ASSESSING LAND DEGRADATION THROUGH LAND USE/LAND COVER CHANGE AND SOCIO-ECOLOGICAL ANALYSIS IN THE RURAL SEMI-ARID AREA OF THE GREATER SEKHUKHUNE DISTRICT MUNICIPALITY, SOUTH AFRICA

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ABSTRACT

Land degradation (LD) is a major global environmental challenge that impacts the socio-ecological systems (SES) and livelihoods of vulnerable communities. This study evaluates LD dynamics in rural South Africa, between 1990 and 2019, using Land Use and Land Cover Change (LULCC) detection based from remotely sensed data and socio-ecological system analysis in the Greater Sekhukhune Municipality, South Africa.

Firstly, LULCC impacts on LD were analysed using LD indicators i.e., LULCC, and Normalized Difference Vegetation Index (NDVI), both calculated from multi-temporal Landsat satellite imagery. Then key-informant interviews were used to analyse the driving mechanisms of the changes in the habitat structure. Secondly, to apportion human and climate (rainfall) induced LD, the residual trend (RESTREND) approach was adopted using linear regression and Mann-Kendall (MK) trend test between NDVI and rainfall. Thirdly, the Drive Pressure State Condition and four Responses ($DPSCR_4$) framework was used to assess the SES analysis. Furthermore, key informant interviews with government officials, group discussions with local herders and traditional authorities, and scientific literature data were triangulated to form the basis of systemic analysis of and application of $DPSCR_4$. Land Degradation Neutrality (LDN) was integrated into the framework to provide responses that inform sustainable land management (SLM).

Results indicated that shrub/grassland constituted the most extensive type of LULC in the study area and increased by 53%. The increase in shrub/grassland is mainly due to the 69% loss of thicket/dense bush. Results also showed a substantial expansion of bare soil (52% in the dry season) and residential (76%) areas over the 30 years. The annual rate revealed that the highest loss of LULCs were mines and quarries, subsistence, commercial and thicket/dense bush by 2.69%, 2.65%, 2.3%, and 1.86% per year from 1990 to 2019, respectively. LULCC affected vegetation productivity of the district as NDVI negative trend increased at the steeper slopes in the dry season. During the wet season, there were indications that prolonged droughts and overgrazing hamper vegetation recovery. Key informants indicated that the main LULCC drivers contributing to LD are soil erosion, cropland abandonment, and overgrazing, which further promote bush encroachment.

Spatial RESTREND revealed that 11.59% of the district is degraded by anthropogenic activities, while 41.41% is degraded by a decline in annual rainfall associated with drought.

The study also noted that increased vegetation biomass in some parts of the district may be due to bush encroachment promoted by heavy grazing that has altered ecological processes and changes in rainfall regime.

The $DPSCR_4$ analysis revealed that the main anthropogenic activities driving LD in the district are overgrazing, disempowerment and poverty, land tenure, unsustainable land use management practices, and cropland abandonment that further promotes bush encroachment. Topography, dispersive duplex soils, climate variability and change are natural factors that predispose the district to gully formation and soil erosion, especially when combined with human activities. The study further revealed that using remote sensing, $DPSCR_4$ SES and LDN framework, provides a deeper understanding of LD and effectively informs policy and integrated land use plans to address LD and sustainable livelihood opportunities.

Key words: Land Use and Land Cover Changes, LD, NDVI, Rainfall, RESTREND, SES, $DPSCR_4$.

PREFACE

The research presented in this dissertation was conducted at the Council for Scientific and Industrial Research (CSIR), Gauteng, Pretoria, from February 2021 to May 2022, under supervision of Prof. Abel Ramoelo and co-supervised by Prof. John Odindi, Dr. Jean-Marc Mwenge Kahinda, and Mr. Ashwin Seetal. The author declares that the work presented in this research is her own original work, except where otherwise acknowledged using references, and that the work has never been submitted to any other institution of higher learning.

Motsoko Juniet Kgaphola Signed [redacted] Date 23 March 2023

As the supervisor of the candidate, I certify that the above-mentioned statement is true, therefore approve this dissertation for submission.

Prof. Abel Ramoelo Signed [redacted] Date 23/03/2023

Prof. John Odindi Signed [redacted] Date

Dr. Jean-Marc Mwenge Kahinda Signed [redacted] Date 23 March 2023

Mr. Ashwin Seetal Signed [redacted] Date 23 March 2023

DECLARATION

I Motsoko Juniet Kgaphola, declare the following:

1. Except where states otherwise acknowledged using references, the research presented is my genuine work,
2. This research work has never been submitted to any institution of higher learning for the fulfilment of a degree, diploma, or certificate.
3. This dissertation does not contain other peoples' pictures, data, graphs, or other information except indicated by referencing.

Motsoko Juniet Kgaphola Signed [redacted] Date 23 March 2023

Publications and conference presentations

Publications

Kgaphola, M.J., Ramoelo, A., Odindi, J., Mwenge Kahinda, J. Seetal**,** A. R. & Musvoto, C. **Impact of land use and land cover change on land degradation in rural semi-arid South Africa: case of The Greater Sekhukhune District Municipality**. (*Environmental Monitoring and Assessment: EMAS-D-22-02654*): Accepted for Publication. [CHAPTER 2]

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Dedication

The dissertation is dedicated to my loving and supportive family.

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CHAPTER 1
General Introduction

1.1 INTRODUCTION

LD is a major global environmental issue that affects over three billion people, particularly in developing countries (Global Environment Facility, 2022). It is defined as the prolonged reduction of ecosystem function and productivity from which the land does not recover without interventions (Bai et al., 2008; Weldemariam, 2017). Globally, approximately 25% of the land is degraded, with more than 70% of dryland in South America, Asia, and Africa affected by degradation (Barbier & Hochard, 2016). The loss of ecosystem services emanating from LD amounts to approximately 10% of the world's annual gross products, severely affecting the resource-based livelihoods of 1.3 to 3.2 billion people in developing countries (Olsson et al., 2014; R. Scholes et al., 2018; Shukla, 2019). Therefore, it is critical to assess the LD process to develop mitigation strategies and promote sustainable land management (SLM) and improve livelihoods (Gonzales Inca, 2009; Ibrahim et al., 2015).

LD is a complex phenomenon, particularly in the developing worlds due to its interdisciplinary nature constituting climatic, geographical, economic and socio-ecological aspects (Vogt et al., 2011). Several factors cause LD, which can either be anthropogenic or natural (Bai et al., 2008; Safriel, 2007) and are categorised into two broad direct and indirect causes (Nkonya et al., 2016). Direct anthropogenic factors mainly include unsustainable use of land resources for agriculture (Adeel et al., 2005). Poor land use practices such as mono-cropping, excessive application of fertilisers, unsustainable irrigation practices, overgrazing, overstocking, and unsustainable fuel wood harvesting directly cause LD (Adeel et al., 2005; Mirzabaev et al., 2015). Indirect anthropogenic factors are socio-economic elements such as local policies and institutional designs that have a great influence on the access and management of land (Nkonya et al., 2016).

While institutional factors such as land governance affect demand for land and management, biophysical factors are natural drivers that determine land use and susceptibility of land to degradation (Orr et al., 2017). The most important biophysical factors linked to degradation include increasing temperatures, climatic variability and extreme weather events, soil characteristics and erodibility, topography, drainage, and slope steepness (Global Environment Facility, 2022; Nkonya et al., 2016; Shukla et al., 2019). These factors are interrelated and change erosion rates, vegetation cover, composition and biological processes below-ground, i.e., bacteria and fungi (Shuab et al., 2017; Shukla et al., 2019).

In rural areas of the developing world, LD has increasingly become complex and its effects on rural livelihood are more severe. In semi-arid regions, climate variability and poor land practices accelerate LD process (Olagunju, 2015), such that more than 70% of the land in South Africa is intensively degraded (Department of Environmental Affairs, 2016). In South Africa, native ‘‘homelands’’ (characterised by communal areas) have extensively degraded rangelands and severe soil erosion due to anthropogenic factors, mainly overgrazing (T. M. Hoffman & Todd, 2000). In the Limpopo province for instance, the spatial development framework of the Greater Sekhukhune District Municipality (GSDM) reports that poor agricultural methods, overgrazing, and overstocking, especially in communal areas, are the main drivers of environmental degradation in the district (The Greater Sekhukhune District, 2019).

The United Nations Convention to Combat Desertification (UNCCD) was formed in 1994 to address LD (UNCCD, 1994). LD can be mitigated through Land Degradation Neutrality (LDN) program launched at the 2012 United Nations Conference on Sustainable Development (Rio+20) (Cowie et al., 2018). LDN provides a scientifically-sound basis for measuring, monitoring, and understanding the extent and causes of LD at national and landscape levels (Kairis et al., 2014). The LDN program provides three LDN indicators i.e., (1) Land Use and Land Cover Change (LULCC); (2) Land Productivity (NDVI), and (3) Carbon Stocks, to assess and monitor LD progress (Cowie et al., 2018). LDN also provides interventions to encourage effective policies that promote sustainable land management (SLM) (Cowie et al., 2018).

Several studies have utilised remotely sensed data to monitor and assess spatio-temporal trends of LD by analysing LULCC and land productivity (Ganasri & Dwarakish, 2015; Karnieli et al., 2008; Mashame & Akinyemi, 2016; Matchi et al., 2012). Satellite remote sensing offers an opportunity to quantify, map, and detect patterns of LULCC and land productivity due to its reliable geo-referencing procedures, digitisation for computer processing, repetitive data collection, and access to remote areas, at different seasons and scales (Chen et al., 2005; Lu & Weng, 2007; Rahman et al., 2011). On the other hand, conventional techniques for studying and monitoring LD are resource intensive, thus, are normally carried out at field level, with irregular intervals, and financially unviable (Z. Bai & Dent, 2009; Gao & Liu, 2010; Xie et al., 2008). Remote sensing also offers an opportunity to assess land productivity through Normalised Difference Vegetation Index (NDVI) derived from satellite imagery (Huang & Kong, 2016). The Residual Trend (RESTREND) of the NDVI method has been applied to provide spatial information to distinguish LD induced by anthropogenic activities from that of rainfall using gridded NDVI and rainfall satellite imagery (Chu et al., 2019; Huang & Kong, 2016; Li et al., 2012; Wang et al., 2010; Wessels et al., 2007). However, there is dearth in studies that distinguish LD caused by human and climatic factors.

A Social-Ecological Systems (SES) framework can be used to analyse the interactions between society, the ecosystem, and the consequences thereof (Itzkin et al., 2021). The Drivers-Pressure-State-Impact-Response (DPSIR) has been adopted as a Social-Ecological System (SES) analytical framework by United Nations Environmental Programme (UNEP) and applied to various environmental studies across Europe (Masó et al., 2019; Song & Frostell, 2012; United Nations Environment Programme, 2007). The Drivers Pressure Stressors Condition and four Responses ($DPSCR_4$) framework is derived from DPSIR framework that utilises impact rather than condition, with condition referring to the state of the environment (Itzkin et al., 2021). In addition, the $DPSCR_4$ framework has four responses, namely, stressor source reduction, existing stressors remediation, ecological restoration, and ecological recovery (Itzkin et al., 2021). The application of the DPSIR model has seldomly been applied in developing semi-arid regions, moreover, $DPSCR_4$ application still lacks in literature to understand dynamics of LD and four 'responses' to the system to achieve LDN (Itzkin et al., 2021).

Whereas studies have linked LULC to LD (e.g., (T. M. Hoffman & Todd, 2000; Meadows & Hoffman, 2002), explicit information on such linkages are limited in literature for most semi-arid regions. LULC dynamics studies and driving mechanism across time and space is crucial as it provides a foundation for the sustainability of natural resources (Meshesha et al., 2016). Furthermore, studies throughout the world and South Africa have rarely distinguished and mapped LD caused by human factors from climatic factors i.e., rainfall. A serious challenge on the study of LD is that there is no clear consensus on the existence and the extent of LD (Food and Agriculture Organization (FAO), 2008; Wessels et al., 2007). As a result, studies often focus on the degree or reality of LD (Herrmann et al., 2005; Prince et al., 1998). Moreover, linkages of human actions and climate factors in a system have rarely been explored, particularly using the $DPSCR_4$ SES framework. Generally, the $DPSCR_4$ has not been adopted in many studies, therefore, a deeper understanding and responses to LD are necessary. A SESs approach is key to achieving a LDN and improving livelihoods in rural areas. Therefore, this research presents holistic causes and impacts of LD by assessing LULC changes, distinguishing anthropogenic LD from effects of rainfall. Furthermore, the research provides a systematic approach to understanding explicit drivers of these LULC changes and LD through identifying potential points of leverage to adapt and manage interventions in the Greater Sekhukhune District Municipality, Limpopo, South Africa.

1.2 STUDY AIM AND OBJECTIVES

The aim of this study was to assess long-term spatio-temporal impacts of LULCC on LD, driving factors and recommend SLM practices to achieve LDN in the Greater Sekhukhune Municipality, South Africa. The objectives were:

1. To assess the evolution of LULC from 1990 to 2019 and its impacts on LD using multispectral satellite imagery,
2. To distinguish human-induced LD from rainfall effects using the RESTREND method from 1990 to 2019 and
3. To identify drivers of LD and SLM interventions (Responses) using SES analysis of $DPSCR_4$ and LDN frameworks.

1.3 RESEARCH QUESTIONS

1. How have changes in land use and land cover contributed to LD from 1990 to 2019?
2. Is LD from 1990 to 2019 due to human factors or rainfall effects?
3. What are the drivers of LD and what SLM interventions (Responses) can be applied to achieve LDN in the Greater Sekhukhune District Municipality?

1.4 HYPOTHESIS

1. Remotely sensed data and techniques could generate spatio-temporal information that enables assessment, monitoring, and addressing LD.
2. RESTREND analysis can be applied to distinguish human-induced LD from effects of rainfall.
3. Social-Ecological Systems approach provides a comprehensive understanding of LD in Response to Land Use and Cover Changes using $DPSCR_4$ analysis.

1.5 CHAPTER OUTLINE

The dissertation is arranged into four chapters with the introductory chapter providing an overview of the thesis by highlighting the background of LD. The introductory chapter outlines the aim and objectives, research questions, and hypotheses of the research. The second and third chapters are based on three journal articles that address the research objectives and questions. Finally, the fourth chapter provides a synthesis of the research through overview of objectives, conclusion and recommendations.

Chapter two is a journal article accepted for publication with the *Environment Monitoring and Assessment Journal*. The focus of the research was to provide long-term spatio-temporal information on LULC changes using wet and dry season multispectral Landsat images. The evolution of these changes was analysed through change detection techniques to quantify contributing factors of LD. Furthermore, land productivity using NDVI (computed from Landsat images) was quantified and analysed to reflect the impacts of LULCC on the production biomass of the district and LD. Key-informant semi-structured interviews were used to understand potential driving mechanism of changes in LULC that contribute to LD.

Chapter three is based on two published journal articles, the first article published with the *Sustainability Journal* and the second article published with the *Applied Sciences Journal: Special Issue "Remote Sensing Applications in Agricultural, Earth and Environmental Sciences"*. The chapter provides a comprehensive system structure of LD across disciplines by modelling complex social and ecological drivers using systems thinking principles. Firstly, it distinguished anthropogenic LD from rainfall effects, and secondly analysed the drivers using an SES approach to propose responses to achieve LDN. RESTREND analysis was used to distinguish LD caused by human drivers from rainfall effects using wet season NOOA NDVI due to data availability and spatio-temporal considerations. The study provided a theoretical understanding of LD by applying a socio-ecological system using $DPSCR_4$ analysis. The $DPSCR_4$ framework utilised key-informant semi-structured interviews, engagements with Tribal Authorities and a workshop session with local herders. This was followed by various sources of scientific DPSIR-related literature to define and understand LD in the GSDM using a systems analysis approach. $DPCR_4$ has been adopted as a system dynamic model, approach and a tool to understand a complex socio-ecological system's structure of patterns, and processes with their feedback loops.

Chapter four provides a synthesis of the study by reviewing objectives, and conclusive remarks and provides recommendations.

CHAPTER 2
Impact of Land Use and Land Cover Changes on Land Degradation

This chapter is based on a manuscript currently under revision:

Kgaphola, M.J., Ramoelo, A., Odindi, J., Mwenge Kahinda, J. Seetal, A. R. & Musvoto, C. **Impact of Land Use and Land Cover Change on Land Degradation in rural semi-arid South Africa: Case of The Greater Sekhukhune District Municipality**. (*Environmental Monitoring and Assessment: EMAS-D-22-02654*): Accepted for publication.

2.1 ABSTRACT

In semi-arid regions, the influence of interactions between society and biophysical variables are complex. These variables significantly alter the land cover and degrade landscape's structure and ability to respond to land management interventions. Hence, this study sought to investigate impacts of land use and land cover changes (LULCC) on LD (LD) and driving mechanisms of habitat fragmentation in Greater Sekhukhune district municipality (GSDM), South Africa. The study used multi-temporal remotely sensed images from 1990 to 2019 over an interval of five years to assess the influence of LULCC on LD. LULCC impacts on LD were analysed using LD indicators; Normalized Difference Vegetation Index (NDVI) and LULCC. Key-informant interviews were used to assess drivers of LULC change and LD. Results revealed that mines and quarries, subsistence, commercial and thicket/dense bush had the highest declining annual rate of 2.69%, 2.65%, 2.3%, and 1.86% per year from 1990 to 2019, respectively. There was also a loss of vegetation cover, with the most common LULC conversions being 129255.85 Ha of shrub/grassland to bare soil, 110625.63h Ha of thicket/dense bush to shrub/grassland and 64465.42 Ha of shrub/grassland to residential. LULCC affected vegetation productivity as NDVI change negative trend is increasing at steeper slope in dry season. The main LULCC drivers contributing to LD are soil erosion, cropland abandonment and overgrazing that promote bush encroachment. It is highlighted that urgency is needed from government, tribal authorities and land users to address LD with land management policies focused on integration, coordination and awareness.

Keywords: Land use land cover changes, LD, NDVI, Climate variability, Land management

2.2 INTRODUCTION

Monitoring anthropogenic land use and land cover changes (LULCC) is critical for understanding human interactions with the environment at the local, regional, and global levels (Tiwari & Kamlesh, 2011). Whereas humans have been deriving livelihoods from the natural environment for centuries, recently, the extent and intensity of uses have increased significantly. The expansion of infrastructure and agriculture due to pressure arising from the ever-increasing population growth has accelerated land transformation and degradation (Benton et al., 2021). LD affects 70% of drylands in South America, Asia, and Africa (Barbier & Hochard, 2016). In rural areas of the developing world, degradation has increasingly become complex and its effects on rural livelihoods are more severe (Z. G. Bai et al., 2008; Safriel, 2007). Therefore, it is crucial to assess and monitor the impacts of LULCC to understand how they affect landscape productivity and sustainability (Gonzales Inca, 2009; Ibrahim et al., 2015).

Land is a crucial natural resource made of soil, water and the associated flora and fauna (land cover). Anthropogenic land uses have changed the land cover and rapidly and extensively disrupted ecosystems and service provision (Watson et al., 2014). The demand for and unsustainable use of natural resources has intensified and changed land covers, severely degrading the structure, and functioning of ecosystems (Shukla et al., 2019). Land conversion through injudicious land use practices such as unsustainable wood harvesting, overgrazing, overstocking, and unsustainable agricultural practices on arable lands, accelerate the loss of ecosystem services and LD process in arid and semi-arid areas (Mani et al., 2021).

LD is thus "the long-term loss of ecosystem function and productivity caused by disturbances from which the land cannot recover unaided" (Z. G. Bai et al., 2008). The United Nations Convention to Combat Desertification (UNCCD) was launched in 1994 in effort to stop LD (United Nations Convention to Combat Desertification (UNCCD), 1994). Despite the almost thirty-year-long endeavours throughout the globe, the situation has worsened. In 2012, the LD Neutrality (LDN) concept was introduced at the UN Conference on Sustainable Development. The aim of LDN is to meet future food and fuel demand without further degrading our finite land resource base (Orr et al., 2017). Therefore, three LD indicators are recommended to track progress towards LDN; these include land use and land cover changes, productivity of land and carbon stocks (Orr et al., 2017). These indicators address ecosystem changes, ecosystem health and habitat fragmentation because of land use and other factors (Orr et al., 2017).

In South Africa, land use is a particularly complex issue, partly due to the physical planning policies of the previous political dispensation. Under the 1913 Land Act, 13% of land was kept in trust as homelands from which approximately 50% of black people (about 3.5 million) were resettled (Fox & Rowntree, 2001). The constraint high population densities of people and livestock led to degradation of land (T. M. Hoffman & Todd, 2000; Meadows & Hoffman, 2002). Until 1994, the land tenure system classified land as homelands (currently communal areas) under the ownership of the state, and private farms owned by white farmers or small towns (T. M. Hoffman & Todd, 2000). Thus, the communal areas have been neglected for a very long time environmentally and politically since the 1960s, the 1930s and colonial age (Ross, 1999). In the communal lands of South Africa, improper land use practices increased the rate of LD and resulted in reduced land productivity and loss of biodiversity (T. M. Hoffman & Todd, 2000). Currently, there are land conflicts arising from ownership, access, and rights i.e., land tenure contributing to poor land use practices and environmental degradation (Duraiappah et al., 2000). Communal areas are mainly characterised by rangeland overgrazing, unsustainable wood harvesting, growth of unpalatable plants and soil erosion (T. M. Hoffman & Todd, 2000). Hence, many communal areas of the North-West, the Northern Cape, the Eastern Cape, the Mpumalanga, and the Limpopo provinces are severely degraded (Dubovyk et al., 2015; Graw et al., 2016).

In the Limpopo province, inappropriate agricultural practices, overgrazing and overstocking, especially in communal areas, are reported as the main drivers of environmental degradation in the Greater Sekhukhune District Municipality (The Greater Sekhukhune District, 2019). These inappropriate uses of land have increased cropland abandonment in smallholder communal fields (Briassoulis, 2020). Generally, cropland abandonment alters the ecological environment such that there are changes in the albedo, and vegetation patterns that affect ecosystem services, soil fertility, hydrological regimes, carbon sequestration, hydrological regimes, and biodiversity (Blair et al., 2018). Besides anthropogenic activities that alter the environment, natural factors such as climatic change and extreme weather events, topography, and soil properties (erodibility, fertility, depth) also influence cropland abandonment (Rey Benayas et al., 2008). Therefore, new approaches that focus on the rates and predictors of habitat conversion and LD have attracted significant interest (Defries & Townshend, 1999).

Several studies have used remotely sensed data to assess and monitor the spatial and temporal variability of landscape transformation and the environment by assessing LULCC (Ganasri & Dwarakish, 2015; Karnieli et al., 2008; Mashame & Akinyemi, 2016; Matchi et al., 2012).

Conventional techniques of LULC monitoring such as map interpretation, field surveys, literature reviews and ancillary and collateral data analysis are time-consuming, done over irregular periods and financially unviable (Xie et al., 2008). Satellite remote sensing can quantify, map, and detect LULCC patterns due to its accuracy in geo-referencing methods, digitisation suitability, repetitive data collection, computer processing and the possibility to access remote areas during different seasons (Chen et al., 2005; Lu & Weng, 2007; Rahman et al., 2011).

