Targeting new climate-resilient feeds and forages in the smallholder mixed farming systems of East Africa

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Declaration

I, Mercy Fakude, hereby declare that the master's thesis titled "Targeting new climate-resilient feeds and forages in the smallholder mixed farming systems of East Africa" is my original work. All other sources of data and information are acknowledged. I declare that this research work has never been submitted to any other university for grading purposes other than the National University of Ireland Galway.

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List of abbreviations

CO_2	Carbon dioxide
DMP	Dry Matter Production
ENSO	El Niño-Southern Oscillation
FEAST	Feed Assessment Tool
FACE	Free-Air Carbon dioxide Enrichment
FAO	Food and Agricultural Organization
GIS	Geographic Information System
IPCC	The Intergovernmental Panel on Climate Change
LGP	Length of Growing Period
LTU	Livestock Tropical Unit
NPP	Net Primary Production
PET	Potential Evapotranspiration
WUE	Water-use efficiency

Abstract

The availability of feed resources all year round is perceived as a prerequisite to improving livestock productivity, thereby promoting sustainable livelihoods. The mixed farming systems of East Africa require feed interventions which will maintain feed availability all year round to improve livestock productivity. However, introducing feed interventions requires due attention to the demand side of the interventions and the context of the farming system.

This study focused on two key feed constraints and two adoption factors in the mixed farming system of East Africa. The two feed constraints of focus were feed quantity and seasonal feed scarcity, and the two adoption factors were land availability and water availability. Four maps showing feed quantity, seasonal scarcity, land availability and water availability were produced using geographic information system (GIS). Thereafter, the four maps were overlaid to produce a single map showing 16 domains of feed availability and feed adoption factors for Kenya, Tanzania, and Uganda. From the sixteen (16) domains, four (4) highly contrasting domains were selected. The selected domains were ranked from very low to very high feed availability, with domain 16 representing very low, domain 7 representing low, domain 4 representing medium and domain 2 representing very low. These four domains were found in Kenya and Tanzania indicating variations in feed availability within the counties. However, the only domain found in Uganda was domain 16 which indicates very low feed availability and 12 months of feed scarcity. Predictions of suitable feed interventions were made based on the domain properties using the FEAST/Techfit logic.

Keywords: Feed quantity, Seasonal scarcity, Land availability, Water availability, Domains

1. Introduction

Agricultural systems in low and middle-income countries are currently faced with tremendous challenges which are predicted to increase in the future. These challenges include the population, which is projected to grow globally from the current 7.3 billion to 9.7 billion in 2050 and further reaching 11.6 billion in 2100 (Kc and Lutz, 2017). At the same time, about 800 million people are currently food insecure (Fischer et al., 2002). Most of this growth in population is expected to emerge in Africa, where agriculture is a pillar of sustainable livelihoods and incomes (Misselhorn et al., 2012). Therefore, the agricultural system needs to double its productivity by 2050 to meet the demands of this populace and to maintain food security (Tscharntke et al., 2012). In addition, improved standards of living and rapid urbanization in developing countries have resulted in a substantial shift in diets, thereby leading to a greater demand for livestock products (Godfray et al., 2010, Thornton et al., 2009). The population is moving from the consumption of basic staples to the consumption of more diverse meat-based diets (Kearney, 2010). Therefore, efforts to increase production of livestock products such as meat and milk to satisfy the increased demand will result in a higher demand for feeds and forages for livestock. However, the major threat is that this increase in demand for feed resources for livestock is occurring in the setting of climate change.

Climate change will continue to alter rainfall distribution, lead to temperature increases and increase the occurrence of droughts and floods (IPCC, 2012). These climate variabilities will negatively impact livestock productivity by decreasing the quality and quantity of forage, thereby affecting the health and nutrition of livestock significantly (Fischer et al., 2002).

Smallholder farmers in Sub-Saharan Africa, particularly East Africa are vulnerable to the negative impacts of climate change, primarily because they are in the tropics, their livelihoods and incomes depend on the productivity of livestock and they lack resources and policies which enhance their capacity to adapt to climate change (Morton, 2007, Bryan et al., 2013). Moreover, most of the adaptation methods assume a one-size fits all approach or a top-down approach, whereas different farmers in different geographic locations require varying adaptation methods. Therefore, farmers need adaptation methods which meet their specific requirements and context to reduce vulnerability and build resilience.

The objectives of the study were to:

1. Evaluate the effects of current climate conditions on forage availability and quantity in the smallholder mixed farming systems.
2. Assess the effects of the current climate on seasonal availability of forage in the smallholder mixed farming systems.
3. Determine areas vulnerable under current climate conditions.
4. Recommend feed interventions suitable to address feed gaps under current climate conditions based on their match to system condition using the FEAST/Techfit sheets.

2. Literature Review

Introduction

A significant increase in livestock productivity is necessary in order to meet the growing demand for meat and dairy products. Therefore, an increase in the production and availability of high quality feeds and forages is crucial to enhance livestock productivity and improve the livelihoods of farmers in areas such as East Africa (Herrero et al., 2010). The population of East Africa, particularly Kenya, has been recording an exponential increase from the 1950's and this increase is projected to continue up until 2050 and beyond (Figure 1). The World Bank has reported that most of the population will become concentrated in urban areas (Figure 2), which is an indication of urbanization and an increase in incomes (AASR, 2016). As the population grows and moves to urban areas, the FAO predicts (Figure 3) that consumption of livestock products will also increase (FAO, 2014). Therefore this calls for smallholder farmers in mixed farming systems to increase the production of feeds and forages to enhance the health and nutrition of livestock**,** thereby meeting the demand for meat, milk, and eggs whilst increasing their incomes (Kiptot et al., 2015). As there is a need to increase the production of feeds and forages, climate change, on the other hand, continues to negatively impact livestock productivity through the scarcity of feeds and forages, especially in the dry season (Nardone et al., 2010). The scarcity of feeds and forages is a challenge that is inevitable and propels the need to target new climate-resilient feed resources to improve livestock productivity.

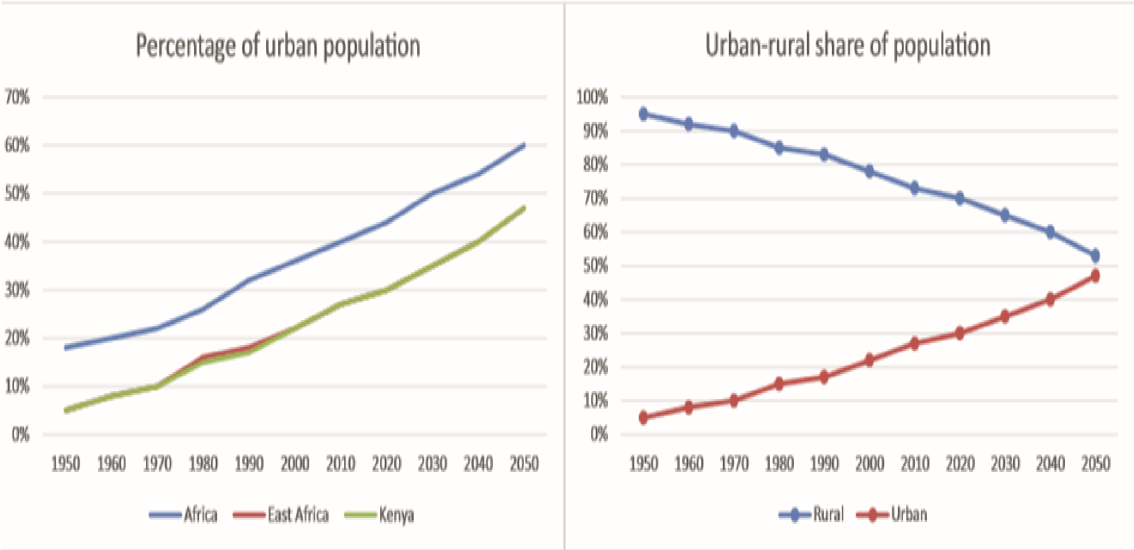

Figure 1: Projections of urban population and urban-rural population split

Source: (World Bank, 2016)

