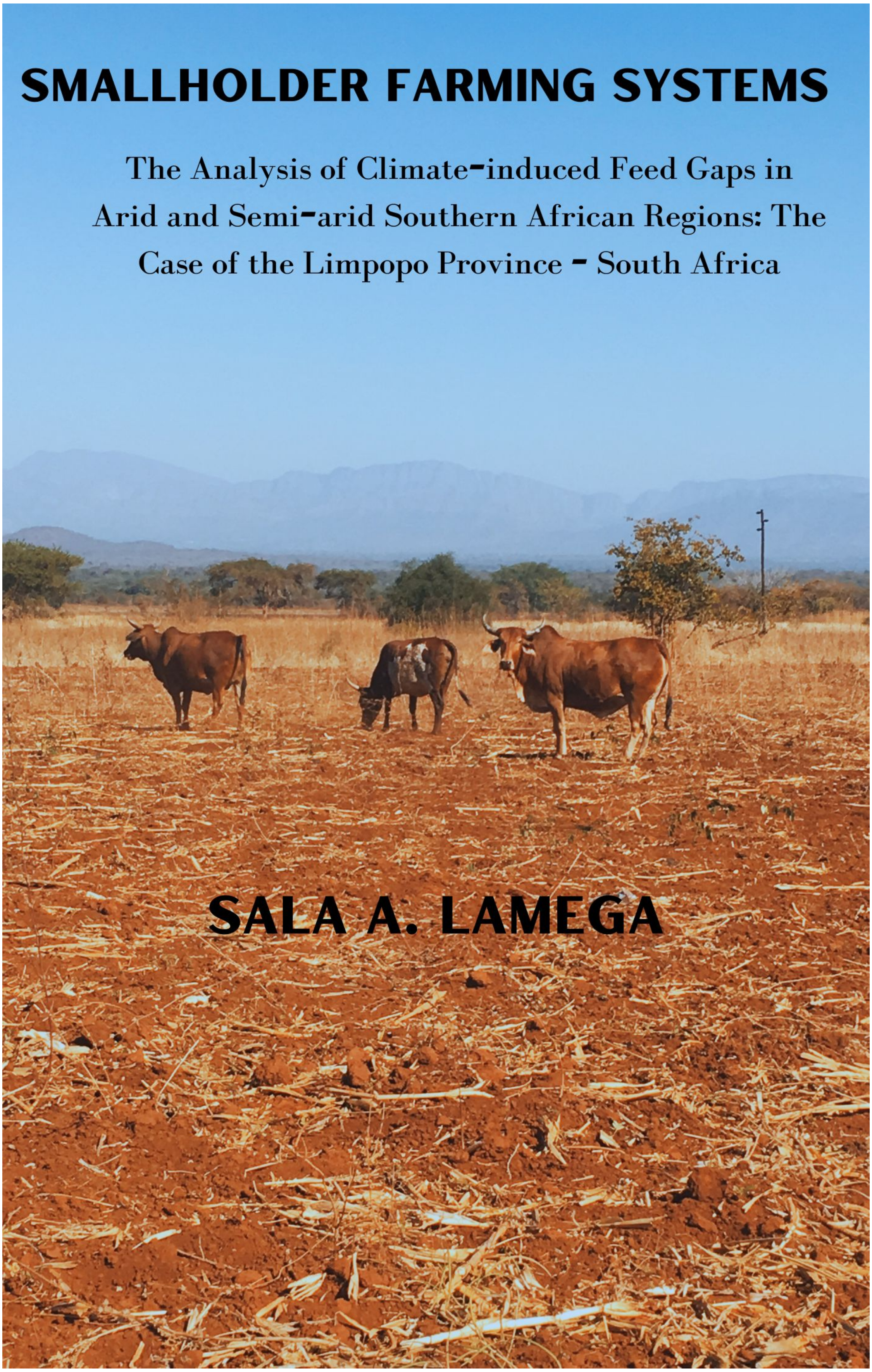
SMALLHOLDER FARMING SYSTEMS
The Analysis of Climate-induced Feed Gaps in Arid and Semi-arid Southern African Regions: The Case of the Limpopo Province - South Africa
SALA A. LAMEGA

The Analysis of Climate-induced Feed Gaps in Arid and Semi-arid Southern African Regions: The Case of The Limpopo Province - South Africa.

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A dissertation submitted for the degree of

Doctor of Philosophy Ph.D.

Göttingen, 21st July 2022

This work is dedicated to the memory of my father who did not live long enough to see the fulfilment of this Ph.D. Dad, your love and sacrifices have inspired this work. Rest in perfect peace! Also, to my mother, I wish to say thank you – I could never have done this without you.

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This PhD work was financially supported by the German Federal Ministry of Education and Research through the SALLNet project grant number *01LL1802A*
Date of oral examination: 21st, July 2022
Date of online submission: May, 2023

The thesis was typeset using Markdown. Thanks to the oxford thesis template available in Github.

D7

“Fear of man will prove to be a snare, but whoever trusts in the LORD is kept safe.”
Proverbs 29:25

“This is what the LORD Almighty says: “In a little while I will once more shake the heavens and the earth, the sea and the dry land. I will shake all nations, and what is desired by all nations will come, and I will fill this house with glory”, says the LORD Almighty
Haggai 2:6-7

“Who is he who speaks and it comes to pass, when the Lord has not commanded it?”
Lamentations 3:37

Acknowledgements

I would like to profusely thank my supervisor Prof. Dr. Johannes Isselstein for giving me the opportunity as a doctoral researcher at his chair. During the course of this work, I have been inspired by many qualities including your leadership, and I am most grateful for your great support. I wish to extend my gratitude to Prof. Kingsley Ayisi for enabling a conducive environment for my field work during my stay in South Africa and for his support throughout the duration of this work. Very big thanks to Prof. Dr. Eva Schlecht for her mentorship and who did not hesitate to serve as a supervisor on the thesis committee.

I am forever indebted to Dr. Munir Hoffmann who first trusted in my capabilities by recommending me for a student assistant position during my MSc. and later for this doctoral position. Your endless support and trust remain one of the reasons why this work became a reality. Two other persons that deserve a special mention are Dr. Martin Komainda and Dr. Dela-Dem Fiankor. Martin, I sincerely appreciate your availability and your academic support throughout this research. And to you Edem, I have been able to withstand the challenges of this research because of you. Thank you for filling the big brother's role!

Vielen Dank to all the "Grasslanders" (special thanks to Barbara Hohlmann), colleagues from the SALLNet poject, and friends for their support. A shout out to the *XY whats'app group* for the thorough discussions on matters of the heart: "Manchester United"! Those discussions eased my mind at times when the "going was tough". To my sisters Chimene and Brigitte, your brother finally did it!

My gratitude to you all goes beyond words! All glory, however, belongs to God.

Sala Alanda Lamega
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July 2022

Abstract

In the southern areas of Africa, climate hazards such as prolonged drought are among the phenomena that have negatively affected the farming systems. In relation to livestock, productivity is constrained by the shifts in vegetation dynamics that translate into feed gaps. Therefore, opportunities to cope with seasonal or inter-annual feed gaps for smallholder livestock keepers are urgently needed. Against this background, we investigated one of the most susceptible provinces to drought risks in South Africa, the Limpopo province, the seasonal occurrence of feed gaps.

Firstly, we used a survey technique to derive specific on-farm information regarding the seasonal feed availability and the current adaptation options as perceived by the rural smallholder farmers. We linked the survey information to vegetation-modeled data of the surveyed sites using aDGVM (adaptive Dynamic Global Vegetation Model) and elemental nutrient analysis of grazed grasses during the winter period. We analyzed these data to draw conclusions on the patterns of feed gaps across farm types (e.g. livestock only, mixed crop-livestock) and locations (warm arid, warm semi-arid and cool semi-arid).

Secondly, to have a broader picture of the available forage resources, we calculated the forage balance of the study province in relation to cattle keeping. Here, we linked the results to the assessment of the land use types (soil nutrient analysis of rangelands and arable lands) and crude protein levels of available feeding resources in periods of feed gaps. We found that a negative forage balance in the province, and degraded land use types may be strong drivers of the seasonal feed gaps.

Thirdly, additional on-farm data (e.g. cattle feces samples, cattle tail hair) were analyzed for the C and N isotope signatures. These samples were analyzed to assess and identify the triggers of feed gaps and their impacts on the farming systems. Here, we used isotopic signature techniques (δ^{15}N and δ^{13}C) to highlight livestock nutritional stress/differences across the locations and farm types. Stable isotopes are an important tool that can be used to describe and quantify different diet sources. Particularly, hair tissues contain dietary archive information that can temporally and spatially inform us on the environment. In line with this, the results confirmed that feed when available to livestock is usually “protein-deficit” which may be the cause of feed gap impacts such as animal weight losses.

The results indicated that feed gaps follow strong seasonal patterns and suggest that strategies to cope need to be context-specific. Furthermore, the results of this study set a strong foundation to inform drought risk management in a smallholder livestock farming context. The results can serve as a step toward developing context-specific management options for improved livestock systems. Also, this study calls for further mixed crop-livestock systems research focusing on a whole-farm modeling approach to evaluate the system against climate scenarios and different management options.

Keywords: Crop-livestock systems, Drought, δ^{15}N, δ^{13}C, Smallholder systems, Climate risks

Zusammenfassung

In Afrika südlich der Sahara wirken sich klimatische Risiken, wie lang anhaltende Dürren, negativ auf die landwirtschaftlichen Produktionssysteme aus. Die Viehwirtschaft in den überwiegend kleinbäuerlich geprägten Strukturen ist davon besonders betroffen, weil eine starke Abhängigkeit von der Produktivität des Savannengraslands besteht, welche stark durch Dürren zurückgeht, wodurch saisonal Futterlücken (sog. feed gaps“) resultieren. Insbesondere der niederschlagsfreie Winter zählt zu den kritischen Perioden innerhalb eines Jahres, wobei inter-annuell Variation in der Stärke von Wintertrockenheit auftritt. Daher sind Möglichkeiten und Anpassungsstrategien an die saisonal auftretenden Futterlücken dringend erforderlich. Vor diesem Hintergrund untersuchten wir in einer der trockenheitsanfälligsten Provinzen Südafrikas, der Provinz Limpopo, das saisonale Auftreten von Futterlücken. Dafür wurden auf ausschlieSSlich viehhaltenden Betrieben sowie auf Gemischtbetrieben mit Ackerbau und Viehhaltung Untersuchungen vorgenommen. Um die Klimavariation in der Provinz Limpopo abzubilden, wurden diese Betriebstypen in unterschiedlichen agro-klimatischen Regionen (warm-arid, warm-semiarid und kühl-semiarid) aufgesucht. Zunächst haben wir eine Umfrage durchgeführt, um spezifische Informationen über die saisonale Futterverfügbarkeit und aktuelle Anpassungsmöglichkeiten unter Kleinbauern zu erhalten. Wir verknüpften die Erhebungsdaten einerseits mit Berechnungen anhand eines Vegetationsmodells zur Bestimmung der Produktivität des Savannengraslands der untersuchten Standorte. Andererseits wurden Elementarnährstoffanalysen des im Winter beweideten Savannengraslands vorgenommen, um Rückschlüsse auf die Muster der Futterlücken in den verschiedenen Betriebstypen (z. B. nur Viehhaltung, Mischkulturen mit Viehhaltung) und agro-klimatischen Regionen (warm-arid, warm-semiarid und kühl-semiarid) zu ziehen. Um ein umfassenderes Bild der verfügbaren Futterressourcen zu erhalten, berechneten wir zweitens die Futterbilanz der Studienprovinz in Abhängigkeit von der Viehbesatzdichte. Wir verknüpften diese Berechnungen mit einer agronomischen Bewertung der Landnutzungsarten Weide und Ackerland. Hierfür wurden Bodennährstoffanalysen sowie Futterqualitätsanalysen durchgeführt. Dabei stellte sich heraus, dass unter Einbezug der Graslandproduktivität und des Aufkommens von Ernteresten des Ackerlands eine negative Futterbilanz in der Provinz die Hauptursachen für die saisonalen Futterlücken sein können.

Diese sind auf Betriebsebene aber nicht weit verbreitet, um die Risiken klimabedingter Futtermittellücken zu verringern. Drittens wurden Analysen stabiler Isotope von Boden- und Futterproben sowie von Schwanzhaaren und Dungproben der Rinder auf den untersuchten landwirtschaftlichen Betrieben vorgenommen. Hierbei lag der Fokus auf der saisonalen Dynamik von Kohlenstoff-(C) und Stickstoff-(N) Isotopensignaturen, die den Ernährungsstress in Abhängigkeit von Betriebstypen und agro-klimatischen Regionen aufzuzeigen können und einen Rückschluss auf die Futterverfügbarkeit in Zeiten der Futterlücken zulassen. Insbesondere Haargewebe enthält Informationen aus dem Ernährungsarchiv, die uns zeitlich und räumlich über die Umwelt informieren können. In diesem Zusammenhang bestätigen die Ergebnisse einen ťťProteinmangelťť, was die Ursache für Gewichtsverluste der Tiere sein kann. Die Ergebnisse zeigen, dass Futterlücken starken saisonalen Mustern folgen und legen nahe, dass Strategien zur Bewältigung kontextspezifisch sein müssen. Darüber hinaus bilden die Ergebnisse dieser Studie eine solide Grundlage für das Dürrerisikomanagement in der kleinbäuerlichen Viehhaltung. Die Studien zeigen auch die Notwendigkeit weiterer Forschungsarbeiten zu gemischten Ackerbau- und Viehzuchtsystemen auf, die sich auf einen Modellierungsansatz für den gesamten Betrieb konzentrieren sollten, um das System im Hinblick auf Klimaszenarien und verschiedene Managementoptionen zu bewerten.

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List of Abbreviations

aDVGM . . . . adaptative Dynamic Global Vegetation Model

AEZ . . . . . . Agro-ecological Zone

CL . . . . Crop-Livestock

CP . . . . Crude Protein

CR . . . . Crop Residues

DEA . . . . . . Department of Environmental Affairs, South Africa

DM . . . . . . Dry Matter

DMI . . . . . . Dry Matter Intake

FM . . . . Fresh Matter

FS . . . . Feed Supplements

GPP . . . . . . Gross Primary Production

L . . . . Livestock

ME . . . . Metabolizable Energy

General Introduction

0.1 Introduction

The risks of large climate uncertainties remain the most discussed topics in relation to farming systems in southern Africa. The risks of climate-related impacts such as prolonged drought periods, however, are highly context-specific but these impacts are expected to be larger in arid and semi-arid environments where resources for adaptation are limited (Godde, Mason-DCroz, et al. 2021). The current and projected impacts of these climate uncertainties on livestock systems can never be overstated as these are major concerns for livestock productivity (Godde, Mason-DCroz, et al. 2021; Descheemaeker, Amede, et al. 2010; Niang et al. 2015; Thornton et al. 2015). Consequently, severe livestock feed or forage gaps as a result of climate variability constitute net impacts on livestock farming in these vulnerable environments. Therefore, creating resilient or improved livestock systems that will support livelihoods will require a fundamental understanding of processes in current land-use types in order to assess synergies and trade-offs between the system components inherent to the farming practices. These system components constitute the households, rangelands, arable lands, livestock, soil, and climate. The livestock production system, particularly, has a high degree of variability. In line with this, a sound assessment of the temporal pattern of feed as affected by site-specific farming types and climate could serve as an entry point for developing adaptation options.

There has been a considerable amount of work on climate risk assessment across vulnerable farmers and strategies to enhance the farming system in the southern African region (Elum et al. 2017; Homann-Kee Tui et al. 2015; Simelton et al. 2013; Wilk et al. 2013). Nonetheless, future climate uncertainties will increase and call for context-specific exploration of factors associated with feed gaps and adaption options by linking the system components to the structural diverse farming practices.

0.2 Risk of climate variability in Southern Africa: background and problem statement

Rangeland systems are important as they play a vital role in providing important ecosystem services. It is estimated that rangelands occupy about one-fifth of the world's total land surface, therefore, making them economically, socially, and ecologically significant (Liao et al. 2018; Riginos 2009). Rangelands provide a food source and contribute to the sustenance of people's livelihoods, especially in livestock-dependent environments of low-income countries (Godde, Boone, et al. 2020; Liao et al. 2018; Sandhage-Hofmann 2016). In comparison to other land-use systems, rangeland systems are important for maintaining biodiversity (Newbold et al. 2015), and carbon storage (Garnett et al. 2017). However, rangelands are currently threatened by global climate change where potential impacts are believed to have a negative effect on the net primary production, thereby affecting livestock system functionality (Godde, Boone, et al. 2020). This is particularly true for Southern African regions where rangelands are an integral part of the rural-based mixed farming systems (Marandure, Bennett, et al. 2020; Nyamushamba et al. 2016; Tavirimirwa et al. 2019; Vetter et al. 2020).

The farming practices in Southern Africa are predominantly mixed crop-livestock systems (Masikati et al. 2015) characterized by the interaction of grazing resources (rangelands), rain-fed crop production, and the interdependencies between the livestock and the rangeland components. However, the region has been identified as one of the most vulnerable regions to climate extremes and variability (*Climate Change 2007* 2007; Masson-Delmotte 2019; Niang et al. 2015) susceptible to severe and prolonged drought (Dai 2013), and increased temperature (Niang et al. 2015). Hence, the natural systems are subjected to the high year-to-year variability of climate. For example, water and feed resources are impacted as a result of these changes which in turn increase the instability of current grazing systems for livestock production. In effect, empirical studies conducted in semi-arid and arid Southern Africa have demonstrated the vulnerability of rangeland vegetation dynamics, consequently, livestock production systems (Descheemaeker, Zijlstra, et al. 2018; Scheiter, Gaillard, et al. 2018). Furthermore, the impacts of these changes on livestock growth, health, and production are well documented in the literature and include reduced feed intake, weight losses, semen production, and quality as well as changes in behavior (Descheemaeker, Amede, et al. 2010; Moore et al. 2009; Nardone et al. 2010). The lack of adequate forage resources to support livestock production and maintenance due to intra-seasonal or inter-annual feed gaps caused by climate change is the most detrimental to livestock production. Nevertheless, the capacity of a farmer to adapt to forage gaps due to vegetation trends is often complex and may be dependent on various factors such as farm types, farm location, herd size, structure and management, and farmer's objectives and financial capacities (Godde, Mason-DCroz, et al. 2021; Marandure, Bennett, et al. 2020).

In South Africa in particular, a key feature of the projected climate change future is the rise of temperatures and the decrease in the rainfall patterns (DEA 2017). These anticipated changes may also have devastating effects on agriculture (Archer et al. 2019; Thomas et al. 2007; DEA 2017) particularly on vulnerable smallholders or rural farmers. The question of creating a resilient crop-livestock system in the face of climate variability that will support sustainable livestock intensification remains. To address the livestock feed shortage in South Africa, for instance, quality forage production has been emphasized (Truter et al. 2015), but the smallholder sector has been neglected in the discussion (Vetter et al. 2020). The problem, nevertheless, is that a system-oriented model that supports smallholder mitigation options in the face of climate vulnerability fails to consider the integrated system components (Rötter et al. 2021). Therefore, potential avenues for livestock keepers should first be based on the assessment of the feed system across farm types and locations amid climate uncertainties. In effect, such an integrated assessment of smallholder farms in relation to feed gaps could help develop context-specific mitigation strategies against the frequent climate-induced forage risks.

0.3 Description of the study location

This study was conducted in one of the nine provinces of South Africa, the Limpopo province. Limpopo is the northernmost province and is surrounded by Zimbabwe, Mozambique, and Botswana, but also by Mpumalanga, Gauteng, and North West; a few other South African provinces. The Limpopo province covers a total area of 125,755 km^2 and is divided into 5 districts and 22 local municipalities (*Community Survey 2016* 2018) (Figure 1). In 2016, the overall population of the Limpopo province was about 5.8 million with the vast majority (97%) being Black Africans (*Community Survey 2016* 2018). The census data also showed that the population in the rural areas of Limpopo is mainly Black Africans who are most likely to be food insecure according to a study by De Cock et al. (2013). There are three distinct climatic regions in the studied province which are mostly described as arid, semi-arid, and sub-humid (Mpandeli et al. 2015) with an increasing annual rainfall

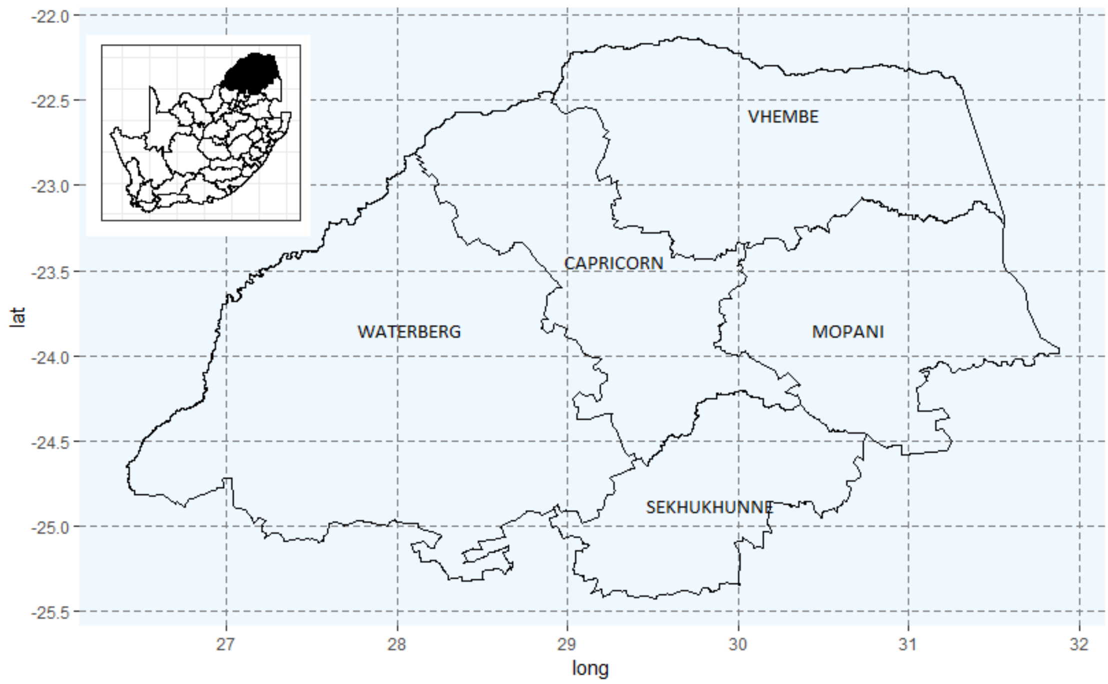

Figure 1: A map showing South Africa (top-left) and the Limpopo province (center)

of 300 – 600 mm. Generally, the summer season (December – February) receives the most rainfall while the remaining seasons hardly receive any precipitation. Mean minimum and mean maximum temperatures range from 10 to 12°C and 24 – 27°C respectively with the lowest temperatures in the dry and frost-free winter (June – August) and highest in the wet summer (up to 50°C).

In general, the farming practices in South Africa follow two distinct systems mainly due to regulated land tenure policies (Gwiriri et al. 2021). The unequal distribution of agricultural land was the essence of the racially-driven apartheid regime which favored "White" farmers. Therefore, one finds a commercially oriented agricultural sector characterized by private land ownership, dominated mostly by White farmers and a subsistence agricultural sector that is characterized mainly by communal land tenure. The latter sector is predominantly "Black" smallholder farmers. Recently, to bridge the gap between these two extreme farming practices, land reform policies in the country have empowered medium-scale farmers to become emerging commercial farmers (Gwiriri et al. 2021). In the study area, farming is done by both commercial and smallholder farmers, however, in the rural areas, households engage in subsistence farming (Rootman et al. 2015; Stroebel et al. 2011). In relation to livestock keeping, rural cattle ranching is practiced mainly

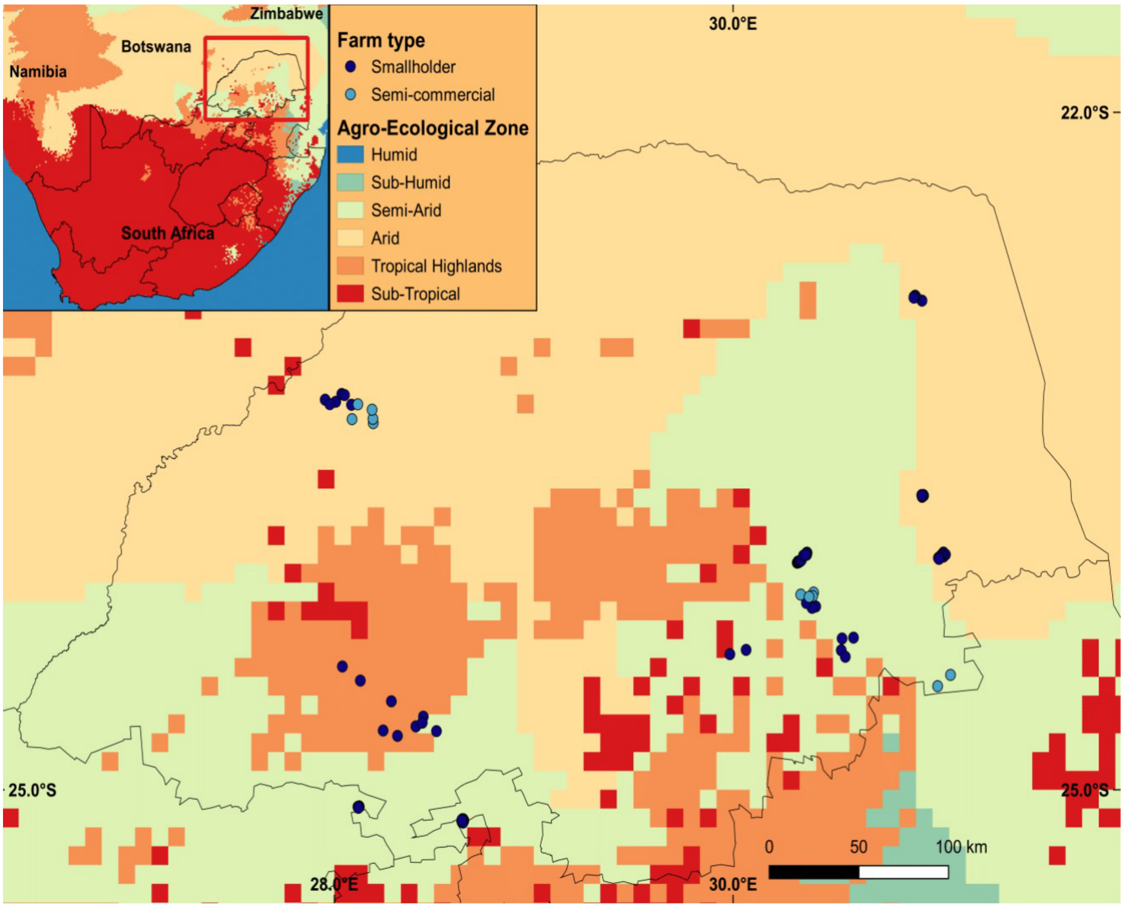

Figure 2: Map showing all the sampled locations for the overall study across different climate gradients (see chapter 2)

year-round on communal rangelands (Mapiye, Makombe, et al. 2018; Marandure, Dzama, et al. 2020). Rural livestock keeping is usually coupled with crop cultivation, though previous studies in the province demonstrated water as one of the most limiting factors for smallholder farms under rain-fed agriculture (DEA 2017; Oni et al. 2012).