Remotely sensed data and techniques could generate LULC information that enables the assessment, monitoring and addressing LD (Magee et al., 2011; Murayama et al., 2015). The Landsat programme provides the longest medium spatial resolution satellite imagery since it was launched in 1972 and has been widely used to compute LULC (Pandey et al., 2021; Rocchio et al., 2005). There are various factors to consider when choosing the appropriate classification technique (i.e., supervised, or unsupervised; parametric or non-parametric) and accuracy. These include the spatial data resolution, the sensor type, the classification scheme and the accessible classification software, the training/validation data sources and accuracy assessment data (Huang, 2005; Jensen, 2015). From these factors, it is essential to select the right algorithm to attain suitable classification accuracy results with less processing time (Lu & Weng, 2007). Parametric supervised algorithms such as linear discriminant analysis, multinomial logistic regression (MLR) and Maximum Likelihood Classifier (MLC) have been adopted and are often considered standard for comparison purposes (dos Santos et al., 2011; McRoberts, 2009; Shafri et al., 2007). Detecting changes in LULC requires up-to-date and accurate assessment on the initial and final LULC types, and analysis of ‘‘from-to’’ (Giri et al., 2005). Therefore, Change Detection (CD) tools in various remote sensing software allows for up-to-date and accurate LULCC data for assessment of consequences of the changes on the environment.

This study addresses an existing knowledge gap by examining and mapping LULCC to understand its impact on LD in semi-arid South Africa. Whereas there are studies linking LULCC to LD (e.g., (T. M. Hoffman & Todd, 2000; Meadows & Hoffman, 2002) explicit assessment and information on these linkages is limited in the body of literature for most semi-arid regions. Studies throughout the world and South Africa have also explored the biotic, abiotic, and environmental impacts of LULCC (James et al., 1999; Leidinger et al., 2017; Ludwig et al., 2001). However, at local levels i.e., below the district, most studies on LULCC considered a very small scale or analysed and emphasized phenomena such as deforestation among others (Matchi et al., 2012). Alternatively, this study focuses on all the LULC units within the study area and reflects detailed information on the land use dynamics of grazing and crop production, which have been largely ignored. A spatial and temporal study of LULC dynamics and its driving mechanisms is crucial as it provides a basis for the sustainable utilisation of natural resources (Meshesha et al., 2016). Hence, rates and predictors of habitat conversion are fundamental for developing effective strategies and design policies for sustainable natural resource utilisation and management.

This study will contribute to providing detailed information on the dual land use administration system that resulted in prevalent degradation in communal areas under traditional leadership and its dynamics on grazing and crop production which have not attracted much attention in previous studies. Whereas there are studies linking LULC to LD (e.g., Hoff, 1999 and Meadows and Hoffman, 2002), explicit information of such linkages in rural districts remains scarce in literature for most semi-arid regions. Most importantly, there is still substantial arguments on the extent to which land degradation takes place under various management and land tenure systems and their drivers of LD (Fox & Rowntree., 2001). This is particularly relevant in rural South Africa, where a dual land administration system i.e., the traditional (tribal) and the modern (legalised) land use system govern the district, resulted in land use conflicts that changed and degraded the land (Pinto-Ledezma et al., 2014).

The study used remote sensing to provide long-term spatio-temporal information to assess LULCC and LD. It investigated the impact of LULCC on LD and assessed potential driving factors in the Greater Sekhukhune District Municipality. The objectives were to; (1) assess the evolution of LULCC from 1990 to 2019 in the Greater Sekhukhune District Municipality, (2) quantify and analyse LULCC, identify driving factors and impacts on LD.

2.3 MATERIALS AND METHODS

2.3.1 Study Area

The Greater Sekhukhune District Municipality (Figure 2:1) is in the Limpopo province, the northmost part of South Africa between (24°5'.10" S, 25°21'.27" S and 29°3'40"E, 30°44'.30" E). The district has four local municipalities (Elias Motsoaledi, Ephraim Mogale, Makhuduthamaga and Fetakgomo Tubatse) covering approximately 1352800 hectares. The total population is approximately 1, 090,424 mainly living in rural communal areas (Statistics South Africa, 2018).

The district is in a semi-arid environment, with an annual rainfall of approximately 560 mm and average summer temperatures of approximately 23°C (Stronkhorst *et al*., 2009). The geology dominating the area is ultramafic substrates, known as serpentine soils of the Rustenburg layered suite bushveld complex (Gourmelon et al., 2016). These soils are mainly nutrient deficient -e.g., Nitrogen, Potassium and Phosphorus- and characterised by high concentrations of heavy metals -e.g., Cadmium, Zinc and Nickel- (Gourmelon et al., 2016). Topography is characterised by undulating hills ranging from hilly to mountainous and it is approximately 494 m above sea level (The Greater Sekhukhune District, 2019). Natural grassland thicket, bushveld, bush clumps and high fynbos land covers dominate the district.

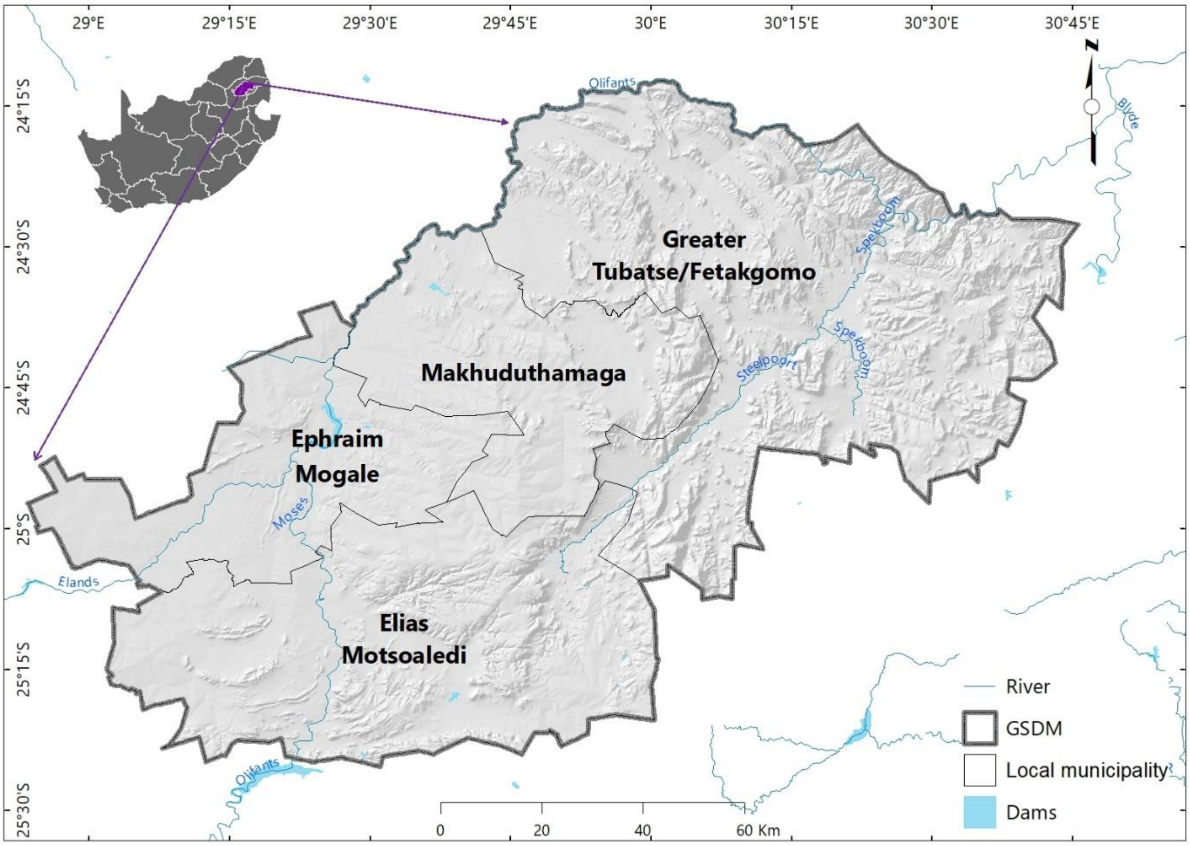


Figure 2:1. The Greater Sekhukhune District Municipality and its four local municipalities.

Agriculture is important in the district, with commercial farming accounting for 7.7% and subsistence farming 18.1% of the land use in the district (The Greater Sekhukhune District Municipality, 2020). However, most of the croplands have been abandoned and water scarcity, land conflicts, a high number of land claims, and inappropriate infrastructure and services pose future agriculture concerns in the area (Mpandeli et al., 2015; The Greater Sekhukhune District, 2019). Unlimited access to communal grazing and lack of fencing in fields is intensifying LD because of low herbaceous basal cover (T. Hoffman & Ashwell, 2001; Shackleton et al., 2013).

2.3.2 Methodology

This study used a mixed-methods approach that integrates quantitative and qualitative techniques to better understand LULCC, LD, their drivers, and impacts. Using remote sensing (RS) and Geographical Information Systems (GIS) techniques, seasonal LULC images were classified from Landsat Operational Land Imager sensor (OLI) and Thematic mapper (TM) scenes. The impacts and drivers of LULCC on LD were analysed using change detection of LULC and key informant interviews.

2.4 DATA COLLECTION

2.4.1 Remotely Sensed Data

Given that long-term monitoring is required, Landsat satellite images with 30m spatial resolution were downloaded from the United States Geological Survey (USGS) Global Visualization Viewer (HTTP:// glovis.usgs.gov/) dataset for the years 1990, 1995, 1999, 2005 and 2010, 2015, 2019 (30 years at five-year interval). To capture and assess seasonal climatic variability and change over the Limpopo province, seasonal images were selected from the wet and dry seasons. The rain peaks in January and February, hence these months were used for the wet season as there is ample agricultural and vegetation growth and filled water bodies while the dry months used were May to August as these are the driest months (Mpandeli et al., 2015). Good-quality images with less than 10% cloud cover were collected (Table 2.1). However, some wet season images had cloud cover of more than 10% due to peak rainfall, hence December and March images had to be used for some years. Only one image had a cloud cover of over 10% (i.e., 14%), hence the results were not compromised and based on data availability, some years close to the year of study were downloaded.

Table 2.1. Landsat 5, 7 and 8 Images for wet and dry season

Satellite	Sensor	Path/ row	Wet season Date of image acquisition	Cloud cover %	Dry season Date of image acquisition	Cloud Cover %
Landsat 5	TM	170/078	1990/03/03	0	1990/06/16	0
		169/078	1990/12/09	10		
		169/077	1990/03/03	1	1990/06/16	0
		170/077	1990/03/12	14	1990/06/23	3
		169/077	1995/02/06	0	1995/06/30	0
		169/078	1996/03/12	0		0
		170/077	1995/03/17	1	1995/06/21	9
		170/077	1999/03/12	1	1999/06/16	0
		170/078	1999/02/24	0	1999/06/16	0
		169/077	1999/02/17	9	1999/05/08	0
		169/078	1999/02/17	0	1999/05/08	1
Landsat 7	ETM+	169/077	2005/02/25	2	2005/06/01	0
		169/078	2005/02/25	1	2005/06/17	0
		170/077	2005/02/16	6	2005/06/08	0
		170/077	2010/03/18	2	2010/07/24	5
		169/078	2010/02/07	1	2010/07/17	0
		169/077	2010/02/07	1	2010/08/18	0
		169/077	2015/02/21	1		
		169/077			2015/06/05	0.09
		169/078	2015/02/13	3.17	2015/06/21	4
		170/077	2015/01/03	1.19	2015/06/12	3.01
Landsat 8	Oli	170/077	2019/03/19	1.87	2019/08/26	0.01
		170/078	2019/03/20	0	2019/08/26	0.07
		169/077			2019/08/19	0.01
		169/078	2019/02/24	7.4	2019/08/19	0.05

2.4.2 Key-Informant Interviews

For data collection. interviews were conducted with key informants selected for their extensive experience and knowledge of the GSDM. A non-probability sampling method was used to identify informants, whereby key informants are recruited by other key informants to become part of the sample (snowball method). In this case, official from the Limpopo Department of Agriculture and Rural Development (LDARD) based in the GSDM identified other key informants who had more than seven years of experience in natural resources use and management (e.g. for grazing, cropping, fuelwood, and other purposes)(Payne & Payne, 2004).

A semi-structured questionnaire was used to interview 11 key informants from the Limpopo Department of Agriculture and Rural Development (LDARD) based in GSDM (Table 2.2). The key informants, interviewed individually, included natural resource managers, crop production, animal production and extension services per local municipality.

Table 2.2 Key informants interviewed in GSDM per local municipality and years of experience working in the municipality and field.

Local municipality	Key informant	Field of expertise	Years of experience
Fetakgomo	1	Extension services	40
	2	Natural Resource Management	13
	3	Natural Resource Management	14
Tubatse	4	Natural Resource Management	12
	5	Crop Production	14
Makhuduthamaga	6	Natural Resource Management	12
	7	Crop Production	24
Elias Motsoaledi	8	Animal production	10
Ephraim Mogale	9	Extension services	7
	10	Extension services	15
	11	Animal production	12

The semi-structured questionnaire was designed to acquire historical LULC changes, physical factors, socioeconomic, and cultural data and to determine the driving factors of LD and their impacts (Appendix). The key informant interviews aimed to provide perspectives on important land management related issues in the district and to identify progress and gaps in addressing land degradation issues. Discussion included driving mechanisms of LULC changes, grazing and rangeland management and the impacts of factors on LD experienced in the district over the past 30 years. The interviews also included discussion around information on laws and regulations that affect access to land, use and impacts observed over the years.

Majority of land in rural South Africa is controlled by traditional structures, with Traditional Authorities (TAs) (chief and their council) playing a key role in land allocation and land use decisions (Musvoto, Kgaphola and Mwenge Kahinda, 2022). As part of understanding the driving mechanisms of LULCC and LD in GSDM, open informal discussion sessions were held with 17 Traditional Authorities, where they were asked for their perceptions and experiences on the following:

- Activities based on natural resource and land use.
- State of land and natural resources.
- LD, its causes, and impacts on land use activities.
- Agricultural activities currently practiced in the area.
- Role of Traditional Authorities on the management of land and addressing LD.

2.5 DATA ANALYSIS

The study used these RS classification and mapping techniques: LULC classification scheme, satellite image pre-processing, satellite image classification, accuracy assessment, change detection and post-classification of LULCC.

2.5.1 Classification Scheme

Due to the diverse LULC types, it is important to classify land according to use potential and characteristics (Rhind, 1993). The South African national standard for Land Cover Classification System (Department of Rural Development and Land Reform (DRDLR), 2019) was used to map the existing LULC in the study area (Table 2.3). The broad hierarchical level 1 was applied on Landsat images to identify existing LULC. Furthermore, since the study investigates the impacts of LULCC on LD, levels 2 and 3 were applied to identify barren, cultivated and residential land for a detailed mapping of these classes.

Table 2.3 LULC classes and their descriptions (Department of Rural Development and Land Reform, 2019)

LCC Level	Class name	Description
2	Commercial cultivation	Cultivated lands used primarily to produce rainfed, annual crops or primarily to produce centre pivot/non-pivot irrigated for commercial markets. Typically represented by large field units, often in dense local or regional clusters.
2	Subsistence Cultivation	Rainfed, annual crops for local markets and/or home use. Small field units, often in dense local or regional clusters.
1	Shrub and grassland	Perennial grass, sparse trees, impoverished woodlands, very sparsely distributed, low-lying shrub species.
1	Thicket/Dense bush	Bushland, dense shrubs.
1	Bare/Exposed rock	Bare, exposed areas and transitional areas.
3	Eroded land	Non-vegetated (bare) donga and gullies associated with significant natural or anthropogenic erosion activities along or in association with stream and flow lines.
1	Mines and Quarries	Areas in which mining activities have been conducted. This includes both opencast mines and queries, surface infrastructure, mine dumps
1	Residential	Built-up areas used for residential (town or villages), commercial and services, and transportation.
1	Water bodies	Water reservoirs and water channels. Includes all natural and artificial surface water.

2.5.2 Satellite Image Pre-processing

The Landsat Collection level 2 satellite images collected for this study were pre-processed for radiometric (including atmospherically corrected surface reflectance) and geometric correction upon collection (Ganasri & Dwarakish, 2015). Furthermore, image enhancement technique, histogram equalization and surface reflectance were applied to improve image quality. Colour balancing was applied using the colour corrector tool and balance using the first-order dodging method.

2.5.3 Image Classification

A supervised classification method was applied to Landsat images after creating LULC class training sites with distinct spectral signatures. The maximum likelihood classifier method was applied to execute the classification. A maximum likelihood algorithm was applied because the method uses the digital number of the training sites and its mean, variance, and covariance (Sisodia et al., 2014). The maximum likelihood algorithm uses the probability of a pixel member data class in its decision-making.

Supervised classification is an iterative process where collected training samples must be evaluated and edited as images are classified to increase accuracy. A minimum of 10 training sites were collected for each land class and for each study period as recommended by literature to adequately create signature files and classify images using a maximum likelihood classifier (MLC) (Meshesha et al., 2016). Then, training samples were re-evaluated, re-edited and re-collected if training samples are not accurate, the process is repeated (Meshesha et al., 2016). High-resolution Google satellite images were used as secondary sources to improve classification accuracy (Cao, 2016; Kobayashi et al., 2013). The figure below depicts spectral signature plots of LULC training samples collected for each study years to show expected surface reflectance for each LULC (Figure **2**:**2**).

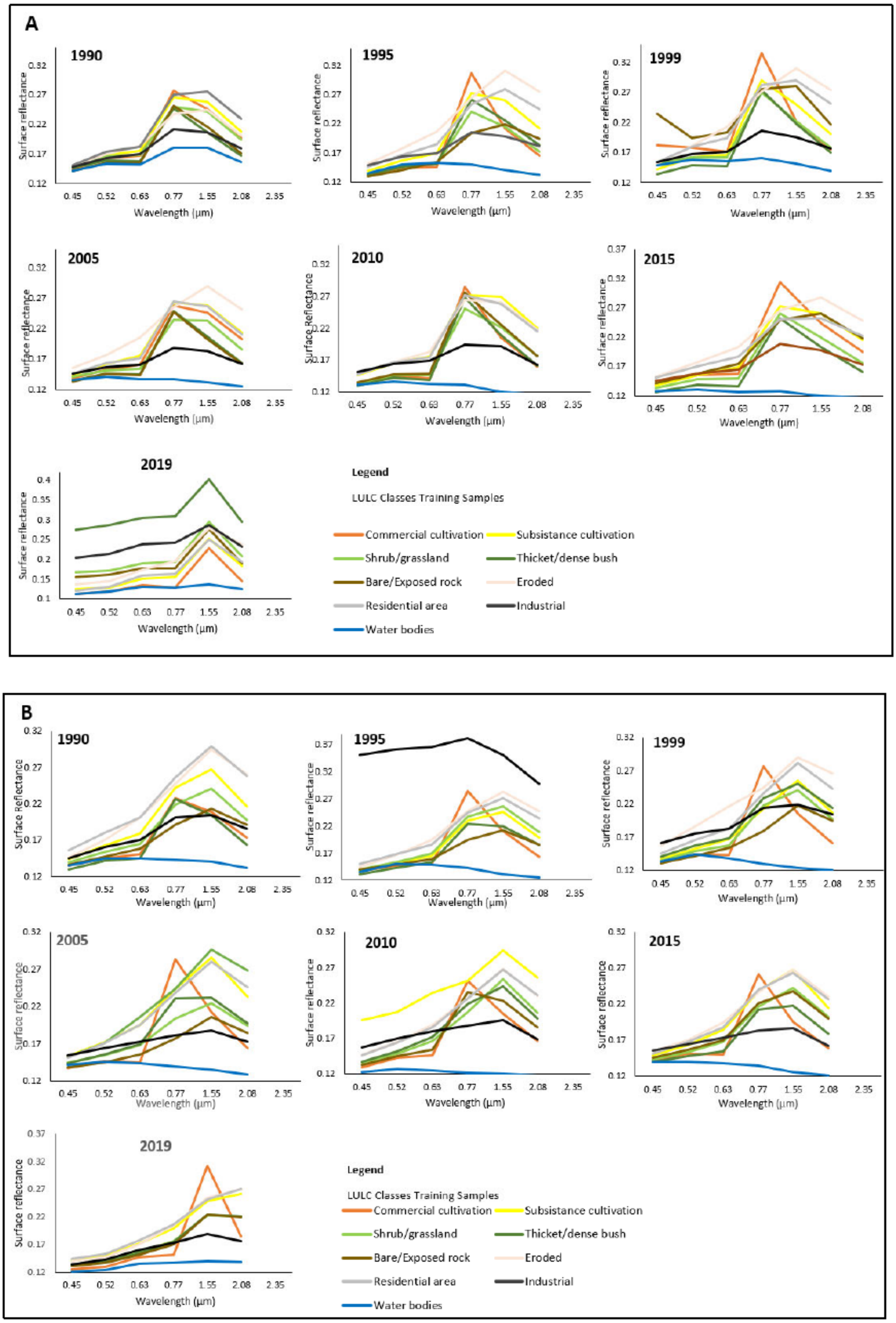


Figure 2:2. Spectral signature for LULC classes training samples of wet (A) and dry (B) season per study years.

The surface reflectance pattern of the training samples was as expected. The first few wavelengths (bands) generally recorded high reflectance as a result of atmospheric scattering. Then the spectral signature depicted a sharp increase of surface reflectance in the near infrared at about 0.77 micrometer (band 4) due to absorption by oxygen in the atmosphere. Water, industrial land and commercial cultivation have distinct spectral signatures so these classes will be easy to differentiate for wet and dry season. The spectral signatures of eroded land and built up were very similar as well as shrub/grassland and subsistence cultivation, so, these classes will be very challenging to distinguish for both seasons.

2.5.4 Accuracy Assessment

One of the popular accuracy assessment approaches is the error matrix (Foody, 2004). An error matrix represents the accuracy of each LULC category and commission and omission errors in the classification (Congalton, 1991). The Overall Accuracy (OA) indicates the total number of correctly identified samples in the classification results compared to the total number of samples classified in the image. Accuracy assessment was tested using the ArcGIS software to produce an error matrix report with the OA and kappa coefficient. The sampling strategy used was the equalised stratified random method selector that creates equal randomly distributed points within each class (Congalton, 1991). The number of random points was 10 times the number of test pixels for each class. Since there are nine land cover classes in this study, 30 test pixels for each land cover were randomly created resulting in a total of 270 test pixels to assess classification accuracy. High-resolution google satellite images were used to collect reference points.

2.5.5 Change Detection

LULC change and NDVI (land productivity) (computed from Landsat images) were used as indicators of LD in this study set out by United Nations Convention to Combat Desertification (UNCCD) and recommended for tracking progress towards LDN (Orr et al., 2017). LULC provide the first indication of changing vegetation cover and habitat fragmentation (Cha et al., 2020; Orr et al., 2017). Land productivity captures changes in ecosystem functions and health (Cowie et al., 2018).

