Spatiotemporal Monitoring of Desertification of the Sahel Region Using Remote Sensing and GIS, Case Study of Sudan

by

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Abstract

Desertification is a significant global environmental challenge, historically affected arid and semi-arid Sudan within the vulnerable Sahel region. Driven by climatic variability and human activities, prior research on Sudan had limitations regarding temporal/spatial coverage and integrated factor analysis. This study comprehensively analyzed the spatial distribution and extent of LULC in Sudan between 2003 and 2022, evaluated spatiotemporal variations in vegetation cover, and assessed the relationships between NDVI, climatic factors (precipitation, temperature), and population density. Utilizing readily available remote sensing data, the research employed MODIS (MOD13Q1, MCD12Q1), CHIRPS precipitation data, ERA5 Land Surface Temperature data, and WorldPop population density data. The findings of the study revealed a complex environmental narrative for Sudan, balancing persistent challenges with encouraging signs of vegetation growth. A notable shift toward increased vegetation cover was observed across significant portions of the country. The study also found rainfall to be a highly statistically significant positive predictor of vegetation health. While extreme maximum temperatures in the northern regions act as a dominant limiting factor for vegetation, high population densities, particularly around urban centers like Khartoum, were found to exert pressure on surrounding land resources. The findings of the study underscore the need for spatially differentiated and integrated land management strategies that leverage natural regeneration, implement smart water management, and address human pressures for sustainable development and resilience in the face of ongoing climate change.

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List of Abbreviations

ANR - Assisted Natural Regeneration

BRIDGES - Boosting Restoration, Income, Development, Generating Ecosystem Services

CGIAR - Consultative Group on International Agricultural Research

FAO - Food and Agriculture Organization

GEE - Google Earth Engine

GIS - Geographic Information Systems

GGW - Great Green Wall

ICZ- Intertropical Convergence Zone

LDN - Land Degradation Neutrality

MODIS - Moderate Resolution Imaging Spectroradiometer

NDVI - Normalized Difference Vegetation Index

OLS - Ordinary Least Squares

UNEP - United Nations Environmental Programme

UNCCC - United Nations Convention to Combat Desertification

UN FAO - United Nations Food and Agriculture Organization

UNFCCC - United Nations Framework Convention on Climate Change

Chapter 1: Introduction

1.1 Background

Globally, it is estimated that about 41% of the earth's surface has been engulfed by aridity (Bauer & Stringer, 2009), and more than 2 billion people are reported to reside in these areas (Johnson et al., 2007). The global demography of people living in extreme poverty corresponds with people living under harsh conditions in arid regions, especially in developing countries (Cornet, 2002). According to Ibrahim et al. (2022), desertification aggravates poverty and further exposes inhabitants of arid communities to discomfort by limiting their adaptability to harsh environmental conditions.

The United Nations Convention to Combat Desertification (UNCCD) defines desertification as land degradation in arid, semi-arid, and dry sub-humid areas resulting from many factors, including natural processes and human activities (Sivakumar, 2007). Desertification occurs in drylands, areas that get less precipitation than is evaporated or consumed by plants throughout part or the entire year. Drylands have very limited water and soil moisture. According to Huang et al. (2020), the global distribution of aridity zones indicates that semi-arid, arid, and hyper-arid regions are particularly susceptible to desertification. In the recent past, Africa has been notably affected, with vast portions of the continent, including the Sahara Desert and the adjacent Sahel region, classified within the hyper-arid and arid zones, underscoring its vulnerability to land degradation.

Africa has about 10 million km^2 of drylands, and much of the continent is experiencing or is at risk of desertification according to the United Nations Food and Agriculture Organization (UN FAO (2021). FAO (2021) found that up to 64% of Africa's productive land is degraded, and desertification affects 45% of the total land on the continent. Over 7.5 million km^2 of land in Africa is at high risk of desertification, and about 400 million people live in drylands in Africa, and 22 million people live at high risk of desertification (Reich et al., 2004). According to Mandal (1990), the Sahara Desert is encroaching southwards at a rate of 5-6 km per year. Research conducted by Thomas & Nigam (2018) showed that the Sahara Desert has expanded over the 20th century, notably southward in summer, indicating the retreat of the northern edge of the Sahel rainfall belt.

The term Sahel (an Arabic word for shore) is used to refer to the semi-arid zone of the Sahara Desert (Le Houérou & LeHouérou, 1989). Pu & Cook (2012) reported that the Sahel is one of the world's warmest regions, with a short summer rainy season of three months. According to (Abdi et al., 2013), climatologically, the Sahel is characterized by frequent droughts; low, poorly distributed, and highly variable monthly and seasonal unpredictable rainfall and varying vegetation, from sparse grasslands to more wooded areas. The Sahel has suffered several extreme droughts that have been related to climate change since the 1960s and have, in turn, caused large losses of livestock and brought famine to millions of people (Hein & De Ridder, 2006).

Temperatures in the Sahel are rising rapidly at a much faster rate than the global average, and the Sahel will experience higher degrees of warming sooner than the rest of the world (UNFCCC, 2020). The Sahel region is known for its semi-arid climate, stretching across the African continent just south of the Sahara Desert, from the Atlantic Ocean in the west to the Red Sea in the east. The countries in the Sahel experience a transitional climate between the arid Sahara to the north and the more humid savannas to the south.

Desertification in Africa is not limited to the Sahel region but even countries farther from the Sahara such as Ethiopia has at least 70% of land threatened and 80% of land in Kenya is vulnerable to desertification as well, while the assessment done by FAO and UNEP suggests that the desert is moving at an annual rate of 5 km in the semi-arid areas of West Africa (DTE, 2016).

The Sahel is one of the world's regions that is most affected by degradation and desertification. To address the diverse impacts of desertification that many countries in the Sahel regions were faced with, 11 countries within the region and the international community implemented a land restoration program known as the African Union strategy on the Great Green Wall (GGW) in 2007 (UNCCD, 2020). One of the objectives of the UNCCD was to reach Land Degradation Neutrality (LDN) by 2030, which is also included in Sustainable Development Goal (SDG) 15. SDG 15 aimed to protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification and halt and reverse land degradation, and halt biodiversity loss. According to Goffner et al. (2019), the initiative progressively expanded to include 21 countries on the African continent.

Sudan, which is located in the semi-arid (Sahel) region, has been severely affected by climate variability, leading to reduced agricultural productivity and increased vulnerability of local populations (Iizumi et al., 2021). According to Mohamed et al. (2016), the expansion of desert conditions in Sudan is driven by both natural and anthropogenic factors, including overgrazing, deforestation, and unsustainable farming practices. Sudan has experienced frequent episodes of drought and land degradation, with desertification being a significant environmental concern.

Previous research, exemplified by the work of Yagoub et al. (2017), employed MODIS (MOD13Q)1 to detect vegetation cover change in Sudan. However, that analysis only covered the period from 2001 to 2013. Moreover, Yagoub et al. (2017) conducted their analysis on the combined territory of Sudan and South Sudan, thus providing a less focused investigation for present-day Sudan. In addition, this study incorporates Land Use and Land Cover (LULC) data to look at from and to changes (LULC in 2003 versus 2022) and develops a statistical model to attempt to explain the changes. These datasets, offering crucial LULC classification information

(Friedl et al., 2010a), are integrated to provide a more precise evaluation of vegetation changes beyond the exclusive use of NDVI trends.

Additionally, prior analyses largely concentrated on mapping NDVI trends and did not comprehensively incorporate climatic (temperature and precipitation) and population (population density) variables to enhance the explanatory power of the research. Despite considerable research, much of the existing work focused either on climatic factors such as rainfall variability or on human-induced land degradation, often ignoring the potential for a holistic approach that integrates both aspects (Geist & Lambin, 2002; Herrmann & Hutchinson, 2005).

The overall objective of this study is to ascertain whether the desertification trends observed in that period had persisted, reversed, or intensified in the subsequent years up to 2022, considering the rapid rate at which climate change is occurring over the past decade. Therefore, a more comprehensive, higher-resolution, and methodologically robust assessment of land cover trends in present-day Sudan was conducted to help understand the status of vegetation in Sudan over the past two decades.

1.2 Research Objectives

The goal of the research was to explore and apply GIS and remote sensing-based change detection methodology, utilizing readily available remote sensing data to analyze land use and land cover changes, as well as assess vegetation health over time. The specific objectives are as follows:

- To analyze the spatial distribution and extent of LULC and vegetation changes in Sudan over the past two decades (2003-2022).
- Evaluate the spatiotemporal variations in vegetation cover over the past twenty years using NDVI and LULC data obtained from satellite imagery. It is hypothesized that there is a significant temporal fluctuation in NDVI values that indicate seasonal and inter-annual

vegetation changes, with overall declining trends in areas affected by land degradation and desertification.

- Analyze the relationships between NDVI, climatic factors (precipitation and temperature variations), and population density in Sudan. NDVI assessment of vegetation in Sudan is hypothesized to be negatively correlated with increasing temperature and population density and positively correlated with precipitation.

To help achieve the above objectives, the researcher answered the following questions:

1) *Which areas in Sudan have experienced the most significant changes in LULC using change detection techniques in GIS from 2003 to 2022?*
2) *What are the spatiotemporal trends in vegetation cover in Sudan over the past two decades as indicated by NDVI and land cover data from satellite imagery?*
3) *Are there substantial variations in precipitation, temperature, and population density that influence the patterns and extent of desertification in Sudan?*

1.3 Significance of the Study

According to Field & Barros (2014) and also as reported by Olorunfemi et al. (2022), there have been changes occurring in the distribution and dynamics of all types of terrestrial ecosystems in Africa, including deserts, grasslands and shrublands, savanna and woodlands, and forests. After this, there was an observation that there was an expansion of the desert and a contraction of the total vegetation areas. As revealed by Thomas & Nigam (2018), the Sahara Desert has expanded by about 10 percent from 1920- 2013.

This study investigates the trends of desertification in Sudan over the past two decades, contributing significantly to the existing body of literature. By analyzing land cover and vegetation changes, the research provided evidence-based insights into whether desertification in Sudan was persisting, reversing, or intensifying during the study period of 2003 to 2022. This was crucial, considering the ongoing climate change and the documented expansion of the Sahara Desert in previous decades.

Furthermore, this research would contribute to the achievement of Sustainable Development Goal (SDG) 13 (Climate Action), (Mortimer et al., 2023), and Goal 15 (Life on Land) which focus on the protection, restoring and promoting sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss (UNCCD 2020). The delayed and weakened northward shift of the rainbelt (Intertropical Convergence Zone, ICZ) over the Horn of Africa has historically driven drought and famine episodes, particularly during the 1983-1985 and 1999-2000 crises in Ethiopia and Sudan (Issa Lélé & Lamb, 2010; Mera, 2018; Nicholson, 1985). These events illustrate how changes in seasonal rainfall patterns are often tied to shifts in the ICZ, which can lead to widespread crop failure and humanitarian disasters (Nicholson, 2001). Understanding this climatic mechanism is essential in contextualizing contemporary desertification and land degradation, as such anomalies continue to threaten food security in these drought-prone regions ("FEWS NET's Integrated Analytical Areas," 2008; Hammond & Maxwell, 2002). The monitoring and understanding of desertification dynamics provided critical insights necessary for mitigating and adapting to climate change in Sudan. The knowledge generated from this study can inform policies and strategies aimed at combating desertification and its detrimental impacts on vulnerable communities, thereby aiding sustainable land management efforts in the future.

The study would also contribute valuable knowledge on the interplay of climate and population factors in driving land cover change in Sudan. By examining both natural processes and human activities, the research would illuminate their combined effects on land degradation. Specifically, the integration of climatic (temperature and precipitation) and socioeconomic (population density) variables could allow for a more comprehensive identification of the underlying drivers of vegetation health and LULC changes associated with desertification regeneration. Understanding of these drivers is essential for guiding the development of effective strategies for adaptation and resilience in the affected regions.

1.4 Organization of Study

The thesis is organized into five chapters. Chapter 1 provides the background, an overview of the study area, objectives, and significance of the study, as well as the organization of the research study. Chapter 2 presents an in-depth explanation of existing literature in the study area. Chapter 3 provides detailed information on the study area, research data, and methodology. Chapter 4 discusses the analysis and results of the Sudan. Chapter 5 presents the general summary of the findings of the research study.

Chapter 2: Literature Review

2.1 Introduction

Desertification remains one of the most pressing environmental challenges facing arid and semi-arid regions across the globe. This has been characterized by persistent degradation of dryland ecosystems due to climatic variations and human activities. Desertification has far-reaching implications for food security, water availability, biodiversity, and the livelihoods of millions. As climate change intensifies and population pressures grow, it is very important for the understanding of the spatial and temporal dynamics of desertification. To monitor this situation, researchers have increasingly turned to geospatial technologies such as Geographic Information Systems (GIS) and remote sensing. These tools offer a comprehensive framework for monitoring land use and land cover, assessing vegetation health, and climatic conditions worldwide. One of the most widely used indicators for monitoring vegetation dynamics is the Normalized Difference Vegetation Index (NDVI), which is derived from satellite imagery. This chapter reviews the existing body of literature related to the historical background of desertification in Sudan, drivers of desertification, the impacts on livelihoods, and the application of GIS and remote sensing in desertification studies.

2.2 Historical perspective of desertification in Sudan

Sudan is among the countries that are most affected by desertification, and is likely to worsen in the future (Rahamtalla, 2018). According to Khairalseed (2015), over 500,000 km^2 in Sudan are affected by desertification, and about 1.78 million km^2 of Sudan is considered arid or semi-arid, which makes up to 75% of the country's total land area. Sudan is characterized by low, unpredictable, and highly variable rainfall, while temperature and evaporation rates are high. In dry and semidry areas in Sudan, the variability of rainfall can be extremely high to the extent that the daily maximum may reach the annual average (El Gamri et al., 2021). This has led to almost half of the population living in areas affected by desertification. It has been reported by Ahmed et al. (2018) that natural disasters in the contrasting forms of drought and flooding have historically occurred frequently in Sudan and have contributed significantly to population displacement, poverty, diseases, and the under-development of the country.

Desertification has been an ongoing process for thousands of years, but it was not until the 20th century that governments and people realized that it was a threat to their future (Maliva & Missimer, 2012). A report by the Sudan Soil Conservation Committee in 1944 stated that land degradation is primarily caused by human activities such as deforestation, over-cultivation, overgrazing, and frequent fires, rather than climatic variations (Ahmed et al., 2018). Beginning in the 1930s, Sudan began keeping records of rainfall and vegetation. Since that time, the boundary between the semi-desert and the desert has moved south between 50 and 200 km (UNEP, 2007). Desertification is Sudan's most significant environmental challenge, and it is also considered a major contributing factor to rural populations migrating to urban centers, leading to *environmental refugees* (UNEP, 1992).

Between 1950 and 1990, Sudan experienced three prolonged periods of drought, and there is a link between drought and armed conflict. The most severe drought took place from 1980–1984, resulting in widespread displacement and localized famine. Rainfall data for the period was retrieved from the Annual Rainfall Reports (1955-1989) published by the Meteorological Department, Sudan, providing critical insights into precipitation trends and drought patterns (Suliman, 2008). The 1982-1984 drought led to famine, armed conflicts, livestock losses, and economic collapse. Between 1973 and 2006, Darfur lost one-third of its forested area, as documented in the UNEP Post-Conflict Environment Assessment, which used consultations, fieldwork, and remote sensing to analyze environmental degradation (UNEP, 2007).

