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Herding strategies under shifting rainfall conditions: implications for rangeland conservation and pastoralist livelihoods

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HERDING STRATEGIES UNDER SHIFTING RAINFALL CONDITIONS: IMPLICATIONS FOR RANGELAND CONSERVATION AND PASTORALIST LIVELIHOODS

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ABSTRACT

Understanding rainfall variability is of great importance in East Africa, where small-scale farmers and pastoralists dominate. Factors such as fire, herbivory and soil conditions also determine the spatial and temporal plant productivity, influencing livestock production and wildlife sustainability. This study focused on assessing pastoralist herding strategies under varying rainfall conditions as well as their implications to rangeland conservation and pastoralist livelihood. I conducted 241 household interviews, collected information from 52 participants of Participatory Rural Appraisal (PRA), and used rainfall archived data from the Ngorongoro Conservation Area Authority (NCAA) to assess pastoralists' perception and actual trends in rainfall, drought frequency, pasture availability, rangeland cover, and livestock production. I established four exclusion plots of 1 m^2 each within an area of 50 x 100 m at eight sites to quantify the effect of grazing and to estimate grass productivity across season and elevation. Single and multi-species groups of wild herbivores were recorded along road transects in human-dominated landscapes of the Ngorongoro Conservation Area (NCA) in two sampling periods (wet season: November–May and; dry season: June–October) in 2018-2019. Most (71%) pastoralists were aware of general climate change, rainfall variability, and impacts of extreme events on their livestock. The exclusion plots showed that aboveground primary productivity and recovery from grazing was driven by both rainfall ($F_{3, 4} = 19.165$, $p < 0.0001$) and elevation ($F_{2, 3} = 11.319$, $p = 0.023$). Wild herbivore group sizes (Mean ± SE) were larger during the wet (7 ± 1 browsers, 19 ± 2 grazers and 19 ± 3 mixed feeders) than during the dry season (3 ± 0 browsers, 13 ± 1 grazers and 13 ± 4 mixed feeders) and varied seasonally with distance to Ngorongoro crater, streams, and human settlements. The study concludes that rainfall variability and recurrent droughts are the major challenges to livestock production in NCA. Moreover, increasing livestock population and high dependence on grazing resources impact the potential of the rangeland to support livestock and wildlife. The study recommends that wildlife coexistence is crucial for the protection status of this man-and-biosphere reserve, however, the management should determine the optimal resource ratio and the level of stocking densities the rangeland can support.

Key words: Pastoralists, Primary productivity, Grazing, Livestock, Wildlife, Moveable Exclosures, Precipitation

DECLARATION

I, **Cecilia Martin Leweri**, do hereby declare to the Senate of The Nelson Mandela African Institution of Science and Technology that this dissertation is my own original work and that it has neither been submitted nor being concurrently submitted for degree award in any other institution.

Cecilia M. Leweri		04/08/2022
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The above declaration is confirmed by

Prof. Anna C. Treydte		04/08/2022
Supervisor 1	**Signature**	**Date**

Dr. Maurus J. Msuha		04/08/2022
Supervisor 2	**Signature**	**Date**

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CERTIFICATION

The undersigned certify that they have read and hereby recommend for acceptance by the Nelson Mandela African Institution of Science and Technology a Thesis entitled: “Implications for Rangeland Conservation and Pastoralist Livelihoods” and recommend for examination in fulfillment of the requirements for the degree of Doctor of Philosophy in Life Sciences of the Nelson Mandela African Institution of Science and Technology.

Prof. Anna C. Treydte		04/08/2022
Supervisor 1	**Signature**	**Date**

Dr. Maurus J. Msuha		04/08/2022
Supervisor 2	**Signature**	**Date**

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DEDICATION

This work is dedicated to my sons; Mark and Micah that they may be inspired to get highest levels of education in their life time. May this work inspire you positively, to have positive attitudes towards life and all it brings, to see opportunities and seize them, to be honest, to work hard and to be dedicated to achieve the best.

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LIST OF ABBREVIATIONS AND SYMBOLS

COSTECH	Commission for Science and Technology
FGD	Focus Group Discussion
GLMM	Generalized Linear Mixed Model
NCA	Ngorongoro Conservation Area
NCAA	Ngorongoro Conservation Area Authority
PRA	Participatory Rural Appraisal
TAWIRI	Tanzania Wildlife Research Institute
TLU	Tropical Livestock Unit

CHAPTER ONE

INTRODUCTION

1.1 Background of the problem

Rangelands comprise about 50% to 75% of the global land which incorporates natural grasslands, shrublands, savannas and deserts (Walker, 1993). They are characterized by variable supply of forage (Smith *et al*., 2010) due to low and variable precipitation. During moist seasons, most of these lands support large volumes of fodder with relatively high quality (Mbatha & Ward, 2010). The dry seasons, on the other hand, are characterized by scanty amounts of fodder which is also poor in quality (Smith *et al*., 2010). Their ecological dynamics are therefore strongly driven by shifting balances between a combination of soil characteristics and external drivers such as fire, rainfall, and grazing (Anderies *et al*., 2002; Bond & Keeley, 2005; Weber & Gokhale, 2011).

In most parts of Africa, rangelands are primarily used for wildlife management and livestock production practiced by pastoralists since they have diversified their herding strategies to cope with the dynamics and to adjust to climatic variability (Galvin, 1992; Opiyo *et al*., 2015). However, these strategies are increasingly becoming unsustainable because of a wide range of socio-economic, political and anthropogenic factors including increasing human population, a trend projected to continue (Brown & Thorpe, 2008; Holechek, 2009; Holechek *et al*., 2017; Talbot, 1986).

An increasing human population needs more food. Therefore, croplands have expanded, livestock numbers risen and habitats have become more fragmented (Brown & Thorpe, 2008; Holechek, 2009). Therefore, in most parts, the huge open tracks of drylands which facilitated the free movements of wildlife in search of water and forage are virtually gone (Reid *et al*., 2014; Sih *et al.*, 2011). This paradigmatic shift is being compounded by the climate change effects (Anwar *et al*., 2013; Howden *et al*., 2007).

Moreover, increased anthropogenic habitat fragmentation, land use changes and, climate change have altered the environment (Reid *et al*., 2014; Sih *et al*., 2011) and imposed pressure on rangeland resources. Such unstable environmental conditions have altered wildlife behavior (Van Dyck, 2012), reproductive success (Woodroffe *et al*., 2017), and can ultimately impact individual fitness and group sizes, particularly of larger mammals (Holdo *et al*., 2009; M'soka *et al*., 2017). Despite various attempts to tackle these complex interactions (Leong, 2010; Lischka *et al*., 2018; Morzillo *et al*., 2014), few models have included both the impacts of anthropogenic and environmental factors on wild herbivore behavior, group sizes, and their spatial habitat use, particularly in areas of multiple land use and protection (Bhola, *et al*., 2012; Kiffner *et al*., 2019; Knüsel *et al*., 2019).

Humans and livestock increase pressure on rangelands, and add to the complexity of their management, especially in areas where wild herbivores strongly interact with livestock (Baltazary *et al*., 2019; Ogutu *et al*., 2011). Interactions between livestock and wildlife may be both competitive or facilitative, depending on the species concerned, and on the seasonal availability of resources (Du Toit *et al*., 2010; Sitters *et al*., 2009). For example, wild herbivores coexist with domestic herbivores in few subsistence pastoral systems, where water points are abundant (Georgiadis *et al*., 2007; Sitters *et al*., 2009). However, high livestock densities can outcompete indigenous herbivores (Ogutu *et al*., 2010) and reduce wild herbivore group sizes (Butt & Turner, 2012; Prins, 2000) or cause long-term declines in the abundance and diversity of local wildlife (Reid, 2012; Riginos *et al*., 2012). This regularly happens during the dry season, when grazing ranges are constricted near available water resources and when overall forage quality is lower than during the wet season. Group size reduction may impact reproductive fitness of wild herbivores and, hence, their population dynamics (Markham *et al*., 2015; Rudolph *et al*., 2019). With the increasing human and livestock population, there is a pressing need for research concerning the ecology and management of wild herbivores, particularly their group sizes and behavior in relation to the changing environmental conditions.

Tanzanian rangelands play a crucial role in the national economy, they are the main sources of livelihood in semi-arid areas through pastoralism and agro-pastoralism (Boone *et al*., 2002; Opiyo *et al*., 2015; Selemani, 2014; Walker, 1993). They are highly populated with livestock making the country a third country in Africa with the highest number of livestock after Sudan and Ethiopia with an estimate of 25 million cattle, of which 98% are indigenous breeds (Selemani, 2014). Livestock production is the key contributor to exports and contributes to about 7.4% of the country's Gross Domestic Product (NBS, 2012). Additionally, rangelands offer a selection of different critical products, services and value including habitat, biodiversity, products such as charcoal, gums and resin, honey and traditional plant uses (medicine, etc), water production and aesthetic values (Herlocker, 1999). However, the presence of multiple users and multiple uses of the land and resources coupled with changes in rainfall patterns has resulted in complexity in management (Lankester *et al*., 2016; Selemani, 2014).

The Ngorongoro Conservation Area (NCA) is a world heritage and a multiple land use area, established in 1959, encompassing both wildlife conservation and economic development of resident Maasai pastoralists in Tanzania (Niboye, 2010; Rodgers & Homewood, 1986). The NCA illustrates, on a rather small scale, many of the biological constraints and responses characterizing rangelands and pastoralism in East Africa, balancing the competing needs of its multiple users (Boone *et al*., 2002). Livestock production is one of the principal economic activities in NCA and they specifically feed on natural savanna plants composed of scattered trees and shrubs; and annual herbaceous layer which grow in the wet season (Niboye, 2010).

The NCA is currently facing climate change driven challenges (Galvin *et al*., 2004), high human population growth rates (Masao *et al*., 2015), and wildlife-livestock competition attributed to localized overgrazing (GMP, 2010; Broch-Due *et al*., 2000). A large proportion of the NCA is semi-arid, with an average annual rainfall of less than 500 mm, hence, grassland productivity is low and the risk of overgrazing and death from starvation is high (Fyumagwa *et al*., 2007; Niboye, 2010; Reid, 2012; Swanson, 2007). Changes in rainfall patterns have further lessened rangeland productivity and availability, consequently squeezing livestock into smaller areas, making NCA unsustainable for livestock production (Galvin *et al*., 2004). According to Smit and Wandel (2006), the vulnerability to adverse impacts by climate change is higher in areas where the human dependence on the environment is higher.

1.2 Statement of the problem

Previous studies in Ngorongoro Conservation Area (NCA) recommended ways of improving the NCA policy in order to improve conservation efforts and pastoral livelihoods (Galvin *et al*., 1997; Potkanski, 1994; Thornton *et al*., 2003). Similarly, various studies on herbivores examined their population trends and assessed the seasonal stability of wild herbivore communities in the Ngorongoro Conservation Area (NCA) (Estes *et al*., 2006; Estes & Small, 1981; Moehlman *et al*., 1996). In addition, some research assessed how the exclusion of resident pastoralists and their livestock from the Ngorongoro crater would potentially affect wildlife herds (Sinclair & Arcese, 1995). However, there is no empirical information available that disentangles the adversities of rainfall variability on traditional pastoral livelihood strategies and its consequential impacts on rangeland productivity as well as wildlife group sizes of the Ngorongoro Conservation Area (NCA), an up to now successful biosphere reserve model of multiple land use (Homewood & Rodgers, 2004; IUCN, 1979).

1.3 Rationale of the study

Changing climate and variability trigger unpredictable shifts in the ecosystem, which hamper development on the African continent (Connolly-Boutin & Smit, 2016; IPCC, 2013). Available climate data suggest that nearly all key climatic variables have changed on the region in the course of the last century (Cook & Vizy, 2013; Shongwe *et al*., 2011) and the African continent is highly susceptible to such events, a condition intensified by the existence of other stresses, and communities that have a low capacity to adapt (Dunning *et al*., 2018; Judith *et al*., 2017). Climate variability is therefore an added challenge to livelihood strategies, which are inherently sensitive to such stresses, i.e. on rangelands where pastoralism is the main economic activity.

Several studies have reported discrepancy in the susceptibility to climate change and variability among developed and developing countries (Darwin & Kennedy, 2000; Parry *et al*., 2004), with the key impacts (i.e., recurrent food shortages, poverty, and loss of natural resources) occurring on the African continent. In East Africa, rainfall variability has evident wide ranging effects and its devastating impacts are agreed upon by researchers and policy makers but the extent of exposure differs locally (Funk & Verdin, 2010; Omondi *et al*., 2012; Williams & Funk, 2011; Williams *et al*., 2012).

Pastoralists are now suffering from the impacts of climatic tensions (Galvin *et al*., 2009; Msoffe *et al*., 2011) such as rainfall variability, prolonged periods of drought, delayed start and early stop of the rain seasons, and poor management of water have intensified the soil moisture stress problem and, hence, rangeland productivity. The rural underprivileged pastoralists in developing countries are, therefore, the most exposed to the effects of climate change and rainfall variability due to their overdependence on rangeland resources (Anwar *et al.,* 2013; Howden *et al*., 2007; IPCC, 2013). Similarly, the fewer and more unpredictable rainfall events associated with climate change in eastern Africa are therefore likely to reduce the amount of forage available to herbivores and might negatively affect their group sizes (Y. Cheng *et al*., 2011; Hopcraft, 2016; Mccollum *et al*., 2017). The reduced group sizes affect the social organization for ungulates living in herds (Barrette, 1991).

1.4 Research objectives

1.4.1 Main objective

The main objective of this study was to determine the effects of rainfall variability on pastoralist's livelihood strategies and its consequential impacts on rangelands productivity and wildlife group sizes in the pastoral areas of the Ngorongoro Conservation Area (NCA).

1.4.2 Specific objectives

(i) To determine pastoralists perceptions on rainfall variability and its influence on traditional pastoralist livelihoods strategies in the NCA;

(ii) To assess the trends in livestock production and herd sizes over the last ten years and how are they related to rainfall variability;

(iii) To understand the coping options and adaptation strategies by pastoralists to both the sudden-onset of extreme events and the more pervasive climatic change/variability;

(iv) To assess the seasonal changes in the aboveground biomass production and regrowth potential at the diverse elevation levels found within the transhumance system; and

(v) To determine the seasonality in wild mammalian herbivore group sizes and occurrence in response to environmental and human factors

1.5 Research questions

(i) What is the perception of NCA pastoralists towards rainfall variability and its impacts on their traditional pastoral livelihoods and rangeland conditions?

(ii) What are the trends in livestock production and herd sizes over the last ten years and how are they related to rainfall variability?

(iii) What are the drought adaptation and mitigation strategies of NCA pastoralists?

(iv) What are the seasonal changes in the aboveground biomass production and offtake of the diverse elevation levels found within the transhumance system of NCA?

(v) Are the wild mammalian herbivore group sizes affected by seasonality, landscape features, distance to human settlements or the number of livestock present in close proximity to the wildlife groups?

1.6 Significance of the study

This study highlights the significance of practicing rotational grazing during the periods of pasture shortages, among other adaptation measures to ensure long-term persistence and sustainability of pastoral communities. The study reveals how season, distances to the fully protected area of the NCA (NCA Crater) and distances to seasonal streams interactively shape the dynamics of wild herbivore group sizes in a multiple land use area. Understanding these is important as they provide an insight into potential impacts of different conservation management options and research priorities as well as for identifying the appropriate location of interventions. It also provides important data that can be used to draft an urgently needed livestock management plan in the NCA, where livestock numbers are rapidly increasing, threatening the wellbeing of residing native wildlife. The information on how rainfall and grazing pressure impact rangeland productivity will also be used to identify long term trends in livestock population development and for projecting an optimal livestock number that can be supported by NCA.

1.7 Delineation of the study

This study focused on assessing the effects of rainfall variability on pastoralist's livelihood strategies and its consequential impacts on rangelands. In addition, the study analyzed if wild herbivore group sizes were affected by (a) season, given the local climatic projections of greater rainfall variability, both within and between seasons; (b) landscape features such as distance to the fully protected area, i.e., the NCA crater, and distance to streams; (c) distance to human settlements; and (d) the number of livestock present in close proximity to the wildlife groups in the pastoral areas of the NCA. The study also assessed the seasonal dynamics of biomass production and consumption by wild and domestic herbivores across the diverse elevation levels found within the transhumance system of NCA. The study did not consider other aspects of climate change effects other than livestock production, and did not account for the group sizes of other wild animals rather than herbivores.

1.8 Conceptual framework

Rangelands are important providers of ecosystem services, they support both wildlife and livestock population and, hence, contribute to social traditions, economy and resilience of many communities (Coppock *et al*., 2017). Despite their importance, rangeland plant dynamics and, accordingly, wildlife and livestock production are highly sensitive to climate variability in terms of disease transmission (Rose, *et al.*, 2014), herd dynamics (Angassa & Oba, 2013) and forage (Bat-Oyun *et al*., 2016; Holdo *et al*., 2010). Moreover, rangeland sustainability is primarily determined by the ability of the local community to respond to or cope with climate impacts, i.e., adaptive capacity (Godde *et al*., 2020; Speranza *et al*., 2010). Therefore, to adequately assess and monitor the rangeland sustainability integration of socio economic aspects of the local communities, ecological perspectives and economic importance of the area is needed (Fox *et al*., 2009). This study, therefore, focused on ecological and socio-economic aspects of the rangelands; it summarized the criteria for ecological indicators, i.e., forage productivity, the biophysical indicators, i.e., rainfall variability, socio-economic indicators, i.e., number of livestock, grazing management systems and how the ecosystem will respond to the changing indicators, i.e., alternative form of rangeland/adaptive capacity (Fig. 1). If the indicators described above are monitored over time, it is expected that decision makers will be equipped with a set of data to ensure more informed decisions and social acceptability of those decisions.