Habitat fragmentation was monitored using the change detection technique Temporal Image Differencing (TID) method to quantify Change Detection from other LULC classes. Temporal

Image differencing is a process where initial-date image pixels are subtracted from the final-date image pixels, producing a third (change) image (Lillesand, 2014). Area change, land conversions and rate of change are some of the many ways to study land cover change (Meshesha et al., 2016). Area change refers to the change in the extent of a specific LULC class cover from the start to the end of the study period (Equation 2.1) (Meshesha et al., 2016). Rate of change is the rate of change of hectare per year per land class (Equation 2.2). Land conversion refers to the conversion of a type of land into other types at the start and end of the study period with LULC transition matrix applied to determine and quantify the changes. The following formulae were applied to study LULC change:

$$C_e = \frac{T_a(t_2) - T_a(t_1)}{T_a(t_1)} \times 100 \qquad \text{Equation 2.1}$$

where: *C_e is the percentage change in area extent; T_a is the total area; t_1 is the initial time; t_2 is the ending time.*

$$C_r = \frac{\left(\frac{T_a(t_2) - T_a(t_1)}{T_a(t_1)}\right)}{t_2 - t_1} \times 100 \qquad \text{Equation 2.2}$$

where: *C_r represents the annual rate of change; T_a is the total area; t_1 is the initial time; t_2 is the ending time.*

Vegetation dynamics reflect the effects of various interactions of biotic and abiotic factors and disturbance history. Vegetation production is one of the most crucial indicators of LD derived from time-series satellite images at various scales (Fensholt et al., 2013; Holm et al., 2003; Verón et al., 2006). In arid or semi-arid areas, the NDVI is highly correlated with Above-ground Net Primary Productivity (ANPP) (Huang & Kong, 2016), hence, was used as LD indicator. NDVI measures vegetation condition and its health and calculates the difference calculated from the visible red and near-infrared (NIR) portion of the electromagnetic spectrum (Wessels et al., 2007). NDVI is calculated using Equation 2.3 below:

$$NDVI = \frac{NIR - RED}{NIR + RED} \qquad \text{Equation 2.3}$$

where: *NIR represents the reflection in the near-infrared range of the spectrum (nm); RED represents the reflection in the red portion of the spectrum by vegetation cover (nm).*

The values range from −1 to +1 with high values representing healthy/active vegetation while non-vegetated surfaces such as water bodies, and bare land/ rocks are represented by negative NDVI values (Wessels et al., 2007). NDVI was extracted during the wet and dry season Landsat images then Image Differencing was applied for every five years using ERDAS Imagine 2018 software. NDVI change detection images and statistics were acquired using Image Differencing tool and Zonal statistics and interpreted as follows:

- **Negative change**: areas with recurring drought, low to moderate vegetation, extreme temperature and precipitation, expansion of residential areas with reduction in vegetation.
- **No change**: areas with little or no change in vegetation values.
- **Positive change**: areas with improved vegetation and precipitation changes.

The flowchart above (Figure 2:3) outlines the methodology followed in the study to better understand LULCC dynamics and their impact on LD.

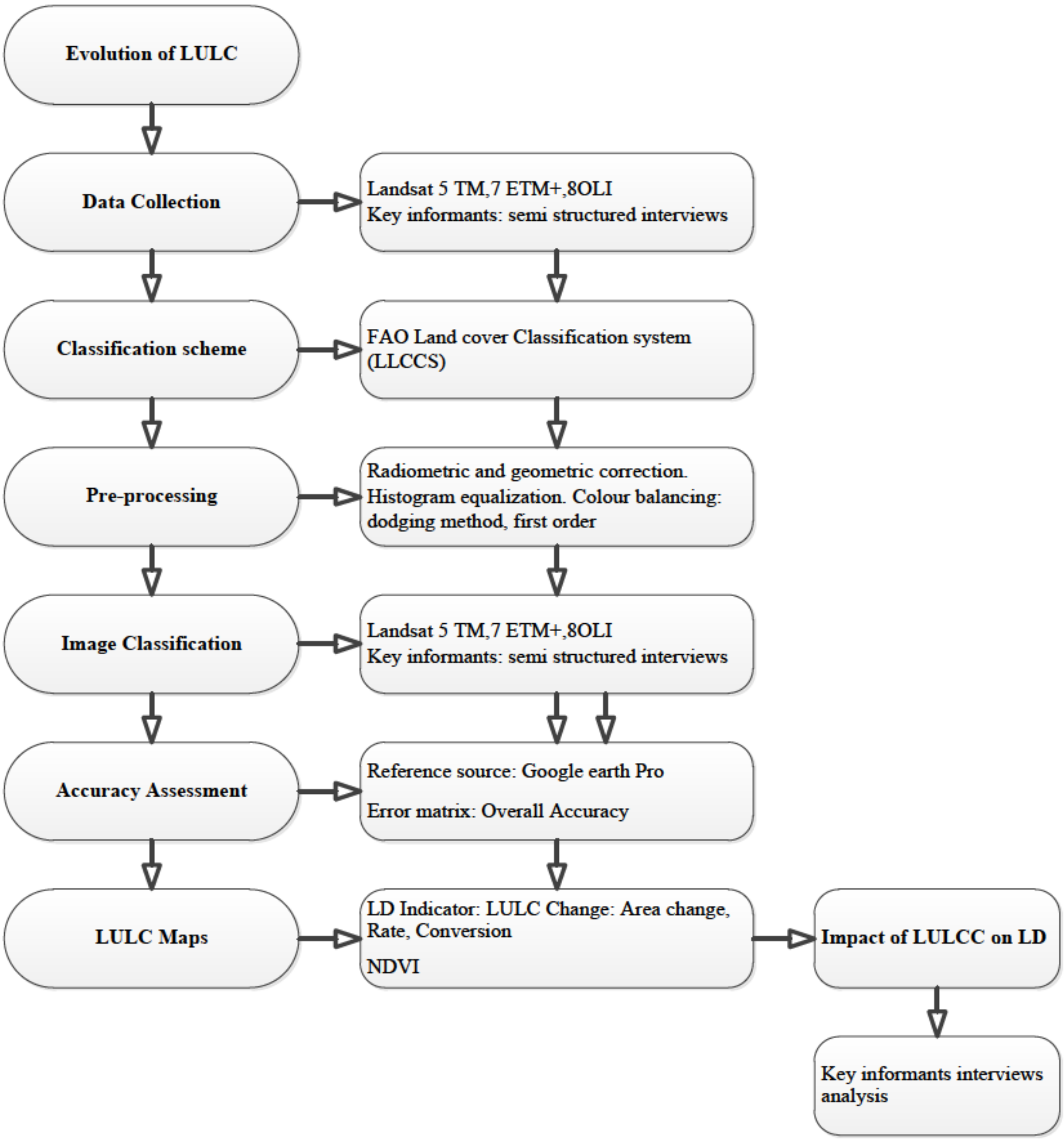


Figure 2:3 Methodology for data collection and analysis

2.6 RESULTS AND DISCUSSION

2.6.1 LULC Classification Accuracy

LULC maps had an overall classification accuracy greater than 85% and a Kappa coefficient equal or greater than 0.82 (Table 2.4), except for the 1995 dry season and the 1999 wet season which had an overall accuracy of 84.07% and 84.81%, respectively. This was reasonably good overall accuracy as per Manandhar *et al*. (2009) recommendation of at least 85%.

Table 2.4 Summary of Wet and Dry season LULC Accuracy assessment.

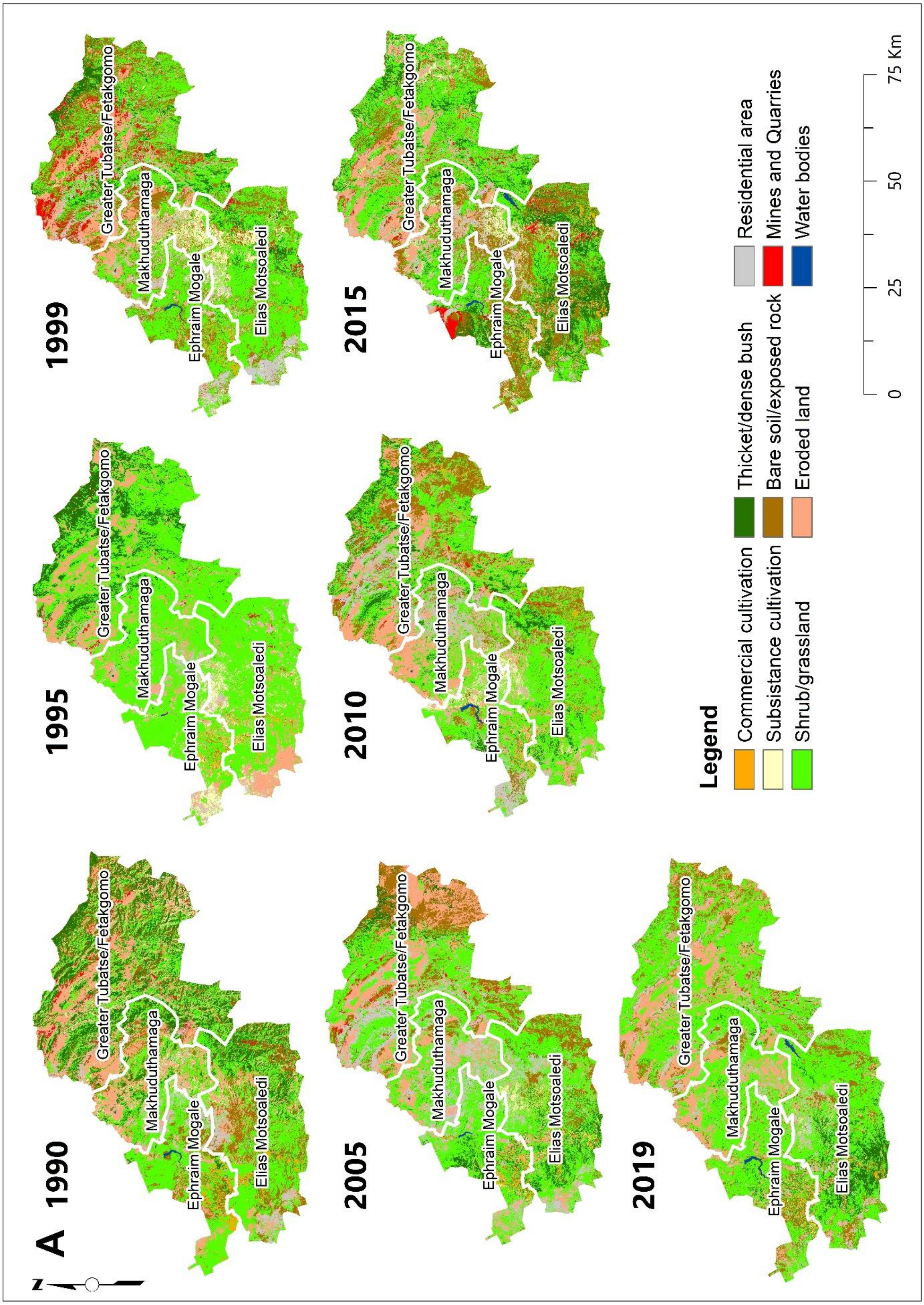
Year	Classified image	Kappa coefficient	Overall Accuracy (%)
1990	Wet	0.85	87.04
	Dry	0.87	88.15
1995	Wet	0.85	87.41
	Dry	0.82	84.07
1999	Wet	0.82	84.81
	Dry	0.85	87.41
2005	Wet	0.83	85.19
	Dry	0.82	84.38
2010	Wet	0.85	87.04
	Dry	0.85	86.30
2015	Wet	0.85	87.04
	Dry	0.86	87.41
2019	Wet	0.86	87.41
	Dry	0.85	86.67

2.6.2 LULC Maps for Wet and Dry Season

LULC classes were mapped for both the dry and the wet seasons at the five-year intervals (Figure 2:4). Identified classes include commercial cultivation, subsistence cultivation, shrub/grassland, thicket/dense bush, bare/exposed soil, eroded land, residential, mines and quarries and water bodies.

The LULC results indicate that shrub/grassland remains the dominant land cover and is spread throughout the district, while commercial cultivation is the main land use in the south to the southeast side of the district. The second dominant land cover is bare/exposed rock prevalent in the southern part of the district. LULCC dynamics show that in the wet season of 2015, an additional 21.06% (284887.37 Ha) of land was left bare and exposed, increasing the susceptibility of land to erosion. The third most dominant land cover in the wet season is eroded land, which is prevalent in the central to northern parts of the district (in the Fetakgomo Tubatse and Makhuduthamaga local municipalities). These local municipalities were characterised by low-lying areas and plains (level plains with some relief and plains with open high hills or ridges) hence the presence of donga and gully features associated with significant water erosion, typically stream and flow line activities. More land was eroded in 2015, reaching 20%

(270512.17 Ha) of the total area. Another indicator of degrading land is that after 1995, Thicket/dense bush in the district had a major reduction in the dry season and was progressively converted to shrub/grassland.


A
1990
1995
1999
2005
2010
2015
2019
Greater Tubatse/Fetakgomo
Makhuduthamaga
Ephraim Mogale
Elias Motsoaledi
Legend
Commercial cultivation
Subsistance cultivation
Shrub/grassland
Thicket/dense bush
Bare soil/exposed rock
Eroded land
Residential area
Mines and Quarries
Water bodies
0
25
50
75 Km
N

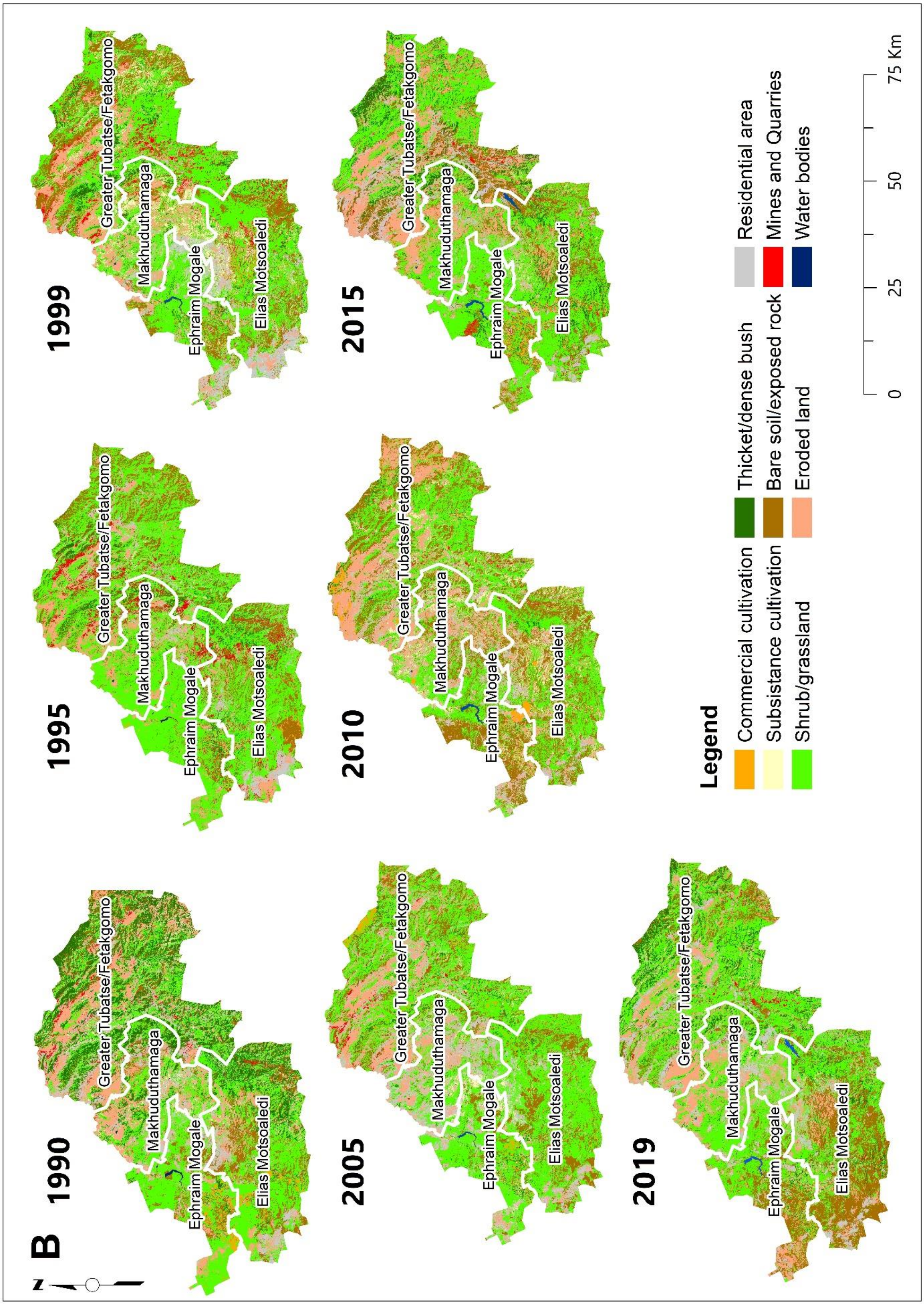


Figure 2:4 Five-year interval (A) wet season and (B) Dry Season LULC of the Greater Sekhukhune District Municipality from 1990 to 2019, mapped from relevant Landsat scenes.

2.6.3 Evaluation of LULCC Influence on LD: LD Indicators

2.6.3.1 LULC Area Change

LULC area changes in the Greater Sekhukhune District were assessed over the 30year period and the following increases were observed during the wet season: a 98% increase in water bodies, a 76% increase in the residential area and a 53% increase in shrub/grassland. The increase in the extent of water bodies is mainly due to the construction of the De Hoop dam completed in 2014 (the 13th largest in South Africa) on the Steelpoort River located in Fetakgomo Tubatse local municipality and covers 1,690 Hectares (Profection Design., 2016; The Greater Sekhukhune District, 2019). However, fieldwork observations indicate that naturally occurring water bodies such as rivers and wetlands have declined in surface area. Shrub/grassland mostly replaced thicket/dense bush, an indication of LD assessed as "vegetation loss" (Cha et al., 2020). The LULCs that declined dramatically by extent are mine/quarries by 81%, subsistence cultivation by 80% and thicket/dense bush by 69% in wet seasons. The decline in subsistence cultivation is due to various reasons such as rainfall variability, the decline in soil productivity and income dependency on the social grants (Mpandeli et al., 2015; Sinyolo et al., 2017). The decline in mine/quarries is due to a decline in operational mines where 18 out of 27 mines are non-operation as a result of commodity demand issues, unavailability of water in the district and lack of off-take agreements for the commodities (The Greater Sekhukhune District Municipality, 2020).

A five-year interval of area changes from 1990 to 2019 was also assessed (Figure 2:5) and revealed that significant changes occurred from 1990 to 1995 and 2010 to 2015. Bare/exposed rock area increased by 3353% from 1995 to 1999 in the wet season, changing from shrub/grassland. Eroded land increased in extent by 74% from 1999 to 2005 in the wet season and between 2005 to 2010 in the dry season by 63% where 79494.00 Ha was converted to eroded land from shrub/grassland. One of the main land use losses in the area was subsistence cultivation by 84% in the wet season between 2010 to 2015 period. These changes occurred due to drought periods recorded in 1990s, 2004, 2016 and 2018 were marked as the driest years during the study period in the district by Mpandeli *et al.* (2015) and Meza *et al.* (2021).

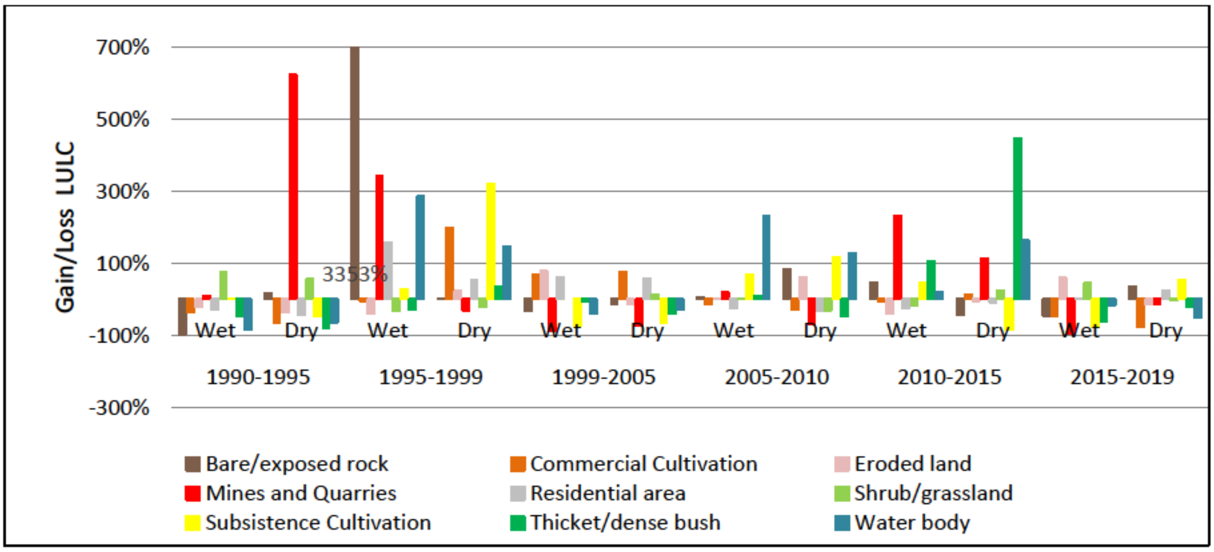


Figure 2:5 LULC Percentage Change-Gain and Loss between different times.

Frequent prolonged drought events, particularly in rangelands of semi-arid regions, have detrimental effects on the ecology that degrade the land and these effects are observed in the LULCC of the study. The frequent prolonged drought conditions reduce vegetation cover, increase bare soil, and exposed the soil to erosion. Moreover, fire occurrence due to frequent prolonged drought events in rangelands (Vetter, 2009), alongside grazing, further reduces vegetation cover and the physical carrying capacity for grazing. The results also reveal the impacts of rainfall variability in the district reported by Mpandeli *et al*. (2015). There is a synergistic effect of prolonged drought and intensive rainfall events that led to LULC changes and LD observed in the district. Following prolonged drought event, intensive rainfall in the district has resulted in soil erosion and gully formation (an increase of bare/exposed rock and eroded land) when high raindrop impact detaches soil particles in the low vegetated cover areas and surface runoff (Mohamadi & Kavian, 2015). This calls for land management policies to be put in place and implemented to prepare for extended drought events.

2.6.3.2 Rate of LULCC

The rate of change of LULC represents the change of hectare/year of each class (Figure 2:6). The highest declining rate of change per year was mines and quarries by 2.69%, subsistence cultivation by 2.65%, thicket/dense bush by 2.30% and commercial cultivation by 1.86% in the wet season over the past 30 years. The reduction of thicket/dense bush increased shrub/grassland in the study area. This is most likely due to deterioration and erosion of topsoil that reduced the quality of soil that can support thicket and dense bush. Shrubs tend to be hardy than thicket/dense bush and can survive in lower-quality soil.

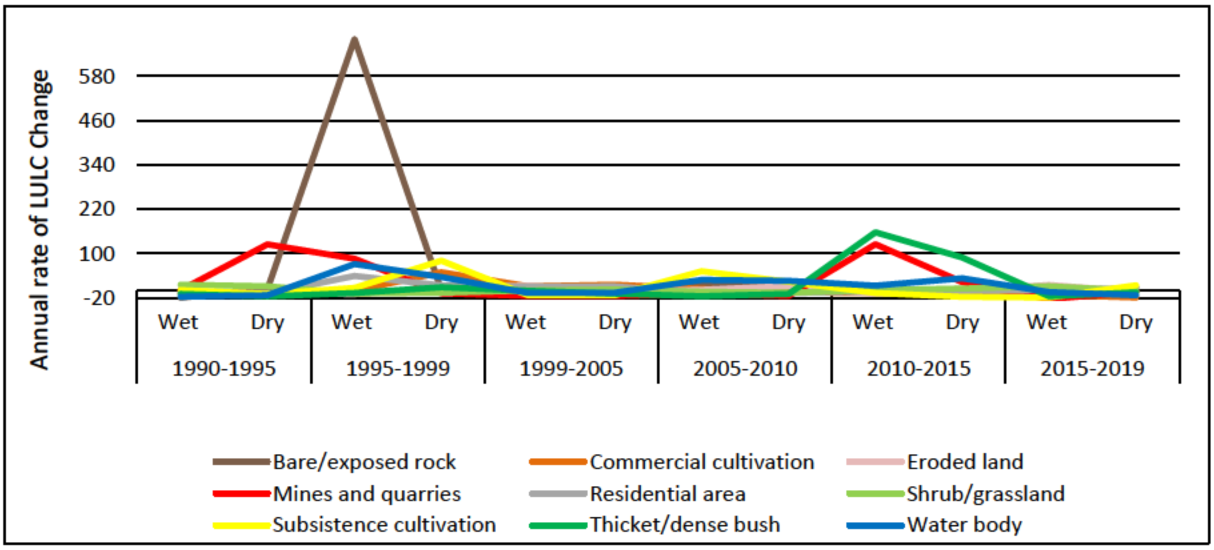


Figure 2:6 Annual rate of LULC change in LULC classes for wet and dry seasons.