Furthermore, previous reports also showed that the Limpopo province is likely to encounter significantly hotter and drier future climates (Dai 2013; Thomas et al. 2007). In effect, the province will experience a decrease in rainfall with an increase in the frequency of occurrences of heat waves and high fire danger. Under low adaptive capacity and without a mitigation strategy, which is usually the case in a smallholder rural farming context, the potential impacts of these weather anomalies on the farming systems are large. There are few studies that address climate change and its impact on the livelihood of smallholder farmers in South Africa in general and the Limpopo province in particular (Elum et al. 2017; Mapiye, Chimonyo, et al. 2009; Rankoana 2016; Thomas et al. 2007). However, there is still an urgent need to investigate the determinants of the feed gaps in relation to climate and farm types across the most vulnerable. Identifying these factors may help develop context-specific adaptation strategies to cope with the risks of climate-induced feed gaps.

0.4 Research objectives

The main objective of this doctoral thesis was to generate information that helps in understanding the limitations to the adaptive capacity to climatic extremes in complex farming systems among rural farmers in Limpopo. Such information may become crucial in order to develop strategies that are context-specific to farming households at different locations. Explicit objectives are as follows:

- Determination and evaluation of farmers' perceptions and current responsive strategies on livestock feed gaps in different agro-ecological zones (AEZ) and across distinct farm types.
- Analysis of on-farm biophysical data (e.g. feed resources, cattle tail hair, cattle dung) across farm types and AEZ based on isotopic techniques
- Evaluation of the farm types with the aim of informing policies and designing adapted strategies to cope with the increasing risks of feed gaps.

To attain these research objectives, a whole range of climatic conditions and farm practices were covered in the province. Stratification according to three AEZ (warm arid, warm semi-arid, and cool semi-arid) and two predominant farm practices (farm types: livestock only, mixed crop-livestock) was implemented. The classification according to AEZ was done based on data generated by IFPRI and HarvestChoice (Figure 2), but also on previous results by Mpandeli et al. (2015) and Mpofu et al. (2017). In effect, the selected AEZ differed in temperature, rainfall distribution, vegetation, and topographic characteristics. On the other hand, two farming practices were distinguished in relation to livestock keeping and categorized as livestock-only and mixed crop-livestock farming. In the rural farming context, a livestock-only farmer is engaged solely in keeping livestock as an alternative source of financial security. This is usually termed the "cattle complex" philosophy where rural cattle farmers keep cattle to validate the socio-economic status associated with livestock rearing (Rootman et al. 2015). Conversely, a mixed crop-livestock farmer usually combines livestock and cropping activities to improve livelihoods and achieve food security (Thornton et al. 2015; Masikati et al. 2015). The latter diversified system uses a complementary and integrated source of livestock and crop production where crop residues play an important role due to biomass scarcity. Both systems, however, primarily depend on rangelands for livestock feed.

This doctoral thesis is subdivided into five main parts. The general introduction is followed by three main chapters, representing three manuscripts (a published article, an accepted article for publication, and a manuscript under review at the time of submission of the doctoral thesis) with distinct methodologies to address the above-mentioned research questions. The first chapter focuses on investigating the seasonal feed availability among livestock-only (L) and mixed crop-livestock (CL) farmers. For this, we used survey techniques to derive on-farm specific data on farmers' perceptions of feed gaps. Such an approach has been previously used to inform farm household socio-economic characteristics but also to inform on livestock production (Masikati et al. 2015; Mapiye, Makombe, et al. 2018; Karimi et al. 2018). Household interviews were conducted with randomly stratified farmers (usually farm managers) accounting for cattle ownership. Farmers were mainly asked about their perception of feed gap patterns, the impacts of feed gaps on livestock, and current adaptation strategies to feed gaps. Furthermore, this chapter links farmers' perceptions to modeled vegetation (daily GPP 1990 — 2019, of the study locations — or nearest sites) using the aDGVM (adaptative Dynamic Global Vegetation Model) to understand the feed gap patterns and further compare (the data) with the perception of the farmers. The aDGVM is an individual-based ecosystem model that stimulates, dynamically, individual plant types such as grass or tree, annual or perennial, and the underlying key physiological and biogeochemical processes (Scheiter and Higgins 2009). The vegetation model has previously been parameterized and tested for rangeland and grazing systems in South Africa and in the studied province (Scheiter, Gaillard, et al. 2018; Pfeiffer et al. 2019). Furthermore, in situations where there is likely no herbage available for cattle consumption (dead and fibrous herbage during the dry period), mineral content could become important in covering the demand in terms of these elements (Costa e Silva et al. 2015). Therefore, the analysis (elemental nutrient analysis) of grazed rangeland biomass during the dry period was performed.

The second chapter which is built on the previous one uses statistical data to estimate the forage supply and demand in relation to cattle ownership in the Limpopo province. For instance, the forage balance (supply - demand) was calculated by estimating the annual supply of forage (crop residues, rangeland biomass) and deriving the annual cattle demand (total cattle head in Limpopo, assuming daily dry matter intake). In addition, an analysis of available resources (soil and feeding resources) across land-use types (e.g. arable land, rangelands) was done to complete the assessment of the farming systems in relation to feed gaps.

Using C and N isotopic signature techniques on cattle feces, and cattle tail hair, the third chapter highlighted the short and long terms dietary information in relation to farm locations and types. Stable isotopes are an important tool that can be used to describe and quantify different diet sources (Schwertl, Auerswald, Schäufele, et al. 2005; Schwertl, Auerswald, and Schnyder 2003a; Schwertl, Auerswald, and Schnyder 2003b). Hence, this technique provides a sound understanding of the animal dietary composition and nutritional stress during periods of feed availability versus periods of feed scarcity. In this chapter, the contribution of C_4 species to cattle diet was further estimated from the C isotopic composition of the feces to investigate the differences in feed supply during a feed gap period.

A general discussion and conclusion chapters conclude this doctoral thesis by summarizing key findings, limitations, and research outlook in an attempt to create a dialogue to support rural policies for the vulnerable farmers in the Limpopo province, South Africa.

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1

It depends on the rain: Smallholder farmers' perceptions on the seasonality of feed gaps and how it affects livestock in semi-arid and arid regions in Southern Africa.

1.1 Abstract[1]

The risk of climate-induced feed gaps, i.e. seasonal deficiencies in forage quantity and quality, is a major constraint for livestock in the dry regions of southern Africa. In South Africa particularly, the frequent occurrence of drought is a challenge for livestock farming and, coping strategies to mitigate feed gaps on smallholder farms are urgently needed. We chose the Limpopo province, of northern South Africa to study livestock farmers' perceptions of the temporal patterns of feed gaps and their perceived impacts on livestock production across different agro-ecological zones (AEZ) and farm types (i.e., livestock only, mixed crop-livestock farms). We combined a semi-structured questionnaire on ninety farms with data from herbage analysis (mineral nutrient concentrations of grasses grazed in winter). Additionally, we explored the effect of seasonal feed availability on feed gaps, expressed as gross

[1]This chapter is published as: Lamega, S. A., Komainda, M., Hoffmann, M. P., Ayisi, K. K., Odhiambo, J. J. O., & Isselstein, J. (2021). It depends on the rain: Smallholder farmers' perceptions on the seasonality of feed gaps and how it affects livestock in semi-arid and arid regions in Southern Africa. Climate Risk Management, 34, 100362.

primary productivity (GPP), based on long-term simulated vegetation data. We found a close correlation between farmers' perceived feed gaps and GPP (Pearson's $r = -0.77$, $p < 0.01$). Farmers' perceptions of feed gaps are related to precipitation deficits that restrict rangeland productivity especially in winter and spring across the AEZ. Consequently, farmers considered that feed gaps occur mainly in winter (80%) followed by spring (30%) and autumn (20%). In addition, our analysis demonstrated that in winter the mineral concentration in rangeland biomass is inadequate to meet the livestock feed requirements. The percentages of farmers who perceived feed gaps and animal weight loss in the winter season did not differ significantly between farm types ($p = 0.40$) and AEZ ($p = 0.41$). Among livestock-only farmers, feed gaps were perceived to occur more in autumn ($p < 0.01$) whereas for mixed crop-livestock farmers the feed gap perception was greater in spring ($p < 0.01$). Farmers located in the drier zone perceived feed gaps more in spring ($p < 0.05$), leading to the significant perception of livestock weight loss for that period ($p < 0.01$). As strategies to deal with feed gaps, farmers rely on crop residues and/or reduction of livestock numbers. To improve the sustainability of the livestock system, our results show that feed gaps follow a strong seasonal pattern and they suggest that intervention strategies do not necessarily need to account for local climatic differences but rather for farm operation types.

Key words: Rangelands, climate risk, cattle, adaptation, South Africa.

1.2 Introduction

Southern African smallholder livestock farming is complex and heterogeneous since the individual components (e.g. water resources, rangelands, feed resources) of the farming systems interact differently across agro-ecological zones, farm types, and typology (Herrero et al. 2013). Rangelands and, in the case of mixed crop-livestock farms, also arable land, play an important role as key feeding resources for livestock, as also discussed by Herrero et al. (2013). Both mixed-crop livestock and livestock-only farming systems are crucial for food production, and particularly in supporting the livelihoods of inherently resource-constrained farmers that mainly rely on grazed rangeland biomass and crop residues for livestock feeding (Descheemaeker, Oosting, et al. 2016; Thornton and Herrero 2015). However, these developed management options are coming under pressure due to climate change, as many regions in southern Africa are affected by changes in rainfall amounts and distribution, increased heatwaves and droughts (Zhao et al. 2015). Moreover, such impacts bring changes in the availability and utilization of resources, with decreased rangeland productivity (Masson-Delmotte 2019).

Consequently, the effects of climate-related drought will affect the quantity and quality of feed and water resources for livestock. This presents a major risk to livestock production, unless adequate coping strategies are found (Rojas-Downing et al. 2017). It is likely that smallholder farmers that rely mainly on natural resources are particularly affected by climate extremes because of their limited technological knowledge and vulnerability to fodder shortages, resulting in feed gaps for the livestock during the year (Kom et al. 2020). Feed gaps, as explained by (Moore et al. 2009), are the result of both biological and socio-economic factors, and they occur during a period of the year when feed supply, and its quantity are insufficient or unavailable to sustain livestock productivity. According to Moore et al. (2009), feed gaps may occur frequently ('regular') due to intra-annual variability in the feed supply, or occur less frequently ('irregular') due to inter-annual variability in the distribution and supply of feed to livestock.

In southern Africa, smallholder cattle farmers rely predominantly on the communal use of natural resources, particularly rangelands. As rangeland productivity is affected by seasonal and inter-annual climate variability, farming households are especially vulnerable to changes in rainfall (Nyamushamba et al. 2016). Various studies in the southern Africa, and to some extent among the southern African development community have suggested that smallholder farmers already perceive climate change and the variability associated with it as weather shocks, such as a decrease in rainfall days as shown in Tanzania (Mkonda et al. 2018) or increased drought and heat in Zimbabwe (Makuvaro et al. 2018). Similar findings have been reported for South Africa (Hitayezu et al. 2017), Botswana and Malawi (Simelton et al. 2013). One of the consequences of such climate-related shocks for communal livestock production is feed shortages, as shown in studies in arid and semi-arid regions of southern Africa (Tavirimirwa et al. 2019; Vetter et al. 2020). Therefore, recognizing farmers' perceptions on when and where feed gaps occur in relation to variations in seasonal productivity of communal rangelands could be very important for targeting strategic interventions. In South Africa in particular, the vulnerability of smallholder livestock farmers to feed gaps might have been further aggravated by previous land policies established in the Apartheid era, under which unproductive communal rangelands were settled by indigenous peoples (Bennett et al. 2013), as well as adaptive incapacities due to low economic resources (Tibesigwa et al. 2016).

In line with this, in Limpopo, the poorest regions of South Africa, efforts for improving the productivity of smallholder cattle farming systems have been implemented through a more efficient use of communal resources (Marandure, Dzama, et al. 2020). Despite such initiatives to support smallholder cattle farmers in Limpopo, there is growing evidence of limitations to achieve high productivity due to psychological, socio-economical, cultural, ecological, institutional and, governmental constraints (Kom et al. 2020; Marandure, Dzama, et al. 2020). For smallholder cattle farmers in Limpopo, the frequent and prolonged drought could be considered as an extended feed gap resulting in low productivity affecting the farming sector negatively. In general the perception of feed gaps at the farm level might vary greatly even within agro-ecological zone (AEZ) in relation to farm types, as some are better adapted than others for various reasons (Mkonda et al. 2018; Thornton and Herrero 2015). Consequently, Mkonda et al. (2018) argued that farmers located in arid zones (the most vulnerable AEZ) were more sensitive and responsive to climate variability and risks to the farming enterprise. Furthermore, farm types are likely to respond differently to climate variability impacts, and earlier studies have shown that mixed crop-livestock systems may be the least vulnerable as they offer diverse feed resource-opportunities for efficient adaptation (Thornton and Herrero 2015; Weindl et al. 2015). In order to further explore these issues, the present study provides insights on farmers' perceptions on the seasonality of feed gaps, the impact on cattle productivity as perceived by effects on animal weight loss, and the coping mechanisms against feed gaps. These assessments are linked to modelled vegetation productivity, and forage mineral nutrient concentrations, could serve to find prime examples for improved climate risk management plans to support smallholder livestock farmers at different farm operational types (i.e. livestock-only, mixed crop-livestock) and for different AEZ.

We hypothesized that the perception of feed gaps and coping strategies is dependent on the extent to which additional feed resources are available. Since mixed crop-livestock farmers have a greater range of available feed resources, we hypothesized that farmers categorized within that system perceive that feed gaps are less frequent or less important. As rangeland productivity is related to rainfall patterns, a second hypothesis is that the perception of feed gaps, and the perception of animal weight loss, are greater in drier AEZ irrespective of the farm type.

1.3 Materials and Methods

1.3.1 Description of the study area

The study was conducted in the Limpopo province of the Republic of South Africa bordering Mozambique, Botswana and Zimbabwe and covers an area of 125,755 km^2 of which approximately 81% is used for livestock grazing (Oni et al. 2012). The climate varies from warm-arid in the Limpopo lowland valleys to humid subtropical in the highlands (Cai et al. 2016) and average rainfall varies from $<$ 200 mm to $>$ 1000 mm (drier in the north-eastern parts and wetter along the Tzaneen valleys). The rainfall in the province mostly occurs in spring till summer (September-February) and in the remaining period there is little or no rain. In summer, the average temperature is about 27°C with maximum temperatures reaching between 45°C to 50°C in the lowlands. The climatic patterns have allowed the development of different vegetation types which include grasslands (mainly C_4 species), savannas, bush Feld, and forests (Mpofu et al. 2017). In 2016, an estimated 369,460 households in Limpopo were engaged in farming activities, predominantly livestock-only farming (43%) but farming households also engage in cropping-only (38%) and mixed systems (18%) (*Community Survey 2016* 2018).

About 90% of Limpopo's population lives in rural communities, so that, farming is dominated by subsistent smallholders for self-supply with a low level of production inputs and technology (Stroebel et al. 2011). Past El Niño events with anomalously low precipitation and extreme heatwaves, with impacts (i.e. severe droughts), have rapidly stressed the agricultural sector in Limpopo (Archer et al. 2017; Hitayezu et al. 2017). Furthermore, climate change projections indicate that the region will become drier with frequent summer dry-spells in addition to the regular winter dry-seasons that particularly affect cattle herd dynamics and productivity (DEA 2017).

1.3.2 Data collection: farm-level information and grass sampling

A survey was conducted among 90 farms with the support of extension officers from June to September 2019. The experimental design refers to a stratified farm household survey based on a semi-structured interview where farm owners or managers answered the questions. For this purpose, farm households were selected in three AEZ representative of the climatic conditions of the province (warm arid n=29, warm semi-arid n=29, cool semi-arid n=32) (Mpandeli et al. 2015) (Table 1.1). In each AEZ, two or three villages were selected and farm households were classified into two farm types, i.e., livestock-only or mixed crop-livestock farming. We collected farm-specific information on the livestock system and production principles (here we defined production as mechanisms to ensure crop-livestock production and sustenance), feed gap patterns and impacts on the production system, coping strategies, and overall constraints to livestock production. The impact of feed gaps on livestock production was measured as farmers 'perception of animal weight loss and death during the period of feed deficit' (Moore et al. 2009).

For the mixed crop-livestock farm type, the crop production component was surveyed as well. The description of the variables is presented in Table 1.2. The questionnaire was divided into four parts. The first part took records of general information (e.g., site information, coordinates, altitude). The second part (questions 1 – 22) considered farming production principles and characteristics (e.g., cattle number, purpose, feeding regime, farm types). Parts three and four reported on the perception of feed gap periods and risks (e.g., perception of feed gap periods, perception of animal weight losses, death due to feed gaps, questions 23 – 34), coping strategies, and constraints (questions 35 – 37). The variables were used to capture the dynamics of feed gap perceptions, i.e. how and when farmers perceive feed gaps, and whether the farmer has developed responses or not. Before we carried out the questionnaire with the local farmers, we trained a facilitator who assisted in understanding and communicating to avoid misinterpretation of questions and answers from English-Local (Pedi and, or Tsonga) and Local-English language.

The surveyed farms were mainly characterized by small herd sizes (90% having 5 – 25 cattle) dominated by culturally and locally well-adapted 'Ngunis' and their crossbreeds. With respect to the cattle feeding regime, farmers depend on communal grazing lands for year-round cattle grazing. Hence, we collected plant biomass samples (grasses only) at the village level on the communal grazing lands to analyze the AEZ-specific rangeland feed source biomass composition. Since sampling was done in the dry season where no growth takes place, the dry grasses (short and tall grasses) were either hand plucked or cut from inside a 50cm x 50cm quadrat near the soil surface. Before sampling, evidence of grazing was searched for (either by sampling near the animals on the rangelands or evidence of relatively abundant dung patches and grazed plants). Four dry grass samples were randomly taken on each grazing site following a longitudinal transect-based approach (5m apart). Samples were dried at 60°C, ground, and analyzed for phosphorus (P), potassium (K), magnesium (Mg), calcium (Ca), sulphur (S), sodium (Na), boron (B), copper (Cu), iron (Fe), manganese (Mn), zinc (Zn) and molybdenum (Mo) using the calcium-acetate-lactate (CAL) nutrient extraction method (Schüller 1969). The concentrations of P and K were determined in continuous flow analysis coupled to a flame photometer (K) or UV/VIS spectro-photometer (P) (San System, Skalar, the Netherlands). The remaining nutrient concentrations were determined using atomic absorption spectrometry (AAnalyst 400, Perkin Elmer Inc, Waltham, USA).

Table 1.1: Characteristics of the selected sites

Agro-ecological zones	Mean altitude (m)	Range of annual precipitation (mm)	Mean cattle number (SD)	Number of livestock-only/mixed crop-livestock farms
warm arid	369	200-300	15.96(8.16)	12/17
warm semi-arid	681	400-500	10.25(6.48)	11/18
cool semi-arid	1097	500-600	45.08(28.6)	28/4

Table 1.2: Description of the variables used for the farm survey.

Variables names	Variable description
Part I: General Information	
Altitude	Continuous
Agro-ecological zones	Dummy (warm arid, warm semi-arid, cool semi-arid)
Coordinates	
Farm ID	
Part II: Farm characteristics	
Farm type	Dummy (livestock only, mixed crop-livestock)
Livestock type	Dummy (sheep, goats, pigs, etc.)
Rearing purpose	Dummy (security, sales, home consumption)
Cattle number	Continuous
Feeding systems	Dummy (year-round, zero grazing, stall feeding)
Crops grown (mixed systems)	Dummy (maize, cowpea, lablab etc.)
Crop yield utilization	Dummy (sales, home consumption, livestock feed)
Crop-growing months	Dummy (months of the year)
Part III: Feed gap perception and risks	
Months of feed gaps	Dummy (months of the year)
Season of feed gaps	Dummy (spring, summer, autumn, winter)
Seasons of feed availability	Dummy (spring, summer, autumn, winter)
Perception of feed gaps frequency	Dummy (regular, irregular)
Perception of animal weight losses	Dummy (yes, no)
Seasons of perceived weight losses	Dummy (spring, summer, autumn, winter)
Perception of animal death due to feed gaps	Dummy (often, sometimes, not likely)
Part IV: Strategies and constraints	
Coping strategies	Dummy (crop residues, feed purchase, feed aid, etc.)
Constraints to livestock production	Dummy (feed, theft, water, access to market etc.)

1.3.3 Modelling patterns of regional feed availability using aDGVM

A dynamic vegetation model was used to quantify the gross primary productivity (GPP) of vegetation within the selected AEZs in order to compare these outputs with the farmer's perception of feed gaps. The GPP is usually expressed as carbon (C) accumulation rate (g C m^{-2} day^{-1}). For this, we extracted GPP from simulations with aDGVM (adaptive Dynamic Global Vegetation Model) presented by Martens et al. (2020). The model has been used previously and evaluated for vegetation simulation studies and dynamics in the context of climate change for South Africa and the Limpopo province (Martens et al. 2020; Scheiter et al. 2018).

The modeling exercises were not developed specifically for this study; Martens et al. (2020) provides all details on aDGVM and the simulation protocol. To understand the feed gap patterns in the Limpopo province and further compare the perception of the farmers (with data), the daily GPP ranging from 1990–2019 was simulated and retrieved for our study locations from the model and then grouped by season (Figure 1.2). For each AEZ, the nearest neighbor sites of available climatic data (average distance between the climatic source and site 20km ± 7km) were used, and mean values (± SD) for vegetation only (grass and tree) are reported.

1.3.4 Statistical analysis

The data analysis focused on perceptions regarding feed gaps and it makes comparisons of the farm types (livestock-only vs. mixed crop-livestock) across AEZs (warm arid, warm semi-arid, and cool semi-arid) and between AEZs across farm types using software R 3.6.0 (R Core Team 2019). For these comparisons, the dependent and independent variables (Table 1.2) from the household survey data were subjected to basic descriptive statistical analyses (mean, frequency, percentage) on farmers' perceptions of feed availability, livestock weight loss and coping strategies, using the prettyR package. A non-parametric test (Chi-square) was performed to test for similarities and differences in the perceptions or coping strategies between dependent variables expressed as percentages of farmers between farming systems across AEZs or between AEZs across farming systems (categorical, binary, and continuous variables) (Tesfahunegn et al. 2019).

For example, we tested for differences in the variability of perception of feed gaps in relation to seasons between farm types, or by testing for differences in the perception between livestock-only and mixed crop-livestock within one season. The Chi-square test is commonly used by adopting the classic Neyman et al. (1933) theorem. The test is normally valid when the percentages being analyzed are not too close to 0% and 100%, which is, unfortunately, the case when considering small sample size. For the analysis, we set the chisqtest () with the function correct =

FALSE that returns the invalidity of the test automatically, which is corrected by implementing the Fisher's test based on Perezgonzalez (2015).

Additionally, we used Pearsons' correlation to identify the relationship between perceived feed gaps (farmers' perception) and actual feed gaps in terms of rangeland vegetation productivity (GPP). This relationship was established by plotting the average daily GPP (g C m^{-2} day^{-1}) per season against the mean proportion of farmers' perception on seasonal feed gaps across the three AEZ (warm arid, warm semi-arid, cool semi-arid). Since binary numbers (0,1) were used to report on farmers' perception on feed gaps i.e., 1 if a farmer perceives feed gaps and 0 when a farmer perceives no feed gaps, the mean proportion was calculated after grouping the perception per season across AEZ. A mean number closer to 0 consequently refers to no feed gap perception.