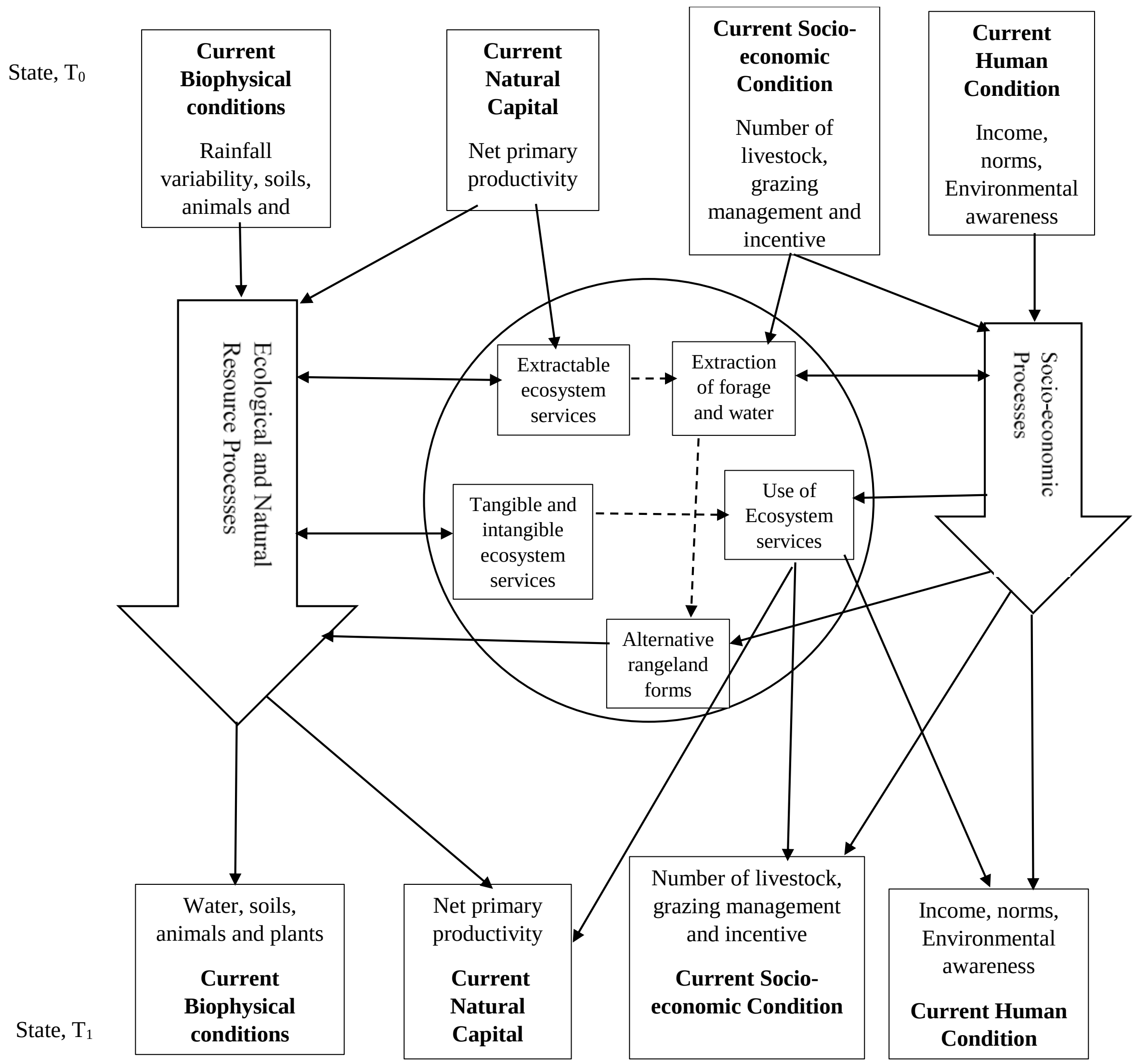

Figure 1: Integrated Socio - economic and Ecologic Conceptual framework for climate change effects on livelihoods and rangelands (Fox et *al.*, 2009)

CHAPTER TWO

LITERATURE REVIEW

2.1 Rainfall variability and rangeland conditions

Rainfall strongly influences human life styles and land use patterns (Marchant & Lane, 2014; Reid *et al*., 2014). As such, areas receiving a minimum of 700 mm of annual average rainfall are likely to be dominated by rain-fed agricultural activities whereas areas with highly variable rainfall regimes are dominated by pastoralism as the main livelihood strategy (Ogutu *et al*., 2008). The rural underprivileged pastoralists in developing countries are, therefore, the most exposed to the effects of the changing climate and rainfall variability (IPCC, 2013). In East Africa, rainfall variability has evident wide ranging effects and its devastating impacts are agreed upon by researchers and policy makers while the extent of exposure differs locally (Omondi *et al*., 2012; Williams *et al*., 2012).

As rainfall becomes more variable, plant tissues increasingly lignify, have lower digestibility (Giridhar & Samireddypalle, 2015; Minson, 1990) and change in composition towards less palatable species (da Silveira *et al*., 2015, Davis *et al*., 2000; Lonsdale, 1999). Therefore, supply of livestock feed remains a major challenge and is most likely to become worse (Kirkbride & Grahn, 2008; Thornton, 2010). Thus, appropriate steps need to be urgently taken, to ensure that the livelihoods of the many pastorals and agro-pastoral communities residing in these areas are improved.

2.2 Rangelands and pastoral use

Pastoralism and agro-pastoralism are persistent land use systems in most of the arid and semi-arid regions of sub - Saharan Africa (Turner & Schlecht, 2019; Unruh, 1990). These regions are characterized by variable rainfall, with mean annual rainfall ranging between 300 and 700 mm (Augustine & McNaughton, 2006; Godde *et al*., 2019; Msoffe *et al*., 2009; Sloat *et al*., 2018), usually concentrated in one or two wet seasons in a year separated by a relatively long dry periods. The pastoral production systems have consequently developed and, over centuries, have gathered traditional ecological knowledge to endure the harsh environmental conditions and exploit the temporary resources in a sustainable manner (Soma & Schlecht, 2018). While pastoralism refers to a production system, in which 50% of gross household income comes from livestock or livestock related activities, agro-pastoralism refers a production system in which more than 50% of gross household income comes from crop production and 10 - 50% comes from livestock (Homewood *et al*., 2012; Homewood & Rodgers, 2004; Thornton *et al*., 2007). However, to date, most pastoral communities have embraced farming or diversified to other livelihood systems, the most common systems being semi-pastoralism and agro-pastoralism (Lane, 1994).

2.3 Pastoral response strategies to impacts of climate change and variability

A number of methods have been established linking pastoral vulnerability and resilience, similar attentions have focused in what way the individual pastoral community responds given their resilience or vulnerability (Dong *et al*., 2011; Martin *et al*., 2016; McCabe, 2003; Opiyo *et al*., 2015). It is at this point where the notion of adaptation and coping have been used. Coping refers to utilization of possessed resources in response to food shortage that include changing livelihood strategies to improve livelihood security (McCabe, 1990; Webb, 1993). Additionally, Ellis (1998) defined coping strategies as response to a decrease in typical sources of livelihood, which include migration, selling household items, receiving food aid, diversification into numerous livelihood sources and reducing the rate of consumption. On the other hand, adaptation is characterized by regulating the whole system in a viable manner rather than dealing with few affected components of the system (IPCC, 2001, 2007, 2013). Thus, adaptation encompasses longer-term shifts, while coping involves transitory adjustment of livelihood strategies in response to shocks and/or stresses on livelihoods (Eriksen *et al*., 2005; Smit & Wandel, 2006). Agrawal and Perrin (2009, presented four diverse sets of adaptation strategies that are the most profitable to the pastoral community: mobility, storage of feed resources, diversification of livelihood strategies, and communal pooling.

Mobility as category of adaptation is a natural response to environmental threats and refers to the distribution of risk across space (Agrawal & Perrin, 2009). It is an opportunistic and traditional grazing management strategy employed by pastoralists in order to endure forage and variability in rangelands (Byakagaba *et al*., 2018; Oba *et al*., 1987; Müller *et al*., 2007). This nomadic life style facilitated periodic vegetation recovery from heavy grazing by domesticated animals (Behnke *et al*., 2011). Mobility in the NCA is established in order to balance the multiple environmental disturbances. Wet season grazing is carried out nearby the NCA village settlements to avoid the wildebeest breeding grounds. During the dry season, pastoralists use various remote grazing site locations, often far away from the village settlements (Leweri, Personal observation). Although rigorous, the seasonal migration of pastoralists is crucial for vegetation regrowth (Boles & Lane, 2016; Dwyer & Istomin, 2008). Livestock mobility allows herds to exploit unevenly distributed feeding resource concentrations (Oba *et al*., 2000) and, hence, this constitutes a traditional grazing management system.

Fodder storage reduces risks experienced over time, hence refers to the distribution of risk across time (Agrawal & Perrin, 2009). Storage as a response to climate change risks involves preservation of pasture and storage of fodder to ensure access to feed during vulnerable periods (Herrero *et al*., 2016; Speranza *et al*., 2010). However, this form of adaptation works best when combined with well-constructed infrastructure, high level of management across households and social groups, i.e., it is considered as an active measure, even where there is a complete livelihood failure (Agrawal & Perrin, 2009).

Diversification of livelihoods strategies also termed as the sharing of threats across asset classes owned by household or collectives (Agrawal & Perrin, 2009). It involves construction of household livelihoods from a range of activities and assets in response to climatic tension (Sabates-Wheeler *et al*., 2008). It is consistent to the extent that subsidy, which flows from assets, are subject to risks and risks have different impacts on the profit streams (Agrawal & Perrin, 2009). Although diversification within the pastoral activities (livestock species) has been the common practice in most households allover rural Africa (Megersa *et al*., 2014; Watson *et al*., 2016), diversification to non-pastoral (across sectors) is also becoming widely use, and options include cultivation, wage or salaried labor, trade and business (Achiba, 2018; Berhanu *et al*., 2007; Little *et al*., 2001; Opiyo *et al*., 2015). As a result, most pastoral communities have faced profound adjustments to their cultural environments to the extent that in some cases their local institutions are unable to quickly adapt to the new challenges, leading into degradation of communally owned resources including the range lands (Dong *et al*., 2011; McCabe *et al*., 2014).

Communal pooling refers to spreading risk across households, which encompasses joint ownership of resources and assets (Agrawal & Perrin, 2009). Pastoralist livelihood strategies have been referred to as naturally self-destructive over the long term according to Hardin (1968) "tragedy of commons", which has been strongly challenged by politicians and anthropologists (Feeny *et al*., 1990; Ostrom, 1990). Research has demonstrated success in jointly and wisely managing communally owned lands over long periods of time, thus, challenging the `tragedy of commons` ideology (Dietz *et al*., 2002; McCabe, 1990; Ostrom, 1990). Communally pooled assets are valuable assets that are accessible to more than one party benefitting all (Dietz *et al*., 2002).

2.4 Barriers to response strategies to climate change and variability impacts in NCA

Mobility and resource partitioning have been successful herding strategies in most pastoral societies for centuries (Lankester *et al*., 2016; Martin *et al*., 2016). However, recent socio-ecological pressures through an increased human population (NBS, 2013; Slootweg, 2018) have restricted movement/tenure system and threats of eviction. It is well understood among the pastoral community that forage is a basic ecological need to pastoral livelihoods, and its availability directly influences their income (Hauck & Rubenstein, 2017; Tessema *et al*., 2014). However, there is pronounced increase and spread of unpalatable invasive plant species in the NCA which further reduce the rangeland quality for both wildlife and livestock (Ngondya *et al*., 2019). Consequently, the majority of pastoralists have changed their livestock selection into small ruminants preferably sheep and goats (Leweri *et al*., 2021). Continuous changes in herding strategies and the rangeland condition of the NCA could impact livestock production, a crucial livelihood of the community.

2.5 Impact of grazing and rainfall on herbaceous vegetation

Rangelands comprise domestic and wild herbivores and, hence, herbaceous vegetation yield becomes the key forage for their survival and nutrient cycling (Augustine & McNaughton, 2006). Regardless of benefiting from the available forage and nutrients, herbivores affect herbaceous productivity differently; ranging from positive, where rangelands have co-evolved with grazing and resilient to it (Augustine & McNaughton, 2006; McNaughton, 1985; McNaughton *et al*., 1996; Noy-Meir, 1995) to negatively, through reduction of photosynthetic area and physical damage through trampling (Frank *et al*., 2018; Fynn & O’Connor, 2000; Zhang *et al*., 2005). Rainfall, conversely, is a major factor driving plant community composition and productivity, especially in arid and semi-arid environments (Knapp & Smith, 2001; Hamann & Wang, 2006) hence a critical driver of rangeland dynamics (Ellis & Swift, 1988).

Understanding rangeland dynamics has gained great popularity in recent years (Briske *et al*., 2003; Van de Koppel *et al*., 2002; Walker, 1993) and a number of hypothesis on the impacts of grazing on grass productivity have been developed (Briske *et al*., 2003; Ellis & Swift, 1988; Illius & O’Connor, 2000; Richardson *et al*., 2005). Moreover, in climatically variable ecosystems, impact of grazing and rainfall on herbaceous vegetation production remains uncertain (Oba *et al*., 2001). Integrating grazing and rainfall experiments with natural productivity has been therefore a useful way of assessing both short and long-term plant community dynamics to provide informed conclusions about grazing and rainfall variability affecting plant communities (Dunne *et al*., 2004; Fraser *et al*., 2009).

2.6 Livestock grazing together with wild mammalian herbivores

Group size and composition are the most basic elements of social organization for ungulates living in herds (Barrette, 1991). Theoretical frameworks explaining variation in group size assume that there is a trade-off amongst fitness relevant expenses and profits and that individuals maintain membership in groups of optimal sizes to maximize fitness (Gueron & Levin, 1995; Markham *et al*., 2015; Pulliam, 1973; Shen *et al*., 2014). There are different optimal group sizes for different species and purposes, e.g., for feeding (Golabek *et al*., 2012), as anti-predator strategy (Baltazary *et al*., 2019; Cooper, 1991; Creel, 2011; Fitzgibbon, 1990; Roberts, 1996) or for reproduction (Bro-Jørgensen & Durant, 2003). In some African ungulates, for example, group sizes and their spatial distributions vary temporarily with season as rainfall governs the quantity and quality of vegetation (Bergström & Skarpe, 1999; Boone *et al*., 2006; Mduma *et al*., 1999). Despite of the significance of long lasting population monitoring and studies on population dynamics and movements (Boult *et al*., 2019; Codling & Dumbrell, 2012; Fryxell *et al*., 2004; Pachzelt *et al*., 2013; Taylor & Norris, 2007), the latter have not yet addressed how livestock feeding affects wild mammalian herbivore group sizes in pastoral and protected areas for conservation planning (Prins, 2000).

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study Area

The study was conducted in four wards of the NCA, a UNESCO World Heritage site in northern Tanzania (3°14'29.56"S and 35°29'16"E; Fig. 1) with a total size of 8256 km^2 (UNESCO, 1979). Ecologically, the area is categorized in three zones; lowlands, midlands and highlands (Galvin *et al*., 2008), and its climatic zones span from semi-arid to montane forest climate, with average annual precipitation between 500 mm up to 1700 mm (Niboye, 2010). Rainfall in NCA is highly seasonal and spatially variable. The eastern slopes of the crater highlands receive on average about 1200 mm/year, whereas the midlands receive about 800 mm/year and the lowlands receive only 400 mm/year (Boone *et al*., 2007). Average annual temperatures lie between 2 °C and 35 °C (Niboye, 2010). The selected four wards: Endulen (midlands), Nainokanoka (highland), Olbalbal (lowlands) and Ngorongoro (Midlands) covers a large elevational levels and varying distances to the fully protected area, i.e., the NCA crater (Fig. 2). The NCA crater fully excludes pastoralists and their livestock herds, whereas other parts of the NCA are shared by both pastoralists and wildlife. This study complied with Tanzanian Wildlife Research Institute (TAWIRI) ethical regulations and permission was granted from both TAWIRI and the Tanzanian Commission for Science and Technology (COSTECH).

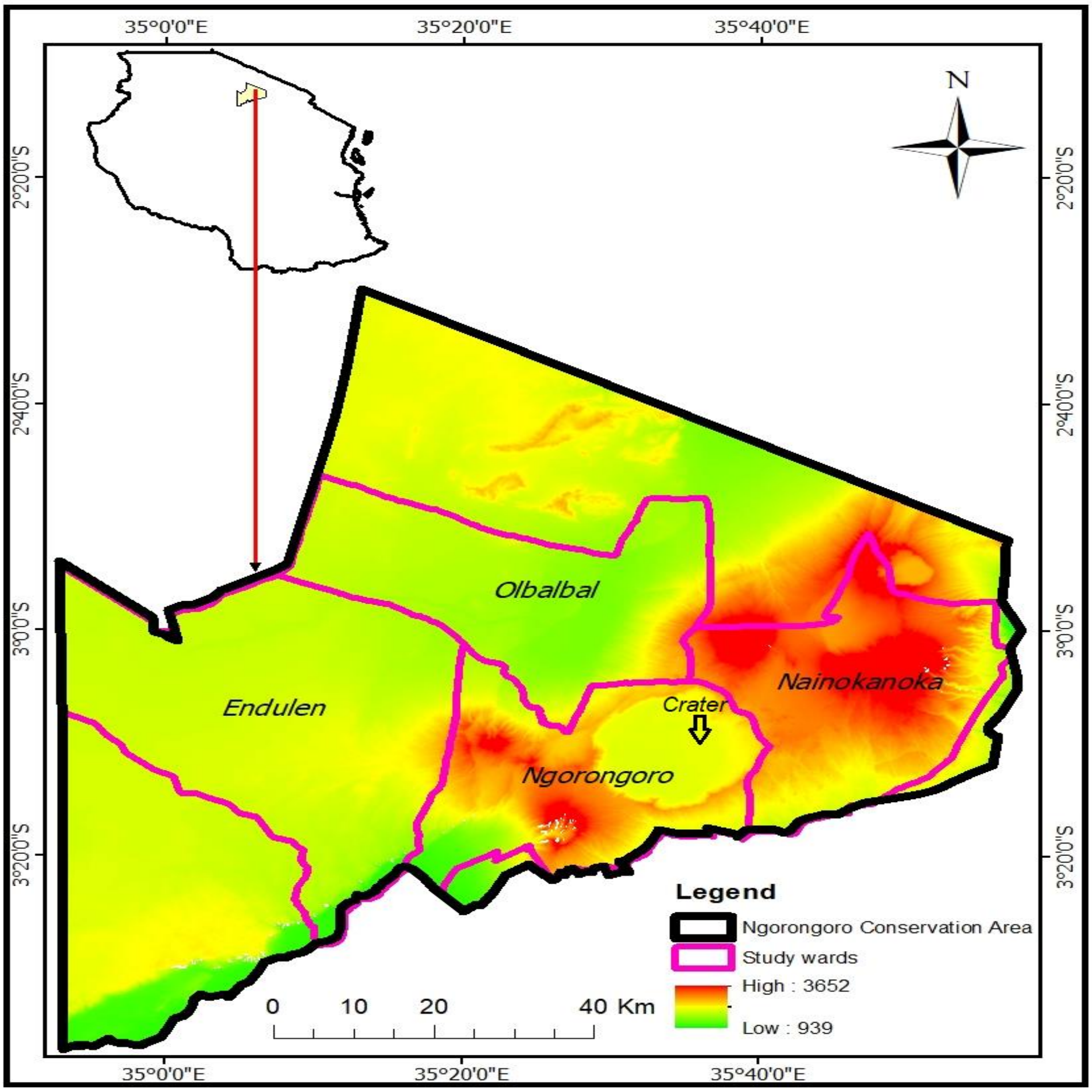

Figure 2: Map of Ngorongoro Conservation Area, Northern Tanzania, showing the four wards selected for this study

The central economic activities in the NCA are livestock keeping and tourism (Melita & Mendlinger, 2013). The livestock species are cattle (*Bos taurus*), goats (*Capra aegagrus hircus*), sheep (*Ovis aries*) and donkeys (*Equus asinus*) whereas the principal wild mammalian herbivore species include plains zebra (*Equus burchelli*), common eland (*Tragelaphus oryx*), blue wildebeest (*Connochaetes taurinus*), African buffalo (*Syncerus caffer*), Grant's gazelle (*Gazella granti*), Thomson's gazelle (*Gazella thomsonii*). Giraffe (*Giraffa camelopardalis*), black rhino (*Dicerosbicornis*) and African elephant (*Loxodonta africana*) are less common in the pastoral areas of the NCA (Odadi *et al*., 2011).