Water bodies, residential areas and shrub/grassland recorded the highest annual growth rate by 3.28%, 2.52% and 1.78% in the last 30 years, respectively. As aforementioned, the increase in water bodies was mainly due to the construction of the De hoop dam completed in 2014 which covers 1,690 Hectares. More soil was also left exposed, increasing susceptibility to erosion in the area as bare/exposed rock increased by 1.75% per year. The spike increases in percentage gain and rate of bare/exposed rock from 1995 to 1999 was due to the recurring drought conditions recorded in the district in the 1990s (Mpandeli *et al.,* (2015).

The spatio-temporal dynamics over five-year intervals indicate a 7.21% annual decrease in commercial cultivation, mostly between 1990 and 1995 and subsequent annual decrease of 11.79% between 2015 and 2019 in the wet season. The area under subsistence cultivation decreased at an annual rate of 12.39% from 1999 to 2005 and a subsequent major annual decrease of 18.94% from 2015 to 2019 in the wet season. The area experienced the highest residential growth rate of 39.52% between 1995 and 1999 and again by 6.86% between 2015 and 2019. Thicket/dense bush declined between 1990 and 1995 by an annual rate of 15.81% in the dry seasons and from 2005 to 2010 by 14.95% in the wet seasons. The highest decline of thicket/dense bush, subsistence cultivation and commercial cultivation in recent years may reveal that the vegetation and soil productivity struggles to recover after dry seasons due to prolonged drought and/or human activities such as unsustainable land use practices. Murray-

Tortarolo *et al*. (2016) report that changes in water availability over the dry season affects vegetation throughout the year, driving changes in regional ANPP thus during the wet season.

2.6.3.3 LULC Conversions

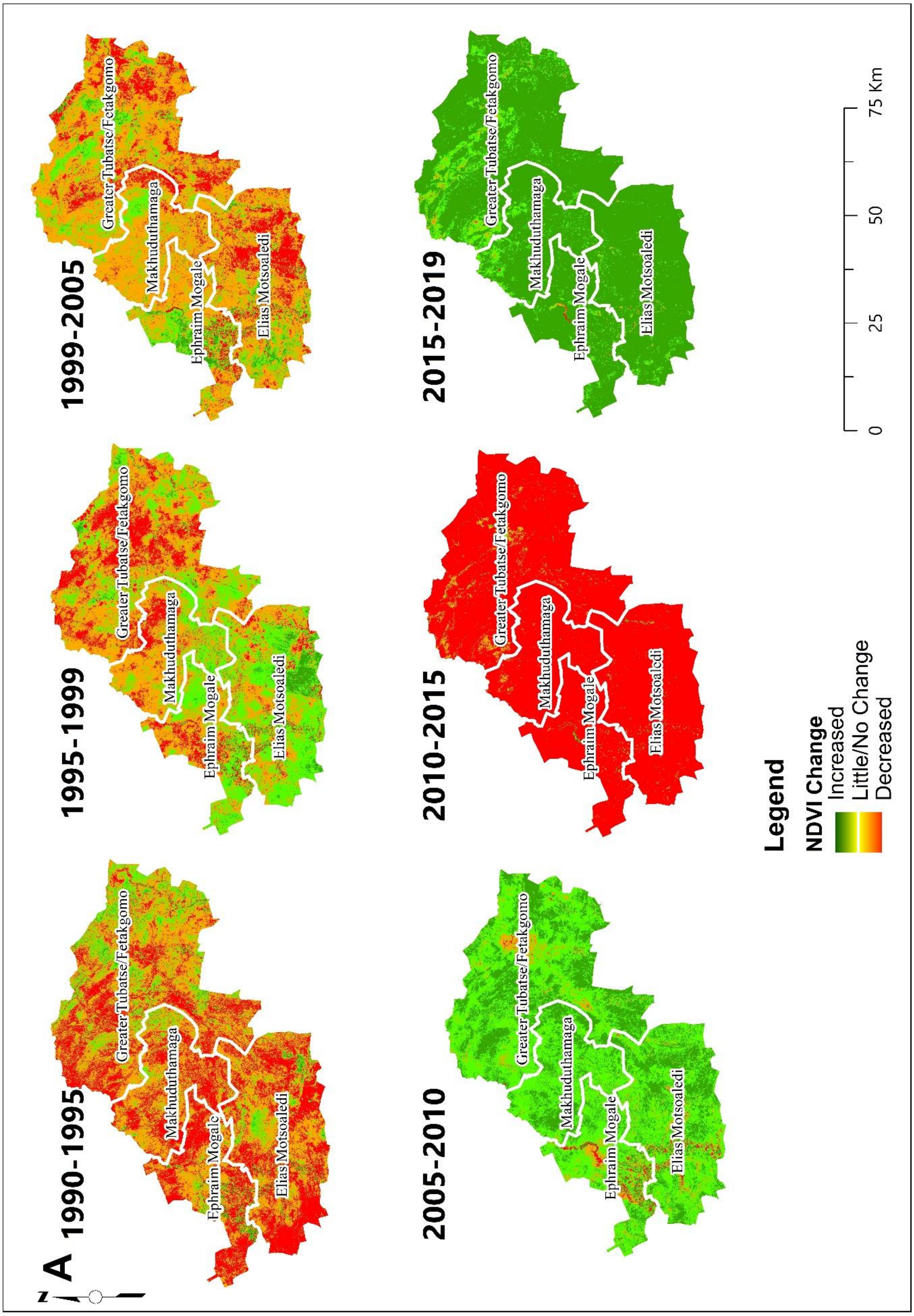
The land use land cover conversions also reveal that land productivity is declining as shown in Table 2.5. LULC conversion was conducted using the transition matrix and the 14 most common conversions (Table 2.5) for their respective seasons. The highest conversion was from shrub/grassland to bare/exposed rock by 129255.85 Ha (9.55% of total area) between the 2015 to 2019 dry season followed by thicket/dense bush to shrub/grassland by 110625.63 Ha (8.18% of total area) between 2010 to 2015 wet season, and lastly, shrub/grassland to bare/exposed rock by 109736.63 Ha (8.11% of the total area) between 2010 to 2015 wet seasons. These highest conversions and other conversions (Table 2.5) reveal that the productivity of the ecosystem in the district is degrading as forested land is declining and replaced mainly with shrub/grassland and thereafter a few years converted to bare/exposed rock and residential area. These conversions may be because of both natural and man-made factors. One of the man-made conversions that are noted is the conversion of 64465.42 Ha of shrub/grassland to the residential area between 1995 to 1999.

Table 2.5 14 most common LULC Conversion, period, and season

Rank	**From Class name**	**To Class name**	**Period**	**Season**	**Area (Ha)**
1	Shrub/grassland	Bare soil/exposed rock	2015-2019	Dry	129255.85
2	Thicket/dense bush	Shrub/grassland	2010-2015	Wet	110625.63
3	Shrub/grassland	Bare soil/exposed rock	2010-2015	Wet	109736.63
4	Shrub/grassland	Bare soil/exposed rock	1995-1999	Dry	92186.56
5	Shrub/grassland	Eroded Land	2005-2010	Dry	79494.00
6	Thicket/dense bush	Bare soil/exposed rock	1990-1995	Dry	76749.93
7	Eroded Land	Shrub/grassland	2015-2019	Dry	74632.24
8	Residential	Shrub/grassland	2005-2010	Wet	73953.02
9	Bare soil/exposed rock	Shrub/grassland	2015-2019	Dry	71890.83
10	Bare soil/exposed rock	Shrub/grassland	2010-2015	Wet	70188.57
11	Bare soil/exposed rock	Shrub/grassland	2005-2010	Wet	69619.38
12	Bare soil/exposed rock	Shrub/grassland	1990-1995	Dry	69079.58
13	Shrub/grassland	Bare soil/exposed rock	2005-2010	Wet	65193.11
14	Shrub/grassland	Residential	1995-1999	Dry	64465.42

2.6.3.4 *Land Productivity-NDVI Change*

The second indicator of LD is land productivity i.e., NDVI, shown in Figure 2:7 (A & B) and trends in Figure 2:8 (A & B), obtained between 1990 and 2019 in a five-year interval. There is an increasing negative NDVI change in both seasons, with a steeper trend in the dry season. The wet and dry season show similar trends of NDVI change in productivity and shows that the productivity of the area has been declining from 1990 to 2005 and started picking up between 2005 to 2010 and from 2015 to 2019. The wet season (Figure 2:7A) recorded higher negative changes in 1990 compared to the dry season, while the dry season (Figure 2:7B) recorded higher negative changes between 1999 to 2005.


A
1990-1995
1995-1999
1999-2005
2005-2010
2010-2015
2015-2019
Greater Tubatse/Fetakgomo
Makhuduthamaga
Ephraim Mogale
Elias Motsoaledi
Legend
NDVI Change
Increased
Little/No Change
Decreased
0
25
50
75 Km
N

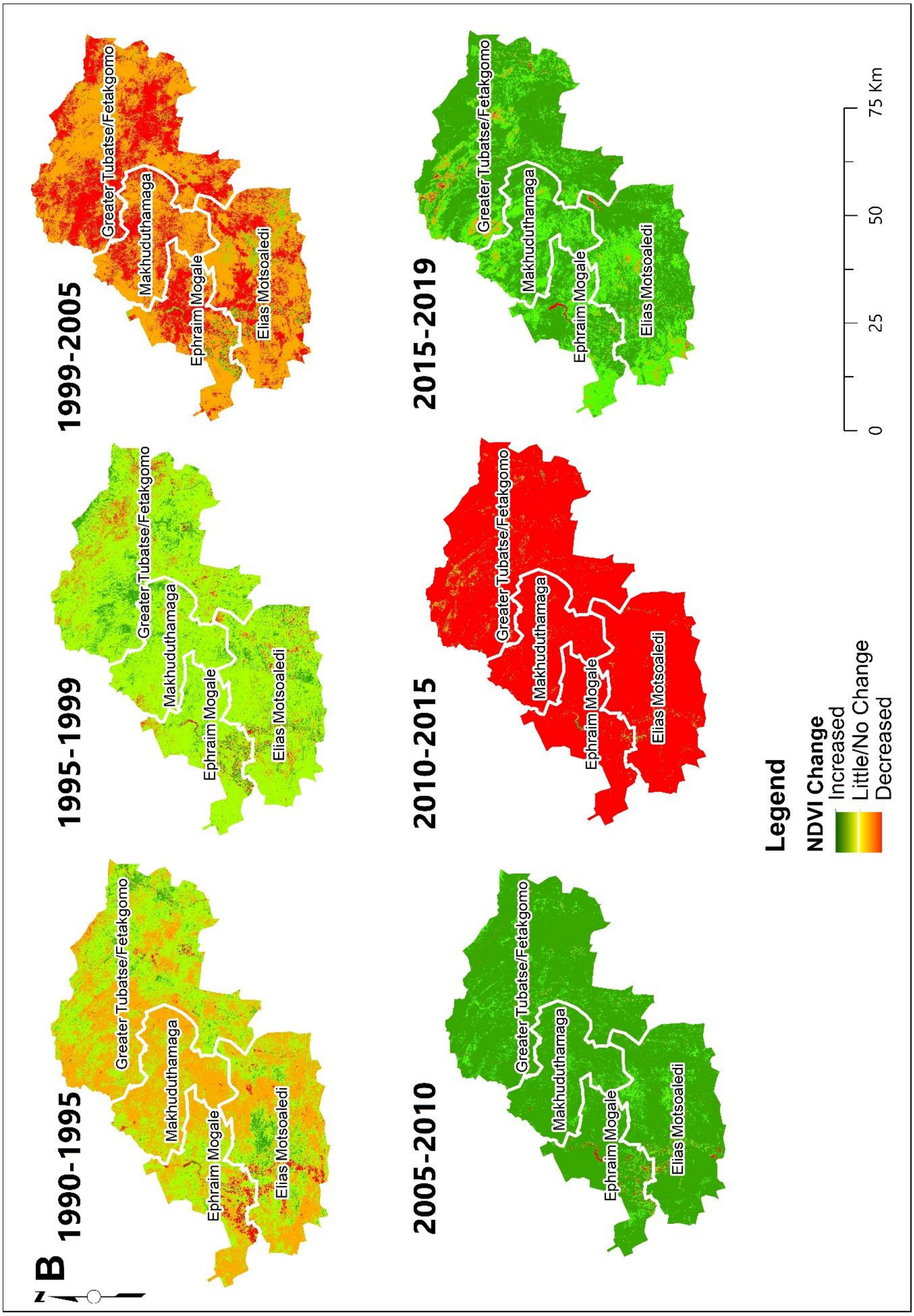


Figure 2:7 Five-year interval Negative NDVI Change for Wet ((A) and Dry (B) Season between 1990 to 2019 using Image Differencing.

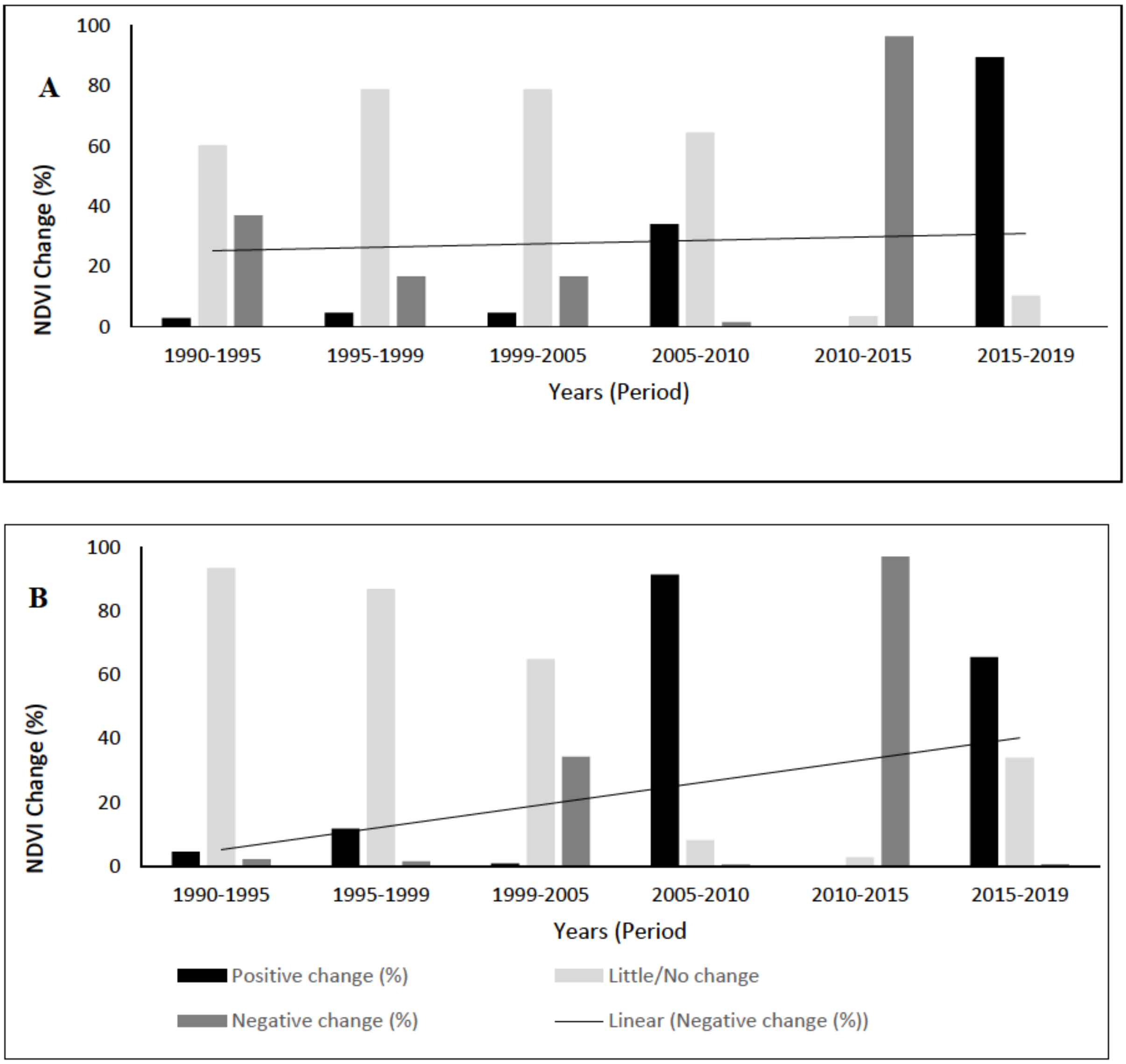


Figure 2:8 NDVI change trend of Wet (A) and Dry (B) seasons from 1990 to 2019.

The district then faced an extreme decline in productivity between 2010 and 2015, both wet and dry seasons with the highest NDVI negative changes of 96.39% and 97.05%, respectively. The LULC conversion shows that it was during this period (2010 to 2015) that the second common conversion was recorded and this was thicket/dense bush converted to shrub/grassland then subsequently shrub/grassland replaced with bare/exposed rock. In 2019 for both wet and dry seasons, there was an increase in NDVI, however, increasing vegetation productivity could be associated with bush encroachment as invasive species and pioneer species where vegetation suppresses palatable plant species and grasslands (Graw et al., 2016).

Bush encroachment was observed across the communal/rangeland of the district and could be an indicator of prevalent LD. Therefore, vegetation health and productivity of the area are declining, and this is consistence with LULC changes and rates that show the overall reduction in thicket/dense bush, shrub/grassland and subsistence and commercial cultivation. The steeper increasing negative NDVI change trend in dry season and increasing negative NDVI trend in wet season is also consistent with Kumar *et al*. (2015) and Murray-Tortarolo *et al*. (2016)who note that the dry season ecosystem plays a vital role in annual land productivity as vegetation production shows that the wet season cannot recover. This means that the area is subject to frequent drought, moderate to low vegetation, extreme precipitation and temperature, vegetation decline and production decline that cannot recover unaided i.e., LD. Human drivers of LD such as overgrazing and unsustainable land use practices i.e., unsustainable wood harvesting, have been degrading communal rangelands (T. Hoffman & Ashwell, 2001) so it is important to explore and document these factors as an initial step to achieving LD Neutrality (Cowie et al., 2018).

2.7 POTENTIAL DRIVING FACTORS OF LULCC AND LD IN THE DISTRICT: LINKING RS RESULTS (LULCC AND NDVI) AND KEY INFORMANT INTERVIEWS RESULTS

A semi-structured questionnaire was used to interview key informants i.e., natural resource managers, crop production, animal production and extension services per local municipality from the Limpopo Department of Agriculture and Rural Development (LDARD) based in Sekhukhune District as well as Traditional Authorities. A total of 11 key informants and 17 Traditional Authorities were interviewed and the results in the document highlight key findings related to the drivers of LULCC that lead to LD in the district. The key informant interviews revealed that the main drivers of LULC changes contributing to LD were soil erosion, increase in bare soil due to overgrazing and lack of grazing management, cropland abandonment, settlement encroachment into productive cropping land, policy and institutional changes, wood harvesting and land tenure.

2.7.1 Soil Erosion and Increase in Bare Soil Cover

The interviews highlighted that soil erosion in the area is mainly due to human-induced activities exacerbated by flash floods. Overgrazing was noted as the main contributor of increased eroded land and bare soil because of uncontrollable/lack of rotational grazing. All key informants noted that grazing capacity has also been reduced due to inappropriate and/or absence of grazing management i.e., rotational grazing. Overstocking and lack of fencing due to vandalization of fences have contributed to LD. Illegal sand mining was noted as one of the contributors to soil erosion, removal of natural vegetation and extension of existing gullies, further degrading the landscape.

2.7.2 Settlement Encroachment into Cropping Land, Cropland Abandonment and Bush Encroachment

The key informants noted an expansion of residential areas in the district due to increasing population. The expansion of residential areas results in settlements encroaching into cropping lands. This has resulted in a decline in croplands and crop production. Abandonment of croplands was reported by all informants to be widespread and is due to rainfall variability, lack of interest in agriculture as a livelihood, a growing crisis of an ageing farmer population due to young people being disinterested in farming, migration, and improper cropping methods such as lack of crop rotation. Cropland abandonment increases the likelihood of LD. Musvoto *et al.* (2022) noted that abandoned croplands in GSDM are prone to degradation, mainly the occurrence of soil erosion, as soil conservation methods are no longer applied.

Cropland abandonment and overgrazing are noted to promote bush encroachment. Studies show that there is bush encroachment on abandoned croplands because of climate change i.e., increase in carbon dioxide levels and lack of land management i.e., mostly overgrazing (Buitenwerf et al., 2012; Graw et al., 2016; Stephens et al., 2016; Stevens et al., 2017). Bush encroachment reduces grass cover and the grazing capacity for livestock where vegetation suppresses palatable plant species and grasslands (Graw et al., 2016). There is also an increase in stocking rates i.e., overstocking, and lack of rotational grazing due to lack of grazing field management, hence further degradation, and low vegetation available for livestock grazing.

2.7.3 Policy and Institutional Changes and Land Tenure Conflicts

Key informants emphasized that the increasing unsustainable use of natural resources resulting in its progressive depletion contributed to LD. This mostly took place after 1998 when most policies and institutional changes were implemented, following their introduction post-1994. The key informants emphasized that the phasing out of the rangers post-1994 who used to enforce local grazing management decisions, sustainable wood harvesting and overall rangeland management has led to the unsustainable use of resources, no form of accountability and lack of coordinated communal land management. There has been a perceptions of communal land as vulnerable as a result of assumptions that land users are unable to make local rules and regulations as a collective for the sustainable management of common resources. This reflects the concept of the "tragedy of commons" paradigm (Hardin, 1968). Key informants highlight that individual users act independently for their self-interest and cause a depletion of resources through this uncoordinated action. The absence of rangeland management institutions in the district has also resulted in vandalism of erosion control structures and theft of fences for rangeland management to control animal movement in communal land, as also noted by Itzkin *et al*. (Itzkin et al., 2021). Indeed, the lack of adequate tenure security and the absence of local communities to create accountable communal property associations (CPAs), under the Communal Property Association Act of 1996, to strengthen property rights and facilitate local resource management (Blatchford, 2013), has led to unsustainable land use practices and degradation.

Despite these communal rangeland management setbacks, a legal system through traditional councils has been enabled to play an important role in the local administration of communal areas when the Communal Land Act was introduced in 2004 (Ntsebeza, 2005; Republic of South Africa, 2004). However, accountability and management of land by traditional councils require coordination with the local community and awareness of actions and consequences to the environment as the issue of institutional control over land in communal areas remains controversial (Bennett, 2013). As a result, environmental degradation has been observed in the district through mismanagement of the use of natural resources in the rangeland that has resulted in the loss of shrub/grassland and thicket/dense bush and cropland abandonment. Cropland abandonment has increased significantly, partly due to free-roaming animals in various villages that have discouraged subsistence farmers to continue cultivating in the communal area as they do not have fences to protect their crops due to lack of capital.

