DOCTORAL (PhD) DISSERTATION

University of Sopron

Roth Gyula Doctoral School of Forestry and Wildlife Management Sciences

Understanding and Predicting the Potential Impacts of Climate Changes and Anthropogenic Drivers on Savanna Ecosystems

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1. Introduction

Climate change is a major global driver of ecosystem transformation, profoundly altering species distributions, vegetation structure, and ecological processes (IPCC, 2022; Yasin et al., 2024; Musa et al., 2024). Over the past century, global temperatures have increased by approximately 0.74 °C, with accelerated warming since the mid-1970s exceeding that of any comparable period in the last millennium (IPCC, 2022; Zohrabi et al., 2014; Babatolu & Akinnubi, 2013). Minimum temperatures are rising faster than maximum temperatures in many regions, increasing stress on species with narrow thermal tolerances (Hughes et al., 2003; Guan et al., 2015; Yasin et al., 2025). At the same time, atmospheric CO_2 concentrations have increased by nearly 100 ppm above pre-industrial levels, affecting plant physiology and ecosystem functioning (IPCC, 2014; IPCC, 2022; Coleine et al., 2024).

In addition to climatic changes, ecosystems are increasingly exposed to anthropogenic pressures such as agricultural expansion, deforestation, overgrazing, and habitat fragmentation, which reduce ecosystem resilience and adaptive capacity (Jump & Peñuelas, 2005; Musa & Sahoo, 2023; Abuelbashar et al., 2022). The interaction between climatic and human-induced stressors amplifies ecological vulnerability, with up to 30% of global species projected to face elevated extinction risk under combined pressures (Maclean & Wilson, 2011; Musa et al., 2024; Yasin & Mulyana, 2022).

Savanna ecosystems are particularly sensitive to these interacting drivers due to their structural heterogeneity, climatic variability, and ecological constraints (Colwell et al., 2008; Deutsch et al., 2008; Yasin et al., 2024). In Africa, savannas form extensive transitional landscapes between deserts and tropical forests and provide essential ecosystem services, including biodiversity conservation, carbon storage, soil stabilization, and livelihood support (Harrison & Jackson, 1958; Fahmi, 2017; Siddig et al., 2018; Musa & Sahoo, 2023; Yasin & Mulyana, 2022).

In Sudan, savanna ecosystems are structured by rainfall gradients, soil properties, fire regimes, and human activities, resulting in strong spatial variability in species composition (Fahmi, 2017; Musa et al., 2024; Gurashi et al., 2024). Drought-tolerant species dominate northern zones, while mesic southern regions support diverse woody species, including *Acacia seyal*, *Combretum hartmannianum*, and *Anogeissus leiocarpus* (Ibrahim & Osman, 2014; Yasin et al., 2024; Musa et al., 2024).

However, Sudanese savannas are increasingly undergoing degradation driven by rising temperatures, rainfall variability, and prolonged droughts, which affect tree growth, mortality, and regeneration (Fahmi, 2017; D'Odorico & Bhattachan, 2012; Yasin et al., 2025). These climatic stressors, combined with anthropogenic pressures such as deforestation and land-use expansion, lead to reduced woody cover, altered species composition, and declining ecosystem functionality (Smith et al., 2019; Musa et al., 2024; Coleine et al., 2024). Despite their importance, these ecosystems remain underrepresented in integrated climate impact assessments (Musa et al., 2024; Coleine et al., 2024).

A major limitation is the lack of spatially explicit and long-term integrated studies that simultaneously address climate variability, land-use change, vegetation dynamics, and species-level responses. Existing research is often fragmented and rarely incorporates socio-economic and policy dimensions (Abuelbashar et al., 2022; Fahmi, 2017; Lu et al., 2023; Musa et al., 2024; Hemida et al., 2023).

Recent advances in remote sensing and machine learning provide powerful tools to overcome these limitations. Multi-temporal satellite data enable large-scale monitoring of vegetation dynamics, while algorithms such as Random Forest (RF), Support Vector Machine (SVM), and Classification and Regression Trees (CART) support robust modeling of complex ecological relationships (Gorelick et al., 2017; Huete et al., 2002; Belgiu & Drăguţ, 2016; Pal, 2005; Raczko & Zagajewski, 2017). In addition, species distribution models (SDMs) enable prediction of species responses to future climate scenarios and identification of climate refugia (Moss et al., 2010; Ludwig et al., 2013; Yasin et al., 2024; Coleine et al., 2024).