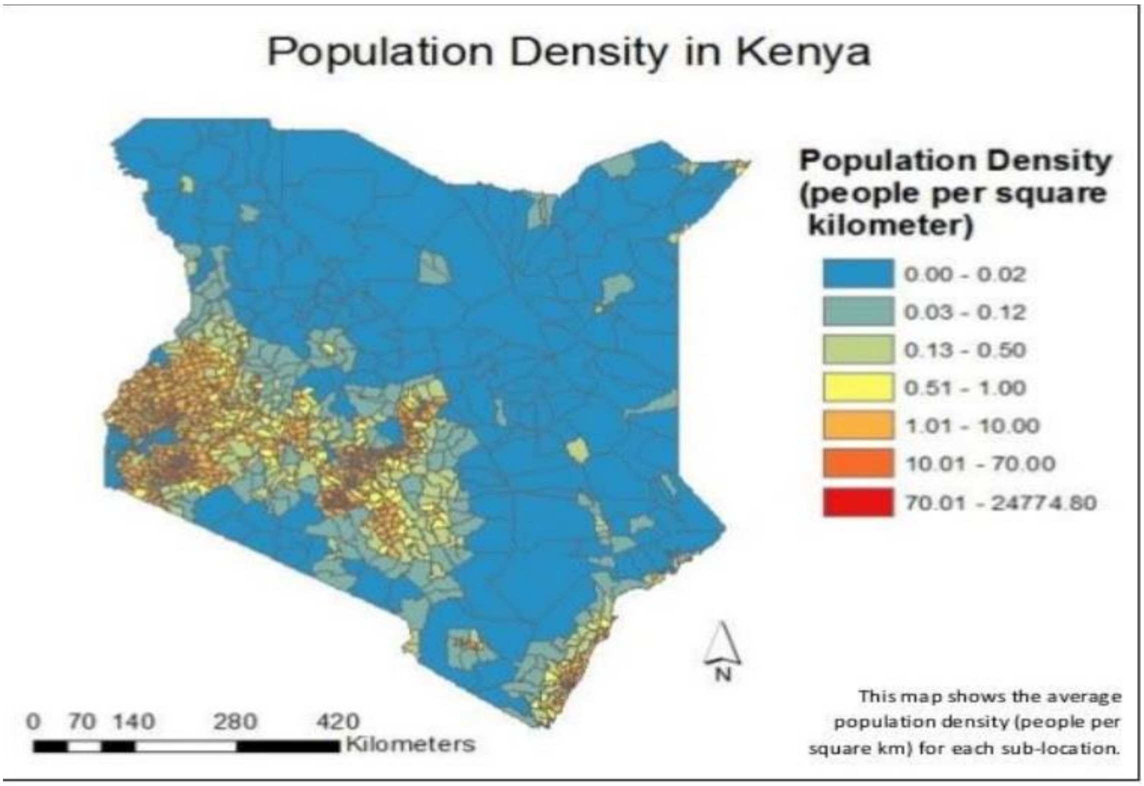

Figure 2: Population density in Kenya

Source: (Based on Kenya National Bureau of Statistics, 2009) (World Bank 2016)

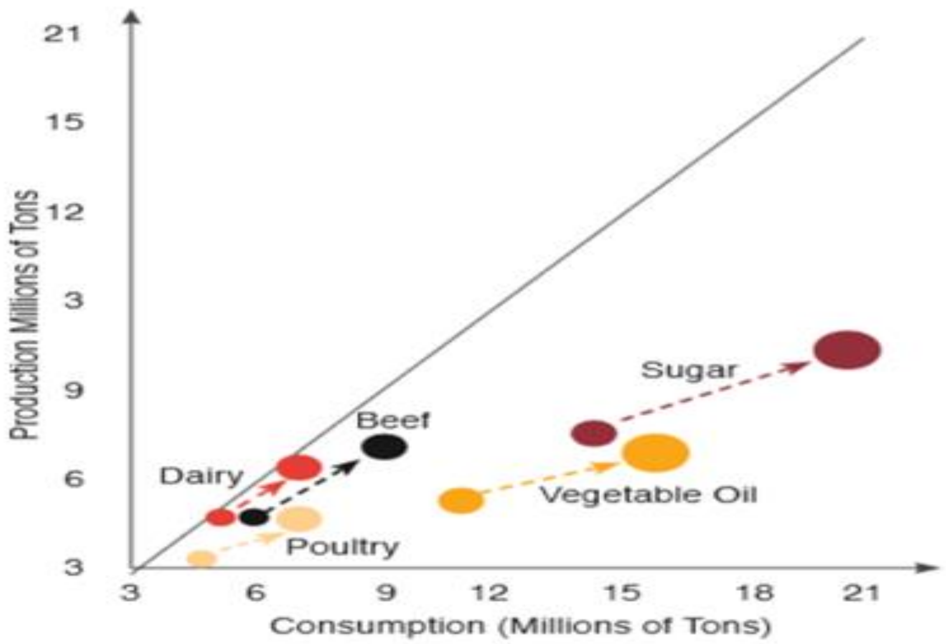

Figure 3: Projected trends in Sub-Saharan Africa commodity production and consumption

Source: (FAO, 2014) (Africa Agriculture Status Report, 2016

2.1. Impact of climate change on livestock systems

Forage crops are vital for livestock productivity, nutrition, and health. However, climate change impacts livestock systems through factors that determine the quality and quantity of forage crops (Thornton et al., 2009). These factors include atmospheric CO_2 concentration, precipitation, and temperature.

2.1.1. Atmospheric carbon dioxide (CO2) concentration on forage crops

The atmospheric concentration of CO_2 is rising from a pre-industrial value of 280 ppm, has now topped 400 ppm and has been rising by about 2 ppm per year for the last decade. These atmospheric CO_2 levels are projected to increase further in the coming years (Ciais et al., 2014). The effect of the increasing CO_2 concentration on plants is not clear-cut as research shows a wide variation in the long-term response of plant species (Lüscher et al., 1997). It should be noted that the rate of photosynthesis is not only regulated by CO_2 but there are other environmental factors such as nutrient levels and water availability which interact with CO_2 concentration to influence plant growth (Kramer, 1981, Kirschbaum, 1994). CO_2 plays a primary role in photosynthesis, thereby stimulating crop growth and yield. As CO_2 levels are projected to rise, there is a need to review the correlation that may exist between crops and rising CO_2 levels in combination with water availability and other climatic stresses as this may affect the productivity and availability of forage crops.