1.4 Results and Discussion

1.4.1 Seasonality of feed perception and the vegetation growth

More than 50% of the surveyed farmers across all AEZ and farm types perceived the 4-month period of June to September to be affected by feed gaps, with the peak months being July and August, when 80% of the farmers perceived feed gaps (Figure 1.1A). In spring (September-November), about 30% of the farmers feed gaps, and in autumn (March-May) it was only about 20%. The summer (December-February) was clearly the season of feed availability, linked to precipitation in that period. No farmer perceived year-round feed gaps while less than 10% of the total thought that there are no feed gaps. These perceptions indicate that farmers are indeed aware of the erratic occurrence of precipitation and low productivity of vegetation associated with perceived animal body weight losses (80% in winter, 40% in spring, Figure 1.1B). In Limpopo, vegetation patterns are strongly linked to precipitation and this explains the clear and obvious perception of feed gaps in winter across farm types and AEZ. The perception of feed gaps is in accordance with the modelled vegetation growth rates (Figure 1.2) which, unsurprisingly were associated with the seasonal rainfall. Using the modelled results, we found that the calculated annual GPP sum for each AEZ shows an increase over the years considered (1990 – 2000, 2001 – 2010, 2011 – 2019) (Figure 1.2).

The overall increase in the annual GPP sum across AEZ is partly related to an increase in the average annual rainfall in the region. In their description of rainfall frequencies in the Limpopo region, Thomas et al. (2007) showed a notable intra to inter-annual variability in the rainfall record. This variability is presented by a rainfall trend towards February – April, which could explain the increase over time in the daily GPP for the autumn months (March – May). Aside from that, the increase in GPP over time, as suggested by Martens et al. (2020), can be explained by a combination of other factors, which may include increased concentration of atmospheric carbon dioxide. In line with our modelled GPP results, Hyvärinen et al. (2019) who investigated vegetation patterns in the semi-arid areas of South Africa using Landstat multispectral data and soil adjusted vegetation indices, attributed the increase in vegetation productivity to increased precipitation.

Therefore, although vegetation dynamics and productivity in semi-arid and arid regions are influenced by both biotic and abiotic factors, rainfall patterns or water availability are particularly reported as the main driver of its productivity. This may explain why the accumulated seasonal values of the summer GPP (Figure 1.2) were largest in the cool semi-arid AEZ which receives more summer rainfall (Table1.1,1.3), the years of mean GPP values ranged from 12.67 – 14.97 g C $m^{-2}season^{-1}$), and the lowest GPP values were in the warm arid AEZ (6.13 – 8.69 g C $m^{-2}season^{-1}$). The accumulated GPP values in the warm semi-arid AEZ for the summer were intermediate (7.26 – 9.3 g C $m^{-2}season^{-1}$) between the two zones. For 1990-2000 the accumulated sum of GPP in g C m^{-2} for the cool semi-arid, warm arid and warm semi-arid zones was 22.7, 14.3 and 15.0. For 2001-2010, corresponding GPP values were higher at 24.9, 18.1 and 18.1 and for 2011-2019 values were higher still at 27.4, 19.8 and 21.2.

The results suggest that the common grazing resources among smallholder farmers in Limpopo are constrained by low precipitation in the winter and spring seasons especially. The modelled GPP near to zero during winter (June-July-August) (Figure 1.2) is related to the model assumption of leaf fall during the dormant stage of development without any carbon assimilation (Martens et al. 2020) but is also related to a lack of precipitation during the winter dry season. In this regard, we found a strong negative and significant relationship ($P < 0.01$) while comparing the average daily GPP (g C m^{-2} day^{-1}) accumulated per season against the mean proportion of farmers' perception of seasonal feed gaps (Figure 1.3, winter and spring seasons especially. The modelled GPP near to zero during winter (June-July-August) (Figure 1.3). This indicates that the farmers' perceptions on the seasonality of feed gaps are associated with temporal changes in rangeland productivity. Therefore, when GPP is low the mean perception value based on proportion of farmers' answers is closer to 1 (1= feed gaps).

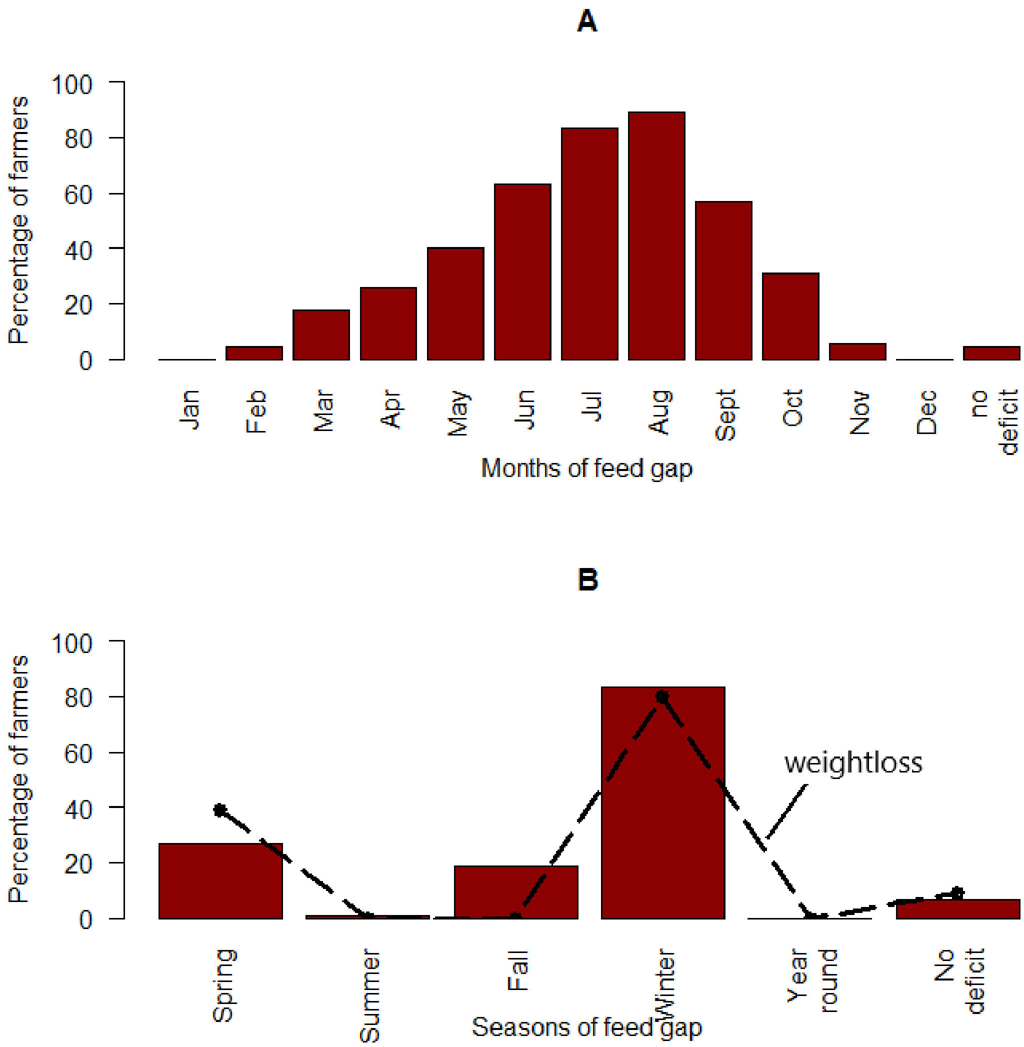

Figure 1.1: Perception of feed gaps by months (A) and by seasons (Spring: Sept-Nov, Summer: Dec-Feb, Autumn: Mar-May, Winter: June-Aug) (expressed as % of total farmers) with the corresponding perceived feed gpas impact given as animal weight loss (black line) (B)perceived weightloss (B) across farm types and agro-ecological zones (also expressed as % of total farmers).

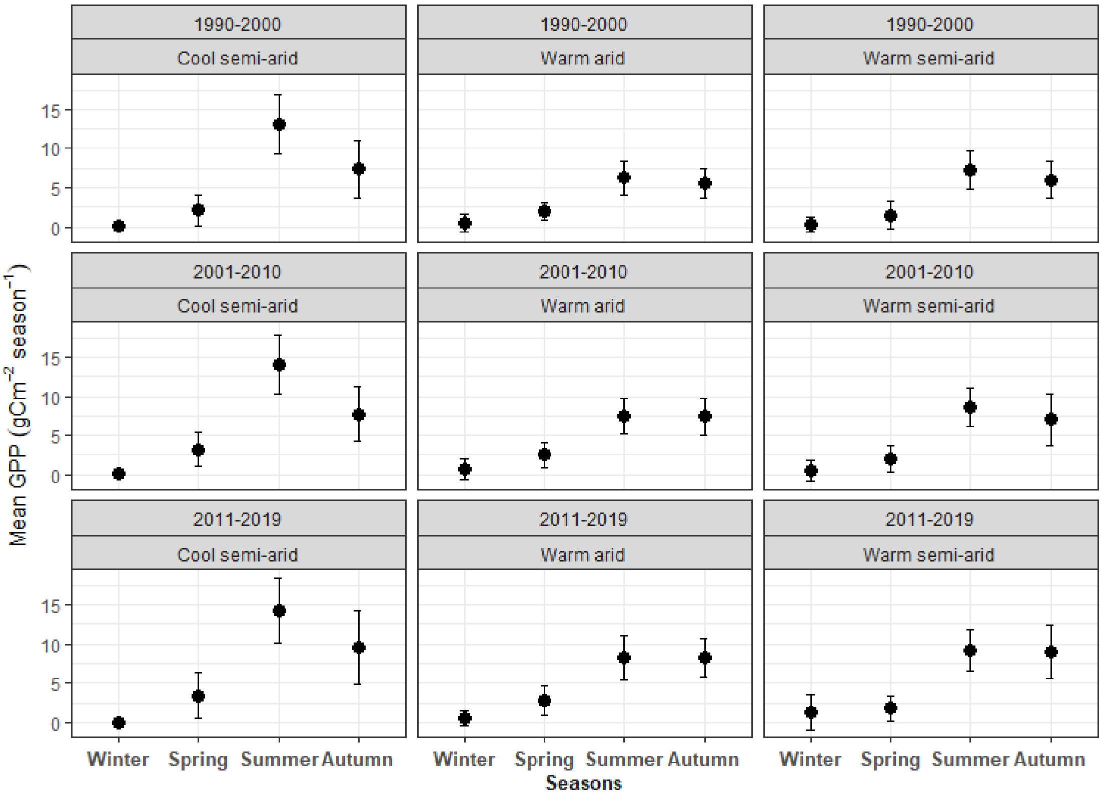

Figure 1.2: Summary of the modelled accumulated mean GPP per season (spring: Sept-Nov, summer: Dec-Feb, autumn: Mar-May, winter: Jun-Aug) (±SD) in g Cm^{-2}Season^{-1} across agro-ecological zones (results reported for 1990–2000; 2001–2010; 2011–2019).

Furthermore, to increase the feed dry matter intake by cattle, there is the need to increase the feed quality. This is because an adequate supply of macro-nutrients and trace elements is crucial to promote cattle live weight gain. For instance Costa e Silva et al. (2015) estimated the dietary requirements for maintenance for beef cattle and assuming a live weight of 300 kg (1.2 Tropical Livestock Unit (TLU), 1TLU = 250kg), the macro-nutrient requirement (g kg^{-1} day^{-1}) for maintenance is 9.7 Ca, 15.4 P, 5.6 Mg, 16.7 K, 6.5 Na and 11.1 S, and the requirement for trace elements (mg kg^{-1} day^{-1}) is 67.4 Cu, 1545 Fe, 70.5 Mn, and 451 Zn.

The mineral nutrient concentration in the rangeland forage sampled in the present study (Table 1.3) was in the range reported previously for semi-arid and arid zones (Hussain et al. 2008) but is not adequate to meet the requirements of the grazing cattle. Given these values are appropriate for the local breeds, rangeland forage concentrations of nearly all nutrients are insufficient to meet cattle requirements in this period. In addition, the crude protein content of rangeland biomass has been reported to be extremely low (2.7% in dry-matter) during the winter period (Moyo et al. 2012).

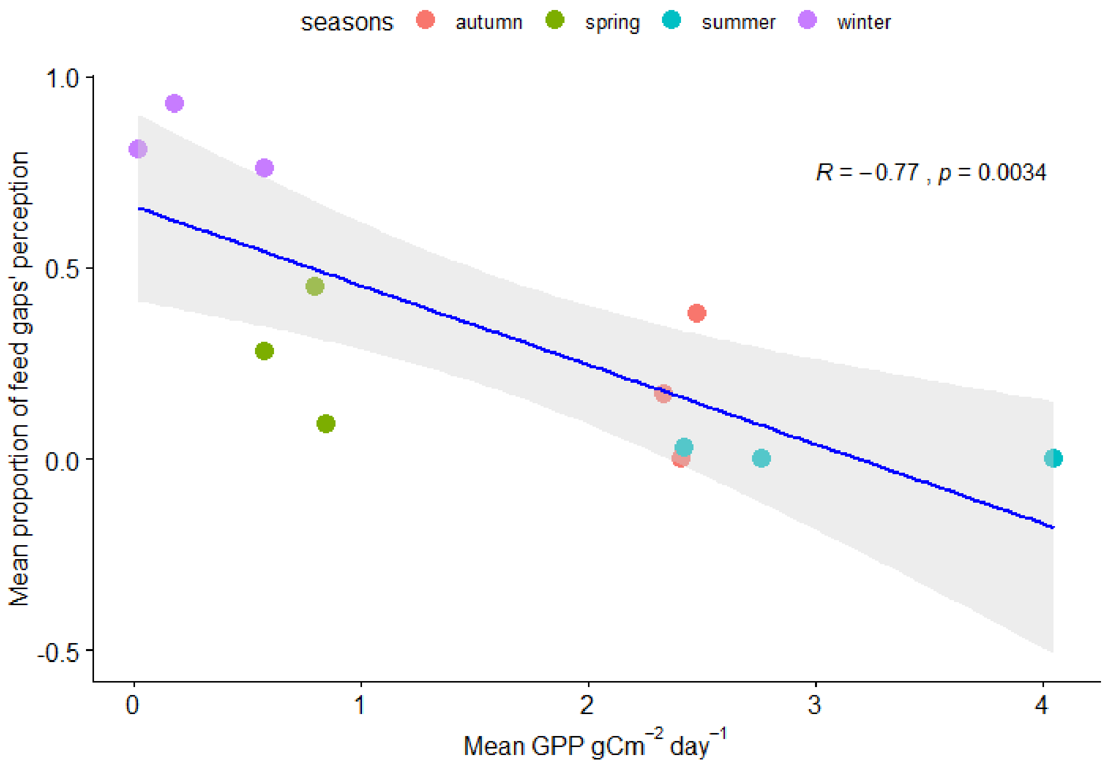

Figure 1.3: Correlation (Pearson method) between the daily mean GPP accumulated per season and the mean proportion of perceived seasonal feed gaps across AEZ and farm type

Consequently, in addition to the problem of feed gaps, the available forage does not meet the nutritional demands of cattle in terms of its nutrient mineral content. In addition, increasing growth of drought-tolerant shrubs during the dry seasons, many of which are avoided by livestock, further reducing the feed value of rangelands (Hitayezu et al. 2017; Mapiye, Chimonyo, et al. 2009). Even though the dry matter intake is affected by a number of different factors (e.g. body weight, environmental factors, feed level and type), the perceived body weight loss of livestock, specifically during winter and spring (Figure 1.1B) can be linked to the combination of a scarcity of feed resources and the mineral composition of the available forage.

Table 1.3: Mean values (±SD) of macro and micro-nutrient content of grazed grasses in the winter period across three agro-ecological zones (two sites per AEZ, four samples per site)

Nutrients	Warm arid	Warm semiarid	Cool semiarid
P (g/kg)	1.26	0.49	0.63
	(0.75)	(0.09)	(0.62)
K (g/kg)	13.41	11.12	7.23
	(3.17)	(6.68)	(2.59)
Mg (g/kg)	2.02	2.78	0.91
	(0.66)	(0.29)	(0.36)
Ca (g/kg)	3.54	3.24	2.81
	(0.28)	(0.38)	(1.38)
S (g/kg)	1.38	1.37	1.59
	(0.11)	(0.78)	(0.76)
Na (g/kg)	3.14	0.41	0.28
	(2.01)	(0.06)	(0.05)
B (mg/kg)	7.46	5.16	4.32
	(3.18)	(1.18)	(1.73)
Cu (mg/kg)	11.71	4.88	2.92
	(4.58)	(0.99)	(0.48)
Fe (mg/kg)	422.13	314.75	186.83
	(88.77)	(106.43)	(44.27)
Mn (mg/kg)	74.29	80.01	157.55
	(25.26)	(30.42)	(116.59)
Zn (mg/kg)	34.75	38.84	32.73
	(13.56)	(10.52)	(11.06)
Mo (mg/kg)	0.86	0.43	0.72
	(0.11)	(0.19)	(0.21)

1.4.2 Perceptions of feed gaps by farm types

There was no significant difference between farm types in the proportion of perceived feed gaps in winter (86% and 79% for livestock-only and mixed crop-livestock farmers, respectively) (Table 1.4). Nevertheless, the perception of feed gaps in spring and autumn differed significantly between farm types. Approximately 46% of the mixed crop-livestock farmers perceived feed shortages in spring while among livestock-only farmers 12% perceived feed gaps in spring. Contrarily, a larger proportion of livestock-only farmers perceived feed gaps in the autumn (33%), which was not the case for mixed crop-livestock farmers (0%).

In many parts of southern Africa, subsistence crop production is part of a culture-based mechanism for sustaining livelihoods (Nyamushamba et al. 2016). Smallholder cropping is generally restricted to crops such as maize and beans, and the residues from these crops provide an additional feed resource for livestock keeping once crops on arable land are harvested, especially in arid and semi-arid regions (Thornton and Herrero 2015). Therefore, the low perception of feed gaps in spring on mixed crop-livestock farms may be related to a limited amount of crop residues during late winter through spring. Typically, farmers start sowing as soon as first rainfall occurs in the region which can vary between October and December. Harvesting of crops is between March and May, and crop residues are left directly on the fields for livestock during autumn and winter. For mixed crop-livestock farmers, the perceptions on forage scarcity in spring is further reinforced by low rangeland growth rates during that time (Figure 1.2). Meanwhile, livestock-only farmers rely heavily on the rangelands as the primary feed source. Consequently, feed shortages are experienced shortly after the onset of the autumn season where the growth on rangelands has already ceased (Figure 1.2).

The availability of cropping residues in mixed crop-livestock farms may, therefore, be a distinct advantage over livestock-only farms in helping to minimize the vulnerability to feed gaps before the winter dry season. Furthermore, the occurrence of feed gaps is accepted to be a regular intra-seasonal phenomenon that does not depend on farm types, as reflected in the perception of animal weight loss (Table 1.4). Only a small but significant proportion (15%) of mixed crop-livestock farmers asserted that they did not perceive feed gaps throughout the year. Previous contextual studies have shown the vulnerability of the livestock farming systems to current climate variability (Rojas-Downing et al. 2017; Thornton, van de Steeg, et al. 2009). Through similar assessments, Weindl et al. (2015) expected a shift from single-purpose livestock farming to mixed crop-livestock farming especially under a climate vulnerable to drought. In line with this expectation, Tibesigwa et al. (2016) investigated the climate impact among single crop, livestock-only, and mixed crop-livestock farmers in areas prone to drought, and found that the mixed system was the least vulnerable. Our findings support these claims, although no systematic differences in the perception of the impacts of feed gaps' were found between the farming systems. Although mixed farms may have the possibility to feed from crop residues, the perception of seasonal weight loss appears to be the same across the different farm types.

This is because the decrease in forage resources affects the availability of nutrients (Table 1.3) which presents problems for farmers from both farm types. Moreover, few mixed crop-livestock farmers claimed that they always preferred their cattle to graze on the dry pasture in the period of feed gaps rather than feeding maize residues as the latter is perceived to be of poorer quality. Despite this affirmation, the main coping strategy among farmers interviewed in this study reflects the use of on-farm feed resources (crop residues) which complements the limited amount of forage for grazing during the dry seasons. This strategy was significantly noted for mixed-crop livestock farmers. The integration of arable cropping coupled with livestock production increases the flexibility of the farming system to cope not only with socio-economic issues, but also climate variability as demonstrated by studies in Zimbabwe (Homann-Kee Tui et al. 2015).

This is particularly true among the rural farmers in Limpopo who generally suffer from the effects of economic inequality, causing further resource-constrained problems (Kom et al. 2020). Additionally, farmers who are more secure financially may purchase fodder, thereby reducing the competition between farms for the use of crop residues. In periods of severe drought, where the coping measures (e.g. crop residues, feed purchase) are insufficient to deal with feed gaps, farmers reported reducing their herd size. This coping strategy is common among livestock keepers in arid and semi-arid zones. According to Karimi et al. (2018), it may be linked to a number of factors including the social and economic status (e.g. livestock number, access to capital) of the farmer. Hence, a farmer who has access to sufficient feed residues, or capital to purchase required amounts, may not be forced to reduce the herd size during feed gaps.

As we envisaged, due to poor economic resources (and to some extent the failure of reducing herd size) some farmers, at times may not engage in any coping strategies. The proportion of farmers admitting this situation is greater among the livestock-only farmers (37%) than among the mixed crop-livestock farmers (5%) (Table 1.4), thus confirming the vulnerability of the sole livestock keeping system. The argument here, which is supported by Taruvinga et al. (2016),is that a 'no strategy' as observed among resource-constrained livestock farmers in South Africa, is generally conditioned by several factors such as social and financial status.

In the drier areas of southern Africa, the challenge of feed supply in quantity (Mapiye, Makombe, et al. 2018; Vetter et al. 2020) and quality (Maleko et al. 2018) is the biggest constraint and key to maintaining smallholder livestock production irrespective of farm type, as shown by the results of the present study. The proportion of farmers recognizing this challenge was significantly greater among livestock-only farmers (78%) than mixed crop-livestock farmers (54%) (Table 1.4). Our first hypothesis is thus confirmed, as the results between farm types showed that livestock-only farmers are likely to perceive the existence of more feed gaps. Though this perception of feed gaps and the attitude towards it may be motivated by social pressures, as mentioned above, the analysis here supported the risks of feed gaps due to limited complementary feeding resources among livestock-only farmers in Limpopo.

Table 1.4: Comparisons of the perception responses (% of farmers) to feed gaps, feed availability, frequency of feed gaps, animal weight loss due to feed gaps, weight loss in seasons of feed gaps, animal death due to feed gaps, coping strategies and constraints to production. P-values refer to the comparison of each proportion of the farmers'responses between farm types based on Chi^2 test

	Livestock only (n=51)	Mixed (n=39)	P-values
Feed gap perception			
Feed gaps in winter	86%	79%	0.40
Feed gaps in spring	12%	46%	<0.01
Feed gaps in summer	2%	0%	1.00
Feed gaps in autumn	33%	0%	<0.01
Perception of feed availability	**good-satisfactory-low**	**good-satisfactory-low**	
Feed availability (whole year)	18%–65%–12%	31%–59%–10%	0.45
Feed quality in period of feed gaps	0%–14%–78%	5%–15%–79%	0.38
Feed quality in period of feed abundance	51%–39%–2%	69%–20%–3%	0.26
Frequency of feed gaps	**regular-irregular**	**regular-irregular**	
Frequency of feed gaps	75%–25%	67%–33%	0.42
Animal weight loss due to feed gaps	**yes–no**	**yes–no**	
Animal weight loss	94%–5%	85%–15%	0.13
Weight loss in seasons of feed gaps			
Weight loss in winter	84%	74%	0.12
Weight loss in spring	41%	36%	0.56
No weight loss	4%	15%	0.07
Animal death due to feed gaps	**often–sometimes–not likely**	**often–sometimes–not likely**	
Animal death	1%–37%–53%	18%–31%–51%	0.50
Coping strategies			
Government aid	22%	23%	0.86
Feed purchase	72%	56%	0.11
On-farm resources	57%	85%	<0.01
Feed budgeting	4%	5%	1.00
Reduce herd size	63%	45%	0.72
Feed storage during summer	18%	4%	0.15
Pasture management	0%	4%	0.18
Other strategies	37%	5%	<0.01
Constraints to production			
Feed availability	78%	54%	<0.05
Unavailability of aid (feed aid)	12%	10%	1.00
Access to water (households, farms)	43%	46%	0.78
Theft	45%	64%	0.07
Animal walking distance to get water	8%	31%	<0.01
Animal walking distance to get pasture	10%	38%	<0.01
Diseases	43%	49%	0.60

1.4.3 Feed gaps for different Agro-ecological zones

The results of the differences in perception between AEZ indicated that farmers, despite their agro-ecological location, are not affected differently by the winter dry period (June – August, Table 1.5). Across all AEZ, the winter season is a period of precipitation deficit that leads to decreasing availability of pasture forage sources (Figure 1.2; (Mpandeli et al. 2015)). However, farmers perceived feed gaps in spring and autumn differently. Among farmers located in the warm arid zone, 45% of perceived feed gaps occurred in spring, which was the highest proportion, ahead of farmers in the warm semi-arid (26%) and cool semi-arid zone (9%). In the autumn, 37% of farmers in the cool semi-arid climate zone perceived feed gaps, followed by 17% of farmers in the warm arid zone and 0% in the warm semi-arid zone.

As expected, and supported by Pfeiffer et al. (2019), values for rangeland productivity in Limpopo were constrained in zones where the annual rainfall is below 500 mm (Figure 1.2). Farms located in the warmer region of the present study, where the average annual precipitation is about 300 mm, do not therefore have favourable conditions for forage production. Hence, the largest proportion of farmers that perceived feed gaps in winter (93%) and spring (45%) were found in the warm arid zone. In addition, in the warm arid zone, there was a significantly higher proportion of farmers who reported suffering from a regular intra-annual feed gaps often leading to livestock losses (Table 1.5).