2.3 Drivers of Desertification

Desertification results from multiple interactions between physical, biological, political, social, cultural, and economic factors (Rastgoo & Hasanfard, 2022). Desertification is not just the existence of deserts extended within the territory, but means the destruction of vital productive potential, leading to the emergence of conditions of the desert environment on these lands (Mabbutt, 1978).

Desertification is driven by both natural processes and human activities, though scholars debate their relative significance. Some researchers, like Huang et al. (2015), emphasized climate change as the primary cause, while others, such as Mercuri (2008), attributed it mainly to human activities. Bestelmeyer et al. (2015) and D'Odorico et al. (2013) consider both factors equally responsible. Climate change contributes through rising temperatures, altered precipitation patterns, and increased aridity, leading to further desert expansion (Kröpelin et al., 2008).

However, human activities play a dominant role in desertification, particularly in the Sahara. Agricultural practices such as land clearing, over-cultivation, inappropriate soil management, and water misuse accelerate land degradation (AbdelRahman, 2023). Overgrazing and herd concentration further degrade rangelands, while deforestation for construction, fuelwood, and charcoal exposes soil to erosion and climate extremes (Glantz & Orlovsky, 1983). These human-driven factors intensify desertification, often surpassing the effects of climate change.

2.4 Socio-economic Impact of Desertification

Within the context of defining desertification, many words are used to describe the phenomenon, some of which complement each other, while others appear to be contradictory. Nevertheless, a fact on which they all agree is that desertification is viewed as an adverse environmental process. As an important global ecological and socioeconomic problem, desertification not only causes the deterioration of the ecological environment but also reduces agricultural productivity and income (Sterk & Stoorvogel, 2020). According to Dregne. (2002), desertification negatively impacts agriculture and water resources, leading to food insecurity and economic challenges.

Studies have shown that prolonged droughts significantly reduce water availability and agricultural productivity, leading to competition over scarce resources. According to Saad et al. (2018), drought in Sudan has caused desertification, reduced grazing lands, and increased conflicts between farmers and pastoralists. This is particularly evident in areas where livelihoods are heavily dependent on rain-fed agriculture.

Ahmed et al. (2018) analyzed historical climate and conflict data and found a correlation between periods of extreme drought and spikes in violent clashes. Their study indicated that when traditional water sources dry up, migratory pastoralist groups move into farming areas, leading to disputes over land use.

In Darfur, the effects of prolonged drought have intensified ethnic and tribal tensions. According to Gray & Kevane (2008), competition for water and arable land was a key driver of the Darfur conflict, with environmental degradation exacerbating existing grievances. Olsson

(1993) noted that the severe famine during 1984 directly affected half the population of 25 million, and the death rate reached 3% of the population per month.

Additionally, desertification has a significant impact on ecological sustainability, energy security, national security, air quality, etc (Adeagbo et al., 2021; Balima et al., 2022). Desertification is one of the main factors that causes the migration of rural populations to urban centers (Rahamtalla, 2018). Thus, it drives human migration patterns and can contribute to social unrest (Femia & Werrell, 2012). That is, desertification can erode the economic base of communities heavily reliant on agriculture and natural resources, where reduced agricultural output and employment opportunities can lead to income losses and increased poverty, which causes human migration from the affected area (Reynolds et al., 2007).

2.5 Remote sensing and GIS as tools for monitoring and assessing climate change and desertification

According to Mason & Schmetz (1992), remote sensing is the science of deriving information about an object from measurements made at a distance from the object, where the focus is on the systems that measure electromagnetic energy. In a broad sense, remote sensing is concerned with detecting and recording electromagnetic radiation from the target areas in the field of view of the sensor instrument. The reflection may be directly from separate components of the target area, such as solar energy emitted from the area, or it may be reflections of energy transmitted to the target area from the sensor itself (Ouchra et al., 2022).

Desertification, as a process of land degradation in arid, semi-arid, and dry sub-humid areas, is often driven by climatic variations and human activities. Remote sensing, with its ability to collect data from a distance, has become an invaluable tool for monitoring, assessing, and understanding these complex phenomena. According to Dawelbait & Morari (2012), remote sensing is one of the most effective tools for desertification assessment, and it has long been suggested as it is a time and cost-efficient method for observing dryland ecosystems.

Geographic Information Systems (GIS), on the other hand, are indispensable tools in environmental monitoring that offer a solid basis for capturing, storing, analyzing, and visualizing spatial data. According to Burrough et al.(2015), GIS is defined as computer-based systems for handling geographically referenced data, providing the analytical framework necessary to understand complex interactions between natural processes and human activities across space and time. In environmental studies, particularly those focused on desertification and land degradation, GIS facilitates the mapping of vegetation trends, land use or cover changes, and ecological risk assessments (Lambin et al., 2003). GIS enables researchers to analyze the spatial datasets alongside other layers such as climatic, topographic, or socio-economic data, to detect patterns and drivers of land degradation (Lillesand et al., 2015). According to Jensen (1996), remote sensing delivers the raw spectral information, while GIS adds spatial intelligence and contextual interpretation, making the two technologies highly complementary.

According to Pettorelli et al. (2014), satellite-based remote sensing is often used to monitor changes in climate, land cover, and vegetation. Advanced satellite sensors, such as those on the Moderate Resolution Imaging Spectroradiometer (MODIS) and Landsat platforms, provide important data for assessing climate change and desertification. Moreover, Normalized Differential Vegetation Index (NDVI) and Advanced Very High-Resolution Radiometer (AVHRR) derived from remote sensing data are used to monitor vegetation health and changes, providing valuable insights into desertification processes (Pettorelli et al., 2014).

Yagoub et al. (2017) analyzed land cover changes in Sudan (2001-2013) using MODIS data, linking NDVI trends to climate factors. The study found NDVI improvement in the southern Sudan (0.9% of the area) and degradation in the middle and east (0.5%), with seasonal variations. NDVI correlated positively with precipitation and negatively with temperature, highlighting the climate's role in vegetation dynamics. Gezahagn (2016) utilized remote sensing and GIS to conduct a spatial assessment of NDVI as an indicator of desertification in Ethiopia, a Sahelian country located in the Horn of Africa. Similarly, Lamqadem et al. (2018) employed the Normalized Difference Vegetation Index (NDVI) to map desertification in Morocco.

Additionally, Yang et al. (2022) analyzed changes in NDVI across the Sahel region of Africa (2000-2020) using MODIS data as the primary source for monitoring desertification, with Landsat imagery via Google Earth for direct verification and accuracy assessment of 86.78%. Their study highlighted the significant influence of temperature and precipitation on NDVI, particularly within the desert/grassland biome of the Sahel transition zone.

2.6 Sustainable Efforts in Combating Desertification

The Sudan government formed the National Committee for Combating Drought and Desertification, led by the National Research Council and the Ministry of Agriculture, between 1972 and 1976. In 1977, the committee published a report on desertification in Sudan, along with suggestions for projects to solve the problem (Ahmed et al., 2018). In 1991, the International Convention to Combat Desertification was put into effect, and Sudan launched numerous projects to combat desertification, including programs to restore the Gum Arabic Belt and promote grassland development (Sudan National Action Programme, 2006). The term *gum arabic belt* is used to indicate a zone of mainly 520,000 km2 in an area which extends across central Sudan between latitudes 10° and 14° N, accounting for one-fifth of the country's total area (Adam, 2011).

Desertification is still regarded as a serious threat to sustainable development and human life in Sudan, despite efforts to combat it (Ahmed et al., 2018).

Apart from the previous initiatives to combat desertification in the 1970s in Sudan, the United Nations Convention to Combat Desertification also launched the Great Green Wall (GGW) initiative in 2007 across 11 countries, including Djibouti, Eritrea, Ethiopia, Sudan, Chad, Niger, Nigeria, Mali, Burkina Faso, Mauritania, and Senegal. The GGW was a Pan-African initiative to restore and sustainably manage land in the Sahel-Sahara region to address both land degradation and poverty (UNCCD, 2020). In Sudan, the GGW intervention zones focused on six drought-affected states, including North Darfur, Kordofan, Kassala, River Nile, Northern State, Khartoum State, and integrating afforestation, sustainable land and water management, and community-led restoration strategies Consultative Group on International Agricultural Research (CGIAR), 2022). According to the UNCCD, country-specific reviews highlight progress in restoration but emphasize ongoing challenges of financing, institutional capacity, climate variability, and the need for more interdisciplinary monitoring.

In summary, our capacity to assess and monitor desertification and climate change has been transformed by the application of GIS and remote sensing. It gives researchers and policymakers an important way to gather regional-scale data, which they can use to better understand these intricate environmental issues and create mitigation and adaptation plans.

Chapter 3: Study Area and Research Methodology

3.1 Introduction

Understanding the dynamics of LULC changes, climatic variations require a critical analysis of both the spatial environment as well as the analytical procedures. This chapter gives an overview of the research area, delineating its geographic, climatic, and socio-economic characteristics that make it a focus point to study environmental changes that contribute to desertification. This chapter also describes the data, and the methodology employed to analyze LULC, vegetation health, and climatic variability over the past two decades in Sudan.

3.2 Study Area

Sudan was historically the largest country in Africa until 2011, when South Sudan seceded, forming an independent nation (Mohamed Nour, 2015). Sudan is in the northeastern part of Africa and is bordered by the Central African Republic to the southwest, South Sudan to the south, Ethiopia to the east, Egypt to the north, and Chad to the west. To the northeast, it has a coastline along the Red Sea. Geographically, Sudan lies between latitudes 8° and 23° N and longitudes 22° and 38° E. It is divided into four distinct climatic zones: arid, semi-desert, savannah, and subtropical (Osman & Shamseldin, 2002). The country features diverse landscapes, including vast deserts, mountain ranges, and the Nile River, which flows from south to north, serving as a critical water source for both agriculture and human settlements.

Sudan is divided into 18 provinces, also referred to as states or wilayat (Figure 3.1). These administrative units play a crucial role in local governance and resource management.

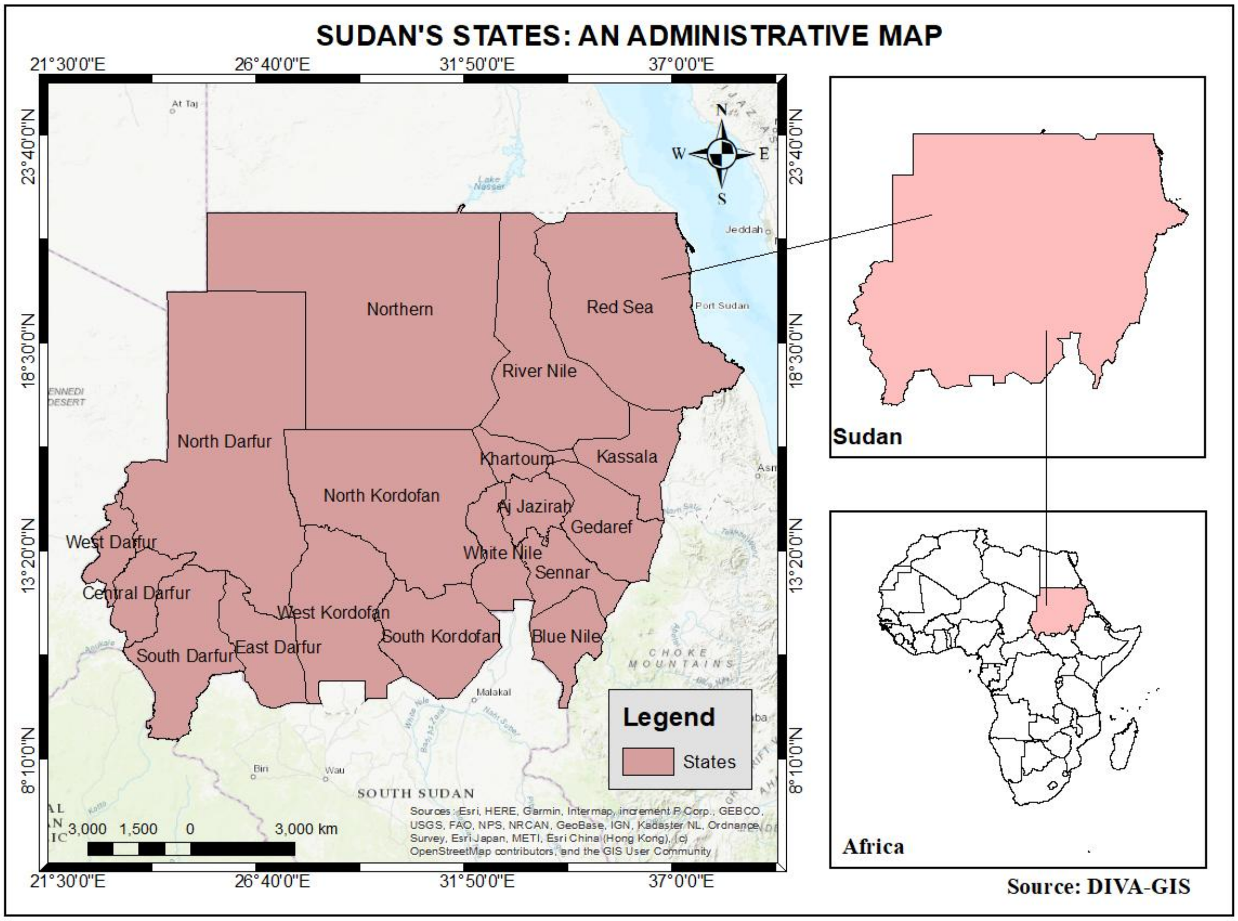


Figure 3.1. Map of Study Area.

Agriculture plays a vital role in Sudan's economy, employing or sustaining up to 80% of the population (Mahgoub, 2014). The sector contributes significantly to food production, raw materials, and foreign exchange earnings. Sudan possesses vast expanses of cultivated land, primarily located between the Blue Nile and White Nile rivers, as well as between the Blue Nile and the Atbara River. Additional arable areas are found in valley plains where irrigation is widely practiced, along with the narrow Nile Valley.

Over 40% of Sudan’s total land area is covered by pastures and forests (Mahgoub, 2014). Livestock rearing is a major socioeconomic activity, particularly in the regions of Kordofan and

Darfur. The country has an estimated livestock population of 134 million, including 3 million camels, 40 million cattle, 49 million sheep, and 42 million goats, with more than 90% raised under traditional pastoral systems (Babiker, 2015). Livestock herding remains a key economic activity and a major source of livelihood for nomadic and semi-nomadic communities, but it can also have an adverse impact on the land.

Sudan's vast natural resources have made it susceptible to internal conflicts and environmental challenges. Urbanization, coupled with prolonged civil wars, has caused significant demographic shifts and pressure on land resources. Civil disturbances began in western Sudan in 1985, following the last of five major droughts in the 20th century (Alredaisy, 2024). The Darfur conflict, which escalated in the early 2000s, resulted in a humanitarian disaster, with many Sudanese refugees fleeing to Chad. The conflict has been largely attributed to competition over natural resources, particularly grazing lands and water (Robinson, 2005).