Various plants respond to CO_2 differently depending on their photosynthetic pathways. Thus, plants such as potatoes, sweet potatoes, wheat, rice, and legumes such as alfalfa possess a C3 pathway and are reported to be highly responsive to CO_2 concentrations given sufficient water and nutrients (Poorter, 2003). Plants such as maize, sorghum, millet, sugarcane are instead reported to be less responsive to CO_2 concentrations (Brown and Byrd, 1993, Kim et al., 2006). CO_2 substantially increases herbage growth, dry matter production and yield in C3 species but early research reported this effect to be minimal in C4 species (Ehleringer et al., 1997). Thus this may shift the suitability of some forage species and lead to changes in pasture composition such as an imbalance in the ratio of grass and legumes (Thornton et al., 2009). However, tropical grasses such as Rhodes grass, Napier grass, and Brachiarra grass use the C4 pathway and are reported to be highly responsive to elevated CO2 (Ghannoum et al., 2000). In both C3 and C4 plants, CO_2 enrichment causes decreases in stomatal conductance and transpiration thereby improving water-use efficiency (Lawlor and Mitchell, 1991), this encourages increased crop yield in conditions of mild water stress (Thornton et al., 2009). Supporting this, Olesen and Bindi (2002) reported that the response of plants to high concentrations of CO_2 enhances the efficient use of resources such as water, light, and nutrients in both C3 and C4 species. Downing et al. (2000) further recorded that water use efficiency (WUE) in wheat has been found to increase by about 50 to 60% with the doubling of current CO_2 concentration. Similarly, Drake et al. (1997) reported that the doubling of CO_2 concentration resulted in an average reduction of 20% of stomatal conductance. Taken together, this information suggests that the changes in the atmospheric CO_2 concentration may have a positive impact on forage crops which possess the C3 pathway. The relative effects of CO_2 concentration on wheat grain yield are shown in Figure 4 (Drake et al., 1997).

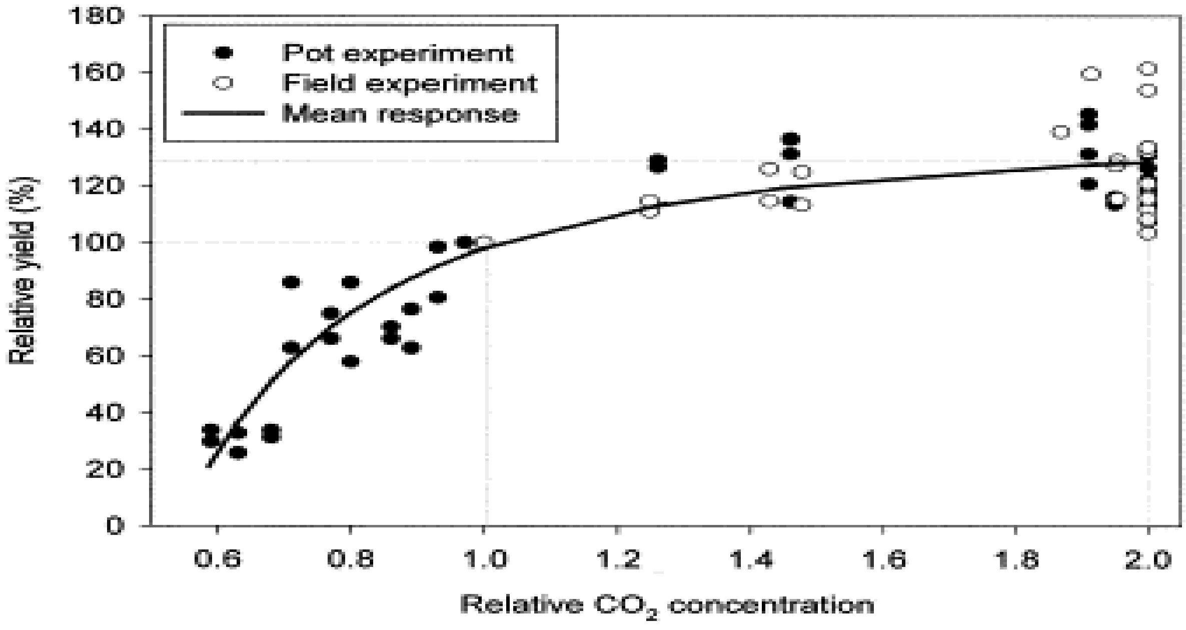

Figure 4: Effects of CO2 concentration on wheat grain yield under experimental conditions

Taken from (Downing et al., 2000).

Furthermore, research conducted earlier generally showed that C4 plants will not respond substantially to elevated CO_2 conditions (Ehleringer et al., 1997). However, recent studies based on FACE have reported the opposite (Reich et al., 2018, Wang et al., 2011). Walker et al. (1999) reported an increase in biomass of C4 grasses which were subjected to less intensive cutting treatment under CO_2 enrichment, while grasses under intensive cutting treatment were unresponsive. These findings not only show a positive relationship between CO_2 and growth but also reveals the major role which can be played by grazing management in increasing current and future quantity of forage crops under elevated atmospheric CO_2 levels. A review of responses of wild C3 and C4 Poaceae to elevated atmospheric CO_2 reported an increase in leaf biomass and leaf area, with a total biomass of 33% and 44% for C3 and C4 species respectively. Furthermore, an increase in tillering was observed in C3 and an increase in leaf area on C4 (Crush and Rowarth, 2007, Wand et al., 1999). Similarly, Xie et al. (2015) reported an increase in maize plant height, kernel yield per ear and an increase in WUE under elevated CO_2 levels. In agreement, Owensby et al. (1997) reported a significant increase in above-ground biomass in the C4 species of a tallgrass prairie which was subjected to elevated CO_2 and this increase in biomass was attributed to the ability of C4 species to mitigate water loss under elevated CO_2 during a dry year. These findings indicate the tolerance of C4 grasses to drought under high CO_2 levels and suggest that C4 grasses may thrive in the drought periods caused by climate change. However, elevated CO_2 levels reduced leaf N content. Similarly, Milchunas et al. (2005) reported a decrease in the crude protein yield of *B. gracilis* which is a C4 species and an increase in the crude protein yield of *S. comata* which is a C3 species. Milchunas et al. (2005) further reported that continued drought conditions under elevated CO_2 reduced fiber yields of *S. comata* more than that of *B. gracilis*. This is an indication that the increasing atmospheric CO_2 levels are most likely to affect livestock production through reducing forage quality, thereby altering species composition. The mean total biomass production under elevated and ambient CO_2 is shown in Figure 5 (Owensby et al., 1997).