Our results are consistent with recent literature for the southern African region, which shows that smallholder livestock keepers perform poorly under warmer climates (Descheemaeker, Oosting, et al. 2016; Mpofu et al. 2017). According to Descheemaeker, Oosting, et al. (2016), lower rainfall and higher temperatures under such a climate may have direct effects on the physiological functions of the livestock leading to losses. Moreover, approximately 17% of farms in the cool semi-arid zone perceived the existence of feed gaps in autumn (March – May) (Table 1.5). This larger proportion of farmers in the cool semi-arid zone experiencing feed gaps in autumn, compared to those in the warm arid and warm semi-arid zones, is also likely to be influenced by an imbalance of farm types in the dataset for that zone (28 livestock-only and 4 mixed crop-livestock farmers, recognizing that farm types are nested in AEZ, Table 1.1). As mentioned above (section 1.4.2), livestock-only farmers significantly perceived feed gaps in autumn because of their dependency on rangeland pasture where the productivity decreases in March – May.

In the warm semi-arid zone, 52% of farmers believed that feed availability is adequate to maintain the annual production and farmers in this AEZ appear to be the least affected by the frequent occurrences of feed gaps. This could be explained by the environmental conditions for forage production being influenced not only by rainfall patterns but also by soil type, as reported (Mpofu et al. 2017) in the context of the performance of Nguni calves across different AEZ in Limpopo. In that study, there was a significantly lower performance in the arid zone where precipitation is about 300mm and the land has been affected by soil erosion, with low water holding capacity and limited plant available nutrient content. The combination of these limitations has caused reduced nutritional value of rangeland biomass.

Linstädter et al. (2014) linked rangeland production to some significant drivers such as biotic (e.g. grazing) and abiotic (e.g. soil texture); these differ locally causing shifts in the vegetation and thus in the variability of livestock response. In the present study, the dominant soil texture in the warm arid and cool semi-arid zones was sandy loam with low water holding capacity, whereas the dominant soil texture in the warm semi-arid zone is clay loam that can store more water and maintain rangeland production for a longer period without rainfall. Differences in perception in the warm semiarid zone could be attributed to soil variables and also the availability of a larger grazing area with less bush encroachment. However, this also depends on the community-level stocking density, which was not covered in the present study.

The interaction of these pedo-climatic conditions and socio-economic factors may also explain part of the significant differences in the perceptions by farmers with regard to feed gaps, feed availability and the frequency of feed gaps between different AEZ (Table 1.5).Moreover, differences in the strategic approach by farmers to cope with feed gaps further explained the vulnerability of farmers located in the warm arid zone to the frequent occurrence of feed gaps. Strategies included purchasing feed, relying on the resources of crop residues from arable lands, and reducing herd size, among others. Farms in the warm arid zone recorded the greatest proportion (93%) of reliance on residues from their on-farm resources. Despite this, a high proportion (79%) additionally need to sell some animals to cope with the seasonal changes in the feed resources during the dry period (Table 1.5). Thus, forage shortages were always included among the major concerns for constrained farmers in Limpopo (Mapiye, Makombe, et al. 2018; Marandure, Bennett, et al. 2020) but farmers that are the most exposed to climate hazards remain the most vulnerable to feed gaps (Karimi et al. 2018).

As hypothesized, the impact of feed gaps is larger in the drier AEZ. Farmers across all the considered farm types and AEZ have listed numerous challenges which demonstrate the adverse vulnerability of the local livestock farming systems to environmental and social shocks (Table 1.4 and 1.5). Among the obvious challenges, the lack of water availability was thoroughly discussed. Access to water for smallholder farms is a common challenge in the semi-arid and arid zones in Southern Africa (Descheemaeker, Amede, et al. 2010). Water resources are an important part of livestock production systems and water scarcity is a fundamental issue that affect small farms particularly in the arid and semi-arid regions which have no access to watering infrastructures (Ricciardi et al. 2020). According to Ricciardi et al. (2020), 76.7% of small farms are located in water-scarce regions with disparities between irrigation schemes and coverages. South Africa is generally a water-challenged country with limited irrigation options for smallholder farmers. Current low rainfall patterns and high temperatures extend the vulnerability of the livestock systems, (DEA 2017). However, a specific challenge reported by farmers in this study is the walking distance to access water on rangelands. Other common challenges noted are (i) the unavailability of governmental feed aid (or feed aid not sufficient to improve feed supply in periods of feed gaps), (ii) diseases (livestock heartwater diseases, which is the main death cause of cattle and calves (iii) small grazing land with bush encroachments (iv) predators, and (v) access to capital . These challenges have been identified in the smallholder context as socio-economic, ecological and political issues that govern rural farmers and their production systems (Chepkoech et al. 2020). Furthermore, lo lack of coping strategies for rural farmers as noted in South Africa and in Limpopo specifically may be linked directly to farm typology, as poor farmers or farmers with no access to capital may fail to adapt (Mapiye, Makombe, et al. 2018).

Table 1.5: Comparisons of the perception responses (% of farmers) to feed gaps, feed availability, frequency of feed gaps, animal weight loss due to feed gaps, weight loss in seasons of feed gaps, animal death due to feed gaps, coping strategies and constraints to production. P-values refer to the comparison of each proportion of the farmers'responses between agro-ecological zones based on Chi^2 test

	Warm arid (n=29)	Warm semi-arid (n=29)	Cool semi-arid (n=32)	P-values
Feed gap perception				
Feed gaps in winter	93%	76%	81%	0.41
Feed gaps in spring	45%	26%	9%	<0.05
Feed gaps in summer	0%	3%	0%	0.64
Feed gaps in autumn	17%	0%	0%	<0.01
Perception of feed availability	**good-satisfactory-low**	**good-satisfactory-low**	**good-satisfactory-low**	
Feed availability (whole year)	3%–14%–76%	52%–0%–48%	16%–19%–63%	<0.01
Feed quality in period of feed gaps	0%–7%–86%	3%–31%–66%	3%–6%–84%	<0.05
Feed quality in period of feed abundance	28%–62%-3%	100%–0%–0%	50%–38%–3%	<0.01
Frequency of feed gaps	**regular-irregular**	**regular-irregular**	**regular-irregular**	
Frequency of feed gaps	90%–10%	45%–55%	78%–22%	<0.01
Animal weight loss due to feed gaps	**yes–no**	**yes–no**	**yes–no**	
Animal weight loss	97%–3%	83%–17%	91%–6%	0.21
Weight loss in seasons of feed gaps				
Weight loss in winter	86%	72%	81%	0.36
Weight loss in spring	66%	10%	41%	<0.01
No weight loss	3%	17%	6%	0.21
Animal death due to feed gaps	**often–sometimes–not likely**	**often–sometimes–not likely**	**often–sometimes–not likely**	
Animal death	34%–41%–24%	0%–31%–69%	6%–31%–63%	<0.01
Coping strategies				
Government aid	3%	17%	19%	0.38
Feed purchase	66%	48%	81%	<0.05
On-farm resources	93%	72%	44%	<0.01
Feed budgeting	0%	3%	9%	0.32
Reduce herd size	79%	38%	66%	<0.01
Feed storage during summer	38%	17%	16%	0.08
Pasture management	0%	10%	47%	<0.01
Other strategies	0%	10%	47%	<0.01
Constraints to production				
Feed availability	97%	24%	81%	<0.01
Unavailabilit y of aid (feed aid)	7%	21%	6%	0.18
Access to water (households, farms)	28%	66%	41%	<0.05
Theft	62%	76%	25%	<0.01
Animal walking distance to get water	14%	41%	0%	<0.01
Animal walking distance to get pasture	17%	48%	3%	<0.01
Diseases	59%	62%	19%	<0.01

1.4.4 Limitations of the study and recommendations

It is known from previous studies on the perspective of farmers that the livestock production suffers from climate change impacts. Based on the findings of the present study, where the perception of seasonality of feed gaps is linked to rangeland productivity and mineral nutrient content in the forage, evidence for seasonal adaptation or intervention strategies is provided that has relevance for the whole southern African agro-climatic region. However, the results from the present study may suffer from small sample size. Additionally, other factors besides rangeland productivity may account for the seasonality.

For example, the animal weight loss could also be related to increased metabolic energy requirements for maintenance caused by the greater effort for walking in the search for grazing sites of sufficient quality during the dry period. The current smallholder community-rangeland-based livestock systems in southern Africa are generally in jeopardy due to rangeland degradation (Nyamushamba et al. 2016). Therefore, high stocking density could also lead to a quick decline in the quantity of forage, as demonstrated in the dry areas of South Africa (Vetter et al. 2020) and Zimbabwe (Tavirimirwa et al. 2019). Thus, from an ecological point of view, in communal livestock areas, where high stocking density could be problematic, appropriate herd size should be regulated to accommodate proper grazing management. However, Tavirimirwa et al. (2019), in their review of management options for communal grazing lands in Zimbabwe, reported a failure in the implementation of the destocking policy. This is because it threatens the economic, and socio-cultural importance of keeping livestock since farmers normally attempt to maximize their herd size. Nevertheless, this policy could still be attainable in South Africa if destocking is subsidized for communal livestock keepers to be more in balance with the poor quantity and quality of forage during that part of the season.

Moreover, crop residues are important for the smallholder livestock sector (Thornton and Herrero 2015). However, in view of the perceived low quality, the establishment of a reliable testing system to determine the quantity and quality of cropping residues would contribute to a basis for coping that would also provide additional employment, should a trans-regional trade of residues develop. According to Tavirimirwa et al. (2019), future attempts in improving communal rangelands in arid and semi-arid areas should focus on improving fallow lands for controlled grazing. Therefore, it will be necessary to strategically focus on the farm types (i.e. livestock-only, or mixed crop-livestock) rather than on AEZ to improve the feed base.

In addition, it is important to develop irrigation schemes that will provide watering points for the livestock, thus reducing the walking distances required during periods with feed gaps. It is also essential that future cattle development programs are targeted to facilitate the exchange of knowledge through proper training (e.g. water harvesting techniques) are targeted (Mapiye, Makombe, et al. 2018). Furthermore, the capacity of smallholder farmers in South Africa to implement these options can be influenced by many factors, including the type of feed gap, farmers' objectives, availability of infrastructure and provision of financing (Marandure, Bennett, et al. 2020). Thus, in future studies, in order to evaluate rural policy, attempts to cope with feed gaps should be evaluated by farm types and the seasonality of feed gaps. Therefore, there is the need to evaluate the bio-economic effects of integrating different forage or feed conservation strategies, in a way to diversify the feed-base across smallholder farms as demonstrated in Mozambique (Cumbe et al. 2021) or in Zimbabwe (Descheemaeker, Zijlstra, et al. 2018) to support a final decision making.

1.5 Conclusion

Based on the approach we used in this study, it emerged that smallholder livestock farmers generally suffer from feed gaps during the dry winter seasons irrespective of farm type. We firstly hypothesized that mixed crop-livestock farms are less affected by feed gaps than the livestock-only farms. This hypothesis is partly confirmed since mixed crop-livestock farmers were able to compensate for a decline in community rangeland biomass production in autumn. Though the differences reported between agro-ecological zones may be related to farm types within the zones to some extent, livestock-only farmers in arid zones may be the group most affected by feed gaps. Our second hypothesis, that the severity of feed gaps increases with aridity irrespective of farm type is also supported. Measures to reduce or cope with feed gaps do not necessarily need to account for local-climatic differences but rather for different farm operation systems. However, overcoming the frequent occurrences of feed gaps may prove to be difficult and complex as it is not only governed by biological factors, but also by farmer's socio-economic capacities. While we are aware that farmers on their own cannot afford to incorporate these suggestions, these specific policies/strategies can be implemented with the support of government institutions, credit institutions and scientists. Further livestock or mixed crop-livestock research in this context should consider assessing risks and feed-based balance strategies perhaps through a whole-farm modelling approach for the region.

1.6 References

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2

Feed gaps among cattle keepers in semi-arid and arid Southern African regions: A case study in the Limpopo province, South Africa.

2.1 Abstract[1]

Rural livestock farmers in the semi-arid and arid areas of Southern Africa face large uncertainties due to a high intra-seasonal and year-to-year variability in rainfall patterns which affect forage resources to livestock causing feed gaps. Creating resilient communal livestock farming systems will require the understanding of the feed gaps as perceived by livestock farmers and an assessment of available feed resources. In this chapter, we estimated the annual feed balance (i.e. forage supply – forage demand) based on statistical data and report on the perception of feed gaps across 122 livestock farmers in the Limpopo province, South Africa. In addition, we analysed available feed and soil resources during the dry season across land use types. We found a negative feed balance, an indication of feed gaps for livestock farms, mainly in winter and spring. Farmers perceived a combination of factors such as drought, infrastructure, capital, and access to land as the major causes of feed gaps. Furthermore, our analyses of feed and soil resources point at low crude

[1]A version of this chapter has been accepted for publication as a book chapter as Lamega, S.A., Klinck, L., Komainda, M., Odhiambo, J. J. O., Ayisi, K. K. & Isselstein, J. in "Sustainability of southern African ecosystems under global change: Science for management and policy interventions", Springer

protein (e.g. ~5% in rangeland biomass) and poor soil nutrient contents (e.g. %N < 0.1). To support rural policies and improve the livestock systems, there is a need to combine the most appropriate site-specific options in optimizing the feed supply.

Keywords: Feed systems, drought, climate risk, adaptation strategies, Crude protein, communal rangelands.

2.2 Introduction

".. And also the effects of global warming, we are feeling it here. This drought, it might take long, it can be here for a very long time. We experience it almost every year and every year it's a little bit harsher than in the previous year." (farmer from Maruleng Municipality, Limpopo Province)

In many parts of southern Africa, livestock plays a very important role in the livelihood of rural dwellers (Nyamushamba et al. 2016). According to a report by Köhler-Rollefson (2004), livestock contributes, in cash only, up to 38% to the agricultural Gross Domestic Product in the region and about 90% of the livestock keepers can be classified as smallholders. A smallholder is often characterized as a resource-constrained farmer that operates livestock primarily for subsistence purposes but also as a major risk alleviating activity (Köhler-Rollefson 2004). Keeping livestock has been reported to improve household income through sales of animals, milk and dairy products (Maleko et al. 2018). Smallholders also depend on cattle production for household consumption and, in a mixed crop-livestock system, the integration of cattle also provides benefits such as dung for manure, draught power for tillage cropping, and transport (Thornton et al. 2015). In the Limpopo province of South Africa, keeping livestock in the smallholder systems remains a cultural-based strategy important for financial security (Marandure, Dzama, et al. 2020). In respect to the smallholder livestock farming sector in the province, Stroebel et al. (2011) reported small herd size (for instance, less than 10 head of cattle) with low or no-input management and poor breeding objectives. Hence, the sector is generally characterized by low productivity (Mapiye, Chikwanha, et al. 2019).

Despite an already challenged livestock production system, climate change and variability pose an additional threat, representing a major concern to the production systems (Nardone et al. 2010). Throughout the Southern African region, there is evidence of negative effects of lower rainfall, increased temperature, prolonged droughts (Archer et al. 2019; Makuvaro et al. 2018; Simelton et al. 2013; Ziervogel et al. 2014) with adverse effects on livestock and the livelihoods of smallholder farmers in the arid and semi-arid areas (Batisani et al. 2021; Descheemaeker, Oosting, et al. 2016). In South Africa, Ziervogel et al. (2014) and Archer et al. (2019) have explicitly demonstrated climate anomalies such as exacerbated weather events (e.g. prolonged drought, increased temperature, change in the distribution and frequency of rainfall, drying up of water bodies). Such changes have significant negative impacts, particularly for smallholder livestock and mixed crop-livestock systems that are associated with natural grazing on communal rangelands and rainfed agriculture (Thornton et al. 2015). Prolonged drought, as a result of annual or seasonal variation in the rainfall patterns, is reported to be the most challenging or damaging by its effect on rangelands (Godde, Boone, et al. 2020; Vetter et al. 2020) and in rainfed agricultural systems (Meza et al. 2021). It is now widely accepted that alterations in forage provision will increase with climatic variability (Godde, Mason-DCroz, et al. 2021) leading to feed gaps.

For livestock, a feed or a forage gap generally addresses a period during which the animal's feed/forage demand is higher than the feed/forage supply. As explained by Moore et al. (2009) a feed gap is a consequence of the combination of bio-economic factors such as seasonal forage growth, livestock feed intake, farmers' objectives and financial capacities. In the communal smallholder livestock context, a feed gap is also dependent on additional factors such as herd size, structure, and management, or natural resource governance (Vetter et al. 2020). A feed balance may undergo considerable seasonal variation within one year, or vary considerably from one year to another due to environmental factors (e.g. seasonal rainfall, severe year to year drought) that govern rangeland's biomass productivity. Therefore, two types of feed gaps occur due to these variations which can be referred to as a "regular" feed gap and an "irregular" feed gap. A regular feed gap occurs every year on account of the seasonal changes in forage growth (e.g. autumn to winter, winter to spring or summer to autumn), while an irregular feed gap typically occurs once every few years due to a year-to-year variability (e.g. the years of severe drought in 2015 – 2016 and recently 2018 – 2020). In livestock production systems, feed gaps are important phenomena setting the potential for farm productivity. As argued by Bell (2009) and Moore et al. (2009), the capacity of a livestock keeping enterprise to maintain or sustain animals during periods of feed gaps is regarded as the safe carrying capacity of the enterprise that could improve profitability. This is because feed gaps, whether regular or irregular, may affect the livestock directly or indirectly, consequently affecting productivity.

A direct effect of a feed gap according to Moore et al. (2009), reduces the forage intake by livestock, forcing the animals to lose weight. According to Schlecht et al. (1999) the variation of the forage availability from the rainy to dry seasons not only leads to a decline in feed quantity but also in its nutritive quality. For instance, during a feed gap, the energy provided to cattle from the dry and fibrous (i.e. less nutritious) pasture is not sufficient for an efficient catabolism of their body tissue. Therefore, a feed gap, when it occurs does not only contribute to the decline in

the maintenance of the cattle energy status but also has economic implications for the farmer (return on sales). Moore et al. (2009) further argued that feed gaps may affect livestock indirectly through decreased and poor sperm production, ovulation rates all of which have significant effects on breeding performance. For instance, beef bull calves that are fed below their maintenance requirements (in terms of energy and protein) may encounter sexual immaturity with decreased sperm production (Thundathil et al. 2016). Therefore, nutrition deficiency as caused by feed scarcity during the dry season would firstly affect the livestock's residual feed intake. This would cause a decline in the feed efficiency in relation to cattle growth rate, consequently affecting the morphological development. Additionally, nutrition deficiency is also known to impact lactation and embryo survival affecting the reproductive capacity of the livestock systems (Thundathil et al. 2016).
A very recent integrated drought risk assessment by Meza et al. (2021) revealed the Limpopo province of South Africa as one of the most exposed provinces to extreme drought, resulting in decreased rangeland productivity and crop yields. Thus, the frequent and major drought periods facing cattle keepers could be considered as extended feed gap periods. A sound assessment of the seasonal livestock feed gaps through the perceptions of vulnerable livestock farmers, and data on available feed resources during the dry period (quality and utilization) may be crucial for the development of adequate recommendations. Providing adequate supplementary nutrients to the nutritionally-challenged livestock in periods of feed gaps will be crucial in improving livestock production and increasing profitability (Bell, Moore, et al. 2016). For this, we assessed the contribution of crop residues to the feeding regime of cattle, to clearly identify periods where feed is unavailable to meet animal's demand. One of the urgent priorities is to find a proper way to deal with the seasonal feed gaps for rural livestock farmers to facilitate resilience towards improved livestock systems. The principal goal of this chapter is to inform the general public and policy makers on climate-induced feed gaps that represent a threat during periods of feed scarcity, particularly to communal livestock production.

2.3 Materials and Methods

2.3.1 Study area

The study was conducted in Limpopo, the northernmost province of South Africa which is characterized by semi-arid climatic conditions with low and variable precipitation (Mpandeli et al. 2015). The province receives about 600mm rainfall per annum, most of which that occurs between October to April. The summer season

(December – February) is hot and wet with an average maximum temperature about 27°C while the winter (June – August) is cool and dry with 15°C. Soils in the study area are predominantly reddish-brown loamy sand soils of typically low nutrient content (Munjonji et al. 2020). The typical natural vegetation is an open bush savannah woodland and natural grasslands, i.e. rangelands, dominated by C_4 grass species. Based on a recent survey the population increased from 5.4 Mio. to nearly 6 Mio. by 2016 with 38.2 % of all households involved in agricultural activities and 36 % in livestock production (*Community Survey 2016* 2018). However, livestock keeping is mostly integrated with cropping activities where maize (*Zea mays L.*), cowpea (*Vigna unguiculata*), groundnut (*Arachis hypogaea*), butternut (*Cucurbita moschata*), spinach (*Spinacia oleracea*), and water melon (*Citrullus lanatus*) were the most frequently and simultaneously cultivated crops. The vast majority of cattle farmers (95%) are users of communal lands with variable herd size (5 – 80) due to resource endowment. Moreover, the several government-owned natural reserves (e.g. rangelands) in the province remained a constraint as it reduces the availability of agricultural and grazing areas for livestock farming (Rootman et al. 2015). The communal cattle farmers in Limpopo support the "cattle complex" philosophy where keeping livestock is rather an alternative source of financial security. The most widespread is a cross-bread between Nguni and Brahman cattle and the respective pure-breeds. Other popular breeds include Bonsmara and Afrikaner.

2.3.2 Data collection and analysis

Data used for this chapter were collected from two sets of surveys and a focus group discussion conducted at different stages of a research project. Firstly, the preliminary survey was conducted during September to November 2018 across 32 cattle farms in the arid and semi-arid areas of the Limpopo province on the basis of communal livestock keeping. A follow-up survey was carried out during June to September 2019 across 90 cattle farms (see more details in Lamega et al. (2021)) (Figure 2.1, data extracted from *Agro-Ecological Zones for Africa South of the Sahara* (2015)). The surveys were conducted using a semi-structured questionnaire instrument (KoBoToolbox) (Deniau et al. 2017) which was delivered on a basis of a personal interview with the farmers. The questionnaire mainly assessed farmer's perception of (i) months of feed unavailability; (ii) feeding regimes and strategies; (iii) weight losses during feed gaps; and (iv) adaptation responses/constraints to adaptation. Additionally, open-ended interviews with selected farmers were conducted to further explore the perceived feed gap challenges. The responses were recorded, transcribed and reported based on Miles et al. (2014). In 2020, a one-day online feedback workshop was conducted with a few key farmers to discuss research results and identify management options. Selected results are averaged and reported in this chapter.

Secondly, aside from the perceptions of farmers on the seasonality of feed gaps and their effects on livestock production, the likelihood of winter feed gaps was further evaluated through the assessment of grazed rangeland biomass, crop residues, feed supplements, and selected soil nutrient levels. For instance, on communal rangelands and cropping lands, rangeland biomass and crop residues were sampled respectively by cutting from inside a 50cm by 50 cm quadrat along a longitudinal transect (5m apart). At the farm-level, we collected whenever possible (i.e. if farmer had access), supplemental feed residues that may be used to feed cattle during that period. Collected feed samples were oven-dried at 60°C, ground and then analysed for relative abundance of stable isotopes of nitrogen using an elemental analyzer (NA 1110; Carlo Erba, Milan) interfaced (ConFlo III; Finnigan MAT, Bremen) to an isotope ratio mass spectrometer (Delta Plus; Finnigan MAT). The nitrogen content in the feed samples is given as mass ratio in dry matter (%N) which was then multiplied by 6.25 to obtain crude protein concentration in the respective feed sample. In addition, soil samples (0–10 cm, diameter 2 cm), were taken after removal of biomass on rangelands or cropping lands. Per quadrat, three samples were taken, which consist of 15 subsamples from one transect at a particular site. The soil was homogenized, cleared of any foreign materials, dried at 105°C, sieved (2 mm) and analysed using the Calcium Acetate Lactate (CAL) extractable method (Schüller 1969). Soil pH was determined in water while the concentrations of P and K were determined in continuous flow analysis coupled to a UV/VIS spectro-photometer (San System, Skalar, the Netherlands). The remaining nutrient concentrations were determined using atomic absorption spectrometry (AAnalyst 400, Perkin Elmer Inc, Waltham, USA).