The Great Green Wall (GGW) initiative in Sudan is part of a larger African Union-led effort to combat desertification and land degradation across the Sahel region (UNCCD, 2020). In Sudan, the project focuses on restoring degraded lands in arid zones by planting drought-resistant trees, promoting agroforestry, and supporting natural regeneration. Efforts such as the FAO–Turkey Boosting Restoration, Income, Development, Generating Ecosystem Services (BRIDGES) project have restored approximately 5,000 hectares of degraded land in areas like Kassala State by engaging local communities in activities such as farmer-assisted natural regeneration, water harvesting, soil fertility management, and native species planting. These interventions aim to improve soil fertility, enhance vegetation cover and support livelihoods, and build resilience against climate change (Food and Agriculture Organization of the United Nations, 2017). Despite challenges like limited funding and harsh climatic conditions (Ganawa, 2022), Sudan's role in the

GGW highlights the importance of localized ecological restoration in tackling environmental degradation.

3.3 Materials and Methods

Monitoring desertification as a function or the presence or the absence of vegetation using remote sensing and GIS requires a comprehensive and spatially explicit approach that integrates multisource datasets and advanced analytical techniques. Given the increasing concern over land degradation in arid and semi-arid regions, particularly in the Sahel zone, this study employs geospatial technologies to identify, map, and analyze patterns and drivers of desertification or vegetation reestablishment across Sudan over the past two decades.

Satellite remote sensing plays a central role in this research by enabling the observation and measurement of electromagnetic radiation reflected or emitted from the Earth's surface. This facilitates the detection of vegetation health and changes, land cover transitions, and climate-related variables that influence desertification dynamics (Pettorelli et al., 2014). Geographic Information System (GIS) complements remote sensing by allowing spatial integration, visualization, and analysis of various environmental and socioeconomic datasets. This section describes the data sources, tools, and methodological procedures that were employed to assess and analyze vegetation trends in Sudan.

3.3.1 Data

To achieve the research objectives, the study utilized a range of remotely sensed and geospatial datasets to assess the long-term changes in LULC, vegetation health, precipitation, surface temperature, and population distribution in Sudan. Specifically, the Moderate Resolution Imaging Spectroradiometer (MODIS) products, MOD13Q1 (Terra Vegetation Index) and

MCD12Q1 (Land Cover Product) (Friedl et al., 2010b), were obtained via Google Earth Engine (GEE). GEE is a cloud-based geospatial platform that provides global access to time-series satellite imagery, analytical tools, and scalable computing capabilities (Gorelick et al., 2017).

In addition to MODIS data, the study employed precipitation data from the Climate Hazards Group Infrared Precipitation with Station (CHIRPS) (Ghozat et al., 2022), Land Surface Temperature data from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 (Yilmaz, 2023), and population density from the WorldPop dataset. These datasets were selected for their consistency, spatial and temporal coverage, and relevance to vegetation analysis. Table 3.1. provides a comprehensive overview of all datasets used in the study, including their sources, spatial resolutions, temporal ranges, and geographic coverage.

Table 3.1: An overview of datasets and their characteristics.

Dataset	Source	Spatial Resolution	Temporal Coverage	Geographic Coverage
NDVI MOD13Q1	Google Earth Engine	250 sq meters	2000 - Present	Global
LULC MCD12Q1	Google Earth Engine	500 sq meters	2001 - Present	Global
CHIRPS	Google Earth Engine	0.005 x 0.005 sq meters	1981 - Present	50º S to 50º N latitude globally
WorldPop Population Density Data	WorldPop Project	100 sq meters	Varies by region, typically	Global

			2000 – Present	
ERA 5	Google Earth Engine	0.25º x 0.25º sq meters	1950 - Present	Global

3.3.2 Data Processing

The study utilized Google Earth Engine as the primary platform for extraction and initial preprocessing. GEE is a cloud-based geospatial computing platform launched by Google in 2010, designed for large-scale environmental data analysis and satellite imagery processing (Amani et al., 2020; Zhao et al., 2021). It enabled efficient access to multi-temporal satellite datasets and facilitated the computation of vegetation indices and LULC classification for the study area. For further spatial analysis and the production of thematic maps, ArcGIS Pro version 3.4 was employed. This desktop GIS software provided the necessary tools for advanced spatial analysis, visualization, and map creation. In addition, Microsoft Excel was used for performing basic statistical analyses, including data cleaning, summary statistics, and preparation of inputs for interpretation.

3.3.3 Analytical Approaches / Methods

The study employed the International Geosphere-Biosphere Programme (IGBP) land cover classification scheme to categorize LULC types within the study area. This classification scheme, developed by Friedl et al. (2002), consists of 17 distinct LULC categories for Level 1 Type 1, including various forms of vegetation, urban areas, water bodies, and barren or sparsely vegetated land. The use of this standardized and globally recognized scheme provided a comprehensive framework for detecting and analyzing LULC changes over time. By adopting the IGBP classifications, the study was able to systematically assess ecological transformations and better understand the dynamics of vegetation change across Sudan. This approach served as a foundational method for capturing complex land surface patterns and evaluating the environmental impacts associated with desertification processes.

In assessing vegetation health and coverage across the study area, the Normalized Difference Vegetation Index (NDVI) was employed for the period from 2003 to 2022. NDVI is one of the most widely used indices in remote sensing studies for detecting and quantifying vegetation cover (Marzen et al., 2011). NDVI has also been used in several studies as a key indicator for monitoring desertification, particularly in arid and semi-arid environments (Gillespie et al., 2018). It is derived from the red (R) and near-infrared (NIR) reflectance values captured by satellite sensors. The NDVI was calculated using the formula:

$$\mathbf{NDVI = (NIR - R) / (NIR + R)}$$

Where *NIR* represents the reflectance in the near-infrared band, and *R* represents the reflectance in the red band.

The NDVI values range between -1 and +1. A positive value close to 1 indicates healthy vegetation cover, while values close to 0 indicate less or no vegetation coverage over the study region. This index provided a reliable measure of vegetation vigor, with values indicating healthier and denser vegetation. In this study, NDVI served as a primary metric for evaluating vegetation trends and detecting areas of land degradation over the study period.

To examine the relationship between vegetation and the posited desertification factors, Ordinary Least Squares (OLS) was employed as a statistical modeling technique. OLS is a commonly used linear regression method that estimates the relationship between a dependent variable and one or more independent variables by minimizing the sum of the squared differences between observed and predicted values (Montgomery et al., 2013). This method is appropriate for identifying and quantifying the extent to which climatic and socio-economic variables influence vegetation changes, as captured by NDVI. Researchers have employed Normalized Difference Vegetation Index data to analyze the relationship between human activities, rainfall variability, and vegetation cover to desertification over an extended period of 20 to 30 years (Dardel et al., 2014; Herrmann et al., 2005). In this study, the dependent variable was the Normal Difference Vegetation Index (NDVI), while the independent variable included precipitation, temperature, and population density data. These independent variables have been considered in literature as some of the variables that impact vegetation growth. OLS is calculated using dependent and independent variables. This is calculated as,

$$\mathbf{y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots\ldots \beta_n X_n + \mathcal{E}}$$

where y is the dependent variable, β is the coefficient, X represents the explanatory or independent variable, and $\mathcal{E}$ also represents the random error term or residual.

In this study, random sampling was conducted in ArcGIS Pro prior to running OLS regression to ensure validity and spatial representativeness. Given the spatial heterogeneity nature of Sudan, and the varying nature of both dependent and explanatory variables, generating a set of randomly distributed sample points, each location within the study area had an equal chance of selection, reducing sampling bias among observations. The dependent variable was NDVI, serving as an indicator of vegetation density, while the independent variables included population density, maximum temperature, and precipitation. To ensure comparability among variables measured on different scales, the study further applied Min-Max normalization to independent or explanatory variables. Normalizing the variables allowed the coefficients to be interpreted on a common, unitless scale, making it easier to compare their relative influence on NDVI. The Min-Max normalization technique transforms each variable X to a scale between 0 and 1 using the formula:

$$\mathbf{X_{normalized} = X - X_{min} / X_{max} - X_{min}}$$

Where X_{min} and X_{max} represent the minimum and maximum values of the variables, respectively. This scaling technique preserves the relationships and distribution of the original data while eliminating units (Chandrashekar & Sahin, 2014). The process was performed using Python, and the normalized data were subsequently used for the OLS regression model.

Chapter 4: Analysis and Results

4.1 Introduction

Understanding the intricate dynamics of land degradation, particularly desertification, is paramount for sustainable environmental management, especially in vulnerable regions like Sudan. Desertification poses a significant challenge globally, and in Sudan, it has historically been linked to a complex interplay of climatic, socioeconomic, and spatial factors. The nation's diverse landscape, spanning arid northern deserts to more fertile southern savannas, experiences varied environmental pressures that necessitate a detailed investigation into their driving forces. This research aims to comprehensively analyze these factors and their influence on vegetation as an indicator of increasing or decreasing desertification in Sudan over a two-decade period, specifically from 2003 to 2022.

To achieve this, the study employs a robust methodology that includes the analysis of spatial patterns and statistical modeling, notably Ordinary Least Squares (OLS) regression. A central component of the analysis is the Normalized Difference Vegetation Index (NDVI), which serves as a crucial dependent variable due to its reliability as an indicator of vegetation health and land use/land cover (LULC) changes, especially in arid and semi-arid regions. By examining the distribution and changes in NDVI alongside independent variables such as rainfall, temperature, and population count, this study seeks to elucidate the spatial patterns and relationships between these key variables driving or reversing desertification across Sudan. The findings derived from maps and statistical insights into these relationships are critical for informing strategies to address the persistent challenges of sustainable land management in a country already vulnerable to climate variability.

4.2 Spatial Distribution and Extent of Desertification in Sudan

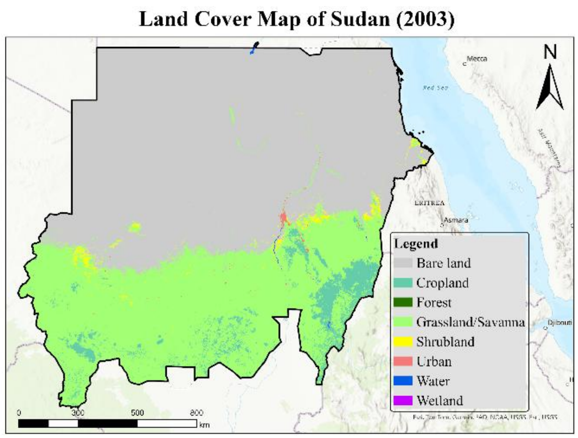
According to Jansen & Gregorio (2002), the understanding of the interactions between LULC in their spatial and temporal appearances is fundamental to the comprehension of LULC change. LULC describes how human activities and natural processes have altered the physical, chemical, and biological properties of land, resulting in changes to the Earth's surface (Turner et al., 2007). To effectively assess the changes in LULC, it is important to classify the different LULC categories and perform change detection analysis. Classification provides a structured approach for identifying and categorizing the Earth's surface properties, which is important for understanding spatial and temporal transformations in LULC patterns (Campbell & Wynne, 2011). Through change detection, researchers can quantify the extent and nature of the specific and various changes over time.

4.2.1 LULC Distribution

The first objective of study was to analyze the spatial distribution and extent of vegetation in Sudan over the past two decades (2003-2022), this overarching goal served as a guide for answering the question of this specific research question: *Which areas in Sudan have experienced the most significant changes in LULC change detection techniques in GIS from 2003 to 2022?* The objective was addressed by conducting a detailed analysis utilizing the MODIS MCD12Q1 LULC dataset for the study period. The classification and analysis of the above datasets provide insights into the changes in LULC types over time, effectively indicating the areas that experienced vegetation gain, degradation, or stability across Sudan.

A comparative analysis of LULC data for the years 2003 and 2022 revealed a significant shift in vegetation types and surface coverages across Sudan. Figures 4.1a and 4.1b show the

LULC of Sudan in 2003 and 2022, indicating the various vegetation cover in the region, namely, bare land, cropland, forest, cropland/savanna, shrubland, urban, water, and wetland.



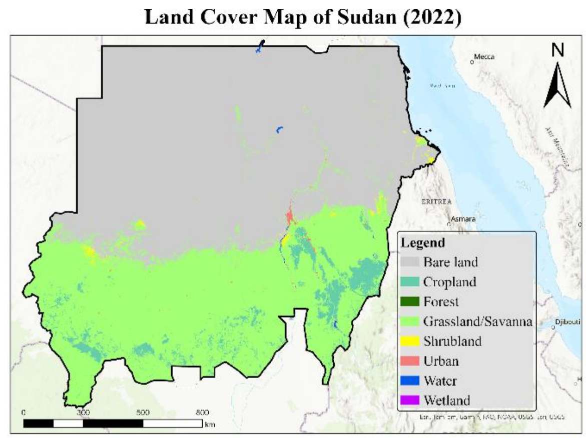


Figure 4.1a: LULC Map of Sudan (2003)   Figure 4.1b: LULC Map of Sudan (2022)

During the period between 2003 and 2022, Sudan experienced notable shifts in LULC composition as shown in Table 4.1. Bare land remained the dominant LULC type, though its extent declined from 1,115,694.60 km^2 (60.5%) in 2003 to 1,082,17.82 km^2 (58.7%) in 2022, indicating a modest reduction of 1.8%. These decreases corresponded with an increase in grassland and savanna areas, which expanded from 631,316.44 km^2 (34.2%) to 677,345.88 km^2 (36.7%), suggesting moderate vegetation recovery or regeneration across parts of the country. This observed shift from bare land to grassland/savanna areas aligns remarkably well with broader regional patterns documented across the Sahel, supporting research on the regreening of the Sahel following the devastating droughts of the 1970s and 1980s (Fensholt & Proud, 2012; Herrmann et al., 2005). Cropland declined slightly from 79,272.78 km^2 (4.3%) to 73,832.50 km^2 (4.0%), possibly due to land degradation, abandonment, or conversion to other LULC. Shrubland experienced a more substantial reduction, nearly halving from 14,042.53 km^2 (0.8%) to 6,295.89 km^2 (0.3%), which may reflect vegetation degradation or a transition into grassland or bare land. This reduction in shrubland coverage represents a concerning trend that warrants further investigation, as shrubland plays crucial ecological roles in arid environments, providing habitat for wildlife, preventing soil erosion, and serving as a source of fuelwood and fodder for local communities. According to Brandt et al. (2016), the Sahel has shown that woody vegetation can be particularly vulnerable to human pressure, especially in areas where fuelwood collection is intensive.

Urban areas, while still minimal in coverage, showed a slight increase from 3,381.49 km^2 (0.2%) to 3,440.60 km^2 (0.2%), indicating steady urban expansion. Water bodies also increased marginally from 1,175.94 km^2 to 1,707.09 km^2, potentially due to improved detection for seasonal changes. Wetlands and forest cover, though both occupying very small portions of the land area, increased from 84.14 km^2 to 136.56 km^2 and from 7.44 km^2 to 39.67 km^2, respectively, reflecting limited but positive ecological changes in some localized areas.