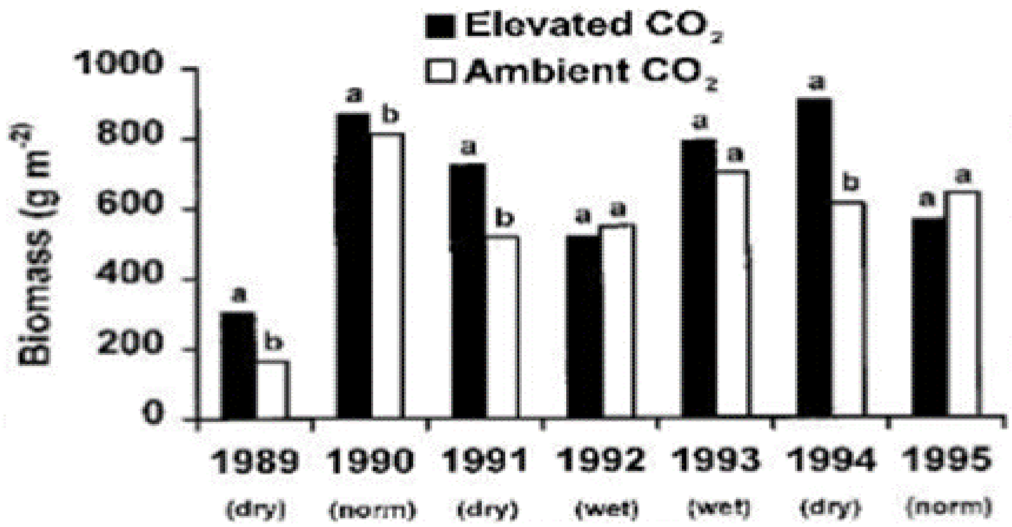

Figure 5: Mean total above-ground biomass for native tallgrass prairie exposed to elevated and ambient CO2 for the indicated years

2.2. Impact of climate change on temperature and rainfall distribution in relation to crop-livestock productivity

A range of climate models show median temperature increases between 3 °C and 4 °C in Africa by the end of the 21st Century (Bryan et al., 2013, Wolfram and David, 2010). In agreement with this, various authors have reported variabilities in temperature and precipitation distribution and intensity, especially in Sub Saharan Africa (Kotir, 2011, Hendrix and Glaser, 2007). The rainfall pattern in SSA is influenced by large-scale intra-seasonal and inter-annual climate variability including occasional El Niño-Southern Oscillation (ENSO) events in the tropics which result in increased frequency of extreme weather events such as droughts and floods. Though the interaction between climate change and ENSO is not clearly understood but reports show that climate change will largely influence the way in which ENSO functions in increasing occurrences of floods, droughts, and rainfall variabilities in future (Sheffield and Wood, 2008, Field, 2012). Eastern equatorial Africa experiences a dominant ENSO influence in the short rainy season during October to November (Kotir, 2011). ENSO is associated with reduced rainfall and high temperatures in this region, and the influence of climate change on ENSO may increase these climate variabilities. Therefore, expected changes in rainfall distribution and temperature caused by the influence of climate change on ENSO will have a substantial impact on crop and livestock productivity as they affect the length of the crop growing season, crop growth, potential crop yield and soil water availability (Porter and Semenov, 2005), livestock health and nutrition (Thornton et al., 2007).

As these climatic variabilities are expected to shift length of the growing period, shifts in the ranges of crop suitability, weeds, insects, and diseases are expected. These shifts may also risk feed and food availability, accessibility, utilization and stability (Kotir, 2011). However, parts of the tropical highlands where cool temperatures constrain crop growth will benefit from the rising temperature as they likely enhance crop growth (Thornton and Herrero, 2014). Therefore, changes in rainfall distribution and increases in temperature and drought occurrences may shift the suitability of forages and decrease feed availability in some areas. Over and above all, suitability of forage species and feed availability will depend on the optimal temperature the forage species require for growth and reproduction. Climate change may lead to a decline of forage species which require low temperatures and extended periods of rainfall, thereby increasing the availability of feeds which can thrive under high temperatures and erratic rainfall.

2.3. Impact of climate change on mixed farming systems

Mixed farming systems are systems in which crops and livestock are integrated on the same farm, they are also termed mixed crop-livestock farming systems (Thornton and Herrero, 2014). In these systems, crops sustain livestock productivity by providing feed in a form of crop residues, while livestock provides inputs such as manure and traction for subsequent crops (Duncan et al., 2016). Kruska et al. (2003b) defined the mixed system as “a livestock system in which more than 10 percent of the dry matter fed to animals comes from crop by-products, stubble or more than 10 percent of the total value of production comes from non-livestock farming activities”. There are two types of mixed system and these are:

i. Rainfed mixed farming systems - these are mixed systems in which more than 90% of the value of non-livestock farm production comes from rainfed land use.
ii. Irrigated mixed farming systems, these are mixed systems in which more than 10% of the value of non-livestock farm production comes from irrigated land use (Kruska et al., 2003a).

The mixed systems are a source of income for people in the developing world and they play a substantial role in enhancing food security as they provide most of the staples and feed resources and they are reported to produce 90 percent of the world’s milk supply and 80 per cent of the meat from ruminants (Herrero et al., 2013a). Changes in the climate affect smallholder mixed farming systems through increasing or decreasing the length of growing period (LGP). The length of the growing period is significant to production systems as it determines the duration in which cropping is possible, thereby affecting the spatial distribution of crops (Vrieling et al., 2013). Thornton et al. (2009) defined LGP as “the period in days during the year when rainfed available soil moisture supply is greater than half the potential evapotranspiration (PET)”. Different forage species found in the mixed systems require different LGP, hence varying species occur in different agro-ecological zones. Kruska et al. (2003b) and Thornton et al. (2009) used the systems classification method of (Seré et al., 1996) which uses LGP to classify agro-ecological zones as the LGP determines the type of agro-ecological zone and forage suitability. The categories resulting from the systems classification method are as follows:

- arid/semi-arid is characterized by a length of growing period that is less than or equal to 180 days.
- humid/sub-humid is characterized by a length of growing period greater than 180 days.
- tropical, with a daily mean temperature, during the growing period, of between 5 and 20 °C.
- temperate, is characterized by one or more months with monthly mean temperature, corrected to sea level, below 5°C.

As climate change will cause a change in the LGP, this will also cause a shift in these agro-ecological zones leading to a complete change in forage suitability (Kurukulasuriya and Rosenthal, 2013). Thornton et al. (2002) showed that a decrease or an increase in the LGP will result in a movement of the boundary for growing forage species such as maize. The shift in LGP may present both opportunities and risk. For instance, Thornton et al. (2002) showed that the southern parts of Kenya and the northern parts of Tanzania were not suitable for maize cropping in the year 2000 but, an increase in the LGP in 2050 is predicted to be parallel to a reduction in rainfall variability and this will support the cropping of maize as a fodder crop, thereby presenting an opportunity for farmers to have adequate livestock feed. In contrast, some parts of Tanzania, Ethiopia, and Uganda were suitable for maize cropping in the year 2000 but, a decrease in LGP is predicted to completely phase out the suitability of maize, leaving a high need of feed resources (Thornton et al., 2002). Furthermore, higher temperatures in higher latitudes will increase the growing season and expand crop suitability. However, in lower latitudes, higher temperatures are expected to constrain forage production (Kurukulasuriya and Rosenthal, 2013). In agreement, Washington and Hawcroft (2012) reported a geographic expansion in the suitability of cassava while sweet potato showed a decrease in suitability in the East African region under warmer temperatures. The expansion of cassava suitability may be attributed to its nature of requiring higher temperatures for growth. Therefore, this implies that cassava may be an attractive feed option under climate change. Similarly, Odira (2016) reported an expansion in the suitability area of sugarcane in western Kenya in 2050 under climate variabilities. Therefore, as it is projected that the quality of feeds will reduce under climate change, sugarcane in the form of molasses may be an attractive feed option to supplement feed quality. Taken together, this information suggests that farmers in mixed farming systems are most likely to build resilience through the adoption of feed options which their suitability will fall within the cropping boundary and positively respond to the high temperatures. Expected changes reported by Thornton et al. (2002) in the length of the growing period are shown in *Figure 6*. Expected movement of cropping boundary caused by climate change is shown in *Figure 7*.

