The effects of drought and stocking density on vegetation productivity and the resilience of rangelands in Lesotho

School of Animal, Plant and Environmental Sciences (APES)

Liakae Ramasimong

(770270)

A Research Report submitted to the Faculty of Science, University of the Witwatersrand Johannesburg in fulfilment of the requirements for the degree of Master of Science (Coursework and Research Report)

In Environmental Sciences

Supervisors: Prof. Sally Archibald, Dr. Emma Archer

2019

Declaration

I Liakae Ramasimong hereby declare that this Research Report which is submitted for the Degree of MSc Environmental Sciences at the University of the Witwatersrand, Johannesburg is my own, unaided work. It has not been previously submitted for the examination of any degree at any other university.

Ramasimong.....

28th March 2019

Abstract

A significant portion of southern Africa is used for livestock production – both commercial and subsistence. The productivity of these natural grasslands depends, to varying degrees, on the soils and rainfall, as well as historical land management practices. Livestock farming practices may affect rangeland productivity, depending on the stocking rate, type of livestock and management activities. Moreover, these rangeland systems are also subject to periodic droughts, which can result in livestock mortality. How ecosystems respond to these droughts, and recover from these droughts, is likely to be, to an extent, affected by the previous history of stocking. Several studies on the effects of droughts on ecological processes in rangelands have been conducted and documented. However, the interactive effects of stocking practices and droughts on these rangelands are still poorly understood, despite the anticipated increase in both livestock populations and global change stressors such as droughts. Such a knowledge gap hampers development of effective mitigation strategies in these ecosystems. This study aims to investigate the relative impact of droughts (with reference to the 2015/2016 drought) and stocking densities on rangelands of Lesotho, and to determine the resilience of these ecosystems after perturbations. Such findings provide a conceptual framework for better understanding and appropriately managing ecosystems. The study was conducted in Lesotho, where long-term rainfall and stocking rates for different years were used to identify their combined effects on vegetation cover. The results show that droughts had a pronounced impact on vegetation productivity while the impacts of stocking rates were not really significant. However, a significant relationship between the altitude and stocking rates was observed ($P= 0.032$). In particular, the lowlands rangelands of Lesotho are relatively more heavily stocked than the mountain region. Similarly, vegetation loss was more evident in the lowlands region during drought episodes, although the mountain region showed a slower recovery after drought. This relatively slow recovery could possibly be related to low temperatures and shorter growing season in the mountain region.

Dedication

This master's research report is solely dedicated to my loving mom, Mrs Mamookho Ramasimong.

Acknowledgments

Firstly, I would like to give thanks to the Almighty Father for His divine mercy and blessings upon me throughout my studies.

I would like to convey my heartfelt gratitude to my supervisors, Prof. Sally Archibald and Dr. Emma Archer for their immeasurable effort, guidance, patience, encouragement and constructive advice throughout the compilation of this research report. I cannot thank them enough for their inspiration and support, both financially and academically. My sincere gratitude also goes to the School of Animal, Plant and Environmental Sciences for the enrolment opportunity as well as the assistance with the required administrative issues. I am also indebted to the University of the Witwatersrand through the Postgraduate Merit Award (PMA) for providing funding for my studies.

It is my pleasure to thank the Lesotho government departments and Ministries consulted during the study, specifically the Lesotho Meteorological Services staff, Bureau of Statistics staff, as well as the Ministry of Forestry, Range and Soil Conservation staff for providing me with all the necessary information. Special thanks are also extended to Mr Pokotho Sekhatha for his time and dedication in ensuring that I got all the required information from the Ministries and Dr Moses Cho from the Council for Scientific and Industrial Research (CSIR) in Pretoria for providing me with the required NDVI data. Without the role played by these people, this study would not have been a success.

My whole-hearted gratitude goes to my mother, Mrs Mamookho Ramasimong for her financial and spiritual support, encouragement and believing in me and to my entire family and friends for their moral support. Finally, I would like to thank the Bako family for their support during my studies.

May the Almighty God bless you all abundantly!!

Table of Contents

List of abbreviations and acronyms

AVHRR	Advanced Very High Resolution Radiometer
BOS	Bureau of Statistics
°C	Degrees Celsius
CPF	Country Programming Framework
CSIR	Council for Scientific and Industrial Research
CV	Coefficient of Variation
DOM	Department of Environment
ENSO	El Nino-Southern Oscillations
EVI	Enhanced Vegetation Index
FAO	Food and Agriculture Organization
GDP	Gross Domestic Product
GHGs	Green House Gases
GIS	Geographic Information Systems
IFAD	International Fund for Agricultural Development
IPCC	Intergovernmental Panel on Climate Change
LHDA	Lesotho Highlands Development Authority
LMS	Lesotho Meteorological Services
LSU	Livestock Unit
MAR	Mean Annual Rainfall
MDAT	Multi-Agency Drought Assessment Team
MFLR	Ministry of Forestry and Land Reclamation
MNR	Ministry of Natural Resources
MODIS	Moderate Resolution Imagery Spectroradiometer
NDVI	Normalized Difference Vegetation Index
NOAA	National Oceanic and Atmospheric Administration
SADC	Southern African Development Community
SPI	Standardized Precipitation Index
SRV	Senqu River Valley
SSA	sub- Saharan Africa
SST	Sea Surface Temperature
UN	United Nations

UNDP-GEF	United Nations Development Programme- Global Environment Facility
UNFCCC	United Nations Framework Convention on Climate Change
WFP	World Food Programme
WMO	World Meteorological Organization

List of Figures

List of Tables

Chapter 1: General introduction

1.1 Understanding the problem

It is projected that by 2050, the global population will reach approximately 9.3 billion, of which over 60 percent will be living in towns (Mandleni, 2011). Much of the population increase is anticipated in the developing countries, with the increase in the sub-Saharan Africa (SSA) particularly projected at 1.2 % per annum (Thornton, 2010). It is also expected that the demand for livestock products in SSA and South Asia will have nearly doubled by that time (Thornton *et al*., 2015). This being the case, livestock production must increase to meet the globally growing demand. The challenge, however, will be on how to increase livestock production in spite of the persistent impacts of climate change. A range of studies have indicated that extreme events such as droughts associated with climate change have severely affected agricultural production, with impacts expected to become more pronounced over time (Thornton *et al.,* 2009). For the past 30 years, climate change has reduced global agricultural production by 1-5 % in every ten years (Thornton *et al*., 2015) – although due to more intensive farming practices and genetic engineering, overall productivity has so far been able to keep up with the demand.

While there is a growing demand for livestock products globally, rangelands in certain areas are continuously degrading as a result of improper management (Showers, 1989; Vetter and Bond, 2012). Poor grazing systems in the grasslands is one of the main factors ascribed to the rapid conversion of these lands (Bodner and Robles, 2017). With increased grazing pressures, nutritious species of grass are endangered, while soil compaction and erosion inhibit the regrowth of fresh grass (Treydte *et al.,* 2017). In addition, accelerated changes in climate have aggravated pressures on these lands (Zhou *et al.,* 2018). Research in drought-stricken areas around the world has established that there has been loss of vegetation cover and productivity, shifts in species, as well as the mortality of grasses in rangelands due to droughts (Bodner and Robles, 2017).

Given that climate change impacts are likely to increase in severity for certain sectors in the coming decades, research on the assessment of vegetation dynamics triggered by anthropogenic factors is crucial (Zhou *et al.*, 2018). Such research may be useful in terms of assessing the possible mitigation strategies to climate change impacts such as droughts, and the means for drought recovery (Bodner and Robles, 2017). A study on the seasonal impacts of rainfall variability, grazing pressures and the recovery of rangelands is an active area of research, which has been conducted by a number of scholars including Archer (2004), O'Connor (1994) and O'Connor (1993). However, gaps still remain in our knowledge in this area.

1.2 Climate change and livestock production

Despite the fact that livestock production plays a critical role in the livelihoods of many rural communities, there is relatively limited information on the impacts of climate change on livestock. Most studies on climate change impacts in agriculture focus more on crop production, while there is less attention on livestock production impacts (Sirohi and Michaelowa, 2007; Thornton *et al.*, 2009; Nesamvuni *et al.*, 2012).

Livestock plays a critical role in supporting the livelihoods of millions of people world-wide (Thornton, 2010). Globally, approximately 1.3 billion people are employed in livestock industries, while around 600 million smallholder farmers in developing countries support their livelihoods through livestock production (Herrero *et al*., 2009). Currently, in developing countries, livestock production is the most rapidly growing subsector in agricultural production (Thornton, 2010). Particularly in Africa, this sector significantly contributes to income generation, employment creation and food security, while it is also a source of agricultural inputs, since it provides organic fertilizers and draught power (Gerber *et al.*, 2010).

Over 200 million Africans rely on livestock as their source of income through the sales of meat, milk and skins (Hoffman and Vogel, 2008). In addition, livestock serves as bride price payment in certain countries, while it further functions as an investment or even insurance when dealing with risks such as droughts (Kabubo-Mariara, 2009). In Africa, it contributes

significantly to a number of countries' GDP, contributing a range - from a minimum of 20% in Ugandan agricultural GDP to a maximum of 88% agricultural GDP in Somalia (Gerber *et al.,* 2010). In the Southern African region, livestock is a major sector of the agricultural economy, since more than 60% of the total land area in this region is not suitable for cropping (Dzama, 2016).

Ironically, livestock contributes to climate change through the emissions of greenhouse gases (GHGs), generating about 18% of the GHG global emissions (FAO, 2012), and studies indicate that climate change is responsible for substantial negative social, economic, environmental (Ayal and Filho, 2017) and agricultural impacts in sub-Saharan Africa. There is, as mentioned previously, a clear relationship between livestock production and rainfall variability (Kgosikoma, 2006). Climate change affects livestock mainly in two ways; either directly or indirectly (IFAD, 2009). Direct effects include changing rainfall patterns and high temperatures, which induce physiological stress and spread of the prevailing vector-borne diseases and macro animal parasites (Nkondze, 2014). Indirectly, livestock are affected by climate change through changes in feed resources, including their quantity, quality and temporal and spatial distribution (Rust and Rust, 2013). Rainfall variability has a significant impact on herbaceous production (Fynn and O'Connor, 2000).

Climatic conditions are, of course, persistently changing and evolving (Mishra and Singh, 2010). According to Nkondze (2014), the Intergovernmental Panel on Climate Change (IPCC) (2007) defines climate change as the alteration in climate conditions which can be recognized by the variability in the climate properties that are persistent for a long time period. Globally, climate change effects result in alterations in: temperatures, intensity, spatial distribution and timing of precipitation, levels of atmospheric carbon-dioxide and water availability (Lu *et al.,* 2017; Strzepek *et al.,* 2010). The IPCC has shown that annual global temperatures, along with temperature extremes have increased in recent years (Davis-Reddy and Vincent, 2017). Such warming has intensified the earth's hydrological cycle, as well as the mean surface temperatures (Mishra and Singh, 2010), thereby driving extreme climate events such as floods, storms and droughts (Nkondze, 2014). It is anticipated that in the mid-late 21st century, the tropical zone of Asia and Africa could incur substantial changes in both the intensity and frequency of drought (Udmale *et al.,* 2015). As a result of the projected increase in the intensity, frequency and duration of drought in most arid and semi-

arid regions, negative drought impacts are expected to further intensify (Keshavarz *et al.*, 2017).

Drought is a recurrent, gradually occurring phenomenon (Hao and Singh, 2015) which is characterized by precipitation deficiency over a long time period (Dai, 2011); accompanied frequently by increased temperatures (Davis-Reddy and Vincent, 2017), lasting for months or even years (Solh and van Ginkel, 2014). It is caused by a range of variables acting on numerous time scales with diverse temporal and geographic distributions (Homdee *et al.*, 2016). It is generally defined based on the frequency of the occurrence, the degree of dryness as well as the magnitude at which it occurs. If the frequency and the rate of precipitation remain critically low for extended periods of time, drought intensifies and propagates to other hydrological cycle components (Marcos-Garcia *et al*., 2017). It has significant adverse impacts on ecological, agricultural, social, cultural and economic areas in a range of climatic regions, more especially in rain-fed areas (Mathbout *et al.*, 2018). For instance, between 1900-2013, it is estimated that there have been 642 drought incidences globally, which resulted in the deaths of 12 million, over 2 billion affected, while the economic loss was estimated at USD 135 billion (Masih *et al*., 2014).

As depicted in Figure 1, depending on the degree of water deficit, drought impacts can be categorized into four types, namely meteorological, agricultural, hydrological and socio-economic droughts (Mathbout *et al.*, 2018). Meteorological drought is the lack of precipitation over a wide area for a period of time, hydrological drought is a period of inadequate surface and subsurface sources of water, agricultural drought combines the characteristics of both hydrological and meteorological droughts that results in a decline water resources and soil moisture which consequently leads to crop- failure, and socio-economic drought comprises meteorological, agricultural and hydrological droughts characteristics that result in the failure of water resources to meet population water demand (Craft *et al.*, 2016).

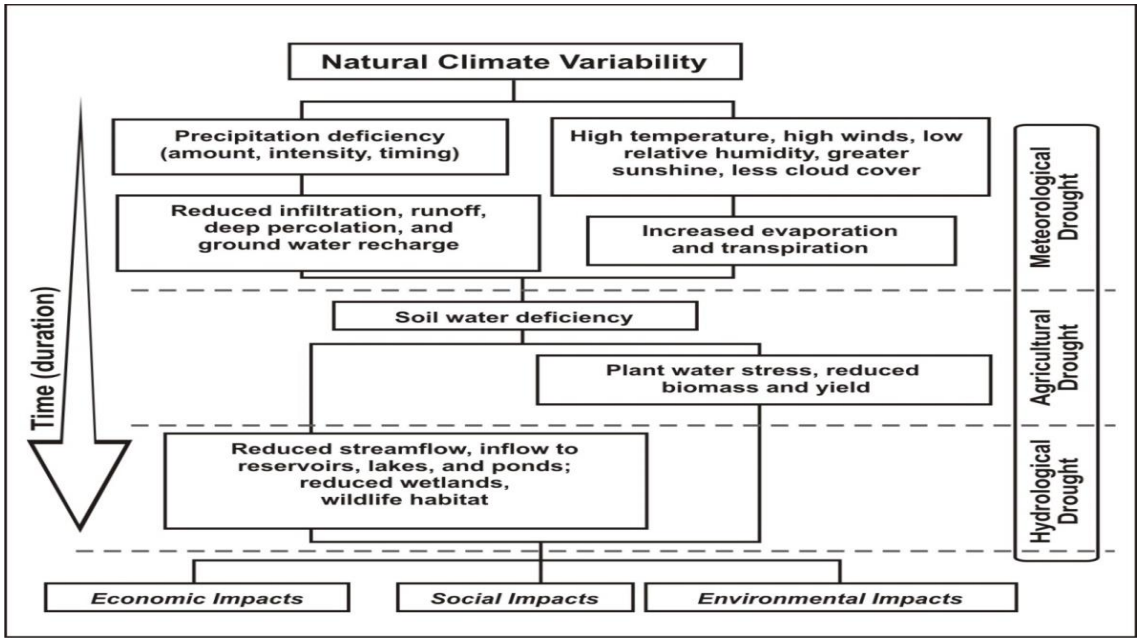

Figure 1.1: A sequence of different drought types (Source: Zargar *et al.*, 2011).

Periodic droughts have been a regular phenomenon in Southern African countries owing to the region's high rainfall variability. Rainfall records and reports indicate severe droughts in the late 1920s, early 1930s, 1950s and again in the 1970s (Malherbe *et al.*, 2015). Additionally, intense and widespread droughts were also experienced during 1982-84 (Dube and Jury, 2002), 1991-92, (Baudoin *et al.*, 2017: Unganai and Kogan, 1998), 1997-98, 2014-15 (Davis-Reddy and Vincent, 2017), as well as the most recent 2015/2016 El Niño drought (Bahta *et al.*, 2016). The extent of drought impacts depends on the drought intensity and the duration (Baudoin *et al.*, 2017). Some countries in southern Africa which are highly dependent on primary industry are severely impacted by droughts (Belle *et al.*, 2017).

Droughts are expected to impose pressure on natural resources (Keshavarz *et al.*, 2017), particularly on biodiversity, agriculture and food security, water availability and human health (Udmale *et al.*, 2015), of which a number of scholars consider agriculture as the most susceptible sector (Howden *et al.*, 2007: Nesamvuni *et al.*, 2012) due to its high sensitivity to climatic variability (Mohmmed *et al.*, 2017). As mentioned previously, poor and vulnerable rural people in developing countries are particularly susceptible to drought impacts, since many rely on natural resources, agriculture and livestock production for survival, which are amongst the highly sensitive sectors to climate (IFAD, 2009). In some cases, drought impacts are exacerbated by its proximity to the previous years' drought, such that households do not

have an opportunity to recover. This being the case, recurrent droughts can put communities at risk, such that their livelihoods may increasingly diminish (Keshavarz *et al.,* 2017).

1.3 The influence of drought on vegetation productivity

In rangelands, drought effects are observed on the productivity and composition of grass. As drought intensifies, this reduces soil water content (Heitschmidt *et al.,* 2005), and thus less drought resistant plants wilt, while some die off. This may eventually result in vegetation mortality of some grasses, thus changing the composition of different grass species within the rangelands (Illius and O'connor, 1999). Droughts thus not only result in reduced production during the drought period, but they may also alter productivity after the drought – especially if the composition changes from perennial to annual grasses (Vetter, 2009: Vetter and Bond, 2012). Moreover, a lower cover of perennial grasses can exacerbate soil erosion, resulting in the overall deterioration of ecosystem capacity (Ruppert *et al.,* 2015). However, there is also strong evidence that under certain conditions, grass productivity and species composition can recover very quickly – within a year – from droughts (O'Connor,1994), as the grass species in these environments are adapted to rapid regrowth and recruitment during periods of sufficient rain recovery of productivity. Droughts therefore can affect livestock production significantly, but impact duration depends on the severity of the drought, and the degree to which the grass layer was affected.

On the other hand, as mentioned earlier, drought impacts on grass communities and livestock production can be exacerbated by poor land-use. Inappropriate grazing systems in rangelands impose cumulative impacts on vegetation in grazing lands over the long term (Illius and O'Connor, 1999). Intense grazing, especially during and after droughts, can impact vegetation's ecological processes such as net primary production, vegetation growth dynamics as well as plant species composition (Heitschmidt *et al.,* 2005). Such a process was also observed by Fynn and O'Connor (2000) in their study on stocking rates effects on vegetation production in semi-arid rangelands. Drought-affected rangelands frequently produce less palatable grasses that are insufficient and less nutritious for livestock. When these drought- impacted lands are poorly managed, through overstocking, for example, the impacts further intensify, to the extent that recovery is difficult, as mentioned earlier (Dejene

et al., 2011). We therefore expect the resilience of the grassland to drought to be affected by the stocking rate and land management activities before the drought.

Equilibrium and disequilibrium rangelands

The sustainability of grazing lands in Africa and other regions has been under a great debate (Vetter, 2005). Studies conducted in African rangelands ecosystems have assumed that these systems are equilibrial (stable) systems which become unstable as a result of overgrazing and overstocking (Ellis and Swift, 1988). The equilibrium theory thus assumes that systems in equilibrium are regulated by biotic factors between animals and their environment (Ellis and Swift, 1988: Vetter, 2005). In this system, it is believed that livestock numbers have a great influence on vegetation (Venter *et al*., 2006). However, the disequilibrium model assumes that there is little impact of herbivores on the rangeland vegetation as their population is controlled by abiotic factors (environmental fluctuations); thus is likely that disequilibrium can be experienced during the prolonged drought periods or in very dry environments when there is no vegetation production from which the herbivores can compete (Gillson and Hoffman, 2007). Since in the disequilibrium system, climatic factor is the major driving force, the system can be perceived as event driven than management driven. However, the difference between the equilibrium and disequilibrium systems in some areas cannot be distinguished as the disequilibrium systems can sometimes react like the equilibrium systems (Venter *et al*., 2006)

It is therefore important to understand the basic management and reclamation principles so that these principles can be applied correctly for sustainability in rangelands (Venter *et al*., 2006). In equilibrium systems, where instability is triggered by biotic factors, stability can be maintained by introducing disturbances which will either influence the resource or consumer density (e.g. decreasing the stocking rates) or by introducing mechanisms which will minimize the strength of interactions in the system (Ellis and Swift, 1988). Where destabilization is caused by strong stochastic forces (e.g. abiotic perturbations), stability is regained by incorporating compensatory mechanisms or through maximizing the model ecosystems spatial scale (Ellis and Swift, 1988). According to Vetter (2005), this can be achieved through the opportunistic stocking strategies and mobility promotion. The specific method applied to stabilize rangeland ecosystems thus depends on what one identifies as the significant source of ecosystem destabilization (Ellis and Swift, 1988).

Some ecosystems are able to maintain their similar structure and not shift to a different state and function in the face of perturbations (Chaffin and Scown, 2018). This is known as ecological stability or ecological resilience (Linstadter *et al*., 2016). Sometimes disturbances, either internal or external can exceed or weaken system resilience, thus causing the system to shift to a different but stable state (Chaffin and Scown, 2018). Ecosystem resilience is therefore an important factor in sustainable natural resources production and ecosystem services in complex regimes which are faced with surprises and uncertainties (Elmqvist *et al*., 2003). There are a number of methods that have emerged to measure ecosystem resilience (Quinlan *et al*., 2015). Some ecological approaches are using models to measure resilience (Holling, 1973), some emphasize statistical signals approach (Quinlan *et al*., 2015) while other resilience measurement approaches have been developed in climate change adaptation fields (Tyler and Moench, 2012). In this study, resilience was measured in terms of vegetation adaptation to climate change.

1.4 Remote sensing for drought quantification

Drought impacts vary significantly on the environment, depending on the intensity and frequency of drought. For awareness and preparedness, it is generally important to detect and quantify drought. It has, however, been challenging to identify and acquire the most appropriate sources of data to use for drought analysis. It is insufficient for one to exclusively rely on meteorological data to relate and assess drought occurrence in various regions, since drought frequency and intensity varies with regions (Peters *et al.*, 2002), and the impacts are also influenced by prior land-use activities.

Further, with regard to meteorological data, information is only collected from the weather stations with sparse coverage. This makes it difficult to obtain information, particularly from remote areas. This being the case, collected meteorological data may be inadequate (Wan *et al.*, 2004). To counteract such a challenge, remote sensing has been introduced as the alternative source of information for identification of drought affected areas. Monitoring both vegetation and climate through remote sensing data and weather station data is critical for identifying and tracking the intensity and extent of drought (Malherbe *et al.*, 2015).

Since the 1960's, remote sensing became the essential source of aerial photographs, and has since been developed into a significant sector, with substantial satellite data products for measuring a variety of environmental indices (Maskova *et al.*, 2008). The use of remotely sensed data has a number of advantages over meteorological data, more especially when determining the impacts of drought on vegetation (Vicente-Serrano, 2007); (a) the captured information covers a wide area, (b) spatial density of the collected data is very high; (c) it provides information even on areas with sparse weather stations (Peters *et al.*, 2002) while it also allows drought affected areas to be identified (Vicente-Serrano, 2006).

One of the commonly used remote sensing metrics for measuring vegetation productivity is the Normalized Difference Vegetation Index (NDVI), derived from the Advanced Very High Resolution Radiometer (AVHRR) data (Barbosa *et al*., 2006). This index represents the variance between near infra-red and red reflectance which indicates the amount of green, photosynthetically- active vegetation on the environment. High NDVI implies high photosynthetic leaf area of the vegetation canopy captured in the ecosystem (Peters *et al.*, 2002). Green, actively photosynthesizing plants are characterized by high NDVI. These green, healthy plants absorb more visible light, and also reflect a large portion of near-infrared light whereas drought-affected plants and bare ground have both low light absorption and near-infrared refection capacity (Tucker and Choudhury, 1987).

NDVI images which are spatially continuous and frequent enough to monitor seasonal patterns can be acquired from a range of satellite sensors. Traditionally, NDVI is among the first vegetation indices (VIs) to be used (Maškova *et al*., 2008). For the past 20+ years, the Advanced Very High Resolution Radiometer of National Oceanic and Atmospheric Administration (NOAA-AVHRR) derived NDVI has been globally used to analyze time-series changes in land cover and use, but scientists may currently frequently use the Moderate Resolution Imagery Spectroradiometer (MODIS) NDVI product, which has a higher spatial and temporal resolution (Maškova *et al*., 2008). The MODIS NDVI 8-day composite data product (MOD09A1) provides a cloud corrected NDVI value every 8 days (Gu *et al*., 2008). Since images are constantly captured in MODIS, it provides a long-term record of data, which is useful in monitoring studies (Maškova *et al*., 2008). It can therefore be considered suitable for monitoring continuous phenomena such as drought. It should be noted that it has been found that MODIS NDVI has a number of limitations, mainly due to its low sensitivity to vegetation background canopy, as well as atmospheric variability (Rocha

and Shaver, 2009). Partly in recognition of such limitations, the Enhanced Vegetation Index (EVI) has been developed, which is more sensitive to vegetation background reflectance and incorporates the concept of atmospheric resistance into the NDVI (Matsushita *et al.,* 2007).

1.5 Livestock production in Lesotho

According to Multi-Agency Drought Assessment Team[1], agriculture is critical for a large proportion of livelihoods in Lesotho, more especially in the rural households (MDAT, 2016). The most frequently practiced agricultural activities in the country include crop production, fisheries, forestry as well as livestock production, with cattle, sheep and goat production dominating in livestock (Lesotho Country Programming Framework -CPF, 2017), while most crops grown include maize, sorghum, wheat (Maoela, 2010) and beans. Livestock production contributes significantly to the country's GDP (WFP, 2006). The majority of Basotho consider livestock production as a store of wealth. For instance, in 2005, it was estimated that out of 1.9 million population, over 170 000 people were engaged in livestock herding, with a clear indication that this sector contributes significantly to rural development (CPF, 2017). Production in the agricultural sector has, however, declined over the years, from 30% GDP contribution in 1980s to less than 20% (Maoela, 2010), mainly due to the growth of other sectors, such as mining, manufacturing and services. In recent years, this sector has failed to keep pace with the increasing population (SAFEGE, 2012).

Notwithstanding the decline in agricultural production, livestock production remains the dominating sub-sector in agriculture, with a contribution of 51%-61% to the agricultural GDP from 1999-2008 (Lewis *et al.,* 2011). The most commonly reared animals in the country include sheep, goats and cattle, with the populations of about 1.2 million, 845 000, and 650 000 respectively, (FAO STAT, 2013). Mountain areas are characterized by high livestock populations, with sheep and goats kept in bulk numbers, while cattle herds are kept by the majority of households (Lewis *et al.,* 2011). The sector plays a vital role in sustaining rural populations' livelihoods by providing food, income through wool, mohair and animals sales (MDAT, 2016), organic fertilizers, draught power (Gerber *et al.,* 2010), as well as a form of investment. Animals are also used in traditional ceremonies such as funerals and weddings.