3.2 Research design and procedure

A longitudinal research design, a repeated observations of the same variables over short or long periods of time (Caruana *et al*., 2015; Singer & Willett, 2003) was adopted and baseline information was gathered in March 2018. Follow up data were collected after every three months for a period of 12 months in order to capture the seasonal cycle of vegetation production and removal at the different elevation levels found inside the transhumance grazing scheme. The approach was preferred over the cross-sectional method because it allows collecting information about seasonal trends (Farrington, 1991; Caruana *et al*., 2015) Statistical analysis were carried out using different packages in R version 3.1.6 (R Core Team, 2018).

3.3 Socio-economic data collection

A multistage sampling was used to select the eight villages (two from each of the fours study ward) for the survey so as to ensure collection of information from areas which differ in terms of human density, pasture quality, wildlife numbers and distribution, access to tourism activities and availability and access to social services. Sample households were randomly drawn from a list of household heads available in the respective village. A sample of 5% of the village population was interviewed (Fox *et al*., 2009). A household was defined as a unit which, comprises individuals who live together within a single compound whose production and consumption activities are done together (Fox *et al*., 2009). Information reported in this section consists of data collected based on a case pastoralists' perceptions and experiences on rainfall variability, rangeland condition and livestock production. Focus group discussions (FGD) and individual questionnaires informed on the perceived changes in rainfall pattern, rangeland condition and livestock production.

3.4 Focus group discussion (FGD)

Four Focus Group Discussion (FGD) meetings (Plate 1 (A & B) were conducted in each of the four wards with eight to twelve participants (Braun & Clarke, 2013; Guest *et al*., 2006), in March, 2018. The participants for the FGD were village executive leaders including village elders, most of whom were cattle owners. All participants were formally invited by the Ward Executive Officers (WEO) in advance of the group meetings. Focus Group Discussion meetings were carried out by the main researcher and one research assistant, who helped in setting up the meetings and taking notes during discussions. A checklist was used to facilitate the discussions. Pastoralists were asked to rank the concepts for each topic under discussion according to how important they were in their contexts. All discussions were conducted in Swahili language, audio-taped and later transcribed into English.

Plate 1 (A & B): **A group of pastoralists in Focus Group Discussion (FGD) meetings in Endulen (A) and Nainokanoka (B) wards (Fieldwork, 2018)**

3.5 Questionnaire survey

A structured questionnaire was used to collect information on the social economic status of the pastoralists concerning the rainfall variability, rangeland condition and livestock production. A total of two hundred and forty on (241) household heads were interviewed between March and June, 2018. The consent for participation in the survey was sought before administering questions where the researcher explained the reason for asking questions and request for a pastoralist's permission. All individuals interviewed during the survey were household heads who lived in the area for a minimum of ten years.

3.6 Determination of pastoralists perception on rainfall variability and its influence on traditional pastoralist livelihoods strategies in the NCA

This objective aimed to documents the perception of the NCA pastoralists towards rainfall variability and its impacts on their traditional pastoral livelihoods and rangeland conditions. It was hypothesized that pastoralists will perceive reduced lengths of rainfall seasons and more frequent droughts as the main indicators of rainfall variability and that drought incidents will be reflected by massive cattle die off, but will be less visible for sheep and goats, similar to what has been recorded in Ethiopia (Angassa & Oba, 2013) and South Africa (Vetter *et al*., 2020).

3.6.1 Survey of pastoralists perception

During the household interviews, interviewers asked respondents to reply to questions concerning rainfall variability, drought incidence, forage and water availability and rangeland cover. Information collected during the focus groups discussions included the trends in climate incidents, perceived changes in rangeland condition and grazing initiatives to adapt to shifting rainfall. This information was complemented with the long-term rainfall data (1967 – 2018) acquired from the Ngorongoro Conservation Area Authority (NCAA).

3.6.2 Statistical analysis

Rainfall patterns, demographic characteristics of the households and the pastoralists perceptions on climate variability were presented using the descriptive statistics. The Standardized Precipitation Index (SPI) was calculated using the SPI package in R version 3.1.6 (R Core Team, 2018). This index reflects the number of standard deviations, by which the observed cumulative rainfall differs from the long term mean and is reflected as an applicable method for monitoring droughts in East Africa (Ntale & Gan, 2003). Monthly precipitation time series were also aggregated annually and in monthly trimesters as December–January–February, March–April–May, June–July–August and September–October–November, which correspond to short dry, long rain, long dry and short rainy season, respectively, to observe potential changes at the seasonal scale. HydroTSM package (Zambrano-Bigiarini, 2020) in RStudio was used because of its capability functions in the management, analysis, interpolation and plotting of time series from daily and monthly data.

A logistic regression model was further used to test whether age group (three age groups, 18 – 35, 36 – 55 and 56 – 75 years), education level (access to information and technologies as primary and secondary education) and location of the village (lowlands, midlands and highlands) affects the perception of pastoralists on changes in climate and its variability. The selection of these factors carefully focused on the view that they govern a pastoralist's understanding and ultimate response to climate variability. To assess the factors which influence pastoralists perception on rainfall variability, the following variables were used change in precipitation (ChangePrecip), change in the length of rainy season (LengthRainS), droughts occurrences (DroughtOcc), availability of grazing land (GrazingAvail), grassland vegetation cover (VegCov) and grass species diversity (GrassSpecDiv). The drop1 function was further used to select the most influential variables based on *p*-value and the likelihood ratio test (LRT). Y was the dependent variable, denoting either change or no change in the perceived conditions. The general model is:

$Y=b_0 + b_1X_1 + b_2X_2+\ldots\ldots\ldots +b_nX_n$ …………………… (*Equation 1)*

Where Y= represents either no use of a herding strategy (0) or use of a herding strategy (1), b_0 is the intercept, b_1 to b_n are regression coefficients, and X_1 to X_n are perceptions selected to be tested against climate change factors.

Information from the FGD were transcribed, sorted and coded into their appropriate categories. The critical opinions were used to complement the household information.

3.7 Assessment of the trends in livestock production and herd sizes over the last ten years and how are they related to rainfall variability

This objective explored the trends in livestock production and herd sizes to portray rainfall variability as one of the drivers of livestock dynamics.

3.7.1 Survey on pastoralists livestock production and herd sizes

Household heads were asked questions on socio-demographic aspects of the households, including livestock numbers and limitations to livestock production. This information was complemented with the long-term livestock data (1967 – 2018) acquired from the NCAA.

3.7.2 Statistical analysis

Descriptive analysis for the structured (closed) household questionnaire was performed using frequency tables. Livestock production was analysed from the livestock number owned by household and complemented by livestock trend data based on Ngorongoro Conservation Area Authority (NCAA) archived data spanning from the years 1967 to 2017 and were complemented by rainfall datasets. I assessed the change in proportion between cattle and shoats in that time period and described the reasons for the observed change. To quantify the different livestock types and sizes, the Tropical livestock Unit (TLU) was used, with 1 TLU = one cow with a body weight of 250 kg (Chilonda & Otte, 2006). TLU measurement can help assessing rangeland carrying capacity and stocking rates through quantifying the different fodder consuming domesticated animal species (Rothman-Ostrow *et al*., 2020). The commonly used TLU in eastern Africa are cattle = 0.7, sheep = 0.1, goat = 0.1, pig = 0.2 and chicken =

0.01 (Jahnke, 1982). Regression analysis was used to assess the relations between livestock populations and rainfall variability.

3.8 Understanding the coping options and adaptation strategies by pastoralists to both the sudden-onset of extreme events and the more pervasive climatic variability

This objective aimed to understand the coping options and adaptation strategies by pastoralists on the sudden onset of extreme evets and more pervasive climatic variability. It was also hypothesized that the mean livestock mortality rates will decrease with intervention measures (supplemental food and mobility) and demographic variables (herd and household size) because pastoral communities tend to keep large herds as a strategy to cushion the family from climatic and environmental shocks, and big household sizes to distribute labour among them.

3.8.1 Survey of pastoralists perception

Household interviews included questions on herd mobility and intervention measures taken to reduce the impact of droughts and associated livestock mortalities.

3.8.2 Statistical analysis

As analysis of the rainfall data indicated a drought during the 2015-2016 period (see details in Chapter 4), a logit model was used to identify factors influencing cattle deaths during this period using the variables "number of cattle owned before drought", "supplemental feeds" and "household size":

$$log[P_{ij}/(1 - P_{ij})] = \gamma_0 + \gamma_1 x_{1j} + \gamma_2 x_{2j} + \gamma_3 x_{3ij} \text{ ……………… } (\textit{Equation 2})$$

Where P_{ij} is the likelihood of death of cattle in a herd the j household (P_{ij} =1 death occurrence and 0 otherwise), γ_0 is the intercept, γ_1 to γ_5 are regression coefficients, x_{1j} is the pre-drought cattle herd size, x_{2j} is the size of the family, x_{3j} is feed supplementation (x_{3j} =1 supplemented herds and 0 otherwise). For herds that experienced mortalities during a drought, mortality rate was computed as the number of dead cattle divided by the number of cattle owned before the drought year. A generalized linear model (GLM) with poisson distribution was further used to identify factors which influence variation in mortality rate.

3.9 Assessment of the seasonal changes in the aboveground biomass production and regrowth potential at the diverse elevation levels found within the transhumance system

This objective explored the seasonal changes in the aboveground biomass production and regrowth potential at the diverse elevation levels found within the transhumance system. It was hypothesized that the caged plots will yield more biomass than the uncaged due to limited grazing pressure and that the midlands will be more productive compare to the highlands and lowlands because productivity is strongly linked to rainfall seasonality and amount, and expected higher productivity with higher rainfall, with a peak in the onset of the rain season followed by a saturation in productivity toward higher rainfall levels. The midlands of the NCA receive rain relatively frequently and are relatively moist compared to the highlands, which are cold and dry and the lowlands, which are hot and dry.

3.9.1 Collection of the herbaceous standing biomass and residual aboveground biomass

Clipping experiment that simulated herbivory was carried out in eight sites (Fig. 3) from April 2018 to March 2019. To measure the consequence of grazing, the difference in standing biomass between the caged and un-caged plots was attributed to removal by grazing mammalian herbivores (Mbatha & Ward, 2010). Four caged plots of 1 m^2 each were established within an area of 50 x 100 m of the eight sites, two in each ward named Nainokanoka (highlands), Olbalbal (lowlands) and Ngorongoro and Endulen (midlands), and one in each village (a total of n = 32 exclusions per season). The selection aimed at a proportional sampling of grazing lawns within the open grassland defined by < 5% tree and shrub cover and devoid of large bushes and trees of > 4 m height (Stähli *et al*., 2015). Grazing lawns are distinct grassland community type, characterized by short-stature and with their persistence and spread promoted by grazing (Hempson *et al*., 2015).

The overall time-period encompassed one long rainy season, one short rainy season, one short dry season and one long dry season. Clipping was done after every three months using a moveable cage technique (McNaughton *et al*., 1996). During the initial clipping date (March 2018), the herbaceous vegetation of four randomly selected quadrats were cut to ground level, and 1 x 1 m (Plate 2) cages were established over four other, randomly selected quadrats. Feeding was allowed on the un-caged quadrats, whereas the caged quadrats remained un-grazed during each assessment period. At each clipping session, vegetation within the four caged quadrats was cut. At the same time, herbaceous vegetation of other four randomly selected un-caged plots were cut at the beginning of the experiment to allow estimation of forage production, biomass and removal through grazing.

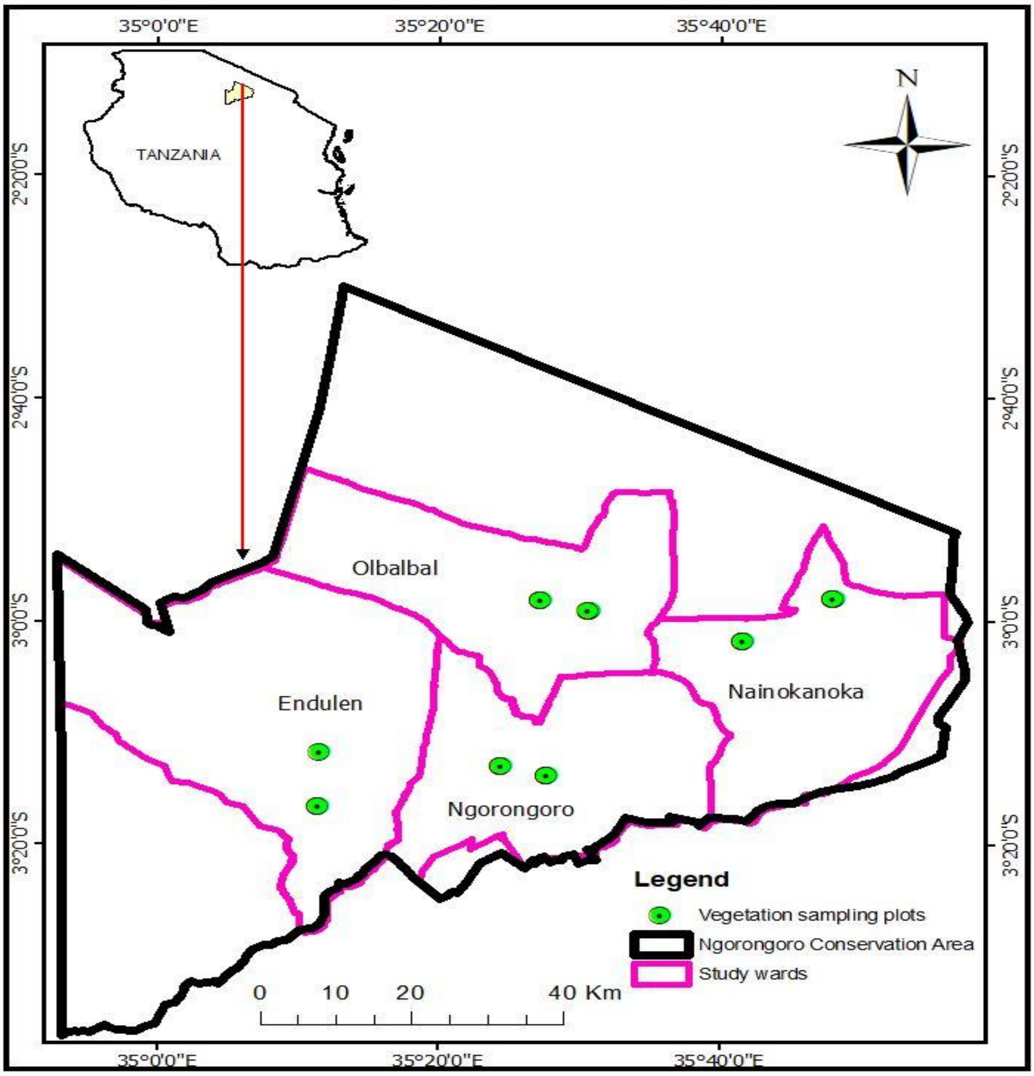

Figure 3: Map of Ngorongoro Conservation Area, Northern Tanzania, showing locations of clipping experiment sites in the selected wards; Nainokanoka, Ngorongoro, Endulen and Olbalbal

After every three months, the four enclosures were then mounted over four new, randomly selected (unclipped) quadrants, that were maximum of one meter away from the initial point, and the whole process was repeated at each clipping date (Charles *et al*., 2017). All herbaceous biomass was cut to ground level. The clipped materials were collected in paper bags, left to dry until a constant weight was reached (<3 d) (Stähli *et al*., 2015) and then weighed using a digital balance scale.

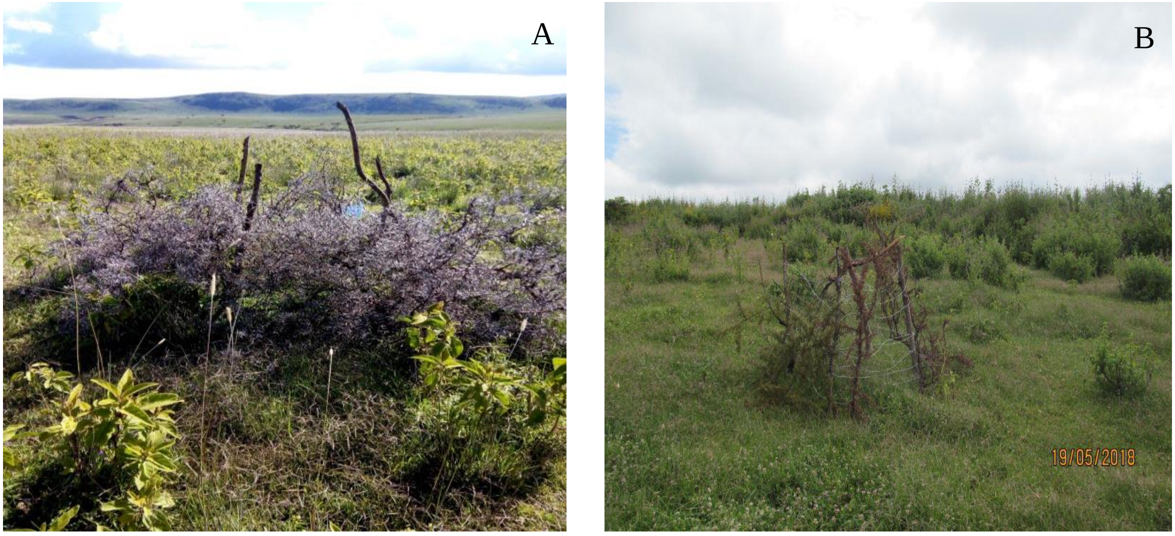

Plate 2 (A & B): Experimental set up of grazing exclusion treatments in Olbalbal (A) and Endulen (B) in the Ngorongoro Conservation Area (Fieldwork, 2018)

3.9.2 Estimation of off - take by herbivores and biomass productivity

The estimated off-take by herbivores (Off Herb) was calculated as the change between the standing biomass in caged and un-caged treatments (Keya, 1997; Mbatha & Ward, 2010). Following McNaughton (1985), I further derived foraging intensity as (GrazInt) as [1 - (un-caged/caged)] aboveground biomass at the end of each sampling time. Foraging intensity was defined as the collective effects foraging animals have on rangelands throughout a particular time period (Augustine & McNaughton, 2006). The resulted metric of 0 to 1 reflects the extent of pressure put forth by the herbivores on the herbaceous aboveground biomass during a particular time period. The index was set to zero when grazing does not reduce plant biomass below control levels and will approach one as grazing increase. The metric indexes were further used to provide the three pre-established grazing intensity categories based on the percentage utilization of the palatable grass and sedge herbage; lightly grazed (<20%); moderately grazed (20 – 50%); and heavily grazed (> 50%) (Holechek *et al*., 1998).