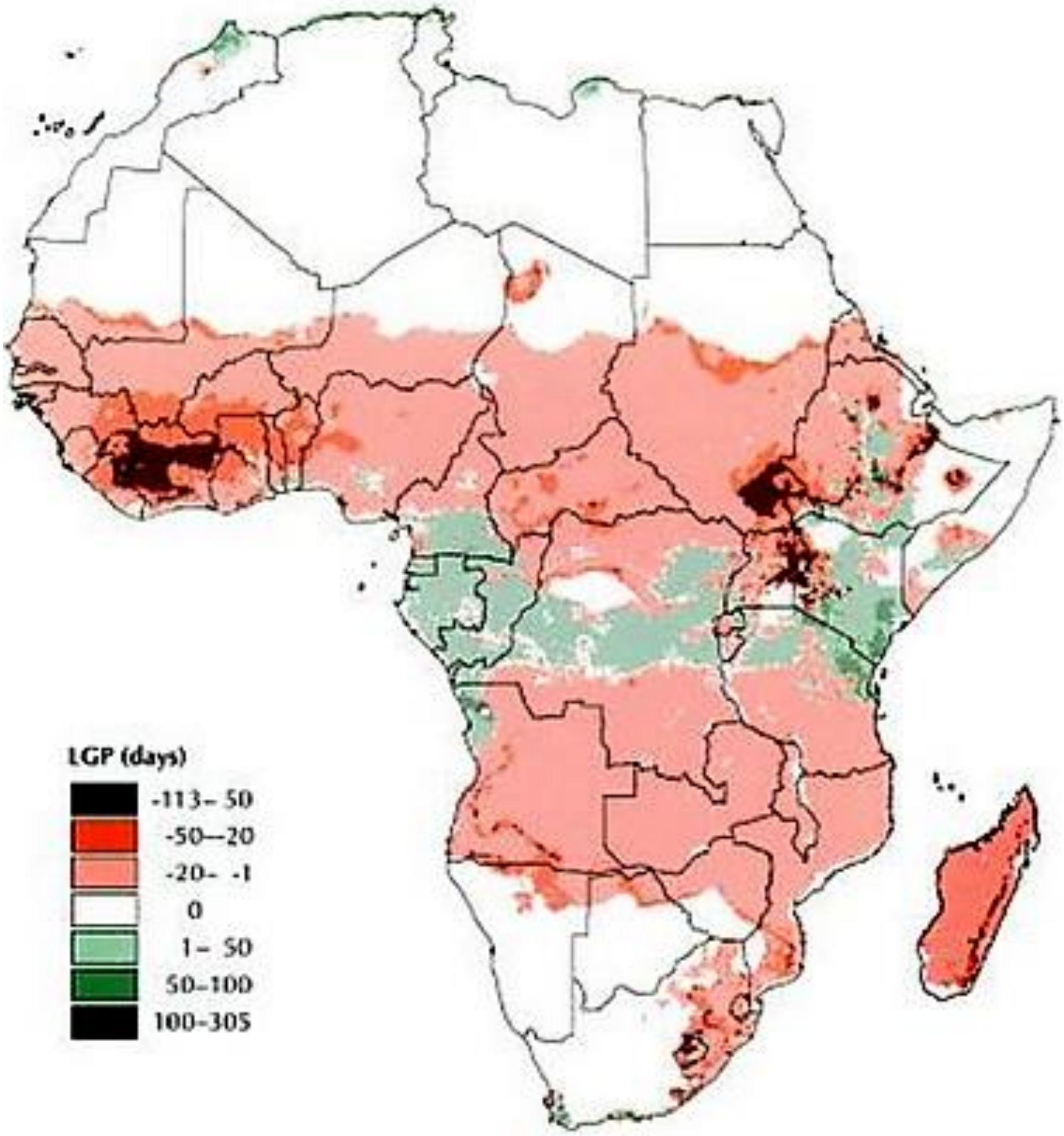

Figure 6: Predicted changes in the length of growing period from 2000 to 2005

Source: (Thornton et al., 2002)

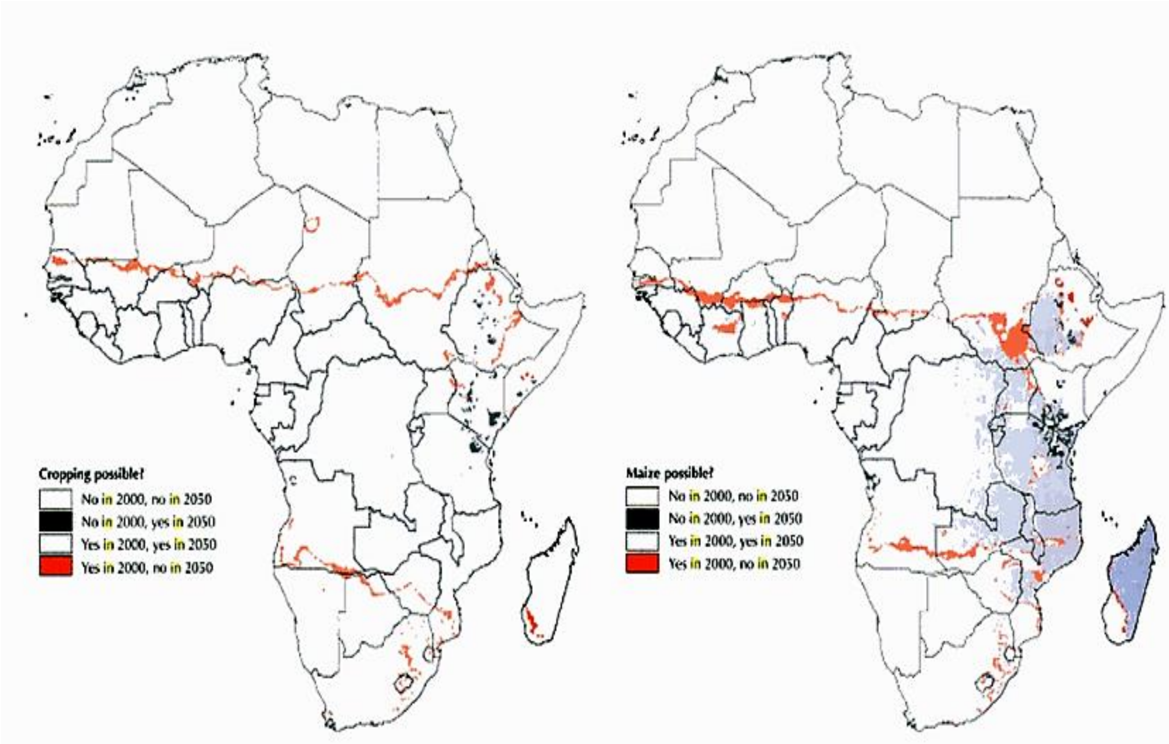

Figure 7: Predicted changes to cropping boundaries and limits of maize cultivation in Africa from 2000 to 2050

Source: (Thornton et al., 2002)

2.4. Factors affecting adoption of different feeds and forages

There exists a knowledge gap with regards to the non-climatic or socioeconomic factors which determine the choice of livestock feeds and forages smallholder farmers adopt. Various researchers (Kiptot et al., 2015, Parwada et al., 2010, Deressa et al., 2009) have conducted case studies on the socioeconomic factors which determine the adoption of other climate change adaptation methods, such as conservation agriculture and agroforestry. Therefore the determinants or factors reported by previous research may be applicable to the adoption of new climate-resilient feeds and forages, as these also represent a climate change adaptation method.