[1] MDAT: Drought impact assessment body under the coordination of Disaster Management Authority (DMA) in Lesotho.

Lesotho is considered highly vulnerable to climate change due to its reliance on rain-fed agriculture (Dejene *et al.*, 2011). Research on the impacts of droughts on livestock production is, as yet, limited in the country. It is further assumed that livestock species may respond differently to variability in climate. This study is therefore conducted to investigate the impacts of drought on livestock production, with the main focus on cattle, sheep and goats as well as the rangelands response to droughts and grazing management.

1.6 Purpose of Study

1.6.1 Aim

To investigate the relative impact of the 2015/2016 drought and stocking density on forage production in Lesotho. This research will be guided by the following objectives:

1. To determine the intensity of the 2015/2016 drought in Lesotho
2. To assess forage changes over the years, and compare changes in high versus low stocking areas;
3. To compare low versus high altitude grasslands after a drought in high versus low stocking areas.

1.6.3 Hypotheses

1. In the mountain zone, grazing lands are overstocked compared with the lowland zones.
2. Drought impacts are more significant in areas that were previously degraded.
3. The mountain grasslands will recover slowly after drought impact, relative to the lowlands.

1.7 Research report structure

This study is organized as a series of chapters which address different components. Chapter 2 addresses the first objective on the weather of Lesotho, and also determines the intensity of the 2015/2016 drought relative to other drought years. Chapter 3 presents vegetation cover change over the period under study, and livestock stocking densities, which addresses the second and the third objectives. The overall conclusions of the study are presented in Chapter 4.

Chapter 2: Rainfall variability and drought characteristics in Lesotho

Abstract

Consideration of rainfall trends and drought is presented for Lesotho, which relies heavily on rain-fed agriculture. Based on the monthly precipitation from 1985/1986 to 2016/2017 sourced at a range of rainfall stations in the country, rainfall trends were examined. The standardized precipitation index (SPI) at three and twelve month temporal scales was also analyzed. Analysis at both SPI scales identified different temporal and spatial distribution of drought events, which also varied in severity. The study further shows that 12-month SPI was less severe in comparison to 3-month SPI. Significant drought episodes that affected the country between 1985/1986 and 2016/2017 were recognized at both scales, with the most intense annual droughts recorded in 1991/1992 and 1994/1995, while the most intense summer drought was recorded in 2015/2016. The spatial distribution of these drought episodes was slightly different, although they were both widespread. The 2015/2016 summer drought affected the entire region (100%), whereas the 1991/1992 and 1994/1995 annual drought affected 93.4% and 90.9 % of the country respectively. However, from both seasonal and annual SPI's, 2015/2016 was widespread, and long-lasting. Finally, drought patterns in different agro-ecological zones did not show any significant trends.

Keywords: Rainfall variability; Drought; Standardized precipitation index (SPI); Lesotho

2.1 Introduction

Within the field of climate change, consideration needs to be given to climate variability, which significantly affects freshwater variability and agricultural production (Kumar *et al.*, 2010). Due to climate change, rainfall characteristics, including rainfall extremes, rainfall amount and rainfall seasonality have been altered in certain areas, thus affecting drought characteristics (Deng *et al.*, 2017). Predicting the effects of climate change on extreme events is challenging in areas such as southern Africa that are intrinsically subject to high rainfall variability (Ambrosino, 2011; Jury, 2013). Rainfall variability is measured in terms of its inverse, the coefficient of variability or the interannual variability; whereby high variability indicates low rainfall. Systems with high rainfall variability, with the coefficient of variation (CV) greater that 33% experience frequent droughts and such systems are likely to show non-equilibrium dynamics (Ellis and Gavin, 1994: Kgosikoma, 2006). High rainfall variability in southern African region has been attributed to a range of factors, partly due to the El Niño Southern Oscillation (ENSO) (Nicholson and Kim, 1997). Similarly, variability in the regional sea surface temperature (SST) in Atlantic and Indian Oceans has influenced southern African rainfall variability (Driver, 2014).

Although ENSO is poorly predicted at a longer time scale, it is roughly experienced after every 2 to 7 years (Davis-Reddy and Vincent, 2017). According to Nash (2017), the effect of ENSO on southern African precipitation has been recognized for over three decades. Generally, ENSO affects the region when an ENSO event has stimulated fluctuations in the SST for both the Indian and Atlantic oceans (Nash, 2017). ENSO results in a decline in rainfall occurrences across most southern African countries, while the eastern part of the sub-continent experiences increased rainfall intensity (Valimba *et al*., 2006). Previous studies indicate that this sub-continent has experienced four significant drought events since 1980. Droughts are, therefore, a consistent feature of southern African climate systems, although they vary in their regional extent and their severity (Rouault and Richard, 2005). For example, in the 20th century, a severe drought occurred in 1930s, again in the late 1950s and in the early 1980s (Malherbe *et al*., 2015). Since the 1982 drought, there have been other, less severe periods of below average rainfall (Benkenstein, 2017). The 2015/2015 drought has been suggested to be of similar intensity to these droughts- hailed as the “worst drought in 50 years” (Benkenstein, 2017). However, the impacts of drought vary regionally, and it is not certain if the most recent drought was the most severe to date in Lesotho.

According to Benkenstein (2017), the El Niño event had affected the southern African region's rainfall in the previous year (2014/2015) and the situation further deteriorated in 2015/2016, when the onset of summer rainfall was delayed by several months (Rembold *et al* 2016). After the rainy season had begun, rainfall continued to be significantly below average across most parts of this region, with extremely high temperatures (Rembold *et al.*, 2016). Most areas received less than 75% of the average rainfall from October 2015 to February 2016 (Benkenstein, 2017), with the condition at peak between late November to early December 2015 (van Zyl, 2016). Therefore much of the region experienced almost two full growing seasons of below-average rainfall, and in some areas of the Lowveld, the drought did not break until late in December 2016. The 2015/2016 El Niño-attributed drought forced five SADC countries, namely Lesotho, Swaziland, Namibia, Malawi and Zimbabwe, to declare states of drought emergency nationally, while Mozambique and South Africa declared drought emergencies partially (Dzama, 2016).

The 2015/2016 El Niño attributed drought in Lesotho

Agricultural emergencies induced by climate have become a regular feature in the Mountain Kingdom of Lesotho (CPF, 2017). The country was among those countries critically affected by the 2015/2016 El Niño related drought in the southern African region, with reports demonstrating significantly impacted agricultural production for the season (WFP, 2016). In Lesotho, the drought commenced in September 2015, with the October to December period reported as the driest (Rembold *et al.*, 2016). Due to such harsh climate conditions, most water sources, such as dams and rivers, were depleted, and this led to severe water shortage (WFP, 2016). According to the Disaster Management Authority (DMA, 2015), towards the end of 2015, 15 percent of the country's total population was already experiencing acute water shortages. Consequently, vegetation wilted due to intensive heat coupled with low rainfall; thus leading to stressed pasture (UN-Lesotho, 2016). According to the Food and Agricultural Organization of the United Nations (FAO, 2016) on its drought briefing in Lesotho, there were cases of drought-related livestock deaths in both the Senqu Valley and lowlands regions of Lesotho.

Despite an increasing number of studies focusing on historical climate in this area, there are still large parts of this region where previous rainfall variability information is still limited, including Lesotho (Nash and Grab, 2010). Although rainfall is recorded at several stations across the country, this has never, to our knowledge, been compared or analyzed. This chapter therefore aims at investigating the long-term rainfall pattern and the drought years in Lesotho, with the main emphasis on the 2015/2016 drought. The intensity of this drought in selected districts, which are located at different agro-ecological zones, was also quantified.

2.2 Materials and methods

2.2.1 Study area

The study was conducted in Lesotho, a mountainous country located in southern Africa. It lies within the coordinates; 28˚30' S to 30˚40 S and 27˚00 E and 29˚30 E, and covers a total land area of 30 355 km^2, which is entirely landlocked by South Africa (Figure 2.1) (Fitchett *et al.*, 2016). In general, Lesotho is located at high altitude, ranging from 1500m to 3482m above sea level, (UNDP-GEF, 2011). There are four agro-ecological zones namely, mountains (regarded as the core of the rangelands and the largest zone, which covers two-thirds of the total land area) with the altitude ranging from 2,200 to 3,482m above sea level; the foothills (1,800 -2,200 m); lowlands (1,500 -1,800m) as well as Senqu River Valley (SRV) (Figure 2.2). According to the Bureau of Statistics (BOS, 2012), these zones are covered in ten administrative districts.

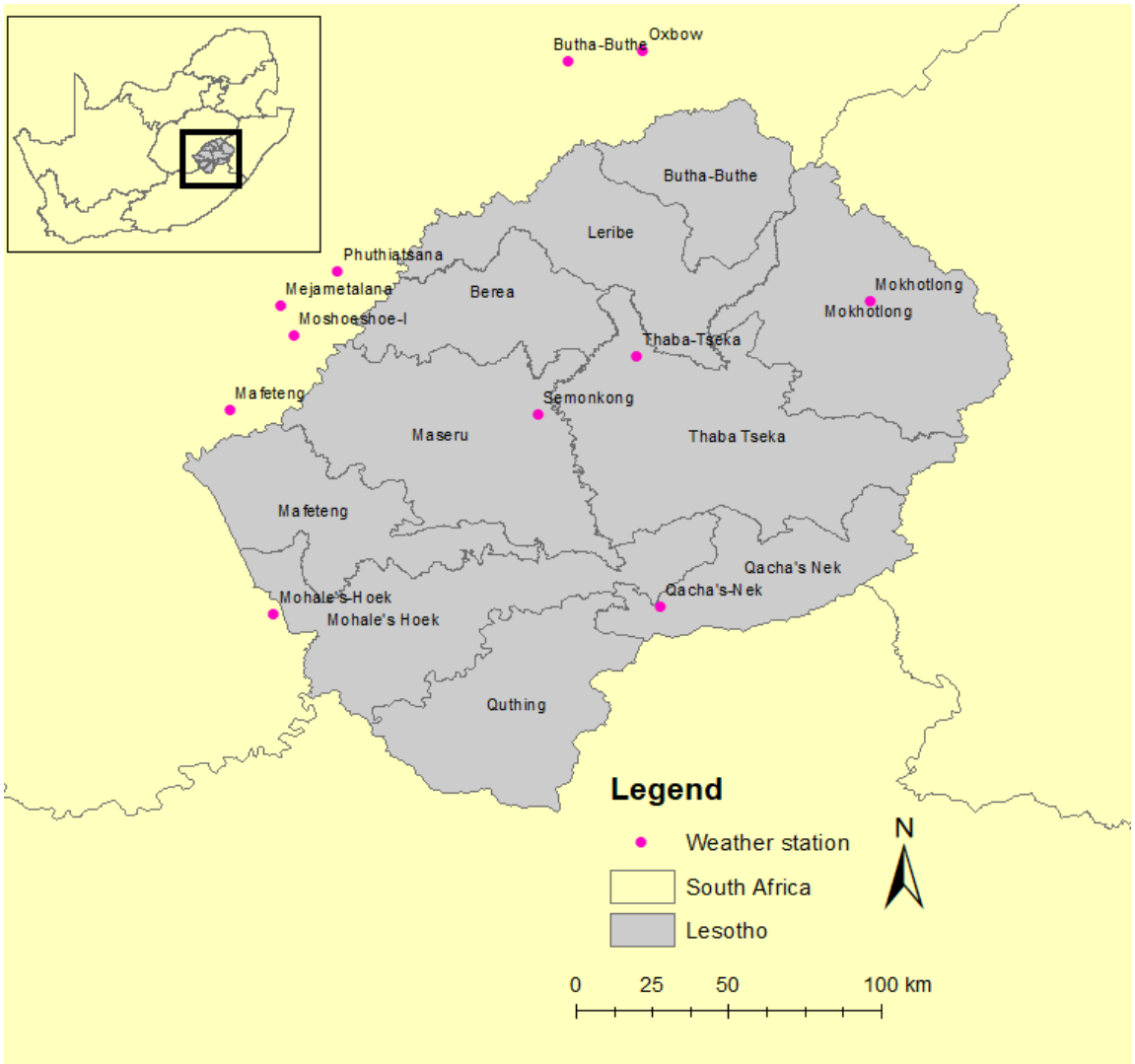

Figure 2.1: The location of the rainfall records used in this analysis.

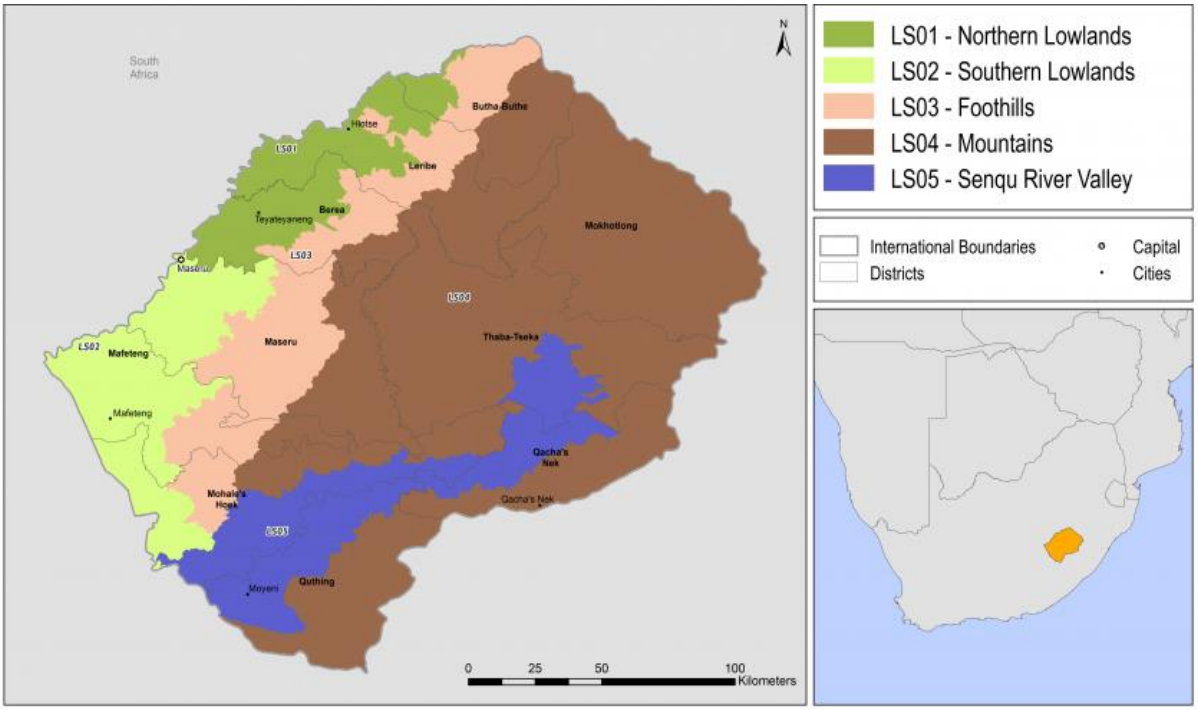

Figure 2.2: The agro-ecological zones of Lesotho (Source: FEWS NET, 2011)

2.2.2 Climate

Lesotho's climate is semi-arid to sub-humid, and the country experiences seasonal rainfall (UNDP-GEF, 2011). According to Maoela (2010), the location of the country in the Karoo basin significantly influences its climate, and there are generally four seasons;

- Summer; from November to January with temperature range between 27-30˚C
- Autumn; from February to April with temperatures between 9.5 and 25˚C.
- Winter; from May to July with ranges in temperatures from -10 to 12˚C.
- Spring; from August to October with temperatures ranging from 11-22˚C.

Summers are characterized by high temperatures and rainfall, while winters are known to be snowy, with very low temperatures and rainfall, whereas autumn and spring are intermediate seasons between winter and summer respectively (Olaleye *et al.*, 2014). The recorded mean maximum temperatures in January range between 16.5˚C and 30˚C, whereas the monthly mean winter temperatures can reach as low as -10˚C (Maoela, 2010). Extremely low temperatures are characterized by high-pressure systems (Nash and Grab, 2010). In particular, regions situated at an altitude > 2500 m a.s.l are typically cool, with temperatures in summer not exceeding 16˚C, while winters are extremely cold (Grundling *et al.*, 2015). These extreme temperatures lead to severe frost and snowfalls from May to September (Grab

and Nash, 2010). Snowfall is common in the highlands (Ziervogel, 2004), whereas it is occasional in the lowlands (Nash and Grab, 2010), and frost occurs across the country (Ziervogel, 2004). In the mountains, snow falls about 8 times per year, with its depth range between <5 to 120 cm, which is equivalent to 100 mm of rainfall on average (Grundling *et al*., 2015), while in the lowlands it can fall once in 2.3 years (Grab and Nash, 2010). The rainfall pattern of the regional lowlands of Lesotho is highly correlated to the summer rainfall in South Africa (Maoela, 2010).

Researchers observe that the country's precipitation, which is highly variable, both spatially and temporally, is strongly influenced by both the cold Benguela current in the Atlantic Ocean and the warmer Indian current in the Indian Ocean (Maoela, 2010). The overall average rainfall is 737mm; although it varies greatly within the zones (UNDP-GEF, 2011). The districts located in the south-western part of the country are the driest (Leipzig, 1996). The mean annual rainfall experienced ranges from 425mm in the lowlands to 1097mm in the Mountain region (Ziervogel, 2004). However, according to van Zinderen-Bakker and Werger (1974), the annual rainfall in the country can exceed 1600mm, and this signifies the highest rainfall in southern Africa – the country thus serves as a key source of water to the surrounding arid and semi-arid regions. A distinct rainfall season (approximately 80% of the annual rainfall) is normally experienced from October to April, with peak rainfall in December and January, while less than 10% is experienced in the winter season (Nash and Grab, 2010).

Lesotho is recognized as one of the most water-rich countries in sub-Saharan Africa, with water resources contributing to approximately 8-10% gross domestic product (GDP). Through the Lesotho Highlands Water Project (LHDA), the country supplies South Africa with water. In spite of the country being endowed with the highest percentage of clean water resources, drought events are, as mentioned previously, widespread (UNDP-GEF, 2011); with the agricultural sector highly affected by climate change impacts (Huber-Lee *et al.*, 2016). This generally suggests that drought response measures are necessary. In previous years, the country experienced a number of droughts with varying severity; three of them in 1983/84, 1992/94, 2006/07 (Maoela, 2010), as well as the most recent one in 2015/2016 (MDAT, 2016).

2.2.3 Data used

2.2.3.1 Rainfall

The recorded long term daily rainfall data from eleven weather stations of Lesotho used in this study was obtained from the Lesotho Meteorological Services (LMS). These data have thus far had limited application in scientific research, and represent a useful resource for climatologists and modelers. The location of these weather stations is indicated in Figure 2.1 above. This daily data was aggregated to monthly data. There was a common date range of data used in most stations (1985 to 2017), although Mejametalana and Phuthiatsana stations had different ranges (1987-2017 and 1993-2017 respectively). Generally, all the weather stations had missing data, with proportions varying among the stations. For, instance, Mejametalana station (Maseru district) had the least number of missing days, with the average proportion of 0.03, while Phuthiatsana station in Berea district had the highest average proportion of 0.20 (Appendix). Out of the ten districts of the country, two (Leribe and Quthing) had significant missing weather station data (> 0.20 average proportion) hence they were not included in this study. Because Lesotho is a summer-rainfall region all annual rainfall calculations were done on a "rainyear" (July to June) rather than a calendar year.

Rainfall gap filling

In cases where there were less than or equal to ten missing days per month, those missing days were replaced using the sample average method. According to Pappas *et al.*, (2014), the filling of sporadic value gaps can be undertaken using figures from time-adjacent observations of the same location. From this study, the average of four observations adjacent to the gap were calculated (i.e. (average of four observations before the gap +average of four observations after the gap)/2). When all the short (<10 days) gaps had been filled, if a month still had longer (>10 day) gaps, or if it was missing completely, the rainfall for that month was filled using the average rainfall for that month over all years. This monthly gap-filling is not ideal, as it averages out inter-annual variability. However, it is necessary to have a dataset with no missing data to calculate most drought indices, so this was necessary. The output was a filled monthly dataset with no missing values.

2.2.3.2 Altitude

Information on altitude was acquired for relating rainfall variations in different stations to the altitudes at which they are located. The altitude map for Africa was downloaded from USGS EarthExplore (https://earthexplorer.usgs.gov), and then clipped to Lesotho's spatial extents as a shapefile in ArcGIS, so as to identify the zonal statistics of the country's altitude per district.

2.2.4 Methods

Statistical analysis of data was done using R Statistical programming software (version 3.4.0) and Microsoft Excel. To determine the mean annual rainfall, minimum and maximum rainfall, as well as the coefficient of variation for eight districts, rainfall data obtained from the Lesotho Meteorological Services (LMS) for the selected years was tabulated and organized in Excel, and then analyzed using descriptive statistics. This data was also used to establish rainfall trends at different stations. The Standardized Precipitation Index (SPI) for 3-month and 12-month time scales was also calculated, based on the monthly precipitation using the Precintcon package in R.

2.2.4.1 Standardized Precipitation Index (SPI)

Drought indices are essential tools used for both drought planning and monitoring (Mathbout *et al.,* 2018). Although several indices have been developed (Dabanli *et al.,* 2017), SPI is a universal index which is recommended by the WMO (Mathbout *et al.,* 2018). It is a drought index which was developed by McKee *et al.,* (1993) for meteorological drought assessment (David and Davido, 2016). This index is widely used due to its several advantages relative to other indices (Dabanli *et al*., 2017) such as; its flexibility to be used at various timescales (Yao *et al*., 2018), its simplicity by using only rainfall, which allows for drought quantification even when other hydro-meteorological parameters are unavailable, as well as its ability to quantify drought on any timescale at any location with consistency (Dabanli *et al.,* 2017).

According to Asadi Zarch *et al.,* (2015), to calculate the SPI, a gamma probability is fitted to long term precipitation records. The cumulative density function (CDF) of the gamma is then transformed to a normal distribution using the equiprobable transformation (Hayes *et al.,* 1999). According to Khan *et al.,* (2008), SPI can be expressed as:

$$\text{SPI} = \frac{X_{ij} - X_{im}}{\sigma}$$

where

X_{ij} - seasonal precipitation at the ith rainguage station and jth observation

X_{im} – long-term seasonal mean

σ – standard deviation

Based on the objective of the research, SPI can be used to quantify 3-months, 6-months, 9-months, 24 months drought (Homdee *et al*., 2016) or even 48-months drought (Wu *et al*., 2017). For instance, SPI-3 can be used to calculate short- term droughts (seasonal) such as agricultural droughts, which are related to soil moisture conditions (Dabanli *et al*., 2017), while long-term scale SPI's such as a 48-month SPI is suitable for long term droughts that affect water resources (Wu *et al.,* 2017). Negative SPI symbolizes periods of droughts, while positive SPI denotes wet conditions (Sohoulande Djebou, 2017). A detailed procedure for calculating SPI is provided by Shadeed (2013) and Vicente-Serrano (2006). Longer drought indices require longer time periods in the dataset to produce accurate results. As we only had a maximum of ~30 years of data, the 3-month and 12-month SPI's were used to quantify drought intensity in Lesotho at different time-scales. The classification of SPI drought categories as presented by Wu *et al*., (2017) is shown in Table 2.1.

For identifying annual droughts that the country experienced, the number of weather stations in each SPI-12 class was calculated for each year, and the severity of drought from each station was classified based on SPI drought classification (Table 2.1). Once the identified droughts from all the stations were classified in terms of their severity, each class was then divided by the total number of weather stations to derive the extent of these different drought periods across the country. To determine the summer droughts, SPI-3 was calculated for each year for all weather stations, and the summer months (November, December and January)

extracted for further analysis. The severity of summer drought for each year was classified based on SPI drought classification (Table 2.1). Once the stations had been classified in terms of the severity of summer droughts they experienced, each class was then divided by the total number of weather stations to derive the extent of these summer droughts across the country.

Table 2.1: SPI drought categories classification

Level	SPI	Classification
1	SPI > 0	No drought
2	-1 ≤ SPI<0	Mild drought
3	-1.5 ≤SPI <-1	Moderate drought
4	-2.0≤SPI <-1.5	Severe drought
5	SPI < -2.0	Extreme drought

2.3 Results

2.3.1 Rainfall variability in Lesotho and the influence of altitude

The results in Table 2.2 show high rainfall variability among the weather stations. From the results, it can be inferred that the minimum annual rainfall received varied from 268 mm in Mohale's Hoek to 801 mm in Oxbow station. In terms of the annual maximum rainfall received per district, Thaba-Tseka experienced the lowest maximum rainfall (979 mm), whereas Oxbow and Butha-Buthe stations, which are both located in Butha-Buthe district, received the highest amount of rainfall (1573 mm and 1413 mm respectively). On average, Mokhotlong station received the lowest mean annual rainfall (MAR) (628 mm), while Oxbow received the highest MAR (1209 mm). The coefficient of variation (CV) varies between stations, ranging from 16 % to 28 %. The results also indicate that areas with low mean annual rainfall experienced high variability.

Some weather stations are situated at different altitudes, though they may be found in the same district. It can be noted that Mokhotlong, Thaba-Tseka and Semonkong stations are found at high altitudes (Figure 2.3). Literature indicates that Oxbow is also among the high altitudes weather stations situated at 2630 m a.s.l. (Grundling *et al.*, 2015). Additionally, Mokhotlong, Butha-Buthe and Thaba-Tseka are among the districts with the highest average altitude (2740 m, 2500 m and 2448 m respectively) (Table 2.2). Comparing rainfall

variability with the average altitude, it can be noted that most stations located at high altitude also experience high MAR. For instance, Butha-Buthe, Qacha's Nek and Maseru were among the top five districts with high MAR as well as high average altitude, except for Mokhotlong and Thaba-Tseka, which are both located at high altitude but have the least MAR (Table 2.2).