Total productivity was calculated as the variation in dry weight biomass of the caged plots between the end of a sampling time and the first dry weight biomass of an adjacent un-caged plot at the start of the period (equation 3). For subsequent sampling times, biomass clipped in the un-caged plot was used as the first biomass estimate for the next period. Due to variability between covers in caged and un-caged plots, sometimes biomass of the caged treatment would be less than the un-caged treatment, and so the data also includes negative productivity values, this is also demonstrated by Charles *et al*. (2017).

$$Productivity\ (gm^{-2}day^{-2}) = \frac{Dry\ biomass\ Caged_{t1}(g) - Dry\ biomass\ Un{-}caged_{t0}(g)}{harvest\ period\ (days)}\ (Equation\ 3)$$

3.9.3 Statistical analysis

Data on the aboveground biomass was tested for normality using the Shapiro Wilk test ($P \leq 0.05$) and log transformed to reduce heteroscedasticity. Statistical differences between the grazing treatments (un-caged, caged) at different elevations and seasons was tested using a Linear mixed model with Restricted Maximum Likelihood function (REML) (Virk *et al*., 2009). The seasonal differences in aboveground biomass were examined by using model which employed 'elevation * treatment (caged/uncaged)' and 'season * treatment (caged/uncaged)' as fixed effects. To justify the non-independence structure of the data site was included as a random effect structure. Because the experimental setup has repeated measures, I used a temporal auto-correlation. Bonferroni post-hoc was further used to test the effect of Treatment*Elevation on the aboveground biomass. Accumulated total productivity, was also analyzed using linear mixed models similarly as the aboveground biomass.

To examine the elevations or seasons when grazing treatments had a significant effect a Tukey Honest Significant Difference (HSD) method that controls Type I error was applied. To test whether the aboveground biomass of particular seasons differed significantly with that of previous season Planned contrasts ($P = 0.05$) were undertaken using a 2-sided t-test and the overall LMM mean squared error for each treatment.

3.10 Determination of the seasonality in wild mammalian herbivore group sizes and occurrence in response to environmental and human factors

This objective explored the seasonality in wild mammalian herbivore group sizes and occurrence in response to environmental and human factors. I hypothesized that larger wild herbivore groups will be formed during the wet season than during the dry season, i.e., when forage is abundant, and water is generally close by. It was expected that larger groups will be formed closer to the streams due to the higher availability of water and food compared with areas further away from streams (de Boer *et al*., 2010; Redfern *et al*., 2003). Furthermore, I expected that groups will be larger in areas of low competition with livestock, away from settlements.

3.10.1 Observation of wild and domestic herbivores group sizes

Group sizes of wild herbivores were recorded during the four sampling periods that traversed each season (Wet: November–May and; dry: June–October) in 2018-2019. Four roads were chosen as transects, each of those transects visited four times during the entire study period. Each transect covered the following lengths and elevation: Transect 1 covered 55.8 km length and was distributed across an average (±SD) elevation of 2097 ± 288 masl; transect 2 covered 68.1 km and 1659 ± 281 masl; transect 3 covered 35.9 km, and 1337 ± 58 masl; and transect 4 covered 56.5 km and 2448 ± 90 masl. Roads were repetitively sampled using the road strip census method, where animals were counted from the car within a certain strip width (Hirst, 1969). The car was driven at a constant speed of 25 km/h for six hours each day, 3 h in the morning (07:00 – 10:00 h) and 3 h in the evening (15:30 – 18:30 h) (Varman & Sukumar, 1995).

Observations of wild mammalian herbivore groups were restricted to distances within 250 m from the road to enhance visibility. For each sighting, I recorded the GPS coordinates, counted the number of individuals in the group (defined as individuals within 50 m of each other), and used a rangefinder (Bushnell Elite 1500) to measure the perpendicular distance between the location of wild herbivore group and the observer. The distances of all observed wild mammalian herbivore groups to the Ngorongoro crater rim, the nearest boma, i.e., livestock enclosure, settlement, and the nearest stream were obtained using QGIS version 3.6.

As the sample sizes for groups of some individual species were rather low the wild herbivores were categorized into browsers, i.e., giraffe (*Giraffa camelopardalis*), into grazers, i.e., zebra (*Equus burchelli*), wildebeest (*Connochaetes taurinus*), and buffalo (*Syncerus caffer*), and into mixed feeders, i.e., Grant’s gazelle (*Nanger grantii*), and Thompson’s gazelle (*Eudorcas thomsonii*) (Estes & Otte, 2012). Livestock groups were categorized into “cattle” and “shoats”, i.e., both groups of sheep and goats, since it was difficult to distinguish the two species in large mixed herds. In addition, I used a dataset of boma locations collected by the Tanzania Wildlife Research Institute (TAWIRI) during an aerial census in the year 2016 and refer to them as settlements.

3.10.2 Statistical analyses

A generalized linear mixed model (GLMM) was applied to analyse the potential effects of season (wet vs dry), distance to the NCA crater, distance to streams (seasonal rivers in the ecosystem), elevation, livestock herds in close proximity and distance to settlements on group sizes of wild herbivores. To account for repeated samples from the same transects, transects was nested in seasons and included them as a random factor. Sampling date was further included as a random factor that was partially crossed with transects. It was nested because the same transects were surveyed in different seasons and crossed because some road sections belonging to particular transects had to be traversed in order to get to another transect (Schielzeth & Nakagawa, 2013). All pair-wise correlation coefficients between the metric variables were no less than -0.4 and no more than 0.4, indicating low levels of co-linearity (Agresti *et al.*, 2013).

A zero-truncated negative binomial regression model was applied because the observed group sizes were always larger than zero and the empirical histogram indicated that the data was strongly over-dispersed (Zuur *et al.*, 2009b). The positive negative binomial distribution was given by:

$$f(y_i; k, \mu_i | y_i > 0) = \frac{\frac{\Gamma(y_i+k)}{\Gamma(k)\times\Gamma(y_i+1)}\times(\frac{k}{\mu_i+k})^k\times\left(1-\frac{k}{\mu_i+k}\right)^{y_i}}{(1-(\frac{k}{\mu_i+k})^k)} \qquad (\textit{Equation 4})$$

where y_i are the $i = 1, 2, \ldots, n_i$ observed wild herbivore group sizes, Γ is the gamma function, μ_i is the mean of the ordinary binomial distribution and k is the dispersion parameter (Zuur *et al.*, 2009c, 2009b).

The initial model (Appendix 1, S 1.) was based on the theory that variation in the environment, human activities, and competition with livestock affect the availability of resources that enable wild herbivores to form groups (du Toit *et al.*, 2017). Wild herbivore group sizes were analysed in relation to their feeding guilds and season. Interactions between season and human, environmental and livestock variables was also incorporated in the initial model because it was expected that these covariate effects may vary seasonally (Table 1). The perpendicular distances of animal groups to the observer were accounted for because herbivore group sizes could have been affected by the presence of a vehicle and closeness to roads (Appendix 1, Table 1).

Backwards selection of variables with the lowest P-values using the drop1 function was further used to select the most influential variables using Likelihood Ratio (LR) tests (Zuur *et al.*, 2009a). Variables were deleted from the full model (Appendix 1, S 2 – 7 and Table 2 - 7.) starting with interaction and main effects of the variables with the highest *P*-values until all remaining variables had *P*-values below 0.05 (Ratner, 2010). Throughout the process, we kept distance to the observer as a confounding variable in the model.

During the selection procedure, seasonal interaction effects for sheep and goats were eliminated first (Appendix 1, S 2), followed by the main effect of sheep and goats (Appendix 1, S 3), seasonal interaction effects for cattle (Appendix 1, S 4) and the main effect of cattle (Appendix 1, S 5). The last variables to be eliminated were seasonal elevation effects (Appendix 1, S 6) and finally the main effect of elevation (Appendix 1, S 7). Distance to observer was always maintained in the model during the variable selection process to account for a potentially confounding road effect on animal group sizes.

Wild herbivore group sizes were predicted from the reduced model (Appendix 1, S 7.) in relation to the environmental, human and livestock variables for each feeding guild and season. Post hoc Tukey HSD Pairwise comparisons were applied for group size differences between feeding guilds. The positive negative binomial models were implemented via the glmmTMB R-package.

Table 1: Description of variables used to model the group sizes of wild herbivores in response to environmental variables, human settlements, and livestock presence in the Ngorongoro Conservation Area (NCA), Northern Tanzania

Variable Name	Category	Data range (min - max)
Distance to streams (km)	environment	0.0 - 7.5
Distance to the NCA crater (km)	environment	0.3 - 31.7
Elevation (masl)	environment	1288 - 2654
Number of cattle in close proximity	livestock	1 - 250
Number of sheep and goats in close proximity	livestock	1 - 842
Distance to nearest settlement (km)	human	0.1 - 5.6
Dry season versus wet season	season	

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Results

4.1.1 Pastoralists social and economic status, rainfall patterns and variability

(i) Pastoralists social and economic status

Participants engaged in the study included 82% (n=197) men and 18% (n=44) women, most of them (62%) were within the age of 36−55 years, followed by 29% being 18 - 35 years old, 6% were 56 – 75 years old and the rest (4%) were older than 75 years. Most (80%) households consisted of up to ten family members. About half of respondents (52%) were literate, the dominant level of education being primary education (49%, n=118). Primary income generating activity was livestock keeping in 95% of the households compared to tourism activities, employment and small business which scored less (Table 2).

(ii) Rainfall patterns and variability

The study area had a bimodal rainfall characteristic with mean (±SD) monthly rainfall of 73.5 ± 84.3 mm over the years from 1967 to 2018 (Fig. 4). The Standardized Precipitation Index (SPI) showed prolonged moderate dry weather periods ($-1.29 \leq$ SPI <-0.80), recorded in 1995/1996 and 2015/2016, and exceptionally dry weather (SPI $<= -2$), recorded in between 1991 and 1998 and between 2012 and 2016 (Fig. 5). The mean precipitation varied from 0 mm to >300 mm per season over the study period (Fig. 6). The highest annual mean precipitation (≥300 mm) was recorded in the long rainy season of the year 1983, and similar amounts were recorded in 1997 during the El Niño effect. The lowest annual mean precipitation 0 mm was recorded in the dry years on 1996 and 2015. The short rainy season had its highest mean precipitation (150 mm) in 1969, which happened only once in the entire period of 50 years, while the period between 2015 and 2016 presented instances of lowest values of precipitation. Hence, rainfall variability occurred within the season, from season to season, and even from year to year.

Table 2: Demographic and selected characteristics of pastoralist household heads in the study villages (n = 241). The questionnaire was conducted in Ngorongoro, Nainokanoka, Endulen and Olbalbal wards between March and June, 2018

Demographic characteristics	Number (n)	Percent (%)
Sex		
Men	197	82
Women	44	18
Age (years)		
18 - 35	67	29
36 - 55	144	62
56 - 75	15	6
>75	8	3
Family size		
≤ 10	193	80
> 10	48	20
Education		
No formal education	116	48
Primary education	118	49
Secondary education	7	3
Livelihood		
Primary income generating activity		
Livestock keeping	230	92
Secondary income generating activity		
Small business	10	4
Livestock keeping	9	4

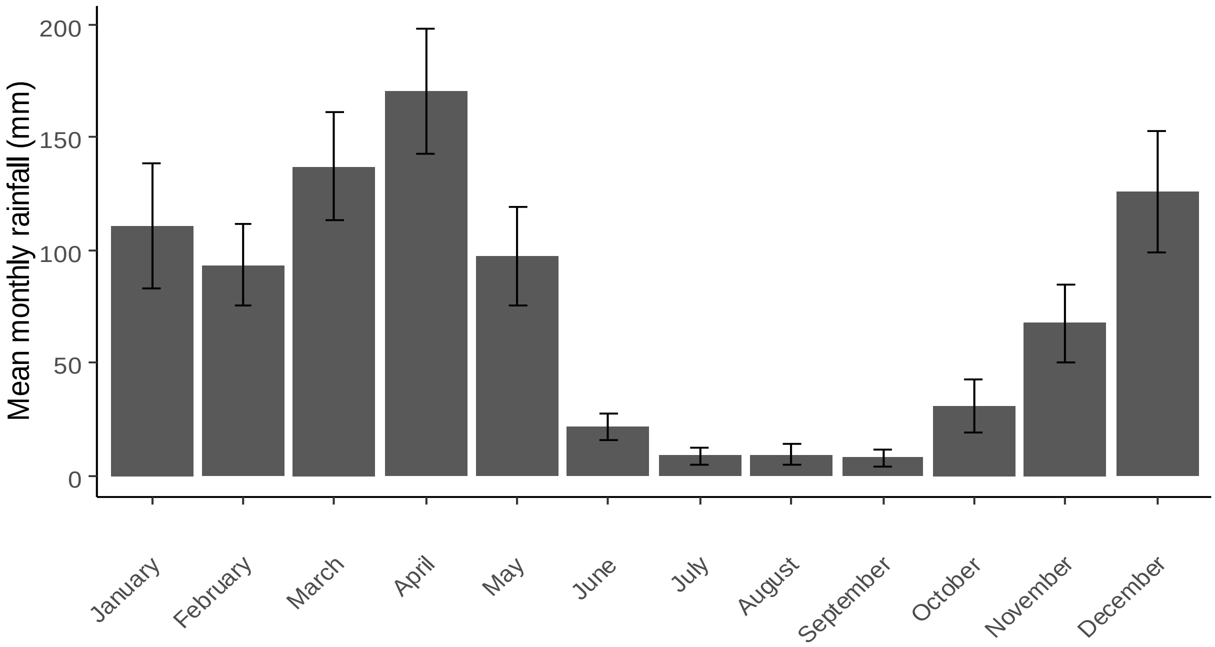

Figure 4: **Mean (grey bars, whiskers = standard deviation) monthly rainfall of NCA showing bimodal patterns (overall monthly mean = 73.5 mm, SD = 84.3 mm, from 1967 to 2018). Data source: Ngorongoro Conservation Area Authority (NCAA)**

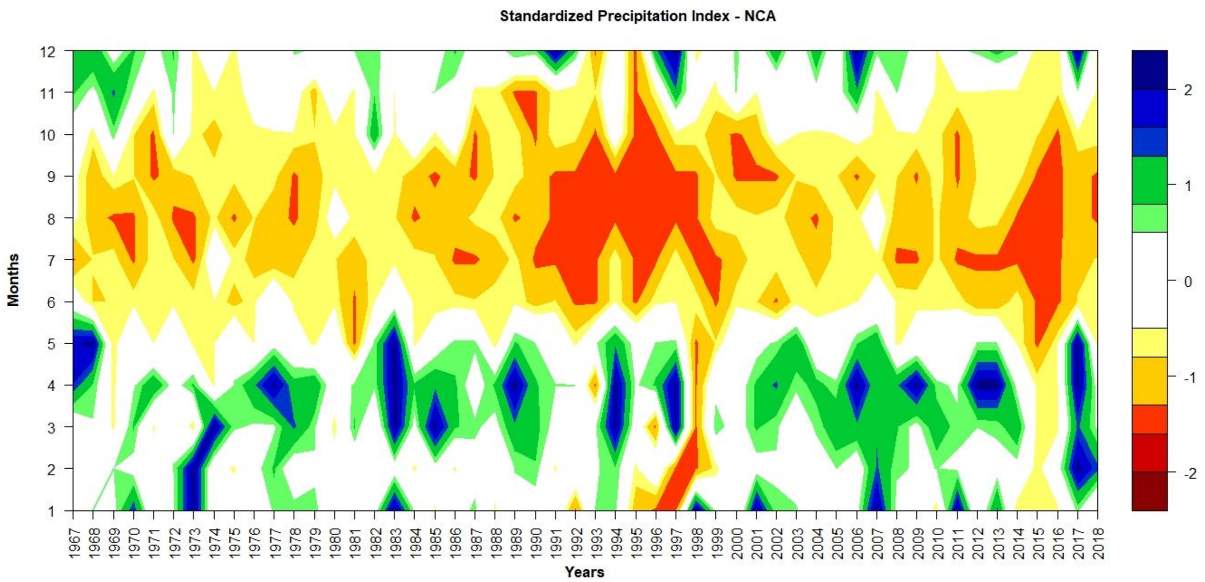

Figure 5: **Standardized Precipitation Index (SPI) for Ngorongoro Conservation Area, Northern Tanzania. Dry periods are denoted by relatively high negative deviations (SPI ≤ -1.0)**