Land tenure, particularly in Ephraim Mogale local municipality is mainly contributing to cropland abandonment and degradation. Key informants highlighted that land conflicts have led to more land lying fallow due to land claims and a lack of capital after land redistribution that mostly occurred after 1998. Forested land has declined due to unsustainable wood harvesting throughout the years and has been converted to shrub/grassland cover. Efforts have been made in the past to address some of the negative changes in the area such as the eradication of bush encroachment, fencing to control animal movement, soil erosion control structures, conservation agriculture and other SLM practices. However, key-informants emphasised that all stakeholders involved in the use and allocation of land must be engaged when making decisions that will affect the use of land. There is an emphasis on transparency, informed decisions, proper management, and community engagement when embarking on SLM activities, accountability, and awareness.

2.8 SUMMARY OF FINDINGS

This study was carried out to assess the LULCCs and impacts on land degradation in GSDM, particularly challenges faced in traditional rural district with dual land use system in semi-arid environments. The findings of the study reveal that the district is slowly changing from savanna biome to a grassland and this has severe impacts on livelihoods of the rural community, particularly pastoralists and rainfed farmers. Bush encroachment was one of the main concerns in the district contributing to land degradation and reducing the grazing capacity as more farmers are engaged in livestock farming, sharing a communal land. Therefore, it is recommended that a further study of causes of bush encroachment and species invading the communal rangelands needs to be carried out. The impacts experienced in the district is prevalent in much rural districts of the country and the findings provide detailed causes of these challenges. This serves as a foundation for modern system and tribal authorities to coordinate and address these challenges for policy formulation.

Efforts have been made to address LD, however, vandalism and lack of accountability from the community remain a challenge. Key informants emphasised that there must be transparency from all key stakeholders in terms of land use and tackling LD. Proper land use management through an informed decision on impacts, community engagement and awareness is crucial to achieving LDN in the district and communal areas across South Africa. Therefore, the study highlights that there is a need for a sense of urgency from the government, land users and tribal authorities as custodians of natural resources to address LD and promote SLM activities and sustainable livelihoods.

CHAPTER 3
Socio-Ecological System understanding of Land Degradation in Response to Land Use and Land Cover Changes

This chapter is based on two manuscripts:

Kgaphola, M.J., Ramoelo, A., Odindi, J., Mwenge Kahinda, J., Seetal, A. & Musvoto, C. **Social-Ecological Systems Understanding of Land Degradation in Response to Land Use and Cover Changes in the rural semi-arid of The Greater Sekhukhune District Municipality.** *(Sustainability* 2023, 15(4), 3850; https://doi.org/10.3390/su15043850 *):* published.

Kgaphola, M.J., Ramoelo, A., Odindi, J., Mwenge Kahinda, J. Seetal**,** A. R. **Apportioning human-induced and climate-induced land degradation: Case of The Greater Sekhukhune District Municipality.** (*Applied Sciences.* 2023, 13(6), 3644; https://doi.org/10.3390/app13063644 *):* Published.

3.1 ABSTRACT

LD (LD) is a major risk to sustainability and the functioning of socio-ecological systems (SES), especially in arid/semi-arid regions. Identification and assessment of LD is important to determine the appropriate interventions, land management and restoration. Therefore, this study aimed to assess LD through socio-ecological analysis in the rural semi-arid of the Greater Sekhukhune District. The first objective was to distinguish anthropogenic LD from rainfall using spatial residual trend (RESTREND) analysis of Normalized Difference Vegetation Index (NDVI) from 1990 to 2019, while the second objective was to assess drivers of LD using Drive Pressure State Condition and four Responses ($DPSCR_4$) framework (modified from Drive Pressure State Impact and Response (DPSIR) as SES. Key informant interviews, workshops with local herders and Tribal Authorities (TA), and scientific literature were triangulated to form a systemic analysis of $DPCSR_4$. LD Neutrality (LDN) was integrated into the framework to provide responses to inform sustainable land management (SLM). Spatial RESTREND results revealed that 11.59% of the district is degrading due to human impacts while 41.41% is due to the effects of rainfall. $DPCSR_4$ analysis shows that the main anthropogenic activities driving LD include overgrazing, land tenure, poverty and disempowerment, unsustainable land use and cropland abandonment that further encouraged bush encroachment. Natural factors

such as topography, dispersive duplex soils and climate variability and change predispose the district to gullies and soil erosion, and in combination with human activities, it exacerbated LD. The study revealed and recommended several responses that can be integrated into the land use plan and management using the $DPSCR_4$ and LDN framework to improve the conditions of the landscape and provide sustainable livelihoods in the area.

Keywords: LD, Social-Ecological Systems, RESTREND, $DPCSR_4$ (DPSIR), sustainable land management, Integrated land use plan and management

3.2 INTRODUCTION

Land use and land cover changes (LULCC) have intensified the functioning of socio-ecological systems and impacts, including LD. LD (LD) is defined as a prolonged reduction of ecosystem function and productivity as a result of several factors from which the land does not recover without appropriate interventions (Weldemariam, 2017) and has increasingly become a major global environmental problem (Gibbs & Salmon, 2014; Grumbine, 2014). Global estimations show that approximately 1.5 billion people are affected by LD, most of which are the developing world's rural poor (Z. G. Bai et al., 2008; Barbier & Hochard, 2016; Safriel, 2007). Identification and understanding of LD in an integrated social-ecological system (SES) is important to analyse how changes shape the functioning of ecosystems, and the synergies and trade-offs (Okpara et al., 2018) to identify appropriate interventions, land management and restoration.

In South Africa, LD is a serious concern, impacting rural communities and their livelihoods (Itzkin et al., 2021; Mani et al., 2021; R. J. Scholes & Biggs, 2004). Whereas biophysical factors influence land use potential, socio-economic factors i.e., institutional policies and governance influencing demand for land, determine land management (United Nations Convention to Combat Desertification, 2022). Historical inequity and its institutional policies of access to natural resources and land in South Africa have accelerated the pace of LD where almost 60% of land is degraded with 91% subject to desertification (T. Hoffman & Ashwell, 2001; Mani et al., 2021). Pre-1994, almost 3.5 million people were forced to resettle in homelands, now known as communal areas (Fox et al., 2007). This resulted in high population densities of people and livestock exerting pressure on the environment, degrading the land in communal rangelands (T. M. Hoffman & Todd, 2000; Meadows & Hoffman, 2002).

Communal areas of the Limpopo province of South Africa are regarded as one of the most degraded areas in the country (T. Hoffman & Ashwell, 2001). The Greater Sekhukhune District Municipality (GSDM) within the province is a former homeland characterised by degraded communal areas due to among others overgrazing, overstocking and injudicious agricultural practices (The Greater Sekhukhune District, 2019). Mitigating this problem requires identification and understanding of complex interactions of socio-ecological drivers as this is important to develop adaptive integrated management actions and determine significant trade-offs for future sustainability.

Yengoh et al. (2016) recommend four variables to assess, monitor, and map LD. These include (1) identifying drivers of degradation i.e., various human-induced or natural factors; (2) type of degradation i.e., drought, wind and water erosion, salination; (3) degree of degradation i.e., light to extreme; and (4) extent of degradation i.e., area affected. The Normalized Difference Vegetation Index (NDVI) has been used as an indicator of LD in arid or semi-arid areas because of its high correlation with Above-ground Net Primary Productivity (ANPP) (Huang & Kong, 2016). Various studies have shown that rainfall strongly influences vegetation growth and distribution (Huber et al., 2011; Martiny et al., 2006; Wessels et al., 2007; Zhang et al., 2021), as a result, rainfall is a crucial predictor of vegetation production.

The NDVI data availability from National Oceanic and Atmospheric Administration-Advanced Very High-Resolution Radiometer (NOAA-AVHRR) has facilitated significant research on LD (Lupo et al., 2001; Tucker et al., 2005). However, the results are normally dominated by irregular rainfall patterns, related seasonal and drastic changes in LULC (Wessels et al., 2007), making LD indistinguishable. Residual Trends (RESTREND) method has been widely used to distinguish LD resulting from anthropogenic factors from those occurring due to rainfall effects (Chu et al., 2019; Huang & Kong, 2016; Li et al., 2012; Wang et al., 2010; Wessels et al., 2007). The method reveals the spatial patterns of LD drivers factors at cell resolution.

Following the identification of degraded areas affected by either humans or rainfall, it is crucial to assess and understand how humans or rainfall have impacted the land in a system to identify appropriate intervention measures. A Social-Ecological System (SES) is a framework that is applied to reflect human interactions with the ecosystem, and how they affect each other (Itzkin et al., 2021; Petursdottir et al., 2013). Drive Pressure State Impact Response (DPSIR) is a SESs analytical framework adopted by United Nations Environmental Programme (UNEP) and was widely applied in several environmental research studies across Europe (Agard et al., 2007; Masó et al., 2019; Song & Frostell, 2012). The DSPIR is a framework that structures and organises indicators to reflect the cause-effect linkages between the ecosystem and society and facilitate decision-making (Tscherning et al., 2012). However, one of the major shortcomings of DPSIR is differentiating impacts from state, it suggests that there is an ecosystem's natural state and that impacts include deviation from that state (Harwell et al., 2019). Another weakness of the DPSIR is that it overlooks stressors which is a crucial component of the system, thus not accounting for the relationship between causes and their effects on the environment (Harwell et al., 2019).

The DPSIR framework was modified to Drivers-Pressure-Stressors-Condition-Responses ($DPSCR_4$) framework, with impact revised to condition, where condition reflects the state of the environment. The $DPSCR_4$ framework was adjusted to include four types of responses, i.e., stressor source reduction, existing stressor remediation, restoration of the ecology, and recovery of the ecology (Harwell et al., 2019; Itzkin et al., 2021). The $DPSCR_4$ model defines 'drivers' as the human and natural forces driving LD, these drivers then exert 'pressure' on the environment, which then causes chemical, physical, or biological 'stressors' (Schlegel & Huchzermeyer, 2018). The drivers, pressures and state affect the 'condition' of the ecological structure and processes that affect the social-ecological system (Schlegel & Huchzermeyer, 2018). Management actions through four types of societal and ecological 'responses' can feed back to the system to achieve LD neutrality (LDN).

Despite its wide use in Europe, DPSIR has seldom been adopted in developing countries like South Africa, furthermore, the $DPSCR_4$ has not been adopted in many studies. Therefore, a deeper understanding and responses to LD SESs is key to achieving a LDN and improving livelihoods in rural areas. Moreover, the connection between anthropogenic pressures and environmental indicators as well as existence of complex interlinkages between them in the GSDM are not well documented. Hence it is important to better comprehend the causational relations, processes and complexities between a wide set of anthropogenic activities and their impacts on the environment.

Therefore, this study aimed to monitor and map drivers of LD and assess the drivers using an SES approach to propose responses to achieve LDN. The first objective was to spatially distinguish between human-induced LD and rainfall effects using RESTREND analysis, while the second objective was to assess LD using a system's application of $DPSCR_4$ and LDN frameworks to identify drivers of degradation and intervention to inform sustainable land management of the GDSM. This case study adds value to the South African context to better understand LD drivers and process by integrating several disciplines' perspectives to identify potential leverage points to promote sustainable land management interventions.

3.3 MATERIALS AND METHODS

3.3.1 Study Area

The study area is located in the northern part of South Africa within the Limpopo province, Greater Sekhukhune District Municipality - 24°5'.10" S, 25°21'.27" S and 29°3'40"E, 30°44'.30" E (Figure 3:1). The district has four local municipalities with approximately 1352800 hectares. The total population is approximately 1, 169 762, the majority of which is rural and communal (Statistics South Africa, 2018).

The local municipalities of the district are Fetakgomo Tubatse, Ephraim Mogale, Elias Motsoaledi and Makhuduthamaga. The study area is in a semi-arid region, with an annual rainfall of approximately 560 mm and moderately fluctuating temperatures with summer temperatures of approximately 23°C (Stronkhorst, 2009). The geology is mainly ultramafic substrates (i.e., serpentine soils) of the Rustenburg layered (Gourmelon et al., 2016). These soils are nutrient deficient and characterized by heavy metals (e.g., Cadnium, Zinc and nickel) (e.g., Cadnium, Zinc and nickel) (Gourmelon et al., 2016). Topography is undulating and have an altitude of approximately 494 m above sea level (The Greater Sekhukhune District, 2019). The biome of the district is mainly savanna with some grassland. The dominating land covers are high fynbos, bushveld, natural grassland thicket, and bush clumps land covers.

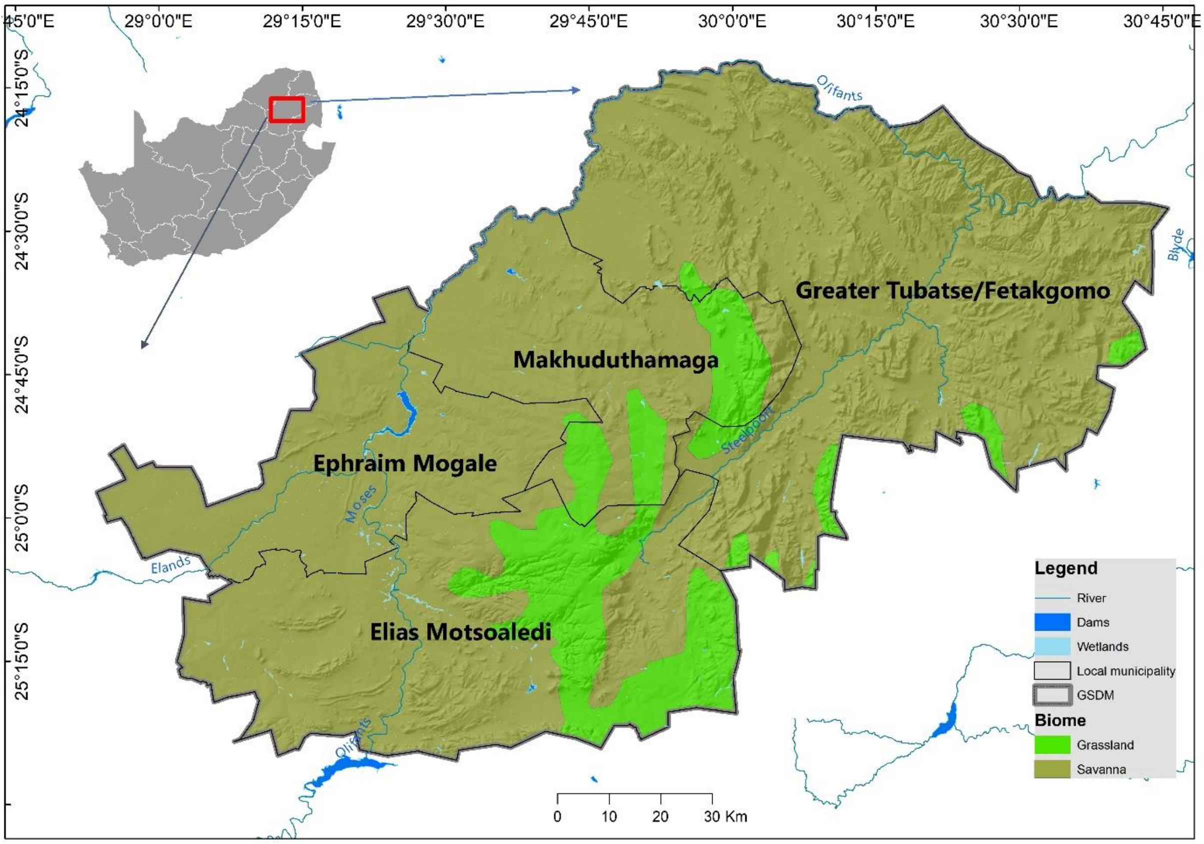


Figure 3:1 The Greater Sekhukhune District Municipality.

Agriculture dominates the land use in the district, with commercial accounting for 7,7% of the district and subsistence farming by 18.1% (The Greater Sekhukhune District Municipality, 2020). However, most of the croplands have been abandoned and water scarcity, land conflicts, a high number of land claims, and inappropriate infrastructure and services pose future agriculture concerns in the area (The Greater Sekhukhune District, 2019). Unlimited access to communal grazing and lack of fencing in fields is intensifying LD because of low herbaceous basal cover (T. Hoffman & Ashwell, 2001; Shackleton et al., 2013).

3.3.2 Methodology

The study used mixed methods approach that integrates quantitative and qualitative research to address research objectives. RESTREND analysis is a quantitative method that was used to distinguish and quantify areas degraded due to anthropogenic activities or rainfall. $DPCR_4$ framework was adopted as a qualitative method to systematically develop a dynamic model and decision support tool for understanding a socio-ecological system's structure across various disciplines. Complex patterns and processes of social-ecological events are modelled and the relationships are linked with feedback loops, utilising the principles of systems thinking (Pinto-Ledezma & Rivero Mamani, 2014).

3.3.3 Data Collection

3.3.3.1 NDVI Dataset

Normalized Difference Vegetation Index (NDVI) data obtained from satellite images is an important proxy utilised to reveal dynamics of vegetation production in response to the climate variability and drought conditions (Kalisa et al., 2019). NDVI data obtainable from NOAA-AVHRR sensors has been used in various studies to analyse the dynamics and trends of vegetation production in various regions (Anyamba & Tucker, 2005; Bao et al., 2014; Salim et al., 2009). Given that long term monitoring is required from 1990 for this study, MODIS daily NDVI data spans from 2002 so NOOA NDVI dataset was used. With regards to Landsat, daily wet data was not available for all scene required for the study and cloud cover was very high so it was challenging to collect the data hence NOAA had daily wet seasonal data available from 1990. NDVI is computed using Near-InfraRed (NIR) and the visible RED spectral bands because healthy vegetation highly reflects in the NIR and absorbs in the RED bands, respectively (Muavhi & Woyessa, 2021). The NDVI is derived as follows:

$$NDVI = \frac{NIR - RED}{NIR + RED} \quad \text{Equation 3.1}$$

Where: NIR represents reflection in the near-infrared spectrum (nm) range; RED represents the reflection in the red portion of the spectrum by vegetation cover (nm)

The values range from −1 to +1 with high values representing healthy/active vegetation while non-vegetated surfaces such as water bodies, bare land/ rocks are represented by negative NDVI values (Wessels et al., 2007).

NDVI satellite data from the AVHRR NOAA weather satellites (https://www.ncei.noaa.gov/data/avhrr-land-normalized-difference-vegetation-index) was used in this study. The data contains gridded daily NDVI from NOAA Climate Data Record (CDR) of AVHRR Surface Reflectance. While NDVI derived from Global Inventory Monitoring and Mapping Studies (GIMMS) database is widely used (Tucker et al., 2005), the NDVI derived from NOAA CDR database was used due to limited access to GIMMS dataset.

Furthermore, NOAA CDR NDVI data has higher spatial resolution of 5km than GIMMS, that has 8km spatial resolution. Moreover, the NOOA CDR dataset has substantial improvements that include better geolocation accuracy and the use of center of each grid as reference for consistency with other heritage records (Franch et al., 2017). The study acquired NDVI data from 1990 to 2019 of 0.05^{o} (5km) spatial resolution, 1-day temporal resolution and projected on a 0.05-degree x 0.05-degree global grid (Franch et al., 2017). NDVI from the growth season (October to April) was used in this study as it represents vegetation growth status and is highly correlated with the growing season rainfall (Archer, 2004; Pei et al., 2019; Wessels et al., 2007). The NDVI data was then weighted by number of days acquired for each growing season.

3.3.3.2 Rainfall Dataset

Satellite-based rainfall dataset from Precipitation Estimation of Remotely Sensed Information using Artificial Neural Networks—Climate Data Record (PERSIANN-CDR) (Ashouri et al., 2015) was acquired for the study. The data was developed by NOAA's Center for Hydrometeorology and Remote Sensing (CHRS) and includes daily precipitation approximation from geostationary satellites built on neural networks algorithm derived from daytime visible and infrared imagery (Ashouri et al., 2015). PERSIANN-CDR dataset spatial resolution is 0.25^{o} in latitude. Ashouri *et al* (2015) compared PERSIANN-CDR and rain gauge data and concluded that it can be used to monitor rainfall and assess contributing factors to changes in the rainy season due to its good performance and long temporal coverage (more than 30 years). Mean wet season gridded precipitation data in the 1990–2019 study period for the Greater Sekhukhune District was downloaded (https://chrsdata.eng.uci.edu/) and resampled to match the spatial resolution of 0.05° from NDVI data using ArcGIS 10.7.

3.3.3.3 Key informant Interviews

Key informant interviews were used to collect data and participants were selected based on their extensive expertise and knowledge in the GSDM (Payne & Payne, 2004). A non-probability sampling method was used to identify informants, whereby key informants are recruited by other key informants to become part of the sample (snowball method). In this case, official from the Limpopo Department of Agriculture and Rural Development (LDARD) based in the GSDM identified other key informants who had more than seven years of experience in natural resources use and management (e.g., for grazing, cropping, fuelwood, and other purposes. A list of 11 key informants were interviewed individually from the Limpopo

Department of Agriculture and Rural Development (LDARD) based in GSDM (Table 3.1). The key informants interviewed were natural resource managers, crop production, animal production and extension services per local municipality.

Semi-structured questionnaires were used to interview experienced key informants in the use and management of natural resources (e. g. for grazing, cropping, fuelwood, etc) (Appendix).

Table 3.1 Key informants interviewed in GSDM per local municipality and years of experience working in the municipality and field.

Local municipality	Key informant	Field of expertise	Years of experience
Fetakgomo	1	Extension services	40
	2	Natural Resource Management	13
	3	Natural Resource Management	14
Tubatse	4	Natural Resource Management	12
	5	Crop Production	14
Makhuduthamaga	6	Natural Resource Management	12
	7	Crop Production	24
Elias Motsoaledi	8	Animal production	10
Ephraim Mogale	9	Extension services	7
	10	Extension services	15
	11	Animal production	12

The key informant interviews were used to collect information to identify key factors of the system and their connectivity. The interviews were aimed at providing an overview of the important challenges facing the district and to identify the gaps and progress in addressing LD. The semi-structured questionnaire was designed to acquire historical LULC changes, physical factors, socioeconomic, and cultural data and to determine the driving factors of LD and their impacts. The information extracted from the interviews was to understand the modern land management system to identify the key factors of the system and its linkages. The key informant interviews aimed to provide perspectives on important land management related issues in the district and to identify progress and gaps in addressing land degradation issues. Discussion included driving mechanisms of LULC changes, grazing and rangeland management and the impacts of factors on LD experienced in the district over the past 30 years.

The interviews also included discussion around information on laws and regulations that affect access to land, use and impacts observed over the years.

3.3.3.4 Workshop Session with Local Herders

A group discussion was held with a group of 15 local herders in Mphanama village as natural resource users. The herders were all males, from middle aged to older aged based in Mphanama Village i.e., in the area almost all pastoralists are males with one female due to cultural dynamics. The group was selected based on a non-probability sampling method to identify participants with participants recruited by other participants to become part of the sample (snowball method). The aim of the discussion was to get more information on historical and current pastoral conditions, the impact of degradation on pastoral capacity, livelihoods and adaptation mechanisms. Some questions are related to how they are organized as a group and what are the rules for governance and grazing management from their perspectives.

3.3.3.5 Discussions with Traditional Authorities

Land in many parts of rural South Africa is under the control of traditional leaders, with Traditional Authorities (TAs) (chief and their council) playing a key role in the way land is used (Musvoto, Kgaphola and Mwenge Kahinda, 2022). Traditional Authorities are custodians of almost half of the land (48%) in the Sekhukhune District (Cooperative Governance and Traditional Affairs, 2020) and how they influence the land allocation and use in areas under their jurisdictions. Informal group discussion sessions were held with 17 TAs in Fetakgomo Tubatse and Makhuduthamaga municipalities. The objective of the discussions was to obtain the TAs' perspectives and experiences of land use and LD. The discussions covered the state of the land and natural resources, LD, its causes and interventions used to address LD in the district, including land uses and users and rules governing the use of the land. Changes in land use benefits obtained from land and natural resources, including if and how these benefits have changed over time were also discussed.