Table 2.2: Statistical analysis of the country's annual rainfall

District	Station name	Annual rainfall (mm) Minimum rainfall	Maximum rainfall	Mean annual rainfall	CV (%)	Average altitude per district (m)
Butha-Buthe	Oxbow	801	1573	1209	16	2500
Butha-Buthe	Butha-Buthe	579	1413	862	21	2500
Qacha's Nek	Qacha's Nek	470	1115	819	18	2256
Maseru	Moshoeshoe 1	490	1260	783	24	2056
Berea	Phuthiatsana	437	1130	754	20	1910
Mohale's Hoek	Mohale's Hoek	268	1344	736	28	1937
Maseru	Mejametalana	399	1103	732	25	2056
Maseru	Semonkong	319	1099	699	28	2056
Mafeteng	Mafeteng	388	1158	676	27	1779
Thaba-Tseka	Thaba-Tseka	416	979	637	21	2448
Mokhotlong	Mokhotlong	374	1136	628	24	2740

*** CV**- Coefficient of Variation

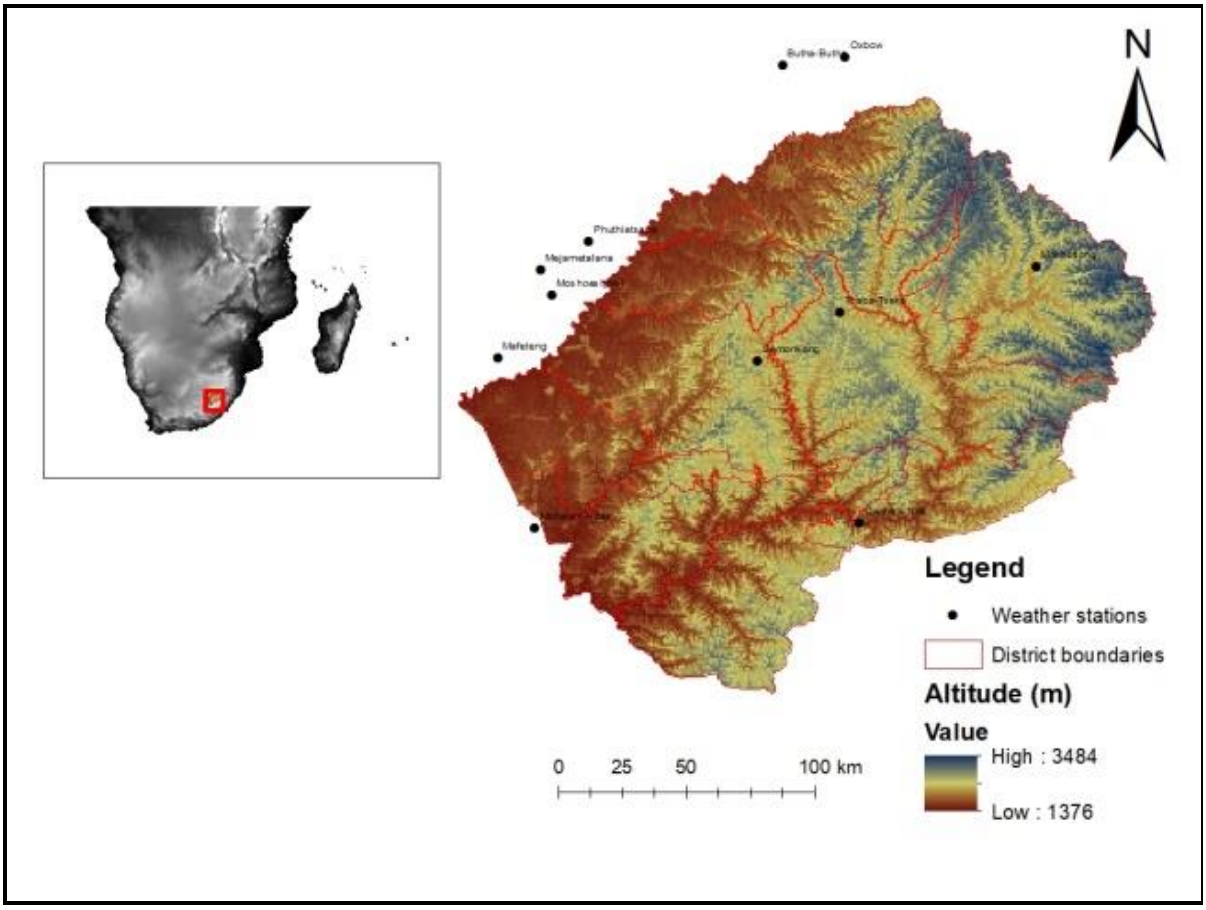

Figure 2.3: The altitudes for different weather stations in Lesotho.

Figure 2.4 represents a set of rainfall trends in different districts of Lesotho, which display year-to-year variation in rainfall, whereby the red line indicates trend over the years. The results clearly indicate that average rainfall has not changed in almost all the stations, except for Butha-Buthe station, which shows a slight increase in rainfall; and Semonkong station, which reflects a steady increase in rainfall. The simple regression analysis for Semonkong rainfall station indicated a significant increase in rainfall over years, with the p-value of 0.0005. In most stations, the average rainfall ranges between 700 mm and 800 mm. Most of these stations experienced above average rainfall in 1987/1988, 2000/2001 and 2009/2010 years, whereas there was a general below average rainfall in 1991/1992 to 1994/1995, 2003/2004 and 2015/2016.

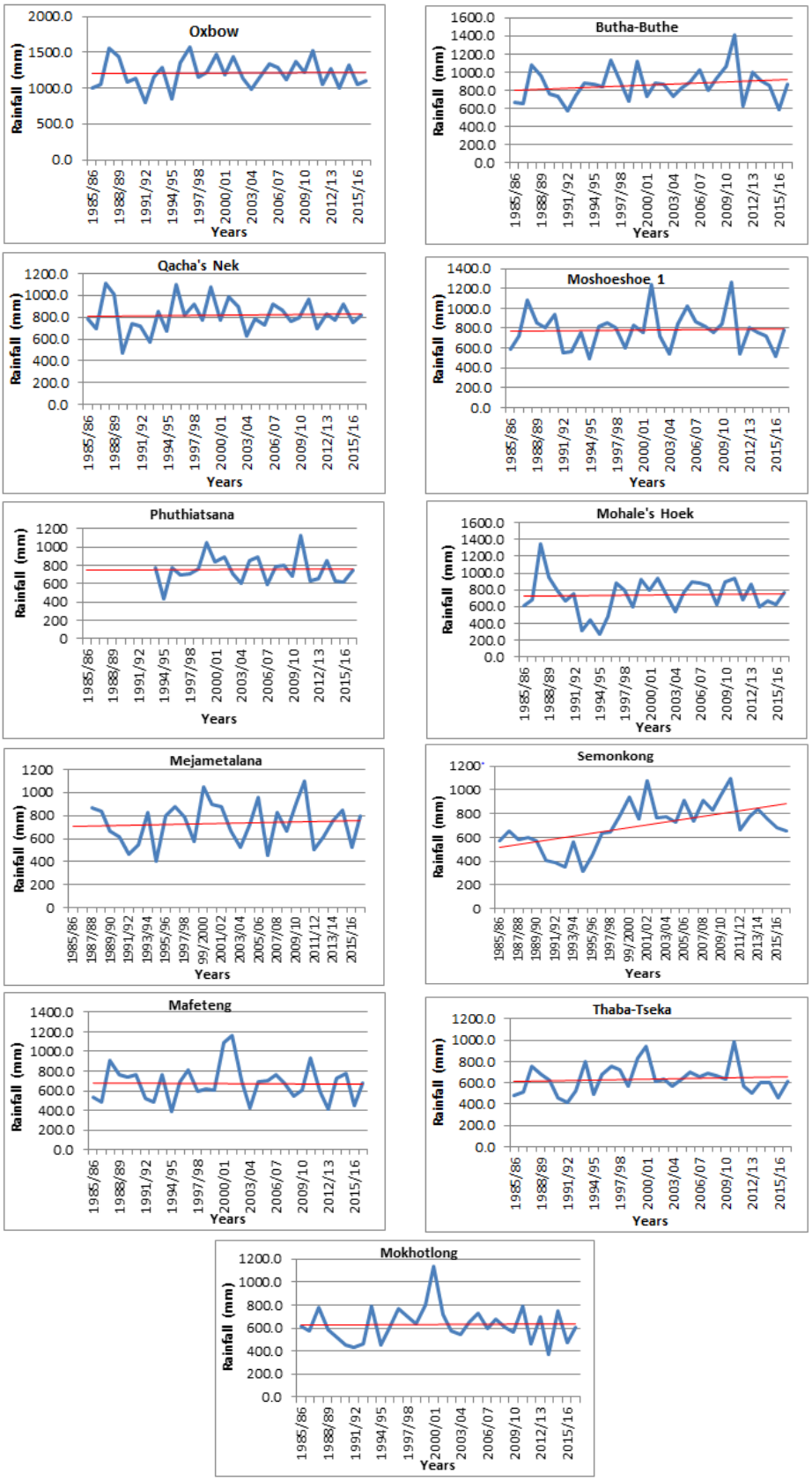

Figure 2.4: Rainfall trends for different stations in Lesotho (Oxbow, Butha-Buthe, Qacha's Nek, Moshoeshoe 1, Phuthiatsana, Mohale's Hoek, Mejametalana, Semonkong, Mafeteng, Thaba-Tseka and Mokhotlong) in the order of decreasing MAR

2.3.2 The spatial distribution of droughts in Lesotho

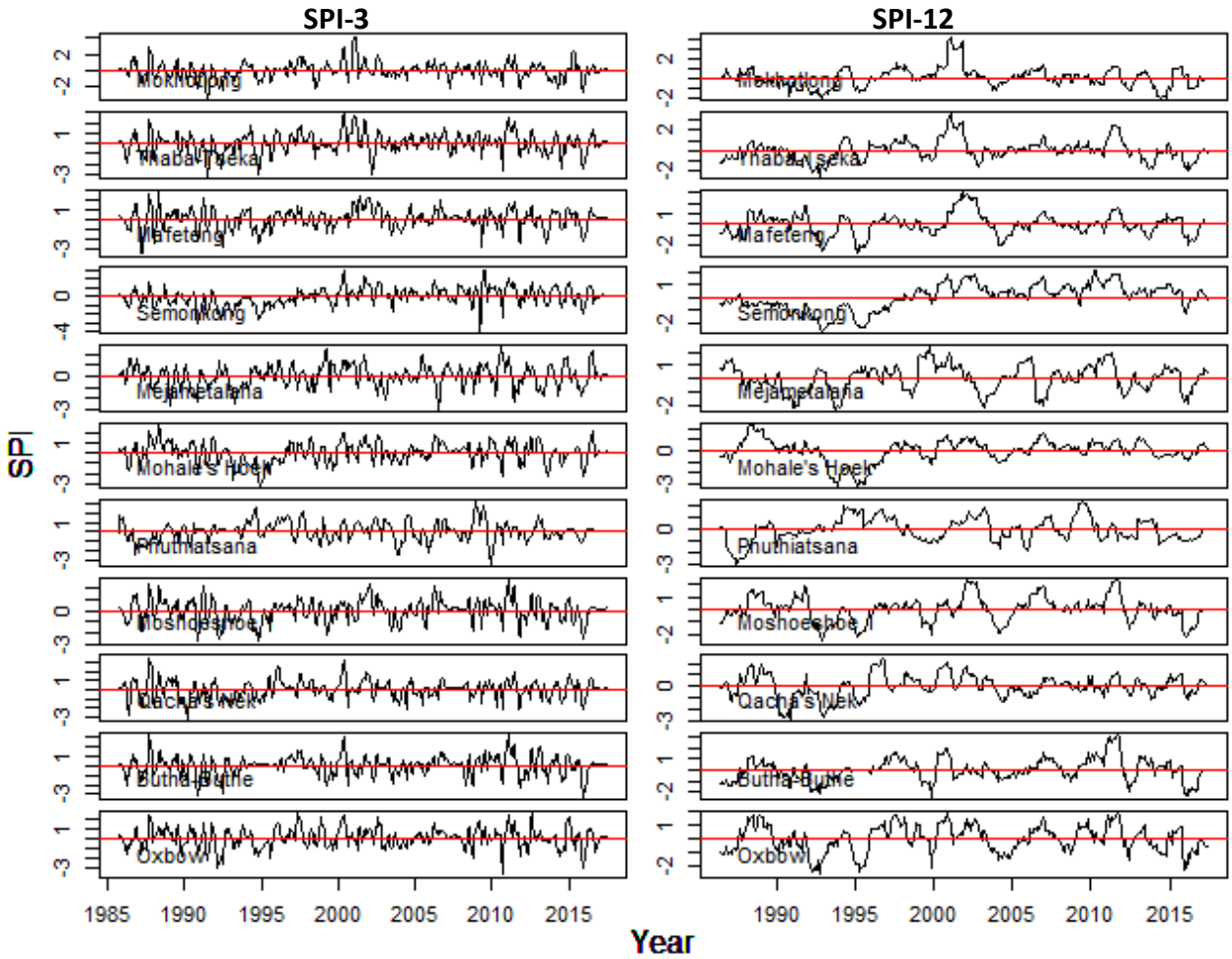

Figure 2.5: Seasonal and annual drought patterns in different rainfall stations of Lesotho (Mokhotlong, Thaba-Tseka, Mafeteng, Semonkong, Mejametalana, Mohale's Hoek, Phuthiatsana, Moshoeshoe 1, Qacha's Nek, Butha-Buthe and Oxbow respectively).

Results show that negative SPI trends were recurrently experienced over the entire country (i.e in all the stations) over the course of the 30 year time period (Figure 2.5). There is, however, significant drought variation in different districts, although there are some remarkably common drought periods in the entire region (e.g early 1990s drought). It can also be noted that different scales of SPI show similar patterns of drought variation in the long-term, even though they may demonstate some differences in the intensity and duration of particular drought incidences. For instance, based on SPI-3, districts experienced dominant droughts in the early 1990's and mid 2000's, while SPI-12 graphs not only demonstrate the

intensity but also the magnitude of droughts experienced. From those graphs, the predominant droughts were recorded in the early 1990's, mid 1990's, mid 2000s and mid 2010's. Conversely, late 1980's , early 2000s as well as early 2010's were humid.

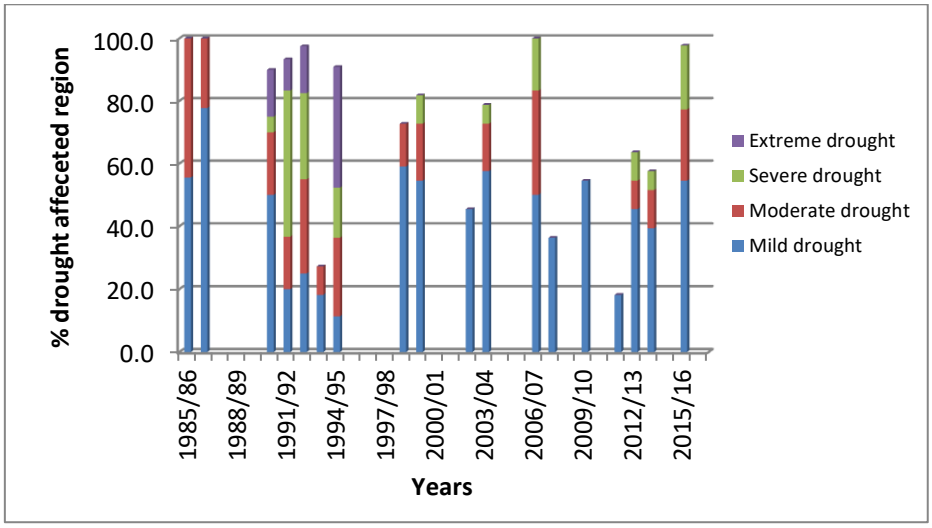

Figure 2.6: Percentages of rainfall stations affected by a series of annual droughts (SPI-12) in Lesotho.

In this study, SPI-12 was used to identify the variability of annual droughts, while SPI-3 was used to present seasonal droughts. The seasonal droughts studied in this section were specifically summer droughts (November- January) that occurred in Lesotho, since it was mentioned earlier that 2015/2016 was more of a summer drought in the country. Such an approach will help in comparing the intensity and magnitude of the 2015/16 drought to other summer droughts that the country experienced.

Percentages of weather stations affected by annual droughts (SPI-12) from 1985/1986 to 2015/2016 are presented in Figure 2.6. It can be noted that years without bars indicate non-drought years. From the figure, widespread recurrent droughts with various severities can be clearly identified. These droughts include the 1985/1986, 1986/1987, 2006/2007, 2015/2016, 1992/1993 and 1991/1992 events respectively. Over 50% of the region was affected by mild drought in 1985/1986, 1986/1987, 2006/2007 and 2015/2016 years. The most severe to extreme annual droughts (12-month SPI) were recorded in 1991/1992 (when severe to extreme droughts affected 56.7% of the region), 1992/1993 (42.5%), 1994/1995 (54.5%),

2006/2007 (16.7%) and 2015/2016 (20.5%). The 1991/1992 and 1994/1995 droughts were the most intense annual droughts, although they did not cover the entire region. Comparatively, in 2015/2016, there was no area affected by extreme droughts (0%) in this region, while 20.5% was affected by severe droughts, 22.7% affected by moderate droughts while 54.5% experienced mild droughts. It can thus be inferred that 2015/2016 drought was less intense, compared to the 1991/1992 and 1994/1995 annual droughts.

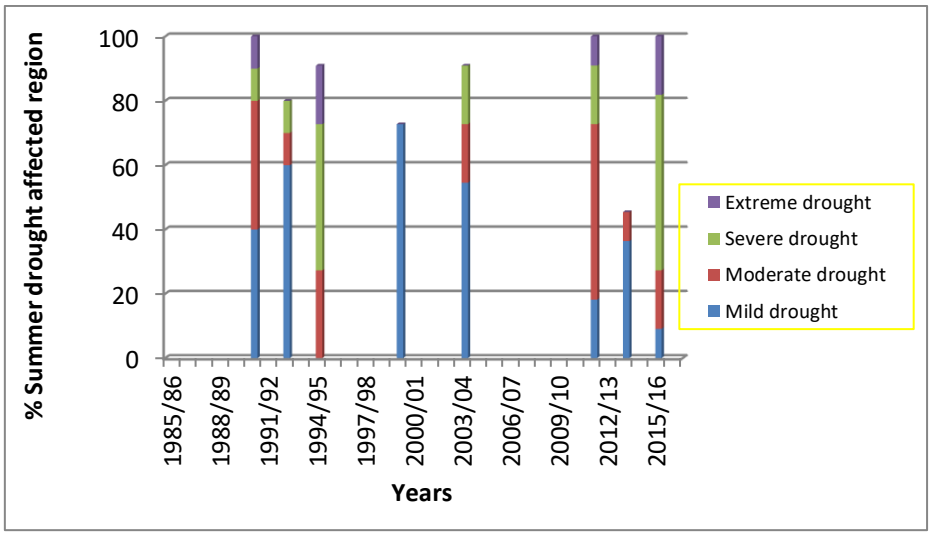

Figure 2.7: Percentages of rainfall stations affected by a series of summer droughts in Lesotho.

Figure 2.7 illustrates the severity of the summer droughts experienced in Lesotho. From the figure, the three most widespread summer droughts, which affected the whole country in 1990/1991, 2011/2012 and 2015/2016, are clearly illustrated. The most severe to extreme summer droughts (3-month SPI) were recorded in 1990/1991 (when severe to extreme summer rainfall affected 20% of the region), 1994/1995 (63.7%), 2011/2012 (27.3%) and 2015/2016 (72.7%). 2015/2016 was clearly the most intense, with 9.1%, 18.2%, 54.5% and 18.2% of the region affected by mild, moderate, severe and extreme droughts respectively. Although the 1991/1992 and 1994/1995 droughts did not impact the entire region, they are also identified as being amongst the most intense droughts that the country experienced.

Despite the fact that the two SPI time scales present slightly different results, they both show that 2015/2016 was amongst the most widespread droughts in Lesotho since 1985/1986, although there were some more intense droughts experienced (e.g. the 1994/1995 drought).

From the above figures, 100% of the region was affected by the 2015/2016 summer drought, while 97.7% was affected by the 2015/2016 annual drought - an indication that despite the fact that it was not as severe as some other droughts in the last 30 years, it was long-lasting. Table 2.3 results for SPI-3 indicate that extreme droughts were experienced in the northern region of the country, from both rainfall stations of Butha-Buthe district. Mafeteng, Mohale's Hoek, Qacha's Nek, Thaba-Tseka, Mokhotlong and part of Maseru (Moshoeshoe 1 site) experienced severe droughts, whereas other areas of Maseru district (around Mejametalana and Semonkong sites) experienced moderate droughts. In Berea, mild droughts were experienced.

Based on SPI-12, severe droughts covered Butha-Buthe and parts of Maseru (adjacent to Moshoeshoe 1 site), while areas near Mejametalana site (Maseru) and Thaba-Tseka districts experienced moderate droughts. Mild droughts covered a larger area of the country including Berea, Maseru (areas around Semonkong), Mafeteng, Mohale's Hoek, as well as Qacha's Nek districts. Only Mokhotlong did not experience drought.

Table 2.3: 2015/2016 summer drought assessment by SPI-3 and SPI-12

		Drought category	
Station name	**District**	**3-month SPI**	**12-month SPI**
Oxbow	Butha-Buthe	Extreme	Severe
Butha-Buthe	Butha-Buthe	Extreme	Severe
Phuthiatsana	Berea	Mild	Mild
Mejametalana	Maseru	Moderate	Moderate
Moshoeshoe 1	Maseru	Severe	Severe
Semonkong	Maseru	Moderate	Mild
Mafeteng	Mafeteng	Severe	Mild
Mohale's Hoek	Mohale's Hoek	Severe	Mild
Qacha's Nek	Qacha's Nek	Severe	Mild
Thaba-Tseka	Thaba-Tseka	Severe	Moderate
Mokhotlong	Mokhotlong	Severe	No drought

2.4 Discussion

Overall, the analysis shows that the 2015/2016 drought was comparable to other severe regional droughts in the last 30 years. Historically, southern Africa experienced several droughts with different severities. Studies indicate that the region was struck by intense

droughts in 1980s, and also during the summers of early 1990s, which led to significant declines in livestock and crop production (Richard *et al*., 2001). Moreover, these droughts resulted in devastating impacts on water resources, the environment, industries and national economies (Unganai and Kogan, 1998).

During the 1982-84 drought years, maize production dropped in southern Africa south of 15˚S, while the whole southern region lost up to 90% of livestock during the 1982/1983 drought (Mwafulirwa, 1999). Some studies stated that the 1991/1992 drought as the worst in more than a century, which affected most of the southern African countries, including Lesotho (Green, 1993). Most areas in the region experienced dry conditions during this period, receiving 20-70% of the average rainfall, while temperatures were extremely high (Davis-Reddy and Vincent, 2017). This resulted in a tenfold decline in maize production, with massive losses of livestock reported in Botswana, Namibia, South Africa and Zimbabwe (Mwafulirwa, 1999). Generally, this drought period led to about 70% of the crop failure, which resulted in 11.4 million tonnes of cereals being imported (Davis-Reddy and Vincent, 2017). Out of a regional population of approximately 130 million, 18 million people were directly faced with starvation (Unganai and Kogan, 1998). In Zimbabwe, to counteract the shock after the 1991/1992 drought, families had to sell their livestock (goats in particular) in order to sustain consumption levels, despite the fact that they had reared those goats as an investment (Benson and Clay, 1998). According to Mwafulirwa (1999), the 1992 drought in southern Africa surpassed the 1982/1983 drought in intensity.

Based on the most recent drought reports, some scholars have identified 2015/2016 as the most severe drought since 1930 in South Africa (Davis- Reddy and Vincent, 2017). Others reported that the country had experienced the lowest average precipitation since 1904 during this period, with the average of 403 mm relative to the total average rainfall of 608 mm in other years - which was even less than that experienced during the severe drought of 1992, as well as the dry years between 1930 and 1933 (Brink, 2016). The general cereal shortage for 2015-16 stood at 7.90 million tonnes, relative to the 3.9 million tonnes for the 2014/2015 marketing year (Davis-Reddy and Vincent, 2017). In Lesotho, the FAO report on 2015/2016 drought briefing stated that water availability and rangelands for livestock deteriorated significantly as a result of this drought, with livestock drought- related deaths reported mainly

in the Lowlands and Senqu River valley regions. From the interviewed communities in Mohale's Hoek, Quthing and Butha-Buthe districts, approximately 20% of them reported livestock deaths, while other districts reported 5-15 % of drought-attributed livestock deaths. The poor quality of rangelands and pastures consequently affected livestock sales as the quality of livestock deteriorated (FAO, 2016).

Using SPI-12 to identify the annual drought series, this study reports the most extreme drought periods since 1985/1986 to have occurred in 1990/1991, 1991/1992, 1992/1993, 1994/1995, 2006/2007 and 2015/2016. Certain of these drought episodes coincide with the previously reported intense and widespread droughts experienced in Lesotho. For instance, according to Maoela, (2010), in the previous years, Lesotho experienced droughts in 1983/1984, 1992-1994, as well as 2006/2007 periods, although they varied with severity. Also, the Lesotho Meteorological Services (LMS, 2007) reported widespread below average rainfall between 2006 and 2007, which affected the whole country.

Although other studies had reported 2015/2016 as the worst drought year experienced in decades, in this study focused on Lesotho, 2015/2016 was not found as the most severe as compared with other drought years- even though the summer season of 2015/2016 was the driest summer recorded in this study. Such a finding might, it must be noted, be attributed to the fact that the drought index used did not incorporate temperature. It is presumed that consideration of other drought indices which use both precipitation and temperatures might have shown different findings as compared to those observed in this study. Especially when understanding climate change impacts, it would be important to consider rainfall and temperature, as there are clear patterns of increasing temperatures in the region, which would result in more extreme water stress for plants even if the reduction in rainfall was not as severe as other years.

It is thus critical to use complementary data, such as data on vegetation greenness, to assess the impact of this drought event. Research related to drought indices based on remote-sensing is likely fundamental for drought early warning systems (Yao *et al.*, 2018). To take a human dimensions perspective, the same reduction in rainfall can be a more extreme drought event if

their livelihoods are more negatively affected. The objective assessment of the severity of the drought that has been performed here thus needs to be linked to information on rangeland productivity and resilience, to assess its impact, and to inform and formulate response strategies for future droughts.

2.5 Conclusions and recommendations

The spatio-temporal drought evolution in Lesotho was investigated using both SPI-3 and SPI-12. It can be concluded, based on the analysis of these two indices, that drought patterns and characteristics greatly vary in Lesotho from year to year. Although 2015/2016 was identified as one of the most intense drought years, the results showed that there have been more intense annual droughts experienced in the country previously. 1991-1994 was the longest drought wheraes 2015/2016 was the driest summer drought recorded in the 1985/1986 to 2016/2017 period. The study results may be useful for developing drought monitoring plans in the country, as well as other climatically similar regions.

Nonetheless, to advance knowledge regarding Lesotho climate, further studies using other types of drought indices are necessary to provide concrete evidence regarding the evolution of droughts in the country, as well as their severity and impacts. Further, it is crucial to link such studies with ecological research for better understanding of drought severity and extent, which could also help in the assessment of environmental response and resilience to drought pressures. In the southern African region, there is still a challenge in terms of drought mitigation and effective adaptation response, which may be exacerbated in the future, mainly due to increased population in certain areas, challenges in drought risk management, environmental degradation and increased water demand (Masih *et al*., 2014). As it is anticipated that low seasonal rainfall coupled with high temperatures will be more frequent in the SADC region in future (Archer *et al*., 2017: Davis-Reddy and Vincent, 2017), as well as the entire African region (Masih *et al*., 2014), more integrated efforts for the comprehensive response to climate change are thus crucial for mitigation of these anticipated adverse droughts impacts.