A participatory study was undertaken by Deressa et al. (2009) to gain knowledge on the factors which affect farmers choices of adaptation methods to climate change in the Nile Basin of Ethiopia. The authors recorded the existence of a set of socioeconomic factors affecting the farmers' choices of adaptation methods to climate change, and these factors may be applicable to the adoption of feeds and forages by smallholder farmers in the mixed farming systems. These factors include: level of education, size of household, gender of the head of household, age of the head of household, farm income, nonfarm income, livestock ownership, extension on crop and livestock, information on climate change, farmer-to-farmer extension, credit, number of relatives (i.e. social capital), farm size in hectares, distance to output market in kilometres, distance to input market in kilometres, local agroecology (lowlands), and local agroecology (Midlands), land availability and water availability.

Likewise, Gyau et al. (2012) conducted a case study in Cameroon and recorded that adoption by smallholder farmers may be determined by factors such as market prices, the supply of seeds and seedlings, and land tenure. This was in line with the findings of a case study conducted by Parwada et al. (2010) in Zimbabwe on assessing the adoption of agroforestry technologies among smallholder farmers. Parwada et al. (2010) recorded factors such as level of awareness among farmers, land ownership, and land size, drought, labor and local institutions, employment status, and training. Supporting this information, Gyau et al. (2014) conducted a case study in Côte d'Ivoire on assessing the farmer attitudes and intentions towards trees in cocoa (*Theobroma cacao* L.) farms. The authors reported that adoption is influenced by extension and certification programs, diseases affecting cocoa, geographic zone, the age of the farmers, household size, the supply of seedlings and training which ensure maximum profitability. Furthermore, a 2015 study in Kenya assessed the preference and adoption of livestock feed practices among farmers in dairy management groups and reported that information sources (i.e., neighbours, radio, extension services), level of education, gender and belonging to a farmer group can substantially affect adoption of feeds and feed practices (Kiptot et al., 2015).

2.41. Gender of the household head

According to a study in Ghana, female-headed households are more likely to have little or no access to extension information compared to male-headed households. As a result, high adoption of beneficial interventions is observed on male-headed households (Doss and Morris, 2001) and this unequal access to information between males and females is attributed to traditional social barriers (Tenge et al., 2004). Moreover, a study in Uganda conducted by Katungi et al. (2008) showed that social capital is an important factor in information exchange and men generally have better access to social capital than women. Contrary to these findings, Nhemachena and Hassan (2007) recorded that households headed by women are more likely to adopt climate change adaptation methods and the authors attributed these findings to the evidence that women do most of the agricultural work at a household to a region level, thereby having vast experience and information on profitable management practices. Therefore, these findings suggest that both women and men can play significant roles in the adoption of climate-resilient feeds and forages.

Research indicates an interaction between education level and adoption decisions. Low level of education is associated with less access to information on beneficial interventions leading to a low rate of adoption of adaptation methods. On the other hand, high level of education is associated with high access to information leading to a high rate of adoption of adaptation methods (Asfaw and Admassie, 2004). Likewise, Fosu-Mensah et al. (2012) linked the education level of a household head to access to information on improved technologies and production challenges. Therefore, this information suggests that farmers adoption of feeds and forages as an adaptation method to climate change may vary according to farmers' level of education.

2.4.2. Land ownership (land tenure)

Land ownership (tenure) plays a vital role in the adoption of adaptation methods (Fosu-Mensah et al., 2012). Land renters are less likely to adopt adaptation methods that require longer-term investments such as conservation agriculture, crop diversification. On the other hand, landowners are most likely to adopt adaptations methods that only yield benefits in the longer term (Soule et al., 2000) and this may be applicable also in the adoption of climate-resilient feeds and forages such as fodder trees and shrubs, fodder leaf meals and short duration fodder crops such as oats, maize, and sorghum**.** Likewise, a study conducted by Gebremedhin and Swinton (2003) in northern Ethiopia recorded that land ownership encourages long-term investments such as in stone terraces. Furthermore, land ownership positively affects the adoption of adaptation methods as the adaptation methods will directly provide long-term benefits to the owner (Prokopy et al., 2008).

2.4.3. Access to credit

The availability of credit enables farmers to purchase inputs needed for adaptation methods such as improved crop varieties or fertilizers (Le Dang et al., 2014). A meta-analysis conducted by Pattanayak et al. (2003) on adoption rates for agroforestry practices recorded that there is a positive correlation between resource endowments such as credit and the rate of adoption of adaptation methods. Likewise, Tambo and Abdoulaye (2013) reported that access to credit or loan facility plays a vital role in the adoption of new technologies as it eases farmers from cash constraints and allows them to easily purchase inputs. These findings were in line with the findings of a study by Bryan et al. (2009) which concluded that the lack of access to credit by farmers slows down that rate of adoption of adaptation methods.

2.4.4. Age of the household head

Age of the household head is associated with years of farming experience (Deressa et al., 2009). (Maddison, 2007) cited that experience in farming increases the probability of uptake of adaptation measures to climate change and this was in agreement with (Deressa et al., 2009) findings which reported that an increase in the number of years of experience increased farmers' probability of adopting adaptation methods. On the contrary, Knowler and Bradshaw (2007) and Perz (2003) cited that the age of a farmer has no significant effect on the adoption of conservation agriculture. On the other hand, Bekele and Drake (2003) argue that age of the farmer *cannot* be treated as a determinant in the adoption of conservation agriculture because older farmers may adopt conservation agriculture on the basis of farming experience, while younger farmers may invest in conservation agriculture due to their education awareness on the longer-term benefits. On the other hand, Rahman (2007) reported that older farmers may be skeptical and reluctant to adopt new technologies for pig farms in India.

2.4.5 Access to extension services

Various studies have reported that modern agricultural technologies are most likely to be adopted by households which have access to extension services (Abdulai and Huffman, 2005). Extension services, therefore, play a significant role in influencing adoption decisions (Pannell et al., 2006). Moreover, the contact of extension workers with farmers commonly determines the farmers' access to climate change adaptation information. Furthermore, access to information through extension services reduces farmers' uncertainty on the performance of a new technology (Shiferaw and Holden, 1998). A study conducted in Ghana by Doss and Morris (2001) on the adoption of agricultural innovations by farm households, women were found to have less or no access to extension services leading to lower adoption rates than men. However, the author did not attribute these findings to gender issues. Rather these findings were attributed to the extension workers preferring to visit farmers working on large-scale farms, and farmers who have already adopted improved technologies.

2.4.6. Labour availability

A larger household size is assumed to allow farmers to adopt adaptation methods which are labor intensive due to the number of individuals who can share the labor (Hassan and Nhemachena, 2008, Dolisca et al., 2006). However, some members of a large household may be required to participate in off-farm activities to gain diverse incomes in a household, leaving fewer individuals to do on-farm activities (Tizale, 2007). Therefore, this information suggests that farmers with small household size are less likely to adopt labor-intensive adaptation methods.

2.4.7. Access to markets

Hassan and Nhemachena (2008) and Deressa et al. (2009) referred to "access to markets" as the distance to input market in kilometers and distance to output market in kilometers. Market access is one of the factors which play a significant role in the adoption of adaptation methods. For instance, a shorter distance to the input market enables farmers to easily acquire or buy seeds or seedlings.

2.4.8. Level of farmers awareness of climate change

Farmers perception of climate change contributes immensely to the adoption of climate change adaptation methods (Maddison, 2007). Nhemachena and Hassan (2007) reported that farmers who observed the long-term alterations in temperature and rainfall had a high probability to adopt adaptation methods as they were aware how these changes in the climate affected yield.