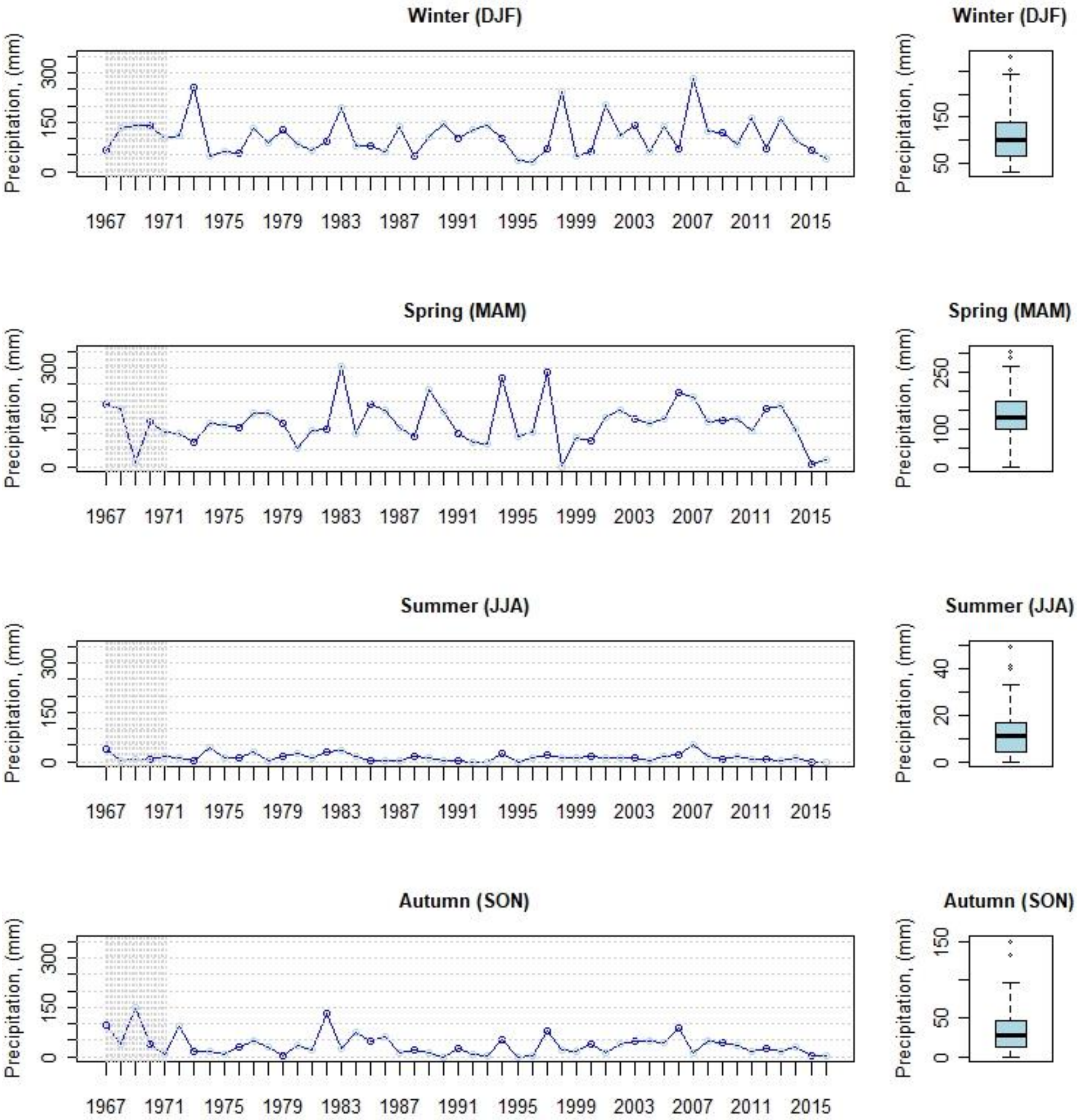

Figure 6: Time series and boxplots of seasonal precipitation for the periods from January, 1967 to December, 2016 for the entire Ngorongoro Conservation Area

4.1.2 Pastoralists' perception on rainfall variability and its influence on traditional livelihood strategies

More than two thirds (71%) of the interviewed respondents were informed of recent changes in rainfall patterns and an increased frequency of droughts, floods, and disease outbreaks. They identified human land-use activities such as deforestation, desertification, and improper grazing practices as the main factors impacting deterioration of rangelands. The majority (79%) of pastoralists claimed that the amount of rain per season has increased over the last ten years but rainfall events had become more unpredictable and shorter in duration (Table 3). Most respondents (76%) also perceived an increase in drought frequencies.

Table 3: The proportion (%) of pastoralists that perceived changes in climate and rangeland condition in the Ngorongoro Conservation Area, Northern Tanzania, for the period of ten years between year 2008 and 2018 (n = 241)

Variable	**Decrease**	**Increase**	**No change**
Climatic conditions			
Precipitation	4	79	17
Length of rainy season	61	11	28
Flood occurrences	15	21	64
Drought occurrences	16	76	8
Rangeland condition			
Time spent for finding good grazing land	14	63	23
Availability of grazing land	50	30	20
Grassland vegetation cover	60	21	19
Grass species diversity	62	34	4
Shrub land cover	3	73	23

About two thirds, i.e., 63%, and 73% of the 241 respondents mentioned that they need more time for finding good grazing areas and that shrub land cover has increased, respectively. More than half (50%, 60%, and 62%) of the respondents mentioned a decrease in availability of grazing land, grass cover, and grass species diversity, respectively. Drought was mentioned to be the likely cause of decrease in grazing land by 21% (P = 0.008) while the remaining factors such as an increase in human and livestock population remained less important.

Information and technology accessibility (reflected by level of education of household head) significantly influenced pastoralists' perception on the change in the duration of the rainy season (LengthRainS) (LR-test $_{2,3}$ = 8.5, P = 0.014). Moreover, location of the village significantly influenced perception on the change in the availability of grazing land (GrazingAvail) (LR-test $_{2,3}$ = 16.8, $P \leq 0.001$) (Table 4).

4.1.3 Livestock productions and how they related to rainfall variability

All 241 surveyed households owned some livestock, the average TLU owned per household was 28 but ranged from 3 to 140 TLU (Table 5). Most (88%) respondents reported selling livestock, (cattle, sheep, and goats), which provided a mean annual income of US$ 1540 per household, while selling milk was not common (only 15% of respondents). The mean annual gross value of livestock products (estimated as livestock sold, slaughtered, and given away as gifts) was US$ 1881, with a median of US$ 2011, highlighting a small number of wealthy households. This estimate did not include sales of hides or milk consumption, which were only occasionally done.

Table 4: Factors influencing smallholder herders' perceptions of climate change and variability (Likelihood Ratio Test and P-value) in the four wards of the Ngorongoro Conservation Area (N= 241). The questionnaire was conducted in Ngorongoro (n = 53), Nainokanoka (n = 80), Endulen (n = 53) and Olbalbal (n = 55) wards between March and June, 2018

	ChangePrecip	**LengthRainS**	**DroughtOcc**	**GrazingAvail**	**VegCov**	**GrassSpecDiv**
Age group	5.71 (0.127)	2.096 (0.553)	2.81 (0.422)	2.14 (0.543)	1.69 (0.638)	2.65 (0.450)
Education level	1.71 (0.424)	8.48 (0.014) *	2.49 (0.288)	0.89 (0.641)	0.72 (0.698)	4.29 (0.117)
Location of the village	0.58 (0.749)	0.48 (0.789)	1.72 (0.424)	16.85 (<0.000) ***	3.05 (0.217)	0.38 (0.829)

ChangePrecip = Change in precipitation, LengthRainS = change in the length of rainy season, DroughtOcc = droughts occurrences, GrazingAvail = availability of grazing land, VegCov = grassland vegetation cover and GrassSpecDiv = grass species diversity. Age group, education level and location of the village are explained in data analysis section.

Table 5: Household livestock number owned and annual incomes (in US$) from various livestock production activities (n = 241). TLU = Tropical Livestock Unit based on a 250 kg body weight

Livestock	Min	Max	Median	Mean	±SD
TLU owned	3	140	23	28	21
Value of livestock sold	0	4133	1644	1540	838
Value of livestock consumed	0	767	311	322	174
Total livestock production	**0**	**3333**	**2011**	**1881**	**973**

(i) Livestock herd sizes over the last ten years

In particular, 68% of the household heads mentioned cattle as the most vulnerable livestock type, that the average number of cattle per family is decreasing, and that cattle were generally in deprived condition. Despite of the recurrent rainfall variability, the proportion of sheep and goats owned by households has increased by 54% and 63%, respectively (Fig. 7).

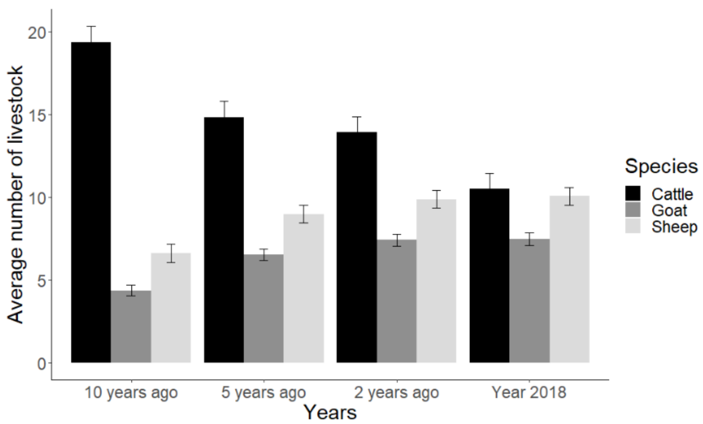

Figure 7: Average (±SE) livestock number owned by a household in the surveyed villages of the NCA from 2008 to 2018 (based on interviews)

(ii) Livestock archived records from the NCAA and how they relate to rainfall variability

The NCA authorities archived records showed that the number of cattle had been about 161 034 whereas the number of sheep and goats was 100 689 at the time of establishment of NCA in the 1960s, summing up to a TLU of 79 617 and a per capita TLU of 10 (Fig. 8) However, the number of cattle has decreased to 115 562 while sheep and goats increased to 181,281, summing up to a TLU of 99 022. Despite the higher TLU recorded in 2016, this TLU has further reduced the per capita TLU to 1 in the year 2016, which is strongly associated with the increase in human population (Fig. 8a). Moreover, from the time of establishment of NCA, the number of people has been steadily increasing (R^2 = 0.96, P < 0.001), as did the number of sheep and goats (R^2 = 0.71, P = 0.002) and cattle (R^2 = 0.55, P = 0.028) whereas the TLU per capita steadily decreased (R^2 = -0.7, P <0.003) as per Fig. 8 a - d. The observed increasing number of sheep and goats complements to 54% and 63% increase in the proportion of sheep and goats reported during the interviews. The mean annual rainfall of NCA accounted for only 46% (R^2), (P = 0.076) and 32% (R^2), (P = 0.222) of cattle, and sheep and goat population variability, respectively.

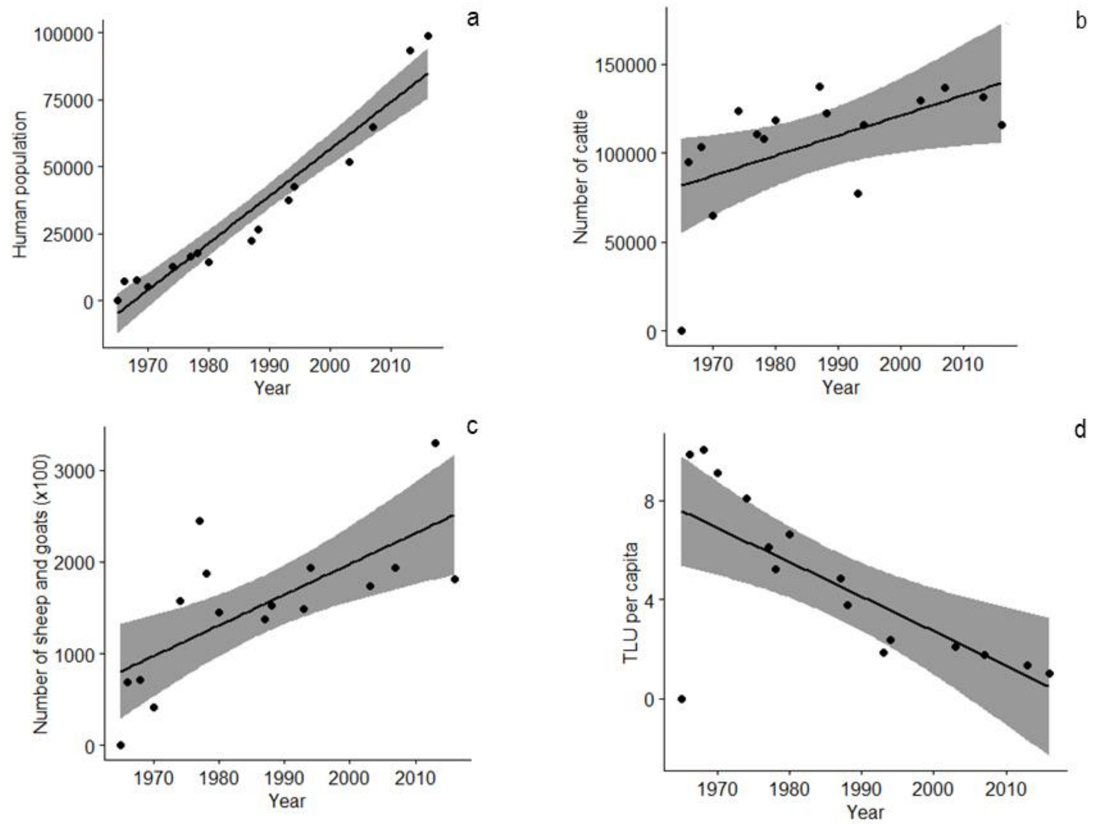

Figure 8: Human (A), cattle (B), sheep and goat (C) populations and Tropical Livestock Unit (TLU) per capita trends in NCA from 1967 to 2016 (NCAA Archived data). Black line denotes the fitted population and the shaded regions are the 95% confidence bands

The mean annual rainfall of NCA accounted for only 46% (R^2), (P = 0.076) and 32% (R^2), (P = 0.222) of cattle, and sheep and goat population variability, respectively.

4.1.4 Pastoralists' coping options and adaptation strategies to extreme events

During the 2015/2016 drought occurrences, 112 herds (47%) of the interviewed 241 pastoralists experienced cattle losses. Mortality rate barely decreased, by 2% (*P* = 0.116) and 2% (*P* = 0.697) with increasing number of cattle in the herd and increasing household size, respectively. Death occurrences were more likely to be prevented (LR-test $_{1,2}$ = 4.1, *P* = 0.042) in households which practice mobility, as well as with an increase in number of cattle in the herd (LR-test $_{1,2}$ = 30.4, *P* <0.001) but feeding cattle with supplementary feeds did not significantly reduce the odds of death occurrences (LR-test $_{1,2}$ = 0.1, *P* = 0.799), (Table 6). The quantities of the various feeds purchased and their sufficiency for the target animals were difficult to assess because the pastoralists did not keep records of livestock feeds.

Table 6: Factors influencing death occurrence and mortality rate in cattle herds for the years 2015/2016

Predictor variables	**Mean**	**Death occurrence**		**Mortality rate**	
		Odds Ratio	***P***	**Estimated coefficients**	***P***
Number of people HH^{-1}	7.7	0.1	0.772	-0.022	0.697
Pre-drought cattle numbers HH^{-1}	20.4	30.4	<0.001	-0.021	0.116
Feed supplement (yes/no)		0.1	0.799	0.219	0.576
Mobility (yes/no)		4.1	0.042	0.148	0.762

Death occurrence based on the full number of surveyed households (n = 241). Mortality rate based on the number of households that experienced deaths (n = 112), HH = household.

4.1.5 Seasonal changes in the aboveground biomass production and regrowth potential at the diverse elevation levels found within the transhumance system

Aboveground biomass was significantly affected by grazing impact ($F_{1, 40}$ = 56.967, *P* < 0.0001), season ($F_{3, 40}$ = 19.165, *P* < 0.0001), and elevation ($F_{2, 40}$ = 11.319, *P* = 0.023). Further, the interaction between treatment (caged/uncaged) and season ($F_{3, 40}$ = 6.642, *P* = 0.001) and between treatment and elevation was significant ($F_{2, 40}$ = 17.643, *P* < 0.0001), indicating that the impact of grazing was not uniform across sites. Grazing intensities ranged from 0.75 to 0.85 at the sites in highlands and midland (Table 7) that were dominated by grasses of medium height while lowlands had low grazing intensities (Table 7).

Table 7: Restricted Maximum Likelihood (REML)-adjusted mean (±SE) of accumulated aboveground biomass (gm-2) for each site and treatments and the resulting grazing intensities

Elevation	**Caged**	**Un-caged**	**Grazing intensity**	***P***
Lowlands	61.6 ± 29.2	37.3 ± 30.4	0.39	0.838
Midland	775.5 ± 145.2	117.1 ± 31.7	0.85	0.001
Highland	184.3 ± 65.0	46.7 ±18.0	0.75	0.049
Overall mean	411.6 ± 88.2	75.5 ± 17.2	0.82	

P values represent Bonferroni post-hoc results for Treatment*Elevation effect in overall split-plot ANOVA.

The mean (± SE) grass productivity across the entire experiment was relatively higher in the midland averaging 7.2 ± 0.9, followed by highlands with 2.1 ± 1.1 and lowlands 0.4 ± 0.1. Although elevation was not influencing productivity alone, it modulated the effect of rainfall with more effect in midland. The highest average (± SE) grass layer productivity was recorded during the wet season; lowlands 2.1 ± 0.9, midlands 15.3 ± 2.8 and highlands 6.6 ± 1.5. During the driest harvest/clipping periods of September, the overall productivity decreased dramatically both in highland, midland and lowlands, averaging -0.1 (±0.01), -3.1 (±1.4) and -0.4 (±0.3) g m^{-2} per day, respectively (Fig. 9).

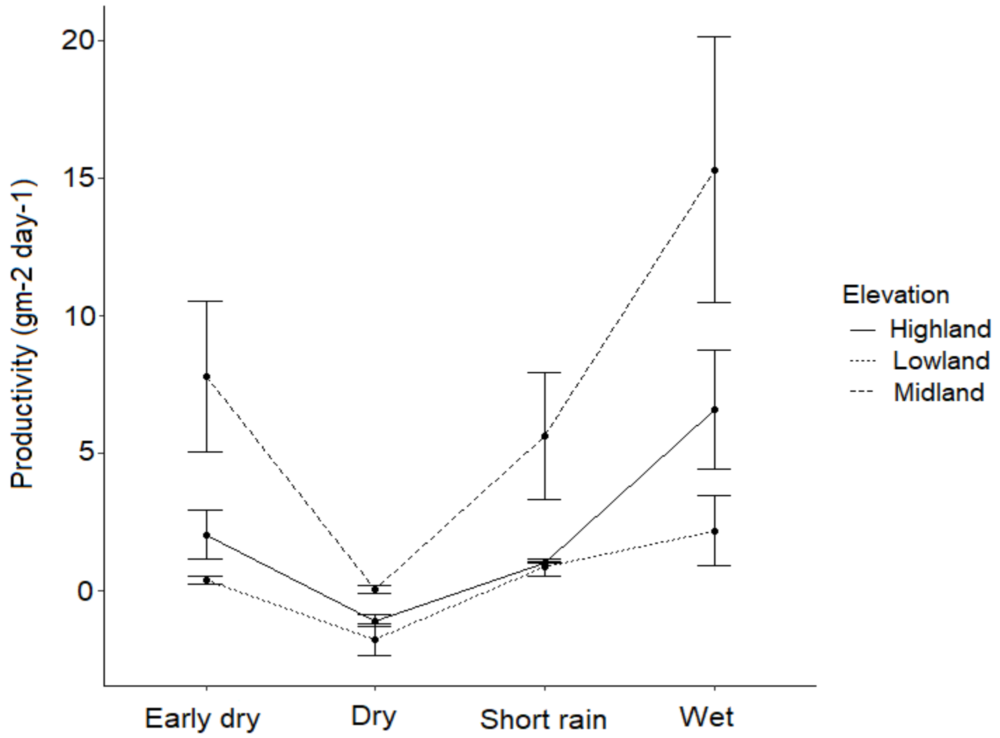

Figure 9: Mean (±SD) daily productivity for each sampling interval in the highlands (Nainokanoka, solid line), lowlands (Olbalbal, dotted line) and midlands (Ngorongoro and Endulen, dashed line)

4.1.6 Seasonality in wild mammalian herbivore group sizes and occurrence in response to environmental and human factors

(i) Larger wildlife groups were formed during the wet season

One hundred and seventy-six (176) groups of wild mammalian herbivores were observed (Fig. 10), with more observations (98; 56%) during the wet season than during the dry season (i.e. 78 (44%). Of all observed groups, 74% were formed by grazers, 18% by mixed feeders, and 8% by browsers. Grazers had about the same group sizes as mixed feeders (t =-0.02, df = 161, P = 0.999) whereas browsers had smaller group sizes than both grazers (t = -4.02, df = 161, P < 0.001) and mixed feeders (t = -3.42, df = 161, P = 0.002) (Fig. 11).