Finally, we calculated feed balances based on statistical data. However, an uncertain number of young and old livestock is kept in the smallholder sector of Limpopo. According to DAFF (2021) a total of 860,000 heads of cattle were kept in the Limpopo province in 2020. We assumed an average live weight of 450 kg cattle to obtain an estimate of tropical livestock units (TLU = 250 kg live weight) with every TLU consuming 10 kg dry matter daily. These values consequently represent the cattle livestock forage demand. We further derived an estimate of crop residue yields from maize production as based on Kutu (2012) who reports a stover proportion of 0.41 for maize production in Limpopo. The so calculated

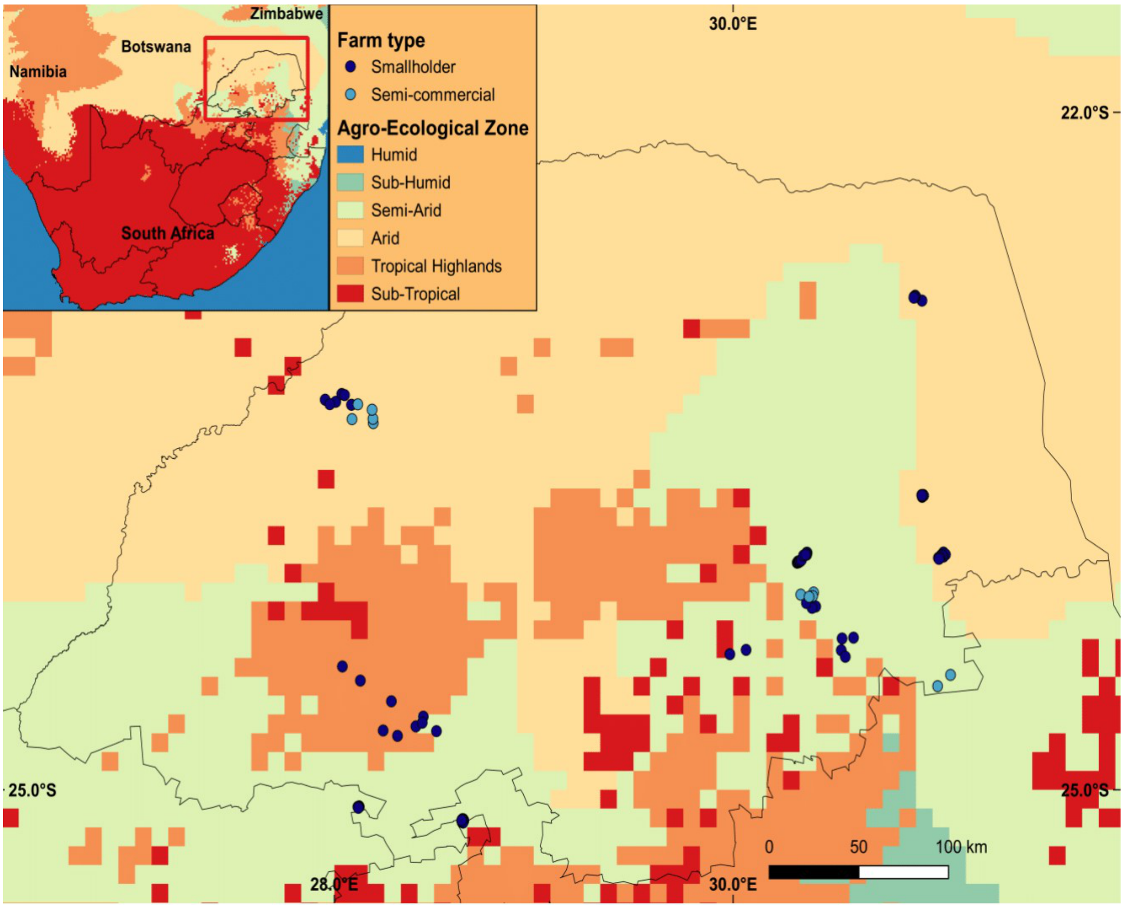

Figure 2.1: Sampled locations across the semi-arid and arid zones in Limpop (122 farms, including 11 semi-commercials dotted in blue)

maize residue amount was added to an estimate of rangeland biomass, as extracted from Martens et al. (2020) and Avenant (2019), to obtain an estimate of the forage supply. The survey data was analysed in R (R Core Team 2019) using descriptive statistics to report on the perception of feed gaps across farmers and characterise the quality of feed and soil resources across sites.

2.4 Results and Discussion

2.4.1 Estimation of feed balance in the Limpopo province

The severity of feed deficit in the cattle livestock sector of Limpopo was derived by calculating feed balances. According to our calculation about 1.484,753 TLU are kept in Limpopo per year. With a daily forage demand of 10 kg DM per day and TLU, an estimated annual forage demand of about 5.7 million tones for cattle is expected in Limpopo (see Table 2.1).

Table 2.1: Annual forage balance calculated for the Limpopo region

Year	**What**	**Value**	**Reference**
	Maize grain yield (t)	231000	(Statista, 2021)
2020	Stover % (total above-ground maize)	0.41	(Kutu, 2012)
	Total maize biomass (t)	391525	Calculated
	Stover biomass total (t)	160525	Calculated
Mean 2011–2019	Rangeland biomass supply (t DM/ha)	0.54	(Martens et al. 2020)
	Rangeland available for grazing (ha)	7400000	(Avenant, 2019)
	Rangeland biomass supply (t)	4015968	Calculated
	Annual feed demand by cattle (t)	470850	Calculated
	Feed supply total (t)	4176494	Calculated
	Feed demand total (t)	5650200	Calculated
Balance	**Supply - demand (t)**	−1473706	Calculated

In many parts of Southern Africa, major forage resources to cattle livestock, may constitute of rangeland biomass and maize residues from cropping lands (Homann-Kee Tui et al. 2015; Masikati et al. 2015). On the supply side we, consequently, used maize production and rangeland biomass production to estimate forage supply. According to Avenant (2019), approximately 7.4 Mio. ha of rangeland is available for grazing in the Limpopo province. Maize is the most commonly grown crop, especially on smallholder farms. (Statista 2021) estimated a total volume of 231.000 t maize in 2020 (Table 2.1). According to Kutu (2012), who has analysed maize production systems in two locations in the Limpopo province, a stover proportion of 0.41 of total aboveground maize biomass can be assumed. Using this proportion, we estimated a total of 160,525 t of maize stover biomass that is potentially available to be used as forage when maize is harvested which usually takes place in March (autumn) at the end of the wet season. A reliable calculation for the productivity of rangeland is far more complex. We used results of modelled rangeland productivity for the province and for our study sites (Martens et al. 2020), to calculate the seasonal rangeland productivity across the arid and semi-arid zones which gave an annual estimate of 0.228 t C/ha per year. Assuming that dry matter (DM) biomass contains 42% C we used an annual value of 0.54 t DM/ha of rangeland which was applied to a rangeland area of 7.4 Mio. ha (76% of total rangeland area Table 2.1). Not all of the rangeland area in Limpopo is considered suitable for grazing, because of shrub and tree cover, area protection or urbanization.

Consequently, we found an annual feed supply of 4,176,494 t that is unable to sustain the demand for cattle (5,650,200 t), resulting in a negative feed balance (Table 2.1). Avenant (2019), used a different approach to calculate the carrying capacity of rangeland in the study area. Using the estimated values for rangeland production in that study, 0.488 t DM/ha is very close to the value used in our approach (0.54 t DM/ha). According to our estimation, we found a shortage in feed supply on an annual basis (Table 2.1), taking into account that there are two major constraints underlying our calculations. Firstly, we only used predominantly statistical data, and we did not consider livestock species other than cattle although small ruminants are important forage consumers in the region. In addition, we did not account for forage quality which is likely limiting the utilization capacity of maize residues and rangeland biomass during a large part of the year (especially winter). According to Descheemaeker, Zijlstra, et al. (2018), the requirements of metabolizable energy (ME) range from 45 to 65 MJ ME/day per animal. As known from other studies, maize residues never reach values > 6 MJ ME/kg DM when harvested at physiological maturity (Terler et al. 2019). In addition, grass ME concentration ranges usually between 6.5 to 10.3 MJ/kg DM in the dry and the wet season respectively, which points at a shortage of forage with sufficient quality in the dry season. But not only quality is likely limiting in the dry season. When using the annual forage balance data for monthly calculations, we found strong support for a serious shortage in feed supply during winter and spring (Table 2.2). Forage quantity and likely quality are, consequently, critical issues for the livestock sector.

Table 2.2: Derived seasonal feed balance as monthly feed supply from rangeland and maize stover (t) against the seasonal feed demand by cattle livestock (t). TLU: Tropical livestock units, DM: dry matter

Season	Months	DM demand (t)/cattle (TLU)	Maize stover (t)	Rangeland biomass (t)	Feed balance (t)
Summer	Jan	470850	0	1866444	1395594
Summer	Feb	470850	0	1866444	1395594
Autumn	Mar	470850	160525	1571619	12612994
Autumn	Apr	470850	53508	1571619	1154277

Season	Months	DM demand (t)/cattle (TLU)	Maize stover (t)	Rangeland biomass (t)	Feed balance (t)
Autumn	May	470850	17836	1571619	1118605
Winter	Jun	470850	0	108063	−362787
Winter	Jul	470850	0	108063	−362787
Winter	Aug	470850	0	108063	−362787
Spring	Sep	470850	0	469254	−1596
Spring	Oct	470850	0	469254	−1596
Spring	Nov	470850	0	469254	−1596
Summer	Dec	470850	0	1866444	1395594

Moreover, to check the assumptions made for the calculation of the feed balance, a sensitivity analysis was carried out where, under constant average live weight of 450 kg, the daily forage DM intake was varied from 10 to 4 kg (Figure 2.2A) or, where under constant average forage intake of 10 kg per day, the live weight was varied from 450 to 300 kg (Figure 2.2B). These calculations have an effect on the annual feed requirement. The data show that already at about 7 kg DM intake per day a negative balance is no longer to be expected (Figure 2.2A). On the other hand, a positive balance can only be expected at an average herd weight of 300 kg DM which is unusually low. The assumption made about live weight, consequently, has little weight for the problem of the feed gap evaluation. For the exact forage requirement, however, it would be good to generate accurate information on the variation of forage intake of the cattle in Limpopo which is the prerequisite to understand the contribution of other potential forage sources

2.4.2 Feed gap as perceived by livestock farmers

Across the arid and semi-arid zones, winter and spring are the seasons of feed deficit according to the farmers. While feed shortages are perceived to be most severe during September and October (spring), the duration of experienced shortages was generally one month longer for some farmers (3.4 vs. 2.4 months) (see Lamega et al. (2021)). The heterogeneity between farms plays an important role in the perceptions of the seasonal patterns of feed gaps. For instance, farmers' perceptions of feed gaps did not differ significantly during winter as both mixed crop-livestock and specialist livestock-only farmers were equally affected. However,

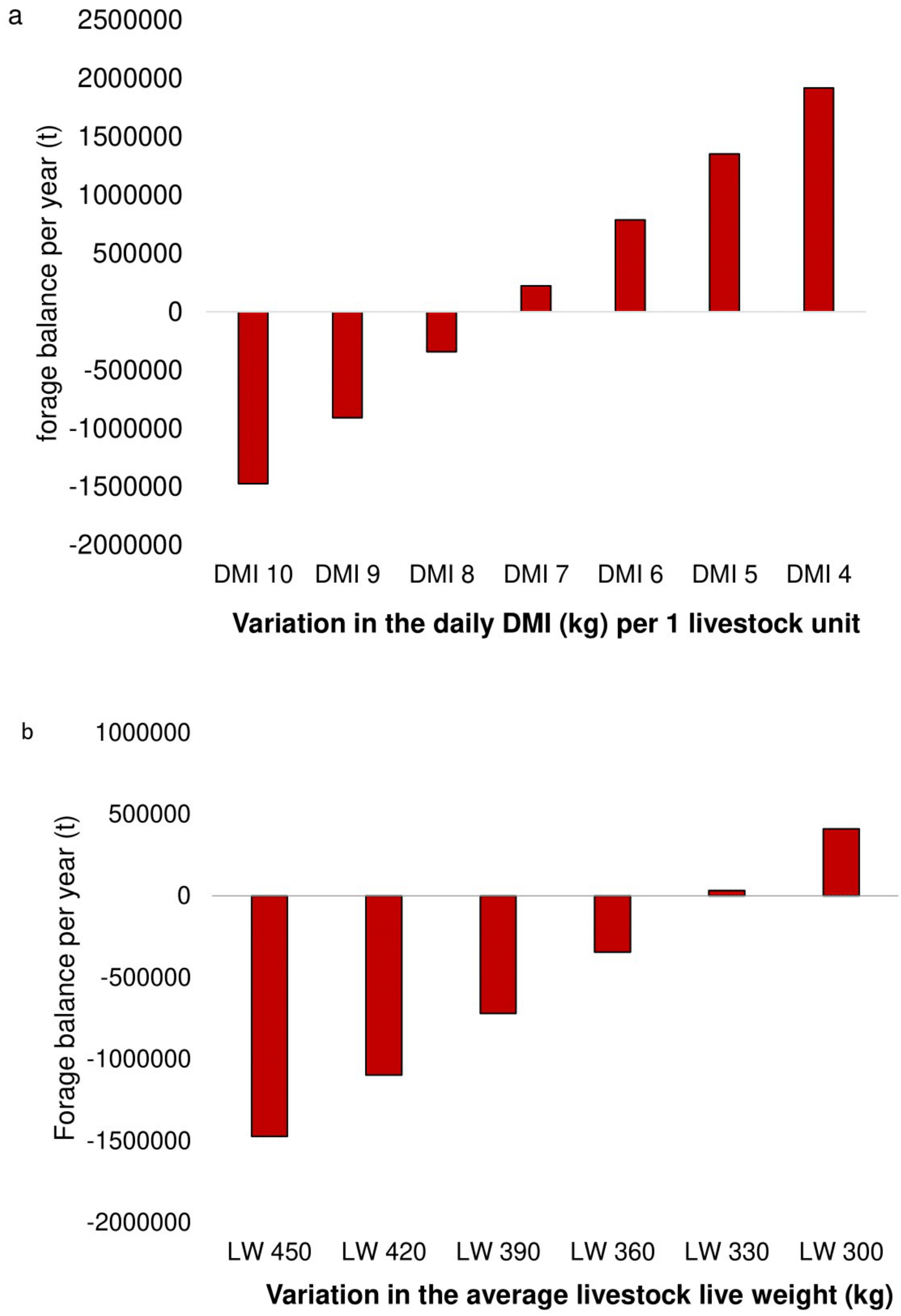

Figure 2.2: Sensivity analysis of forage balance as affected by (a) the variation in daily dry matter intake and (b) the variation in cattle liveweight on a daily 10kg DMI

the perceptions of feed gaps in autumn and spring differed between both farming systems irrespective of their locations.

Cattle livestock farmers did not follow a controlled mating schedule for selective breeding but allowed for natural breeding instead. Animals from farmers that are little endowed (> 50 cattle head) were reported to be weaned at around 7 months, whereas typical smallholder farmers (< 20 cattle head) reported a weaning age of about 11 months. Calves commonly wean later when they receive milk of poorer nutritive value from their dams. During drought, pregnant and lactating cows suffer from nutrient deficiency which is likely mirrored in lower reproductive performance of the offspring. Furthermore, limited flexibility in securing water availability is a limiting factor in the feed-drought nexus. Access to water sources is tightly linked to access to land and thus taps, boreholes, dams or streams. Hence, most smallholding livestock keepers fully rely on communal or community water sources:

'The taps are almost always dry. For us to get the water in the morning, it can last maybe, if you're lucky, three hours and many people don't have boreholes, they're just relying on this municipal water to make sure they feed water to the animals.' (Smallholder farmer, semi-arid zone).

Smallholder farmers in our study area perceived the phenomenon of "drought" particularly manifesting in its biophysical dimension, that is, the perception in the decline in water availability and rangeland productivity. Thus, livestock husbandry under (semi)arid conditions requires a form of adaptive capacity that allows farmers and herders to respond flexibly. For example, by producing their own feed or seeking out extensive grazing lands, they could face the harsh climatic condition. Access to and utilization of extensive rangelands is crucial when animals (and herders) are required to cover greater distances to water sources, during prolonged droughts when dams and communal watering holes dry up. Farmers would then move their animals to alternative water sources further away or fetch water with motorized vehicles. If feed in the dry period is already critically limited, the additional caloric costs i.e. animals covering extra distances for pasture and water, may translate into poor livestock health (Ouédraogo et al. 2021).

A rough on-farm assessment on the body condition score (BCS) demonstrated that animals relying solely on communal rangelands are indeed on average closer to drought-induced starvation (BCS of ∼ 2.01 with 0 = emaciated and 5 = over-fat). In many cases, in communal livestock systems, livestock farmers or managers do not look into maximizing operating profit, instead maximizing or maintaining herd size, remains the priority (Stroebel et al. 2011; Tavirimirwa et al. 2019).

Therefore, the risk of feed gaps may not only be associated with the unproductivity of rangeland during the dry season but it may also be related to the high costs of producing/purchasing feed, concentrates and or conservation of forage. It is likely that farmers that may have access to capital are more flexible in their modes of feed provision (Chikowo et al. 2014). Such farmers may draw from a variety of on-farm produced crops, forage, silage and commercial supplements. In some extent these livestock farmers that are more endowed may dispose of private boreholes and wells to alleviate the impacts of feed gaps. Moreover, in areas with sufficient annual rainfall, ground water may be important in maintaining the productivity of rangeland biomass, hence, reducing feed gaps risks significantly. In the arid zones of Western Limpopo, some farms even employed water-intensive fodder crops like sugar cane (*Saccharum officinarum*) or Blue Buffalo Grass (*Cenchrus ciliaris*). Also, in the arid zones of Eastern Limpopo, livestock may graze on Mopane tree leaves (*Colosphospermum mopane*), which are available on the rangelands but become scarce with the extended dry period.

Furthermore, farmers perceived feed shortages not directly as a result of bio-physical drought, but rather linked to low overall farm profitability and low returns in investments (Figure 2.3). Aside the obvious climate-induced drought, farmers mentioned a variety of limitations including insufficient technical extension support, poor local beef demand, poor access to external markets and contract farming. These limitations were all perceived as impediments to profitability and business growth. One farmer related the exclusive nature of contracts in the retail sector to favouring commercially-oriented farmers only:

"We [small – semi farmers] don't get access to Spar [supermarket]... direct straight. We are under someone else, it's a [white] middleman. We can't grow. From 1914 to today, no successful farming in here, we just do farming for pleasure or whatever, to make a living."

Commercially-oriented cattle production, on the other hand requires high-caloric and nutritious feed throughout the year to regular off-take to auctions and abattoirs. Supplements thus play a crucial role, whether produced on-farm or bought off-farm and it requires a certain financial margin for investments in feedstuffs (Figure 2.3). In contrast, in the communal setup, a feed gap is essentially linked to the availability of grazing areas which accommodate community-level stocking density. Additional feed is rather linked to farm types (if farmer engages in cropping) or capital (if farmer can purchase feed). Since smallholders are mostly financially constrained, they tend to be low adopters of feed gap strategies. The most common strategy

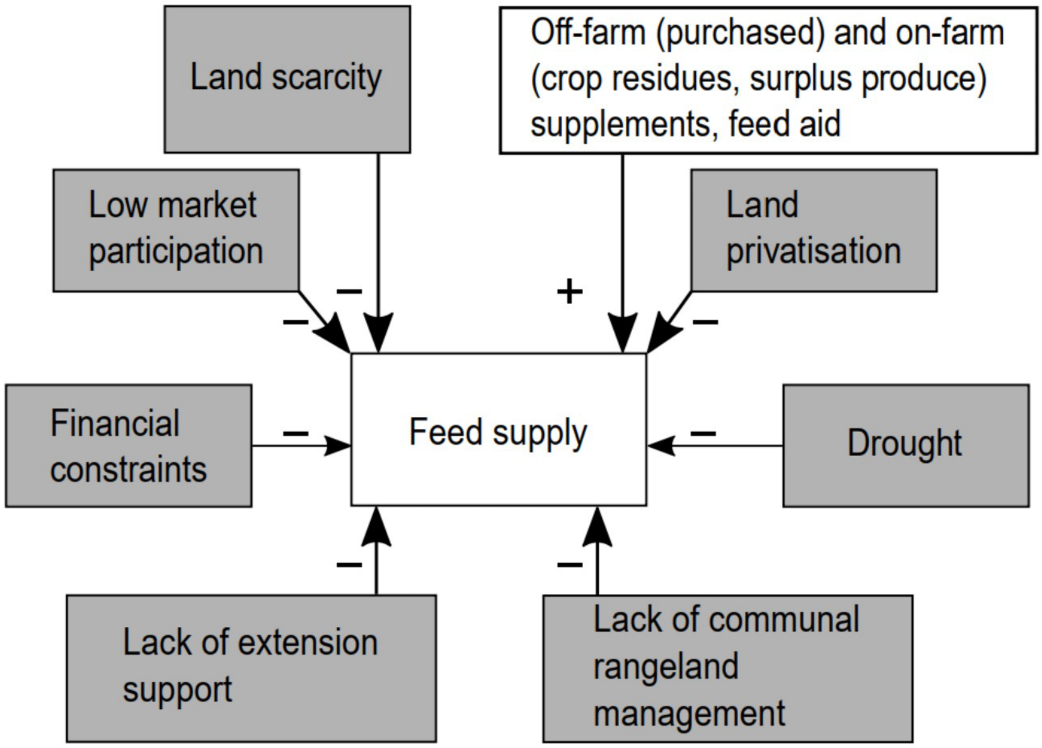

Figure 2.3: Concept map summarising perceived root causes (grey) and feed gap mitigation strategies (white) for livestock farmers during feed gaps

is the use of readily available crop residues during the autumn (Table 2.2), which serves as an additional feed input for livestock farms at no cost. Under severe drought conditions, where crop residues alone are not enough, farmers may reduce their livestock number to balance feed requirements. These strategies are associated with the socio-economic challenges of the smallholder livestock sector that render it vulnerable to feed gaps (Lamega et al. 2021; Marandure, Bennett, et al. 2020; Mapiye, Chimonyo, et al. 2009).

2.5 Results of available feed and soil resources

2.5.1 Feeding resources

Cattle rely heavily on the productivity of rangelands. In the study area in particular, rainfall patterns have created a vegetation gradient that may differ from the arid to the semi-arid zones. According to Mpofu et al. (2017) the veld type (an indigenous grazing and or browsing vegetation composed of any sort of plant species capable to reproduce itself undecidedly under existing environmental conditions) varies from sweet and mixed in the arid areas to sourveld in the semi-arid areas with prevailing grass species such as *Panicum maximum*, *Aristida transvaalenesis*, *Eragrostis curvula*, and *Themeda triandra*. A sweet veld according to Trollope et al. (1990) is a veld that retains acceptable nutritive values of its forage plants after maturity, utilizable throughout the year by livestock while a sourveld shows sharp declines in forage quality with ongoing maturation. A mixed veld is an intermediate veld between the sour and sweetveld with an acceptable quality supply of forage to the livestock. Our analysis in terms of crude protein (CP) concentration of the dry rangeland biomass in winter showed low herbage quality across the studied sites in the Limpopo province with a maximum of 5.3% (Table 2.3).

Table 2.3: Cattle feeding resources with corresponding crude protein (CP%)/(standard deviation SD) during the dry season. Site regroups about two-three villages where rangeland biomass and tree leaves are collected on communal rangelands, crop residues and suppplements collected at farm level. *Site 2 = only one farmer had access to feed supplements.

Feed resource	Site	Number of samples	Crude protein (%)(SD)
Rangeland biomass	Site 1	10	5.3(1.7)
Rangeland biomass	Site 2	10	4.6(1.8)
Rangeland biomass	Site 3	26	4.2(1.4)
Crop residues	Site 1	5	9.7(1.3)
Crop residues	Site 2	10	4.5(0.9)
Crop residues	Site 3	–	–
Feed supplements	Site 1	7	11.3(3.3)
Feed supplements	*Site 2	1	10.7(–)
Feed supplements	Site 3	12	12.2(9.4)
Tree leaves	Site 1	10	9.1(1.5)

Hence, the quality of the fibrous and dead herbage is poor. Even lower values of 2.7% CP were reported in a previous study by Moyo et al. (2012) in the winter period due to low growth and senescence. Nevertheless, in situations where there is hardly any herbage to consume, mineral nutrient may help livestock to cover some of its elemental demand irrespective of low protein or energy concentrations. The mineral nutrient concentration is likely insufficient to meet the livestock's nutritional demand (Lamega et al. 2021). In response to the dry and fibrous pasture during the dry season with low CP concentration, cattle may increase the selective retention time for feed particles in the rumen, hence, improving fibre digestion. However, this response to feed gap is hardly adequate to avoid the loss in body tissue which is associated with reduced nutrient supply and metabolic processes (Moore et al. 2009; Schlecht et al. 1999). The scarcity of grazing resource in terms of quality (Table 2.3) and quantity (Tables 2.1 and 2.2, (Figure 2.2)) along with increasing bush encroachments on the grazing rangelands (Mogashoa et al. 2021) is, therefore, a call for supplementary feeding.

Crop residues are the first source of additional feed across the study sites. In mixed crop-livestock systems in particular, crop residues represent supplementary feed for livestock in the dry season (Masikati et al. 2015). Therefore, the management of these residues on-farm may differ significantly in relation to the utilization as feed (Rusinamhodzi et al. 2016). Generally, the availability of crop residues coincides temporally with times when rangeland productivity declines (in terms of quantity and quality, see Figure 2.4), making them a valuable feed resource.

Figure 2.4: The communal grazing resource depleted during the dry season

Figure 2.5: Supplemental feed made up of dry crop residues and tree leaves collected from a farmer during the dry season

Crops such as maize, pumpkin, groundnut and cabbage are found in the fields and the straw and stover left at harvest are used for livestock feed. In line with this, Mapiye, Chimonyo, et al. (2009), who explored the cattle keeping system among 218 smallholder farmers in the study province, showed that about 70% of the total farmers used crop residues to cope with the feed shortages during the dry season. The importance of crop residues is further demonstrated in Figure 2.5 as a farmer collects and stores for use in periods of feed gaps. The crop residues in the present study showed higher CP concentration than the rangeland biomass sampled (Table 2.3) or the CP concentration of 4% obtained for maize residues in a study by Mudzengi et al. (2020). It is likely that crop residues are a mixture containing at least parts of C_3 plants such as legumes with higher CP concentration (~ 10%). Low protein concentration during a feed gap may be associated with low digestibility and, hence, poor livestock performance (Mudzengi et al. 2020). Despite disagreements presented by the utilization of crop residues on smallholder farms, i.e. "mulching or no mulching" (Valbuena et al. 2012), a mixture of crop residues may serve as a good source of additional feed. However, the quality and quantity of the residues should be more in balance with animal's demand especially in period of pasture scarcity (winter, spring), to significantly contribute to feed gap mitigation.