Table 4.1: LULC Classification and Percentage Distribution in Sudan (2003-2022)

Land cover	**Area (km^2)**		**Percentage Change**
	2003	**2022**	
Bare land	1,115,694.60	1,082,173.82	-1.8%
Grassland/Savanna	631,316.44	677,345.88	2.5%
Cropland	79,272.78	73,832.50	-0.3%
Shrubland	14,042.53	6,295.89	-0.4%
Urban	3,381.49	3,440.60	0.0%
Water	1,175.94	1,707.09	0.0%
Wetland	84.14	136.56	0.0%
Forest	7.44	39.67	0.0%

The results in Figure 4.2 show a marked decrease in bare land, which remains the dominant LULC type, though its extent declined by over 33,000 km^2 (a 1.8% reduction). Concurrently, grassland/savanna LULC increased by approximately 46, 000 km^2, indicating moderate vegetation growth, possibly due to natural regeneration or sustained efforts to reverse desertification.

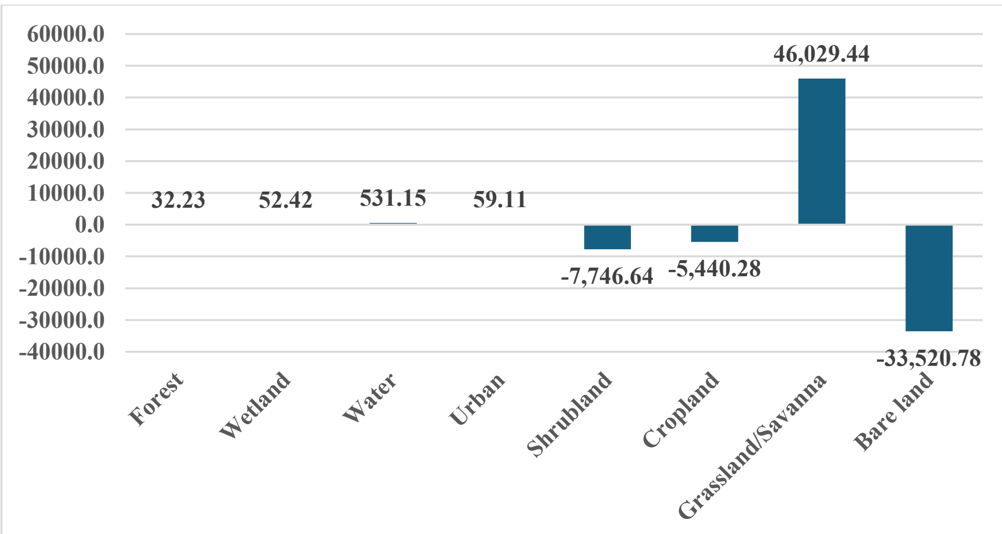


Figure 4.2. LULC change in Sudan (2003 to 2022)

Other notable observations from the LULC analysis include a slight decline in cropland areas, which decreased by approximately 5,440 km^2. Shrubland experienced a more significant reduction of about 7,746 km^2, potentially indicating a transformation in vegetation structure or degradation into grassland or bare land. Urban areas, although limited in spatial coverage, expanded modestly by 59 km^2, suggesting a gradual trend toward urbanization. Additionally, there were minor increases in the extent of wetlands, forests, and water bodies; however, these changes were negligible in terms of their overall percentage contribution to national LULC.

4.2.2 Land Cover Transitions and Vegetation Change

To better understand the LULC changes between 2003 and 2022, a LULC transition matrix was developed. This matrix tracks how each LULC category in 2003 changed over time, identifying which categories remained stable and which transitioned into different types. To interpret the environmental significance of these changes, mean NDVI values were calculated for each transition. By combining the transition data with NDVI analysis, it is possible to assess whether specific areas experienced greening, degradation, or remained unchanged. Table 4.2 highlights LULC transitions, offering valuable insight for understanding trends such as vegetation growth, land degradation, or deforestation.

Table 4.2. LULC Transitions and Associated NDVI (2003-2022)

Transition	**Area (km²)**	**Mean NDVI**	**Interpretation**
Bare land to Bare land	1,078,156.72	0.3	Persistent bare areas with low vegetation growth
Bare land to Grassland/Savanna	35,056.99	0.3	Moderate greening; likely natural growth
Bare land to Cropland	2.05	0.5	Strong vegetation gain; possible agricultural expansion
Bare land to Shrubland	1,946.78	0.3	Vegetation recovery towards shrub cover
Cropland to Grassland/Savanna	29,123.75	0.3	Agricultural abandonment with moderate regrowth

Cropland to Cropland	50,191.73	0.3	Stable agricultural areas
Grassland/Savanna to Cropland	23,893.91	0.3	Cropland expansion into savanna
Grassland/Savanna to Bare land	3,250.73	0.3	Degradation is likely due to overgrazing or drought
Shrubland to Grassland/Savanna	9,544.19	0.3	Possible shift in vegetation type or improved biomass cover

The largest area of stability was bare land, remaining bare, covering over 1 million km^2. This persistent pattern highlights regions that have experienced little to no vegetation growth over two decades. This finding identifies regions that have shown potential areas from which the desert will spread. This persistence of degraded conditions is consistent with research on ecological thresholds and alternative stable states, where severely degraded lands may become locked into degraded conditions that are difficult to reverse (Scheffer et al., 2001).

On the other hand, transitions from bare land to vegetated classes, particularly grassland/savanna and shrubland, represent positive ecological shifts and indicate areas of vegetation growth contrary to the prevailing desertification hypotheses. The transitions from bare land to vegetated classes, while covering smaller areas, represent critical opportunities for landscape restoration. The 46,000 km^2 expansion of grassland/savanna areas suggests that natural regeneration and human-influenced processes are active in certain regions, possibly facilitated by improved rainfall patterns, reduced grazing pressure, or active restoration interventions. This finding is encouraging when viewed in the context of the Great Green Wall (GGW) initiative, which aims to restore 100 million hectares of degraded land across the Sahel by 2030 (Mirzabaev et al., 2021; UNEP, 2012). Recent remote sensing study analyses reveal that GGW initiative regions have experienced trends in increasing vegetation cover (NVDI) (Deng et al., 2024). According to the UNCCD (2020), the GGW initiative has successfully produced 1.9 million plants and seedlings for restoration activities, and 2.3 million hectares of land have been restored, including 85,000 hectares of degraded land and the Assisted Natural Regeneration (ANR) of about 2,500 hectares of forests.

Notably, agricultural land remained relatively stable, with over about 50,000 km^2 of cropland persisting across both years. However, the transitions of some cropland to grassland/savanna or bare land suggest local-scale abandonment or land degradation. The mean NDVI values associated with each transition further underscore the vegetation dynamics. Transitions to cropland typically recorded the highest NDVI values (up to 0.5), indicating denser vegetation, while transitions to bare or degraded lands had lower NDVI values (0.2-0.3)

The observed spatiotemporal patterns in LULC change suggest that, while Sudan continues to be dominated by bare and semi-arid landscapes, there has been a modest by meaningful shift toward increased vegetation cover in some areas. The expansion of grassland and savannas, along with gains in shrubland and cropland in specific zones, points to localized improvements in land conditions. These improvements are possibly driven by reduced land pressure, climate variability, or sustainable land management practices.

4.3 Spatiotemporal Variations in Vegetation Cover in Sudan

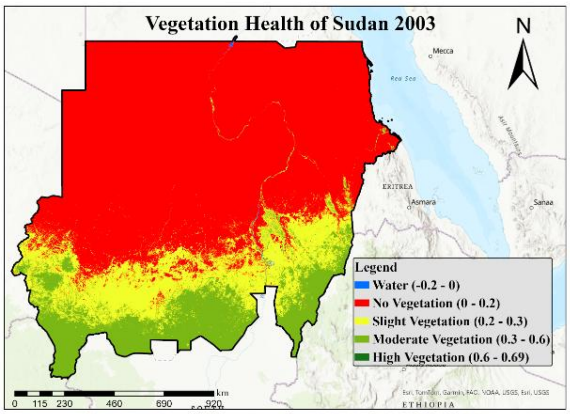
This section presents the results related to the second objective of the study, which is to evaluate the spatiotemporal variations in vegetation cover over the past twenty years using NDVI and LULC data obtained from satellite imagery in Sudan. The analysis was conducted using multitemporal NDVI data derived from the MOD13QI satellite product, which served as an effective indicator of vegetation health and LULC dynamics in arid and semi-arid regions. Changes in NDVI values over the study area period provided insight into the loss or recovery of vegetative cover across Sudan, thereby helping to map the areas undergoing degradation. The results are organized into three key components as follows:

1) NDVI-based vegetation classification for 2003 and 2022, illustrating the status of vegetation and barren lands at both time points,
2) Spatiotemporal NDVI change detection, identifying areas of vegetation loss, gain, and stability over the study period, and
3) State-level analysis of average NDVI change, offering a detailed view of vegetation trends across Sudan's 18 states.

These findings collectively provide a spatial and quantitative assessment of the vegetation status in Sudan, highlighting both vulnerable regions and areas demonstrating ecological improvement. This is supported by thematic maps, statistical summaries, and interpretation of patterns observed across the country.

4.3.1 NDVI-Based Vegetation Classification

In this study, MODIS-derived NDVI data from 2003 and 2022 were classified based on the NDVI value range from -1 to 1. According to Al-doski et al. (2013), the water, cloud, and snow tend to reflect more light in the visible band than near-infrared band, resulting in negative NDVI values. Features like bare soil and rock ground typically have NDVI values of around zero. Healthy green vegetation, however, reflects more significantly in the near-infrared band than in the visible, leading to high NDVI values closer to +1. Based on this information, the two dates of NDVI images were classified into five classes using the NDVI value ranges. The classes included Water (-0.2-0), No Vegetation (0-0.2), Slight Vegetation (0.2-0.3), Moderate Vegetation (0.3-0.6), and High Vegetation (0.6-0.75) as shown in Figures 4.3a and 4.3b.



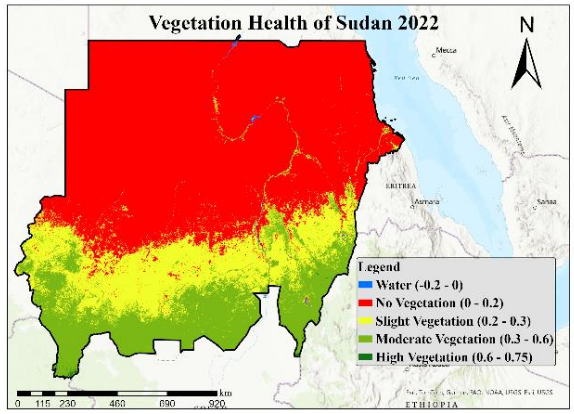


Figure 4.3a. NDVI map of 2003 Figure 4.3b. NDVI map of 2022

A notable and generally positive trend of vegetation growth was observed across Sudan during the study period. As shown in Figure 4.2, the No Vegetation class, which was the dominant LULC in 2003, covered approximately 1,276,215.83 km^2 (69.2%) of the country. By 2022, this significantly reduced to 1,175,916.69 km^2 (64.0%), marking a substantial decrease of 100,299.15 km^2 or 5.4%. This reduction reflects a promising shift in land cover towards categories with denser vegetation.

In line with this, areas categorized under Slight Vegetation saw a considerable expansion, increasing from 298,129.97 km^2 in 2003 to 332,499.52 km^2 in 2022, a gain of 34,369.55 km^2 (1.9%). Similarly, Moderate Vegetation also expanded remarkably, gaining 62,950.37 km^2 (3.4%) over the same period. These changes collectively indicate a progressive increase in vegetation cover across large parts of Sudan, particularly in regions that previously exhibited sparse vegetation. Even the High Vegetation class, despite its relatively limited spatial extent, demonstrated a marked increase, growing from 332.11 km^2 in 2003 to 2,384.17 km^2 in 2022, an increase of over 2,000km^2. These positive shifts in high vegetation areas could be attributed to a combination of factors, including improved land management practices, afforestation efforts, expansion of irrigation, or localized climatic changes that favor vegetation growth. Furthermore, a minor increase of 883.27 km^2 was observed in areas classified as Water. While this change is small in absolute and percentage-wise (0.0%), it may reflect seasonal variations, improved water body detection, or localized hydrological shifts.

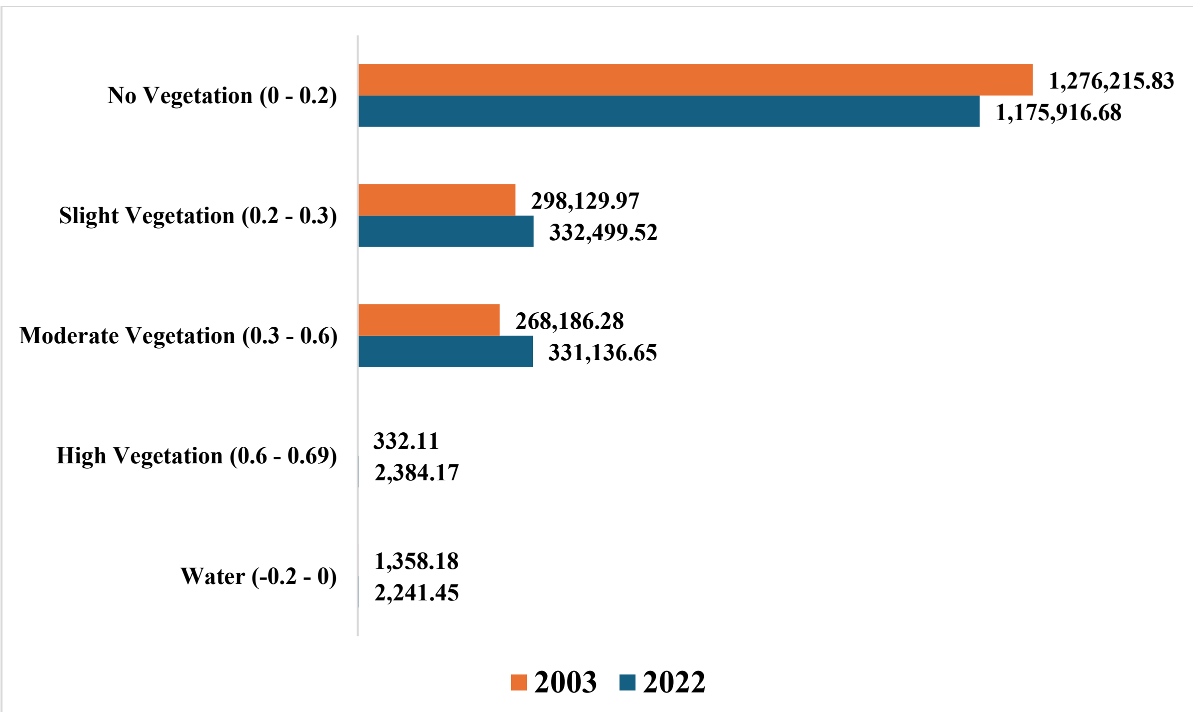


Figure 4.4. Proportion of NDVI corresponding to landmass area for 2003 and 2022 (km^2)

Overall, these findings strongly suggest a positive trend in vegetation reestablishment after decades of drought, with a net gain in areas falling under higher NDVI thresholds. While these results offer encouraging evidence of vegetation growth, possibly reflecting the combined effects of land rehabilitation programs, climate variability, or shifts in LULC patterns, further investigation is necessary to distinguish between natural regeneration and human-induced transformations.