3.3.4 Residual Trend (RESTREND) Analysis

The Residual Trend Analysis (RESTREND) method assumes that vegetation production has a strong relationship with climatic factors, mainly rainfall, hence it was applied to detect the natural impact on vegetation production over a period (Wang et al., 2010; Wessels et al., 2007). The RESTREND method is an effective tool to differentiate between climate factors (rainfall) and anthropogenic activities on changes in vegetation with negative values representing degraded area while positive values mean vegetation has improved (Li et al., 2012). In case of a significant decrease in residuals, the degradation of vegetation is human induced (Huang & Kong, 2016), while an insignificant increase or no trend of residuals means that NDVI variations are due to climatic variables (Chu et al., 2019).

3.3.4.1 Regression Analysis

Regression analysis of NDVI against rainfall was applied using a pixel-wise ordinary least square (OLS) regression model using a statistical software package R-Studio. The pixel-wise OLS model is a statistical method that models linear relationships between a response and one or more predictor variables. The OLS reduces the error/residual sum of the squares and is applied in various environmental studies (Foody, 2004). The RESTREND method measures the linear relationship between an independent variable (x) and a dependent (y) and it is represented by the equation:

$$Y = mx + c + e \qquad \text{Equation 3.2}$$

where: y *represents the response variable (NDVI),* m *is the gradient (slope),* x *is the predictor variable (rainfall),* c *is the intercept. Per unit change of x, e represents the error for every change of x.*

The widely used RESTREND method carries out the following three steps: (1) modelling pixel-wise OLS regression between the wet season observed NDVI and rainfall per pixel, (2) difference of residuals between the observed predicted sum of NDVI (predicted by rainfall) from the linear model is derived, and (3) a new OLS regression is carried out to model the residuals against time, representing a residual trend (RESTREND). The residual trends represent changes in the production of the vegetation not explained by rainfall and these are interpreted as a proxy for LD (Montfort et al., 2021).

3.3.4.2 Mann-Kendal Non-Parametric Trend Analysis Applied on RESTREND

Mann-Kendall (MK) trend, a robust nonparametric statistical method, was applied to examine RESTREND in the study area. Mann-Kendall’s coefficient computes the consistency of the increasing or decreasing trend and has been widely applied in environmental studies (Wessels et al., 2007). Mann-Kendall trend analysis was applied to test the magnitude and significance of the slope to determine whether degradation in the district has been influenced by human activities or rainfall. Theli-Sen (Sen) slope estimates the magnitude of the residual trend and is not sensitive to outliers (Huang & Kong, 2016). The MK test is calculated using a statistic S formula:

$$S = \sum_{k=1}^{N-1} . \sum_{k=1}^{N} sgn(X_k - X_j) \qquad \text{Equation 3.3}$$

Where: *N is the numerical data points, x_k and xj are the values at time k and j (k > j), respectively, sgn represents sign (Adarsh & Reddy, 2015).*

The Sen's slope estimator determined the magnitude of the trend in NDVI or rainfall data. The Sen's slope test computes linear rate of change and intercepts with the formula:

$$ST_m = \frac{X_k - X_j}{k - j} for\ (1 < j < k < n) \qquad \text{Equation 3.4}$$

Where: *ST=slope, m=median, n=number of data points and k, j=indices.*

$$p_t = X_t - r * t \qquad \text{Equation 3.5}$$

Where: *r=median STk (median from all slopes) with intercepts computed for every time steps t and p is the intercept.*

Sen's slope estimates the magnitude of NDVI and rainfall increase or decrease per year. MK significance test was used to test the statistical consistency of the Sen's slope trend at 95% confidence interval (*p*=0.05) (Huang & Kong, 2016). MK trend test has been widely used and is less sensitive to outliers, missing values and irregular data distribution (Udelhoven et al., 2009).

3.3.5 System Dynamics and Systems Dynamic Modelling- DPSCR$_4$ Model

The system dynamics approach aids in providing a clear illustration, analyses, and comprehension of complex systems. The triangulation of key informant interviews, workshop with local herders and tribal authorities and scientific literature provided the basis for the application of DPSCR4 and systematic analysis to understand LD in the GSDM. The diagram below (Figure 3:2) illustrates a systemic outline of expert knowledge on the DPSCR4 framework to combat LD using a SESs approach adapted from Itzkin *et al.* (2021).

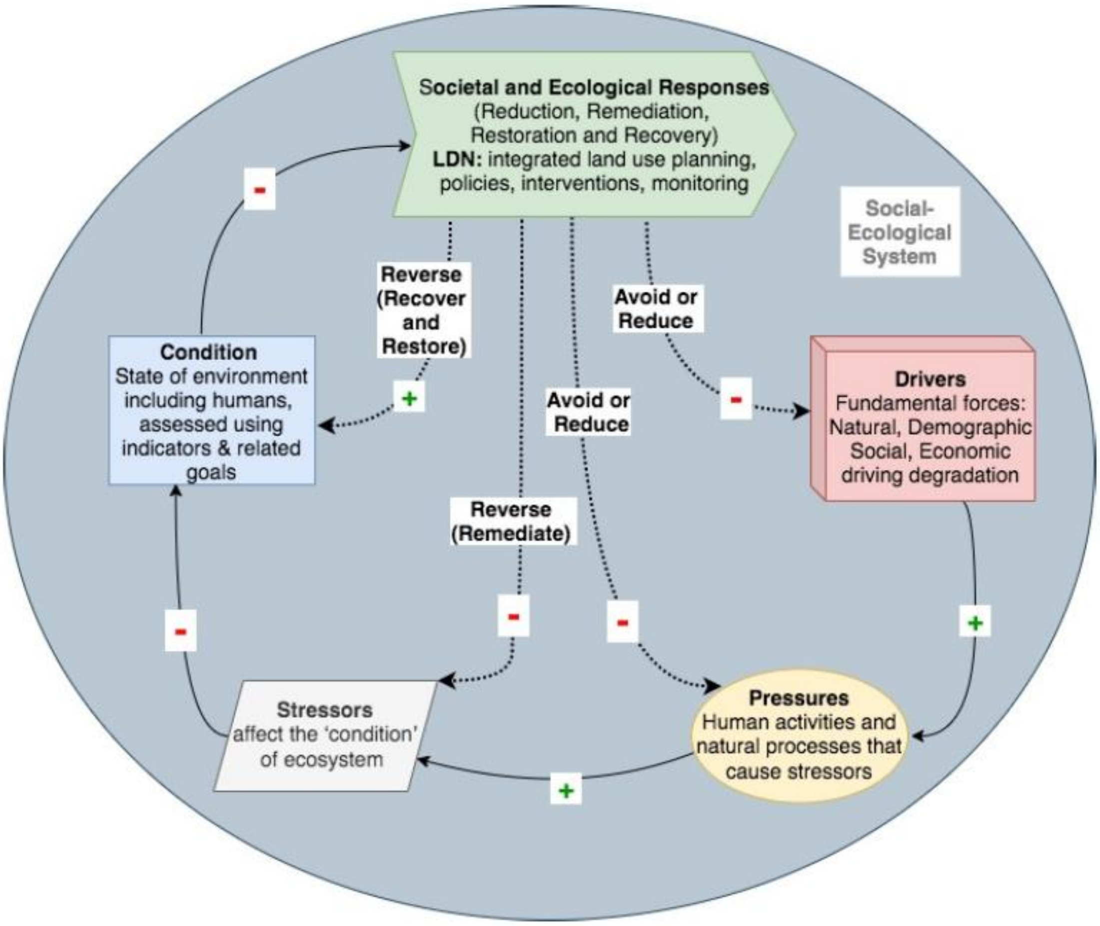


Figure 3:2 DPSCR4 framework to combat LD using a SESs approach relationship, adapted from Itzkin *et al*. (2021).

The framework takes an integrated approach that avoids and reduces potential LD and reverses the existing degradation of land (Orr et al., 2017). The DPSCR4 framework has prescribed three global indicators of ecosystem services: LULCC, land productivity (NDVI), and carbon stocks (Orr et al., 2017). Itzkin *et al.* (2017) applied several characteristics that made LDN suitable in their case study and applicable in this study. These include its explicit focus of the SES approach, its implementation at the local scale, easily adapted to DPSCR4 (previously applied in DPSIR) and its participatory integrated land use plan to achieve the LDN.

The $DPSCR_4$ components are each described as follows:

3.3.5.1 Drivers

Drivers of LD are factors that cause changes or may result in behaviour changes in the socio-ecological system. Several studies report drivers of environmental changes affecting the socio-ecological system as demographic, institutional, economic, political, technological development, and sociocultural factors (Geist et al., 2006). These drivers can either be natural or anthropogenic or both, which can be differentiated as direct or indirect. Direct drivers have a proximate influence on the system and LD while indirect drivers are underlying causes of one or more drivers changing the system.

3.3.5.2 Pressures

The definition of pressure as provided by Oesterwind *et al.* (2016) is the result of human activities and natural drivers directly affecting the ecosystem and changing the natural environment. Unsustainable human activities aggravated by natural disturbances such as recurrent drought or rainfall variability i.e., flash floods, lead to LD and desertification (Harwell et al., 2019).

3.3.5.3 Stressors

Stressors occur due to pressures that the ecosystem experience and can be the physical, chemical, or biological factors that directly have an effect on the state of the environment (Harwell et al., 2019). Stressors are represented by a set of descriptors of system attributes and are the result of a relationship between cause and effect because of pressures (Harwell et al., 2019; Oesterwind et al., 2016). Because of pressures, the environmental state is affected i.e., the quality of several environmental compartments (soil, water, air, habitat alteration etc) (Weldemariam, 2017).

3.3.5.4 Conditions

Conditions reflect the environmental state including ecosystem services, ecological health and human well-being due to pressures and stressors and these are assessed using indicators and related goals. Conditions of the system are articulated by various sets of system attributes that are described and affected by pressures and stressors, are explained by type, degree, and rate of LD at a certain time, location or may be new to the system such as toxic chemicals

(Weldemariam, 2017). Examples of condition descriptors are water quality, vegetation, soil, sediment, species composition and habitat structure.

The descriptor condition used in the study was vegetation i.e., seasonal NDVI, to assess the extent and rate of LD (Schlegel & Huchzermeyer, 2018). Vegetation dynamics indicate the effects of various climatic, biotic and abiotic environmental interactions, and disturbance history (Huang & Kong, 2016). Vegetation production is one of the widely applied indicators of LD using time-series remotely sensed images at a landscape or regional level (Fensholt et al., 2013; Holm et al., 2003; Verón et al., 2006). In arid or semi-arid areas, NDVI is significantly associated with above-ground net primary productivity (ANPP) (Huang & Kong, 2016), hence was used as an indicator for LD.

NDVI change was calculated to monitor and assess whether the environmental condition is degrading, and the extent to show total area affected (Yengoh et al., 2016). Negative NDVI change represented areas subject to frequent drought, moderate to low vegetation, extreme temperature and precipitation, and expansion of residential area with a decline in vegetation. Positive NDVI change showed areas with positive precipitation and improved vegetation conditions and positive gain in agricultural areas. Areas with No NDVI change show little or no change in vegetation condition.

NDVI was obtained using Landsat 5-7 images (30m resolution) from 1990 to 2019 on a five-year interval and processed with ERDAS Imagine 2018 software. NDVI change detection images and statistics were acquired using the Image Differencing tool and Zonal statistics.

3.3.5.5 Responses

The framework takes an integrated approach that avoids and reduces potential LD and reverses the existing degradation of land (Orr et al., 2017). The $DPSCR_4$ framework prescribes three global (biophysical) indicators of ecosystem services: LULCC, land productivity (NDVI), and carbon stocks (Cowie et al., 2018). Itzkin and others (Itzkin et al., 2021) applied several characteristics that made LDN suitable in their case study and applicable in this study. These include its explicit focus of the SES approach, its implementation at the local scale, easily adapted to $DPSCR_4$ (previously applied in DPSIR) and its participatory integrated land use plan to achieve the LDN (Figure 3:2).

3.4 RESULTS

The results for assessing LD in the Greater Sekhukhune District Municipality are presented in three sub-sections. The first section assesses RESTREND results that distinguish between human-induced LD from rainfall. The second section shows key informant interviews and workshops with local herders results that articulate drivers of LULCC and LD. The third section analyse results from $DRSCR_4$ that describe and present systems illustrations to better understand the interconnectedness of social and ecological driving factors of LD in the ecosystem and achieve SLM.

3.4.1 Residual Trend (RESTREND)

The RESTREND of the NDVI time series was modelled by determining the difference between the NDVI observed and the NDVI predicted by rainfall. RESTREND analysis was done by firstly carrying out linear regression models of NDVI against rainfall, then the analysis of the residual NDVI trend over time.

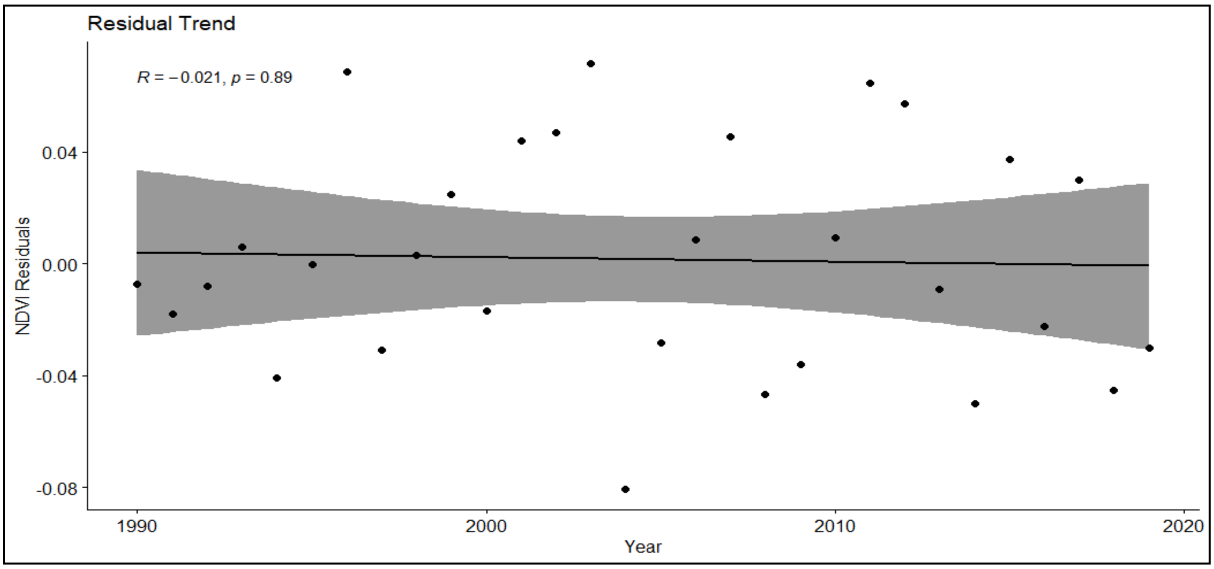


Figure 3:3 Temporal trend of NDVI residuals between 1990 to 2019 averaged over all the pixels in the district, adjusted for rainfall.

The results show that the negative residual trend R-value of -0.021 with a Sen's slope of -0.00018 (Figure 3:3) indicated that there is vegetation degradation in Sekhukhune District Municipality. The *p*-value of 0.89 recorded in the residual trend means that degradation in the district is due to rainfall. In the district, a strong negative decline of NDVI residuals, for instance, in 1994, 2004, 2008, 2014, and 2018, could indicate human-induced degradation. On the other hand, the strong positive spike of NDVI, in 1996, 2003 and 2007 may be as a result of variability of rainfall in the area.

RESTREND was spatially analysed to articulate areas of significant positive or negative trends of the residual NDVI using the Mann-Kendall trend. These areas show vegetation dynamics caused by factors other than rainfall variability i.e., human activities, through an overlay process of negative NDVI residuals that are significant. Areas with an insignificant residual trend or no trend are explained by rainfall changes, while the significant negative (degraded) and positive (improved) vegetation production changes reflect changes induced by anthropogenic activities. RESTREND analysis revealed that the NDVI residual trend magnitude decreased mostly in the central to the western part of the district by 53% then increased in the north to the western part of the district by 40.99% (Figure 3:4 &

Table **3.2**). This shows that more than half of the district is experiencing degradation in vegetation production.

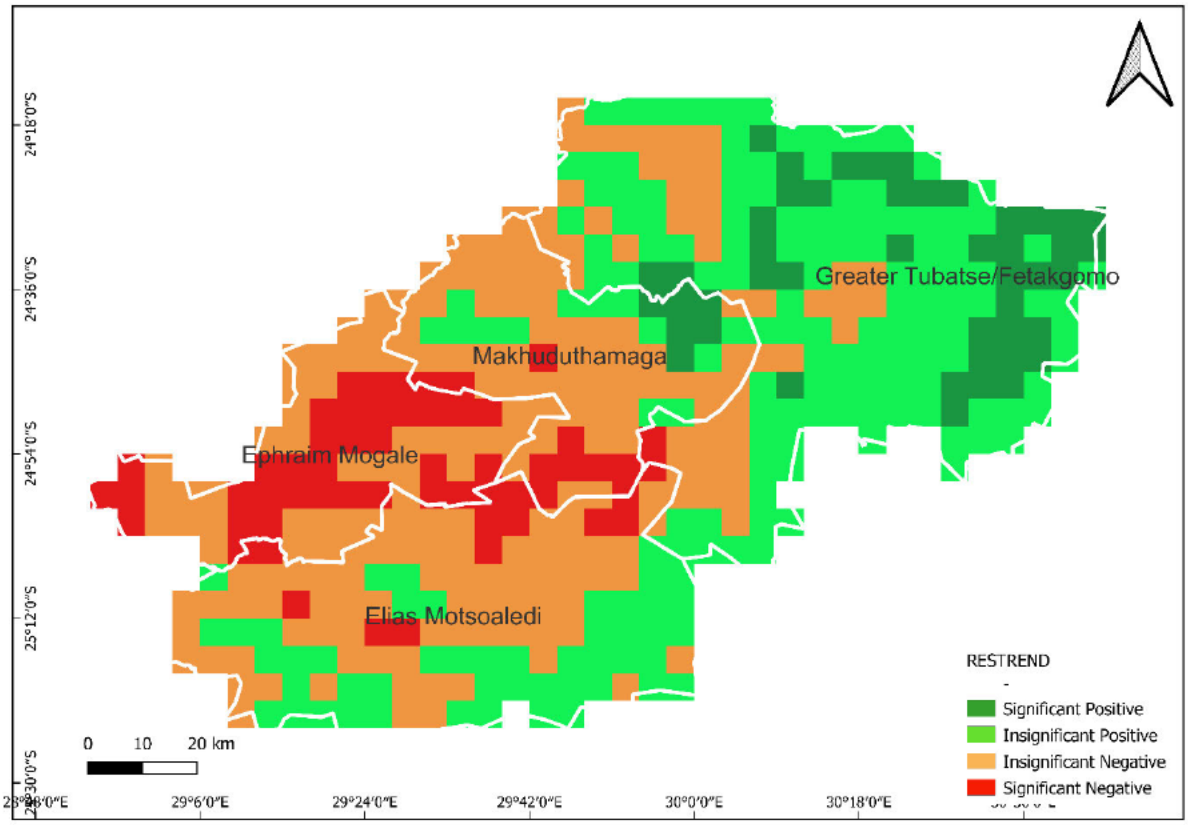


Figure 3:4 Spatial NDVI RESTREND pattern

Table 3.2 Statistics of Mann-Kendall NDVI RESTREND analysis

Mann-Kendall NDVI RESTREND	**Residual Trend Slope (Magnitude)**			**Significance of Residual Trend (Vegetation trends explained by human activities)**		**Insignificance of Residual Trend (Vegetation trends explained by Rainfall)**	
	Positive	Negative	Stable	Significant Negative (degraded)	Significant positive	Insignificant Negative (degraded)	Insignificant positive
Pixel Numbers (8 km)	198	256	56	56	46	200	180
Proportion Statistics (%)	40.99	53.00	6.01	11.59	9.52	41.41	37.27

Areas that significantly experienced a decrease in NDVI RESTREND are central to the western portion of the district (Ephraim Mogale and Makhuduthamaga local municipality) by 11.59% (Figure 3.4). The RESTREND magnitude showed a significant increment of 9.52% in the north to the eastern portion of the district in the Fetakgomo Tubatse local municipality, which means that vegetation improved due to other reasons apart from rainfall. The study further shows spatial patterns of areas that degraded or improved in vegetation cover due to changes in rainfall (Figure 3:4). The majority of the degradation in the district is due to rainfall. The degradation due to rainfall decline largely occurred in the entire district, approximately 41.41%, except for the northern to the western part of the district in Fetakgomo Tubatse local municipality.

3.4.2 Drivers of LD: LULCC that Lead to LD Identified During Interviews and Workshop

The LULC change is a result of cumulative interrelated factors between socioeconomic, institutional, demographic and biophysical drivers (Gedefaw et al., 2020). The results from key informant interviews and perspectives/experiences from traditional authorities of LULCC that contributed to LD in the Greater Sekhukhune District are summarised below. Furthermore, the main drivers of LULCC and LD were analysed together with results from the workshop with local herders as these different stakeholders had the same perceptions/experiences.

Key informant interviewees identified and perceived several agents as the main drivers for land use and land cover change that contribute to land degradation (Table 3.3). The main drivers were inappropriate grazing management system/overgrazing, governance, inappropriate soil management, deforestation, removal of natural vegetation (all 100%), settlement encroachment into cropping land (90.91%) and soil erosion (90.91%). If the traditional and the modern systems had an integrated and coordinated system, such as land use plans and knowledge sharing such as indigenous knowledge from the traditional system and technical knowledge from the modern system, land degradation could be reduced and avoided.

Table 3.3 Drivers of degradation in the GDSM as perceived by Limpopo Department of Agriculture and Rural Development (LDARD) key informants (N=11)

Drivers of LD in the GDSM	Number of mentions	%
Overgrazing/Grazing Management: Poor agricultural practices and rangeland management	11	100
Physical Factors (steep terrain, erodible soils)	2	18.18
Cropland abandonment	9	81.82
Soil erosion	10	90.91
Unplanned settlement/settlement encroachment into cropping land	10	90.91
Governance Issues: social and cultural arrangements, local rules and regulations affecting access to resources	11	100
Climate and Extreme weather (droughts, storms)	6	54.55
Inputs and infrastructure: (roads, markets, Co-operatives, fencing to manage animal movement etc.)	10	90.91
Alien invasive species	6	54.55
Climate change	9	81.82
Poverty and Disempowerment	7	63.64
Historical, socio-political factors	3	27.27
Deforestation and removal of natural vegetation	11	100
Land tenure	7	63.64
Population pressure	8	72.73
Inappropriate Soil Management	11	100
Disturbance of hydrological regime (improper surface and groundwater recharge)	10	90.91
Sand mining	7	
Veld fires	2	18.18

The results of discussions with traditional authorities on the prospects and experiences of land degradation and its drivers are declining rainfall and increasing droughts leading to shrinking wetlands and water scarcity. Water sources such as rivers and dams are silted up due to sand mining and soil erosion. Settlement encroachments into arable and rangelands has also increased. The increase in population and livestock population has led to pressure on rangelands and because of poverty, pastoralists lack additional livestock feed such as crop residue. This has led to overgrazing causing gullies, bush encroachment and alien invasive species.

