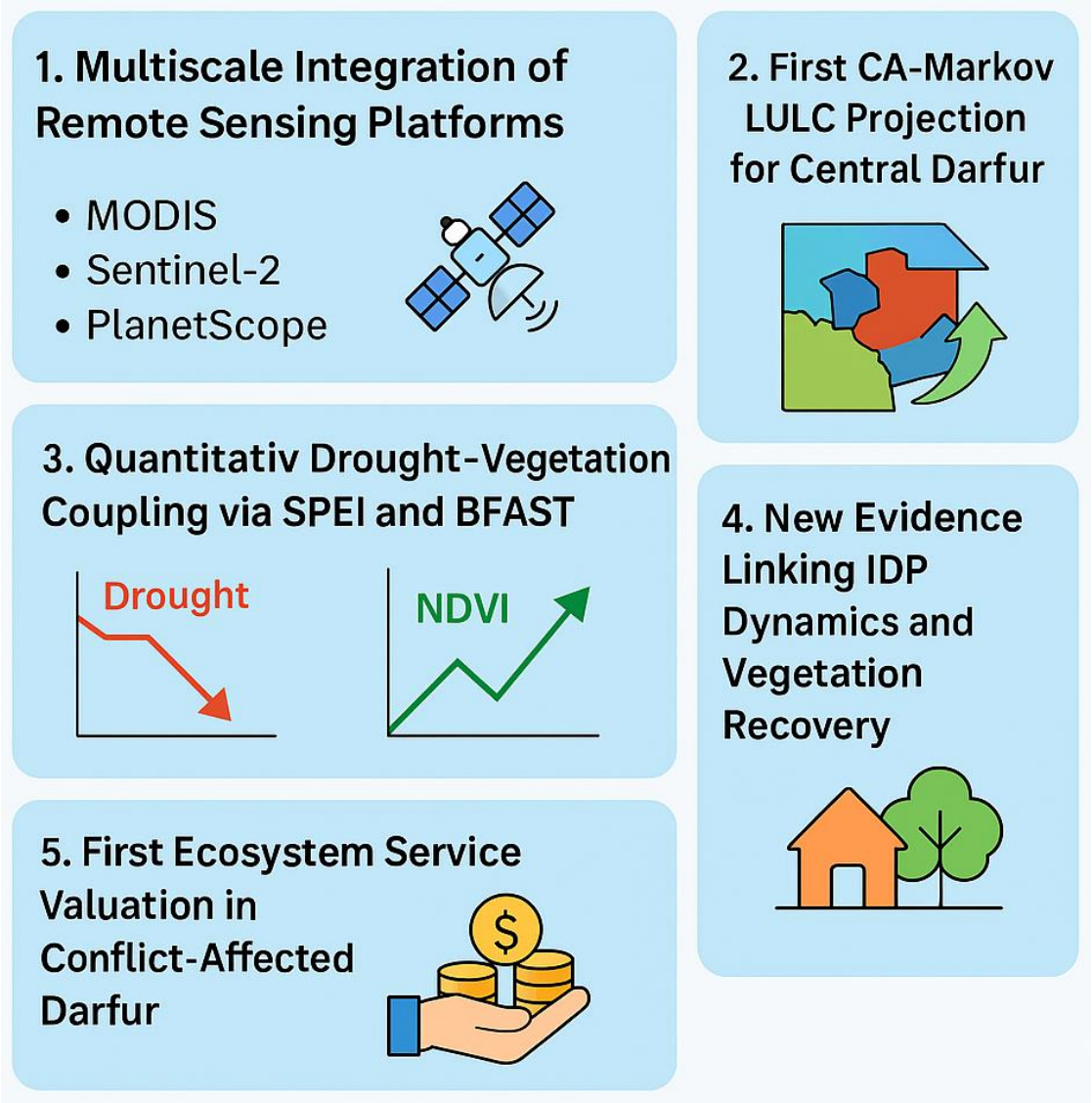

Figure 2. The New Scientific Findings Graphical Map.

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