4.3.2 Spatiotemporal NDVI Change Detection

A detailed spatiotemporal analysis of NDVI changes provided a nuanced view of vegetation dynamics across Sudan between 2003 and 2022, identifying areas of both concern and improvement. The landscape was categorized into five distinct classes based on the magnitude of vegetation change: significant vegetation loss, moderate loss, no change, moderate gain, and significant vegetation gain, as shown in Figure 4.5.

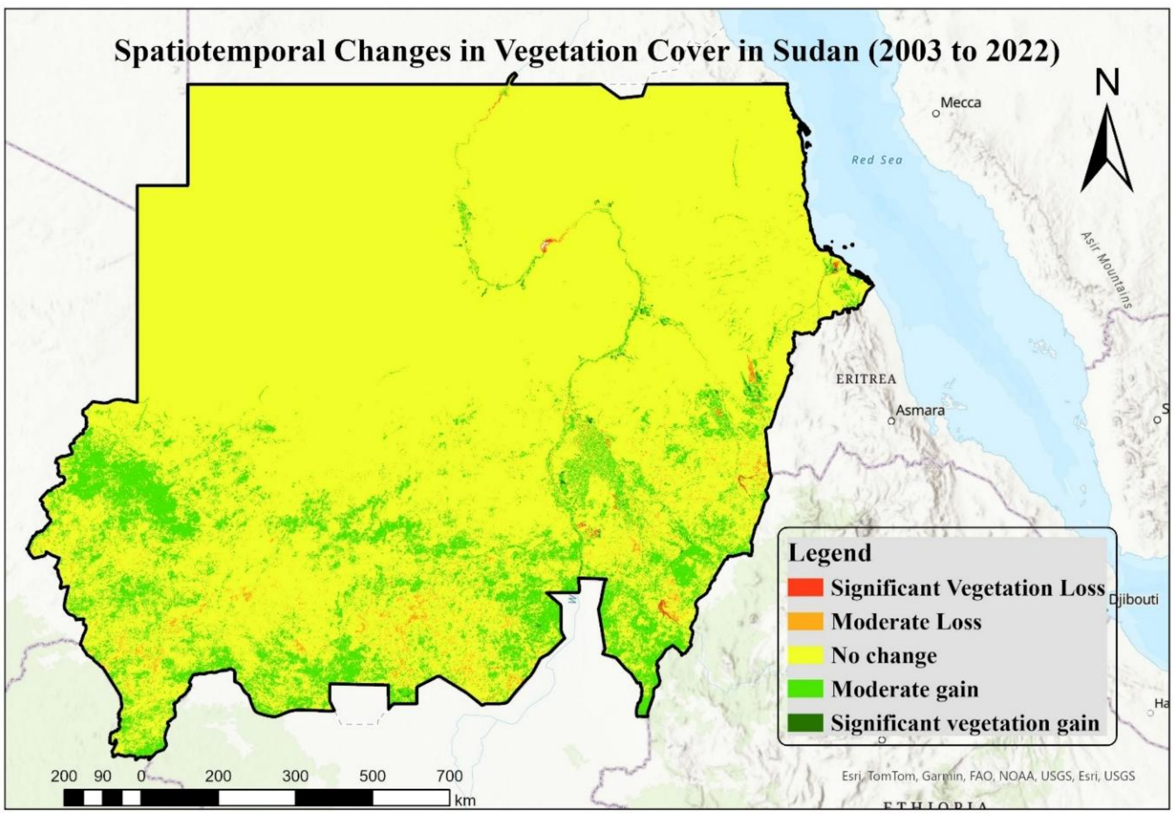


Figure 4.5. Spatiotemporal Changes in NDVI in Sudan (2003 to 2022)

The analysis revealed that the vast majority of Sudan's landmass, approximately 88.1%, experienced negligible change in vegetation cover, indicating a general ecological stability over the 20 years. However, certain areas did show decline; about 0.8% of land (14,039.82 km^2) underwent moderate vegetation loss, and about 0.1% (1,069.88 km^2) experienced significant vegetation degradation. These localized losses are likely linked to factors such as climate variability, prolonged droughts, ongoing land degradation processes, and unsustainable land-use practices.

Likewise, areas demonstrating vegetation recovery were more extensive and substantial. Moderate vegetation gain accounted for about 11.0% of the total area (202,285.4 km^2), indicating widespread positive shifts. Furthermore, 0.1% (1,823.26 km^2) of the country experienced significant vegetation increase. These encouraging positive changes may be associated with various factors, including improved land management practices, targeted afforestation programs, or favourable climatic conditions in specific regions. This spatial variation vividly underscores the heterogeneous nature of desertification and vegetation dynamics in Sudan, which are influenced by a complex interplay of both natural environmental factors and human-driven activities.

4.3.3 State-Level Analysis of Average NDVI Change

A state-level analysis of average NDVI change was conducted to understand the spatial variability of vegetation trends across Sudan, a country characterized by diverse ecological zones and socio-political context. Mapping NDVI changes at the state level is crucial for a better understanding of how vegetation dynamics vary across the entire country, where localized greening or degradation patterns may be overlooked at the national-level assessment. Sudan is a country where political instability, conflict, displacement, and uneven resource allocation have had impacts on LULC, environmental degradation, and rural livelihoods.

According to Ahmed et al. (2024), natural causes of LULC changes include droughts, natural fires, and changes and variations in climatic conditions, while the common anthropogenic drivers of LULC changes comprise agriculture expansion, deforestation, urbanization, mining, and armed conflicts. Armed conflicts have a great impact on land-based resources, especially vegetation and wildlife (M. Mohamed et al., 2020). In states affected by conflict and displacement, such as Darfur and parts of South Kordofan, land abandonment or unsustainable exploitation may influence vegetation cover differently than in stable areas, which may lead to a decrease or increase in NDVI. As indicated in Figure 4.6, analysis of average NDVI values by state-level between 2003 and 2022 reveals varying trends across the entire country's 18 states. All states recorded a positive NDVI change, indicating an overall trend of vegetation increase, albeit at varying degrees.

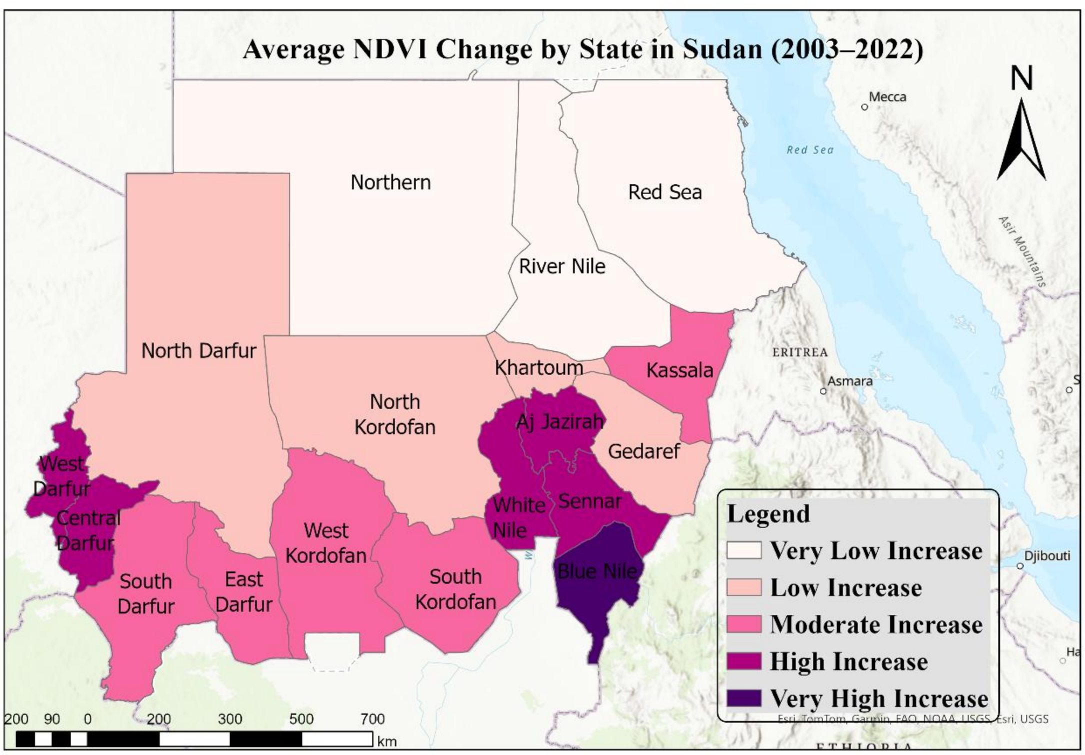


Figure 4.6. NDVI Change by State (2003-2022)

States such as Blue Nile (ΔNDVI = +0.044). Central Darfur (+0.034), West Darfur (+0.034), and White Nile (+0.033) experienced the most notable moderate to significant vegetation gains. These improvements could potentially be a result of advantageous local climate conditions, the implementation of reforestation projects, or a reduction in land pressure usage, possibly due to migration or conflict-related displacement in some parts of the regions.

On the other hand, states like Northern (+0.005), Red Sea (+0.007), and West Darfur (+0.034) showed minimal vegetation changes as indicated by NDVI values, reflecting the harsh arid conditions and limited potential for vegetation recovery in these desert-dominated regions. However, the persistence of degraded conditions in northern Sudan reflects challenges that are common across the arid margins of the Sahara. According to Huang et al. (2016), most arid regions may face increasing challenges as global temperatures continue to rise. This is largely reflective of their inherent arid nature and the limited potential for natural vegetation growth within these regions. Interestingly, Aj Jazirah and Sennar also recorded noticeable improvements (both +0.03), which could be driven by the presence of irrigation-supported agriculture and proximity to the Blue Nile.

Table 4.3. Summary of NDVI Change Across Sudan States (2003-2022)

States	**NDVI 2003**	**NDVI 2022**	**NDVI Change**	**Interpretation**
Aj Jazirah	0.231	0.262	0.03	Noticeable vegetation improvement
Blue Nile	0.365	0.409	0.044	Significant vegetation gain
Central Darfur	0.303	0.337	0.034	Moderate improvement in vegetation cover

East Darfur	0.321	0.346	0.025	Slight vegetation improvement
Gedaref	0.259	0.279	0.019	Slight improvement in vegetation
Kassala	0.165	0.185	0.021	Mild increase in vegetation cover
Khartoum	0.133	0.146	0.014	Slight vegetation recovery
North Darfur	0.127	0.143	0.016	Slight vegetation gain
North Kordofan	0.142	0.157	0.015	Small but positive vegetation change
Northern	0.098	0.103	0.005	Minimal vegetation improvement
Red Sea	0.089	0.096	0.007	Minimal vegetation improvement
River Nile	0.097	0.103	0.006	Minimal vegetation improvement
Sennar	0.299	0.329	0.03	Noticeable vegetation improvement
South Darfur	0.345	0.374	0.029	Moderate vegetation gain
South Kordofan	0.35	0.375	0.025	Slight vegetation improvement
West Darfur	0.241	0.275	0.034	Moderate vegetation recovery
West Kordofan	0.268	0.294	0.026	Slight increase in vegetation
White Nile	0.215	0.249	0.033	Moderate vegetation improvement

The consistent increase in NDVI values, as shown in Table 4.3 across all states, though modest in the more arid regions, reflects an encouraging trend towards vegetation restoration or stabilization. However, it is equally important to acknowledge that the limited areas of vegetation loss, though small in percentage, still represent significant ecological concerns that demand prioritization in future desertification mitigation strategies.

4.4 Spatial Patterns of Climatic and Socioeconomic Drivers and Their Statistical Relationships to Vegetation in Sudan

This section addresses the third objective of the study, which seeks to analyze the relationships between vegetation, climatic factors (precipitation and temperature variations), and population density in Sudan. Understanding these spatial relationships is crucial for developing targeted strategies to combat land degradation and promote sustainable land management practices.

4.4.1 Maximum Temperature Distribution

The spatial distribution of maximum temperature in Sudan for 2022, shown in Figure 4.7, reveals a clear gradient in temperature patterns across the country. The map displays five temperature classes, ranging from 30°C (86°F) to 47°C (116.6°F), emphasizing spatial variability across the Sudan. The northern and northeastern parts of Sudan experienced the highest maximum temperature, which ranges from 45°C (113°F) to 47°C (116.6°F). These areas are made up of bare land, as shown in the land cover maps. The areas, including parts of the Northern State and the Red Sea regions, are characterized by arid and desert climates. The persistent high temperatures in these regions underscore the severe climatic conditions and contribute to desertification processes.

The western, northwest, southwestern, and southeastern parts of Sudan recorded relatively lower maximum temperatures ranging between 30°C (86°F) and 43°C (109.4°F). These regions are known for receiving higher precipitation, which helps to mitigate some of the extreme heat effects. According to Niang et al. (2014), consistent warming trends observed in the Sahel and surrounding arid zones over the decades exacerbate environmental stress and reduce agricultural productivity. Prolonged exposure to high temperatures, particularly above 43°C (109.4°F), can accelerate evapotranspiration rates, reduce soil moisture, and increase vegetation stress. These processes are directly linked to the expansion of desertification fronts (Huang et al., 2020).

While the NDVI indicated a generally positive trend across Sudan with an increase in slight and moderate vegetation and a decrease in areas with no vegetation, the northern and central parts, which showed negative NDVI values indicating an absence of vegetation due to arid characteristics, are precisely the regions experiencing the highest temperatures. This demonstrates how temperature profoundly impacts vegetation and its significant implications for land cover dynamics, agricultural viability, and water resource management across Sudan.