Supplementary feed plays a crucial part in livestock production as they can greatly improve the productivity of the livestock (Bell 2009; Bell, Moore, et al. 2017). In South Africa, different conventional supplements and agro-industrial by-products are available for purchase (Marandure, Bennett, et al. 2020). However, such feed purchase depends on the socio-economic status of a farm, but also on the intensity of the livestock production. For smallholder livestock farming that is often financially constrained, first choice supplementary feeds constitute crop residues, and agricultural or household waste. However, our results of CP concentration show that feed supplements are more valuable than anticipated particularly when compared to rangeland biomass, which should be beneficial for the livestock enterprise during feed gaps overall.

However, since the quantity of supplementary feed may depend on herd size, resource-constrained farmers may fail to purchase enough to sustain production. In this case, a farmer will strategically feed animals that are too weak to search for herbage intake on rangelands. On the other hand, focus could be given to high-performing livestock such as lactating cows. Additionally, browse trees can also provide supplementary feed during the dry season (Mudzengi et al. 2020). Here, we found that indigenous species such as *Colophospermum mopane* (common on rangelands) are rich in crude protein (Table 2.3) and likely other nutrients.

2.5.2 Soil resources

In relation to soil fertility, evidence from the literature demonstrated that the majority of smallholder farmers in the Southern African region face land degradation (Rufino et al. 2011; Zingore et al. 2007), and this phenomenon is particularly true among smallholder farmers in South Africa (Kolawole 2013). We collected soil samples across land use (rangelands and cropping lands) to get an insight on the fertility status (Table 2.4). We are aware that site-specific nutrient allocation in soils, for instance, around home gardens, or fields close to homestead have caused soil fertility gradients, problematic in terms of sustainable land use (Mtambanengwe et al. 2005; Rowe et al. 2006; Zingore et al. 2007).

Table 2.4: Selected soil chemical properties across different land-use types in the studied locations (standard deviation). n = 18(5.3) soil samples (0–10cm) per site.

Site	Land-use type	pH	Ntotal (%)	Ctotal (%)	P (mg/kg)	K (mg/kg)	Mg (mg/kg)
Site 1	Cropland	6.5	0.06	0.66	<1.00	17.45	17.53
		(0.8)	(0.01)	(0.09)	(–)	(3.97)	(2.25)
Site 1	Rangeland	6.3	0.07	0.80	2.40	20.88	20.56
		(0.6)	(0.03)	(0.35)	(1.60)	(6.02)	(9.16)
Site 2	Cropland	5.4	0.10	1.18	<1.00	6.56	24.82
		(0.7)	(0.02)	(0.16)	(–)	(6.20)	(3.42)
Site 2	Rangeland	5.3	0.12	1.55	<1.00	5.53	31.43
		(0.5)	(0.04)	(0.83)	(–)	(3.77)	(12.8)
Site 3	Rangeland	5.0	0.06	0.62	<1.00	9.98	8.58
		(0.7)	(0.03)	(0.31)	(–)	(8.60)	(13.26)

Basing on Kotzé et al. (2013) who evaluated basic soil properties across different land use types and management situations, all the soil nutrients may be limiting plant production. Under communal set up, Kotzé et al. (2013) discussed low nutrient content (e.g. <2% C, < 0.2% N, < 10 mg/kg P). We found similar results for our study (Table 2.4) which demonstrates poor land use conditions. The C/N ratio of c. 10 points at organic matter quality which potentially readily supplies nitrogen to crops. However, both the N and C contents are very low pointing at issues with soil quality. Soil degradation is also a reflection of grazing effects on rangelands as previously discussed by Descheemaeker, Amede, et al. (2010) and Linstädter et al. (2014), thus an issue of stocking intensity (Kotzé et al. 2013). Additionally, in an aerial cover study conducted under similar conditions in South Africa, Dlamini et al. (2014) showed from initially non-degraded soils, that grazing decreased soil organic carbon by 94% while nitrogen decreased by 40% on communal rangelands managed by smallholder livestock farmers. Such a degradation was found under fine sandy loamy soils in the semi-arid zones in South Africa. Most soils in the region where the present study was conducted refer to such soil textures (Swanepoel et al. 2015). Carbon is important for soil nutrient cycling and water storage. Nutrient limitation is generally potentially restricting herbage production. Therefore, soil fertility initiatives with an emphasize on C, N and P through future research may be essential for improving pasture forage supply.

2.5.3 Management options

- **Managing rangeland stocking density; de-stocking to reduce pressure on natural resources:** In their understanding of 'better' rangeland management, stakeholders from our group discussion maintained that communal rangelands were unquestionably overgrazed. Thus, de-stocking or resting periods may be the only reasonable options to restore productivity and close dry-season feed gaps. The role of stocking densities and overgrazing in debates about the management of Southern Africa's rangelands remain a very controversial topic. Despite its persistent promotion to save Africa's rangelands from degradation, the technocratic approach to de-stock the rangelands is not a universal panacea that fits every social-ecological context (Godde, Boone, et al. 2020; Tavirimirwa et al. 2019). Farmers persistently resisted to comply with such top-down approaches that were far from addressing their realities (Tavirimirwa et al. 2019). This is because farmers mainly seek to maximize herd size, hence, destocking initiatives fail to be implemented. Furthermore, grazing schemes or resting periods should not be recommended in this context as they reduce the flexibility of the common grazing resource (Tavirimirwa et al. 2019). However, as argued by Lamega et al. (2021) destocking can be attained if it is subsidized to be in balance with the seasonal feed budget. The longstanding debate still appears to be grounded on different understandings between top-down-oriented policies and stakeholders.

- **On-farm feed production:** Maize stover is particularly an important feed resource on smallholder farms. To improve livestock productivity using maize stover Dejene et al. (2021) demonstrated that upper maize stover fractions had higher total N concentrations and lower fiber content, and varied among different genotypes.
  The production of dry season (winter) forages, such as protein-rich legumes as cover crops, is a traditional practice across Southern Africa, for example, Bennett et al. (2010) have reported that C_3 species such as oats (*Avena sativa L.*) and barley (*Hordeum vulgare L.*) can be inter-cropped with maize during the dry season. Such species can do well under South African winter climate (cool season with low temperature), but with limited water during the winter period, irrigation schemes are crucial for high and effective production. Also, legumes have always been of interest to rural development agendas but their

implementation also met with scepticism among smallholder farmers (Sumberg 2004; Sumberg 2002). For instance, dual-purpose winter forage crops may provide higher feed availability during feed gaps, which can maintain livestock or accommodate higher stocking density. While the 'sustainable intensification' narrative promotes cover crop legumes to close yield and thus feed gaps, the upscaling and practical implementation has been of limited success among smallholding mixed-crop livestock farmers (Tittonell et al. 2013). It is important that feed improvement interventions fully address the quality and quantity of forage (Balehegn et al. 2020). From an agronomic point of view, however, recent field trials prove the underutilized and drought-tolerant legume lablab (*Lablab purpureus*) promising when grown in Limpopo under rainfed conditions (Rapholo et al. 2020). Additionally, forage brassicas have the potential to alleviate regular feed gaps due to high productivity (Bell, Watt, et al. 2020) if integrated as feed-base strategies in drier or mixed farming systems. However, feeding Brassica rapa, has been associated with liver disease in Holstein cows in South Africa (Davis et al. 2021). Therefore, more research is needed in the context of feeding brassicas to local cattle breeds.

- **Feed aid schemes:** Drought emergency support programs subsidize farmers during severe drought with supplementary feed obtained from commercial forage growers according to the farmers. A smallholder farmer commented on the present design of supplementary feeding support:

'I think the other challenge is, if we can get supplements from the government, that will help us a lot. But now they do sometimes, just as I said, I got 20 cattle and then they gave me 5 bags.'

According to the farmers, feed aid comes rarely in period of severe feed deficit. The program follows no specific criterion for acquiring such feed aids. Hence, farmers with very small herd (e.g. 5) may receive a one-time and free of charge supply, the same amount of feed (usually two to five bags of 25 kg) as a farmer that owns 20 plus cattle. In effect, such an approach to feed gap alleviation on smallholder farms is considered among farmers as not responding to the actual issue. A regular reception of such aids may help the livestock enterprise, but the question arises whether such programs can serve as a long-term sustainable adaptation strategy for smallholder farmers.

2.6 Conclusion

As presented in this chapter, feed gaps are generally governed by the environmental conditions that regulate the demand for, and the supply of energy but also the capacity of livestock managers to utilize diverse feed sources. Feed gaps will remain a key issue for livestock farmers in the dry areas of Limpopo amid climate variability. Therefore, developing multiple options for farmers may be beneficial in sustaining livestock throughout the year. The success, however, of any given recommendations must consider location and farm type specificity but also include socio-cultural values associated with livestock keeping. To support rural policies in the face of climate uncertainties, there is a need to reconfigure and restructure the livestock systems in a way that feed sources become more in balance with smallholder stock and their demand on communal rangelands throughout the year. For instance, if the farmer engages in cropping, with access to irrigation, dual purpose C_3 crops may serve as an option for alleviating winter feed gaps or may be used for trading. A cost-benefit analysis in relation to feed production and utilization may be helpful in evaluating adequate feeding strategies. However, the use of modelling to integrate different components of the system and management options as stated by Rötter et al. (2021) will become critical to determine ideal solutions for management issues against feed gaps.

2.7 References

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3

Assessing feed gaps using stable isotope techniques in complex mixed crop-livestock smallholder farming systems.

3.1 Abstract[1]

Stable isotope analysis of ^{13}C and ^{15}N has intensively been used to provide sound information regarding animal dietary composition as affected by ecological events or land use change. In complex South African mixed crop-livestock systems where communal rangelands play an important role, we analyzed $\delta^{15}N$ and $\delta^{13}C$ of cattle feces and hair tissues. We investigated dietary differences between agro-ecological zones (AEZ) and farm types in relation to feed gaps. Farm types were structured according to mixed crop-livestock farms and livestock-only farms with beef cattle as the main livestock species. We found that cattle in mixed-crop livestock farms show no different $\delta^{13}C$ from cattle in livestock-only farms because forage sources consist of C_4 plants irrespective of farming system ($P > 0.05$). A significant interaction effect between farm types and AEZ was found ($P < 0.01$) for the contribution of C_4 plants in the diet as estimated from the $\delta^{13}C$ of feces. Moreover, $\delta^{13}C$ of feces and hair tissues were strongly influenced by AEZ ($P < 0.01$) mainly due to difference in C_3/C_4 diet intake. Meanwhile, the $\delta^{15}N$ showed patterns of nutritional stress probably due to low protein concentrations in the diets across AEZ. The analysis of

[1] A version of this chapter is under revision in Rangeland Ecology & Management

the present study indicates that stable isotopes can be an essential tool in helping understand feed gaps in a diverse livestock production system.

Key words: Diet intake, carbon, nitrogen, mixed farming, rangeland

3.2 Introduction

Communal livestock farmers in southern Africa mainly rely on grazing rangeland to maintain farm productivity (Nyamushamba et al. 2016). Particularly in South Africa, productive pastures are available and exploited during the summer while winter remains a period of unproductivity because of water scarcity (Vetter et al. 2020). This seasonal variation in the pasture forage supply leads to feed gaps, a disparity between the pasture supply and demand by livestock. On-farm level differences exist in the strength of feed gap impact between farm types (i.e. whether farm engages in livestock only, or mixed crop-livestock) favoring mixed crop-livestock farmers to cope with extended drought (Lamega et al. 2021).

In the smallholder context, for instance, a mixed crop-livestock farmer may have the opportunity to feed crop residues during a feed gap period, while a specialist livestock-only farmer is mostly solely reliant on the unproductive rangeland pasture. The severity of feed gap impact on farm-level in terms of livestock responses may consequently vary between farm types and also between climatic zones exposed to different levels of aridity. Usually, the study of feed gap impacts in such complex agro-environmental livestock systems relies on evaluation of the seasonal pasture supply, supplemental feeding regimes and the quality of feed resources which may vary in space and time across regions. The effort in seasonal data collection can be reduced with the alternative of using signatures of stable isotopes to assess feed gaps and link these to feed sources as an indicator of adaptive capacity across regions or farming systems.

Stable isotope analysis is an essential tool for diet origin, and stable carbon (δ^{13}C) and nitrogen (δ^{15}N) isotopes especially, have been extensively used to identify or reconstruct dietary choices of animals in relation to species ecology (Auerswald 2009; Kriszan et al. 2014; Schwertl, Auerswald, Schäufele, et al. 2005; Sponheimer, Loudon, et al. 2006). For the purpose of reconstructing the dietary history, continuously growing tissues such as hair are commonly analyzed since they contain time-series information, incorporated in the tissues through diet consumption (Schwertl, Auerswald, and Schnyder 2003).

Though such tissues are key to quantifying dietary information over much longer periods of time, fecal resources can be employed to document short turnover periods (Codron, Codron, Lee-Thorp, et al. 2005). The δ^{13}C and δ^{15}N values are related to a combination of factors associated with changes in environmental conditions. For instance, aridity (or water stress) (Crumsey et al. 2019), plant available nutrients (Ma et al. 2012), plant nitrogen uptake mechanisms (Wrage et al.

2011) or the protein content of the consumed diet (Sponheimer, Robinson, et al. 2003) and the difference in the dietary proportion of C_3 and C_4 plants (Hammes et al. 2017) can influence δ^{13}C and δ^{15}N values of cattle hair. Therefore, carbon and nitrogen isotopic fractions are important for reporting ecological variability especially through variation of livestock animal diets that change seasonally in response to feed availability. The identification of feed gaps can, consequently, be assessed through the contribution of C_3 and C_4 plants in the short-term as retrieved from isotopic signatures in feces and in the long-term dietary differences between summer and winter in hair tissues (Funck et al. 2020; Hammes et al. 2017; Codron, Codron, Lee-Thorp, et al. 2005). Such information is particularly relevant in combination with farming management data to evaluate environmental impact on livestock production in a scientifically reliable way in order to find future pathways for improved livestock-rangeland systems.

In the present study, we attempt to characterize dietary variation of livestock on smallholder cattle farms in relation to climatic gradients and farm types. Therefore, we aim to explore the differences in feed supply of free-ranging cattle based on knowledge of farm-specific diets during the feed gap season of the year 2019. We present results obtained from data on cattle feeding regimes based on a questionnaire and physical data including isotopic signatures obtained on 90 farms across climatically distinct agro-ecological zones in the Limpopo province, South Africa. The present study hypothesizes that:

- cattle in mixed-crop livestock farms show a different isotopic signature of feces and consequently differences in C_4 plants contribution in diet (as determined from feces) than cattle on livestock-only farms due to supplemental feeding; and

- that due to variation in climatic conditions among seasons, isotopic signature of hair in the dry season differs from the wet season signatures.

3.3 Materials and methods

3.3.1 Description of the study area and design

Study sites were located in South Africa's Limpopo province with latitudes ranging from 22° 10' to 25° 10' and longitudes from 26° 10' to 32°. The climate in the province is associated with cool dry winters (June – August) and hot wet summers

(December – February) and therefore classified as semi-arid with high inter-annual variability in the total amount of rainfall rendering rural farm households vulnerable to feed gaps (Lamega et al. 2021). The studied sites differ with respect to altitude and precipitation and were grouped according to three different agro-ecological zones (AEZ): warm arid, warm semi-arid and cool semi-arid. The warm arid zone receives the lowest average amount of annual rainfall ~400 mm while the cool semi-arid is the zone of highest average annual rainfall ~600 mm. The warm semi-arid is in between with an average rainfall of ~500 mm. The highest temperature is recorded during the hot summer (up to 45°C in the warm arid) and drops during the winter season where the average minimum temperature is lowest 15°C in the cool semi-arid zone. The province provides a high diversity of rangeland vegetation characteristics that changes progressively with precipitation, but is generally dominated by perennial C_4 grasses (Makhado et al. 2016; Mutanga et al. 2006). Livestock farming is commonly integrated into cropping systems in the province, with free-range grazing on communal rangelands (Stroebel et al. 2011).

3.3.2 Data sampling: on-farm survey and on-farm physical data collection

The field work for the present study was conducted between May and October 2019. In a first step, a survey questionnaire was centrally designed and implemented to record background information on farm characteristics, management and cattle livestock feeding regime in relation to the perception of feed gaps (for further details see Lamega et al. (2021). The on-farm survey was conducted in two to three rural villages within each AEZ. In total seven villages were studied with 90 cattle livestock farmers participating. These were grouped into two different ex ante selected management conditions, namely livestock-only (n=51) and mixed crop-livestock farmers (n=39). During the dry season, mixed crop-livestock farmers are of advantage of feeding crop residues to their animals as additional feed while livestock-only farmers supply their herds from rangelands only pointing at variation in feed supply between farming systems and also AEZ where the crops grown vary. Cattle for beef production is the main production purpose and the breeds include predominantly Nguni and Brahman, but also Beefmaster, Bonsmara and their crossbreeds.

On each farm, we selected two adult cattle from which we collected feces and tail switch hair samples. Cattle feces and tail hair were sampled between 6:00 and 7:30 a.m., before the animals were released for the day. About 200 g fresh matter of feces was collected from ground level immediately after excretion. Samples were put in sealed plastic bags, cooled, later oven-dried at 60°C and ground into a homogenous powder for isotopic analysis (see section Isotopic analysis). A bunch of tail switch hair was cut with scissors close to the skin-base of each animal. The hair samples were put in plastic bags and frozen until further processing. In order to assess differences in the isotopic composition in relation to seasonally dynamic ingested feed resources, we carefully chose the longest growing hair of each animal sample during laboratory processing.

For this, we followed the approaches reported by (Hammes et al. 2017). First, we assumed a constant hair growth rate of 2.5 cm per month regardless of the cattle breed and secondly, we assumed that the isotopic signatures are affected by the feed resources only. Since the feeding regime is dynamic over the season, the isotopic signatures stored in the hair can consequently be used as archive for information of feed resources during specific parts of the year (Schwertl, Auerswald, and Schnyder 2003) over long-term periods. For this, the isotopic signatures retained in different hair segments are assigned to specific parts of the year (Figure 3.1) as derived according to constant growth rates of hair (Schnyder et al. 2006; Sponheimer, Grant, et al. 2003a). This information allows for assessments of seasonality of feed resources and, consequently, feed gaps. We assumed a requirement of 80 days before one feeding regime is visible in a fragment of the hair (Schwertl, Auerswald, and Schnyder 2003). However, to be as accurate as possible, we selected hair samples from each AEZ and cut each cm (1 cm) along the hair for analyses. Based on the assumptions and the analyses, an appropriate hair segment of 2 cm was assumed to reflect the diet for a particular month within a season. For instance, for each hair, 2 cm was cut into tin aluminum capsules to represent diets at the time of sampling in the dry season and another 2 cm part to represent the wet season (Figure 3.1).

To be able to provide quantitative information on feed resources in the feed gap period (winter), grass samples from communal rangelands and crop residues from arable lands were obtained at the village level during the dry season of 2019 (sampled between May and October). Additionally, feed samples that may have been fed to the animals or that we have seen the animals were feeding on (e.g. leaves of *Colophospermum mopane* in the arid zone) were obtained by taking one sample of about 200 g FM for analysis. Since we started data collection in the dry season, rangeland forage plants (consisting of grasses only) were senescent at the time of sampling. Before sampling, evidence of grazing was searched for (either by sampling near the cattle on the rangelands or evidence of relatively abundant feces and grazed plants was sought out). Five grass samples were taken randomly on each grazing

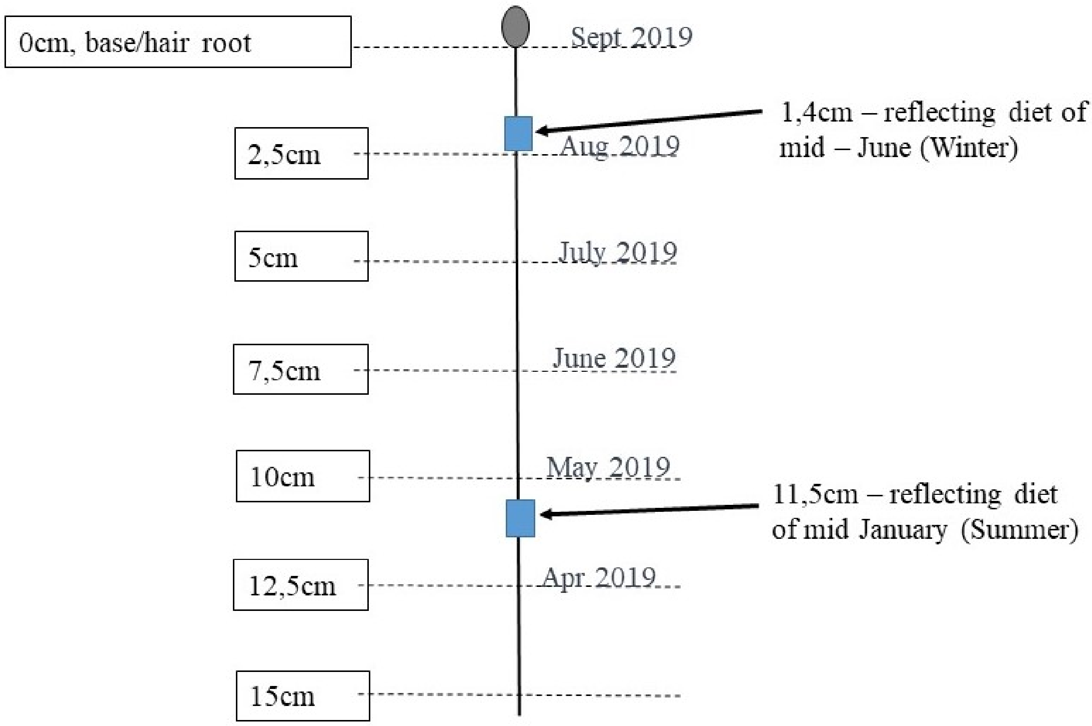

Figure 3.1: overview of cattle hair as sampled and analyzed. Selected sections (blue) for analysis representing the winter and the summer seasons

site following a longitudinal transect-based approach (5m apart). Grass samples were manually cut at ground level using hand shears in a 50cm x 50cm quadrat. In total, 178 feces samples, 134 hair sections from 67 hair samples and 81 feed samples (grass, crop residues, feed supplements, tree leaves), across AEZ and farm types were analyzed in the present study.

3.3.3 Isotopic analyses

For logistic reasons cattle among AEZs were not sampled within the same month but in a period between May and October. Animals in the semi-arid warm region were sampled already in May, June and July 2019. These hair samples were omitted from the analysis because of inadequate prediction of dietary information of the dry period of 2019 which starts in May. Only the hair samples from the months of September and October in the arid warm and semi-arid cool zones were, therefore, submitted to the isotopic analyses leaving the semi-arid warm season out in this part.

Cattle hairs were dipped overnight in distilled water to remove dirt contaminants and washed in an ultrasonic solution with deionized water, dried (40°C for 48h) and placed in a 2:1 methanol:chloroform solution for 2 hours thereafter. The hairs were afterwards soaked and rinsed on several occasions in deionized water before oven-dried at 40°C for 48h. These guidelines have been intensively used to prepare cattle hair samples for stable isotopic analysis previously (Hammes et al. 2017; Li et al. 2012; Schnyder et al. 2006). The feces, feed and soil samples were ground to pass a 0.2 mm screen. Then subsamples of ~3 mg were placed into 0.5mm x 0.3mm tin capsules for isotopic analysis. Total N and C concentrations as well as the isotopic signature (δ^{13}C and δ^{15}N) were determined with a Delta Plus infrared-mass spectrometer (IRMS) coupled with a continuous-flow isotope ratio-mass spectrometer Conflo III-Interface (Finnigan MAT, Bremen, Germany) to an elemental analyzer NA1110 (Carlo Erba Instruments, Milano, Italy). As reference, N_2 and CO_2 were used, which were calibrated against the reference substances IAEA N1 and IAEA N2, IAEA NBS18 and IAEA 600, respectively. Acetanilid was used as internal standard. Values of δ^{13}C and δ^{15}N are reported per mil (‰, standard = atmospheric air) as described below. Precision of repeated measurements of laboratory standard was < 0.2.

3.3.4 Data analyses

The statistical analysis was carried out using the R software version 3.6.0 (R Core Team 2019). To understand the feeding regime within the cattle livestock systems across the different AEZ, the survey data of farm and feeding management was subjected to descriptive statistics. Sampled feed resources and their isotopic compositions were also analyzed by descriptive statistics because individual farm feed items were not obtained in a balanced way. For instance, feed supplements or crop residues lack on most livestock-only farms.

In addition, since rangeland is communal property and, hence, representative for a village but not a particular farm, it, therefore, cannot be linked to individual cows or explain variation between cows on different farm types within AEZ. To study the effects of AEZ and farm types on the isotopic values of the hair and feces, we used linear-mixed effects models in the "nlme" package, and ran independent models on the following response isotope variables: $^{13}C_{feces}$, $^{15}N_{feces}$, $^{13}C_{hair}$, $^{15}N_{hair}$. However, the statistical models for ^{15}N and ^{13}C of the hair additionally included season as fixed effect which was not tested in the models for feces. For all models, we considered individual animals as a random effect. The most parsimonious model with the lowest Akaike Information Criterion (AICc for small sample sizes) was chosen using the 'MuMIn' package for analysis of variance. We checked the normality of the model residuals graphically in qqplots. Data were then log-transformed whenever necessary. Post-hoc comparisons of means of ^{15}N and ^{13}C were followed by Tukey's HSD test using the 'emmeans' package for significant influencing factors. We estimated the percentage of C_4 plant intake of individual animals from the feces using a dual endpoint mixing model according to Codron, Codron, LeeThorp, et al. (2007):

$(\delta^{13}C_{C3plants} + \Delta\delta^{13}C - \delta^{13}C_{feces})/ (\delta^{13}C_{C3plants}\ \delta^{13}C_{C4plants})$

where $\Delta\delta^{13}$C is assumed to be – 0.9‰, which is the magnitude of discrimination between the animal tissue and source endpoints (Codron, Codron, LeeThorp, et al. 2007). This approach relies on global plant 13C mean values of -27.0‰ and -12.7‰ for C_3 and C_4 plants, respectively (Codron, Codron, LeeThorp, et al. 2007; Sponheimer, Grant, et al. 2003a). However, we used a specific δ^{13}C value of -26.0 ‰ for C_3 plants that reflects the vegetation of the study sites during the dry season according to Codron, Codron, Lee-Thorp, et al. (2005). The values of the C_4 percentage intake obtained from the feces were also subjected to linear-mixed effects models, analyzed using the fixed effects of AEZ, farm types and their interaction. The individual cow was used as random effect.