Chapter 3: The impacts of droughts and livestock grazing on vegetation and the resilience of Lesotho rangelands

Abstract

Recurrent droughts coupled with poor stocking management impose a significant threat to semi-arid rangelands. Studies on the influence of droughts and grazing intensity on vegetation cover have been widely conducted and documented, yet the effects are, as yet, poorly understood. Studies addressing this knowledge gap could provide a basis for the development of policies and management tools which facilitate sustainable ecological and economic development. Rangelands in Lesotho are considered degraded, thereby threatening livestock production which heavily relies on them as well threatening the water infiltration capacity of the Lesotho Highlands Water Project which is a significant contributor to the country's economy. In this study, the effects of rainfall variability and stocking rates on vegetation cover in high versus low attitude grasslands were investigated. MODIS NDVI data from 2001-2017 was used to determine trends in vegetation. Resilience of grasslands to droughts and grazing stresses in different agro-ecological zones was also assessed, in terms of the adaptation of these rangelands to such perturbations. The results suggest that lowlands were overstocked, relative to highlands. However, grazing intensity impacts were not detected. Vegetation was reduced significantly by persistent intensive droughts. Below average productivity was particularly observed in 2005/2006, 2014/2015, 2015/2016 and 2016/2017, with the lowland grasslands seemingly more affected than highlands grasslands. It was, however, evident that highland grasslands recovered relatively slowly after the intensive 2015/2016 drought.

Keywords: Droughts; Rangelands; Stocking rates; Vegetation change; NDVI; Resilience; Lesotho

3.1 Introduction

The kingdom of Lesotho has a total land area of about 3 million hectares, of which roughly 60% are rangelands (Hae, 2016). These rangelands support livestock production, since farmers rarely practice supplementary feeding (Hae, 2016). Livestock is regarded as a valuable property which supports social well-being and wealth in Lesotho (UNDP-GEF, 2011). As the population increases, demand for livestock also increases (Zunckel, 2003). According to the Ministry of Forestry and Land Reclamation, livestock plays a vital role on providing milk, meat and draught power, while it is also a source of income (MFLR, 2014). In addition, thousands of Lesotho men who previously worked in the South African mining sector purchased livestock in numbers when they were retrenched (Zunckel, 2003). Consequently, livestock is kept in large numbers in the country (Hae, 2016).

Research shows that livestock rearing in Lesotho has, however, posed negative impacts on natural resources (MFLR, 2014), such as the rangelands (Zunckel, 2003). These rangelands, which are communally grazed (Zunckel, 2003), are considered overstocked (UNDP-GEF, 2011), and this has led to overgrazing, leaving these lands vulnerable to degradation (MFLR, 2014). According to Showers (1989), degradation in the country has reportedly increased. Further, deterioration in the conditions of grazing lands in the country is also ascribed to recurrent droughts (MFLR, 2014). Generally, researchers across the world observe rapid changes in major grassland biomes, which are ascribed to several driving forces such as intensive grazing by wildlife and livestock, droughts, fire, shrub encroachment and invasion of exotic species (Bodner and Robles, 2017). Of these driving factors, droughts and other climate change related factors have been given more attention in many drought affected areas in an effort to understand the challenges that these conditions impose, further impacts that might be faced in future, as well as how well the grasslands could sustainably be managed under such conditions (Bodner and Robles, 2017).

The impact of heavy grazing on ecosystems, however, is ecosystem specific, and depends on the historical levels of natural herbivores in a landscape, as well as the environmental conditions (Mack and Thompson, 1982). Some ecosystems are much more resilient to heavy grazing than others, and can maintain high primary and secondary productivity

(McNaughton, 1984). Other ecosystems are very sensitive, and productivity will collapse when these are over-utilised (Bowman *et al.*, 2007). Lesotho, being high altitude and dominated by relatively nutrient poor tussock grasslands possibly had quite low grazer numbers in the past (Rushworth pers comm) and the levels experienced currently are probably far higher than the vegetation evolved with. Therefore one would expect these systems not to be resilient to high grazer numbers.

The impacts of periodic droughts and grazing result in a significant shift in rangeland systems (Abdullah *et al*., 2017). Improper grazing is identified as one of the main disturbance factors that lead to the ecological shift due to the loss of rangelands species, changes in rangelands functions and ultimately the ecological degradation globally (Petersen, 2004; Abdullah *et al.*, 2017). Pressures on natural resources as a result of the increasing human and livestock populations, along with inappropriate land use practices exacerbate land degradation and this, in turn, limits the capability to cope during droughts (Fereja, 2017). The vulnerability of grazing lands to droughts in the semi-arid regions can result in significant socio-economic losses in the environment, provided there are no mitigation and adaptation strategies implemented (Iglesias *et al*., 2016).

The relationships between land management, desertification and drought have been emphasized by the government legislations and policies although there is still a limited understanding on drought effects on rangelands and thus people living on such areas are still vulnerable to economic and ecological drought impacts (Vetter, 2009). As a result, this impedes proactive and adequate predictions for developing mitigation strategies (Ruppert *et al*., 2015). Nevertheless, the response of vegetation to environmental pressures depends on the magnitude and frequency of those pressures along with the resilience of the ecosystem disturbed (Harris *et al*., 2014). Some ecosystems are more resilient than others (Vetter, 2009).

3.1.1 Ecological resilience during perturbations

Resilience is commonly defined as the ability of an ecosystem to absorb pressures without shifting to a different state (Sanchez-Pinillos *et al.,* 2016). This ability of the ecosystem to preserve a stable and productive state despite all the pressures is referred to as "ecological stability" or "ecological resilience" (Linstadter *et al*., 2016). It was originally viewed as the time taken by an ecosystem to recover to its steady state after a period of stress (Vetter, 2009; Harris *et al*., 2014). This involves the degree at which the system is able to self-organize, and adapt to the pressure (Elmqvist *et al*., 2003). Resilient ecosystems can be managed very differently from more sensitive ecosystems, and management to maintain ecosystem resilience is very important (Standish *et al*., 2014).

In grassland ecology, resilient grasslands are those that are able to recover and function sufficiently to provide fodder, despite disturbance (Abel and Langston, 2001). Certain studies indicate that African grasslands are highly resilient, since they readily reverse to their initial state after being subjected to intensive grazing (Harrison and Shackleton, 1999). However, other scholars argue that semi-arid grasslands can only recover rapidly provided they are rested from grazing for some time after severe droughts (Danckwerts and Stuart-Hill, 1988). Additionally, the recovery of rangelands depends on grazing history, prior to drought and during the drought period (O'Connor, 1995).

Disturbances that are part of the evolutionary history of the ecosystem normally result in rapid recovery, whereas foreign disturbances induce severe stress, from which the systems may take time to recover or even fail to recover but degrade continuously (Whitford *et al.*, 1999). Moreover, high biodiversity is thought to play a critical role in increasing resilience during perturbations (Perrings and Walker, 1997). Ecosystems may be conservative in their functions and organization, despite the species composition and history. Nonetheless, once the key species are lost or new species invade the areas, such ecosystems can change considerably (Elmqvist *et al*., 2003).

The measurement of ecosystem resilience following the disturbance may provide early warning of the anticipated risks of the ecosystem degeneration to the undesirable state (Whitford *et al*., 1999). It may therefore be an important factor thriving for sustainable natural resources production and ecosystem services (Elmqvist *et al*., 2003). The most pressing questions that could be asked on ecosystems management regarding the resilience could be; how much pressure can an ecosystem absorb before it could shift to a different state and if the ecosystem would be able to recover from such perturbations without any interventions? If well assessed, resilience would then assist managers to decide whether the impacted ecosystems would need intervention to bounce back to the pre-disturbance state or not (Standish *et al*., 2014).

In recent years, research on the assessment of vegetation cover change using satellite-derived data (remote sensing data) has increased popularity around the world (Ji and Peters, 2003; Barbosa *et al*., 2006; Vicente-Serrano, 2007; Harris *et al*., 2014; Zhao *et al*., 2018). Remotely sensed data are valuable for assessing resilience because they often large-scale, temporally frequent measurements of vegetation condition. Combined with field data on climate patterns and socio-economic indicators it can give an integrated picture on the dynamics of socio-ecological ecosystems in changing climates. Knowledge on the vegetation resilience of an ecosystem is critical so as to understand the possible climatic change or anthropogenic impacts on the environment concerned (Harris *et al*., 2014). In this study, NDVI data were used to explore the influence of stocking practices on vegetation cover under different climate conditions.

3.2 History of the vegetation cover change in Lesotho

The Mountain Kingdom of Lesotho generally falls within the grassland biome, which is mostly found on South Africa's high central plateau (Taylor, 2015). Grassland biomes provide a habitat for a diversity of grasses, shrubs, trees, associated fauna and flora (UNDP-GEF, 2009). Information on the historical vegetation cover changes in Lesotho is lacking (van Zinderen Bakker and Werger, 1974), although there are some records on the significant changes in vegetation and their driving forces, documented by the European missionaries and travellers who lived in the country during the colonial era (Hae, 2016). Historically, the

environmental conditions and rangelands management of Lesotho can be traced from the 1700s, when the country was inhabited by the Bushmen (San people). They were hunter-gathers who solely relied on wild plant leaves, roots, and wildlife hunting for living. Their environmental impacts were limited, because they did not settle permanently but moved from one place to the other (Hae, 2016). Moreover, the numbers of indigenous grazing animals in these high-altitude grasslands were probably fairly low (Rushworth pers comm). Periodic droughts would have been a part of this ecosystem at this time, but would probably have had less impact on these nomadic people, who had the option of migrating away from drought-affected areas.

Prior to the 1880's, the Basotho had permanently settled in the lowlands, while the valleys of the foothills were used for summer grazing (Quinlan, 1995). The Basotho occupied large areas of the Caledon River valley, from both the west and east sites (Ntsohi *et al.*, 2014). During that period, there was a free movement of wildlife and livestock, although livestock would be moved seasonally through transhumance from the lowland plains in the cold season to unoccupied mountain pastures in summer (Ntsohi *et al*., 2014). According to Showers (1989), traditional use of land in the country posed insignificant disturbance on the native vegetation. There were a strict set of rules and policies in favor of environmental conservation (Hae, 2016). Firstly, cutting down live trees was prohibited, unless there were specific purposes. Only dead wood and branches were harvested once a year. Secondly, despite the destruction of grasslands for cultivation, each field was bordered with large strips of grassland barriers to prevent water run-off on bare soil (Showers, 1989).

After the 1880 gun war, however, the inhabitants in the west of the Caledon River were forced to move to the mountain region where they settled permanently, thereby disrupting the alternating use of resources between highlands and lowlands (Ntsohi *et al*., 2014). Despite the fact that the inhabitants only settled in the late 1800s, in the early twentieth century, livestock impacts on the grazing lands were pronounced and widespread (Morris, 2017). The 1880s also mark the period when Lesotho was colonized by Britain (Hae, 2016). Upon the arrival of the Europeans, new practices which undermined the traditional land use were introduced (Showers, 1989). New farming systems, agricultural techniques and range management

activities helped initiate land degradation (Hae, 2016). Trees were cut down for carpentry, grasslands tilled for agricultural production and shrubs harvested for fuel.

Unfortunately, trees were still scarce in Lesotho, and were only found along river banks, on stony slopes and in ravines (Showers, 1989). The situation was exacerbated when the demand for wheat, which was highly marketable, increased, while new crops were also introduced. Land management guidelines received less attention and this spared grazing lands, and thus animals were moved to marginal lands and more grassland was converted into croplands (Hae, 2016). Consequently, the removal of shrubs, trees and their litter exposed the land to erosion (Showers, 1989). Further, during this era, new animal species were introduced in the country (Quinlan, 1995). In the early 1900's, the national herd had grown and the adverse ecological impacts were becoming apparent. This led to the introduction of grazing management principles, such as rational grazing and stocking rates, which unfortunately had limited impact (Quinlan, 1995). By 1938, 13% of palatable mountain grasses had been replaced with unpalatable dwarf shrubs due to overgrazing (Morris, 2017).

Over the years, the composition of these species in the grasslands changed substantially, with a decline in vegetation cover (UNDP-GEF, 2009). According to the Ministry of Natural Resources, to date, Lesotho is still dominated by extensive grazing systems of communal lands (MNR, 2000). Stocking rates are estimated to have exceeded the carrying capacity by 75% (Mpiti-Shakhane *et al.*, 2002) to 300% (UNDP-GEF, 2011). Consequently, 25 % of Lesotho's rangelands are considered poor in condition, while the rest are regarded as fair (MNR, 2000). In particular, sheep and goat populations and thus the overall stocking rates have increased substantially in recent years, mainly since both types provide valuable income through wool and mohair sales (Lewis *et al*., 2015).

The interaction of land use changes with extreme droughts was likely to cause changes in ecosystem properties (Hae, 2016). We know that recurrent droughts have always been a part of Lesotho's ecology (as mentioned in the previous chapter), but they are rare events, with limited opportunity to study their ecological effects. Moreover, the changing land use practices – moving from transhumant livestock farming to more permanent farming, and

increasing densities of livestock – will likely interact with the drought. Previous coping mechanisms such as migration are no longer an option; hence people who can, will provide supplementary feed to keep their livestock alive during a drought. The recovery of the vegetation after droughts now in Lesotho thus, has to occur together with intense grazing pressure, which is probably not something that it is adapted for (Walker *et al.*, 1987).

It is thus critical to study the 2015/2016 drought – both to know its impacts to inform better disaster management, and to help prepare for future droughts through more informed rangeland management before, during, and after droughts.

Aim

To assess changes in NDVI over the 2015/2016 drought across Lesotho in relation to prior stocking rates

Objectives:

1. To determine whether prior stocking rates or topography affected the vegetation productivity during the drought.

2. To determine whether prior stocking rates or vegetation type affected the vegetation recovery after the drought.

3.3 Materials and methods

3.3.1 Study area

The study was conducted in Lesotho; a mountainous country situated within the south-eastern region of South Africa (Grundling *et al.,* 2015). It is entirely landlocked by Kwazulu-Natal, Free State and Eastern Cape provinces (Figure 3.1) and lies within the coordinates; 28˚30’ S to 30˚40 S and 27˚00 E and 29˚30 E, covering a total land area of 30 355 km^2 (Fitchett *et al.,* 2016). Lesotho is generally located at high altitude, ranging from 1500m to 3482m above sea level (a.s.l.) (UNDP-GEF, 2011).

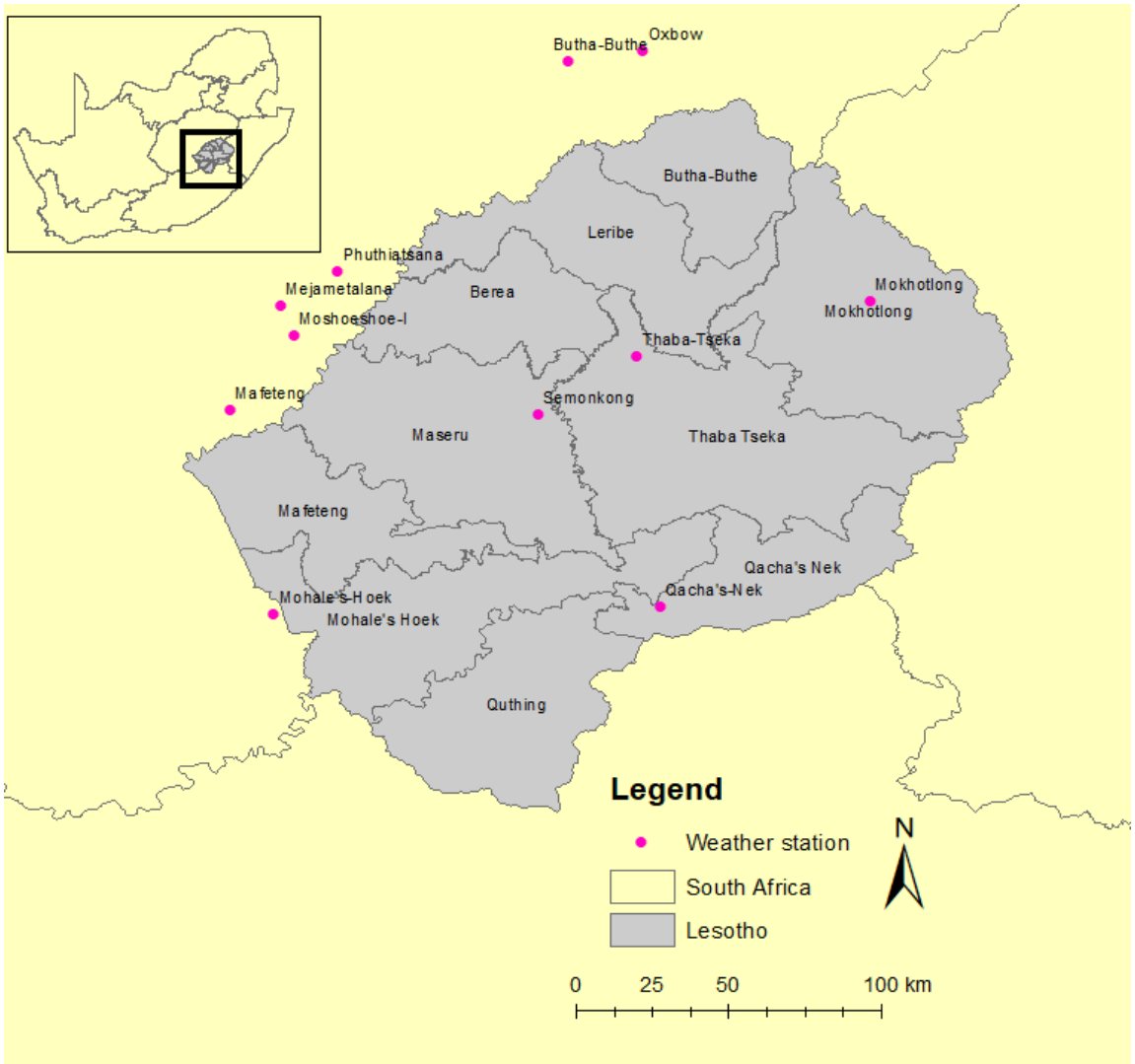

Figure 3.1: Map of Lesotho with the location of weather stations

3.3.2 Topography of Lesotho

The spatial and temporal rainfall distribution in each growing season varies significantly among the agro-ecological zones, and thus determines the suitable agricultural activities in each zone (CPF, 2017). This suggests that each zone experiences distinct vegetation cover change. The country is divided into four agro-ecological zones namely; Mountain region, Lowlands, Senqu River Valley (SRV) and Foothills (Taele *et al*., 2007) as shown from Figure 3.2. According to the Bureau of Statistics (BOS, 2012), these zones are covered in ten administrative districts.

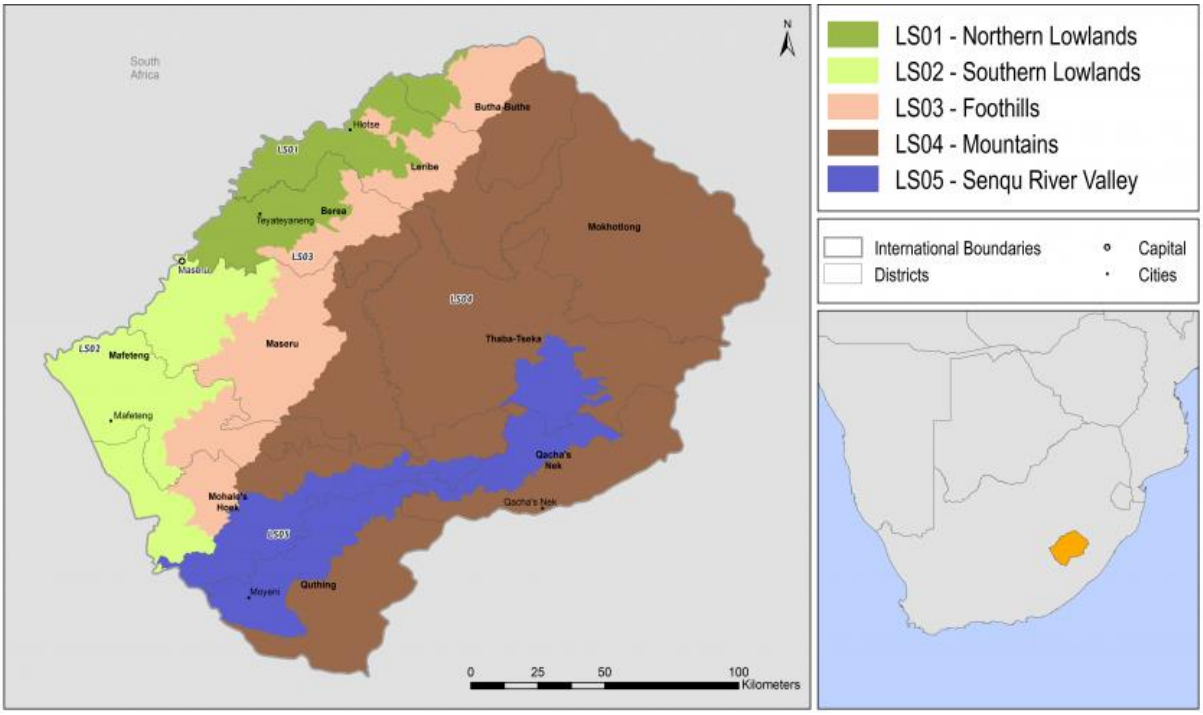

Figure 3.2: The agro-ecological zones of Lesotho (Source: FEWS NET, 2011)

The lowlands region extends from north to south (Maoela, 2010) along the north to western edges of Lesotho (Taele *et al*., 2007). This zone comprises 17 % of the total land area (Taylor, 2015). It lies between the altitudes 1400 m and 1800 m a.s.l. (Majara, 2005), between Caledon River and the foothills of Maluti mountain range (Kobisi and Kose, 2003). According to the Ministry of Natural Resources, northern lowlands are moist; while southern lowlands are moderately dry (MNR, 2000). Northern lowlands have red to brown sandy textured soils, while southern lowlands are clayey (MNR, 2000). The foothills zone is located at an altitude ranging between 1800 m to 2200 m a.s.l. (Majara, 2005). It lies alongside the western range of Maluti mountains, between the lowlands and highlands regions (Kobisi and Kose, 2003) and covers 15% of the country's land area (Taylor, 2015). It is characterized by rich alluvial soils along the valleys while its climate is moist and sheltered (MNR, 2000).

The Senqu River Valley constitutes 9% of the total land area (Taylor *et al.*, 2015). It extends into the southeastern part of the mountain region (Majara, 2005). It is characterized by dry climate with reddish calcareous clay soils, which are not easily penetrated by rainfall (MNR, 2000). The soils in this zone vary greatly from extremely poor to rich, making SRV overall the most unproductive zone in the country (WFP, 2006). This zone is the driest and the most degraded in the country (Kobisi and Kose, 2003). The mountain (Maluti) region occupies

59% (Taylor, 2015) of the central to eastern part of the country (Taele *et al*., 2007). It is situated at an altitude ranging from 2200 m to 3484 m a.s.l. (Majara *et al*., 2005). The zone is characterized by cold and moist climate, with a thin layer of rich black loamy soils which are fragile (MNR, 2000).

3.3.3 Vegetation

There are three chief vegetation zones in Lesotho, namely: the Highveld, Afro-mountain and Alti-mountain grasslands (Majara, 2005). The highveld grassland covers the lowlands as well as the lowest region of Senqu River Valley. In this zone, plant distribution is influenced by the form of the landscape, along with soil moisture, soil depth, soil surface rockiness, as well as grazing intensity. The zone is primarily used for cultivation of maize and wheat, and also for dairy farming (Majara, 2005).

The afro-mountain grassland, which is also referred to as *Themeda Festuca* Alpine Veld (Kopij, 2015) lies at an altitude between 1700 m to 2500 m a.s.l., and comprises the upper region of Senqu River Valley, a large portion of Maluti as well as the foothills (Majara, 2005). This zone has quite uniform grassland, which covers just about half of the country's surface area (Kopij, 2015). Precipitation experienced in this area ranges between 575 mm to 1000 mm, and snow is common in winter (Kopij, 2015). The biome has a variety of plant communities which create a number of habitats (Majara, 2005). Vegetation in this grassland is predominantly used for grazing (Kopij, 2015).

The alti-mountain or afro-alpine grassland is situated in the upper region of treeless alpine mountain (Majara, 2005), just over 2500 m to 3484 m a.s.l (Kopij, 2015). This grassland zone is situated at very high altitudes, where temperatures are extremely low (Majara, 2005). High annual rainfall (over 1000 mm) is typical, with frequent frost occurrence and snow all year round, while temperatures in winter may reach -20˚C (Kopij, 2015). The zone is a significant water catchment area, which is also utilized predominantly for livestock grazing (Majara, 2005).Vegetation in this biome is composed mainly of ericoid shrubs and tussock grass (Kopij, 2015). Generally, in these three grassland zones, there are small patches of forests, woodlands and wetlands. However, these grasslands have been extensively transformed by recent land uses such as livestock grazing, with large parts converted into cultivation areas (Majara, 2005).

3.3.4 Socio-economic conditions of Lesotho

The foothills and the lowlands are the most densely populated zones, with about 70% of the population, while the remaining 30% occupies the Senqu River Valley and the mountain regions (CPF, 2017). Most of the economic activities are confined to the Senqu river valley, foothills and lowlands regions, whilst the mountainous region is more ideal for water resource development, grazing as well as mining (Taele *et al.,* 2007). Diamonds and water are the only important natural resources in the country (Taylor, 2015). The mountainous region was once used for transhumance, although it is now sparsely populated with permanent residents and provides the grazing land to the majority of the country's livestock, especially during summer season (Bisaro *et al.,* 2010) while the western lowlands are intensively used for cultivation (Taylor, 2015).

Despite the increase in urbanization, agriculture still plays a vital role in the livelihoods of the country's population (Ziervogel, 2004). Approximately 50% of the population relies on agriculture as a primary source of income (Taylor, 2015) through livestock farming and subsistence agriculture (Bisaro *et al.,* 2010). The contribution of agricultural sector thus remains critical in determining the socio-economic state of the country (MNR, 2000). Livestock farming remains a significant source of income in rural areas, with goats, sheep and cattle providing more or less the same importance (WFP, 2006).

Initially, agriculture was the most significant contributor to the country's GDP (Obioha, 2010). However, in recent times, agricultural production is low and continues to decline, mostly due to changes in climate (Huber-Lee *et al.,* 2016), coupled with the mountainous topography of the country, severe soil erosion as well as limited arable land (MNR, 2000). In particular, drought prevalence in the 1990's as well as early 21st century considerably affected the sector's contribution to GDP (Obioha, 2010). Climate has therefore been intricately related to the increasing poverty in the country (MNR, 2000).