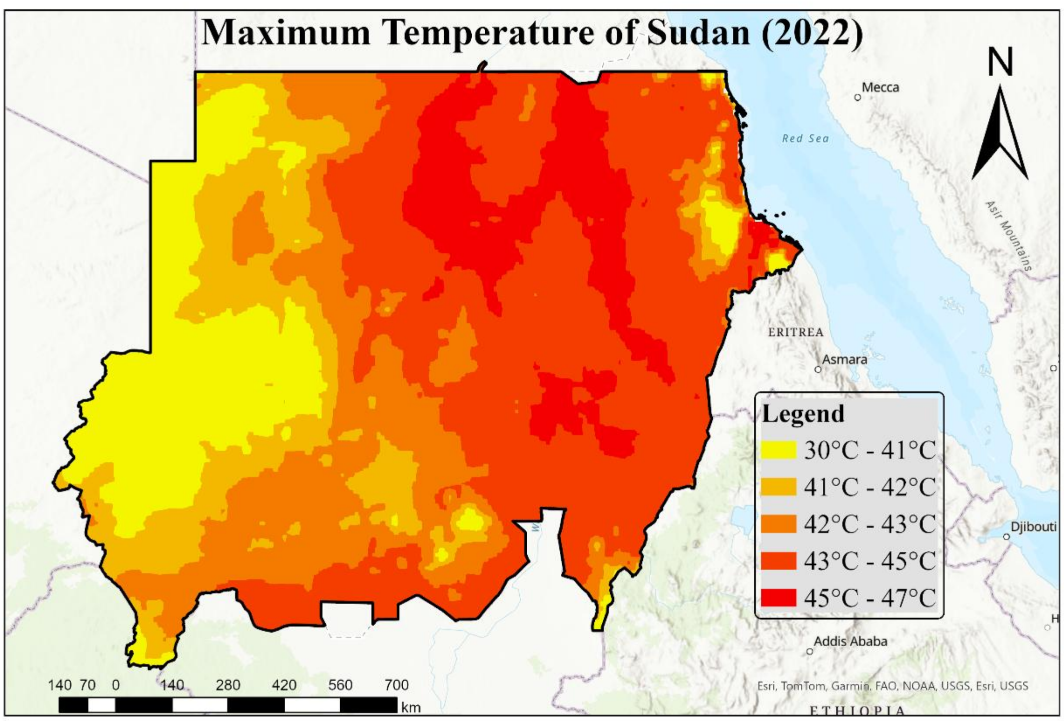


Figure 4.7. Maximum Temperature Distribution Map of Sudan.

4.4.2 Rainfall Distribution

The spatial distribution of rainfall in Sudan in 2022 showed a significant implication for the patterns and vegetation across the country. As shown in Figure 4.8, the northern and central regions of Sudan experienced the lowest average annual rainfall, ranging from 0 - 200mm. The extensive arid zone, which spans the majority of northern Sudan, including areas near the Red Sea and bordering Egypt and Libya, and highly vulnerable to desertification. The persistent low precipitation in the zone exacerbates soil degradation, limits vegetation cover, and intensifies the encroachment of desert-like conditions. Moving southward, the rainfall gradually increases. The semi-arid belt, represented in orange, receives between 200mm and 400mm annually. This transitional zone, while receiving slightly higher precipitation, remains critically dry and susceptible to climatic shocks. Notably, regions in this category have experienced fluctuations in rainfall that fail to sustain reliable agricultural activity, further accelerating land degradation through overgrazing and deforestation.

The savannah zones in the central and southern parts of Sudan exhibit significantly higher rainfall. These include 400-700mm, covering central Sudan, providing marginally suitable conditions for rain-fed agriculture and grazing activities. Areas receiving 700mm – 1000mm, which covers the south-eastern areas, where rainfall is more consistent and supports more vegetation cover. Areas in the receiving 1000m and above, which are closer to the southern border, indicate relatively humid zones with lower susceptibility to desertification. These spatial patterns highlight a clear positive correlation between rainfall variations and vegetation, as rainfall is a primary driver of vegetation growth in arid and semi-arid regions. Studies conducted by (Dardel et al., 2014; Nicholson et al., 2018) revealed that rainfall variability is a determinant of vegetation health and productivity across the Sahel. Areas receiving below 400mm of rainfall per year, which constitute more than half of the Sudan's landmass, are at greater risk. This is consistent with existing literature suggesting that regions receiving less than 400mm annually are ecologically fragile and prone to land degradation under climatic stress and unsustainable land use practices (Campbell & Wynne, 2014; UNEP, 2012).

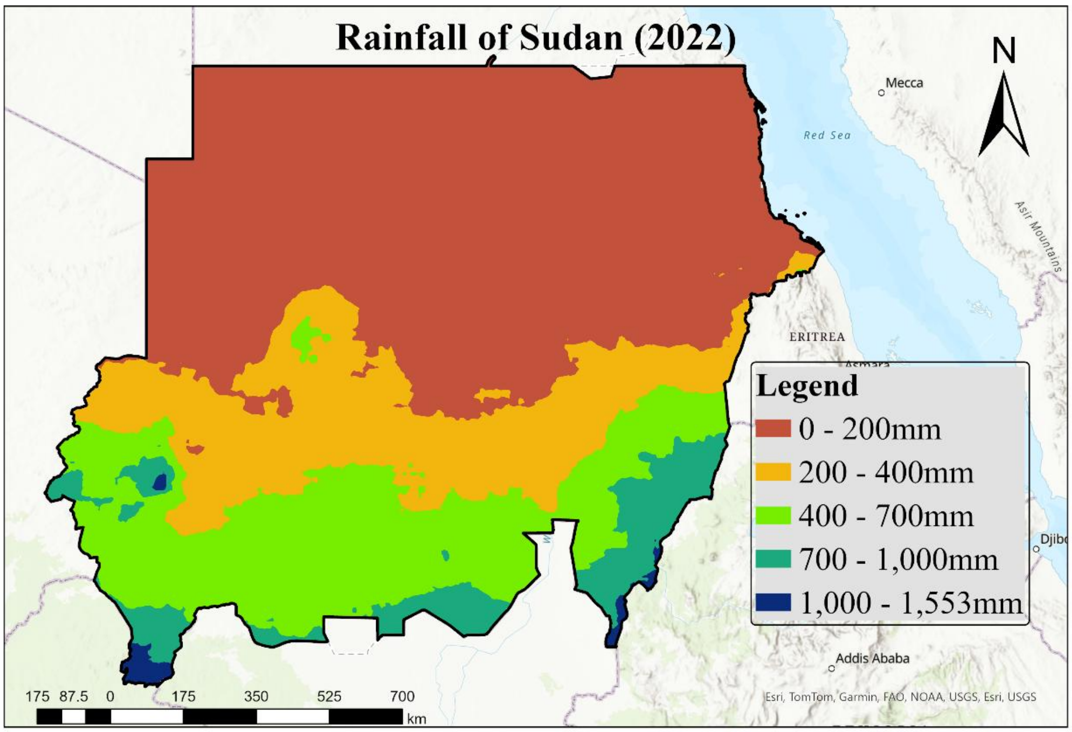


Figure 4.8. Rainfall Distribution of Sudan.

4.4.3 Population Distribution

Sudan's population distribution of Sudan as of 2020 reveals a striking uneven landscape of human settlement and dynamic growth trends, carrying significant implications for environmental pressure and land degradation across the country. The 2020 data was used to compare 2022 data, as it was the most recent dataset of population density covering Sudan available from the WorldPop database. As shown in Figure 4.9, the densest concentrations of people are predominantly found in the central and eastern regions, encompassing the capital, Khartoum, alongside major urban centers such as Kassala, Nyala, and Al-Ubayyid. A closer examination unveils five distinct population density classes, vast stretches of the west, north, and east are sparsely populated, typically with 1-10 persons/km^2, covering the largest proportion of the land at 1,139,401.13 km^2 (61.0%). These areas correspond to the harsh, arid northern and northwestern regions that receive minimal annual rainfall (0-200mm) and experience the highest maximum temperatures (45°C to 47°C or 113°F to 116.6°F), supporting extremely sparse populations due to severe desert conditions and limited water availability. A transitional belt holds about 11-25 persons/km^2, encompassing 366,076.03 km^2 (19.6%) of the landmass. Peripheral urbanizing zones feature about 26-50 persons/km^2, covering about 186,816.34 km^2 (10.0%). The major urban settlements are characterized by about 51-500 persons/km^2, extending over 168,320.82 km^2, and finally, the Khartoum metropolitan area exhibits the highest densities, ranging from 500 to about 7,210 persons/km^2, occupying 7,043.26 km^2 (0.4%) of the landmass. While there is sparse population density in arid zones, the fertile central belts, particularly along the Blue and White Nile rivers, boast higher population densities. This pattern is linked to Sudan’s diverse climatic and ecological conditions, benefiting from moderate rainfall, better infrastructure, and enhanced economic opportunities.

The distribution of population densities in 2020, as indicated in Figure 4.9, highlights a clear concentration in certain areas while vast regions remain sparsely inhabited. These high population concentrations, especially around Khartoum, place immense pressure on land resources. This pressure leads to phenomena such as urban sprawl, vegetation loss, and intensified land degradation. According to Güneralp et al. (2017), growing urban areas pose significant threats to ecosystem integrity and biodiversity. The growth in these areas, fueled by both natural increase and internal displacement from conflicts and climate-induced migration from drier, less hospitable regions, escalates demands on land for housing, agriculture, and fuelwood. These demands often result in deforestation, soil erosion, and reduced vegetation cover, all of which are recognized as key indicators of desertification.

While the overall Normalized Difference Vegetation Index (NDVI) assessment for the study period (2003 - 2022) indicated a generally positive trend across Sudan, with a significant decrement in areas classified as having no vegetation (from 69.2% to 64%) and an increase in slight and moderate vegetation, the evolving spatial patterns of human presence across profoundly interact with the country's diverse climatic and land cover characteristics. This presents a persistent challenge for sustainable land management, particularly in regions already vulnerable to climate variability and water scarcity.

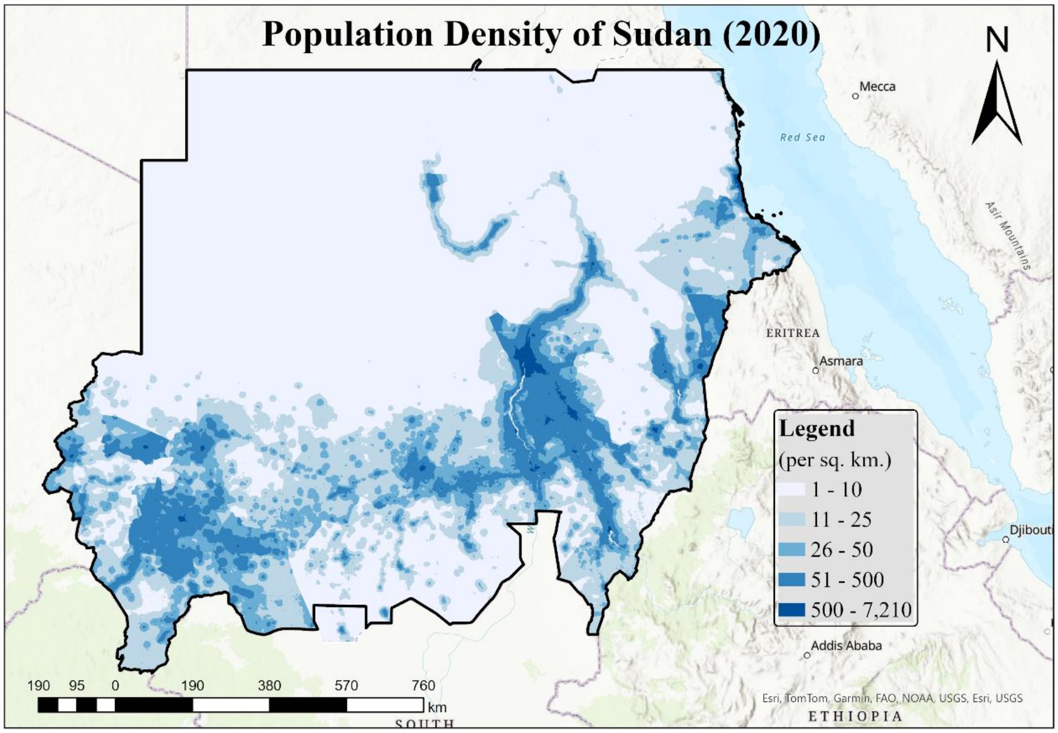


Figure 4.9. Population Density Distribution of Sudan.

4.5 Spatial Relationship between NDVI and Explanatory Variables

In the quest to understand the spatial relationship between desertification drivers in Sudan, an Ordinary Least Squares (OLS) regression analysis was conducted utilizing the Normalized Difference Vegetation Index (NDVI) as the dependent variable, given its reliability as an indicator of vegetation health and land cover changes, particularly in arid and semi-arid regions. The independent variables included rainfall, temperature, and population density.

Table 4.4 Ordinary Least Squares (OLS) Regression Results for Desertification Variables

Variable	Coefficient	P-Value
Independent Variables		
Intercept	0.0261	0.000
TEMPERATURE	0.0597	0.000
RAINFALL	0.5455	0.000
POPULATION DENSITY	-0.0404	0.011

The overall model, as shown in Table 4.4, demonstrated a strong statistical significance, as this approach encompassing 2,223 observations revealed a strong overall model fit with an R-Squared of 0.794130, indicating that approximately 79.4% of the variance in NDVI can be explained by various independent variables. Examining the individual coefficients as presented in the result table, rainfall emerged as a highly statistically significant predictor of NDVI, with a coefficient of 0.5455 and a p-value of 0.000 ($p > 0.54$), strongly aligning with environmental understanding that higher rainfall supports increased vegetation health and mitigates desertification, particularly in Sudan's southern regions. Temperature also showed a statistically significant relationship with NDVI, with a positive coefficient of 0.0597 and a p-value of 0.000 ($p > 0.045$). However, this positive coefficient within the model contrasts with broader qualitative observations that high temperatures, especially above 43°C (109.4°F), accelerate evapotranspiration, reduce soil moisture, and increase vegetation stress, leading to reduced NDVI values in the arid northern and central parts of Sudan. This suggests a complex interaction not fully captured by a simple linear relationship. The population density, on the other hand, despite having a negative coefficient of -0.0404, was also found to be statistically significant at a p-value of 0.011

($p > 0.05$). Nonetheless, its qualitative impact is profound, as high population density concentrations, particularly around Khartoum, are recognized to exert immense pressure on the land resources, leading to urban sprawl, deforestation, soil erosion, and reduced vegetation cover, which are key indicators of desertification.

In summary, while rainfall is confirmed as a crucial environmental driver of vegetation health, the complex and potentially contradictory influence of temperature, along with the qualitative significance of population density, highlights the multifaceted nature of desertification in Sudan and underscores the need for sustainable land management strategies.

Chapter 5: Summary and Discussion

5.1 Introduction

The comprehensive analysis of LULC dynamics and vegetation patterns in Sudan between 2003 and 2022 reveals a complex environmental narrative that provides both encouraging signs of recovery and persistent challenges. The study's finding contributes significantly to our understanding of vegetation trends in the Sahel region while highlighting the entangled relationships between vegetation cover, climatic, socioeconomic, and spatial factors that drive environmental change in Sudan.

Numerous studies have consistently confirmed that desertification is a critical and ongoing environmental challenge in Sudan, particularly in the arid and semi-arid regions of the country. Research by Rahamtalla (2018) stated that Sudan was among the countries that had been affected by desertification, and that, is likely to worsen in the future. Mohamed (2016) revealed significant southward expansion of desert areas in North Sudan, driven largely by declining rainfall, rising temperatures, and unsustainable land use practices. Similarly, Khairalseed (2015) reported that over 500,000 km^2 of land in Sudan are affected by desertification, and that natural disasters in the form of drought and flooding have historically occurred in the region (Ahmed et al., 2018). However, the results of this study reveal a contrasting trend of vegetation growth, where LULC and NDVI values indicated a positive shift towards vegetation gain between 2003 and 2022. This observed improvement in vegetation cover may be attributed to local reforestation, Assisted Natural Regeneration (ANR), and degraded land restoration initiatives under programs such the Great Green Wall Initiatives (CGIAR, 2022; UNCCD, 2020).