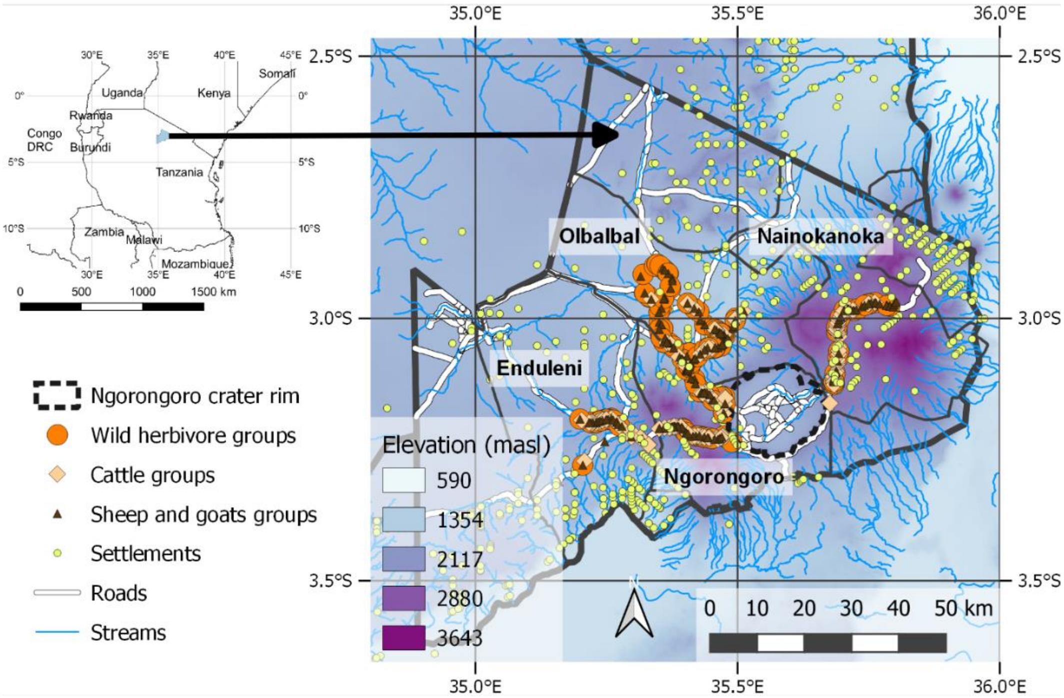

Figure 10: Map of Ngorongoro Conservation Area (NCA), northern Tanzania showing locations of wild and domestic herbivore groups (cattle, sheep and goats) and settlements

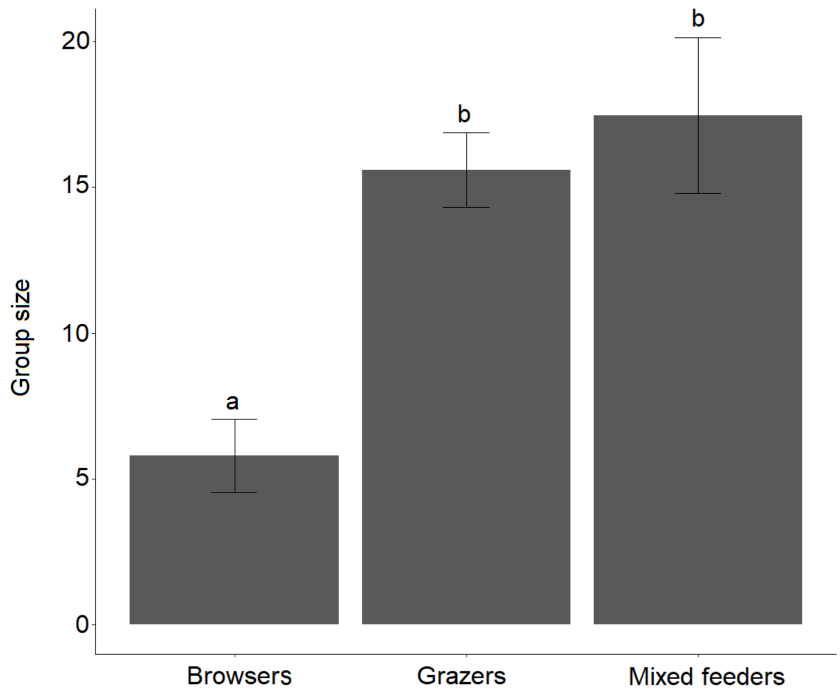

Figure 11: Mean ± SE of group sizes of wild herbivores observed along road transects in the Ngorongoro Conservation Area, northern Tanzania, during March 2018 - February 2019. Boxes with dissimilar letters are significantly different based on Tukey's HSD test at P≤0.05

(ii) Larger groups were formed closer to the fully protected area

Wild mammalian herbivore group sizes varied seasonally with distance away from the NCA crater depending on season (LR-test$_{1, 2}$ = 10.5, P = 0.001). During the wet season, group sizes approximately doubled from about 4 browsers at the Ngorongoro crater rim to 8 browsers at a distance of 32 km away from the crater (Fig. 12A). Similarly, an average group size of 13 grazers and mixed feeders at the crater rim doubled to a group size of 23 grazers and mixed feeders at 32 km away from the crater rim (Fig. 12A). In contrast, during the dry season, the estimated group sizes decreased by about three times with increasing distance away from the NCA crater, i.e., from 7 browsers, 21 grazers and mixed feeders at the crater rim to 2 browsers and 6 grazers and mixed feeders at 23 km distance away from the NCA crater (Fig. 12B).

(iii) Larger groups were formed away from the streams

Wild herbivore group sizes and group locations slightly varied with distance to seasonal streams (LR-test $_{1, 2}$ = 3.7, P = 0.056). The group sizes did not change with distance from the streams during the wet season, they were observed within 7 km distance away from streams (Fig. 12C). During the dry season, the estimated group sizes increased by about three times with increasing distance to 8 browsers, 24 grazers and 25 mixed feeders at 8 km away from streams (Fig. 12D).

(iv) Herbivore groups were larger close to settlements

Wild herbivore groups responded differently to the presence of settlements in each season (LR-test $_{1, 2}$ = 8.5, P = 0.004). During the wet season, wild herbivore group sizes were slightly higher closer to settlements than further, i.e., about 6 km, away (Fig. 12E). However, during the dry season, group sizes decreased from 8 to 1 browsers, 21 to 4 grazers and 22 to 6 mixed feeders with increasing distance away up to about 5 km away from settlements (Fig. 12F).

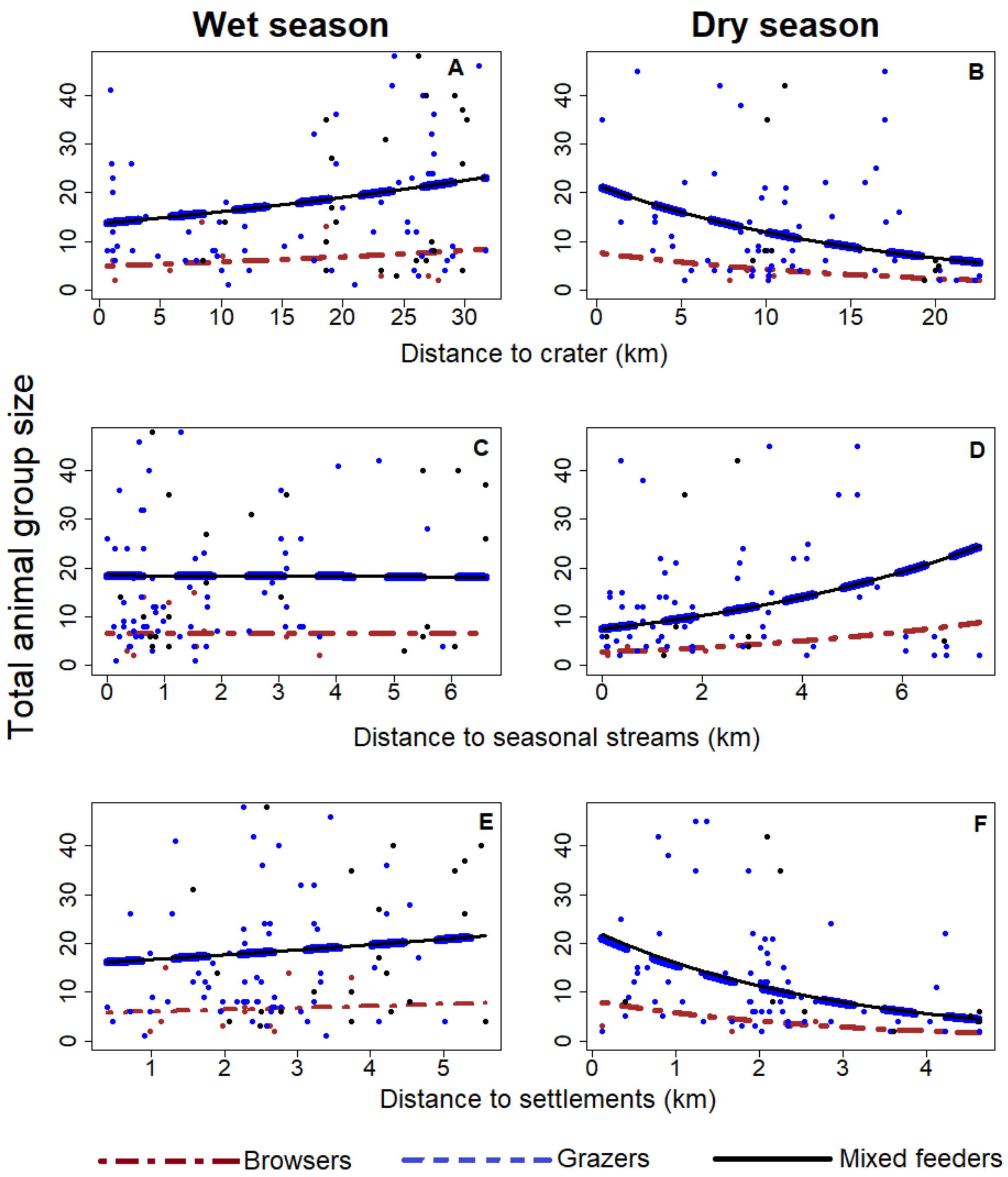

Figure 12: Trends in wild herbivore group sizes for browsers, grazers, and mixed feeders relative to the Ngorongoro crater (A, B), distance to the seasonal streams (C, D), and settlements (E, F) during the wet season (left panel) and dry season (right panel) in the Ngorongoro Conservation Area, northern Tanzania, during March 2018 - February 2019

4.2 Discussion

4.2.1 Pastoralists perception on rainfall variability and its influence of on traditional livelihoods and herding strategy

It was found that pastoralists were aware of the trend of climate variability and changes in their local areas and the impacts were experienced in their major form of livelihoods and herding strategy. Similarly, the PRA discussions revealed that declines in amounts of rain, delayed beginning of rainy seasons, and an early end of rainfall have become frequent. Similar perceptions were reported by pastoralists in other semi-arid rangelands (Debela *et al*., 2015; Sangeda *et al*., 2013; West *et al*., 2008) as well as by farmers in the southern highlands of Tanzania, western and southern Africa (Kangalawe, 2012; Mertz *et al*., 2009; Thomas *et al*., 2007). Respondents acknowledged that the occurrence of frequent droughts has led to severe economic impacts associated with poor markets for their livestock, they reported that the prices kept on declining due to poor health condition of the cattle. Moreover, respondents reported that limited feed and water resources, as well as heat stress has led to reductions in milk yield. Decreased milk production has also been noted in some parts of Tanzania (Magita & Sangeda, 2017). For pastoralists, milk is a staple aliment, reduced supply may pose dangers to food and nutritional security in these communities, particularly for women and children (Opiyo *et al*., 2015). Hence, this research recommends for an improved adaptive capacity among pastoralist communities, this could also be to impart pastoralists with the capacity to process their cattle products into improved products which can add value and hence raise the market price.

The term ‘climate change’ was associated with variability in rainfall, which was a major source of concern being erratic and unpredictable rainfall, which is a typical pattern of conception in communities living in arid areas (Thornton *et al*., 2014). Pastoral communities have strong memories of the years marked by extreme weather conditions and other noteworthy occurrences that resulted in livestock production disruptions (Kimaro *et al*., 2018). The discussion with respondents aimed to collect information about the years which have been characterized by extreme climate events since 1980s to date. These time periods were chosen because they were easy for locals to recall and describe. It is worth noting that the research area has been severely impacted by frequent droughts which have had a negative impact on pastoral life and the ecosystem (Table 8).

Table 8: Historical incidents related to climate variability in the researched villages according to Participatory Rural Appraisal Discussion in Ngorongoro, Nainokanoka, Endulen and Olbalbal wards between March and June, 2018, (N = 52)

Year	Response (Overall opinion across all four wards)
1982/1983	Prolonged drought: massive death of livestock and outbreak of diseases
1998/1999	El Nino rains: more than normal rainfall over a short time period (during the rainy season), which caused destruction of infrastructure, outbreak of diseases and death of livestock due to floods.
2007/8	Several drought spells: massive loss of livestock
2015/16	Severe drought: death of livestock due to lack of grazing resources, drying out of Munge River.

Similarly, analysis of rainfall data collected from NCAA headquarters show a slight overall decline in rainfall between the years 1967 and 2018. Moreover, pastoralists were able to recall years, when there was a significant lack of water and pasture shortages, which correlated with NCAA rainfall data, i.e., two incidents ranged within years of low total precipitation and/or long periods of moderate droughts, as indicated by the SPI and the time series of seasonal precipitation.

A decline in overall rainfall and increased variability is a current concern over a wide range of similar communities across Africa and has been reported in other regions of Tanzania and eastern Africa (Gebrechorkos *et al*., 2019; Magita & Sangeda, 2017; Opiyo *et al*., 2015; Silvestri *et al*., 2012). In NCA where livectock herding follows a cyclical pattern depending on the availability of grazing and water, an increase in rainfall variability has severely impacted pastoralists and is likely to cause conflicts over rangeland resources between pastoralists and wildlife management authorities due to a lack of water and pasture, as was reported in Monduli (Kaswamila, 2009), Kilombero (Bergius *et al*., 2020), Burunge (Bluwstein *et al*., 2016) and many other places in Tanzania, where pastoralism represents the main livelihood basis.

4.2.2 Trends in livestock production and herd sizes over the past ten years and how are they related to rainfall variability

Impacts of rainfall on livestock production has often been expressed as a drastic decline in population of livestock following drought years (Kariuki *et al*., 2018; Kimaro *et al*., 2018). In this study, pastoralists reported that recurrent drought periods have caused massive losses of livestock, in particular cattle. Droughts have led to severe feed shortages and water scarcity, resulting in severe socio-economic impacts (Megersa *et al*., 2014). For example, Borana of Southern Ethiopia faced high cattle losses of up to 37% and 42% of all cattle during severe drought periods in 1983 – 1985 and 1991 – 1993, respectively (Desta & Coppock, 2002). Similarly, during the 2017's drought, NCAA reported to have lost 77,389 head of cattle, 72 881 head of goats and 78 490 head of sheep (NDC, 2017), which, when compared with the livestock count of the previous year (TAWIRI, 2016), translates into a total loss of about 70% of the livestock. Further, droughts make animals more susceptible to infectious diseases, which reduces the ability of animals to survive (Haseeb *et al*., 2019). Since these incidents occured concurrent with a severe drought, which was exacerbated by a shortage of forage for livestock and wildlife, we claim that climate change might be strongly determining livestock mortality.

In this study, sheep and goat populations were moderately associated with mean annual precipitation, reflecting that smaller livestock species can survive well during good conditions (Mapiye *et al*., 2009). Generally, cattle are the most vulnerable livestock due to higher energy requirements than other livestock types (Lesnoff *et al*., 2012; Seo *et al*., 2010). In addition, recovery of cattle populations can take a long time due to disruptions caused by subsequent shocks (decline in population or disturbance in age and sex structure) which can occur under high variability in rainfall events especially due to shorter intervals between repeated droughts (Godde *et al*., 2019; Oba, 2001).

A shift from cattle pastoralism to multispecies livestock keeping has increased over time in response to variability and change in climate (Watson *et al*., 2016). In this study, sheep and goats have slightly increased over the period of ten years while the population of cattle has decreased. This was in agreement with reports by NCAA, where a steady shift from cattle towards small ruminant ownership was recorded, from about 8% of the TLUs in the 1960s to 26% in the present decade. This trend indicates an active selection by pastoralists towards sheep and goats, particularly in times when they need income, as it is a reasonable economic but short-term strategy for quick asset building due to their shot growth time relative to cattle

(Hauck & Rubenstein, 2017). Moreover, studies on feeding ecology suggest that sheep and goats are better adapted to nutritionally poor vegetation than cattle (Jáuregui *et al*., 2009), hence, are likely to survive on a stressed environment. Cattle are large bodied grazing ruminants with relatively higher biomass consumption, their large rumen allows them to consume and digest low quality forage. However, their lips, teeth, and jaw are relatively immobile hence limit their ability to select among plants and plant parts, they can't easily get closer than 5cm from the soil so they can hardly graze in overgrazed areas (Larson *et al*., 2015). Studies in other places of Africa (Rojas-Downing *et al*., 2017; Seo *et al*., 2009) also reported that changes in climate are likely to drive selection of animal species towards those that can cope best with changed environmental conditions. Sheep are an increasingly dominant livestock species in NCA, which might further degrade the rangeland vegetation due to their feeding ecology (Gordon, 2003). Grazing by sheep selectively removes nutritious plants and continually reduces the diversity and species richness of most grasses and vascular plants resulting to increase in herbs, sedges and shrubs (Marrs *et al*., 2020; Milligan *et al*., 2016). Yet, the long-term impact of small livestock grazing under the increasing rainfall variability on the NCA landscape is still uncertain, and appropriate grazing management are required.