Apart from agriculture, remittances play a vital role in the country's economy (Nalane *et al.*, 2012). Lesotho is categorized under countries that depend heavily on migrant remittances in

the world (Crush *et al*., 2010) with the remittance inflows contributing massively to foreign exchange, accounting for 44% of the GDP in 2006 , to 17% in 2014 (Truen *et al*., 2016). South Africa has been the backbone of Lesotho remittances, particularly through mining industry, where a large number of Basotho men are employed, although these numbers have decreased dramatically in recent years, from almost 65 000 in 2000 to only 27948 in 2015 (Truen *et al*., 2016). Since the 1990's the migration patterns from Lesotho to South Africa have changed, with decreasing opportunities for male workers while the number of female migrants has increased, of which half of them are domestic workers, and the rest working in informal sectors, self-employed businesses, commercial farm-work, skilled manual work as well as professionals (Crush *et al*., 2010). In most of the households, remittances are the only source of income (Nalane *et al*., 2012). Most households living without these migrant remittances are worse off, compared to those that have access to them (Crush *et al*., 2010: Nalane *et al*., 2012).

3.3.5 Data used

3.3.5.1 Livestock data

Livestock data for cattle, sheep and goats populations from the ten districts of Lesotho for the years 2009/2010, 2011/2012, 2012/2013 and 2015/2016 was solicited from the Lesotho Bureau of Statistics (BOS). Only certain years were chosen for analysis, since the livestock data was fragmented. The data were available in report format and were transposed into a database and stocking rates calculated (LSU/ ha). These stocking rates were then compared among the different districts in the country.

3.3.5.2 Remote sensing data

NDVI data served as the key indicator of land cover change in this study. The 8 day composited products of MODIS (MOD09A) surface reflectance NDVI images of 1 km resolution from 2001-2017 were used in this study to analyze the impact of drought on vegetation in the country. They were obtained from the Council for Scientific and Industrial Research (CSIR) in Pretoria. These images were spatially continuous, fairly cloud-free, with sufficient temporal resolution to analyze vegetation dynamics. Unfortunately the data

provided did not cover some of the districts on the southern region of the country (part of Mohale's Hoek and Qacha's Nek districts as well as the entire Quthing district).

3.3.5.3 Altitude

Topographical data was acquired to test any correlation between NDVI and altitude in different districts of Lesotho. The altitude map from the digital elevation model (DEM) for Africa was downloaded from USGS EarthExplore (https://earthexplorer.usgs.gov), and then clipped to Lesotho's spatial extents as a shapefile in ArcGIS, so as to identify the zonal statistics of the country's altitude per district.

3.3.6 Methods

3.3.6.1 Analysis of Livestock data

Changes in livestock populations

The livestock populations for cattle, sheep and goats were presented on bar charts to determine the distribution of livestock in different districts. Livestock populations were then plotted using line graphs to identify their trends in different years.

Stocking rates calculation

In rangelands, *prior* knowledge of stocking rates is essential for investigating grazing impacts on vegetation cover (Green *et al*., 2016). From this study, the analyzed stocking rates were for the years; 2009/2010, 2011/2012, 2012/2013 and 2015/2016. It was assumed that all the animals were confined within the boundaries of their districts' grazing areas. All the districts in the country were analyzed in this study. Livestock populations were then converted to large stock units (LSU) so as to aggregate cattle, sheep and goats populations to a standardized value. The conversion factors used were 0.17 for small stock (sheep and goats) and 0.8 for cattle (Vetter and Bond, 2012). There were no specific weights for the recorded livestock, so it was assumed that all the animals' live body weight was equivalent to the

conversion factor for each species. For instance, to convert cattle populations to LSU, a total number of cattle in each district was multiplied by 0.8, while for small stock, it was multiplied by 0.17.

Stocking rates were calculated as the total number of livestock from each district per a given grazing area. In determining the grazing area in each district, the layer for land cover map of Lesotho (with a resolution of 30m by 30m) was downloaded from RCMRD GeoPortal (http://geoportal.rcmrd.org/layers/servir%3Alesotho_sentinel2_lulc2016), and its zonal statistics presented on ArcMap in ArcGIS software. From the information, built-up areas, open water and bare areas were subtracted from the total area of each district. However, woodlands and croplands were included as part of the grazing areas, since animals do graze in these areas. In Lesotho, during the growing season, animals are excluded from cultivated areas but after harvesting in winter, they are seen in numbers in the fields, feeding on stover.

After identifying the grazing areas in all these districts, stocking rates (LSU/ha) were then calculated as the large stock unit (LSU cattle + LSU sheep +LSU goats) in each district / grazing area (ha). The calculated stocking rates were then presented on the maps using ArcMap in ArcGIS, so as to demonstrate the variability of these stocking rates across districts in different years.

3.3.6.2 NDVI analysis

Annual NDVI maps were calculated from the 8-days composite NDVI images using raster and rgdal package in R. To derive these annual NDVI images, 8-days composite images from July to June (rainfall year) images were summed up. A rainfall year for NDVI analysis was used, so that the results could correspond with rainfall analysis from the previous chapter. From 2001-2017, 16 annual NDVI images were generated. Those 16 images were then averaged to create the mean NDVI image over the 16 years. From each of those 16 images, the NDVI value for each annual image was subtracted from the mean NDVI value to assess whether vegetation greenness in that year was higher or lower than average. This allowed for the comparison of areas with lower productivity with those of higher productivity on a common measure (difference from the mean).

3.3.6.3 Altitude vs. NDVI analysis

To determine the relationship between altitude and NDVI from different districts, the NDVI difference maps for 2015/2016 and 2016/2017 were extracted using R. Built-up areas, open water, bare areas and croplands were then deducted from the total land area in each district. The zonal statistics from each map were then extracted to obtain the median difference of NDVI by district. Thereafter, the extracted NDVI values in each year were regressed against the altitude to examine if there is any correlation between the two in different districts during drought (2015/2016) or after drought (2016/2017). However, Mohale's Hoek, Quthing and Qacha's Nek were excluded from this analysis because their NDVI information was either incomplete or completely not covered.

3.3.6.4 Stocking rates vs. NDVI analysis

To investigate the influence of stocking rates on vegetation during and after drought, maps showing the NDVI difference for 2015/2016 drought year and 2016/2017 (after drought) were extracted from R. Built-up areas, open water, bare areas and croplands were then deducted from the total land area in each district. The zonal statistics from each map was then extracted to obtain the median difference of NDVI by district. Thereafter, a regression analysis was conducted whereby these extracted values of differences in NDVI per district were plotted against the 2012/13 stocking rates to determine the influence of heavy stocking on vegetation cover during and after drought. Due to the limited livestock data, the latest pre-drought livestock data (which was 2012/13 in this case), was used for both analyses. Because the livestock data was at the scale of district, a lot of the spatial variability in the NDVI dataset had to average and also work at a district level.

3.4 Results

3.4.1 Livestock populations in Lesotho

The distribution of cattle, sheep and goats in Lesotho for the years, 2009/2010, 2011/2012, 2012/2013 and 2015/2016 is presented in Figure 3.3. It is observed from the figure that generally, sheep populations were notably higher than other species, followed by goats and, finally, cattle. In 2009/2010, Thaba-Tseka had the highest number of sheep, followed by Maseru and then Mohale's Hoek, while Berea had the lowest population. The highest number of goats was observed in Maseru, Mohale's Hoek and Thaba-Tseka respectively, while Berea had the lowest number.

Although the cattle population was relatively low in the country, Maseru, Leribe and Berea districts had higher numbers of cattle, while low cattle population was observed in Quthing. In 2011/2012, the sheep population increased significantly in Mokhotlong, Maseru and Leribe districts. There was a slight increase in goat numbers, while cattle population was largely stable. In the following year (2012/2013), goats' numbers then increased substantially in Maseru district, while there were slight changes with other livestock species in other districts. From 2012/2013 to the 2015/2016 drought year, the sheep population had increased in most of the districts, although there was a significant decrease in Mokhotlong and Maseru. Goat numbers also decreased substantially in Maseru, while there was no significant change in cattle numbers. It can be noted that the effects of the drought are not yet apparent in the 2015/2016 livestock data.

Figure 3.3: Livestock population in Lesotho

3.4.2 Livestock population trends

Figure 3.4 (a) portrays changes in the distribution of cattle, sheep and goats for different years in the country (all districts combined). Generally, cattle and goats show a decreasing livestock trend in recent years, while there is a slight increase in sheep production. From 2009/2010 to 2011/2012, the cattle herd decreased by 9.4% and decreased further by 3.4% in the following year (2012/2013). Between 2012/2013 and 2015/2016, there was a further decline of cattle stock by 9.9%. In sheep production, there was a significant increase in the population between 2009/2010 and 2011/2012 (+26%). The population then declined by 9.4% between 2011/2012 and 2012/2013. However, between 2012/2013 and 2015/2016, there was a slight increase in sheep population (+1.6%). The goat population also increases between 2009/2010 and 2011/2012 (+7.8%). The population then declined dramatically in the following year (11.1%). From 2012/2013 to 2015/2016, goats population further decreased by 16.5%.

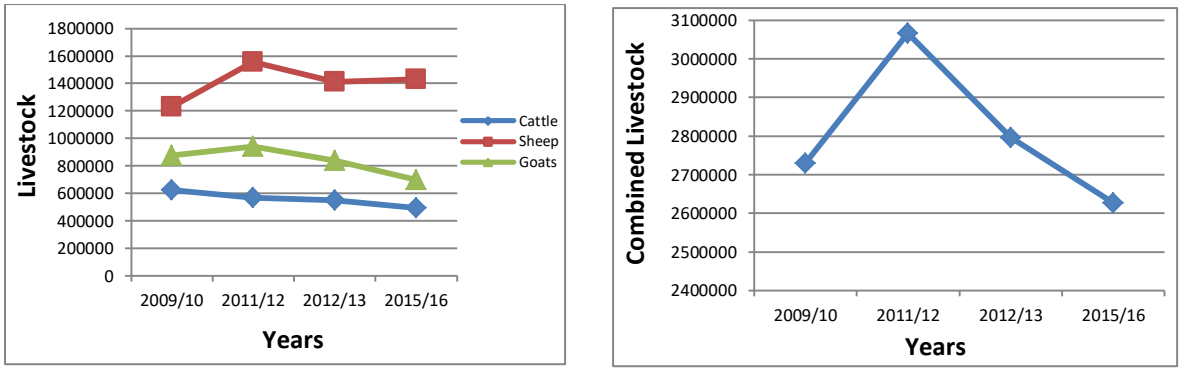

Figure 3.4: Livestock populations for: (a) different livestock types and (b) total livestock in 2009/2010, 2011/2012, 2012/2013 and 2015/2016.

Based on the combined populations for cattle, sheep and goats (Figure 3.4 b); there was a sharp increase in livestock between 2009/2010 and 2011/2012 (+12.3%). These populations, however, declined significantly from 2011/2012 to 2012/2013 (- 8.8%), which declined further by 6.1% between 2012/2013 and 2015/2016 period.

3.4.3 Stocking rates in Lesotho

Figure 3.5 demonstrates changes in stocking rates for the years 2009/2010, 2011/2012, 2012/2013 and 2015/2016. From the figure, it may be inferred that stocking rates varied from one district to the other in different years. Generally, districts in the lowlands region (from north, along the western edges to southern region) were more heavily stocked than the highlands region (located at the eastern region). In 2009/2010, stocking rates at part of Senqu River Valley (SRV) and the lowlands (Butha-Buthe, Leribe, Berea, Maseru, Mafeteng and Mohale's Hoek) ranged from 0.3- 0.4 LSU/ha, while at the other region of SRV and the highlands, they ranged from 0.2-0.3 LSU/ha. Berea and Mafeteng were the most heavily stocked districts, while Quthing, Mokhotlong and Thaba-Tseka were the least heavily stocked districts. Further, in 2011/2012, Leribe, Berea and Maseru were the most heavily stocked districts, with the stocking rates ranging from 0.4-0.5 LSU/ha, whereas Quthing, Mokhotlong and Thaba-Tseka were least heavily stocked, with 0.2 LSU/ ha. The most heavily stocked districts in 2012/2013 were Berea and Maseru, while Butha-Buthe, Quthing, Qacha's Nek, Mokhotlong and Thaba-Tseka were relatively less stocked. Berea was still identified as the

most heavily stocked region in 2015/2016, whereas Mokhotlong was the least heavily stocked[2].

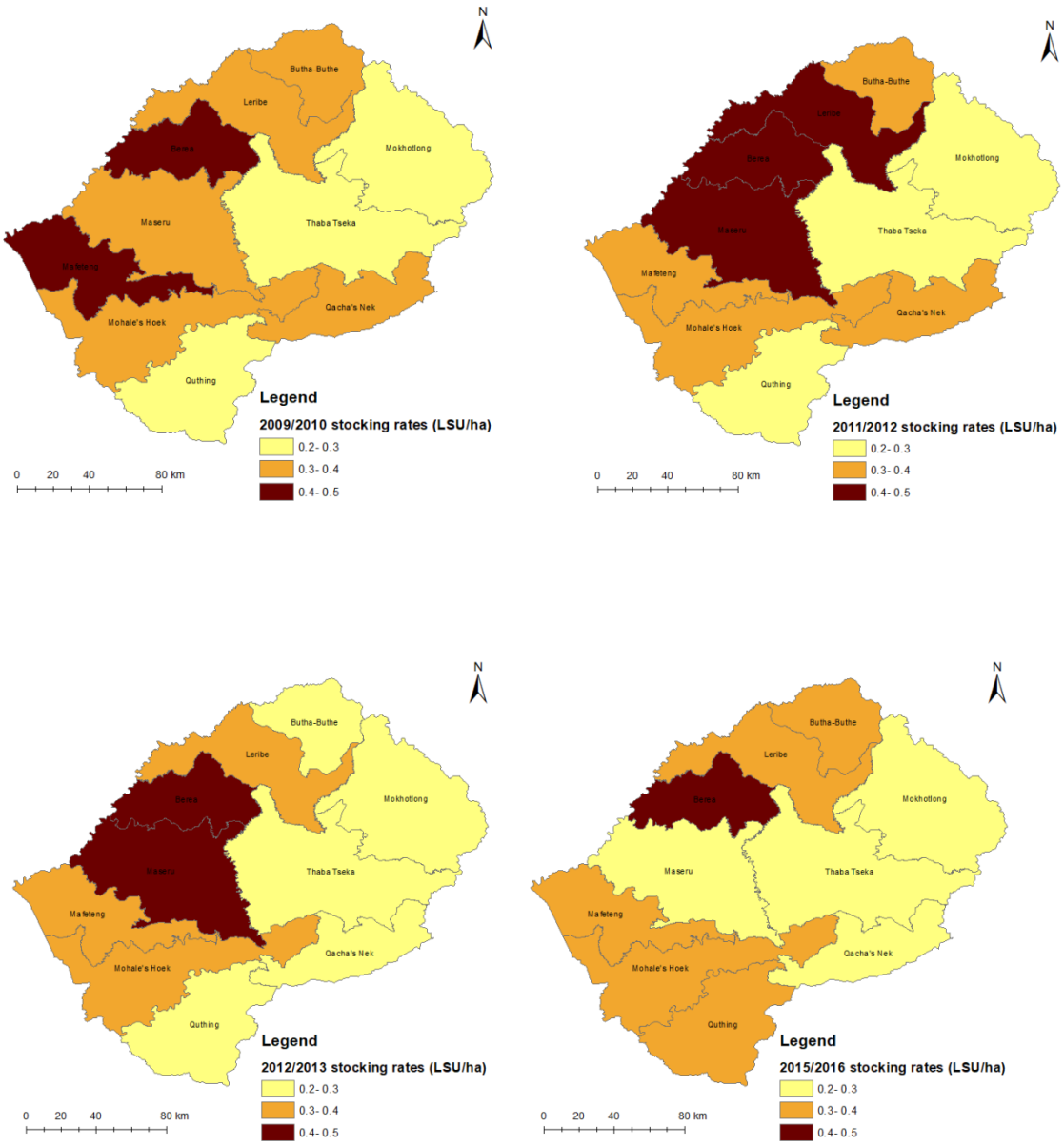

Figure 3.5: Stocking rates at different districts of Lesotho in four different years

Based on the overall stocking rates in the country in different years, the results suggest that stocking intensity has been constant between 2009/2010 and 2015/2016. In 2009/2010,

[2] N.B: High values mean high stocking rates

theoverall stocking intensity in the country was around 0.3 LSU/ha, and the same value was obtained in the subsequent years (2011/2012, 2012/2013 and 2015/2016).

3.4.4 Vegetation cover change in 2001-2017 and its resilience to drought pressure

The examination of the NDVI series from 2001- 2017 showed changes in vegetation cover patterns in different years (Figure 3.6). Green shadings (with high values) denote areas with dense vegetation cover, while yellow to peach shadings with low values indicate areas with low vegetation cover. From 2001/2002 to 2003/2004, dense vegetation dominated the landscape, more especially from the north to the central region of the country. In contrast, there was relatively lower vegetation cover in 2004/2005, particularly towards the south in the western edges of the country, which intensified in the following year (2005/2006). However, in 2006/2007, vegetation cover slightly recovered, although there were still some visible yellow to peach patches which gradually recovered in the following years (2007/2008-

2012/2013). Nonetheless, in 2013/2014, vegetation cover slightly reduced and this reduction progressively intensified in the subsequent years until 2016/2017. From the figure, it can be inferred that 2015/2016 was the most unproductive year, though vegetation in 2014/2015 and 2016/2017 years was also notably low. It can be noted that in thus study, no species composition was collected so the “replacement” vegetation may just be inedible forbs and annual, wiry grasses (which is often the case in degraded lands and after periods of drought).

The difference from the mean for each year from 2001-2017 is presented in Figure 3.7 to demonstrate the resilience of vegetation after pressures. Regions with zero or positive values indicate that the vegetation was less affected by drought, whereas regions with very low difference values were heavily affected by drought. The resilience of different vegetation types in Lesotho is indicated by how quickly they recovered to mean values of NDVI after the drought. During the first three years (2001/2002-2003/2004), vegetation in the country was intact (not affected by droughts). However, after a slight decline in vegetation was observed in 2004/2005, more especially at the western edges of the southern lowlands, it failed to recover in 2005/2006 but further deteriorated.

While some regions were able to recover in 2006/2007, vegetation failed to “bounce back” in most areas, as patches of negative NDVI difference values were still dominating. In the subsequent years (2007/2008-2012/2013), vegetation in most areas had fully recovered. In 2013/2014, a slight decline was observed and it gradually intensified in the following years (2014/2015-2016/2017). Even after drought (i.e 2016/2017), vegetation in Lesotho failed to recover, as the region was still characterised by low vegetation cover. Generally, throughout the years of study (2001-2017), it was noted that the western edges of the southern lowlands were less vegetated relative to other regions.

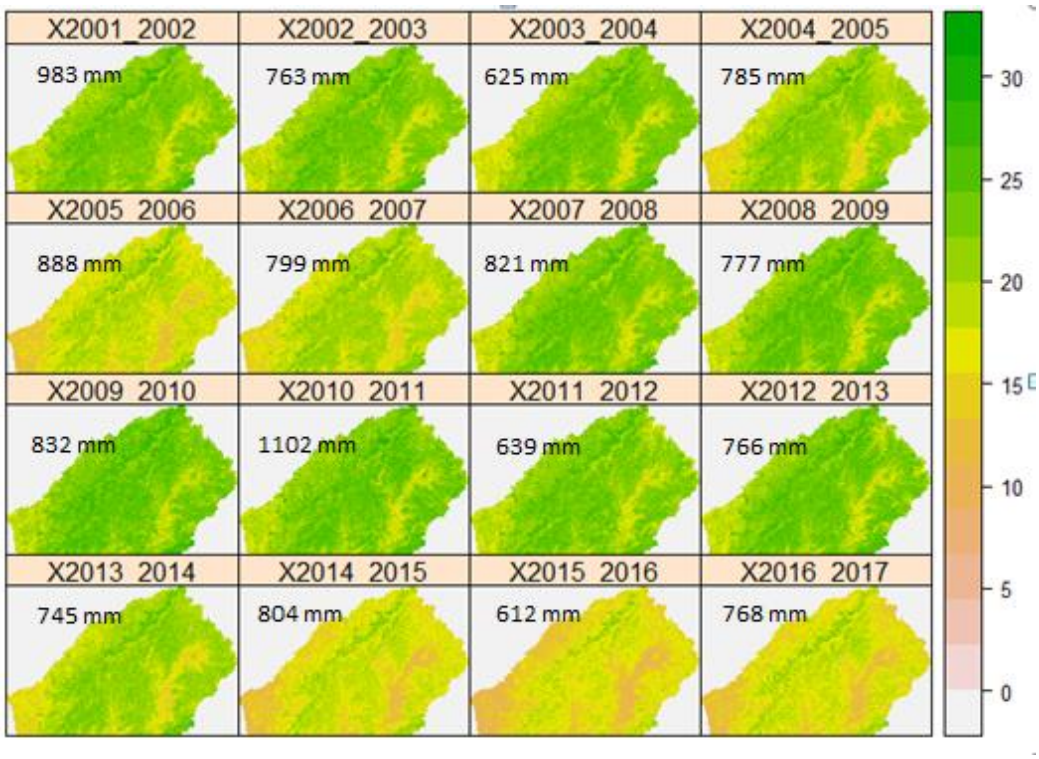

Figure 3.6: Annual (July-June) NDVI trends from 2001-2017 and the rainfall in Lesotho

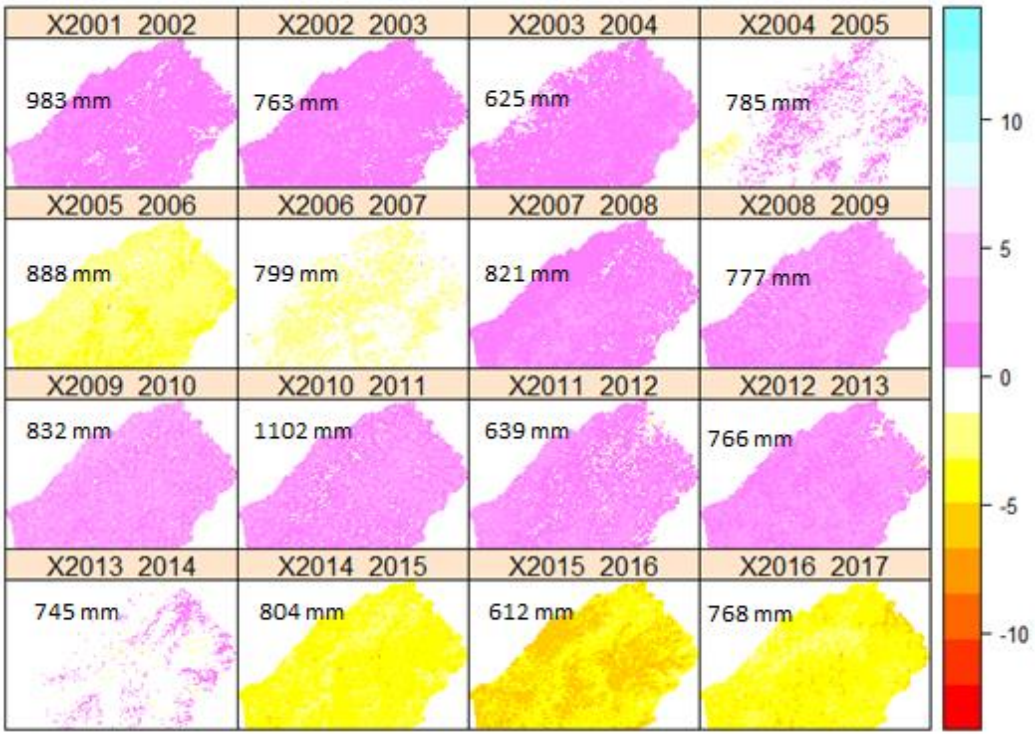

Figure 3.7: The difference from the mean value each year of a 2001-2017 mean NDVI dataset in Lesotho and the rainfall.

3.4.5 The impact of altitude on vegetation cover change

The results on Figure 3.8 present the relationship between altitude and vegetation change during and after drought. In 2015/2016, the influence of altitude was insignificant (F=2.139, P=0.203). The model on this regression explained only 30% of variation in the data (R^2= 0.30), an indication that the model was not good. Inversely, the effect of altitude on vegetation cover after the drought year was marginally significant (F=5.903, P=0.059), while 54% (R^2=0.54) of the variation in the data was explained by the model. From the normal Q-Q plots on both figures (Figures 3.9 and 3.10); the data did not follow a normal distribution. Further, on the residuals vs. leverages plots, there were several influential observations (outliers beyond Cook's distance), which affected both regression lines. Nonetheless, the overall pattern showed that low altitude areas (Mafeteng, Berea and Maseru) had large NDVI differences during the 2015/2016 drought, while high altitude areas (Thaba-Tseka and Mokhotlong) had relatively small NDVI differences. Conversely, after drought (2016/2017), low altitude areas (Mafeteng and Maseru) had low NDVI differences whereas high altitude areas had large NDVI differences (Butha-Buthe, Thaba-Tseka and Mokhotlong respectively)

i.e. low altitude areas were more affected during the drought, but high altitude areas were slower to recover.

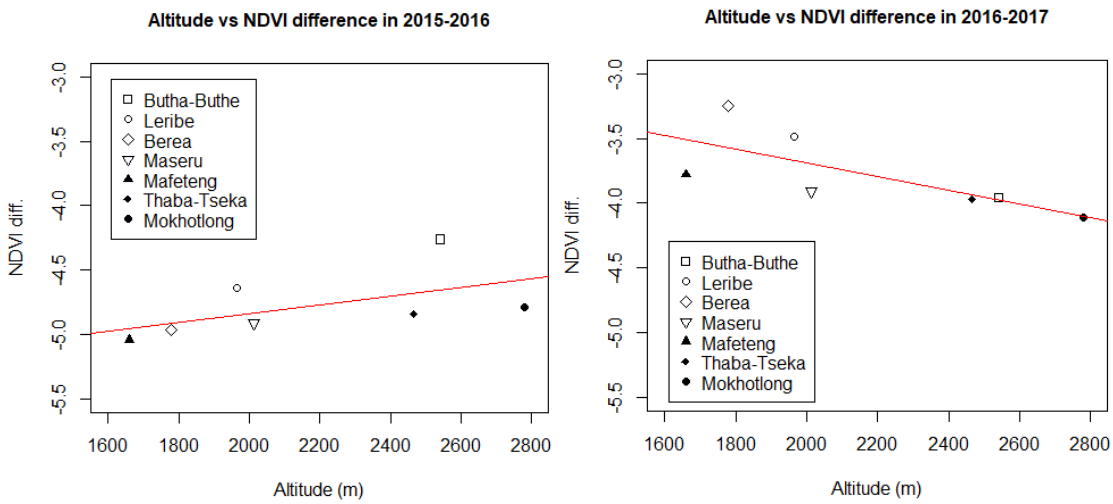

Figure 3.8: The relationship between altitude and vegetation cover change during the 2015/2016 drought and after drought (2016/2017).