2.4.9. Water availability

Water availability plays a major role in the uptake of feed or forage technologies. This is well demonstrated in the rainfed farming systems, in cases whereby introduced feed options have a positive impact on livestock productivity but their uptake remain unsatisfactory due to water shortages following erratic rainfall (Ashley et al., 2018). In rainfed farming systems, the availability of water or soil moisture for growing forage is determined by rainfall distribution and amount. Therefore, erratic rainfall may prevent farmers from adopting feed interventions with high water requirements. Nevertheless, future climate projections show an increase in precipitation for Eastern Africa and a decrease in Southern Africa (Adhikari et al., 2015)

(Barros, 2014). This may enable the mixed farming systems in East Africa to uptake feed options which require water, thereby improve livestock productivity.

2.4.10. Land availability

In developing countries, land allocation for the cultivation of forage crops such as legumes to close the feed quantity gap for livestock feeding is given least priority among farmers due to the growing population which demands the land for growing crops for food, as well as building settlements (Geleta et al., 2013). As a result, land scarcity constrains livestock productivity as feed interventions with a higher land requirement are less attractive despite their positive impact on livestock productivity. Another variable caused by the changes in the climate which influences land availability is rainfall intensity. For instance, rainfall intensity is predicted to increase in East Africa (Nearing et al., 2004). Therefore, high rainfall intensity may degrade land through soil loss making the cultivation of forage impossible (Adhikari et al., 2015). In this context, land availability simply suggests the availability of productive land. Therefore,

degraded land may not be as productive and may prevent the adoption of feed interventions which require land.

2.5 Constraints to livestock productivity in mixed farming systems

Livestock farming is a significant livelihood strategy for people in low and middle-income countries (Kaasschieter et al., 1992, Herrero et al., 2009). Livestock and livestock products are sold to gain household income. Livestock contributes to food and nutrition security through providing protein in a form of meat, milk, and eggs, and also provides traction and returns manure to the soil for future crops in the mixed farming systems (Randolph et al., 2007, Herrero et al., 2009, Lapar and Ehui, 2004). However, changes in the climate affect the livelihoods of people who depend on livestock through limiting livestock productivity. High temperatures and altered rainfall distribution cause shifts in rain-fed forage suitability, resulting to feed seasonality and fluctuations in feed quantity and quality (Nardone et al., 2010).

2.5.1. Seasonal scarcity and feed quantity

Ideally, forage production should match livestock feed requirements all year round for optimum livestock productivity. However, seasonal shortages of feed have been identified as a major constraint to livestock productivity (Smith, 2002, Abate et al., 1993). The rainy season and the warm season are associated with high biomass production which influences high feed availability and improved livestock productivity (Leonard, 2015). The dry season and the cool season are associated with low biomass production, which leads to high feed scarcity and decreased livestock productivity as the available feed fail to meet livestock nutrition requirements (Lukuyu et al., 2009). The resulting livestock nutrition stress negatively impacts smallholder farmers' livelihoods as milk and other livestock products sales decline due to low productivity. The feed scarcity problem is worsened by lack of farmers' knowledge on locally available feed interventions which can be adopted to increase or maintain productivity during the dry season or cool season (Lukuyu et al., 2011). Feed scarcity can be addressed through targeting feed option which can close the feed gap during the dry or cool season. For instance, hay-making and silage-making are attractive options which can be adopted in seasons characterized by high biomass production to close the feed gap in seasons with low biomass production (Simbaya, 2002).

2.5.2. Feed quality

The important feed resources for the mixed farming systems are crop residues and natural pastures. However, these feed resources are often characterized by a low nutritive value or quality in the dry season (Simbaya, 2002). Therefore, poor quality feed falls amongst the major constraints of livestock productivity. Crop residues are associated with high fiber and low protein, which fail to support optimal microbial growth and match livestock nutrition requirements for increased productivity (Ball et al., 2001). This is an indication that farmers need other feed options and interventions which will increase the feeding value of crop residues (Reed and Goe, 1989). Various studies (Wanapat et al., 2009, Sarnklong et al., 2010, Roothaert and Paterson, 1997) have reported on interventions which can be adopted to improve the quality of feed. These interventions include chemical treatment of crop residues using urea, supplementing feed with energy-rich supplements such as molasses, supplementation of feed using protein by-products such as blood and bone and legume leaf meal and the use of fodder trees and shrubs. These feed options improve the nutritive value of feed by increasing digestibility, palatability and crude protein content (Israel and Pearson, 2000). Taken together, adoption of feed with high protein content is likely to improve livestock productivity.

2.6 What is the feed assessment tool (FEAST)?

The Feed Assessment Tool (FEAST) is a tool developed by ILRI. It is a systematic method to assess the availability and use of feed resources. The tool helps in the design of site-specific interventions which enhance feed supply and utilization. The tool encompasses three components. The first component is a focused participatory rural appraisal (PRA) exercise which provides the following:

i. an overview of a farming system
   - the range of farm sizes
   - farm labor availability
   - annual rainfall pattern
   - irrigation availability
ii. a general description of livestock production
   - the types of animals raised
   - the purpose of keeping these animals
   - ease of access to credit
   - availability of necessary inputs
iii. problem identification and potential opportunities

The second component of the tool is an individual farmer survey which involves a short questionnaire which seeks farmers' perception and quantitative information related to farm size, crop yield, portion of grazed feed, portion of purchased feed, seasonal feed scarcity, milk sale and livestock sales. The third component is data analysis. Data collected is entered to the FEAST template. The feast produces an output which consists of a short report with quantitative information on overall feed availability, quality and seasonality and this report is used to help inform intervention strategies. Thereafter, feed interventions which have a potential to mitigate feed constraints were added to FEAST and are named the Techfit sheets. Therefore, these Techfit sheets will guide the recommendations of this project.

2.6.1. FEAST/Techfit approach

Climate change affects the smallholder mixed farming systems through causing increased feed scarcity, and in some cases decrease in feed quality (Sejian et al., 2016). Current production systems are characterized by poorly fed animals which are fed opportunistically with feeds that are immediately available. Thus, feed represents a key limiting factor and it is often the most expensive input in livestock production (Geleta et al., 2013). Smallholder farmers need feed options which will close the feed gap and increase their income.

The FEAST/Techfit approach presents candidate feed technologies or interventions which have a potential to mitigate feed constraints such as feed scarcity during the dry or cool season, feed scarcity during the growing season, feed quantity and feed quality. The Techfit module scores the candidate feed options from low to very high, depending on the intervention's potential to mitigate feed constraints. Therefore, in this manner, feed options which have a high potential to mitigate feed scarcity during dry or cool periods are given a score of four, which represents "very high potential" and such feed options include: irrigated fodder (e.g. grasses, maize, sorghum), purchased crop residues or hay, fodder trees and shrubs, and commercial balanced compounded feeds (e.g. dairy meal), multi-nutrient supplements (e.g. urea molasses, mineral block licks), hay (machine hay making/ manual boxing), and silage and silage making (tube silage/ silos).

Feed options which are scored very high for their potential to mitigate feed scarcity during the growing season include: short-duration /annual fodder crops (e.g. oats, maize, sorghum, vetch), grasses for cut and carry systems (cut from cultivated fodder field under rainfed conditions). Feed options which have a potential to mitigate feed quantity constraints include irrigated fodder (e.g. grasses, maize, sorghum), grasses for cut and carry systems (cut from cultivated fodder field under rainfed conditions) and short-duration / annual fodder crops (e.g. oats, maize, sorghum, vetch).