4.2.3 Pastoralists' coping options and adaption techniques in the face of both quick onsets of catastrophic events and more widespread climate change/variability

Pastoralists in East Africa apply different adaptation measures to lessen the impact of drought on livestock productivity, but their overreliance on livestock leaves them highly vulnerable to climate shocks (Sangeda & Malole, 2014; Sherwood, 2013). In this study, 34% of the interviewed 241 households had on case by case supplemented weak and young ones with crop remains, straw and hay, which still could not reduce death occurrences significantly. Although supplementary feeding is considered a rescue to livestock when there is limited pasture (Angassa & Oba, 2013), it is not an advice to NCA pastoralists as it will keep the livestock population high hence creating management challenges. Respondents also reported mobility as another strategy used to cope with drought, having adapted to the vegetation heterogeneity between mountainous forest and grasslands which influences forage availability for grazing animals in NCA (Niboye, 2010). This agrees with other studies on mobility in communal rangelands of Africa (Descheemaeker *et al*., 2016; Odadi *et al*., 2017; Pas, 2018).

Despite being widely practiced across Africa, mobility needs to be well planned to avoid higher animal mortality resulting from overgrazing (Nkedianye *et al*., 2011; Sulieman & Elagib, 2012). Contrary to expectations, finding showed that large pastoralist households did not suffer from lower cattle losses than small households, which was also reported by Scoones (1992) in Southern Zimbabwe. Moreover, in this study, large households corresponded strongly with big herd size, in which higher records of livestock deaths were inevitable. This demonstrates that big herd sizes do not cushion households against climatic shocks, which is contrary to justifications made on the pastoralists' tendency to increase herd sizes as a risk management technique (Naess & Bårdsen, 2013).

4.2.4 Seasonal changes in biomass production and regrowth potential of the diverse elevation levels of the NCA

Diverse plant communities across the different elevation levels of the NCA have different capacity to produce biomass. The maintained productivity rates across the different elevation levels in wet seasons and overall through a 12 month study period suggest that compensation occurs even at high grazing intensities consistent with previous findings (McNaughton, 1985; Ritchie, 2014). However, the best time of the year to achieve the highest recovery is in the early dry season. The observed complete removal of biomass during dry season followed by complete growth in wet season is also a suggestive of the capacity of the system to regrow even where livestock are dominant herbivores. This is supported by previous findings from semi-arid grasslands where a combination of grazing pressure and drought reduced plant cover and production potential (Augustine & McNaughton, 2006; Porensky *et al*., 2013).

Several studies point out a range of important factors that interact with grazing intensity in explaining the role of plant compensatory growth, such as rainfall seasonality, soil infiltration capacity, fire incidences, and plant species composition (McNaughton, 1985; Ritchie, 2014), However, rainfall is commonly highlighted as the most important driver of vegetation productivity (Bonnet *et al*., 2010; Milchunas *et al*., 1994) and indeed it was found that both elevation levels had drastically lower productivity rates during the time of scarce rainfall. My findings further indicate that productivity continue to increase with increased rainfall suggesting a more beneficial outcome of increased rainfall in protected areas, opposed to the expectations that productivity would saturate toward higher rainfall. In contrast to my observation, a study by Veldhuis *et al*. (2019) showed that plant biomass in Serengeti National park depends less on annual rainfall and suggest that other factors such as increased grazing intensity are important in enhancing productivity.

Study results further revealed a potential influence of grazing intensity on grass productivity, similar to what was observed in a study conducted by Patton *et al*. (2007). Similarly, research by Milchunas *et al*. (1994) also showed that caged plots were more productive than the un-caged plots. This suggests that continuous grazing leads to reduction of total vegetation growth and production of most of the forage plants. Contrary to these observations, studies by Holechek *et al*. (2006) observed a slightly higher production in managed grazing areas than in in exclusions, implying that long-term grazing exclusion might cause stagnation of vegetation growth. Carrying capacity among other rangeland management tools has been successful and a widely used, however there is no simple way of determining it quantitatively (Cheng *et al*., 2017; Tewari & Arya, 2006). The establishment of carrying capacity depends upon many factors such as rainfall, vegetation accessibility and distribution, seasonality, range improvement, and grazing management and yet may vary from year to year in the same site assessed (Abbas *et al.*, 2012; Cheng *et al*., 2017). Rotational grazing would therefore be advantageous to Ngorongoro rangelands if at all pastoralists will practice it considering that long-term use levels on average do not surpass 40% (Holechek *et al*., 2006).

Currently, the Maasai in Ngorongoro practice a seasonal shifting herding strategy based on the bimodal distribution of annual rainfall in order to make efficient use of a variety of rangelands. However, during the focus group discussion, pastoralists mentioned that, with an increasing human and livestock population, the traditional rangeland management practices were being jeopardized or violated. This lead on the scarcity of forage for both wildlife and livestock but if pastoralists will adopt the managed grazing scheme i.e., planned rotational grazing, it means they redistributes grazing pressure along a small land piece while being assured of forage over a long period.

4.2.5 Effect of seasonality, landscape features, distance to human settlements or the number of livestock on wild herbivore group sizes

The observed tendency of herbivores to form larger groups during the wet season and smaller groups during the dry season are consistent with animal grouping theory, which relates group size to resource variability (Bigalke, 1972). Seasonal rainfall variation strongly shapes rangeland vegetation productivity and biomass (Butt & Turner, 2012), which in turn influences wild herbivores to shift towards areas with resource availability. This influence is seen in reproductive fitness (Ogutu *et al*., 2014; Parker *et al*., 2009), species abundance and population structure (Bhola *et al.*, 2012) as well as in group size (Bercovitch & Berry, 2010; Tshabalala *et al*., 2009). The experienced fewer and more unpredictable rainfall events associated with the changing climate in eastern Africa are therefore likely to reduce the amount of forage available to herbivores and might negatively affect their group sizes (Cheng *et al*., 2011; Hopcraft, 2016; Mccollum *et al*., 2017). The reduced group sizes affect the social organization for ungulates living in herds by breaking up of large herds into a number of smaller herds which are not recommendable for herbivores living in herds (Barrette, 1991).

It was found that during the wet season, wild herbivore group sizes increased further away from the NCA crater, possibly because herbivores disperse into short grass plains maintained by livestock grazing (Swanson, 2007). This trend indicates that there is potential benefit from facilitation by livestock for wild herbivores, i.e., areas of short-grass, which provide herbivore populations with high quality forage feed for their growth and reproduction (Odadi *et al*., 2011; Verweij *et al*., 2006). During the dry season, wild herbivore group sizes increased closer to the NCA crater. This might be due to limited food availability further away from the crater, which triggered a strong competition with livestock further away from the crater (Odadi *et al*., 2011).

The Ngorongoro crater rim contains various shrubs and flowering plants (Swanson, 2007), that may attract herbivores during the dry season (Macandza *et al*., 2012; Megaze *et al*., 2018). It was expected that animals at the crater rim will move inside the NCA crater during the dry season. Group sizes of African buffaloes and African elephants (Cornélis *et al*., 2011; Megaze *et al*., 2018), giraffe (Fennessy, 2009), sable, and zebra herds also varied in relation to shrubs and riverine vegetation (Macandza *et al*., 2012). Thus, an increased group size of wild herbivores closer to the NCA crater may be a response to availability of feed and water during the dry season. Moreover, the permanently flowing rivers inside the crater may attract animals in times of low rainfall. Furthermore, the observed increase in wild herbivore group sizes away from seasonal streams during the dry season is likely due to water dependency of the different herbivore species, most herbivores require access to surface water to maintain body fluid homeostasis (de Boer *et al*., 2010; Redfern *et al*., 2003). As the dry season progresses, non-permanent surface water sources dry out, which forces most herbivores to congregate close to the few remaining permanent sources of drinking water (Chamaillé-Jammes *et al*., 2008).

Most studies suggest that associations between wild and domestic herbivores would result in competitive exclusion of the wild herbivores due to overlap in resource use and that domestic herbivores large in herd sizes (Acebes *et al*., 2012; Voeten & Prins, 1999). Contrary to the expectations, during variable selection process sheep and goats were removed first followed by cattle. This implies that changes in wild herbivore group sizes were better explained by variations in the environment (distances to the crater and streams) and human settlements than by the presence of livestock. Data from this study could not offer support for behavioral-mediated factors determining group sizes. Where wild herbivores and livestock were seen together, there was no direct competition or replacement by livestock (pers. obs.). On the other hand, the resource mediated factor remains evident for the observed results. First, resource use by Maasai cattle in NCA closely resembles that of resident wildlife (Du Toit *et al*., 2010) and diets of cattle and wild herbivores including impala, plain zebra and wildebeest overlap in East African savannas (Foufopoulos *et al*., 2002). Secondly, there is no evidence that livestock and wild herbivores compete (Prins, 2000), except for few studies, which indicated absence of wild herbivores within a radius of 10 km away from human settlements (Bergström & Skarpe, 1999).

At NCA, humans might preferentially station their bomas in areas with enough water and grazing options to herd livestock, in particularly cattle, which is in agreement other studies by Ogutu *et al*. (2010); Western & Dunne, 1979), which observed a similar pattern of wild herbivore abundances in relation to water sources. Wild herbivores in NCA may have no choice but to aggregate and increase group sizes close to settlements during the dry season to use the resources available at these sites. Proper conservation planning initiatives which encompass livestock grazing and production would play a great role especially during the periods of low rangeland productivity.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

I found that climate variability is well understood among pastoral communities through their day-to-day experience and observations in NCA. Reduced rainfall and recurrent droughts were reported as major challenges to livestock production due to their impacts on pasture and water availability. In response to changing environmental conditions, pastoralists adapted their herd composition to more diversified livestock species, preferably to those with low plant biomass requirements. This pattern emphasizes the importance of improving the adaptive capacity of pastoralist communities in Tanzania through proactive interventions that lessen vulnerability.

The study further observed that all three elevation levels/categories of the NCA can sustain a high productivity in wet periods and on an annual basis. However, since pastoral livelihoods strongly depend on high grazing resources even in dry periods, and since rainfall is predicted to vary greatly, both intra- and inter seasons (Christensen *et al*., 2007; McSweeney *et al*., 2010), productivity potential of the NCA might decline. A temporal and spatial knowledge on the functional heterogeneity of the rangeland is required to provide baseline for what the system is able to sustain (Hopcraft *et al*., 2010). Moreover, studies on African rangeland management and grazing systems are quite consistent in showing that stocking rate was more vital than the system of grazing in determining vegetation and livestock productivity (Augustine *et al*., 2020; Hawkins, 2017; Mcdonald *et al*., 2019). Management of grazing systems; i.e., rotational grazing alone as being practiced in pastoral communities has no capability to overcome prolonged effects of overstocking and or droughts on vegetation productivity.

The results of this study further demonstrate how the biotic and abiotic factors combined can determine the wild herbivore group sizes in the human dominated landscape of the NCA. Although wild herbivore group sizes were primarily influenced by season and landscape features, the decline in group sizes noted further away from the NCA crater during the dry season may suggest that wild herbivores had fewer resources (food and water) available as a result of land use by people and their livestock.

5.2 Recommendations

This study is one of the few in this iconic Man and Biosphere reserve that quantified how rainfall variability and human-driven factors might impact seasonal movement and group size patterns as well as the seasonal and elevational changes in grass productivity. It also represents a snapshot over two seasons and it is, therefore, recommend that:

(i) Human-wildlife coexistence be spatially defined, and livestock-wildlife overlap hotspots be identified based on the practical and science-based study;

(ii) The most crucial time of recovery for the vegetation is during the early dry season, and midlands seem to be the rangeland area that recovers most quickly, hence rangeland restoration activities should be enhanced during this period to facilitate quick recovery of the overgrazed areas; and

(iii) Determination of the optimal resource ration in the NCA rangelands and the recommendable level of stocking densities as well as the establishment of proper management regimes; i.e. rotational grazing are necessary.

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APPENDICES

Appendix I: Model Selection and Model Summaries

Variable selection steps for analyzing wild herbivore group sizes recorded in Ngorongoro Conservation Area, Tanzania, from March 2018 to February 2019 in relation to feeding guilds, environmental and human variables, and livestock**.**

S1. Initial model

$$\ln(\mu_{ijklm}) = \eta_{ijklm} = \alpha + g_j + s_k + \beta_1 \times x_{i1} + \beta_2 \times x_{i2} + \gamma_{2k} \times x_{i2} + \beta_3 \times x_{i3} + \gamma_{3k} \times x_{i3} + \beta_4 \times x_{i4} + \gamma_{4k} \times x_{i4} + \beta_5 \times x_{i5} + \gamma_{5k} \times x_{i5} + \beta_6 \times x_{i6} + \gamma_{6k} \times x_{i6} + \beta_7 \times x_{i7} + \gamma_{7k} \times x_{i7} + t_{kl} + d_{m,}$$

where η_{ijklm} is the linear predictor for the i'th group size of the j'th feeding guild in the k'th season on the l'th transect and m'th date. The symbol α denotes the general mean, g_j is the effect of the j'th feeding guild, s_k the effect of the k'th season, β_1 is the regression coefficient for distance to observer x_{i1}, β_2 is the regression coefficient for distances to the crater $x_{i2,}$ β_3 is the regression coefficient for distances to streams x_{i3}, β_4 is the regression coefficient for distances to settlements x_{i4}, β_5 is the regression coefficient for elevation x_{i5}, β_6 is the regression coefficient for numbers of cattle x_{i6}, β_7 is the regression coefficient for numbers of sheep and goats x_{i7}, and $\gamma_{1k}, \gamma_{2k}, \ldots, \gamma_{7k}$ are the corresponding seasonal interaction regression coefficients for the metric variables x_{i1}, x_{i2}, …, x_{i7}. The random coefficients of the l'th transect t_{kl} in the k'the season and for the m'th date d_m were normally distributed with a mean of zero.

Table 1: Results of Generalized Linear Mixed Model (GLMM) of the initial model of wild herbivore group sizes recorded in Ngorongoro Conservation Area, Tanzania, from March 2018 to February 2019 in relation to feeding guilds, environmental and human variables, and livestock. "df" degree of freedom, ":" interaction effect, "AIC" Akaike Information Criterion, "LRT" Likelihood Ratio Test, *"P"* is the probability of the chi-squared goodness of fit-test and "0 '***', 0.001 '**' and 0.01 '*'" are significance codes. (Main effects of distances to crater, settlements, sheep and goats, cattle and elevation are not shown)

Explanatory variables	df	AIC	LRT	***P***
<none>		1267.1		
Wild herbivore groups	2	1276.6	13.4786	0.001183**
Season: Distance to streams	1	1270.3	5.1679	0.023009*
Season: Distance to crater	1	1276.0	10.8229	0.001003**
Season: Distance to settlements	1	1274.6	9.4720	0.002086**
Season: Count of sheep and goats	1	1265.2	0.0633	0.801429
Season: Count of cattle	1	1266.0	0.8822	0.347604
Season: Elevation	1	1268.0	2.8978	0.088699
Distance from the observer	1	1267.6	2.4930	0.114356

S2. Eliminating seasonal interaction effect for sheep and goats:

$$ln(\mu_{ijklm}) = \eta_{ijklm} = \alpha + g_j + s_k + \beta_1 \times x_{i1} + \beta_2 \times x_{i2} + \gamma_{2k} \times x_{i2} + \beta_3 \times x_{i3} + \gamma_{3k} \times x_{i3} + \beta_4 \times x_{i4} + \gamma_{4k} \times x_{i4} + \beta_5 \times x_{i5} + \gamma_{5k} \times x_{i5} + \beta_6 \times x_{i6} + \gamma_{6k} \times x_{i6} + \beta_7 \times x_{i7} + t_{kl} + d_m,$$

Table 2: Results of Generalized Linear Mixed Model (GLMM) after the elimination of the seasonal interaction effect for sheep and goats recorded in Ngorongoro Conservation Area, Tanzania, from March 2018 to February 2019 in relation to feeding guilds, environmental and human variables, and livestock. “df” degree of freedom, “:” interaction effect, “AIC” Akaike Information Criterion, “LRT” Likelihood Ratio Test, “*P*” is the probability of the chi-squared goodness of fit-test and “0 ‘***’, 0.001 ‘**’ and 0.01 ‘*’” are significance codes. (Main effects of distances to crater, settlements, sheep and goats, cattle and elevation are not shown)

Explanatory variables	**df**	**AIC**	**LRT**	***P***
<none>		1265.2		
Wild herbivore groups	2	1274.6	13.4262	0.0012149**
Season: Distance to streams	1	1268.4	5.2095	0.0224641*
Season: Distance to crater	1	1275.0	11.8034	0.0005912***
Season: Distance to settlements	1	1273.4	10.1833	0.0014172**
Count of sheep and goats	1	1263.3	0.1322	0.7161340
Season: Count of cattle	1	1264.1	0.8973	0.3435010
Season: Elevation	1	1266.1	2.8900	0.0891293
Distance from the observer	1	1265.7	2.4776	0.1154750

S3. Eliminating main effect for sheep and goats;

$$\ln(\mu_{ijklm}) = \eta_{ijklm} = \alpha + g_j + s_k + \beta_1 \times x_{i1} + \beta_2 \times x_{i2} + \gamma_{2k} \times x_{i2} + \beta_3 \times x_{i3} + \gamma_{3k} \times x_{i3} + \beta_4 \times x_{i4} + \gamma_{4k} \times x_{i4} + \beta_5 \times x_{i5} + \gamma_{5k} \times x_{i5} + \beta_6 \times x_{i6} + \gamma_{6k} \times x_{i6} + t_{kl} + d_{m,}$$