5.2 Key Findings and Their Significance

5.2.1 LULC and Vegetation Cover Trends in Sudan

The most striking findings of this research are the shift toward increased vegetation cover across significant portions of Sudan, which are characterized by a reduction in areas classified as No Vegetation from 69.2% to 64.0% and a corresponding increase in Slight and Moderate Vegetation categories. This 5.4% improvement, representing over 100,000 km² of land transitioning to higher vegetation classes, aligns with the broader regreening of the Sahel phenomenon across the region. The 46,000 km² expansion of grassland/savanna areas and the modest but meaningful increases in forest and wetland coverage demonstrate that ecological recovery from desertification is possible even in severely degraded areas when conditions are favorable.

However, these positive trends must be viewed alongside persistent challenges. The substantial reduction in shrubland coverage, nearly halving from 14,042.53 km² to 6,295.89 km², represents a concerning loss of woody vegetation that plays a critical ecological role in arid environments.

5.2.2 Climate as the Primary Driver of Vegetation Growth

The analysis conducted confirms rainfall as the significant predictor of vegetation health, showing a strong positive correlation with vegetation indices. Sudan exhibits a clear rainfall from the arid north (0-200mm annually) to the wetter south (over 1000mm), which largely determines vegetation recovery potential and agricultural productivity. While temperature patterns reveal that moderate increases might benefit some growth, extreme maximum temperatures reaching 45°C

(113°F).) - 47°C (116.6°F) in the northern regions acts as a dominant limiting factor, resulting in minimal vegetation growth.

5.2.3 Human Dimension

The analysis reveals concentrated human pressure in urban centers like Khartoum, causing disproportionate environmental impacts despite occupying a minimal land area. High population densities over 7,000 persons/km² in these areas exert intense pressure on surrounding land resources, leading to urban sprawl, deforestation, and accelerated land degradation. Although population density's statistical significance was complex, quality evidence undeniably shows its negative impact on vegetation, highlighting the need for more robust modeling approaches to capture these non-linear human-environment interactions.

5.3 Integrated Land Management: Sudan's Path to Recovery

Sudan's environmental changes fit into the bigger regional picture of the Sahel's re-greening, showing encouraging signs that land can indeed recover. Similar to successful efforts in other Sahelian countries like Niger and Burkina Faso, where farmer-managed natural regeneration has proven effective, Sudan has seen significant portions of its land shift to higher vegetation cover. However, this recovery may not be uniform as the northern regions still face persistent challenges, reflecting the broader problem of dryland expansion along the Sahara's arid margins due to climate change. This highlights that environmental outcomes depend heavily on local factors, meaning that there is no single solution that will work everywhere across Sudan's diverse landscape.

For effective land management, it is crucial to focus on smart water management strategies, including strategic irrigation and water harvesting, since rainfall is the primary driver of vegetation health. While irrigation can help restore degraded areas, it is vital to avoid unsustainable water extraction that could cause long-term problems.

5.4 Future Research and Recommendations

This study opens urgent avenues for future research that could enhance understanding of desertification processes, looking into ground-truthing studies to validate remote sensing observations, incorporating multiple vegetation indices, soil assessments, and biodiversity surveys for a more comprehensive picture of ecosystem health. More robust modeling approaches, such as machine learning, are necessary to capture the nonlinear effects of population pressure on the environment. Investigation into the dramatic reduction in shrubland coverage is crucial to understanding its drivers and informing conservation strategies.

Finally, integrating climate projections with LULC modeling is essential for understanding future vulnerability, prioritizing interventions. Given the strong relationship between rainfall and vegetation health demonstrated in this study, understanding how changing precipitation patterns might affect different regions of Sudan is essential for long-term planning.

5.5 Conclusion

The evidence presented in this study demonstrates that while Sudan faces significant challenges from desertification, there are also encouraging signs of vegetation growth and resilience. The modest shift towards increased vegetation cover in many regions, coupled with the identification of specific drivers and spatial patterns of change, provides a foundation for evidence-based management strategies. The heterogeneous nature of the diverse landscape across Sudan suggests that management strategies should be spatially differentiated. Areas demonstrating natural regeneration may benefit from protection and enhancement measures, while severely degraded regions may require intensive restoration interventions.

The success of efforts to combat desertification in Sudan will depend on the ability to integrate scientific understanding with practical management approaches that address both environmental and socioeconomic factors. This study provides a crucial baseline for monitoring future changes and evaluating the effectiveness of intervention strategies. Through continued collaboration between researchers, policymakers, and local communities, and by implementing comprehensive approaches informed by rigorous scientific analysis and sensitive local needs, there is a hopeful path forward to restore degraded landscapes and build more resilient ecosystems capable of supporting both human communities and biodiversity in the face of ongoing environmental challenges.

References

AbdelRahman, M. A. E. (2023). An overview of land degradation, desertification and sustainable land management using GIS and remote sensing applications. *Rendiconti Lincei. Scienze Fisiche e Naturali*, *34*(3), 767–808. https://doi.org/10.1007/s12210-023-01155-3

Abdi, O. A., Glover, E. K., & Luukkanen, O. (2013). Causes and Impacts of Land Degradation and Desertification: Case Study of the Sudan. *International Journal of A Griculture and Forestry*, *3*(2), 40–51. https://doi.org/10.5923/j.ijaf.20130302.03

Adam, H. E. (2011). *Integration of Remote Sensing and GIS in Studying Vegetation Trends and Conditions in the Gum Arabic Belt in North Kordofan, Sudan*. Technical University of Dresden.

Adeagbo, O. A., Ojo, T. O., & Adetoro, A. A. (2021). Understanding the determinants of climate change adaptation strategies among smallholder maize farmers in South-west, Nigeria. *Heliyon*, *7*(2), e06231. https://doi.org/10.1016/j.heliyon.2021.e06231

Ahmed, A., Rotich, B., & Czimber, K. (2024). Assessment of the environmental impacts of conflict-driven Internally Displaced Persons: A sentinel-2 satellite based analysis of land use/cover changes in the Kas locality, Darfur, Sudan. *PLOS ONE*, *19*(5), e0304034. https://doi.org/10.1371/journal.pone.0304034

Ahmed, A., Saad, S. A. M., Seedahmed, A. M. A., Ossman, S. A. M., & Eldoma, A. M. A. (2018). Combating Desertification in Sudan: Experiences and Lessons Learned. In *World Sustainable Development Outlook* (1st ed., Vol. 16, pp. 141–155). WASD. https://doi.org/10.47556/B.OUTLOOK2018.16.10

Al-doski, J., Mansor, S. B., & Shafri, H. Z. M. (2013). *NDVI Differencing and Post-classification to Detect Vegetation Changes in Halabja City, Iraq*. *1*(2), 01–10.

Alredaisy, S. M. A. H. (2024). *The Physical Geography of Sudan: A State's Power and Threats*. *5*(1).

Amani, M., Ghorbanian, A., Ahmadi, S. A., Kakooei, M., Moghimi, A., Mirmazloumi, S. M., Moghaddam, S. H. A., Mahdavi, S., Ghahremanloo, M., Parsian, S., Wu, Q., & Brisco, B. (2020). Google Earth Engine Cloud Computing Platform for Remote Sensing Big Data Applications: A Comprehensive Review. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *13*, 5326–5350. https://doi.org/10.1109/JSTARS.2020.3021052

Babiker, I. A. (2015). Animal Feed Industry in Sudan, Current Status, Problems and Prospects. *Journal of Dairy, Veterinary & Animal Research*, *2*(3). https://doi.org/10.15406/jdvar.2015.02.00036

Balima, L. H., Nacoulma, B. M. I., Da, S. S., Ouédraogo, A., Soro, D., & Thiombiano, A. (2022). Impacts of climate change on the geographic distribution of African oak tree (Afzelia africana Sm.) in Burkina Faso, West Africa. *Heliyon*, *8*(1), e08688. https://doi.org/10.1016/j.heliyon.2021.e08688

Bauer, S., & Stringer, L. C. (2009). The Role of Science in the Global Governance of Desertification. *The Journal of Environment & Development*, *18*(3), 248–267. https://doi.org/10.1177/1070496509338405

Bestelmeyer, B. T., Okin, G. S., Duniway, M. C., Archer, S. R., Sayre, N. F., Williamson, J. C., & Herrick, J. E. (2015). Desertification, land use, and the transformation of global drylands. *Frontiers in Ecology and the Environment*, *13*(1), 28–36. https://doi.org/10.1890/140162

Brandt, M., Hiernaux, P., Tagesson, T., Verger, A., Rasmussen, K., Diouf, A. A., Mbow, C., Mougin, E., & Fensholt, R. (2016). Woody plant cover estimation in drylands from Earth

Observation based seasonal metrics. *Remote Sensing of Environment*, *172*, 28–38. https://doi.org/10.1016/j.rse.2015.10.036

Burrough, P. A., McDonnell, R., & Lloyd, C. D. (2015). *Principles of geographical information systems* (Third edition). Oxford University Press.

Campbell, J. B., & Wynne, R. H. (2011). *Introduction to remote sensing* (5th ed). Guilford Press.

Campbell, J. B., & Wynne, R. H. (2014). *Introduction to Remote Sensing*.

CGIAR. (2022). *The Great Green Wall Initiative in Sudan: Country Review*.

Chandrashekar, G., & Sahin, F. (2014). A survey on feature selection methods. *Computers & Electrical Engineering*, *40*(1), 16–28. https://doi.org/10.1016/j.compeleceng.2013.11.024

Cornet, A. (2002). *Desertification and its relationship to the environment and development: A problem that affects us all.*

Dardel, C., Kergoat, L., Hiernaux, P., Mougin, E., Grippa, M., & Tucker, C. J. (2014). Re-greening Sahel: 30years of remote sensing data and field observations (Mali, Niger). *Remote Sensing of Environment*, *140*, 350–364. https://doi.org/10.1016/j.rse.2013.09.011

Dawelbait, M., & Morari, F. (2012). Monitoring desertification in a Savannah region in Sudan using Landsat images and spectral mixture analysis. *Journal of Arid Environments*, *80*, 45–55. https://doi.org/10.1016/j.jaridenv.2011.12.011

Deng, A., Hao, X., & Qu, J. J. (2024). A Preliminary Assessment of Land Restoration Progress in the Great Green Wall Initiative Region Using Satellite Remote Sensing Measurements. *Remote Sensing*, *16*(23), 4461. https://doi.org/10.3390/rs16234461

D'Odorico, P., Bhattachan, A., Davis, K. F., Ravi, S., & Runyan, C. W. (2013). Global desertification: Drivers and feedbacks. *Advances in Water Resources*, *51*, 326–344. https://doi.org/10.1016/j.advwatres.2012.01.013

Dregne, H. E. (2002). Land Degradation in the Drylands. *Arid Land Research and Management*, *16*(2), 99–132. https://doi.org/10.1080/153249802317304422

DTE Staff. (2016, July). *Desertification in Africa: 10 things you must know* [Print Edition]. Down To Earth. https://www.downtoearth.org.in/natural-disasters/desertification-in-africa-10-things-you-must-know-54430

El Gamri, T., Saeed, A. B., & Abdalla, AbdallaK. (2021). Rainfall of the Sudan: Characteristics and Prediction. *Journal of Faculty of Arts, University of Khartoum*, *27*. https://doi.org/10.53332/jfa.v27i.624

FAO. (2021). *The State of Food and Agriculture 2021*. FAO. https://doi.org/10.4060/cb4476en

Femia, F., & Werrell, C. E. (2012). *Mali: Migration, Militias, Coups and Climate Change*. *13*.

Fensholt, R., & Proud, S. R. (2012). Evaluation of Earth Observation based global long term vegetation trends—Comparing GIMMS and MODIS global NDVI time series. *Remote Sensing of Environment*, *119*, 131–147. https://doi.org/10.1016/j.rse.2011.12.015

FEWS NET's Integrated Analytical Areas. (2008). In M. E. Brown, *Famine Early Warning Systems and Remote Sensing Data* (pp. 135–155). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-75369-8_8

Field, C. B., & Barros, V. R. (with Groupe d'experts intergouvernemental sur l'évolution du climat). (2014). *Climate change 2014: Impacts, adaptation, and vulnerability Working Group II contribution to the fifth assessment report of the Intergovernmental panel on climate change*. Cambridge university press.

Food and Agricultural Organization of the United Nations. (2017). *Building BRIDGES between Turkey and Africa's Great Green Wall (Project brochure).FAO*.

Friedl, M. A., McIver, D. K., Hodges, J. C. F., Zhang, X. Y., Muchoney, D., Strahler, A. H., Woodcock, C. E., Gopal, S., Schneider, A., Cooper, A., Baccini, A., Gao, F., & Schaaf, C. (2002). Global land cover mapping from MODIS: Algorithms and early results. *Remote Sensing of Environment*, *83*(1–2), 287–302. https://doi.org/10.1016/S0034-4257(02)00078-0

Friedl, M. A., Sulla-Menashe, D., Tan, B., Schneider, A., Ramankutty, N., Sibley, A., & Huang, X. (2010a). MODIS Collection 5 global land cover: Algorithm refinements and characterization of new datasets. *Remote Sensing of Environment*, *114*(1), 168–182. https://doi.org/10.1016/j.rse.2009.08.016

Ganawa, E. (2022). *The Great Green Wall initiative in Sudan Country Review. Bogor, Indonesia: Centre for International Forestry Research (CIFOR) and Nairobi: World Agroforestry (ICRAF)*.

Geist, H. J., & Lambin, E. F. (2002). Proximate Causes and Underlying Driving Forces of Tropical Deforestation. *BioScience*, *52*(2), 143. https://doi.org/10.1641/0006-3568(2002)052[0143:PCAUDF]2.0.CO;2

Gezahagn, N. S. (2016). *Spatial Assessment of NDVI as an Indicator of Desertification in Ethiopia using Remote Sensing and GIS* [Master Thesis in Geographical Information Science, Lund University]. http://lup.lub.lu.se/student-papers/record/8877776

Ghozat, A., Sharafati, A., & Hosseini, S. A. (2022). Satellite-based monitoring of meteorological drought over different regions of Iran: Application of the CHIRPS precipitation product. *Environmental Science and Pollution Research*, *29*(24), 36115–36132. https://doi.org/10.1007/s11356-022-18773-3

Gillespie, T. W., Ostermann-Kelm, S., Dong, C., Willis, K. S., Okin, G. S., & MacDonald, G. M. (2018). Monitoring changes of NDVI in protected areas of southern California. *Ecological Indicators*, *88*, 485–494. https://doi.org/10.1016/j.ecolind.2018.01.031

Glantz, M. H., & Orlovsky, N. (1983). *Desertification: A review of the concept*.