However, the application of these approaches in Sudan remains limited, with few studies integrating climate analysis, land-use dynamics, ecological data, machine learning, and species distribution modeling within a unified framework.

Therefore, this study develops an integrated analytical framework to assess the combined impacts of climatic variability and anthropogenic pressures on Sudanese savanna ecosystems. This framework provides a robust scientific basis for conservation planning, adaptive management, and climate change mitigation strategies.

1.1. General Objective

The general objective of this study is to understand and predict the combined impacts of climatic variability and anthropogenic pressures on savanna ecosystems in Sudan by integrating climate analysis, land use/land cover dynamics, field-based ecological assessment, and geospatial machine learning approaches.

This study addresses the following specific objectives:

1. To analyze the long-term climatic variability, trends, and drought patterns in savanna woodlands of southeastern Sudan.
2. To assess the spatio-temporal land use/land cover (LULC) changes and their interactions with climatic variability.
3. To evaluate the changes in woody species composition, diversity, and regeneration in response to climatic variability and anthropogenic pressures.
4. To map the dominant tree species using multi-source remote sensing data and machine learning approaches.
5. To model and predict the current and future potential distribution of Acacia seyal (Delile) under different climate change scenarios.

2. Literature Review

The literature review includes scientific studies related to the main themes addressed in this thesis, including Sudanese savanna ecosystems, climate variability and drought, land use/land cover (LULC) dynamics, vegetation monitoring and modeling, remote sensing and Machine Learning applications, species distribution modeling, and sustainable management and climate adaptation strategies.

3. Research Methodology

3.1. Study Area

The study was conducted in Sudan, with a focus on Blue Nile State and the Elnour Natural Forest Reserve (ENFR). Sudan exhibits strong climatic and ecological gradients, ranging from hyper-arid conditions in the north to semi-humid savanna ecosystems in the south, which strongly influence vegetation distribution and ecosystem dynamics. Blue Nile State, located in southeastern Sudan, represents a transitional zone characterized by a tropical savanna climate with a distinct wet season (April–November) and dry season (December–March), annual rainfall ranging from 300 to 700 mm, and generally high temperatures. ENFR, situated within Blue Nile State, is a low-rainfall woodland savanna established for biodiversity conservation, covering approximately 4,667 ha. The reserve supports diverse woody vegetation dominated by species such as *Acacia seyal (*Delile*)*, *Combretum hartmannianum*, and *Anogeissus leiocarpus*. The area is influenced by surrounding communities through grazing and resource use, contributing to ongoing vegetation change and degradation processes.

3.2 Data Collection

- This study integrated remote sensing data, field observations, climatic datasets, and species occurrence records to assess the impacts of climatic variability and anthropogenic pressures on savanna ecosystems.
- Long-term climate data, including rainfall and temperature, were obtained from the Climatic Research Unit (CRU) dataset and complemented with station observations from the Sudan Meteorological Authority to ensure data reliability and regional consistency. Future climate projections were derived from CMIP6 datasets for scenario-based analysis.
- Multi-temporal satellite imagery from Landsat 5 Thematic Mapper (2008), Landsat 8 Operational Land Imager (2013), and Sentinel-2 Multispectral Instrument (2018 and 2021) was acquired through Google Earth Engine for different reference years to analyze land use/land cover dynamics and vegetation patterns.
- Field data were collected from 229 permanent sample plots established in the Elnour Natural Forest Reserve, where measurements of species composition, tree diameter, height, and regeneration status were recorded during surveys conducted in 2008 and revisited in 2013, 2018, and 2021.
- In addition, environmental variables, including bioclimatic data, soil properties, and elevation, were obtained from global datasets such as WorldClim and SoilGrids to support species distribution modeling. Occurrence records of *Acacia seyal* were compiled from field surveys,

national forest inventories, biodiversity databases, and published studies. These records were standardized and filtered to ensure spatial accuracy and reduce sampling bias.