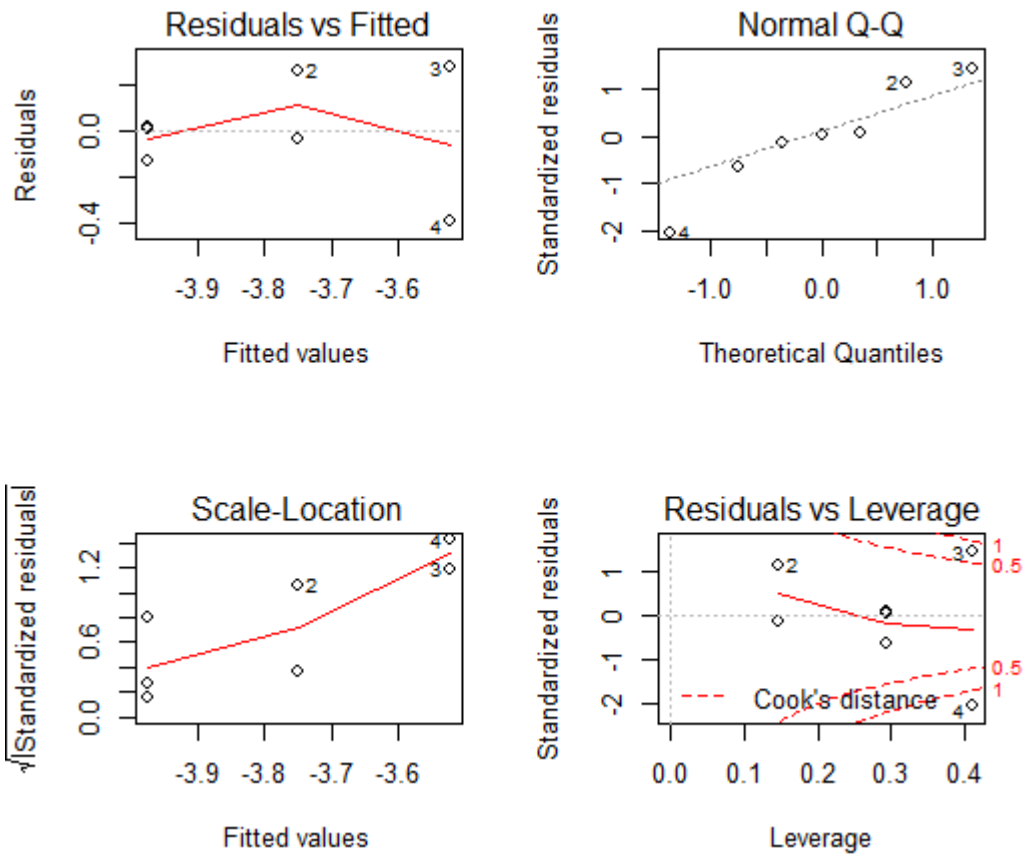

Figure 3.9: Summary regression plots of altitude versus vegetation cover during 2015/2016 drought.

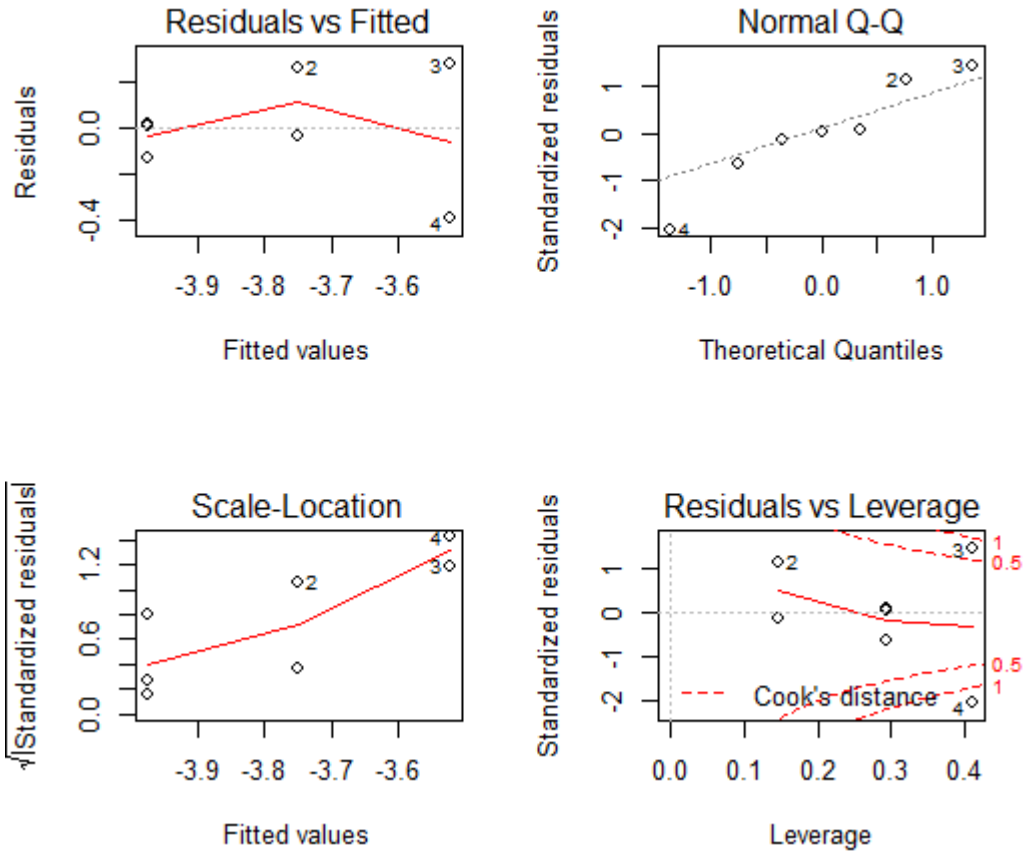

Figure 3.10: Summary regression plots of altitude versus vegetation cover during 2016/2017.

3.4.6 The influence of heavy stocking on the vegetation response during drought and the recovery of vegetation after drought.

From Figure 3.11, the grazing effect on vegetation cover during the 2015/2016 drought was not significant (F= 2.017, P=0.215). Only 29% of the variation in the data was explained by the model, which implies that the model was not strong (R^2= 0.29). Likewise, there was no significant effect of stocking rates on vegetation cover after the drought year (F=3.997, P=0.102), and 44% (R^2=0.44) of the variation in the data was explained by the model. Based on the normal Q-Q plots from both figures (Figures 3.12 and 3.13); the data did not follow a normal distribution. There were rather several influential observations (outliers beyond Cook's distance) on the residuals vs. leverages plots, which greatly influenced both regression lines. There regression line however, showed that areas with big NDVI difference were relatively overstocked (Mafeteng, Berea and Maseru respectively) while those with relatively small NDVI difference were less stocked during drought (Thaba-Tseka and Mokhotlong). In contrary, after drought, areas with small difference in NDVI were

intensively stocked (Berea, Leribe, Mafeteng and Maseru) while districts with large difference in NDVI were less stocked (Butha-Buthe, Thaba-Tseka and Mokhotlong).

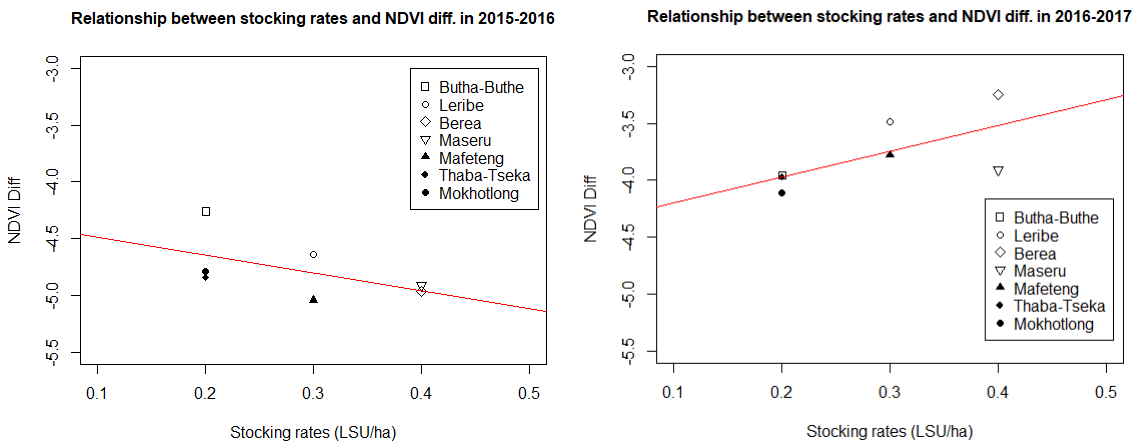

Figure 3.11: The relationship between stocking rates and vegetation cover change during the 2015/2016 drought and after drought (2016/2017).

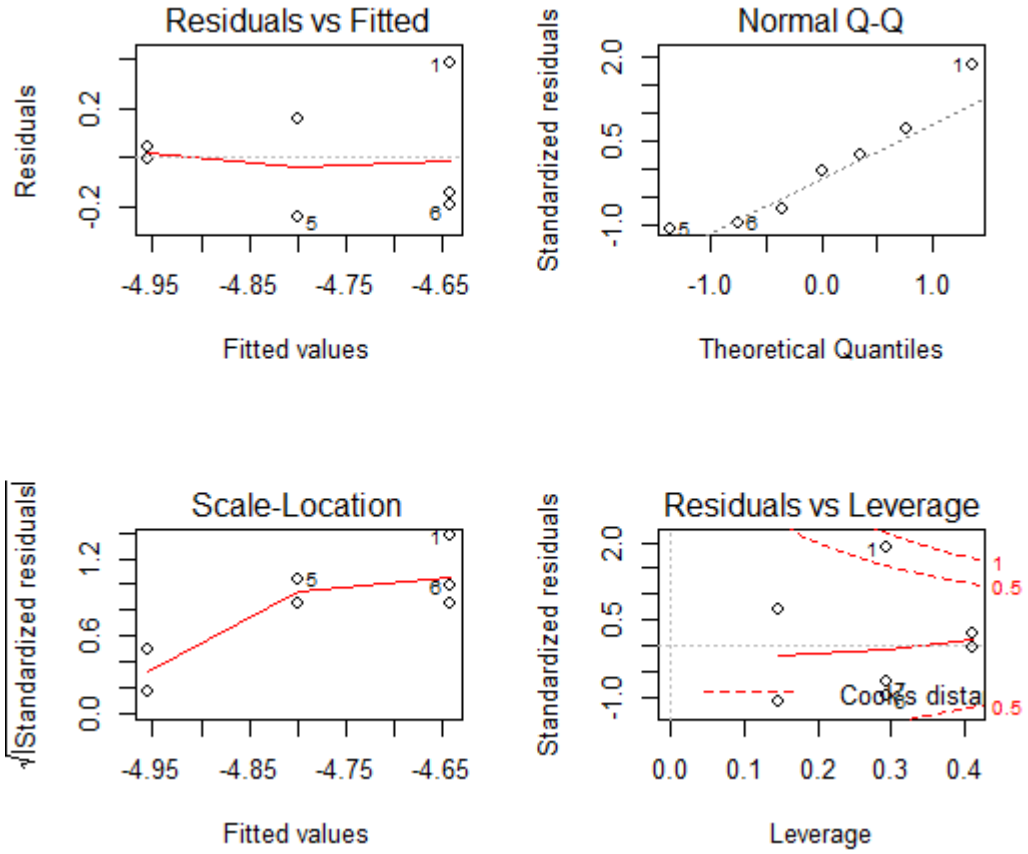

Figure 3.12: Summary regression plots of stocking rates versus vegetation cover during 2015/2016 drought.

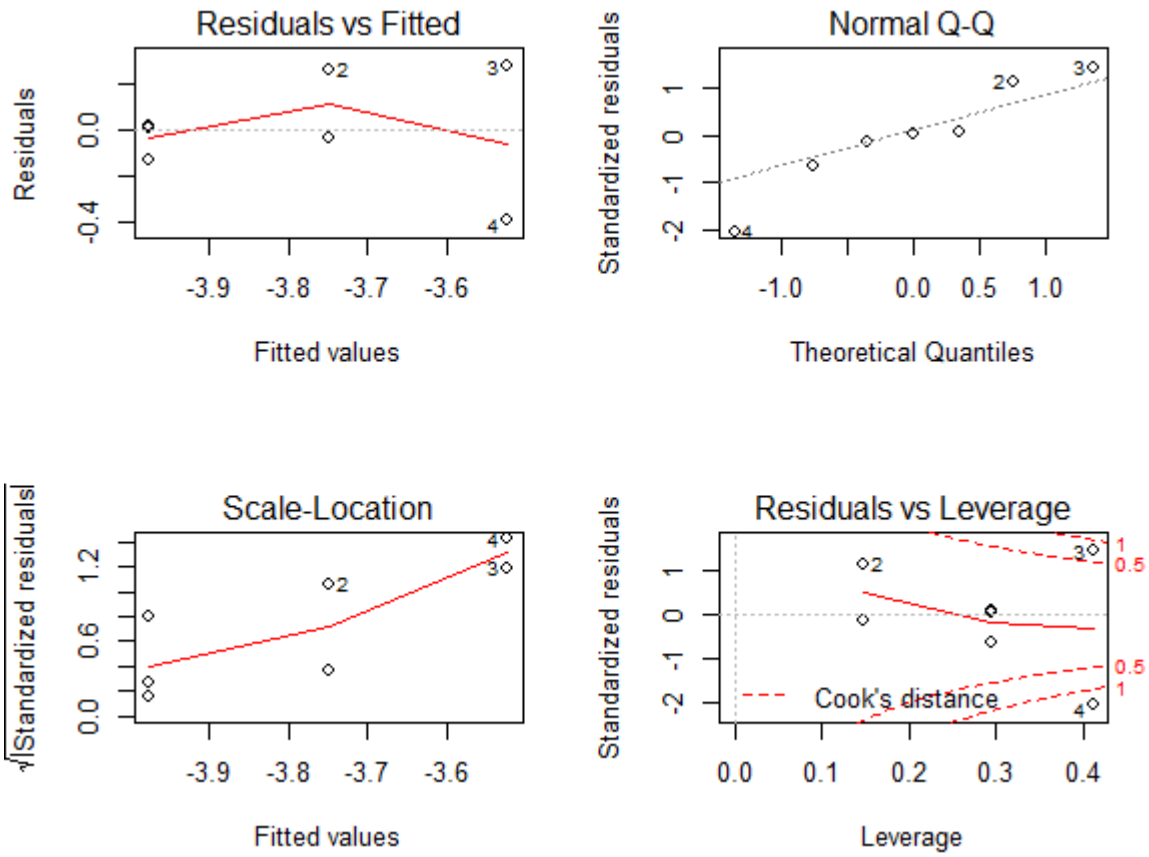

Figure 3.13: Summary regression plots of stocking rates versus vegetation cover after drought (2016/2017).

3.4.7 Does elevation have any effect on stocking densities in Lesotho?

Since both altitude and stocking rates showed similar patterns in their regression analyses against NDVI difference, these variables were plotted against each other to determine their relationship. A highly significant relationship was identified between these two (F= 8.726, P=0.032). In addition, 64 % of data variation was explained by the model, an indication that the model was indeed good (R^2= 0.64) (Figure 3.14). Although the normal Q-Q and the residuals vs. leverages plots show that the data did not follow a normal distribution but had some influential outliers (Figure 3.15), low altitude areas were generally heavily overstocked while high altitude areas were relatively less overstocked. This makes it difficult to assess what the main driver of drought impacts was: altitude or stocking density.

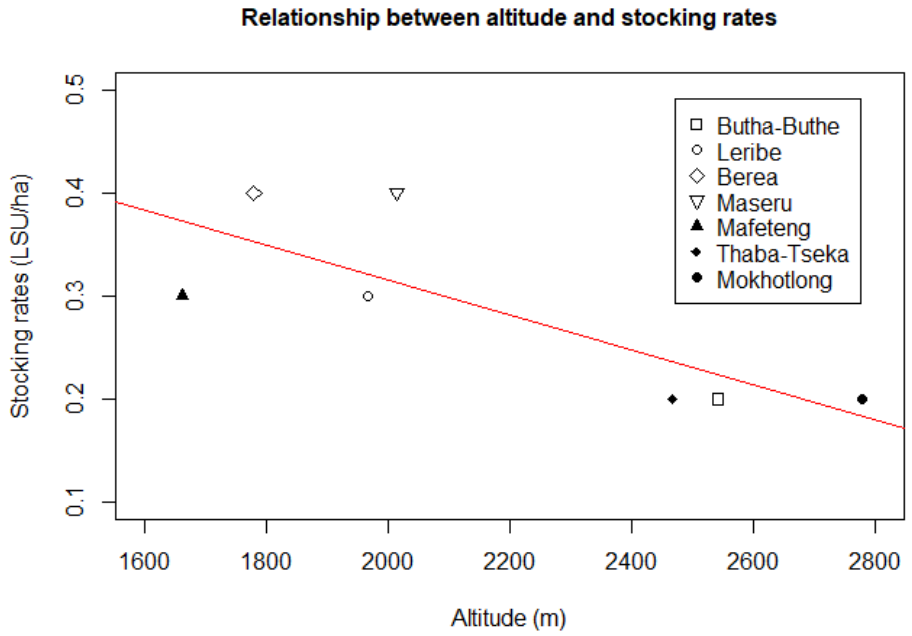

Figure 3.14: The influence of elevation on livestock populations in Lesotho

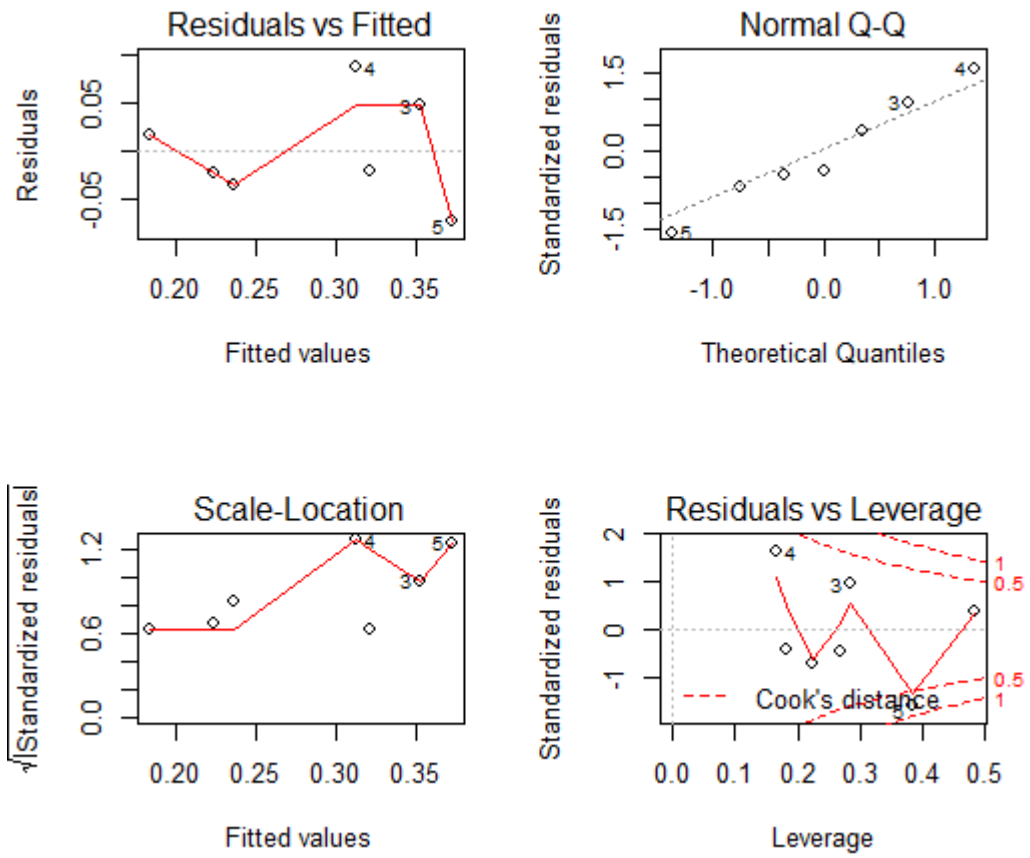

Figure 3.15: Summary regression plots of elevation against stocking rates.

3.5 Discussion

3.5.1 Vegetation conditions and changes in different regions

A number of factors influence regional differences in vegetation cover. As mentioned earlier, grazing intensity and rainfall variability are the two important determinants of structure and composition of grasslands communities (O' Connor, 1993). They both affect forage production in semi-arid rangelands (Fang *et al*., 2014), although rainfall has more pronounced impacts than grazing (O'Connor, 1994). In this study, in addition to the effects of stocking rates and drought on vegetation cover, the topographical influence was also investigated.

3.5.2 Temporal and spatial patterns of livestock and stocking rates

It was observed that livestock populations declined over years, even though the short time period of data available made it difficult to assess whether this was a general trend. Although the populations increased sharply initially (between 2009/2010 and 2011/2012), there was a significant decrease between 2011/2012 and 2012/2013 and a further decrease in 2015/2016. The decline in livestock population after 2011/2012 could have been triggered by the extensive seasonal drought which occurred in 2011/2012 (Chapter 2, Figure 2.7). The situation might have further intensified in 2015/2016 due to the severe 2015/2016 droughts experienced, hence the further decrease in livestock. Nonetheless, based on the recommended carrying capacity of 8 hectares per animal unit (AU) by the Ministry of Forestry and Land Reclamation (MFLR, 2014), the results from this study support the suggestion that Lesotho rangelands are generally overstocked.

It can be inferred that lowlands region was heavily stocked, with the rates ranging from 0.3 LSU/ha to 0.5 LSU/ha, whereby Berea district was significantly over-stocked over the years under study, while the highlands region was relatively less stocked, despite the region being characterized by high livestock numbers. This hypothesis was statistically verified by the regression analysis. Such a finding might be ascribed to the fact that lowlands occupy a

smaller area than the highlands, with fewer rangelands available (Taele *et al*., 2007). Besides, low altitude areas of Lesotho are densely populated, as industrialization is confined to this region, as mentioned earlier.

3.5.3 Interannual variability in vegetation greenness in Lesotho

The overall results from Chapters 2 and 3 show a strong relationship between vegetation cover and rainfall variability. Some years were characterized by significant decline in vegetation cover, whereas with other years, vegetation cover improved. The declines were strongly associated with the occurrence of two serious droughts – but notably lowered vegetation cover persisted well after the droughts had broken (Chapter 2, Figures 2.6 and 2.7; and chapter 3, Figure 3.6). Vegetation declines in rangelands during droughts have been widely reported in southern Africa region (Danckwerts and Stuart-Hill, 1988; O'Connor, 1993; 1994; O'Connor and Roux, 1995; Rothauge, 2000; Archer, 2004), as well as other parts of the world (Heitschmidt *et al*., 2005; Macon *et al*., 2016). As vegetation declines, this may lead to moderately stocked rangelands being heavily stocked during droughts, depending on how much livestock death occurs (Thurow and Taylor, 1999).

Over the entire 17 year period, the interannual variability in rainfall shown in Chapter 2 resulted in interannual variability in vegetation greenness. Overall, the vegetation greenness was influenced by the occurrence of summer drought than annual drought, which is understandable in this seasonal system. Accordingly, a small drought in 2003/2004 which affected vegetation in 2004/2005 can be identified, as well as the more extreme drought which clearly started to affect vegetation in 2014/2015 as well as in the main drought year of 2015/2016. In both instances the below-average vegetation greenness remained for at least a year after the drought broke, indicating a lag effect in the recovery of the grasslands. Low altitude rangelands were more affected during the 2015/2016 drought than the high altitude areas. However, after drought, a slower vegetation recovery was observed in the mountain region than in the lowlands.

3.5.4 Did stocking rates affect drought response in Lesotho?

A key finding of this study was that no significant relationship between the stocking rates and vegetation cover change was identified during the 2015/2016 drought year, and after drought. Even though the lowlands region was heavily stocked, especially the northern to central lowlands compared to the highlands, the influence of stocking rates on vegetation cover in this zone was not detected. A pronounced decline in vegetation in the whole country was rather more influenced by poor rainfall than the stocking rates.

Using only annual stocking rates, precipitation and NDVI averages to determine changes in vegetation was clearly not a perfect predictor in this study, since the seasonal impacts on perennial grasses were ignored. Without doubt, rainfall variability had stronger influence on vegetation cover change, while grazing impacts in the time period under study perhaps had less of an influence. The dominance of rainfall variability over grazing impacts is consistent with several previous studies (O'Connor and Roux, 1995; Ruppert *et al*., 2015; Bodner and Robles, 2017), even though certain studies have showed that intensive grazing during droughts aggravates droughts impacts on vegetation (Fynn and O'Connor ,2000; Ruppert *et al.*, 2015).

According to O'Connor (1994), in rangelands dominated by perennial grasses, high grazing intensities can increase the mortality of grass tussocks during droughts, thereby hindering the establishment of seedlings after droughts, consequently delaying grassland recovery (Bodner and Robles, 2017). In their study, Fynn and O'Connor (2000) found out that intensive grazing during droughts induced substantial declines in perennial grass species such as *Themeda triandra*. This implies that sustainability in rangelands should be prioritized through improved livestock management, by ensuring that grazing pressure is maintained at moderate level (Liao and Clark, 2018). Some studies propose the adjustment of stocking rates depending on the existing condition of the grazing land as one of the alternative management strategies for counteracting drought impacts (Diaz-Solis *et al*., 2009).

3.5.5 Explaining regional differences in drought response

Certain studies not only attribute spatial changes in vegetation to climate but also to the correlation between both climatic and topographic factors (Pinder *et al*., 1997; Carmel and Kadmon, 1999). According to Pinder *et al*., 1997, all types of vegetation in different elevation intervals are influenced by the topographic positions. In their studies, Pinder *et al*., (1997) and Carmel and Kadmon (1999) found a significant effect of topography on vegetation structure. In this study however, there was no significant relationship identified between the elevation and vegetation cover change, both during and after drought. In fact, neither altitude nor stocking rates were good predictors of drought response or drought recovery in different regions of Lesotho. However, they did show the same general trend, which is that low altitudes areas were more overstocked than high altitude areas (Figure 3.14). The most overstocked, low altitude districts included Berea, Maseru, Leribe and Mafeteng whereas Butha-Buthe, Thaba-Tseka and Mokhotlong districts (in that order), located at the higher altitude were relatively less overstocked.