To estimate the relationship between the isotopic composition of feces and hair, we used analysis of covariance and fitted a linear model using the generalized least-squares function (nlme package) with the covariate of either ^{13}C or ^{15}N in feces the AEZ and farm type as fixed effects to predict respective hair value isotopic composition in the dry season. We predicted the models for ^{13}C and ^{15}N of hair based on similar individuals for feces using the 'effects' package, and evaluated the models using the 'caret' package to assess the relationship. Finally, we estimated isotopic fractionation factors between each hair section and individual feces samples by using the broad range of feed resources collected (i.e. $\Delta^{15}N_{hairdiet}$, $\Delta^{13}C_{hairdiet}$ and $\Delta^{15}N_{fecesdiet}$ $\Delta^{13}C_{fecesdiet}$) in order to characterize the consumer-specific feed intake and sites with differing environmental conditions. Particularly, the fractionation of ^{13}C in each potential diet component into feces ($^{13}C_{feces\text{-}diet}$) or hair ($^{13}C_{hair\text{-}diet}$), and between ^{15}N in the potential diet components and feces ($^{15}N_{feces\text{-}diet}$) or hair ($^{15}N_{hair\text{-}diet}$) were obtained.

3.4 Results

3.4.1 Feeding regime and feed resources for livestock during feed gap

In relation to the cattle feeding system, 92% of the farmers in the survey practice a year-round, free and undirected grazing and the remaining 8% practice grazing with a seasonal stall-feeding, particularly in the dry season (Appendix A). Generally, communal rangelands are the main grazing land for livestock (86% of all farmers) but animals of 61% of all farmers also graze on private farmland such as arable fields. Across farm types, more livestock-only farmers practiced year-round grazing (>50%) and utilized the communal rangelands more (>50% of the livestock-only farmers). Approximately 40% of the mixed crop-livestock farmers utilize farmlands (Appendix A). Meanwhile, the percentage of farmers that practice a year-round grazing was fairly distributed across AEZ. A portion of 6% of the farmers in the semi-arid warm zone practice seasonal stall-feeding and 30% of the farmers in that AEZ utilize farmlands which is higher compared to the other AEZ. The lowest percentage of farmers utilizing communal rangelands and farmlands was noted in the semi-arid cool zone (only 2% Appendix A) due to private ownership of rangelands in the latter AEZ.

The feed resources rangeland biomass (grass), crop residues (CR) or others investigated did not show a variation in the δ^{13}C values across AEZ (Appendix B). As expected, the δ^{13}C composition of the grass and CR demonstrated dominance of C_4 plant components with mean values ranging from -14.7‰ to -14.0‰. The sampled feed supplements (FS) represented a mixture of C_3 and C_4 plants as indicated by the wider variation of the δ^{13}C values (-22‰ to -14.0‰). Such FS were dominant in the arid warm and semi-arid cool zones. The only FS sample collected in the semi-arid warm zone showed dominance of C_4 plant components (-12.4‰ Appendix B). The isotopic signature of leaves of the tree *Colophospermum mopane* from the arid zone showed the most negative δ^{13}C values (-27.1‰) indicating the dominance of C_3 plant components. Accordingly, the δ^{15}N values for FS and tree leaves were more depleted than the values for the grasses and CR (not shown).

3.4.2 Effect of farm types and AEZ on feces and on the % C_4 diet contribution estimated from feces

The analysis of variance of the $\delta^{13}C$ values of feces demonstrated that farm types had a minor effect on the isotopic analysis ($P = 0.27$) whereas AEZ played an important and significant role ($P < 0.01$, Table 3.1). The comparison of means showed that $\delta^{13}C$ values in the arid warm zone were significantly lower (more negative) (-20.5‰ ± 0.37) than in the semi-arid warm and semi-arid cool zones (-17.6‰ ± 0.38 and -17.5‰ ± 0.35, respectively, Table 3.2). Similarly, the model for $\delta^{15}N$ values demonstrated a significant effect of AEZ ($P < 0.01$, Table 3.1). Additionally, farm types had a marginally significant effect on $\delta^{15}N$ values ($P = 0.05$). Between AEZ, the $\delta^{15}N$ values were significantly lower in the semi-arid cool zone (4.46‰ ± 0.28) as compared to the arid warm (6.72‰ ± 0.27) and semi-arid warm (5.99‰ ± 0.24) ($P < 0.01$) zones (Table 3.2. Between farm types across all AEZ, $\delta^{15}N$ values were marginally larger for livestock-only (6.07‰ ± 0.19) than for mixed crop-livestock farms (5.25‰ ± 0.24) ($P = 0.05$, Table 3.2). In contrast to the previous analyses of other target variables, the statistical model for the % C_4 diet contribution from the $\delta^{13}C$ composition of feces showed a significant interaction effect between AEZ and farm types ($P < 0.01$, Table 3.1) which was caused by a greater percentage of C_4 dietary proportion on mixed crop-livestock compared to livestock-only farms in the arid warm region while the opposite was true for the semi-arid cool region (Figure 3.2).

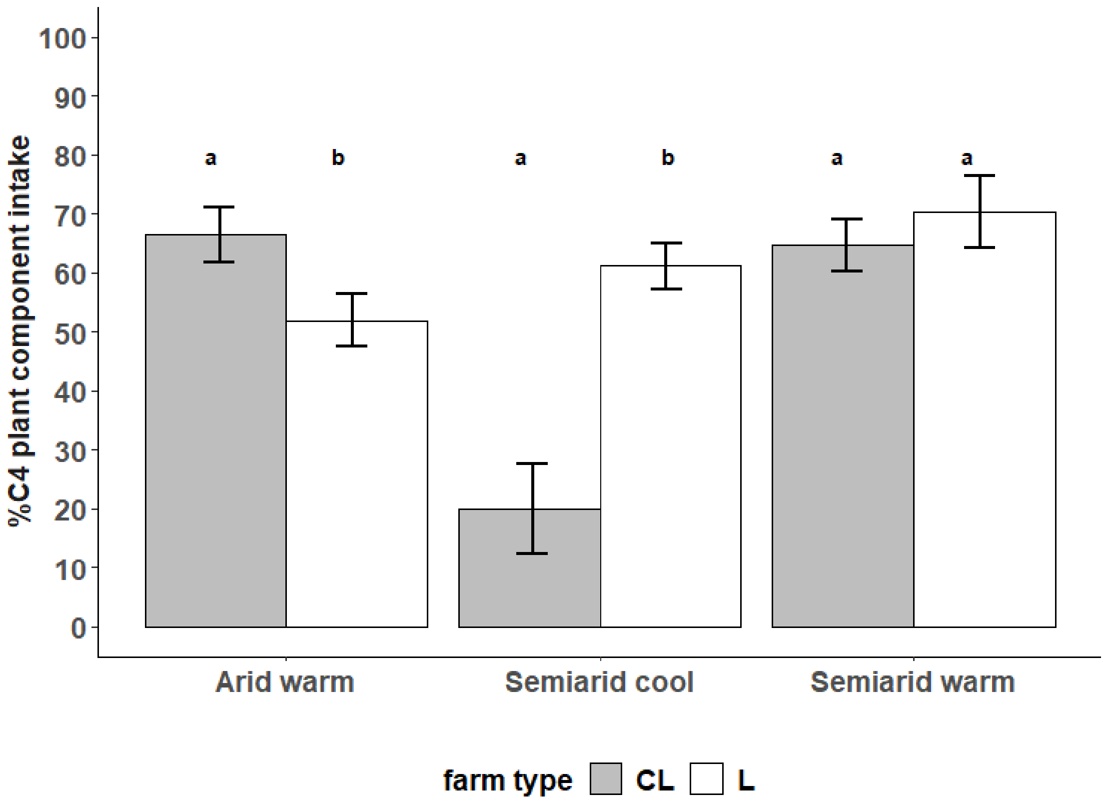

Figure 3.2: The interaction effect (AEZxFarm type) P < 0.05

Table 3.1: Output of linear mixed effects models for the δ^{13}C and δ^{15}N values (‰) and percentage of C_4 dietary proportion (%C_4) of feces. Numerator Df: degrees of freedom, dendf: denumerator df, AEZ: Agro-ecological zones

Target variable δ^{13}Cfeces				
	df	dendf	F	P–value
AEZ	2	84	11.8	<0.01
Farm type	1	84	1.3	0.27
AEZ x Farm type	2	84	0.2	0.85
Target variable δ^{15}Nfeces				
	df	dendf	F	P-Value
AEZ	2	84	7.1	<0.01
Farm type	1	84	3.9	0.05
AEZ x Farm type	2	84	2.8	0.06
		%C_4diet		
	df	dendf	F	P-value
AEZ	2	84	4.75	0.01
Farm type	1	84	4.88	0.03
AEZ x Farm type	2	84	6.76	0.002

Table 3.2: Output of isotope values (δ^{13}C and δ^{15}N) (‰) in feces of cattle during the dry season (n=178). Given are estimated means (standard errors). Lowercase letters indicate significant differences (P < 0.05). AEZ: agro-ecological zone, L: livestock only, CL: mixed crop-livestock

AEZ	$\boldsymbol{\delta^{13}}$**C**
Warm arid	-20.5(0.37)a
Warm semi-arid	-17.6(0.38)b
Cool semi-arid	-17.5(0.35)b
AEZ	$\boldsymbol{\delta^{15}}$**N**
Warm arid	6.72(0.27)b
Warm semi-arid	5.99(0.24)b
Cool semi-arid	4.46(0.28)a
Farm type	$\boldsymbol{\delta^{15}}$**N**
L	6.07(0.19)b
CL	5.25(0.24)a

3.4.3 Effect of farm types, AEZ and season on isotopic composition of hair and the relationship between isotopic values of feces and hair

The δ^{13}C values of the cattle hair were affected by the interaction of AEZ × season (F=25.6, P < 0.01) (Appendix C). Similar to the carbon isotopic composition of feces, the δ^{13}C value of the hair tissue was distinctly different in the arid warm zone compared to the semi-arid cool AEZ. The comparison of means revealed that δ^{13}C values were significantly more negative in the arid zone than in the semi-arid cool zone irrespective of season (Table 3.3). In contrast, the δ^{15}N values of the hair tissue showed no pattern as they were not affected by any influencing factor (Appendix C) ranging from 6.85‰ to 7.84‰ (Table 3.3). We found a significant relationship between the carbon isotopic composition of the hair tissues and the feces ($\delta^{13}C_{feces}$ F = 449.9, P < 0.01; as affected by AEZ F = 133.1, P < 0.01) (Appendix D). A similar relationship was observed for δ^{15}N values of hair and feces ($\delta^{15}N_{feces}$, F = 39.9, P < 0.01; as affected by AEZ F = 15.8, P < 0.01, Appendix D), (Figure 3.3).

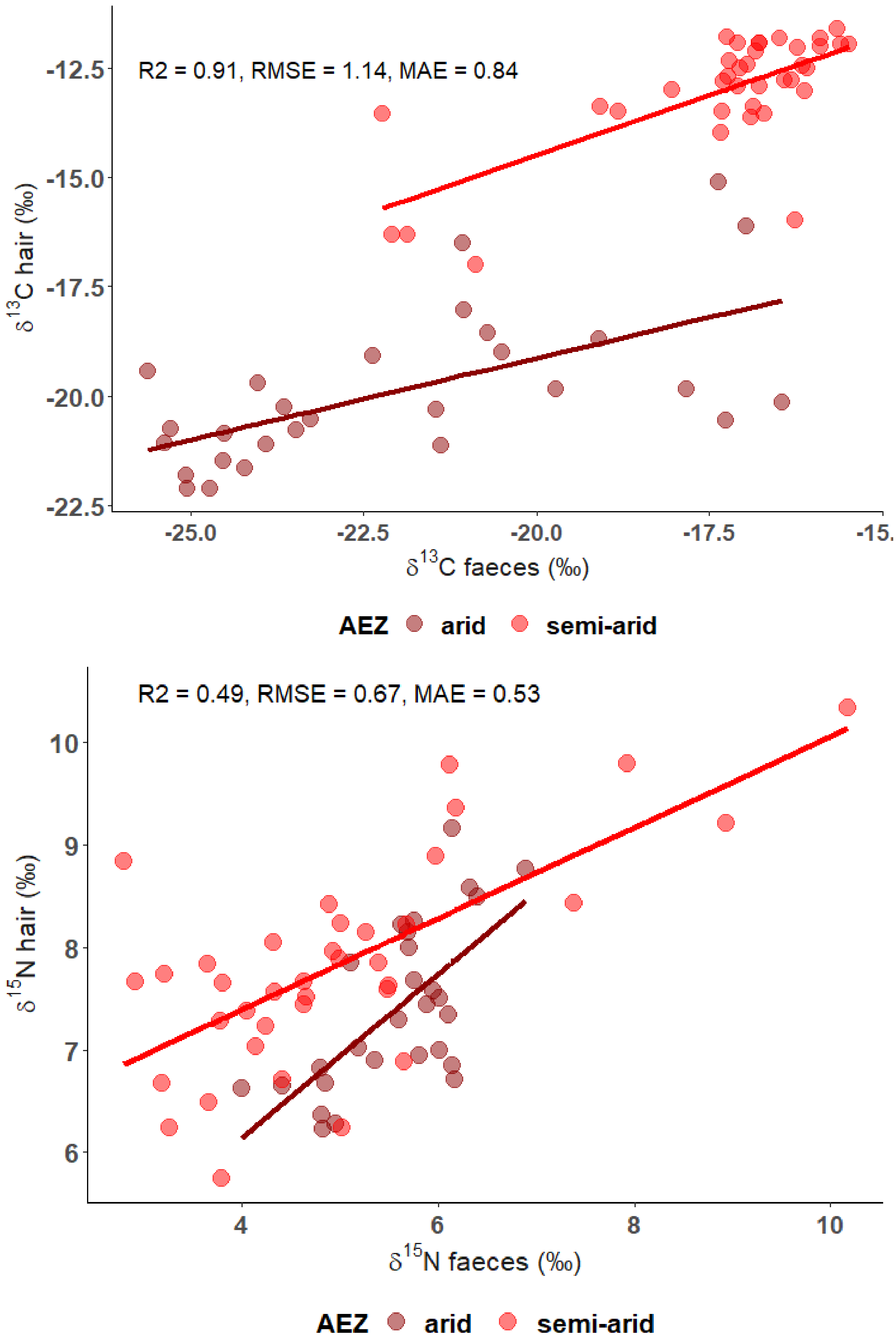

Figure 3.3: Relationships between of the carbon isotopes (top) and nitroegn isotopes (bottom) of feces and hair. $P < 0.05$

Table 3.3: Output of isotope values (δ^{13}C and δ^{15}N) (‰) of cattle hair as affected by AEZ (agro-ecological zones) and Season (n=134). Given are estimated means (standard errors). Lowercase letters indicate significant differences (P < 0.05).

AEZ	**Season**	**δ^{13}Cfeces**
Arid	dry	-19.9(0.4)b
Cool semi-arid	dry	-13.0(0.3)a
Arid	wet	-18.7(0.4)b
Cool semi-arid	wet	-13.9(0.3)a

AEZ	**δ^{15}Nhair**
Arid	7.33(0.2)a
Cool semi-arid	7.74(0.2)a

Using the mean isotopic values of feed resources collected during the dry season (Appendix B), the estimated fractionation factors between diet and tissues were calculated. Particularly, the fractionation between δ^{13}C in the diet into feces ($\delta^{13}C_{\text{feces-diet}}$) or hair ($\delta^{13}C_{\text{hair-diet}}$), and between δ^{15}N in the diet and feces ($\delta^{15}N_{\text{feces-diet}}$) or hair ($\delta^{15}N_{\text{hair-diet}}$) were obtained (Appendix E). The results show that on average, the $\delta^{13}C_{\text{feces-grass}}$ (‰) across AEZ and farm types were -3.87; average values for $\delta^{13}C_{\text{feces-cropresidues}}$ were -4.38; for $\delta^{13}C_{\text{feces-feedsupplements}}$ were -1.88 and values for $\delta^{13}C_{\text{feces-leaves}}$ were largest with +8.49.

However, the estimated fractionation factors between δ^{15}N diet and tissues show that the average values (‰) were generally higher for δ^{13}C~feces-feed supplements~(+4.3), followed by +3.76 for leaves, +2.54 for crop residues and lowest for grass in the semi-arid cool AEZ (+1.98). Also, the mean fractionation values for $\delta^{13}C_{\text{hair-diet}}$ were larger for hair-leaves (+10.72), whereas the mean $\delta^{13}C_{\text{hair-diet}}$ obtained was lowest for hair-crop residues (-4.01) (Appendix E). The calculated mean fractionation values for $\delta^{15}N_{\text{hair-diet}}$ in the arid and semi-arid cool zones were generally larger for hair-feed supplements (+5.6‰), followed by hair-leaves (+5.22‰), and hair-crop residues (+3.86‰). The lowest mean fractionation was obtained for hair-grass (+3.84‰).

3.5 Discussion

In our study, we observed a strong relationship between the carbon isotope composition of feces and of hair. Such a relationship gives us the information of diet consumption in response to animal habitat and conditions, hence, a meaningful indicator of farm practices in relation to cattle feeding regime and climatic conditions. The relationship between the nitrogen isotope of feces and hair was also satisfactory. In this respect, both nitrogen and carbon isotopes provide insights into dietary differences contributing to consumer's diet over a relatively short-time or long-term time scale. Overall, our results show consistency with previous studies that have found a significant relationship between the isotopic information in hair and feces (Crumsey et al. 2019), reflecting isotopic pattern of diet sources. However, our results from the carbon and nitrogen isotopes of the hair tissues show some variation which might be related to various factors. We argue that the difference between carbon and nitrogen isotope values of feces and hair represent short-term and long-term dietary averages, respectively. For example, feces collected at the beginning of the dry season reflect the diet information of that particular time, while each hair section reflects the average dietary consumption over the course of a month – representing the dry and the wet seasons. Similar variation in relation to data acquisition was previously reported by Sponheimer, Grant, et al. (2003b). In addition, against our anticipation, cattle obviously showed only little changes in the dietary composition among seasons which may reduce variation in the isotopic signatures of hair.

Contribution of C_4 plants to diet indicate importance of rangeland biomass during dry period Given the dietary constraints during the winter dry periods, we anticipated that consumption of C_4 plants might be significantly more important for cattle on mixed crop-livestock farms because of crop residues. Contrary to our expectations, the carbon stable isotope results from both feces and hair did not show dietary differences between farm types but rather showed strong dietary differences between AEZ with lower values recorded for the arid zone. The range of δ^{13}C (‰) values of feces of 20.5 to 17.5, and of hair of between 19.2 and 13.0 suggests dominance of C_4 plants across farm types and AEZ. In light of the lower values in the arid zone (20.5 for feces and 19.2 for hair), it is likely that the cattle diets in that AEZ are to some extent composed of C_3 plant species such as the Mopane tree. Fractionation values of isotopic signals have been used to predict the contribution of plant species to diets of herbivores (Oelze et al., 2020; Sponheimer et al., 2003). In controlled-feeding studies, ruminants on either a C_3 or a C_4 diet can have their $\delta^{13}C_{\text{feces}}$ values either enriched (up to 2‰) or depleted (up to -2‰), respectively. Hair tissues may be generally enriched up to 3 – 3.4‰ (Auerswald 2009; Sponheimer, Grant, et al. 2003a; Wittmer et al. 2010). In view of the high average fractionation values for $\delta^{13}C_{\text{feces-diet}}$ (+8.5‰) and $\delta^{13}C_{\text{hair-diet}}$ (+10.2‰)

for Mopane leaves it cannot be considered significantly contributing to diets.

However, there could be considerable variation in the fractionation values between diet and hair or between diet and feces when animals are exposed to mixed diets (Sponheimer, Grant, et al. 2003a) because of variation in organic matter digestibility. A feed with low digestibility may be more reflected in the isotopic fraction of feces (Botha et al. 2005). Furthermore, the authors suggested that an ingested diet consisting of 20% of C_3 plants results in 80% (weighted on isotopic basis) in the feces. As argued by Wittmer et al. (2010) cattle select a diet of better quality when exposed to mixed diets (C_3/C_4) and usually prefer the C_3 plant component. The advantage of herbaceous C_3 species, shrubs or foliage from trees species is that even in the dry season may contain high nutritional values, hence contributing to diet composition among many herbivores (Makhado et al. 2016). The contribution of C_4 species to the diet in the present study averaged a value of 60% as retrieved from isotopic composition of the feces samples obtained during the dry period. Our data, hence, confirm that even in the dry period, cattle mostly rely on C_4 feed, probably mainly grasses from rangelands.

3.5.1 Why does the isotopic composition of potential feed have little explanatory power to predict the diet during dry periods?

The feeding regime results show that cattle are mostly exposed to uncontrolled diets and feed resources with large contributions of rangeland grass supply. A distinct difference between farm types exists because cattle on mixed-crop livestock farms have access to crop residues which is in agreement with a large body of literature from Southern Africa (Homann-Kee Tui et al. 2015; Jaleta et al. 2013; Tarawali et al. 2011; Valbuena et al. 2012). Detection of feed supply resources during the dry season from isotopic signatures as based on the potential feed resources remains challenging because the current feed base may exceed that recorded. No differences in the isotopic signature of grass was found among AEZ and the $\delta^{13}C$ of the grasses are in the range of those previously obtained for the C_4-dominated vegetation in the region (Codron, Codron, Lee-Thorp, et al. 2005; Swap et al. 2004). Similar to the carbon isotope of grass, the $\delta^{13}C$ values of crop residues indicated a strong dominance of C_4 plants, likely maize (*Zea mays L.*). However, $\delta^{13}C$ values among different feeds varied according to distinct photosynthetic pathways. The tree leaves had $\delta^{13}C$ values of approximately -27‰ that indicated a C_3 photosynthetic pathway whereas the feed supplement showed distinct values and considerable variations.

According to variation in cropping systems applied on farm level, supplements may consist of C_3 (e.g. tree leaves, legumes, cabbages) or C_4 dominated (maize) feed, or represent a mixture challenging any investigation into relationships between feed source and consumer isotopic composition. Our results of $\delta^{13}C$ values support evidence for mixed diets (Codron, Codron, LeeThorp, et al. 2007; Hammes et al. 2017) although the actual feed resource and its contribution remain an open question. Our first hypothesis that cattle in mixed-crop livestock farms show a different isotopic signal from livestock-only farm cattle because of supplemental feeding and, generally, a higher C_4 percentage in the diet because of stover feeding must be rejected because the overall signals are masked by a diet consisting mainly of C_4 plants originating from crop residues, feed supplements and rangeland biomass in unknown proportions. The $\delta^{15}N$ values of the grasses and crop residues were generally more enriched (1 – 2‰) than the values of the other feed resources (feed supplements and tree leaves), which might be expected since leguminous trees and forbs generally display lower $\delta^{15}N$ values than non-leguminous plants (Codron, Codron, Lee-Thorp, et al. 2005).

3.5.2 Determining seasonal dynamics of feed supply

We found that within the same AEZ, the carbon isotope information of the selected hairs did not show a seasonal pattern. Generally, water availability is one factor among others controlling $\delta^{13}C$ values of plants, hence, influencing animal tissues or feces when these plants are ingested (Lazzerini et al. 2019; Liu et al. 2007; Swap et al. 2004). For instance, more negative $\delta^{13}C$ values are often associated with water availability in a C_3-dominated semi-arid ecosystem (Liu et al. 2007; Swap et al. 2004), but no relationship is found between $\delta^{13}C$ values of C_4 vegetation and precipitation (Swap et al. 2004). Therefore, we cannot argue rainfall patterns and water availability across AEZ to influence the isotope values.

Besides, Codron, Codron, LeeThorp, et al. (2007) previously demonstrated in the study region that the majority of herbivory animal species do not change their diet across seasons. We assumed a shift towards a C_3-dominated diet as the season progresses towards wetter conditions reflecting isotopic variation among seasons. In view of the lack in seasonal effect, a C_4-dominated diet constant among seasons seems likely irrespective of farm type or AEZ, hence, contradicting our second hypothesis.

The δ^{15}N values in this study is in the range of those previously reported in other studies for cattle feces and hair tissues (Li et al. 2012; Männel et al. 2007; Schwertl, Auerswald, Schäufele, et al. 2005; Wrage et al. 2011). The δ^{15}N values of a consumer as shown by Ambrose et al. (1986) and further by Post (2002) reflect the protein concentration in the diet and are in general more enriched in feces (~ 3.4‰). The δ^{15}N values from the feces were influenced by AEZ and were marginally different by farm types across AEZ. Though there was very little variation in the δ^{15}N values of grass across AEZ, the mean δ^{15}N values of feces were generally higher for cattle in the arid warm zone (6.72‰), and across farm types, mean δ^{15}N values were higher for livestock-only farms (6.07 ‰). The values of the cattle hair were slightly more enriched (+ ~ 1‰), but showed no difference between AEZ and farm types. The high fractionation values between the nitrogen isotope and diets obtained in this study are therefore a reflection of higher δ^{15}N values of consumer tissues.