3.3 Data Analysis

- Data processing and analysis were carried out using a combination of cloud-based platforms, geographic information systems, statistical software, and modeling tools. Climate data were analyzed using Google Earth Engine, R, Statistica, and Microsoft Excel to assess variability, trends, and drought characteristics through the application of the Mann–Kendall test, Sen's slope estimator, and the Standardized Precipitation Evapotranspiration Index (SPEI).
- Satellite imagery was preprocessed and analyzed in Google Earth Engine to generate land use/land cover maps through supervised classification techniques, primarily using the Random Forest algorithm. Change detection and transition analysis were conducted to quantify spatio-temporal landscape dynamics, while accuracy assessment was performed using standard classification metrics.
- Field-based ecological data were analyzed using R, Statistica, and Excel to evaluate species composition, diversity, stand structure, and regeneration status through the application of standard phytosociological and biodiversity indices.
- For tree species mapping, Machine Learning algorithms, including Random Forest, Support Vector Machine, Classification and Regression Trees, and ensemble approaches, were implemented within Google Earth Engine to classify dominant species and assess model performance.
- Species distribution modeling was conducted using the MaxEnt model to predict the current and future distribution of *Acacia seyal* (Deliel). Environmental variables were screened for multicollinearity, and model performance was evaluated using AUC and TSS metrics. Future projections were generated under different climate change scenarios (SSP2–4.5 and SSP5–8.5), and habitat suitability maps were produced to identify potential climate refugia and vulnerable areas.

4. New Scientific Results

This dissertation presents original scientific contributions to understanding land degradation processes, biodiversity dynamics, forest structural change, and climate-driven species distribution in Sudanese savanna ecosystems. These findings are derived from an integrated multi-scale framework combining climate analysis, remote sensing, field observations, and modeling approaches, and are summarized as follows:

4.1. Climate–Drought Mechanism

I demonstrate that drought dynamics in Sudanese savannas are primarily driven by increasing temperature and rainfall variability rather than by total precipitation alone. I quantify how rising temperatures enhance evaporative demand, intensifying moisture stress even under stable or slightly increasing rainfall. This provides region-specific empirical evidence that drought processes are increasingly temperature-driven and establishes the climatic mechanism underlying the observed patterns of vegetation degradation and ecosystem change.

4.2. Semi-Bareland as a Degradation Pathway

I demonstrate that semi-bareland has become the dominant and persistent land-use/land-cover class in Elnour Natural Forest Reserve (ENFR) between 1995 and 2021. I establish that it is not a transitional stage but a stable and self-reinforcing degradation endpoint, representing a terminal pathway of forest degradation in dryland ecosystems.

4.3. Drivers of Forest Degradation

I establish that anthropogenic activities are the primary drivers of forest degradation in ENFR. Illegal logging and charcoal production account for approximately 35% of degradation, followed by overgrazing (25%) and other socio-economic drivers, while climatic factors act primarily as secondary amplifiers.

4.4. Biodiversity Loss and Regeneration Failure

I demonstrate a substantial decline in woody species richness from 35 to 18 species between 2008 and 2021, accompanied by widespread regeneration failure and the absence of successful recruitment in several species. This establishes regeneration collapse as a key mechanism driving biodiversity loss and reduced ecosystem resilience.

4.5. Structural Simplification of Forests

I demonstrate that forest structure is increasingly dominated by small diameter classes (exceeding 43%), while large trees (below 12%) have declined significantly. I show that selective removal of mature trees disrupts cohort development and prevents canopy recovery despite ongoing recruitment, revealing a decoupling between regeneration and structural recovery as a key driver of persistent forest degradation.

4.6. Machine Learning Robustness in Species Mapping

I demonstrate that, under heterogeneous dryland conditions characterized by class imbalance and multi-temporal multi-sensor data, Random Forest (RF) and Support Vector Machine (SVM) provide more robust and consistent species-level classification performance (85–96%) than CART and unweighted ensemble approaches. This establishes that reliable species mapping in Sudanese savanna ecosystems depends critically on algorithm robustness to minority classes and landscape heterogeneity, rather than on overall accuracy alone.

4.7. Climate-Driven Redistribution of *Acacia seyal*

I demonstrate that the distribution of *Acacia seyal* is primarily controlled by isothermality and precipitation during the warmest quarter. I further show that climate change will drive habitat contraction in northern regions and expansion in southern and eastern regions, identifying these areas as climate refugia that are critical for conservation and climate adaptation planning.

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