Table 3: Results of Generalized Linear Mixed Model (GLMM) after the elimination of the main effect for sheep and goats recorded in Ngorongoro Conservation Area, Tanzania, from March 2018 to February 2019 in relation to feeding guilds, environmental and human variables, and livestock. "df" degree of freedom, ":" interaction effect, "AIC" Akaike Information Criterion, "LRT" Likelihood Ratio Test, *"P"* is the probability of the chi-squared goodness of fit-test and "0 '***', 0.001 '**' and 0.01 '*'" are significance codes. (Main effects of distances to crater, settlements, sheep and goats, cattle and elevation are not shown)

Explanatory variables	**df**	**AIC**	**LRT**	***P***
<none>		1263.3		
Wild herbivore groups	2	1272.7	13.3251	0.0012779**
Season: Distance to streams	1	1266.4	5.0968	0.0239694*
Season: Distance to crater	1	1273.0	11.7122	0.0006209***
Season: Distance to settlements	1	1271.4	10.0512	0.0015225**
Season: Count of cattle	1	1262.2	0.8573	0.3544834
Season: Elevation	1	1264.1	2.7633	0.0964496
Distance from the observer	1	1263.7	2.3692	0.1237481

S4. Eliminating seasonal interaction effects for cattle;

$$\ln(\mu_{ijklm}) = \eta_{ijklm} = \alpha + g_j + s_k + \beta_1 \times x_{i1} + \beta_2 \times x_{i2} + \gamma_{2k} \times x_{i2} + \beta_3 \times x_{i3} + \gamma_{3k} \times x_{i3} + \beta_4 \times x_{i4} + \gamma_{4k} \times x_{i4} + \beta_5 \times x_{i5} + \gamma_{5k} \times x_{i5} + \beta_6 \times x_{i6} + t_{kl} + d_{m,}$$

Table 3: Results of Generalized Linear Mixed Model (GLMM) after the elimination of the main effect for sheep and goats recorded in Ngorongoro Conservation Area, Tanzania, from March 2018 to February 2019 in relation to feeding guilds, environmental and human variables, and livestock. “df” degree of freedom, “:” interaction effect, “AIC” Akaike Information Criterion, “LRT” Likelihood Ratio Test, *“P*” is the probability of the chi-squared goodness of fit-test and “0 ‘***’, 0.001 ‘**’ and 0.01 ‘*’” are significance codes. (Main effects of distances to crater, settlements, sheep and goats, cattle and elevation are not shown)

Explanatory variables	Df	AIC	LRT	Pr(>Chi)
<none>		1262.2		
Wild herbivore groups	2	1271.3	13.1409	0.0014012**
Season: Distance to streams	1	1265.0	4.8136	0.0282364*
Season: Distance to crater	1	1271.8	11.6665	0.0006364***
Season: Distance to settlements	1	1270.6	10.4532	0.0012244**
Count of cattle	1	1260.4	0.2317	0.6302370
Season: Elevation	1	1262.3	2.1632	0.1413516
Distance from the observer	1	1262.4	2.2513	0.1335037

S5. Eliminating main effect for cattle;

$$\ln(\mu_{ijklm}) = \eta_{ijklm} = \alpha + g_j + s_k + \beta_1 \times x_{i1} + \beta_2 \times x_{i2} + \gamma_{2k} \times x_{i2} + \beta_3 \times x_{i3} + \gamma_{3k} \times x_{i3} + \beta_4 \times x_{i4} + \gamma_{4k} \times x_{i4} + \beta_5 \times x_{i5} + \gamma_{5k} \times x_{i5} + t_{kl} + d_m$$

Table 5: Results of Generalized Linear Mixed Model (GLMM) after the elimination of the main effect for cattle recorded in Ngorongoro Conservation Area, Tanzania, from March 2018 to February 2019 in relation to feeding guilds, environmental and human variables, and livestock. “df” degree of freedom, “:” interaction effect, “AIC” Akaike Information Criterion, “LRT” Likelihood Ratio Test, “*P*” is the probability of the chi-squared goodness of fit-test and “0 ‘***’, 0.001 ‘**’ and 0.01 ‘*’” are significance codes. (Main effects of distances to crater, settlements, sheep and goats, cattle and elevation are not shown)

Explanatory variables	df	AIC	LRT	***P***
<none>		1260.4		
Wild herbivore groups	2	1269.7	13.2682	0.0013148**
Season: Distance to streams	1	1263.1	4.6511	0.0310344*
Season: Distance to srater	1	1270.4	12.0081	0.0005297***
Season: Distance to settlements	1	1268.6	10.2245	0.0013859**
Season: Elevation	1	1260.6	2.1935	0.1385911
Distance from the observer	1	1260.7	2.2632	0.1324769

S6. Eliminating seasonal interaction effects for elevation;

$$\ln(\mu_{ijklm}) = \eta_{ijklm} = \alpha + g_j + s_k + \beta_1 \times x_{i1} + \beta_2 \times x_{i2} + \gamma_{2k} \times x_{i2} + \beta_3 \times x_{i3} + \gamma_{3k} \times x_{i3} + \beta_4 \times x_{i4} + \gamma_{4k} \times x_{i4} + \beta_5 \times x_{i5} + t_{kl} + d_m,$$

Table 6: Results of Generalized Linear Mixed Model (GLMM) after the elimination of the seasonal interaction effects for elevation recorded in Ngorongoro Conservation Area, Tanzania, from March 2018 to February 2019 in relation to feeding guilds, environmental and human variables, and livestock. "df" degree of freedom, ":" interaction effect, "AIC" Akaike Information Criterion, "LRT" Likelihood Ratio Test, *"P*" is the probability of the chi-squared goodness of fit-test and "0 '***', 0.001 '**' and 0.01 '*'" are Significance codes. (Main effects of distances to crater, settlements, sheep and goats, cattle and elevation are not shown)

Explanatory variables	**df**	**AIC**	**LRT**	***P***
<none>		1260.6		
Wild herbivore groups	2	1270.3	13.6754	0.001073**
Season: Distance to streams	1	1261.6	3.0047	0.083023
Season: Distance to crater	1	1268.7	10.1208	0.001466**
Season: Distance to settlements	1	1266.9	8.2685	0.004034**
Elevation	1	1258.8	0.2060	0.649907
Distance from the observer	1	1260.4	1.7832	0.181756

S7. Eliminating main effect for elevation;

$$\ln(\mu_{ijklm}) = \eta_{ijklm} = \alpha + g_j + s_k + \beta_1 \times x_{i1} + \beta_2 \times x_{i2} + \gamma_{2k} \times x_{i2} + \beta_3 \times x_{i3} + \gamma_{3k} \times x_{i3} + \beta_4 \times x_{i4} + \gamma_{4k} \times x_{i4} + t_{kl} + d_m,$$

Table 7: Results of Generalized Linear Mixed Model (GLMM) after the elimination of main effect for elevation recorded in Ngorongoro Conservation Area, Tanzania, from March 2018 to February 2019 in relation to feeding guilds, environmental and human variables, and livestock. "df" degree of freedom, ":" interaction effect, "AIC" Akaike Information Criterion, "LRT" Likelihood Ratio Test, "*P*" is the probability of the chi-squared goodness of fit-test and "0 '***', 0.001 '**' and 0.01 '*'" are significance codes. (Main effects of distances to crater, settlements, sheep and goats, cattle and elevation are not shown)

Explanatory variables	**Df**	**AIC**	**LRT**	***P***
<none>		1258.8		
Wild herbivore groups	2	1268.8	14.0291	0.0008987***
Season: Distance to streams	1	1260.5	3.6550	0.0559027
Season: Distance to crater	1	1267.3	10.5308	0.0011740**
Season: Distance to settlements	1	1265.3	8.4549	0.0036406**
Distance from the observer	1	1258.8	2.0450	0.1527045

Appendix II: House hold questionnaire

Enumerator	

A. Household Identification and Demography

Ward		
Village		
Name of HH Head		
Please write here the sub-village name (if applicable):		
Distance from the household to the village center. (Village centre refers to the village common gathering place - to be defined as one reference point for each village).	*Distance in minutes of walking*	*Distance in km (Note: the unit is km (1km=1000m)*

B. Household composition

B.1. Household and contact information

Contact information of the household head:	

Confirm that the respondent is the primary respondent; YES or NO *(Household head here refers to the one who manage the entire family now)*	
If he/she is not the household head, please write here name of the primary respondent:	
Please write here name of the secondary respondent:	

B.2. Household head information

Year born of household head (yyyy)	*4 digits (e.g., 1975)*
Gender	
Highest level of education	
What is the main economic activity of the house hold head?	
Was the household head born in this village? YES/NO	
If 'no': what is the period that the house hold head lived in the village? *number of years*	
What is the marital status of household head?	
[Sensitive] How many wives with associated families in your overall/combined household?	
When did you (HH) settle in NCA?	
Where did you come from?	
Why did you move into NCA?	

C. Livestock possession and management

C.1 Livestock possession

1. Number of livestock owned

Type of livestock	Age	Current number owned	Number owned two years ago	Number owned five years ago	Number owned 10 years ago
Cattle	Young males				
	Young females				
	Mature males				
	Mature females				
Sheep/goats	Young males				
	Young females				
	Mature males				
	Mature females				
Donkeys	Young males				
	Young females				
	Mature males				
	Mature females				
Camels	Young males				
	Young females				
	Mature males				
	Mature females				

2. Death occurrences in the herd

Type of livestock	Age	Yes/No	Number lost in two years
Cattle	Young males		
	Young females		
	Mature males		
	Mature females		
Sheep/goats	Young males		
	Young females		
	Mature males		
	Mature females		
Donkeys	Young males		
	Young females		
	Mature males		
	Mature females		
Camels	Young males		
	Young females		
	Mature males		
	Mature females		

3. What are the current herding strategies (choose one)

   i. Restricted herding (intensive and recursive use of the same rangeland areas)

   ii. Semi-extensive herding model (restrictive mobility with some recursive use)

   iii. Extensive herding model (less restrictions on foraging area choices which allow the pursuit of the extensive herding strategy)

D. Land and natural resources

D.1 Pasture/Grazing land

<table>
<tr><td colspan="2">Do you and your household members graze livestock?</td><td></td></tr>
<tr><td>How far is it from the house/homestead to the edge of the nearest grazing land that you have access to and can use</td><td>C.2.1a. Distance (in km)?</td><td>C.2.1b. Distance (in minutes of walking)?</td></tr>
<tr><td colspan="2">C.2.2. Does your household now spend more or less time in finding good grazing areas for your livestock compared to 5 years ago?

More (1)

Less (2)

Same (3)</td><td></td></tr>
<tr><td colspan="2">C.2.3. In general, how has availability of grazing land (physical availability not utilized) changed over the past 5 years? Increase/decrease</td><td></td></tr>
<tr><td colspan="2">What do you think are the causes of decline in availability of grazing land?

Soil erosion (1)

Loss of soil fertility (2)

Floods/droughts (3)

Poor grazing system (4)

Livestock - Wildlife grazing on same land (5)

Others (Specify)</td><td></td></tr>
<tr><td colspan="2">C.2.4. In general, how the length of rain seasons changed over the past 10 years? Increase/decrease</td><td></td></tr>
<tr><td colspan="2">C.2.5. In general, how the amount of precipitation changed over the past 10 years? Increase/decrease</td><td></td></tr>
</table>

C.2.6. In general, how is the grass cover changed over **the past 10 years**? Increase/decrease	
C.2.7. In general, how is the grass species diversity changed over **the past 10 years**? Increase/decrease	
C.2.8. In general, how is flood occurrences changed over **the past 10 years**? Increase/decrease	
C.2.9. In general, how is drought occurrences changed over **the past 10 years**? Increase/decrease	
Has your household planted any woodlots or trees during **the past 10 years**?	

D.4 Grazing (source of fodder)

1. How do you decide on your grazing area?

    i. --------------------------------

    ii. -------------------------------------

    iii. --------------------------------------

2. Which is most preferred grass species by livestock? Mention

    i. ---

    ii. --

    iii. --

    iv. --

    v. --

3. At what time of the day do you graze your livestock? _________________

    Why? ________

4. Do you seasonally migrate with your livestock? YES/NO ----------------

If YES, how long do you stay away from your permanent residence? ------------ (Months)

Season	Specific Local season	Cattle	Shoats	Why (Reason)
January-March				
April - June				
July - September				
October-December				
Other (Specify)				

5. Who migrates with your livestock from your family? ------------------------

6. Where do you commonly sell livestock and livestock products? (*Tick appropriate*)

   Local auction/market

   Market outside the NCA

   Mention town -------------------------

   Individuals at home

   Other (specify) -------------------------------------

7. How much do you receive from selling livestock products?

   Cattle ---------------------------Tshs

   Sheep/goat ---------------------------Tshs

   Milk (litre) ---------------------------Tshs

   Cattle skin ---------------------------- Tshs

   Goat/ sheep skin-----------------------Tshs

E. Adaptation to changing climate

1. What are the grazing strategies used in the period of pasture shortage?

    i. ____

    ii. ____

    iii. ____

    iv. ____

Close: Thanks so much for sharing your concerns and perspectives on these issues. The information you have provided will contribute to develop a better understanding about changing in rangeland condition with respect to grazing and rainfall variability in NCA. Before we conclude the interview, Is there anything you would like to add?

Thank you! *Ahsante sana*! *Ashenaleng*!

Appendix III: Participatory Rural Appraisal (PRA) questions

The participatory village discussion group will include a facilitator, observer/note-taker, and 5-6 selected knowledgeable local participants. Markers and Flip charts need to be brought to the communities for some exercises. Notebooks/paper and pens are needed to make a copy of the outputs (e.g., map, matrix) and for the note-taker to record the discussion during the exercises. In addition, pictures of the outputs can be taken for reference.

1. Seasonal Calendar

Objectives:

i. To understand livelihoods activities and changes in seasonality;

ii. To identify periods of stress and vulnerability (e.g. hazards, disease, hunger, water shortage).

Procedures: this activity should take approximately 1-1.5hrs including discussion. The facilitator should note any events for which the group has difficulty deciding on timing for further confirmation.

Step 1: Prepare flip charts; leave the first column blank and mark off the months of the year on the horizontal axis.

Step 2: Ask participants to list seasons, events, conditions, livelihood activities etc. and arrange these along the vertical axis, and identify the timing of each item accordingly in a 12 months' timeframe. The list should include:

- **Part 1:** *Seasons / Extreme events* (note down any observation in irregular shifting of seasons/events): i) dry season; ii) raining season; iii) any other season; iv) floods; vi) droughts; vii) storms; viii) too hot or cold days; ix) any other extreme event with an impact on local livelihoods. (Mark severe event with 3, 2 for intermediate, 1 for low and 0 for none in the month of relevance).

- **Part 2:** *Livelihood activities* (identify the cycle and details of each activity): i) crop cultivation and other (e.g. land preparation, planting season, and harvesting); ii) livestock raising; iii) other activities. (optional) Problem analysis under each activity. Solutions for problem identified.

- **Part 3:** *Food, water and energy security:* i) period of food shortage; ii) period of water shortage; and iii) period of energy shortage.

- **Part 4:** *Other events* (list particular important events and timing for the community): i) common seasonal illnesses occur; ii) holidays and festivals; and iii) times of migration.

Items	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
I. Seasons/ Events												
1) Wet season												
2) Dry season												
3) Flood												
4) draught												
II. Activities												
1)Livestock grazing areas												
-*Cattle*												
-*Shoats*												
III. Food, water and energy security												
1) Food insecure months												
2) Water insecure months												
IV. Other events												

2. Historical Timeline

Objectives:

i. To get an insight into changes in ecosystem services and other development aspects, and ii) to make people aware of trends and changes over time;

Procedures: this activity should take approximately 1-1.5hrs including discussion. It must be kept in mind that there may be a bias in the timeline as events in recent memory are more likely to be noted.

Step 1: Prepare flip charts, mark the past three decades and future on the horizontal axis.

Step 2: Ask participants if they can recall major events and changes in the community, and arrange these along the vertical axis. The list should include:

- **Part 1:** Changes/trends in resources: i) grazing resources ii) natural resources and products/services; iii) water resources; and iv) others.
- **Part 2:** Changes/trends in livelihood strategies/livestock types
- **Part 3:** Changes in land use and tenure
- **Part 4:** History of development (roads, schools, electricity, etc.)
- **Part 5:** Changes in natural resource policy, public administration, and organization
- **Part 6:** Changes in human and livestock population, migration, and what were the drivers and benefits of the immigration and migration?

Close: Thanks so much for sharing your concerns and perspectives on these issues. The information you have provided will contribute to develop a better understanding about changing in rangeland condition with respect to grazing and rainfall variability in NCA. Before we conclude the interview, Is there anything you would like to add?

Thank you! *Ahsante sana*! *Ashenaleng*!

Appendix IV: Above ground biomass and biomass productivity data recording sheet

Date	Village	Site	% cover				Average veg height				% cover of common species				Biomass				GPS**
			Excl 1	Excl 2	Cntrl 1	Cntrl 2	Excl 1	Excl 2	Cntrl 2	Cntrl 2	Excl 1	Excl 2	Cntrl 1	Cntrl 2	Excl 1	Excl 2	Cntrl 1	Cntrl 2	
NOTES:																			

Appendix V: Seasonal dynamics in group sizes of wild herbivores data collection sheet

Transect	Date	Time	Distance (Km)	Group composition										GPS _Vehicle	Vegetation
				Cttl	SH	WLB	Z	TG	GZ	BF	Spp 1	Spp 2	Spp 3		
NOTES:															

RESEARCH OUTPUTS

Journal Articles

Leweri, C. M., Msuha, M. J. & Treydte, A. C (2021). Rainfall variability and socio-economic constraints on livestock production in the Ngorongoro Conservation Area, Tanzania. *SN Applied Sciences* 3(1), 1-10. https://doi.org/10.1007/s42452-020-04111-0

Leweri, C. M., Bartzke, G. S., Msuha, M. J., & Treydte, A. C. (2022). Spatial and seasonal group size variation of wild mammalian herbivores in multiple use landscapes of the Ngorongoro Conservation Area, Tanzania. Plos one, 17(4), e0267082. https://doi.org/10.1371/journal.pone.0267082

Book Chapter

Leweri, C. M., Kimaro, J., Ntalwila, J., Hariohay, K. M., Sanare, J., Kavana, P., Treydte, A. C., & Fyumagwa, R. (In Press). Pastoralism Resilience Under a Changing Climate and Environment Among the Maasai Communities in the Ngorongoro Conservation Area. In R. Fyumagwa *et al*., (Eds), The Serengeti Ecosystem: Conservation and Livelihood in a changing world (Chapter 12).

Conference Proceeding

Leweri, C. M., Bartzke, G. S., Treydte, A. C. (2019) Are group sizes of wild herbivores influenced by human presence? A case study from Ngorongoro Conservation Area, Tanzania. Proceedings of the 12th TAWIRI Scientific Conference, Arusha, Tanzania.