3.5.6 Did stocking rates affect drought recovery in Lesotho?

From the study, it was discovered that 2003/2004 drought had more effect on the vegetation productivity in the following year (2004/2005) than in the drought year, and the landscape took two years to recover from this moderate drought back to average greenness in 2007/2008. Mild droughts can have surprisingly large socio-economic and ecological impacts (Vetter, 2009). It is therefore, not surprising that there was very little recovery one year after a more severe drought in 2015/2016. It is, however, surprising that this recovery was not correlated with stocking densities on vegetation. Generally, both grasslands (high and low altitude grasslands) responded negatively to droughts, although most highlands areas recovered relatively slowly. This could possibly be related to colder temperatures and shorter growing seasons in the higher altitude areas. Such a finding might suggest that Lesotho rangelands are largely not resilient to perturbations.

It is possible that I did not find a relationship with livestock density and drought recovery because one year after the drought is too short to monitor vegetation recovery. To test this I would need to find locations with similar rainfall or vegetation that were not grazed by livestock and see whether they showed substantial recovery one year after the drought. According to Petersen (2004), management in communally owned rangelands is relatively different from the privately owned rangelands. Communal rangelands are heavily and continuously grazed while the private rangelands are moderately and rotationally grazed. It is therefore likely that there was no significant difference of climate and grazing impacts on rangelands from different agro-ecological zones mainly because Lesotho rangelands are generally communal. So far less than 1 % of these lands are protected (UNDP-GEF, 2011). Had there been private rangelands from these regions to compare their impacts with communal rangelands, it is likely that the study could have identified different results.

3.6 Conclusions and recommendations

It may be concluded that drought significantly influenced vegetation cover in Lesotho, while the grazing regime was of less importance in the periods under study using the methods detailed here. Similarly, previously affected grasslands recovered slowly, and their resilience was entirely dependent on drought intensity. While droughts are common in the country, it is inevitable that their serial multiyear occurrences impact both ecological and economic development. Such a finding shows a clear need for policy makers, rangeland managers and livestock farmers to go beyond drought reactive strategies, and to look for long term adaptive interventions. They must be aware that reducing grazing pressure in rangelands before (if possible), during and after intensive droughts is critical for vegetation recovery. Equally important, supplementary feeding could help reduce the grazing pressure in rangelands and give them some periodic rests.

Even though the impacts of grazing intensities during droughts could not be detected in this study, it is suggested that they could have been more apparent if we had had a lower stocking density area to compare it with. All the districts studied were well above the recommended carrying capacity, so it was not possible to study drought impacts and vegetation recovery without grazing. Since Lesotho rangelands are generally communal, it would therefore be

useful to include data from the adjacent South African provincial and national parks, so as to compare the impacts of grazing on communally overgrazed lands and their rate of recovery as opposed to the private rangelands, which usually have lower stocking densities. For a better understanding, research on the interactive impacts of grazing intensity and rainfall variability on vegetation cover in semi-arid rangelands should therefore involve long-term data sets, particularly in countries such as Lesotho, where knowledge gaps in rangelands and climate are of critical importance.

Chapter 4: General Conclusions and Recommendations

4.1 Interactive impacts of droughts and grazing on rangelands of Lesotho

This study has analyzed changes in vegetation under the changing climate, grazing intensity and vegetation recovery of Lesotho rangelands. Owing to the evidence observed in this study, Lesotho grasslands are indeed likely to be impacted by a changing climate. The study confirms that rainfall variability controls primary production. Recurrent droughts imposed detrimental effects on rangelands, consequently affecting livestock production. Such a finding calls for effective response, based on the best available science, to prevent further economic and ecological loss. However, the intensity of drought was not always proportionally correlated with its impacts on vegetation. Even a quite moderate drought can have a big effect on vegetation production (Vetter, 2009), especially under grazing (Gamoun *et al*., 2016).

Although the effects of heavy stocking on vegetation cover during drought could not be detected, it is still thought that overstocking suppresses vegetation in the rangelands of Lesotho. A long-term study of intensive grazing may have perhaps indicated a significant impact on vegetation. Grazing areas in Lesotho are generally recognized to be overstocked (MFLR, 2014). From the factors considered in this study, it may be concluded that Lesotho rangelands productivity is challenged by a range of factors- thus, providing a robust and understandable scientific evidence base for improved rangelands management is critical. Such an approach would be valuable, since decisions made on grazing management and stocking rates during droughts do not only affect the current condition, but also influence the rate of rangelands recovery after droughts (Hart and Carpenter, 2005).

In spite of certain studies considering drought as an opportunity in terms of reducing competition from mature plants, thereby creating conducive conditions for the establishment of seedlings (Vetter, 2009); this was not found to be the case in this study. Vegetation took a long time to recover during good rains after the intensive drought. Based on the impacts of the moderate drought in 2003/2004, which took a landscape two years to recover back to an average state, it is possible that the impacts of the severe drought in 2015/2016 will be felt for at least another three years. Such an extended effect could impose more impacts on livestock

production in the country, which would threaten the livelihoods of rural communities further. According to UNDP-GEF (2011), rural communities in Lesotho, particularly in the mountain zones are struggling to adapt to the changing climate. It is, however, assumed that drought impacts could not have been as severe, provided the country was readily prepared for such situations and handled them better when they eventually occurred.

4.2 Proposed mitigation and adaptation strategies

Due to the recurrent nature of droughts in arid and semi-arid rangelands, a range of alternative mitigation and adaptation strategies can be considered by policy makers, land managers and farmers to improve the rangelands ecosystem resilience and cope with droughts. Most importantly, reduction of stocking rates constitutes a primary approach to cope with droughts in rangelands. Heavily stocked rangelands are more likely to be impacted than those that are lightly stocked under drought conditions (Smart, 2005). De-stocking minimizes the chances of excessive grazing during dry periods, while it also allows vegetation to recover more rapidly when rains come. In addition, proper rangeland management could help in both soil and water conservation (MDAT, 2016). In areas where droughts are common, Hart and Carpenter (2005) recommend the breeding stock to be maintained at 50-70 % of the overall land carrying capacity. The herd size can be reduced once drought is detected. Less productive stock can be sold while the breeding herd is protected so that after drought recovery, re-stocking can be easily accomplished (Finch *et al.*, 2016). This aids in balancing livestock numbers and forage supply. From economic perspective, it would be more considerate if animals are sold before they could lose excessive weight. Besides, young animals be weaned at an early age and be sold. By so doing, this could reduce nutrient requirement as well as forage demand since lactating animals eat more than dry animals (Howery, 2016).

Additionally, time, frequency and the intensity of grazing in the rangelands plays a critical role. According to Finch *et al*., (2016), the timing of rangelands grazing is very influential on the rate of recovery after the dry period. Heavily grazed pastures experience more forage reduction than moderately to lightly grazed lands. In the same way, plants that are repeatedly grazed have little or no chance to re-grow and thus become stressed. Equally, during certain

times of their growth cycle, plants become more vulnerable to grazing. For instance, most perennial grasses are highly sensitive to grazing during the late boot stage to the early heading period (Howery, 2016). It is therefore crucial to select appropriate grazing management systems such as rotational grazing and proper stocking rates, and to adapt them when drought is predicted. The proposed systems should promote rangeland stability – that is, they must consider among other factors, vegetation type of that particular area, topography as well as the decision makers' management goals of such rangelands. Such systems should be intended to provide periodic rests on grazed animals- while reserving ungrazed areas which could be used in times of drought emergencies. This could facilitate more rapid recovery of the rangelands after droughts.

Apart from the application of flexible and conservative stocking rates, supplementary feeding can be another drought adaptation technique (where available). Supplementary feeding reduces the grazing pressure on rangelands during dry periods in a sense that these lands are given some rest period. Although regulations should ensure that supplementary feeding doesn't end up increasing stocking rates. The conservative use of supplemental forage while sustainably managing livestock production is a key drought adaptation measure. Finally, farmers can select drought adaptive breeds. Some breeds are more resistant to droughts than others. Selection of drought resistant breeds can thus aid in drought adaptation.

In conclusion, notwithstanding the above mentioned proposed strategies, for effective mitigation, adaptation and recovery of rangelands from droughts, cautious, advanced and, most of all, informed planning is critical. Such planning allows decision makers and range managers to consider a numbers of alternative strategies and make decisions in time. Being readily prepared for the "next" drought minimizes adverse drought impacts whereas delayed decision making may result in drought intensification, long-term damage of rangelands resources and ultimately, the economic loss (Howery, 2016). It should therefore be a primary goal to protect rangelands prior to, during and after droughts so as to avoid disastrous situations.

As mentioned previously, there is a crucial need for governments, land managers and communities to be well informed on climate change and its impacts globally. People must

understand that climate change impacts might be profound in the future; hence they should be prepared for such situations. Since poor communities are more vulnerable to the impacts, if the governments are well informed, they will, with strategic support, be able to appropriately assist, and create an enabling environment for adaptation.

Moreover, if communities are aware of the prevailing factors that affect livestock during the extreme weather events, they may consider, with appropriate support, alternative options for survival. Preparedness and adaptation is crucial for the livestock farmers since, for example, they will be more informed on the more resistant livestock species to droughts that they could choose, for adaptation. Since, as mentioned earlier, there is evidence that in the future, droughts will impose continuous challenges to the users of rangelands (Vetter, 2009), this requires more research on the ecological perspective, so as to understand the influence of other drivers as well as the response of these rangelands to droughts so that adequate mitigation strategies could be developed to address these challenges – particularly in a country such as Lesotho, where knowledge gaps in this area persist. For example, a critical finding could be for the development of a livestock early warning system, and a livestock monitoring system to support this area – both underpinned by robust and consistently updated scientific evidence.

4.3 Limitations of study

It should be noted that this study relied exclusively on secondary data, which posed a number of challenges. The major obstacle encountered was having access to the relevant data. Unfortunately, all the three sets of data (rainfall, livestock and NDVI) were limited. As a result, this limited the scope of analysis in both data chapters, as certain of the districts were not covered, although the study was intended to cover the entire country of Lesotho. For instance, for rainfall data, not all the districts were covered from the information provided. Further, there was a significant amount of rainfall gaps for the given weather stations; hence a rainfall gap filling method had to be used. In addition, only a few years of information for livestock populations were available, although a series of years would have been more helpful to identify trends in the stocking rates under different climate conditions. A future study should include NDVI data from just outside the border of Lesotho, in the less heavily

stocked provincial and national parks in South Africa, for a better comparison of the effects of stocking rates on vegetation during drought.

Furthermore, it took more time than anticipated to complete the study, due to delayed required data. Although data collection was scheduled for a month, it took longer to obtain information, especially the rainfall data. The struggle to have access to the required information thus impeded progress. Moreover, limited resources in Lesotho, such as scholarly papers on climate and vegetation cover change, made it difficult to compare and contrast this study with the previous findings. The existing information has gaps and also, is not well documented, thus making studies on vegetation and climate changes of Lesotho indeed challenging. Consequently, this study had to be supported with information from neighbouring countries in the SADC region.

4.4 Recommendations

Research on climate variability coupled with stocking management, and their influence on vegetation cover is crucial in Lesotho, since increased climatic variation is anticipated. There is, therefore, a clear need for researchers and governments to conduct and publish a series of papers, policy briefs on this topic; and to further use such scientific evidence to develop a locally specific long term monitoring system for stocking management and vegetation changes detected over years, as climate varies. Long term studies could be flexible enough to capture all the processes in rangelands and detect how resilient these lands are to both the climatic and anthropogenic pressures. If more studies could be directed to livestock and vegetation, this could support the government, land managers and scientists in developing integrated ideas on how to sustainably manage livestock production and resources in the coming decades when climate continues to change.

Based on the study and the other previous studies, it is clear that Lesotho's vegetation is significantly impacted by climate variability, along with the anthropogenic activities. Droughts are expected to further impose challenges to rangeland users in future (Vetter,

2009). It is suggested that issues surrounding land management be prioritized, and policies and laws be enforced to prevent further vegetation loss. Protection of natural vegetation areas could be a most cost-effective way of minimizing vegetation loss and rangeland degradation. So far there are still very few areas where natural vegetation is protected in Lesotho. Additionally, there are no strict rules enforcing proper grazing management (such as the recommended stocking rates) on communal rangelands. It is therefore necessary that rangelands be given rest, more specially periods after droughts and intensive grazing. In addition, stocking rates should be periodically reviewed so as to accommodate any shifts in environmental or land resources.

Finally, it is acknowledged that precipitation is not the only biophysical factor that influences vegetation cover change, but other factors such as soil quality and temperature play a role. A clear understanding of all significant factors that influence vegetation change can only be achieved through long-term field studies. For example, spatial, geology, soil, temperature data should be available to include in analyses. It is thus essential for more studies to be directed to the influence of other biophysical factors, such that a comprehensive mitigation strategy which incorporates all factors can be proposed. There should be initiatives by the Ministries responsible for monitoring rangelands to ensure that long-term vegetation data in collected and documented with the strategic aim of clearly understanding variability and changes in vegetation over time.

References

Abdullah, M., Rafay, M., Sial, N., Rasheed, F., Nawaz, M. F., Nouman, W., Ahmad, I., Ruby, T., and Khalil, S. (2017). Determination of forage productivity, carrying capacity and palatability of browse vegetation in arid rangelands of Cholistan desert, (Pakistan). *Applied Ecology and Environmental Research*, 15(4):623-637.

Abel, N. and Langston, A. (2001). Evolution of a Social-ecological System: Adaptation and Resilience in the New South Wales Rangelands 1850 to 2020.[online] https://www.researchgate.net/publication/265487995.

Ambrosino, C. (2011). Rainfall variability in southern Africa: drivers, climate change impacts and implications for agriculture. Faculty of Social and Historical Sciences, PhD Thesis, Department of Geography, University College London.

Archer, E. R. M. (2004). Beyond the ‘‘climate versus grazing’’ impasse: using remote sensing to investigate the effects of grazing system choice on vegetation cover in the eastern Karoo. *Journal of Arid Environments*, 57: 381–408.

Archer, E.R.M., Landman, W. A., Tadross, M. A., Malherbe, J., Weepener, H., Maluleke, P. and Marumbwa, F. M. (2017). Understanding the evolution of the 2014-2016 summer rainfall seasons in southern Africa: Key lessons. *Climate Risk Management*, 16: 22-28.

Asadi Zarch, M. A., Sivakumar, B. and Sharma, A. (2015). Droughts in a warming climate: A global assessment of Standardized precipitation index (SPI) and Reconnaissance drought index (RDI). *Journal of Hydrology*, 526: 183-195.

Ayal, D. Y. and Filho, W. L. (2017). Farmers’ perception of climate variability and its adverse impacts on crop and livestock production in Ethiopia. *Journal of Arid Environments*, 140: 20-28.

Bahta, Y.T.,Jordaan, A. and Muyambo, F. (2016). Communal farmers' perception of drought in South Africa: Policy implication for drought risk reduction. *International Journal of Disaster Risk Reduction*, 20:39-50.

Bajgain, R., Xiao, X., Wagle, P., Basara, J. and Zhou, Y. (2015). Sensitivity analysis of vegetation indices to drought over two tallgrass prairie sites. *ISPRS Journal of Photogrammetry and Remote Sensing*, 108: 151-160.

Barbosa, H. A., Huete, A. R. and Baethgen, W. E. (2006). A 20-year study of NDVI variability over the Northern Region of Brazil. *Journal of Arid Environments*, 67: 288-307.

Baudoin, M-A., Vogel, C., Nortje, K. and Naik, M. (2017). Living with drought in South Africa: lessons learnt from the recent El Niño drought period. *International Journal of Disaster Risk Reduction*,23: 128-137.

Belle, J., Sithabile, M. and Ogundeji, A. A. (2017). Assessing communal farmers' preparedness to drought in the Umguza District, Zimbabwe. *International Journal of Disaster Risk Reduction*, 22: 194-203.

Benkenstein, A. (2017). Climate change adaptation readiness: lessons from the 2015/16 El Nino for climate readiness in Southern Africa. *SAIIA*. Ocassional paper 250.

Benson, C. and Clay, E. (1998). The Impact of Drought on Sub−Saharan African Economies: A Preliminary Examination. World Bank technical paper; no. 401, Washington,D.C., USA.

Bisaro, A., Hinkel, J.and Kranz, A. (2010). Multilevel water, biodiversity and climate adaptation governance: evaluating adaptive management in Lesotho. *Environmental Science and Policy*, 13: 637-647.

Bodner, G. S. and Robles, M. D. (2017). Enduring a decade of drought: Patterns and drivers of vegetation change in semi-arid grassland. *Journal of Arid Environments*, 136:1-14.

B.O.S. (2012). 2009/2010 Lesotho Agricultural Census. Livestock report, Volume 2. Minisrty of Finance and Development Planning, Maseru, Lesotho.

Bowman, D.M.J.S., Franklin, D.C., Price, O.F. and Brook, B.W. (2007). Land management affects grass biomass in the *Eucalyptus tetrodonta* savannas of monsoonal Australia. *Austral Ecol.*, 32:446–452.

Brink, E. (2016). Drought Report: Dust to dust. Solidarity Research Institute. South Africa.

Carmel, Y. and Kadmon, R. (1999). Effects of grazing and topography on long-term vegetation changes in a Mediterranean ecosystem in Israel. *Plant ecology*, 145(2): 243-254.

Chaffin, B. C. and Scown, M. (2018). Social-ecological resilience and geomorphic systems. *Geomorphology*, 305: 221-230.

Country Programming Framework (CPF). (2017). The government of the Kingdom of Lesotho and Food and Agriculture Organization of the United Nations. Maseru, Lesotho.

Craft, K. E., Mahmood, R., King, S. A., Goodrich, G. and Yan, J. (2016). Droughts of the twentieth and early twenty-first centuries: Influences on the production of beef and forage in Kentucky, USA. *Science of the Total Environment*, 577: 122-135.

Crush, J., Dodson, B., Gay, J., Green, T. and Leduka, C. (2010). Migration, Remittances and 'Development' in Lesotho. Southern African Migration Programme 2010.

Dabanlı, İ., Mishra, A.K. and Şen, Z., (2017). Long-term spatio-temporal drought variability in Turkey. *Journal of Hydrology*, 552: 779-792.

Dai, A. (2011). Drought under global warming: a review. *WIREs Climate Change*, 2: 45-65.

Danckwerts, J. E. and Stuart-Hill, G.C. (1988). The effect of severe drought and management after drought on the mortality and recovery of semi-arid grassveld. *Journal of the Grassland Society of Southern Africa*, 5(4): 218-222.

David, V. and Davidová, T. (2016). Assessment of summer drought in 2015 using different indices in the catchment of Blanice River. *Procedia Engineering*, 162: 45 – 55.

Davis-Reddy, C.L. and Vincent, K. (2017). Climate Risk and Vulnerability: A Handbook for Southern Africa (2nd Ed), CSIR, Pretoria, South Africa.

Dejene, A., Midgley, S., Marake, M. V.,Ramasamy, S.(2011). Strengthening Capacity for Climate ChangeAdaptation in Agriculture: Experience and Lessons from Lesotho.Food and Agriculture Organization of the United Nations, Rome.

Deng, S., Chen, T., Yang, N., Qu, L., Li, M. and Chen, D. (2017). Spatial and temporal distribution of rainfall and drought characyeristics across the Pearl River basin.

Science of the Total Environment, 619-620: 28-41.

Diaz-Solis, H., Grant, W. E., Kothman, M. M., Teague, W. R. and Diaz-Carcia, J. A. (2009). Adaptive management of stocking rates to reduce effects of drought on cow-calf production systems in semi-arid rangelands. *Agricultural Systems*, 100: 43- 50.

DMA (2015). National mitigation and preparedness plan for drought. Lesotho national response plan to El Niño 2015 to 2016. Maseru, Lesotho.

Driver, P. (2014). Rainfall Variability over Southern Africa. PhD Thesis, Department of Oceanography, Faculty of Science, University of Cape Town.

Dube, L. T. and Jury, M. R. (2002). Meteorological structure of the 1992/93 drought over eastern South Africa from ECMWF and satellite OLR analyses. *South African Geographical Journal*, 84(2), 170-181, DOI: 10.1080/03736245.2002.9713768

Dzama,K. (2016). Is the livestock sector in Southern Africa prepared for climate change? *SAIIA*.Policy briefing153.

Elmqvist, T., Folke, C., Nystrom, M., Peterson, G., Bengtsson, J., Walker, B., and Norberg, J. (2003). Response diversity, ecosystem change, and resilience. *Front Ecol Environ*., 1(9): 488–494.

Ellis, J. and Galvin K. A. (1994). Climate Patterns and Land-use Practices in the Dry Zones of Africa. *BioScience*.44:340-349.

Ellis, J. E. and Swift, D. M. (1988). Stability of African pastoral ecosystems: alternate paradigms and implications for development. *Journal of Range Management*, 41: 450-459.

Ellis, J. E., Coughenour, M. B. and Swift, D. M. (1993). Climate variability, ecosystem stability, and the implication for range and livestock development. In: Behnke, R. H., Scoones, I., Kerven, C. (Eds.), Range Ecology at Disequilibrium: New Models of Natural Variability and Pastoral Adaptation in African Savannas. Overseas Development Institute, London (248pp).

Fang, Q.X., Andales, A. A., Derner, J. D., Ahuja, L. R., Ma,L., Bartling, P. N. S., Reeves, J. L. and Qi, Z. (2014). Modeling weather and stocking rate effects on forage and steer production in northern mixed-grass prairie. *Agricultural Systems*, 129: 103-114.

FAO (2012). Livestock and climate change in the near east region: measures to adapt and mitigate climate change. Food and Agriculture Organization of the United Nations, Cairo.

FAO (2016). Lesotho: El Niño-induced Drought Briefing – February 2016. Food and Agriculture Organization of the United Nations, Lesotho.

FAOSTAT (2013). The Food and Agricultural Organisation's Statistical Database. [online] Available at: http://faostat.fao.org/site/535/DesktopDefault.aspx?PageID=535#ancor.

Fereja, G. B. (2017). The effect of climate change on range land and biodiversity: A review. *International Journal of Research Granthaalayah,* 5(1), 172-182.

Finch, D.M., Pendleton, R.L., Reeves, M.C., Ott, J.E., Kilkenny, F.F., Butler, J.L., Ott, J.P., Pinto, J.R., Ford, P.L., Runyon, J.B. and Rumble, M.A. (2016). Rangeland drought: Effects, restoration, and adaptation [Chap. 8]. *In: Vose, James M.; Clark, James S.; Luce, Charles H.; Patel-Weynard, Toral, eds. Effects of drought on forests and rangelands in the United States: A comprehensive science synthesis. Gen. Tech. Rep. WO-93b. Washington, DC: US Department of Agriculture, Forest Service, Washington Office. p. 155-194., 93,* pp.155-194.

Fitchett J.M., Grab S.W., Bamford, M.K. and Mackay, A.W. (2016). A multi-disciplinary review of late Quaternary palaeoclimates and environments for Lesotho. *South African Journal of Science*, 112(7/8):1-9 [online] http://dx.doi.org/10.17159/ sajs.2016/20160045.

Fynn, R.W.S and O'Connor, T.G. (2000). Effect of stocking rate and rainfall on rangeland dynamics and cattle performance in a semi-arid savanna, South Africa. *Journal of Applied Ecology*, 37: 491-507.

Gamoun, M., Essifi, B., Dickens, C., and Hanchi, B. (2016). Interactive effects of grazing and drought on desert rangelands of Tunisia. *BIOLOGIJA*, 62 (2): 105–115.

Gerber, P., Mooney, H.A., Dijkman, J., Tarawali, S. and de Haan, C. (2010). Livestock in a changing landscape: Experiences and Regional Perspectives. *Island Press*, Volume 2.

Gillson, L. and Hoffman, M. T. (2007). Rangeland ecology in a changing world. *Science*, 315, 53-54.

Grab, S.W. and Nash, D.J., (2010). Documentary evidence of climate variability during cold

seasons in Lesotho, southern Africa, 1833–1900. *Climate Dynamics*, 34(4):473-499.

Green, R. H. (1993). The political economy of drought in Southern Africa 1991-1993. *Health Policy and Planning*, 8(3): 255-266.

Green, S., Cawkwell, F. and Dwyer, E. (2016). Cattle stocking rates estimated in temperate intensive grasslands with a spring growth model derived from MODIS NDVI time-series. *International Journal of Applied Earth Observation and Geoinformation*, 52:166-174.

Grundling, P-L., Linstrom, A., Fokkema, W., and Grootjans, A. P. (2015). Mires in the Maluti Mountains of Lesotho. *Mires and Peat*, 15: 11-21.

Gu, Y., Hunt, E., Wardlow, B., Basara, J. B., Brown, J. F. and Verdin, J. P. (2008). Evaluation of MODIS NDVI and NDWI for vegetation drought monitoring using Oklahoma Mesonet soil moisture data. *Geophysical Research Letters*. 35: 1– 5.

Hae, M. E. (2016). Invasive plant species in Lesotho's rangelands: species characterization and potential control measures.United Nations University Land Restoration Training Programme. [online] http://www.unulrt.is/static/fellows/document/Hae2016.pdf

Hao, Z. and Singh, V. P. (2015). Drought characterization from a multivariate perspective: A review. *Journal of Hydrology*, 527: 668-678.

Harris, A., Carr, A. S. and Dash, J. (2014). Remote sensing of vegetation cover dynamics and resilience across southern Africa. *International Journal of Applied Earth Observation and Geoinformation*, 28:131-139.

Harrison, Y. A. and Shackleton, C. M. (1999). Resilience of South African communal grazing lands after the removal of high grazing pressure. Land Degradation and Development, 10: 225-239.

Hart, C.R. and Carpenter, B.B. (2005). Stocking rate and grazing management. *Rangeland Drought Management for Texans*, E-64: 0501. The Texas A&M University System.

Hayes, M. J., Svoboda, M. D., Wilhite, D. A. and Vanyarkho, O. V. (1999). Monitoring the 1996 Drought Using the Standardized Precipitation Index. *American Meteorological Society*, 80(3): 430-438.

Heitschmidt, R. K., Klement, K. D. and Haferkamp, M. R. (2005). Interactive effects of drought and grazing on Northern Great Plains rangelands. *Rangeland Ecology and Management*, 58(1): 11-19.

Herrero, M., Thornton, P.K., Gerber, P., and Reid, R. S. (2009). Livestock, livelihoods and the environment: understanding the trade-offs. *Environmental Sustainability*, 1:111-120.

Hoffman, T. and Vogel, C. (2008). Climate Change Impacts on African Rangelands. *Society for Range Management*. South Africa.

Holling, C. S. (1973). Resilience and stability of ecological systems. *Annual Review of Ecology and Systematics*, 4: 1-23.

Homdee, T., Pongput, K. and Kanae, S. (2016). A comparative performance anaysis of three standardized climatic drought indices in the Chi River basin, Thailand. *Agriculture and Natural Resources*, 50: 211-219.

Howden, S. M., Soussana, J-F., Tubiello, F. N., Chhetri, N., Dunlop, M and Meinke, H. (2007). Adapting agriculture to climate change. *PNAS*, 104: 19691–19696.