Goffner, D., Sinare, H., & Gordon, L. J. (2019). The Great Green Wall for the Sahara and the Sahel Initiative as an opportunity to enhance resilience in Sahelian landscapes and livelihoods. *Regional Environmental Change*, *19*(5), 1417–1428. https://doi.org/10.1007/s10113-019-01481-z

Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., & Moore, R. (2017). Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote Sensing of Environment*, *202*, 18–27. https://doi.org/10.1016/j.rse.2017.06.031

Gray, L., & Kevane, M. (2008). Darfur: Rainfall and Conflict. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.1147303

Güneralp, B., Lwasa, S., Masundire, H., Parnell, S., & Seto, K. C. (2017). Urbanization in Africa: Challenges and opportunities for conservation. *Environmental Research Letters*, *13*(1), 015002. https://doi.org/10.1088/1748-9326/aa94fe

Hammond, L., & Maxwell, D. (2002). The Ethiopian Crisis of 1999–2000: Lessons Learned, Questions Unanswered. *Disasters*, *26*(3), 262–279. https://doi.org/10.1111/1467-7717.00204

Hein, L., & De Ridder, N. (2006). Desertification in the Sahel: A reinterpretation. *Global Change Biology*, *12*(5), 751–758. https://doi.org/10.1111/j.1365-2486.2006.01135.x

Herrmann, S. M., Anyamba, A., & Tucker, C. J. (2005). Recent trends in vegetation dynamics in the African Sahel and their relationship to climate. *Global Environmental Change*, *15*(4), 394–404. https://doi.org/10.1016/j.gloenvcha.2005.08.004

Herrmann, S. M., & Hutchinson, C. F. (2005). The changing contexts of the desertification debate. *Journal of Arid Environments*, *63*(3), 538–555. https://doi.org/10.1016/j.jaridenv.2005.03.003

Huang, J., Yu, H., Guan, X., Wang, G., & Guo, R. (2016). Accelerated dryland expansion under climate change. *Nature Climate Change*, *6*(2), 166–171. https://doi.org/10.1038/nclimate2837

Huang, J., Zhang, G., Zhang, Y., Guan, X., Wei, Y., & Guo, R. (2020). Global desertification vulnerability to climate change and human activities. *Land Degradation & Development*, *31*(11), 1380–1391. https://doi.org/10.1002/ldr.3556

Ibrahim, E. S., Ahmed, B., Arodudu, O. T., Abubakar, J. B., Dang, B. A., Mahmoud, M. I., Shaba, H. A., & Shamaki, S. B. (2022). Desertification in the Sahel Region: A Product of Climate Change or Human Activities? A Case of Desert Encroachment Monitoring in North-Eastern Nigeria Using Remote Sensing Techniques. *Geographies*, *2*(2), 204–226. https://doi.org/10.3390/geographies2020015

Iizumi, T., Ali-Babiker, I.-E. A., Tsubo, M., Tahir, I. S. A., Kurosaki, Y., Kim, W., Gorafi, Y. S. A., Idris, A. A. M., & Tsujimoto, H. (2021). Rising temperatures and increasing demand challenge wheat supply in Sudan. *Nature Food*, *2*(1), 19–27. https://doi.org/10.1038/s43016-020-00214-4

Issa Lélé, M., & Lamb, P. J. (2010). Variability of the Intertropical Front (ITF) and Rainfall over the West African Sudan–Sahel Zone. *Journal of Climate*, *23*(14), 3984–4004. https://doi.org/10.1175/2010jcli3277.1

Jansen, L. J. M., & Gregorio, A. D. (2002). Parametric land cover and land-use classifications as tools for environmental change detection. *Agriculture, Ecosystems & Environment*, *91*(1–3), 89–100. https://doi.org/10.1016/S0167-8809(01)00243-2

Jensen, J. R. (1996). *Introductory digital image processing: A remote sensing perspective* (2. ed). Prentice Hall.

Johnson, P. M., Maryrand, K., & Paquin, M. (2007). Governing Global Desertification: Linking Environmental Degradation, Poverty and Participation. *Environmental Sciences*, *4*(4), 249–249. https://doi.org/10.1080/15693430701198573

Khairalseed, A. A. R. (2015). *Desertification in Sudan, Concept, Causes and Control*. *5*(2).

Kröpelin, S., Verschuren, D., & Lézine, A.-M. (2008). Response to Comment on "Climate-Driven Ecosystem Succession in the Sahara: The Past 6000 Years." *Science*, *322*(5906), 1326–1326. https://doi.org/10.1126/science.1163483

Lambin, E. F., Geist, H. J., & Lepers, E. (2003). Dynamics of Land-Use and Land-Cover Change in Tropical Regions. *Annual Review of Environment and Resources*, *28*(1), 205–241. https://doi.org/10.1146/annurev.energy.28.050302.105459

Lamqadem, A., Saber, H., & Pradhan, B. (2018). Quantitative Assessment of Desertification in an Arid Oasis Using Remote Sensing Data and Spectral Index Techniques. *Remote Sensing*, *10*(12), 1862. https://doi.org/10.3390/rs10121862

Le Houérou, H. N., & LeHouérou, H. N. (1989). *The grazing land ecosystems of the African Sahel*. Springer-Verlag.

Lillesand, T. M., Kiefer, R. W., & Chipman, J. W. (2015). *Remote sensing and image interpretation* (Seventh edition). John Wiley & Sons, Inc.

Mabbutt, J. A. (1978). The Impact of Desertification as Revealed by Mapping. *Environmental Conservation*, *5*(1), 45–56. https://doi.org/10.1017/S0376892900005270

Mahgoub, F. (with Nordiska Afrikainstitutet). (2014). *Current status of agriculture and future challenges in Sudan*. Nordiska Afrikainstitutet.

Maliva, R., & Missimer, T. (2012). *Arid Lands Water Evaluation and Management*. https://doi.org/10.1007/973-3-642-29104

Mandal, R. B. (Ed.). (1990). *Patterns of regional geography: An international perspective*. Concept Pub. Co.

Marzen, L. J., Szantoi, Z., Harrington, L. M. B., & Harrington, J. A. (2011). Implications of management strategies and vegetation change in the Mount St. Helens blast zone. *Geocarto International*, *26*(5), 359–376. https://doi.org/10.1080/10106049.2011.584977

Mason, B., & Schmetz, J. (1992). Meteorological satellites. *International Journal of Remote Sensing*, *13*(6–7), 1153–1172. https://doi.org/10.1080/01431169208904185

Mera, G. A. (2018). Drought and its impacts in Ethiopia. *Weather and Climate Extremes*, *22*, 24–35. https://doi.org/10.1016/j.wace.2018.10.002

Mercuri, A. M. (2008). Human influence, plant landscape evolution and climate inferences from the archaeobotanical records of the Wadi Teshuinat area (Libyan Sahara). *Journal of Arid Environments*, *72*(10), 1950–1967. https://doi.org/10.1016/j.jaridenv.2008.04.008

Mirzabaev, A., Sacande, M., Motlagh, F., Shyrokaya, A., & Martucci, A. (2021). Economic efficiency and targeting of the African Great Green Wall. *Nature Sustainability*, *5*(1), 17–25. https://doi.org/10.1038/s41893-021-00801-8

Mohamed, M., Anders, J., & Schneider, C. (2020). Monitoring of Changes in Land Use/Land Cover in Syria from 2010 to 2018 Using Multitemporal Landsat Imagery and GIS. *Land*, *9*(7), 226. https://doi.org/10.3390/land9070226

Mohamed, N. A. H., Bannari, A., Mohamed Fadul, H., & Zakieldeen, S. (2016). Ecological Zones Degradation Analysis in Central Sudan during a Half Century Using Remote Sensing and GIS. *Advances in Remote Sensing*, *05*(04), 355–371. https://doi.org/10.4236/ars.2016.54025

Mohamed Nour, S. (2015). Overview of Sudanese Economy and the Status of ICT in Sudan. In S. Mohamed Nour, *Information and Communication Technology in Sudan* (pp. 13–40). Springer International Publishing. https://doi.org/10.1007/978-3-319-13999-9_2

Montgomery, D. C., Peck, E. A., & Vining, G. G. (2013). *Introduction to Linear Regression Analysis* (5. Aufl). Wiley.

Mortimer, A., Ahmed, I., Johnson, T., Tang, L., & Alston, M. (2023). Localizing Sustainable Development Goal 13 on Climate Action to Build Local Resilience to Floods in the Hunter Valley: A Literature Review. *Sustainability*, *15*(6), 5565. https://doi.org/10.3390/su15065565

Nicholson, S. (1985). *Sub-Saharan Rainfall 1981-84*. *24*(12), 1388–1391.

Nicholson, S. (2001). Climatic and environmental change in Africa during the last two centuries. *Climate Research*, *17*, 123–144. https://doi.org/10.3354/cr017123

Olorunfemi, I. E., Olufayo, A. A., Fasinmirin, J. T., & Komolafe, A. A. (2022). Dynamics of land use land cover and its impact on carbon stocks in Sub-Saharan Africa: An overview. *Environment, Development and Sustainability*, *24*(1), 40–76. https://doi.org/10.1007/s10668-021-01484-z

Olsson, L. (1993). *On the Causes of Famine: Drought, Desertification and Market Failure in the Sudan*. *22*(6), 395–403.

Osman, Y. Z., & Shamseldin, A. Y. (2002). Qualitative rainfall prediction models for central and southern Sudan using El Niño–southern oscillation and Indian Ocean sea surface temperature Indices. *International Journal of Climatology*, *22*(15), 1861–1878. https://doi.org/10.1002/joc.860

Ouchra, H., Belangour, A., & Erraissi, A. (2022). Satellite data analysis and geographic information system for urban planning: A systematic review. *2022 International Conference on Data Analytics for Business and Industry (ICDABI)*, 558–564. https://doi.org/10.1109/ICDABI56818.2022.10041487

Pettorelli, N., Laurance, W. F., O'Brien, T. G., Wegmann, M., Nagendra, H., & Turner, W. (2014). Satellite remote sensing for applied ecologists: Opportunities and challenges. *Journal of Applied Ecology*, *51*(4), 839–848. https://doi.org/10.1111/1365-2664.12261

Pu, B., & Cook, K. H. (2012). Role of the west African westerly jet in sahel rainfall variations. *Journal of Climate*, *25*(8), 2880–2896. https://doi.org/10.1175/JCLI-D-11-00394.1

Rahamtalla, N. A. (2018). *Causes and Economic Consequences of Desertification in Sudan*. *3*(1).

Rastgoo, M., & Hasanfard, A. (2022). Desertification in Agricultural Lands: Approaches to Mitigation. In Y. Zhu, Q. Luo, & Y. Liu (Eds.), *Deserts and Desertification*. IntechOpen. https://doi.org/10.5772/intechopen.98795

Reich, P., Numbem, S., Almaraz, R., & Eswaran, H. (2004). Land resource stresses and desertification in Africa. *Agro-Science*, *2*(2). https://doi.org/10.4314/as.v2i2.1484

Reynolds, J. F., Smith, D. M. S., Lambin, E. F., Turner, B. L., Mortimore, M., Batterbury, S. P. J., Downing, T. E., Dowlatabadi, H., Fernández, R. J., Herrick, J. E., Huber-Sannwald, E., Jiang, H., Leemans, R., Lynam, T., Maestre, F. T., Ayarza, M., & Walker, B. (2007). Global Desertification: Building a Science for Dryland Development. *Science*, *316*(5826), 847–851. https://doi.org/10.1126/science.1131634

Robinson, J. (2005). Desertification and disarray: The threats to plant genetic resources of southern Darfur, western Sudan. *Plant Genetic Resources*, *3*(1), 3–11. https://doi.org/10.1079/PGR200451

Saad, S. A. M., Seedahmed, A. M. A., Ahmed, A, Ossman, S. A. M., & Eldoma, A. M. A. (2018). Combating Desertification in Sudan: Experiences and Lessons Learned, In Ahmed, A(Ed.):https://wasdlibrary.org/publications/books/outlook/vol16-2018/. In *World Sustainable Development Outlook* (1st ed., Vol. 16, pp. 141–155). WASD. https://doi.org/10.47556/B.OUTLOOK2018.16.10

Scheffer, M., Carpenter, S., Foley, J. A., Folke, C., & Walker, B. (2001). Catastrophic shifts in ecosystems. *Nature*, *413*(6856), 591–596. https://doi.org/10.1038/35098000

Sivakumar, M. V. K. (2007). Interactions between climate and desertification. *Agricultural and Forest Meteorology*, *142*(2–4), 143–155. https://doi.org/10.1016/j.agrformet.2006.03.025

Sterk, G., & Stoorvogel, J. J. (2020). Desertification–Scientific Versus Political Realities. *Land*, *9*(5), 156. https://doi.org/10.3390/land9050156

Sudan National Action Programme. (2006). *A Framework for Combating Desertification in Sudan in the Context of the United Nations Convention to Combat Desertification*.

Suliman, M. (2008). *The war in Darfur: The impact of the resource element*. http://new.ifaanet.org/wp-content/uploads/2011/12/DarfurpaperinArabic1.htm

Thomas, N., & Nigam, S. (2018). Twentieth-Century Climate Change over Africa: Seasonal Hydroclimate Trends and Sahara Desert Expansion. *Journal of Climate*, *31*(9), 3349–3370. https://doi.org/10.1175/JCLI-D-17-0187.1

Turner, B. L., Lambin, E. F., & Reenberg, A. (2007). The emergence of land change science for global environmental change and sustainability. *Proceedings of the National Academy of Sciences*, *104*(52), 20666–20671. https://doi.org/10.1073/pnas.0704119104

UN FAO. (2021). *Africa Open D.E.A.L: OPEN DATA FOR ENVIRONMENT, AGRICULTURE AND LAND & AFRICA'S GREAT GREEN WALL*. United Nations.

UNCCD. (2020). *The Great Green Wall Implementation Status And Way Ahead To 2030*.

UNEP. (1992). *The state of the environment, 1972-1992 :saving our planet: Challenges and hopes: Report of the Executive Director: United Nations Environment Programme: Corrigendum.* http://digitallibrary.un.org/record/142052

UNEP (Ed.). (2007). *Sudan: Post-conflict environmental assessment* (1. publ).

UNEP (Ed.). (2012). *Global environment outlook 5: Environment for the future we want*. UNEP.

UNFCCC. (2020). *UNITED NATIONS CLIMATE CHANGE ANNUAL REPORT 2020* [Annual]. United Nations. https://unfccc.int/news/climate-change-is-an-increasing-threat-to-africa

Yagoub, Y. E., Li, Z., Musa, O. S., Anjum, M. N., Wang, F., Xu, C., & Bo, Z. (2017). Investigation of Vegetation Cover Change in Sudan by Using Modis Data. *Journal of Geographic Information System*, *09*(03), 279–292. https://doi.org/10.4236/jgis.2017.93017

Yang, Z., Gao, X., Lei, J., Meng, X., & Zhou, N. (2022). Analysis of spatiotemporal changes and driving factors of desertification in the Africa Sahel. *CATENA*, *213*, 106213. https://doi.org/10.1016/j.catena.2022.106213

Yilmaz, M. (2023). Accuracy assessment of temperature trends from ERA5 and ERA5-Land. *Science of The Total Environment*, *856*, 159182. https://doi.org/10.1016/j.scitotenv.2022.159182

Zhao, Q., Yu, L., Li, X., Peng, D., Zhang, Y., & Gong, P. (2021). Progress and Trends in the Application of Google Earth and Google Earth Engine. *Remote Sensing*, *13*(18), 3778. https://doi.org/10.3390/rs13183778