The traditional authorities pointed out that farming had declined and cropping lands had been abandoned. Traditional farming methods, which are not resource efficient reduce soil fertility and damage the environment and natural resources. It was noted that there is a lack of information on appropriate farming techniques such as water conversation, water-smart agriculture, climate-smart agriculture, soil conservation and securing water for livestock. Factors contributing to the decline in crop production include decrease in rainfall, poor livestock management, lack of cropland fencing of croplands, birds, damage to crops by livestock, and consequent abandonment of cropland. Livestock management is a major challenge as livestock move onto croplands, leading to cropland abandonment – pastoralists do not round up their live-stock during the cropping season.

It was also noted that the tribal councils have lost control over land use as they fail to control the residents who change land use without informing them. Activities such as illegal sand mining have increased due to declining agricultural productivity. This has exacerbated the formation of gullies in the area and is destroying croplands. Lack of rangeland management has also intensified where tribal council does not apply any grazing management and stocking rate that further increased the pace of vegetation loss and degradation. Solutions include planting trees, check dams, gabions and planting aloe as vegetative barriers.

3.4.3 Systemic Analysis Results (DPSCR$_4$ framework)

The factors contributing to LD identified in Table 3.4 through the interviews and the workshop were framed in terms of DPSCR$_4$, with relative impacts specifically focused at the scale of the study area. At the scale of this study area, humans are the driving force exacerbated by climate change and variability impacts. The DPSCR$_4$ from Table 3.4 are arranged in two systems diagrams, namely Drivers, Pressures, and Stressors that degrade the land (Figure 3:5) and Integrated Land use planning to achieve LD Neutrality and improve sustainable livelihoods in the Greater Sekhukhune district municipality.

Table 3.4 Drivers, Pressures, Stressors, Condition, and Responses (DPSCR$_4$) for the GSDM

Drivers	Pressures	Stressors	Condition	Responses
Natural drivers: **Soil type** **Topography** **Climate variability and Extreme weather**	Cropland abandonment	Invasive species: Mostly bush encroachment	Reduce LD	Reduction: Environmental Education (provide training and awareness through workshops and social media and traditional media i.e., local newspaper and posts) Ease of access to market programmes Natural resource and management of Land-use (Appoint rangers and environmental protection programmes through cultural and social arrangements) Incorporation of the framework and interventions into Policies and Regulations
Human-induced: **Historical and socio-political factors** **Land tenure**	Governance issues Unplanned settlement/settlement encroachment into cropping land Population pressure i.e. livestock numbers Unsustainable wood harvesting	Low vegetation cover	Improve sustainable livelihoods	Restoration: Removal of invasive species i.e., bush encroachment should be a priority Rehabilitate eroded land. Home garden Agroforestry improves livelihoods while restoring and rehabilitating degraded landscape i.e. microclimate effect
Poverty and Disempowerment	Grazing Management/ Overgrazing: Inappropriate crop and rangeland management Inappropriate soil management	Gully formation	Poverty alleviation through empowerment and improving capacity	Recovery: Rest landscape to enable ecological recovery
Population pressure **Climate change**	Out-Migration Illegal sand mining	Soil erosion		All R4s: LDN integrated land use planning

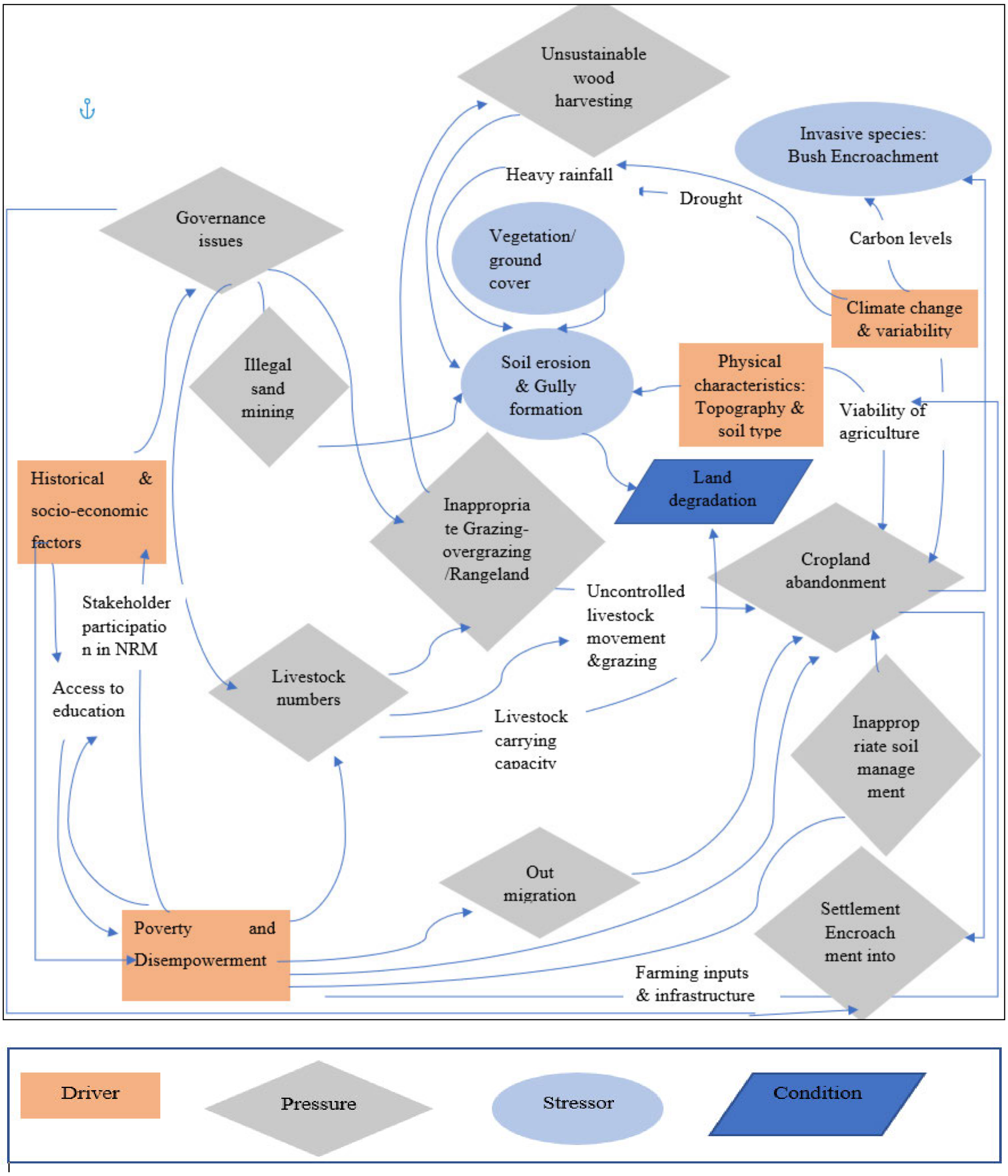


Figure 3:5 Drivers, Pressures, Stressors and Condition of the ecosystem in GSDM.

3.4.3.1 Pressure

Governance issues: Tribal authorities, Local rules and NRM

Pre-1994 dispensation policies restricted and disempowered many people's access to education by forcing indigenous people to reside in the district. After 1994, there was out-migration of the population from communal lands in search of a better way of living. Out-migration contributes to the abandonment of cultivation fields. Key informants also reported that physical characteristics (i.e., topography and soil type) and natural drivers including climate variability and change, and existing LD necessitate enhanced use of farming inputs agriculture to be viable. However, poverty and disempowerment hinder farmers to acquire the inputs, which affects the viability of agriculture; further driving the abandonment of cultivation fields. Social issues i.e., poverty and disempowerment as well governance issues such as uncontrollable livestock movement that damages crops in the fields, and ecological factors i.e., climate variability and change and LD, limit the ability of vulnerable farmers to adapt to these environmental pressures. As a result, there is a lack of interest in agriculture as a livelihood, a decline in ageing farmers (more older people engaged in farming than youth), labour migration and improper cropping methods such as lack of crop rotation. Cropland abandonment was further noted to promote bush encroachment that reduces the grass cover and grazing capacity.

Past and present policies have resulted in unstable governance. The tribal authorities in these areas are custodians of natural resources, however, traditional communal farming/grazing in Southern Africa has often been described as unproductive and directly responsible for degradation (T. Hoffman & Ashwell, 2001; T. M. Hoffman & Todd, 2000). Poverty and disempowerment reduce participation in Natural Resource governance, reinforcing the governance issues. Governance issues in the district have enabled free-roaming livestock and overstocking. Increasing cropland abandonment along with challenges in natural resource management (NRM) and governance has led to grazing on cropping fields, overgrazing and overstocking (led by traditional values and desirability of high livestock numbers). Unstable governance and cropland abandonment has led to unsustainable wood harvesting in the rangeland (abandoned crop fields currently grazing fields) and settlement encroaching into cropping/productive land.

Settlement Encroachment into Cropping and Productive Lands

Settlement encroachment in the district occurs because of population pressure and land availability. The main concern arising from the key informants' interviews was that settlement encroachment into cropping. There is no strict demarcation of land for settlements, croplands and grazing in the district as revealed in the engagements with the tribal authorities and key informants. It was further highlighted that the tribal authority allocates cropping lands that were abandoned for more than ten years for settlement as per their rules. Settlement encroachment into cropping land has further reduced vegetation cover in the district.

Illegal sand mining

Governance issues have led to an increase in illegal sand mining activities in the study area. Key informant interviews emphasised that illegal sand mining contributes to gully formations and degradation. Sand mining is driven by the growth of population, the construction industry and development needs (Ahmed et al., 2020). Most sand mining operations are illegal and directly and indirectly adversely affect the river, lake and ocean ecosystems and human health (Ahmed et al., 2020). Key informants further highlighted that societal behaviour and attitude such as illegal sand mining have led to unsustainable activities that degrade the environment. Specifically, poverty and high unemployment in rural areas have led to illegal sand mining. The traditional authorities highlighted that the locals have ventured into sand mining to earn a living as agricultural production has declined. This has exacerbated the problem of gullies in the area and is destroying croplands as some of the mining is done in cropping areas.

Sand extraction changes the morphology of a river including channel geometry, bed elevation, stability, stream roughness such as the presence of large woody debris and boulders, velocity, and stream discharge (Apel et al., 2012). Illegal mining activities are more localised, involving mainly tractors (using a trailer to load the sand). Illegal sand mining has changed the hydro morphological structure, resulting in high velocity flow, thus the risk of erosion and slope instability of water bodies and surrounding infrastructure increases. Sand extraction also has negatively affected groundwater recharge, diminished aquifers and increased sedimentation (Apel et al., 2012). Illegal sand mining has set an enormous pressure on the ecological function of the environment in the study area due to its unregulated and extensive activities.

3.4.3.2 Stressors

The drivers and pressures of LD in the district have led to multiple stressors on the environment and further degradation. Extreme weather events i.e., heavy rainfall and prolonged drought, low vegetation/ground cover due to droughts and overgrazing, unsustainable wood harvesting and sand mining, have resulted in gully formation and soil erosion across the district. Rainfall variability and high flow velocity due to topography have lowered the stream bottom, contributing to bank erosion of water sources and the overall sedimentation load.

With increasing cropland abandonment, the invasive species on abandoned cropping fields are increasing, degrading the landscape, which in turn reduces the viability of agriculture and grazing capacity that leads to further disuse of cultivation fields and loss of livestock and livelihood in a reinforcing cycle.

Invasive species plant growth is further encouraged by increasing atmospheric carbon levels due to climate change (Graw et al., 2016). As a result, bush encroachment is observed in rangelands across the district and reduced natural vegetation/grassland cover. Climate change also increases the probability of intensive rainfall (increasing soil erosion and gully formation predisposed by physical characteristics of the landscape) and drought (decreasing ground cover, again, increasing soil erosion and gullies) that further degrade the land (Gourmelon et al., 2016; Mpandeli et al., 2015).

Topography, frequent prolonged droughts that reduce the vegetation cover and rainfall variability and intensity, have increased the velocity and sediment flow in Lepellane dam located between Mphanama and Ga-Radingwana village, Fetakgomo Tubatse municipality. Lepellane dam is characterised by sedimentation, consequently, water storage capacity has declined significantly. Sediment load in the Lepellane dam affects the downstream Lepellane river as it also hinders sediment load to the downstream river system, which subsequently will have low sediment input and water required to maintain the river and the aquatic habitats (Amasi et al., 2021).

The Lepellane river support livestock, however, the local herders during the workshop stressed that lack of water and reduced grazing capacity were significantly affecting their livestock and livelihoods. During the workshop, the herders highlighted that the changes in the Lepellane dam and river started 15 years ago and worsened from 2012 to 2014.

3.4.3.3 Condition

The condition of LD is assessed through indicators and related goals of the environment. The goals documented in Table 3. 2.1 is to reduce LD, improve sustainable livelihoods and alleviate poverty through empowerment and improvement capacity.

The indicator used in the study is seasonal NDVI change as vegetation dynamics reflect the effects of various factors, including drivers, pressure, and stressors on the ecosystem. Figure 3:6 shows NDVI change trend results for wet and dry seasons obtained between 1990 and 2019 over a five-year interval in the district. There is an increasing negative NDVI change in both seasons, with a steeper trend in the dry season. The trends show that the productivity of the area has been declining from 1990 to 2005 and started picking up between 2005 to 2010 and

2015 to 2019 in both seasons. The district then faced an extreme decline in productivity between 2010 and 2015, during both wet and dry seasons with the highest NDVI negative changes of 96.39% and 97.05%, respectively in the dry season. This confirms the information mentioned by the local herders during the workshop that the situation in the Lepellane river worsened during this period.

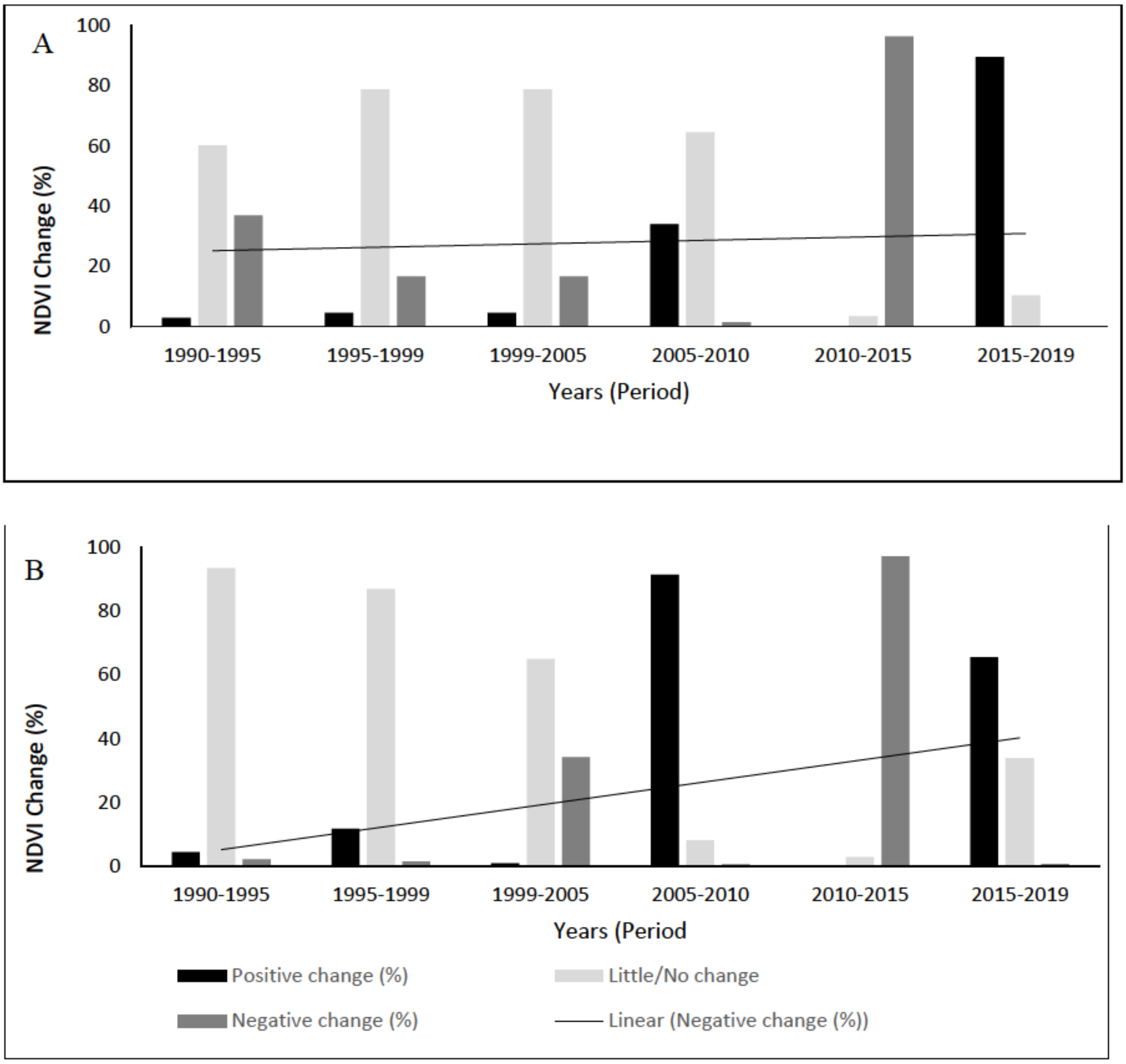


Figure 3:6 NDVI Negative change trend of Wet (A) and Dry (B) seasons from 1990 to 2019.

Murray-Tortarolo *et al.* (2016) report that alterations in the availability of water in the dry season affect vegetation dynamics for the entire year, affecting the regional net primary productivity (measured through NDVI) during the wet season. The prolonged frequent drought events recorded in the district by Mpandeli *et al.* ((2015) and Sinyolo *et al*. (2017) and the increasing steeper trend of negative NDVI change of dry season reveal that the dry season ecosystems play a vital role in annual land productivity. This is observed with the wet season increasing negative NDVI change and struggles to recover after the driest months. Overall, these results show that there is declining vegetation health and productivity in the district and the area is subject to prolonged drought, extreme precipitation and temperature and LD.

3.4.3.4 Response to Reduce, Remediate, Restore and Recover Degraded Land in GSDM

Linkages of drivers, pressures, stressors, conditions and four responses are illustrated in Figure 3:7. A comprehensive analysis of individual factors and potential response provide alternative potential feedback loops and the analysis can be utilized as a foundation for integrated land use planning. Responses to LD reveal suggestions from key informants and local herders to reduce stressor sources, remediate existing stressors and restore and recover the ecology. Key informants were asked what is done to address LD in their respective municipalities and whether there has been the adoption of new Sustainable Land Management (SLM) practices (by farmers and community) and any challenges faced to address LD.

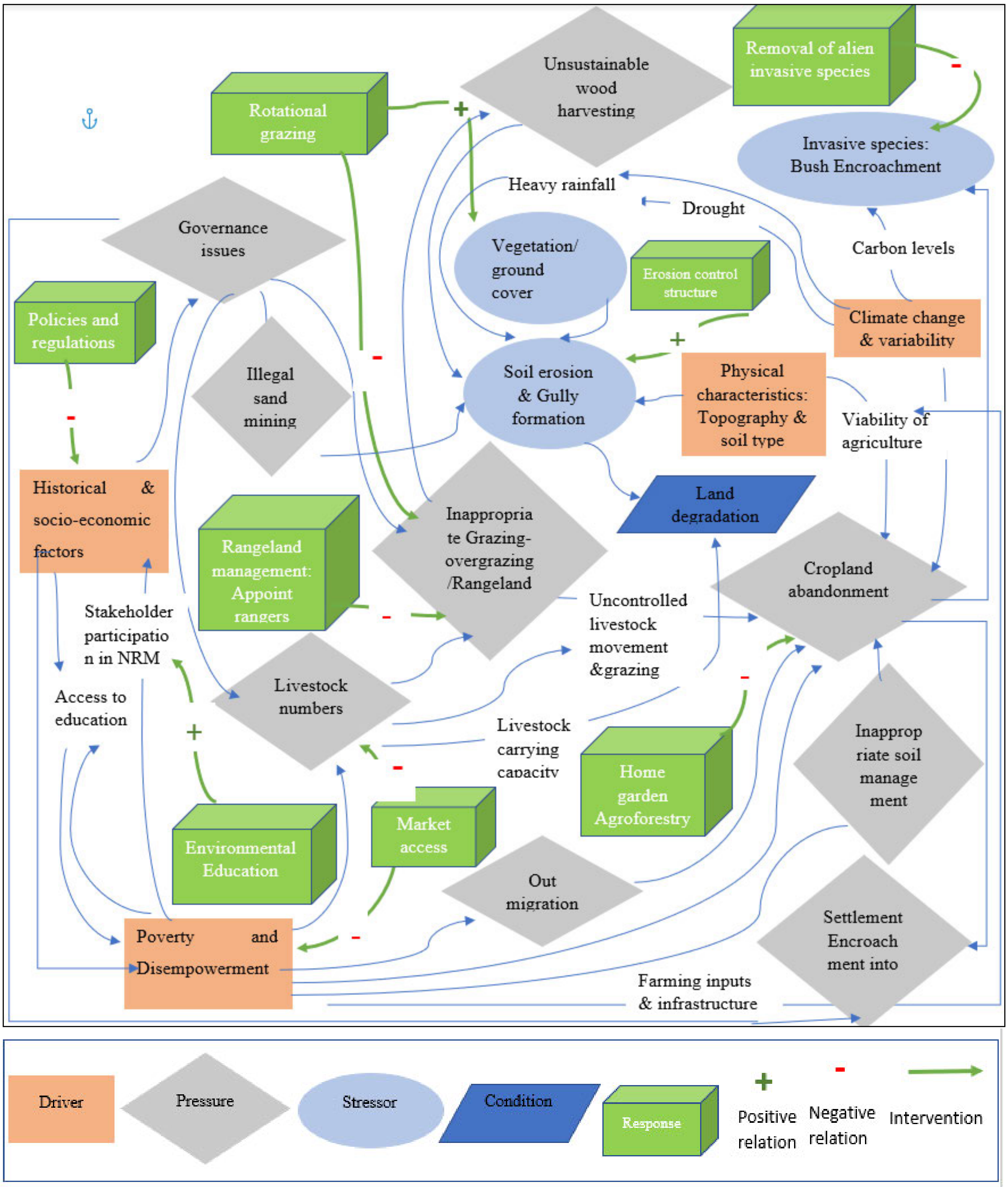


Figure 3:7 Integrated Land use planning to address LD and improve sustainable livelihoods in GSDM

Below are the dynamic approaches for the implementation of response actions aimed at mitigating drivers, pressures and stressors placed on the landscape. The dynamic approaches to the implementation of response actions aimed at mitigating drivers, pressures and stressors on the landscape. Environmental education is the most important measure that will increase community engagement in natural resource management. Key informants mentioned that a

Junior Landcare programme was recently introduced to sensitise and encourage school children to manage natural resources. A participating school adopts a natural resource, such as a river and awards are given to encourage care and maintenance. This is very important for sustainability as the children develop awareness and change their behaviour in the community. An-other important factor is improving market access, which enables livestock keepers to improve and maintain livestock while reducing the quantity. Moreover, policies and regulations need to purposefully address the negative impacts of previous and current policies on the social and environmental conditions of the district. Key informants mentioned that a ranger system policy should be reintroduced in the district as it was before 1994; where rangers were deployed to ensure that communities use resources sustainably and introduce a rotational grazing system.

One of the interventions applied in response to land degradation in the area is eradication of alien invasive species, which directly reduces invasive species population and bush encroachment on the landscape. Other measures that reduce bush encroachment and rehabilitate the rangeland are brush packing, re-seeded half-moons, and selective bush thinning currently applied in the Mphanama village grazing land rehabilitation programme (Figure 3:8). These methods should be upscaled and applied in the degraded parts of the district. Given that more than 50% of the district is covered by rangeland, overgrazing can be reduced, stopped and the degradation trend reversed through a well-designed veld management system.