As mentioned by Gannes et al. (1997), the ^{15}N/^{14}N ratio in animal tissue increases as they are nutritionally stressed. It is argued that ^{15}N enrichment is a response to a negative energy balance (caused by nutrient deficit) that leads to body mass loss from recycling of muscle tissue causing enrichment of ^{15}N (Gannes et al. 1997; Sponheimer, Robinson, et al. 2003; Rysava et al. 2016; Crumsey et al. 2019; Oelze et al. 2020; Funck et al. 2020). Body mass loss due to forage deficit is an issue during feed gaps especially in the arid warm zone on livestock-only farms (Lamega et al. 2021). The absence of difference between seasons for the δ^{15}N values of hair might be explained by limited forage quality even during the growing season. Elsewhere, Moyo et al. (2012) reported satisfactory nutritive values of forage for grazing during the raining season. Therefore, feed gaps may not necessarily be linked only to the quantity of forage available for grazing, but also to the quality throughout the year.

3.6 Conclusion

Our results of the first uncontrolled dietary study among free-ranging cattle in the complex African mixed farming systems show that the rangeland with its C_4 plant composition is the main forage source even in the dry period. None of our initial hypotheses were confirmed. With respect to our first hypothesis, cattle in mixed-crop livestock farms show no different isotopic signature from cattle in livestock-only farms because forage sources consist of C_4 plants irrespective of farming system. Moreover, the availability of crop residues on mixed crop-livestock farms did not necessarily result in a lower percentage contribution of C_4 plants in the diet as compared to livestock-only. Regarding our second hypothesis, we found only little variation in the isotopic signatures among seasons. This result suggests that the cattle had not yet or generally only restricted access to C_3-based plant components in the wet season which would have served as likely explanator for seasonal differences. The variability in the isotope results of feces and hair could be attributed to the variability of potential feed resources, diet composition over time, and variation in farm practices. Such a variation could also be influenced by the extent of feed utilization due to climatic factors and availability based on resource endowment. Nevertheless, stable carbon and nitrogen isotopes can be an essential tool to investigate dietary composition as influenced by consumer's environmental conditions in relation to climate induced feed gaps. A more controlled research on the seasonal comparison of plant isotope across habitat is needed in an attempt to link intra-annual diet consumption to feed gaps.

3.7 References

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4

General discussion & Conclusion

As explained by Moore et al. (2009), feed shortages/gaps are caused by bio-economic factors and in complex farming systems such as the South African farming system, they may be linked to other important factors such as social factors (e.g. access and management of communal rangelands). It was important to investigate feed gaps in such a context – how they developed among farmers in the Limpopo province to facilitate livestock productivity and system resilience. Therefore, this thesis aimed first at understanding the specific factors that are associated with feed gaps in the study region while investigating farmers' current adaptation strategies. In a second step, biophysical data were used to link farmers' perceptions to the ongoing feed gap phenomenon. In doing so, this research will have a strong foundation to support site-specific strategies considering different farm types and distinct locations. Understanding the impacts of the large climate uncertainties on the farm components may help reduce further future sensitivity to feed gaps as compared to the current system.

4.1 What have we learnt from this study?[1]

The thesis covered the extensive farm survey involving the use of interviews in selected AEZ in the Limpopo province. The survey assesses the spatial and temporal availability of feeding resources among farmers that are either practicing livestock-only farming or mixed crop-livestock farming across the AEZ. This approach identified current management practices in relation to feed gaps. Moreover,

[1]Part of this chapter is included in the book chapter, Chapter 2 – which was accepted for publication

on-farm biophysical data (e.g. feces, cattle tail hair) were passed through isotopic analysis (δ^{13}C, δ^{15}N) to provide long-term and short-term information on the feeding resources. This approach was useful in assessing the dietary composition of the feeding resources across AEZ but also evaluate nutritional intake among the selected animals.

In chapter 1 (1.2), by using a combination of household survey, modelled seasonal rangeland biomass, and nutrient analysis of grazed biomass, we demonstrated that climate-induced feed gap risks may be dependent on vulnerability, hazard exposure, and the adaptive capacity of each farm. For instance, farmers that are located in more arid areas are more exposed to feed gaps due to limited rainfall. Moreover, a livestock farmer with limited access to additional feed may be more vulnerable than a farmer who engages in a mixed livestock-crop production with possible supplemental crop residues. By heavily depending on open communal rangelands that are already vulnerable to climatic variability, a resource-constrained livestock farmer may regularly face feed gaps. Despite the heterogeneity of the production systems, a sound assessment of the temporal pattern of the feed availability is a key entry point for any intervention strategies in response to seasonal feed gaps. It emerged from this chapter that, in many cases, resource unavailability prevents farmers to implement adequate coping strategies to reduce or cope with seasonal feed gaps. The modelled vegetation data were retrieved for the nearest neighbor sites of available climatic data. However, it is unlikely that vegetation dynamics differed significantly across the studied sites and the modelled rangeland sites. The evaluation of the shift in seasonal rangeland biomass corroborated with the perceptions of the farmers. This indicates the current conditions of communal rangelands in terms of the quantity of biomass available whereas the elemental nutrient results confirmed the poor quality during potential periods of feed gaps. Besides, a combination of many factors is definitely the root cause of livestock unproductivity in the rural farming context. These factors include small herd sizes with a lack of breeding objectives in the smallholder sector (Stroebel et al. 2011; Tavirimirwa et al. 2019), unavailability of feed (Descheemaeker et al. 2018; Mpofu et al. 2017); which could be linked to grazing area, and high stocking density (Tavirimirwa et al. 2019; Vetter et al. 2020), insufficient incentives (Bryan et al. 2009; Mubiru et al. 2018) and climate variability among others (Nardone et al. 2010).

The good results obtained from chapter two 2.2 in relation to the negative forage balance in the Limpopo Province, and possible degraded land-use types should be an urgent call for drawing adequate options. Nevertheless, a more reliable estimation of the forage balance for the province is far more complex. This chapter mainly used existing statistical data for maize production and crop residues coefficient (Statista 2021; Kutu 2012) to estimate the potential maize residues available. Moreover, the chapter did not solely consider rangelands (communal) for rural livestock production in the province nor did it reflect other livestock species/wild animals that are also important forage consumers. However, the results from this approach were consistent with the results from Avenant (2019) who calculated the carrying capacity of natural vegetation for the different provinces in South Africa. Apropos to this, it is essential to find measures to mitigate further feed gap impacts bearing in mind the already existing farmer's strategies and constraints (1.2). Clearly, there is a need to improve the feed-base system through important intervention policies and training, enabling farm households to successfully respond to the frequent occurrences of feed gaps (Mapiye et al. 2018; Godde, Boone, et al. 2020; Godde, Mason-DCroz, et al. 2021; Marandure et al. 2020). However, as previously stated, overcoming the frequent occurrences of feed gaps may prove to be difficult and complex as it is not only governed by biological factors, but also by farmers' socio-economic capacities. Though the variability in the supply of feed to livestock is linked to the variability in the rainfall patterns that restricts rangeland productivity, the vulnerability of communal livestock farmers to feed gaps may also depend on the adaptive capacities of rural communities (Godde, Mason-DCroz, et al. 2021). Therefore, the effects of feed gaps can highly be site-specific which should be considered.

It is also important to highlight the results of chapter three (3.2). Hair tissues contain dietary information and could serve as an archive of ecological information. Using the isotopic signature techniques on the collected samples of feces and hair tissues, we were able to provide information on the short-term and long-term diet composition of cattle in the study area. The chapter tests this technique on free-ranging cattle in a complex farming system. The complexity of the system showed variation in the C and N isotopic signatures. We argued that the variation reflects the long-term averages of diet accumulated in the tail hair, which were compared to the short-term averages of feces. Similar variations have previously been reported by Sponheimer et al. (2003). The exact detection of feed ingested among free-ranging cattle may be challenging because the current feed-base may exceed that recorded i.e. the extent of feed utilization due to climatic factors and availability at farm level. Nevertheless, the results were consistent with the previous chapters in relation to the occurrence of feed gaps by pointing at nutritional stresses due to less "protein-rich" feed for livestock across seasons.

4.2 Dealing with feed gaps

Any strategies designed to deal with either a regular or an irregular feed gap must be context-specific with direct and indirect effects on livestock production. Moore et al. (2009) proposed two main approaches to deal with the occurrence of feed gaps: tactical and strategical approaches. According to these authors, a tactical response is implemented when needs arise. For instance, a farmer could buy or sell livestock depending on the balance between the number of herd and the available feed. A tactical response could also involve the application of fertilizers to pastures to boost seasonal production in the rainy season. This approach is usually preferable for irregular feed gaps where the supply of feed is less predictable in terms of its magnitude and timing (Bell 2009). Such management aims at the provisioning of conserves obtained during times of excess feed supply. The advantages of tactical responses are that these can easily be implemented without changing the existing land-use or farming patterns and that opportunity costs are generally low in years when the tactical response is not executed. On the other hand, a strategic approach can be deployed for situations with regular feed gaps and requires structural adjustments to the livestock farming system. A strategical response involves the introduction of multi-year permanently available forage shrubs as a feed base and could be an option when we look at the protein deficit feed in the study area.

In a communal setup, a more efficient approach to alleviating feed gaps among resource-constrained livestock keepers in Limpopo should have benefits for the natural resources (e.g. rangelands). However, many approaches to improve the common grazing resources among livestock farmers through improved management have failed as demonstrated in other semiarid and arid areas (e.g. Tavirimirwa et al. (2019)). Nevertheless, insights from systems evaluation emphasize farming system flexibility as a prerequisite for risk adaptation (Thornton et al. 2015). Particularly in the smallholder South African context, in the light of the absence of effective rangeland governance, clear tenure policies, and entrenching inequalities in access to land and resources; smallholders' current drought responses are likely to continue. Policymakers need to have a sense of accountability and interest in co-framing the needs of smallholding livestock keepers. Managing the political framework, thus, begins with understanding and recognizing the concerns and importance of communal livestock for local food security, cultural value, and livelihood asset (Ainslie 2013). The need of strengthening the nutritional status of animals during seasonal feed gaps, through feed quality enhancement, may be achieved using combinations of different options.

Farmers in Limpopo may learn from the pastoralists in the dry areas of Burkina Faso that deal with feed gaps by employing conservation methods such as building up fodder bundles from mowing grasses or plants when they are plentiful (Ouédraogo et al. 2021). The success of any interventions to alleviate feed gaps on smallholder farms is highly dependent on specific local conditions (Balehegn et al. 2020), which cannot be overstated. Moreover, as argued by Balehegn et al. (2020), we need to also consider other related challenges that face smallholder farmers such as market access for selling stock, improved water or irrigation schemes, improved livestock breeding techniques, and diseases, all of which could reduce the effects of feed gaps and improved farm profitability. Also, high sensitivity to feed gaps can also be reduced when appropriate financial opportunities are created for smallholder farmers who could purchase livestock feed to improve the production system thus reducing vulnerability. Furthermore, there is also the need to develop proper research objectives, and set up necessary experiments (surveys, field trials, modelling exercises) as suggested by Garrett et al. (2017) that are site and context-specific to the subject of seasonal feed gaps.

In fact, proper measurement of seasonal herbaceous biomass on communal rangelands will further help understand the distribution of feeding patterns. Such a measurement could prove critical in evaluating the long-run effect of climate variability on the livestock systems but also integrating neglected C_3 species in the cool-winter season in the province. In agricultural systems, a wide range of cover crop species have been selected and grown over the past decades (see (Valbuena et al. 2012; Ngome et al. 2011)). Cover crops are generally grown between two main cash crops to improve production efficiency by decreasing nutrient losses thereby increasing the agronomic and environmental benefits. With a frequent occurrence of climate uncertainties in the Limpopo province, testing potential but neglected cover crops such as *Secale cereale* L., *Vicia villosa* L., *Brassica napus* L for the provision of additional forage may be necessary. In effect, agro-system modelling approaches may be useful in linking the complex interactions of plants (here forage crops), soil, livestock productivity and economic performance under given environmental conditions. Therefore, further livestock or mixed crop-livestock research in this context should consider assessing risks and feed-based balance strategies perhaps through a whole-farm modelling approach.

4.3 References

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Contributions to Chapters

The first essay of the Ph.D (1.2) is published as:

Lamega, S. A., Komainda, M., Hoffmann, M. P., Ayisi, K. K., Odhiambo, J. J. O., & Isselstein, J. (2021). It depends on the rain: Smallholder farmers' perceptions on the seasonality of feed gaps and how it affects livestock in semi-arid and arid regions in Southern Africa. *Climate Risk Management, 34, 100362.*

- **Sala Lamega**: Conceptualization, Data curation and analysis, Project Administration, Writing - original draft, review & editing.
- **Martin Komainda**: Writing - review & editing.
- **Munir Hoffmann**: review & editing.
- **Kingsley Ayisi**: Project administration, review & editing, supervision.
- **Judes Odhiambo**: review & editing
- **Johannes Isselstein**: Conceptualization, Data curation, Funding Acquisition, Project administration, Supervision, Writing - review & editing.

I would like to also thank **Kabisheng Mabitsela** for his support during Data curation and the anonymous reviewers for providing useful feedback on the first submitted draft. Many thanks to Dr. Simon Scheiter for providing the simulated vegetation data for the study locations.

The second essay of the Ph.D (2.2) is accepted for publication as:

Lamega, S. A., Klinck, L., Komainda, M., Odhiambo, J., Ayisi, K., Isselstein, J. (accepted in June 2022): Feed gaps among cattle keepers in semiarid and arid southern African regions: A case study in the Limpopo province, South Africa. Eds: Graham von Maltitz, Guy F Midgley, Jennifer Veitch, Christian Brümmer, Reimund Rötter, Finn Viehberg, Maik Veste. in Sustainability of southern African ecosystems under global change: Science for management and policy interventions* *Ecological Studies, Publisher: Springer Cham Series E-ISSN: 2196-971X*

- **Sala Lamega**: Conceptualization, Data curation and analysis, Project Administration, Writing - original draft, review & editing.
- **Leonhard Klinck**: Data curation and analysis, writing of original draft.
- **Martin Komainda**: Writing - review & editing.
- **Kingsley Ayisi**: Project administration, review & editing, supervision.
- **Judes Odhiambo**: review & editing
- **Johannes Isselstein**: Conceptualization, Data curation, Funding Acquisition, Project administration, Supervision, Writing - review & editing.

Again, many thanks to **Kabisheng Mabitsela** and the Risk and Vulnerability Science Center for enabling a conducive environment for the field work|Data curation in 2018 (Klinck) and 2019 (Lamega). My gratitude to the Editors of the book for their support in the preparation and submission of this chapter.

The third essay of the Ph.D (3.2) is under revision and was submitted as:

Lamega, S. A., Komainda, M., Ayisi, K. K. & Isselstein, J. Tracking the feed gap using stable isotopes in complex South African mixed livestock farming systems *in revisions, Rangeland Ecology & Management, submitted in April 2022*

- **Sala Lamega**: Conceptualization, Data curation and analysis, Project Administration, Writing - original draft, review & editing.
- **Martin Komainda**: data analysis, review & editing.
- **Kingsley Ayisi**: Project administration, review & editing, supervision.
- **Johannes Isselstein**: Conceptualization, Data curation, Funding Acquisition, Project administration, Supervision, Writing - review & editing.

Many thanks to the Colleagues from the Competence Center for isotope analysis (Kosi) of the University of Göttingen. I also appreciate the support from Barbara Hohlmann during the data processing stage of the hair samples. The linguistic revisions from Dr. Alan Hopkins are duly acknowledged.

All Scientific Contribution

- 1– **Lamega, S. A.**, Komainda, M., Hoffmann, M. P., Ayisi, K. K., Odhiambo, J. J. O., & Isselstein, J. (2021). It depends on the rain: Smallholder farmers perceptions on the seasonality of feed gaps and how it affects livestock in semi-arid and arid regions in Southern Africa. *Climate Risk Management, 34, 100362.*

- 2– Roetter, R. P., Scheiter, S., Hoffmann, M. P., Pfeiffer, M., Nelson, W. C., Ayisi, K., **Lamega, S. A.**, ... & Erasmus, B. (2021). Modeling the multifunctionality of African savanna landscapes under global change. *Land Degradation & Development, 32(6), 2077-2081*

- 3– **Lamega, S. A.**, Klinck, L., Komainda, M., Odhiambo, J., Ayisi, K., Isselstein, J. (2022, accepted): Understanding the occurrences of feed gaps among cattle keepers in semiarid and arid southern African regions: A case study in Limpopo. Book chapter in *Sustainability of southern African ecosystems under global change: Science for management and policy interventions Ecological Studies, Publisher: Springer Cham Series E-ISSN: 2196-971X*

- 4– **Lamega, S. A.**, Komainda, M., Hoffmann, M. P., Ayisi, K. K., Odhiambo, J. J. O., & Isselstein, J. (2022). Closing Feed gaps by winter forage production in Limpopo: what is the potential?“, *“XXIV International Grassland Congress/XI International Rangeland Congress proceedings”*

- 5– **Lamega, S. A.**, Komainda, M., Hoffmann, M. P., Ayisi, K. K., Odhiambo, J. J. O., & Isselstein, J. (2022). Assessing Feed gaps on smallholder livestock farms in Limpopo: Production System and Coping Strategies”, *“XXIV International Grassland Congress/XI International Rangeland Congress proceedings*

- 6– Scheiter, S., Behn, K., Pfeiffer, M., Rötter, R., Twine, W., Ayisi, K., **Lamega, S.**, Isselstein, J., Linstädter, A.(2022). Feed gaps and rangeland degradation: Managing smallholder farming systems to reduce feed gaps”, *“Sallnet policy brief: at uni-goettingen.de”*

 4. Scientific contribution

- 7– **Workshop course lead (2022)**, “Carrying capacity of the arid and semi-arid Limpopo rangelands in winter – Management options”, Polokwane, June 2022

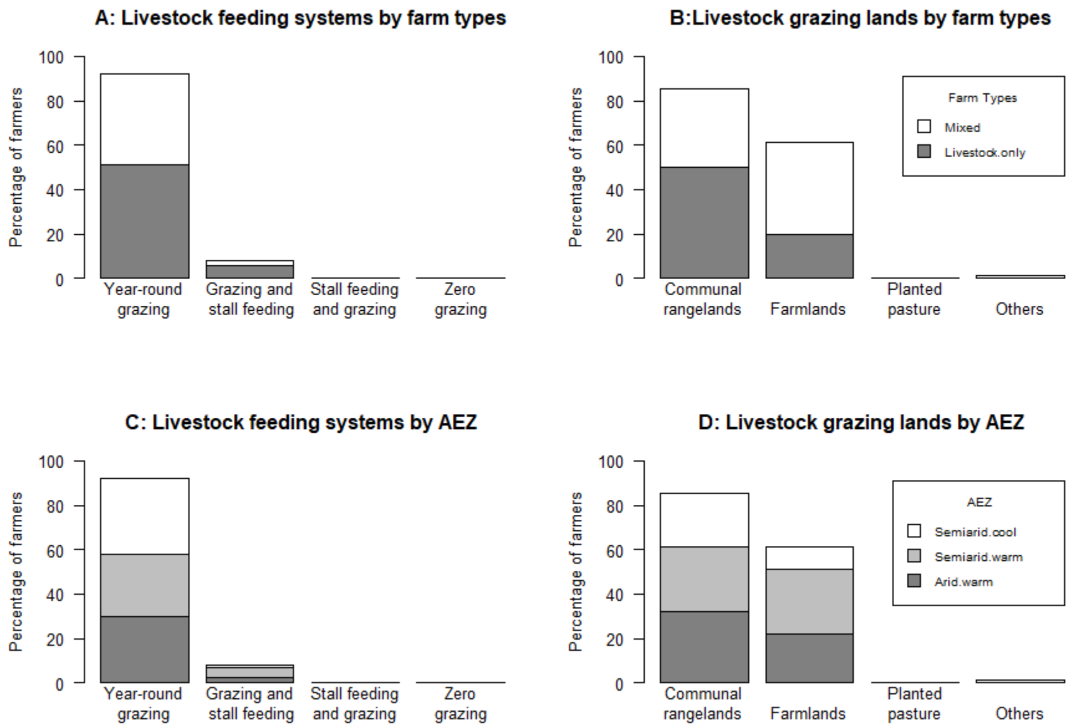
- 8– **Lamega et al** “Landscape Conference (2021)”, “Dealing with seasonal livestock feed gaps in smallholder mixed-farming systems: A case study from Limpopo – online (poster presentation)”

- 9– **Lamega et al** “Tropentag Conference (2018)”, “Soil Fertility Gradients in the Smallholder Cropping Systems in Limpopo Province, South Africa. Ghent, Belgium” Poster presentation

Appendices

Appendices A - E

App A: Cattle feeding regime (left) across the surveyed farms (n=90) and options for grazing lands for cattle farmers



App B $\delta^{13}C$ and $\delta^{15}N$ mean and standard deviation (SD) values of possible feed sources during the dry season across agro-ecological zones. Grass, CR=crop residues, FS=feed supplements, TL= tree leaves.

AEZ	Diets	N	$\delta^{13}C$	$\delta^{15}N$
Arid warm	Grass	10	−14.74 (0.92)	2.49 (1.39)
Semi-arid cool	Grass	26	−14.72 (1.36)	1.93 (1.50)
Semi-arid warm	Grass	10	−14.03 (1.08)	4.89 (1.88)
Arid warm	CR	5	−13.53 (0.29)	4.01 (0.86)
Semi-arid warm	CR	10	−14.56 (1.41)	3.29 (1.78)
Arid warm	FS	7	−17.99 (3.94)	2.15 (0.81)
Semi-arid cool	FS	12	−16.09 (2.69)	1.56 (1.36)
Semi-arid warm	FS	1	−12.35 –	2.77 –
Arid warm	TL	10	−27.10 (0.89)	2.31 (0.72)

App C Output of linear mixed effects models for the isotopic composition of cattle hair. Numerator df: degrees of freedom, dendf: denumerator df, AEZ: agro-ecological zones

Term			$\delta^{13}C$	
	numdf	dendf	F-value	P-value
AEZ	1	31	146.7	<0.01
Season	1	95	0.0	0.88
Farm type	1	31	0.2	0.66
AEZ x Season	1	95	26.5	<0.01
AEZ x Farm type	1	31	0.11	0.74
Season x Farm type	1	95	3.68	0.06
AEZ x Season x Farm type	1	95	1.8	0.19
Term			$\delta^{15}N$	
AEZ	1	31	0.07	0.79
Season	1	95	0.89	0.35
Farm type	1	31	1.79	0.19
AEZ x Season	1	95	0.02	0.88
AEZ x Farm type	1	31	1.06	0.31
Season x Farm type	1	95	0.82	0.37
AEZ x Season x Farm type	1	95	0.04	0.85

App D Output of the analysis of covariance using least square fit between $\delta^{13}C$ and $\delta^{15}N$ of feces and hair as affected by agro-ecological zones (AEZ). Numerator df: Degrees of freedom, AEZ: agro-ecological zone.

Term			
	numdf	F-value	P-value
$\delta^{15}N$	1	39.921	<0.01
AEZ	1	15.771	<0.01
$\delta^{15}N$ X AEZ	1	2.710	0.10
$\delta^{13}C$	1	449.90	<0.01
AEZ	1	133.09	<0.01
$\delta^{13}C$ X $\delta^{15}N$	1	1.630	0.21

App E Fractionation values between selected feed resources and the isotope values of feces and hair/SD across different agro-ecological zones.

Agro-ecological zones	DC feces - Grass	DC feces - CR	DC feces - feed supplements	DC feces - TL	N
Arid warm	−5.92	−7.14	−2.68	6.43	60
	(2.84)	(2.84)	(2.84)	(2.84)	
Semiarid cool	−2.81	−2.97	−1.44	9.57	60
	(1.67)	(1.67)	(1.67)	(1.67)	
Semiarid warm	−2.89	−3.05	−1.52	9.49	58
	(1.51)	(1.51)	(1.51)	(1.51)	
Agro-ecological zones	DN feces - Grass	DN feces - CR	DN feces - feed supplements	DN feces - TL	N
Arid warm	4.42	2.90	4.76	4.60	60
	(1.76)	(1.76)	(1.76)	(1.76)	
Semiarid cool	0.33	1.93	3.66	2.91	60
	(1.36)	(1.36)	(1.36)	(1.36)	
Semiarid warm	1.19	2.79	4.52	3.77	58
	(0.92)	(0.92)	(0.92)	(0.92)	
Agro-ecological zones	DC hair - Grass	DC hair - CR	DC hair - feed supplements	DC hair - TL	N
Arid	−4.54	−5.75	−1.29	7.82	58
	(1.80)	(1.80)	(1.80)	(1.80)	
Semiarid	1.25	1.09	2.62	13.63	78
	(1.71)	(1.71)	(1.71)	(1.71)	
Agro-ecological zones	DN hair - Grass	DN hair - CR	DN hair - feed supplements	DN hair - TL	N
Arid	4.84	3.33	5.19	5.02	58
	(0.80)	(0.80)	(0.80)	(0.80)	
Semiarid	2.84	4.44	6.18	5.43	78
	(1.08)	(1.08)	(1.08)	(1.08)	

THESIS DECLARATION

I hereby confirm that I have written this doctoral thesis independently, that I have not used other sources or facilities other than the ones mentioned, that I have not used unauthorized assistance and that I have not submitted this thesis previously in any form for another degree at any university or institution.
I declare that I have no known competing financial interests or personal relationships that could have appeared to influence the work of this thesis.

Sala Alanda Lamega
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