Howery, L.D. (2016). Rangeland management before, during, and after drought. University of Arizona Cooperative Extension report AZ113[online]http://extension.arizona.edu/sites/extension.arizona.edu/ files/pubs/az1136.pdf.

Huber-Lee, A.,Galaitsi, S., Davis, M., Wishart, M. and Emenanjo, I. (2016). Lesotho: Tackling water insecurity in a changing climate. *Stockholm Environment Institute*. [online] http://hdl.handle.net/ 10986/24905.

IFAD (2009). Livestock and Climate Change.[online] Available at: www.ifad.org/lrkm/index.htm.

Iglesias, E., Baez, K. and Diaz-Ambrona, C. H. (2016). Assessing drought risk in Mediterranean Dehesa grazing lands. *Agricultural Systems*, 149: 65-74.

Illius, A. W. and O'Connor, T. G. (1999). On the Relevance of Nonequilibrium Concepts to Arid and Semiarid Grazing Systems. *Ecological Applications*, 9(3): 798-813.

IPCC (2007). Synthesis Report. Contribution of Working Groups I, II and III to the Fourth

Assessment Report of the Intergovernmental Panel on Climate Change. Core Writing Team, Pachauri, R.K. and Reisinger, A. (Eds.) IPCC, Geneva, Switzerland. pp 104.

Ji. L. and Peters, A. J. (2003). Assessing vegetation response to drought in the northern Great Plains using vegetation and drought indices. *Remote Sensing of Environment*, 87:85-98.

Jury M.R. (2013) Climate trends in southern Africa. *South African Journal of Science*, 109(1/2): 1-11.

Kabubo-Mariara (2009). Global warming and livestock husbandry in Kenya: Imapcts and adaptations. *Ecological Economics,* 68:1915–1924.

Keshavarz, M., Maleksaedi, H. and Karami, E. (2017). Livelihood vulnerability to drought: A case of rural Iran. *International Journal of Disaster Risk Reduction,*21:223-230.

Kgosikoma, O. E. (2006). Effects of climate variability on livestock population dynamics and community drought management in Kgalagadi, Botswana. MSc Thesis, Department of International Environment and Development studies, Norwegian University of Life Sciences.

Khan, S., Gabriel, H. F. and Rana, T. (2008). Standard precipitation index to track drought and assess impact of rainfall on watertables in irrigation areas. *Irrig. Drainage Syst.*, 22:159–177.

Kobisi, K. and Kose, L.E. (2003). A checklist of Lesotho grasses. Southern African Botanical Diversity Network Report No. 17. Pretoria.

Kopij, G. (2015). Avian assemblages in Afro-mountain and Alti-mountain Grasslands in the endemic Maloti/Drakensberg region of Lesotho. *Zoology and Ecology*, 25 (4): 319-326, DOI: 10.1080/21658005.2015.1095854.

Kumar, V., Jain, S. K. and Singh, Y. (2010). Analysis of long-term rainfall trends in India. *Hydrological Sciences Journal*, 55 (4): 484-496.

Leipzig (1996). Lesotho: Country report to the FAO international technical conference on plant genetic resources. Maseru, Lesotho.

Lewis, F., Browne, M., Quayle, L., Oosthuizen, S., and Peerbay, K. (2015). Mapping Climate Change Vulnerability and Potential Economic Impacts in Lesotho: A Case Study of the Katse Dam Catchment. Institute of Natural Resources NPC. Pietermaritzburg.

Lewis, F.,McCosh, J., Pringle, C., Bredin, I. and Nxele,Z. (2011). Lesotho climate change adaptation project; Ecosystems,Agriculture and Livelihoods in the Lesotho Highlands: Likely futures and implications of climate change. (IRN report: Discussion document).Scottsville, South Africa.

Liao, C. and Clark, P.E. (2018). Rangeland vegetation diversity and transition pathways under indigenous pastoralist management regimes in southern Ethiopia. *Agriculture, Ecosystems and Environment*, 252: 105-113.

Linsdtadter, A., Kuhn, A., Naumann, C., Rasch, S., Sandhage-Hofmann, A., Amelung, W., Jordaan. J., Du Preez, C. C. and Bollig, M. (2016). Assessing the resilience of real-world-socio-ecological system: lessons from multidisciplinary evaluation of a South African pastoral system. *Ecology and Society*21(3):35. http://dx.doi.org/10.5751/ES-08737-21033.

LMS (2007). Lesotho Meteorological Services. Agro-Met Monthly Update: May 2007. Maseru, Lesotho.

Lu, H., Wu, Y., Li, Y. and Liu, Y. (2017). Effects of meteorological droughts on agricultural water resources in southern China. *Journal of Hydrology*, 548:419–435.

Majara, N. (2005). Land degradation in Lesotho: A synoptic perspective. MSc Thesis, University of Stellenbosch, South Africa.

Malherbe, J., Dieppois, B., Maluleke, P., Van Staden, M. and Pillay, D. l. (2015). South African droughts and decadal variability. *Natural Hazards*, DOI: 10.1007/s11069-015-1989-y.

Mandleni, B. (2011). Impact of climate change and adaptation on cattle and sheep farming in the Eastern Cape province of South Africa. PhD Thesis, Department of Environmental Management, University of South Africa.

Maoela, M. (2010). Climate change impacts on crop yields and adaptive measures for agricultural sector in the lowlands of Lesotho. MSc Thesis, Department of Physical Geography and Ecosystem Analysis, Lund University, Sweden.

Marcos-Garcia, P., Lopez-Nicolas, A. and Pulido-Velazquez, M. (2017). Combined use of relative drought indices to analyze climate change impact on meteorolgical and hydrological droughts in Mediterranean basin. *Journal of Hydrology*, 554: 292-305.

Mack, R.N. and Thompson, J.N. (1982). Evolution in steppe with few large, hooved mammals. *Am. Nat.***,** 119**:** 757–773.

Masih, F., Maskey, S., Mussa, F. E. F. and Trambauer, P. (2014). A review of droughts on the African continent: a geospatial and long-term perspective. *Hydrol. Earth Syst. Sci*., 18:3635–3649, doi:10.5194/hess-18-3635-2014.

Mašková, Z., Zemek, F. and Kv, J. (2008). Normalized difference vegetation index (NDVI) in the management of mountain meadows.*Boreal Environment Research*, 13: 417–432.

Mathbout, S., Lopez-Bustins, J.A., Martin-Vide, J., Bech, J. and Rodrigo, F.S (2018). Spatial and temporal analysis of drought variability at several time scales in Syria during 1961–2012. *Atmospheric Research*, 200: 153-168.

Matsushita, B., Yang, W., Chen, J., Onda, Y. and Qiu, G. (2007). Sensitivity of the Enhanced Vegetation Index (EVI) and Normalized Difference Vegetation Index (NDVI) to Topographic Effects: A Case Study in High-Density Cypress Forest. *Sensors*, 7: 2636–2651.

McKee, T.B., Doesken,N.J. and Kleist,J. (1993). The relationship of drought frequency and duration to time scales. *Eigth Conference on Applied Climatology*, 17 (22): 179-184.

McNaughton, S.J. (1984). Grazing Lawns: Animals in Herds, Plant Form, and Coevolution. *Am. Nat.*, 124 (6): 863–886.

McVean D. N. (1977). Nature Conservation in Lesotho Report on Current Progress and Forward Planning. United Nations Environment Programme, Maseru Lesotho.

MFLR (2014). National Range Resources Management Policy. Ministry of Forestry and Land Reclamation. Maseru, Lesotho.

Mishra, A. K. and Singh, V. P. (2010). A review of drought concepts. *Journal of Hydrology*, 391: 202-216.

MNR (2000). National report on climate change. First National Communication to the Conference of the Parties to the United Nations Framework Convention on Climate Change. Maseru, Lesotho.

Mohmmed, A., Li, J., Elaru, J., Elbashier, M. M. A., Keesstran, S., Cerdia, A., Martin, K., Reuben, M. and Teffera, Z. (2017). Assessing drought vulnerability and adaptation among farmers in Gadaref region, Eastern Sudan. *Land Use Policy*, 70: 402-413.

Morris, C. (2017). Vegetation gradients around cattleposts in the eastern mountains of Lesotho, *African Journal of Range & Forage Science*, 34(4): 219-225.

Mpiti-Shakhane, L. M ., Kanyama-Phiri, G. Y., Odenya, W. O. and Banda, J. W. (2002). Preliminary results of a stocking rate trial in Lesotho. *African Journal of Range & Forage Science*, 19(1): 63-69, DOI: 10.2989/10220110209485775.

Multi-Agency Drought Assessment Team (MDAT) (2016). Rapid Drought Assessment Report. Lesotho.

Mwafulirwa, N. D. (1999). Climate variability and predictability in tropical southern Africa with focus on dry spells over Malawi. MSc Thesis, Department of Geography and Environmental studies, University of Zululand.

Nalane, L. J., Chikanda, A. and Crush, J. (2012). The remittances framework in Lesotho: Assessment of policies and programmes promoting the multiplier effect. ACP observatory on migration. International Organisation for Migration (IOM).

Nash, D. (2017). Changes in Precipitation over Southern Africa during Recent Centuries. Oxford University Press USA.

Nash, D.J. and Grab, S.W. (2010). “A sky of brass and burning winds”: documentary evidence of rainfall variability in the Kingdom of Lesotho, Southern Africa, 1824–1900. *Climatic Change*, 101(3-4):617-653.

Nesamvuni, E., Lekalakala, R., Norris, D. and Ngambi, J. W.(2012). Effects of climate change on dairy cattle, South Africa. *African Journal of Agricultural Research,*7(26):3867–3872.

Nicholson, S. E. and Kim, J. (1997). The relationship of the El Niño- Southern Oscillation to African rainfall. *International Journal of Climatology,* 17: 117–135.

Nkondze, M. S. (2014). The Impact of Climate Change on Livestock Production in Swaziland: The case of Mpolonjeni Area Development Programme. *Journal of Agricultural Studies,*Vol. 2, No. 1.

Ntsohi, R., Tsolo, C., Nthejane, M. and Ratsele, C. (2014). An investigation into the effectiveness of grazing associations in management of communal rangeland resources. Ministry of Forestry and Land Reclamation, The Lesotho National Conference on Sustainable Land Management, Book of Proceedings :Full Papers.

Obioha, E. E. (2010). Climate variability and food production nexus in Lesotho, 2001–2007. *Journal of Human Ecology,* 32(3): 149-160.

O'Connor, T. G. (1993). The influence of rainfall and grazing on the demography of some African savanna grasses: A matrix modelling approach. *Journal of Applied Ecology,* 30(1):119-132.

O'Connor T.G. (1994). Composition and population responses of an African savanna grassland to rainfall and grazing. *Journal of Applied Ecology*, 31: 155–171.

O'Connor, T.G. (1995). Transformation of a savanna grassland by drought and grazing. *African Journal of Range and Forage Science*, 12(2): 53-60

O'Connor, T. G. and Roux, P. W. (1995). Vegetation Changes (1949-71) in a semi-arid, grassy dwarf shrubland in the Karoo, South Africa: Influence of rainfall variability and grazing by sheep. *Journal of Applied Ecology*, 32 (3):612-626.

Olaleye, A.O., Nkheloane, T., Mating, R., Mahlako, K., Rathebe, K., Letsika, F. and Rasekoele, M.G., (2014). Wetlands in Khalong-la-Lithunya catchment in Lesotho: Soil organic carbon contents, vegetation isotopicsigna tures and hydrochemistry. *Catena*, 115:71-78.

Pappas, C., Papalexiou, S. M. and Koutsoyiannis, D. (2014). A quick gap filling of missing

hydrometeorological data. *Journal of Geophysical Research: Atmospheres*, 119: 9290– 9300.

Perrings, C. and Walker, B.H. (1997). Biodiversity, resilience and the control of ecological-economic systems: the case of fire-driven rangelands. *Ecological Economics*, 22: 73-83.

Peters, A. J., Walter-Shea, E. A., Ji, L., Vina, A., Hayes, M. and Svoboda, M. D. (2002). Drought Monitoring with NDVI-Based Standardized Vegetation Index, *Photographic Engineering and Remote Sensing*, 68(1): 71–75.

Petersen, A., Young, E.M., Hoffman, M.T. and Musil, C. F. (2004). The impact of livestock grazing on landscape biophysical attributes in privately and communally managed rangelands in Namaqualand. *South African Journal of Botany*, 70(5): 777–783.

Pinder, J. E., III, Kroh, G. C., White, J. D. and May, A. M. B. (1997). The relationships between vegetation type and topography in Lassen Volcanic National Park. *Plant Ecology*, 131: 17–29.

Quinlan, P. E., Berbes-Blazquez, M., Jamila Haider, L. and Peterson, G. D. (2015). Measuring and assessing resilience: broadening understanding through multiple disciplinary perspectives. *Journal of Applied Ecology*, 53: 677–687.

Quinlan, T. (1995). Grassland degradation and livestock rearing in Lesotho. *Journal of Southern African Studies*, 21(3): 491-507.

Rembold F., Kerdiles H., Lemoine G., and Perez-Hoyos A. (2016). Impact of El Niño on agriculture in Southern Africa for the 2015/2016 main season. JRC MARS Bulletin – Global Outlook Series, European Commission.

Richard, Y., Fauchereu, N., Poccard, I., Rouault, M. and Trzaska, S. (2001). 20th century droughts in southern Africa: spatial and temporal variability, teleconnections with oceanic and atmospheric conditions. International Journal of Climatology, 21: 873-885, DOI: 10.1002/joc.65.

Rocha, A. V and Shaver, G. R. (2009). Advantages of a two band EVI calculated from solar and photosynthetically active radiation fluxes. *Agriculture and Forest Meteorology*, 149 :1560-1563.

Rothgaute, A. (2000). New ecological perceptions of arid rangelands. AGRICOLA, Neudamm Agricultural College, Windhoek, Namibia.

Rouault, M. and Richard, Y. (2005). Intensity and spatial extent of droughts in southern Africa. *Geophysical Research Letters*, 32 (15702): 1-4, doi:10.1029/2005GL022436.

Ruppert, J.C., Harmoney, K., Henkin, Z. Snyman, H. A.,Sternberg, M., Willms, W. and Linstadter,A. (2015). Quantifying drylands' drought resistance and recovery : the importance of drought intensity , dominant life history and grazing regime. *Global Change Biology*, 21:1258–1270. doi: 10.1111/gcb.12777.

Rust, J.M. and Rust, T. (2013). Climate change and livestock production: A review with emphasis on Africa.*South African Journal of Animal Science*, 43 (No. 3).

SAFEGE (2012). Consultancy for the preparation of the Country Environment Profile of the Kingdom of Lesotho. Final Report. Maseru, Lesotho.

Sanchez-Pinillos, M., Coll, L., De Caceres, M. and Ameztegui, A. (2016). Assessing the persistamce capacity of communities facing natural disturbances on the basis of species response traits. *Ecological Indicators*, 66: 76-85.

Shadeed, S. (2013). Spatio-temporal Drought Analysis in Arid and Semi-arid Regions: A Case Study from Palestine. *Arab J. Sci. Eng.*, 38:2303–2313.

Showers, K. B. (1989). Soil erosion in the kingdom of Lesotho: origins and colonial response, 1830s–1950s, *Journal of Southern African Studies*, 15(2): 263-286.

Sirohi, S. and Michaelowa, A. (2007). Sufferer and cause : Indian livestock and climate change. *Climatic change*, 85: 285–298.

Smart, A. (2005). Drought and Stocking Rate Effects on Forage Yield from Western SD Rangelands. *Forage Focus – BEEF*, South Dakota State University.

Sohoulande Djebou, D. C. (2017). Bridging drought and climate variability. *Journal of Arid Environments*, 144: 170-180.

Solh, M. and van Ginkel, M. (2014). Drought preparedness and drought mitigation in the developing world's drylands. *Weather and Climate Extremes*, 3: 62-66.

Standish, R. J., Hobbs, R. J., Mayfield, ,M. M., Bestelmeyer, B. T., Suding, K.N., Battaglia, L. I., Eviner, V., Hawkes, C. V., Temperton, V. M., Cramer, V. A., Harris, J. A., Funk, J. I. and Thomas, P. A. (2014). Resilience in ecology: Abstraction, distraction,

or where the action is? *Biological conservation*, 177: 43-51.

Strzepek, K.,Yohe, G., Neumann, J. and Boehlert, B.(2010). Characterizing changes in drought risk for the United States from climate change. *Environmental Research Letters*,5: 9.

Taele, B.M., Gopinathan, K.K. and Mokhuts'oane, L. (2007). The potential of renewable energy technologies for rural development in Lesotho. *Renewable Energy*, 32(4): 609-622.

Taylor, S.J. (2015). African mountainous countries and their mountains: The Kingdom of Lesotho. AfroMont Programme Coordinator University of Pretoria, South Africa.

Thornton, P. K. (2010). Livestock production: recent trends, future prospects. *Phil. Trans. R. Soc. B*, 365: 2853–2867.

Thornton P. K., Boone R. B. and Ramirez-Villegas, J. (2015). Climate change impacts on livestock. CCAFS Working Paper no. 120. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). Copenhagen, Denmark. Available online at: www.ccafs.cgiar.org

Thornton, P. K., van de Steeg, J., Notenbaert, A. and Herrero, M. (2009).The impacts of climate change on livestock and livestock systems in developing countries : A review of what we know and what we need to know. *Agricultural Systems*, 101(3): 113–127.

Thurow, T. L. and Taylor, C. A. (1999). Viewpoint: The Role of Drought in Range Management. *Journal of Range Management*, 52(5): 413-419.

Treydte, A.C., Schmiedgen, A., Berhane, G. and Tarekeg, K.D. (2017). Rangeland forage availability and management in times of drought- A case study of pastoralists in Afar, Ethiopia. *Journal of Arid Environments*, 139: 67-75.

Truen, S., Jitsing, W., Kgaphola, K., Chisadza, S., Moeketsi, M., Foshizi, Jimson, L., Imani Consulting and Africa Corporate Advisors (2016). The impact of remittances in Lesotho, Malawi and Zimbabwe. Prepared for FinMark Trust.

Tucker C.J., and Choudhury,B.J.(1987). Satellite Remote Sensing of Drought Conditions. *Remote Sensing of Environment*, 23:243–251.

Tyler, S. and Moench, M. (2012). A framework for urban climate resilience. *Climate and Development*, 4 (4): 311-326, DOI: 10.1080/17565529.2012.745389

Udmale, P. D.,Ichikawa, Y. , Manandhar, S , Ishidaira , H., Kiem, A., S., Shaowei, N. and Panda, S. N. (2015). How did the 2012 drought affect rural livelihoods in vulnerable areas? Empirical evidence from India. *International Journal of Disaster Risk Reduction,* 13: 454–469.

UNDP-GEF (2009). Lesotho Fourth National Report On Implementation of Convention on Biological Diversity. Department of Environment, Maseru, Lesotho.

UNDP-GEF (2011). Demonstrating Project on Community based rangeland management in Lesotho. Orange-Senqu Strategic Action Programme (Atlas Project ID 71598) Technical Report 05 (Rev. 3).Maseru, Lesotho.

Unganai, L. S. and Kogan, F. N. (1998). Drought Monitoring and Corn Yield Estimation in Southern Africa from AVHRR Data. *Remote Sens. Environ*., 63:219–232.

UN-Lesotho (2016). El nino-related Drought: United Nations Office of the Resident Coordinator Lesotho Situation Update. 02. [online] Available at:www.unlesotho.org.

Valimba, P., Camberlin, Y. R., Servat, E. and Hughes, D. (2006). Influences of ENSO and SST variations on the interannual variability of rainfall amounts in southern Africa. *Climate Variability and Change—Hydrological Impacts*, Proceedings of the Fifth FRIEND World Conference, Havana, Cuba.

van Zinderen-Bakker, E. M. and Werger M. J. A. (1974). Environmnent, vegetation and phytogeography of the high-altitude bogs of Lesotho. *Vegetatio*, 29: 37-49.

van Zyl, O. (2016). Southern Africa drought report. Agri SA, South Africa.

Venter, D. B., Rethman, N. F. G. and van Niekerk, W. A. (2006). A review: Old and new approaches to arid zone ecology as a basis for reclamation and management of arid ecosystems. In: Venter, D. B. (2006). An ecological approach to the reclamation and improvement of arid rangelands using adapted fodder plants. MSc Thesis, Department of Plant Production and Soil Science, Faculty of Natural and Agricultural Sciences, University of Pretoria.

Vetter, S. (2005). Rangelands at equilibrium and non-equilibrium: recent developments in

debate. *Journal of Arid Environments,* 62: 321-341.

Vetter, S. (2009). Drought, change and resilience in South Africa's arid and semi- arid rangelands. *South African Journal of Science*, 105: 29-33.

Vetter, S. and Bond, W. J. (2012). Changing predictors of spatial and temporal variability in stocking rates in severely degraded communal rangeland. *Land Degrad. Develop*., 23: 190–199.

Vicente-Serrano, S.M. (2006). Differences in spatial patterns of drought on different time scales: an analysis of the Iberian Peninsula. *Water resources management*, 20(1):37-60.

Vicente-Serrano, S. M. (2007). Evaluating the Impact of Drought Using Remote Sensing in a Mediterranean,Semi-arid Region. *Natural Hazards,* 40:173–208,DOI10.1007/s11069-006-0009-7.

Walker, B.H., Emslie, R.H., Owen-Smith, R.N. and Scholes, R.J. (1987). To cull or not to cull: lessons from a southern African drought. *Journal of Applied Ecology*, 24(2): 381-401.

Wan, Z., Wang, P. and Li, X. (2004). Using MODIS Land Surface Temperature and Normalized Difference Vegetation Index products for monitoring drought in the southern Great Plains, USA. *International Journal of Remote Sensing*, 25:1, 61-72, DOI: 10.1080/0143116031000115328.

WFP (2006). Assessment of 2005/06 Agricultural Production in Lesotho, Support to the Agricultural Season Assessment. Maseru, Lesotho.

WFP (2016). WFP Southern Africa El Niño Situation Report. Situation Report #2.

Whitford, W. G., Rapport, D. J. and deSoyza, A. G. (1999). Using resistance and resilience measurements for 'fitness' tests in ecosystem health. *Journal of Environmental Management*, 57: 21-29.

Wu, J., Chen, X., Yao, H., Gao, L., Chen, Y. and Liu, M. (2017). Non-linear relationship of hydrological drought responding to meteorological drought and impact of large reservoir. *Journal of Hydrology*, 551: 495-507.

Yao, N., Li, Y., Lei, T. and Peng, L. (2018). Drought evolution, severity and trends in mainland China over 1061-2013. *Science of the Total Environment*, 616-617: 73-89.

Zargar, A., Sadiq, R., Naser, B., and Khan, F. I. (2011). A review of drought indices. *Environmental Reviews*, 19 : 333-349.

Zhao, L., Dai, A. and Dong, B. (2018). Changes in global vegetation activity and its driving factors during 1982–2013. *Agricultural and Forest Meteorology*, 249: 198-209.

Ziervogel, G., (2004). Targeting seasonal climate forecasts for integration into household level decisions: the case of smallholder farmers in Lesotho. *The Geographical Journal*, 170(1): 6-21.

Zunckel, K. (2003). Managing and Conserving Southern African Grasslands With High Endemism, *Mountain Research and Development*, 23(2):113-118.

Appendix

Table 1: Proportion of rainfall missing days in Lesotho weather stations

Station name	No. of days	July	August	September	October	November	December	January	February	March	April	May	June	Average
Phuthiatsana (Berea district)	Missing	153	124	171	155	242	157	73	118	63	168	155	152	
	Expected	744	744	720	651	720	744	744	672	744	720	744	720	
	Proportion	0.21	0.17	0.24	0.24	0.34	0.21	0.10	0.18	0.08	0.23	0.21	0.21	0.20
Butha-Buthe	Missing	217	186	211	186	181	216	124	127	124	150	158	150	
	Expected	992	992	960	992	960	992	992	896	992	960	992	960	
	Proportion	0.22	0.19	0.22	0.19	0.19	0.22	0.13	0.14	0.13	0.16	0.16	0.16	0.18
Oxbow (Butha-Buthe district)	Missing	189	157	131	149	165	139	118	185	98	97	73	80	
	Expected	992	992	960	992	960	992	992	896	992	960	992	960	
	Proportion	0.19	0.16	0.14	0.15	0.17	0.14	0.12	0.21	0.1	0.1	0.07	0.08	0.14
Mafeteng	Missing	31	32	74	50	62	64	31	13	1	4	63	40	
	Expected	992	992	960	992	960	992	992	896	992	960	992	960	
	Proportion	0.03	0.03	0.08	0.05	0.06	0.06	0.03	0.01	0	0	0.06	0.04	0.04
Mejametalana (Maseru district)	Missing	62	34	65	69	30	4	0	24	2	3	1	8	
	Expected	930	930	900	930	900	930	930	840	930	900	930	900	
	Proportion	0.07	0.04	0.07	0.07	0.03	0	0	0.03	0	0	0	0.01	0.03
Mohale's Hoek	Missing	93	140	135	124	165	176	124	140	171	121	124	164	
	Expected	992	992	960	992	960	992	992	896	992	960	992	960	
	Proportion	0.09	0.14	0.14	0.13	0.17	0.18	0.13	0.16	0.17	0.13	0.13	0.17	0.15
Mokhotlong	Missing	39	62	100	31	95	63	31	100	66	30	31	60	
	Expected	992	992	960	992	960	992	992	896	992	960	992	960	
	Proportion	0.04	0.06	0.1	0.03	0.1	0.06	0.03	0.11	0.07	0.03	0.03	0.06	0.06
Qacha's Nek	Missing	32	40	46	80	62	87	18	11	16	70	2	1	
	Expected	992	992	960	992	960	992	992	896	992	960	992	960	
	Proportion	0.03	0.04	0.05	0.08	0.06	0.09	0.02	0.01	0.02	0.07	0.00	0.00	0.04

Semonkong (Maseru district)	Missing	31	93	91	92	122	93	31	63	62	60	31	30	
	Expected	992	992	960	992	960	992	992	896	992	960	992	960	
	Proportion	0.03	0.09	0.09	0.09	0.13	0.09	0.03	0.07	0.06	0.06	0.03	0.03	0.07
Moshoeshoe 1 (Maseru district)	Missing	134	126	153	132	136	151	0	80	111	121	98	94	
	Expected	992	992	960	992	960	992	992	896	992	960	992	960	
	Proportion	0.14	0.13	0.16	0.13	0.14	0.15	0.00	0.09	0.11	0.13	0.10	0.10	0.11
Thaba-Tseka	Missing	72	62	120	73	74	93	51	54	31	63	73	71	
	Expected	992	992	960	992	960	992	992	896	992	960	992	960	
	Proportion	0.07	0.06	0.13	0.07	0.08	0.09	0.05	0.06	0.03	0.07	0.07	0.07	0.07