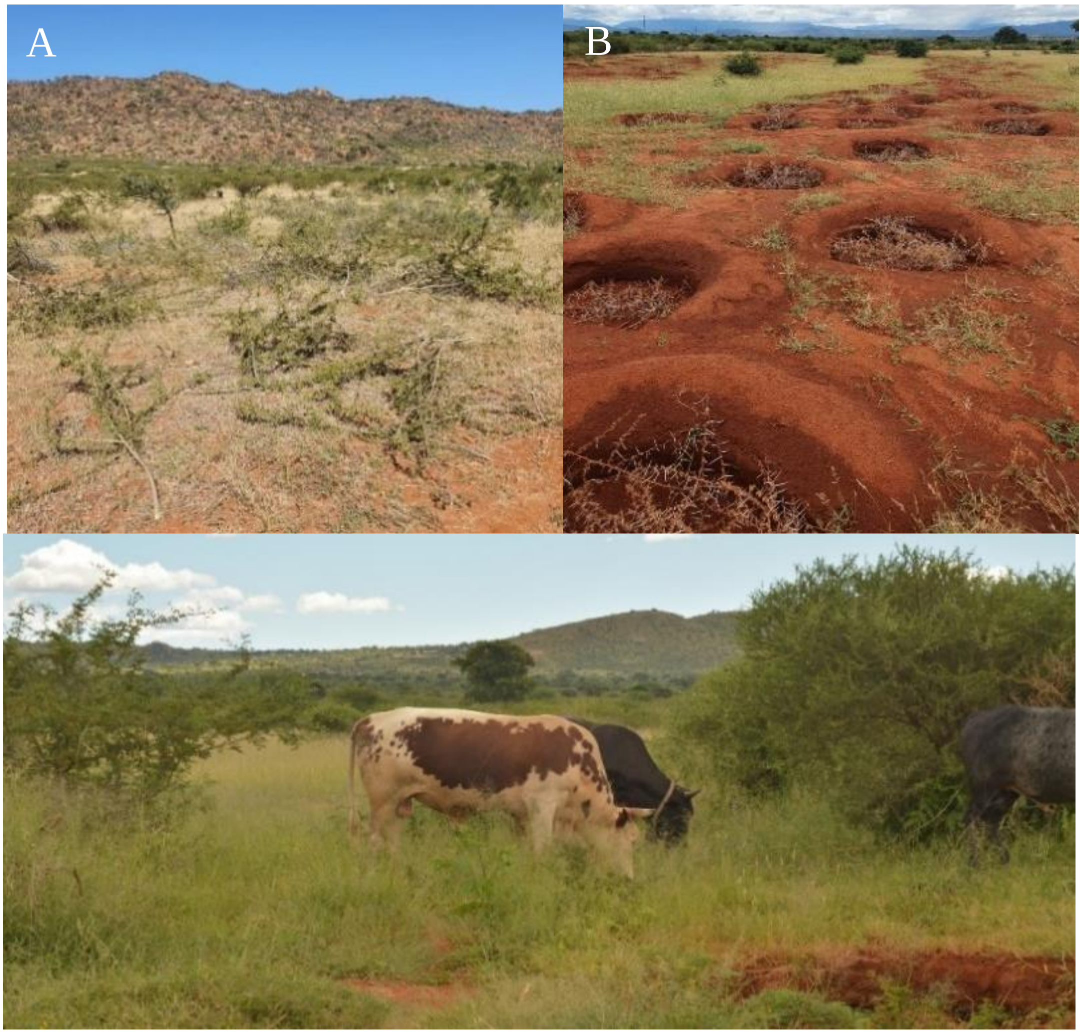


Figure 3:8 Land rehabilitation of the grazing land of Mphanama under the UNDP GEF5 SLM project brush packing (A) and ponding (B) to increase the vegetative recruitment and the survival rate of regenerating plants and of seeded grass.

Home-garden agroforestry should be encouraged throughout the district while livestock roam uncontrolled and cropland are not fenced. This will increase vegetation cover within the settlements, improve livelihoods, and create microclimates.

Although erosion control structures suitable for the site and context were identified, key informants mentioned that vandalism of erosion control structures and fences to control animal movement hinders land rehabilitation. Most of the erosion control structures erected by previous initiatives were toppled by flash floods, never main-trained or vandalised. Therefore, it was suggested in the discussions to form informal institutions with communities that have social and cultural arrangements, local rules and obligations that influence access to and management of resources.

Lack of rangeland management was the main factor contributing to land degradation; therefore, rotational grazing was suggested by local herders during the workshop and key informants to allow vegetative recovery and growth and facilitate ground cover. Land use planning integrated with LDN can prevent, reduce, and reverse land degradation in several ways. These include coordination and transparency of land use plans through workshops (highlighted in key informant interviews) between traditional authorities, local government, natural resources management, and the community. This will further promote stakeholder participation in natural resources management. The Department of Forestry, Fisheries and the Environment has made significant efforts and investment in rehabilitation by erecting soil erosion control structures. In rehabilitation, it is important that community members and traditional authority are engaged from the onset to incorporate traditional knowledge and own the process.

3.5 DISCUSSION

This study assessed LD using an SES approach and proposes responses to achieve LDN. It was crucial to first assess LD by identifying which areas are degraded and whether degradation in those areas is due to human or rainfall impacts. The application of a $DPSCR_4$ SES highlights how LD results from a set of interrelated social and biophysical factors (Hassen & Assen, 2018; Lambin et al., 2003). The results show how the complex land degradation phenomena can be addressed within the framework of two contrasting land use management systems.

3.5.1 LD due to Human Activities or Effects of Rainfall?

The residual trend (RESTREND) of NDVI revealed that LD in the Greater Sekhukhune district is mainly due to the effects of rainfall. Herrmann, Anyamba and Tucker (2005) revealed RESTREND method as an effective technique to identify the drivers of vegetation degradation. The finding of this study is similar to other studies that report that vegetation dynamics in arid or semi-arid regions is very sensitive to rainfall changes (Chen et al., 2005; Li et al., 2012). Furthermore, the district was affected by severe droughts in 2002-2004, 1992, and 2015 (Mpandeli et al., 2015; Vogel & van Zyl, 2016) hence, rainfall was the crucial climate variable in determining vegetation productivity.

Areas that significantly experienced a decrease in NDVI RESTREND are in the central to western portion of the district (Ephraim Mogale and Makhuduthamaga local municipality). This means that the degradation process that largely took place in Ephraim Mogale and

Makhuduthamaga local municipality is a result of human activities noted in the GSDM IDP (2019) such as livestock overgrazing, rural settlement, agriculture, unsustainable fuel wood harvesting and land tenure conflicts. The RESTREND magnitude showed a significant increment of 9.52% in the northern to eastern portion of the district in the Fetakgomo Tubatse local municipality, which means that vegetation improved due to other reasons apart from rainfall.

Insignificant positive RESTREND values recorded in Fetakgomo Tubatse local municipality and some of the southern part of the district in Elias Motsoaledi mean that vegetation production is improving in those areas due to rainfall. Although rainfall in these areas has declined, the reason for the improvement of vegetation in these areas may be attributed to bush encroachment and invasive species which could be an indicator of LD (Saha et al., 2015; Ward et al., 2014). Increasing significant NDVI trends were observed when Graw *et al.* (2016) analysed occurrence of bush encroachment in South Africa. Graw *et al*. (2016) showed that rainfall has the highest impact in five of the significant variables (includes cattle density, carbon dioxide, soil moisture and fire occurrence) identified to explain bush encroachment observed in South Africa. Stephens *et al*. (Stephens et al., 2016) also reported that communal rangelands experienced the greatest increase in bush encroachment cover which doubled in low-rainfall areas.

The RESTREND results showed that majority of the district (53%) is facing LD. However, the 41.41% of the district that revealed an insignificant negative RESTREND may mean that degradation could be attributed to combination of human and climatic factors. Other studies report that the RESTREND method showed that LD was a result of equivalent combination between climate variability and human activities (Dagnachew et al., 2020; He et al., 2015). Therefore, it was important in the study to use a systems analysis to effectively identify which human and climatic factors are driving LD and their interconnectedness to propose intervention measures.

3.5.2 Drivers, Pressure, Stressors and Condition of LD in the GSDM

The $DPSCR_4$ system analysis revealed that natural drivers such as dispersive duplex soils, climate extremes such as prolonged drought and high rainfall intensity, predisposed the district to soil erosion and formation of gullies (stressors). Mpandeli *et al*. (2015) noted that there are recurrent periods of droughts and high rainfall intensity, hence high climate variability has affected productivity in the Greater Sekhukhune district. Climate variability has resulted in formation of gullies and soil erosion, such that when drought events have reduced vegetation cover, the high-intensity rainfall will detach soil particles (dispersive soil noted by Gourmelon *et al.* (2016) in the low vegetation cover areas, and result in soil erosion and gullies (Mohamadi & Kavian, 2015). Literature has also stated that rainfall variability, climate change, soil erodibility and low vegetation cover are natural drivers of LD (Gedefaw et al., 2020; Itzkin et al., 2021; Meadows & Hoffman, 2002; Rey Benayas et al., 2008).

The study has also revealed that there is an interplay between the natural and human factors that aggravated LD in the district. Human activities in combination with natural drivers exacerbate LD in the district. Olsson *et al*. (2019) highlighted that interaction of human and natural drivers in the ecosystem can aggravate LD. Previous and current policies of the country that resulted in ripple down effects of human driving factors that degraded the land noted by Hoffman *et al*. (2000) and Meadows & Hoffman (2002) led to soil erosion and gully formation due to high population densities and subsequent abandonment of cropping fields and lack grazing management. These factors form part of the socio-economic drivers resulting in poverty and lack of governance that result in the widespread degradation of natural resources and ecosystem. Human activities such as unlimited access to communal grazing and lack of fencing in fields is intensifying LD because of low herbaceous basal cover (T. Hoffman & Ashwell, 2001; Shackleton et al., 2013). Post-1994, the opposing forms of modern systems and traditional forms of governance is an on-going source of tension because of the overlapping roles and responsibilities (Itzkin *et al*., 2021). These findings are similar to Itzkin *et al*. (2021) and Kakembo & Rowntree (2003) when LD was studied in Eastern cape province. They further revealed that dispersive soils together with overgrazing and cropland abandonment occurred due to poor governance and poverty. Mpandeli *et al*. (2015) subsequently found that smallholder farmers (practice subsistence farming) in the Sekhukhune district found it challenging to achieve high crop yields because of low and unreliable rainfall, hence cropping fields are abandoned (Mpandeli et al., 2015; Mukwada et al., 2021; The Greater Sekhukhune District, 2019).

The study further showed that poverty and disempowerment led to poor governance of natural resources, i.e., unsustainable land practices and land tenure conflicts. There are various unsustainable land use practices noted in the district due to poor governance such as unsustainable wood harvesting, uncontrolled movement of livestock, overgrazing, overstocking and illegal sand mining. Post 1994 caused governance tension between traditional leadership and local municipal governance systems on governance authorities (Itzkin et al., 2021). There are no rangeland institutions in the area, therefore there is vandalism of fences erected to control animal movement and grazing in communal land as this was also noted by Herd-Hoare (2020). This has led to overgrazing as land does not recover due to lack of grazing management and cropland abandonment as free-roaming livestock destroy crops in the fields (Blair et al., 2018; Itzkin et al., 2021). Cropland abandonment and overgrazing have been reported to encourage bush encroachment in the district. Similar studies also found that communal areas are characterised by abandoned cropland that are overutilised i.e., overgrazing and overstocking, consequently, bush encroachment was observed. Recent studies on bush encroachment reveal woody biomass encroaching on abandoned croplands because of the interaction between climate change and land management i.e., mostly overgrazing and carbon dioxide (Buitenwerf et al., 2012; Graw et al., 2016; Stephens et al., 2016; Stevens et al., 2017).

3.5.3 Towards achieving LD Neutrality: Integration of $DPSCR_4$ and LDN Framework

Integrating $DPSCR_4$ and LDN framework provides focused qualitative approach on the analysis of land use and cover changes that contribute to LD and provide intervention points (Itzkin et al., 2021). The response to LD was applied using LD Neutrality framework in the Greater Sekhukhune district aimed to avoid, reduce, and reverse LD (Orr et al., 2017). The framework was introduced to stimulate effective policy on SLM practices through avoiding and reducing LD interventions and improving land-based natural capital, through rehabilitation in the district (McDonald et al., 2016).

Overgrazing and uncontrollable livestock numbers is the main driving mechanism of degradation in the district. Key informants emphasised that a ranger system that regulates rotational grazing in rangelands developed by the community, would enforce sustainable use of resource. This is achieved with the assistance from tribal authority, LDARD officials and researchers, to monitor and limit activities that start or aggravate erosion. The interventions would require a guide on where various interventions and measures should be applied based on community participatory mapping, biophysical monitoring data, and identifying risk areas or areas severely affected by degradation (Nzuza et al., 2021, 2022). RESTREND has also been applied to guide and identify areas under human-induced LD or effects of rainfall as this could facilitate process of intervention measures (Herrmann et al., 2005).

The study revealed that promoting home garden agroforestry (Musvoto, Kgaphola and Mwenge Kahinda, 2022), livestock associations and facilitating links to marketing opportunities plus building capacity and awareness of community members to participate in these activities, encourage involvement in NRM governance (Itzkin et al., 2021). Integration of these interventions could be applied in a land use plan at a village level to address degradation in the overall district. LD affects the livelihoods or rural communities in the Greater Sekhukhune district and across South Africa. Therefore, an integrated social and ecological study through application of $DPSCR_4$ framework provides clear policy planning and changes in land use and management towards achieving LDN goals.

3.6 SUMMARY OF FINDINGS

LD and absence of integrated natural resource planning is threat to livelihoods of vulnerable rural communities in South Africa. The study aimed at assessing LD by improving social and ecological sustainability using a Social-Ecological Systems approach in GSDM. The first objective was to provide a quantitative analysis of LD by providing a spatio-temporal and spatial differentiation of anthropogenic and climatic i.e., rainfall as the lead factor in semi-arid, LD. Then the study provided a comprehensive analysis of the drivers of degradation in the GSDM and reflected the use of a system's application of $DPSCR_4$ and LDN frameworks to extensively understand LD and promote sustainable land management.

By analysing the correlation between climate factors (i.e., rainfall) and NDVI over the last 30 years, productivity change areas affected by anthropogenic activities from rainfall dynamics were distinguished using the RESTREND method. RESTREND revealed that rainfall was the main contributor to LD in the district, however, the study further revealed the synergistic impact of LD due to the interaction between several socio-economic factors and natural drivers. Climate variability i.e., frequent prolonged drought events and intensive rainfall, have exposed the district to LD, exacerbated by human activities. The findings from the traditional system revealed that the traditional authorities have more insight in communicating and connecting with the community and its values, while the modern system can support traditional authorities with the technical expertise. Coordinated and integrated land use planning coupled with awareness raising through active participation and environmental education was therefore the most important gap that can contribute to the realization of LDN in the study area and other rural semi-arid regions. The study is of critical benefit to South Africa and other developing countries that are experiencing inequities in resource allocation and what can be done to reverse and rehabilitate highly altered landscapes. Therefore, an integrated social and ecological assessment provided an understanding and a foundation for land use management plans that provide win-win benefits to improve the landscape conditions and sustain livelihoods in the Greater Sekhukhune District Municipality.

CHAPTER 4
Synthesis

4.1 INTRODUCTION

The study presented in the dissertation aimed to assess LD by analysing impacts of land use and land cover changes on LD, identify areas affected by either humans or rainfall impacts and understanding the causes and relations of LD in a system in the Greater Sekhukhune Municipality, South Africa. The dissertation presented research work on SLM practices to achieve LDN. This chapter synthesis the dissertation by reviewing the aim and objectives of the dissertation outlined in chapter one from the key findings, making concluding remarks and recommends future studies.

4.2 EVALUATION OF RESEARCH OBJECTIVES

4.2.1 To assess evolution of LULC from 1990 to 2019 and its impact on LD.

Recently, human interactions with the environment have accelerated the pace of land transformation and degradation with climate change and variability exacerbating LD in semi-arid regions. Therefore, it is crucial to monitor and assess the impacts of LULCC to promote SLM practices and to achieve LDN. Landsat satellite data allows long-term monitoring of changes in the environment to assess LD and understand potential driving forces. The study further utilised NDVI as an indicator of LD to reveal the land productivity trend of the district. Analysis of wet and dry season LULCC and key informants show that anthropogenic activities e.g., unsustainable wood harvesting, overgrazing and cropland abandonment, are the main drivers of LD in the district, further exacerbated by the synergistic impact of rainfall variability and intensive rainfall/flash floods. The study further revealed that more land is converted to bare/exposed rock and eroded land and the savannah ecosystem is slowly reduced to a grassland. Results also showed that the wet season struggles to recover after long and intense dry seasons due to climate variability and extreme weather events. These findings reveal that monitoring and assessing LULCC using satellite remote sensing imagery is crucial to provide a basis for addressing LD and key informants to understand reasons for changes and recommendations.

4.2.2 To identify drivers of LD and SLM interventions (Responses) using SES analysis of $DPSCR_4$ and LDN framework in the Greater Sekhukhune District Municipality.

Addressing LD requires identifying and understanding interactions of social and biophysical drivers to develop adaptive integrated management actions and determine significant trade-offs for future sustainability. The study aimed at assessing LD by improving social and ecological sustainability using a SES approach in GSDM. In arid or semi-arid areas, NDVI has been used as an indicator of LD and is strongly correlated with the net primary productivity and rainfall. The RESTREND model has been widely used to distinguish anthropogenic LD from the effects of rainfall using gridded satellite NDVI and rainfall datasets. Drivers Pressure Stressors Condition Responses ($DPSCR_4$) is a Social-Ecological Systems (SES) framework that has been used in the study to provide a comprehensive analysis of society and their interactions with the environment and its consequences and responses to LD. Key informant interviews, workshops and scientific literature were triangulated to formulate systems analysis of and application of $DPCSR_4$ to understand LD in the GSDM.

RESTREND model results revealed that most parts of the district are degrading due to the effects of rainfall i.e., a decline in rainfall and variability. The study revealed that the district, particularly Fetakgomo Tubatse and Makhuduthamaga municipality, is affected by bush encroachment which is also regarded as a type of LD. Bush encroachment may be due to a combination of various factors which still need to be explored further in future studies. RESTREND analysis further revealed that LD in the district could be a result of an interplay between several socio-economic factors and natural drivers. These were assessed using $DPSCR_4$ socio-ecological system analysis. The natural drivers such as duplex soils, topography and climate change predisposed the district to degradation. Then previous and current policies of the country resulted in a ripple down effects of human driving factors such as poverty and disempowerment that led to poor governance of natural resources. Hence, overgrazing due to a lack of rangeland management has been identified as the main driver of degradation in the district. Several interventions were identified in the $DPSCR_4$ through responses, but these require integration and coordination between the municipality, tribal authority and community through awareness and a sense of urgency.

4.3 CONCLUSIONS

The study aimed at assessing LD using land use/land cover change impacts, RESTREND and $DPSCR_4$ in the Greater Sekhukhune District Municipality, South Africa. LULCC over a long period and their impacts on LD revealed that it can form a basis for understanding long-term changes as LD is a slow-onset process. The use of RESTREND offers an opportunity not only to distinguish human-induced or rainfall effects degradation for the overall district but also to identify the driving factor at a cell level. The approach has proven to be useful as it informs land users, policymakers, and natural resource managers to promote intervention measures that effectively address LD. The application of $DPSCR_4$ and LDN frameworks provides a synthesis of the drivers of degradation and interventions to inform sustainable land management of the GDSM. The study highlighted a synergistic impact of climate variability and extreme weather events and that the wet season struggles to recover after the driest season. The findings from the key informants' interviews, focus group discussion with the herders and traditional system revealed that the traditional authorities have more insight in communicating and connecting with the community and its values, while the modern system can support traditional authorities with the technical expertise. Therefore, coordinated and integrated land use planning along awareness raising through active participation and environmental education the most important gap that can contribute to the realisation of LDN in the study area and other rural semi-arid regions. The study is of critical benefit to South Africa and other developing countries that are experiencing inequities in resource allocation and what can be done to reverse and rehabilitate highly altered landscapes. An integrated sociological and ecological systems assessment of LD has shown that it can effectively inform policy and integrated land use plans to produce win-win benefits to improve the landscape conditions and sustainable livelihoods.

4.4 RECOMMENDATIONS

The long-term spatio-temporal data of land use and land cover and changes data, distinguishing human-indued and rainfall effects, and socio-ecological systems study through $DPSCR_4$ approaches have proven to be curial to assess LD. These approaches revealed a major issue of bush encroachment that affects the ecosystem productivity and livelihoods of vulnerable communities that needs to be understood and explored. The study recommends that bush encroachment be studied further to curb LD as this hinders livestock grazing i.e., affecting livelihoods, and has negative consequences on the ecosystem.

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Appendix

Key informant Semi-structured interview Questionnaire- Evaluation of Land Use Land Cover Change influence on LD.

Local municipality:	Fetakgomo Tubatse	Elias Motswaledi	Ephraim Mogale	Makhudumathamaga
Key Informant:	Natural resource manager	Extension officer	Crop Scientist	Animal Scientist

1. How long have you been working in the area? In the years you've worked, what significant changes you have seen in the area? e.g., decline in soil fertility and crop yields, increase in gullies, change in composition of grazing species, invasive species, reduced palatable plant species, reduced ground water table and others.	
2. Where did these changes occur and why in those particular locations?	
3. When did the changes occur and why then? what triggered those changes?	
4. What do you think are the (i) direct causes and (ii) indirect causes are the main reasons for changes in LULC?	
(i) Direct causes (ii) Indirect causes	
(iii) Impact of changes in LULC on LD? Indicate where applies the causes of LD and specify.	
Direct causes	Specify
(i) Inappropriate soil management	
(ii) Poor agricultural practices and rangeland management	
(iii) Excessive wood harvesting and removal of natural vegetation due to:	
(iv) Disturbance of hydrological regimes due to:	
(v) Natural factors: i.e., intensive, or extreme rainfall, climate change and change of seasonal rainfall (perception of land users)	
(vi) Others	
Indirect causes	Specify
(i) Population pressure	
(ii) Land Tenure: Poorly defined tenure security.	
(iii) Poverty: limits land-user investment and choice. use of marginal land prone to degradation such as areas with steep slopes)	
(v) Labour: Shortage of rural labour either through migration and/or ageing) leading to traditional resource conservation practice abandonment i.e., terrace maintenance	
(vi) Inputs and infrastructure: (roads, markets, Co-operatives, fencing to manage animal movement etc.):	

(vii) Informal institutions: arrangement of local rules and regulations, affecting access to resources.	
(viii)Others	
5. What are the potential socio-economic and environmental impacts of LULC changes and LD?	
6. What is done to address these changes? What methods are used to reduce erosion, improve the fertility of soil and water resource management? Where any new methods adopted?	
If adoption of SLM practices	If no adoption of SLM practices
a. Does the measure reduce, prevent or rehabilitate LD?	a. What are the constraints for adoption e.g., tenure insecurity, shortage of land, seasonal migration, lack of capital, labour unavailability)?
b. Are the new practices effective?	
c. What is the percentage of farmers using these practices?	
d. Other	
7. Are there protected areas and why are they protected and how has these impacted livelihoods of rural communities?	
8. What mechanisms are used to control use of land such as grazing periods?	
Formal regulations	Informal (customary) regulations
9. Are there any land use conflicts between the two systems? If so, what are the conflicts and how can they be harmonised i.e., access, use, and right to land?	