Finally, feed options which have high potential to mitigate feed quality constraints include: energy-rich supplements (e.g. molasses), fodder trees and shrubs (e.g. *Leucaena leucocephala*), legume/fodder leaf meals (dried and ground), commercial balanced compounded feeds (e.g. dairy meal), complete mixed rations such as feed blocks and herbaceous legumes, monoculture or mixed with grasses.

2.6.2. Constraints and adoption factors revealed by Feast /Techfit approach

The rate of adoption for feed options depends on a few key issues which are noteworthy. The first key issue is the potential of the feed interventions to solve or deal with the core feed constraints which farmers are faced with. For instance, in areas where feed quantity constrains livestock productivity, adoption of feed options such as legumes is likely to be low as legumes deal well with feed quality constraints (Huisman and Van der Poel, 1994) but do not provide enough herbage to secure high feed quantity. Additionally, in areas where seasonal scarcity limits livestock productivity, adoption of legumes is most likely to fail as legumes provide feed during the growing season, thereby leaving a feed gap after the growing season.

The second key issue in the adoption of feed options pertains to whether the local farming system can provide the requirements of the feed intervention. For instance, annual fodder crops such as maize and sorghum provide the needed quantity and have the potential to mitigate feed scarcity during the growing season, but their adoption might be low as farmers might be put off by its high requirement for land. Additionally, fodder trees and shrubs provide high-quality feed (Norton, 1994) and have the potential to mitigate feed scarcity during the growing season but their adoption might be hampered by their high demand for labour. Furthermore, feed interventions which have long-term benefits such as fodder trees and shrubs are less likely to be adopted in areas where land tenure is an issue, as land may not be guaranteed in the following year. Therefore, this raises a policy implication as (Fosu-Mensah et al., 2012) reported that landowners are more resilient to climate change due to their ability to invest in adaptation methods which yield long-term benefits.

The third key issue which determines uptake of feed interventions is the measurable impact of the feed intervention on livestock productivity. Farmers are more likely to invest in feed options which have a detectable effect on productivity and profit. For example, supplementing poor quality feed with molasses is likely to be attractive to farmers as it improves daily weight gain, thereby increasing income on the sale of live and slaughtered animals due to the increase in weight gain (Ayoola and Ayoade, 1992).

The FEAST/Techfit approach, therefore, provides a useful framework for predicting likely success of a range of feed options under different system conditions and different feed constraint scenarios. This project assesses the potential to map uptake factors and feed constraints to generate feed availability maps which will be used to predict likely suitability of a range of climate resilient feed options.

3. Methods and materials

Mapping of feed constraints and system characteristics is key to matching feed interventions to local conditions in the face of current and future climate change. This study focused on two key feed constraints faced by farmers and two system characteristics in the smallholder mixed farming system of East Africa. The two feed constraints of focus were overall feed quantity and seasonal feed scarcity, and the two system characteristics were land availability and water availability.

Four maps (feed quantity, seasonal scarcity, land availability, water availability) were produced using a geographic information system (GIS). Thereafter, the four maps were overlaid to produce a single map showing sixteen (16) domains of feed constraints and system characteristics for Kenya, Tanzania, and Uganda. From the sixteen domains, four highly contrasting domains were selected, and recommendations of suitable feed interventions were made based on the properties of the four selected domains using the FEAST/Techfit logic (Lukuyu and Duncan, 2014).

The study was conducted using ESRI ArcGIS 10.4 (ESRI, Redlands, CA) and R software (R Core Team, 2017), and variables listed in *Table 1* were mapped at a spatial resolution of 1 kilometer.

Table 1: Proxies of feed constraints and adoption factors

Factor/ Constraint	Proxy	Unit
Feed quantity	Dry matter productivity	Kg DM/km^2/cow/day
Feed scarcity	Dry matter productivity	number of months/years
Land availability	Population density	crop area/person
Water availability	Annual precipitation	millimeters (mm)

3.1. Data Sources

Various sources provided the data sets which were needed to accomplish the study. Overall, the following sources of data were used:

- Net Primary Productivity (Dry Matter Productivity) data from 2008 to 2010 was provided by Copernicus Global Land Services.
- Land cover data from 2015 to 2016 which was used to delineate rangeland was provided by Copernicus Global land services.
- Mixed farming system data was extracted from the livestock production systems data obtained from the International Livestock Research Institute (ILRI) Datasets Portal.
- Pasture density layer was provided by the Food and Agriculture Organization (FAO)
- Cattle density data used to determine annual feed production per animal was obtained from the Food and Agricultural Organization (FAO) Global Cattle Density.
- Population density data was provided by Worldpop.
- Crop area data was provided by the International Institute for Applied System Analysis (IIASA).
- Rainfall distribution maps from 2008 to 2017 were provided by National Oceanic and Atmospheric Administration (NOAA).
- Data for deriving flow accumulation was acquired from (Lehner et al., 2008).

3.2. Mapping of feed constraints

3.2.1. Feed quantity

Feed quantity was defined as the available feed per animal. To determine the available feed quantity per animal, cropland, and rangeland land cover types were delineated using Copernicus LC100 2015 v1.0.1 dataset. Based on this dataset, rangeland includes shrubs, herbaceous vegetation, bare/sparse vegetation and herbaceous wetland in the study area. For the purposes of this study, Dry Matter Productivity (DMP) spatial data spanning a period of 10 years (2008 - 2017) were downloaded from Copernicus Global Land service https://land.copernicus.eu/global/products/dmp. DMP is directly related to NPP (net primary Productivity) and it represents the overall growth rate of vegetation, expressed in kilograms of dry matter per hectare per day (kg DM/ha/day). The DMP data was used to identify the overall growth rate or dry biomass increase of the vegetation (Fetzel, 2016). The DMP data was corrected to estimate available livestock feed using pasture layer from FAO and a feed fraction from cropland which accounts for 24% (Herrero et al., 2013b). The pasture layer shows the fraction of land areas used as pasture land and the fraction of cropland used to support grazing animals. Finally, cattle density data from (Upson et al., 2016) was used to calculate the quantity of feed available per animal per year across the mixed farming systems as mapped by (Herrero et al., 2013b). Therefore, the output shows feed quantity in kilograms of dry matter per cow per day (kg DM cow/day)

Data Processing for the feed quantity map

First, the global netCDF DMP data layers were converted into GeoTIFF file format and clipped to the area of study (East Africa). To obtain actual or physical DMP values, the data layers were divided by 100. These steps were carried out on each (2008 - 2017) DMP data layer. Thereafter, the pasture occurrence and cattle density raster layers were clipped to the area of interest and subsequently resampled to a spatial resolution of 1 km. Furthermore, pasture occurrence data which originally has its values in percent was divided by 100 to have pasture proportions in decimal. To convert cattle density from square kilometer to hectares, the layer was multiplied by 100. The conversion was intentionally done so that the cattle density units reflect those of the DMP. Pasture quantity was calculated by multiplying long-term DMP trend layer by pasture fraction. The output was then divided by cattle density layer to get pasture quantity in kilograms of dry matter per cow per day (kg DM cow/day). Therefore, the final output *(Figure 8)* shows feed quantity in kilograms of dry matter per cow per day (kg DM cow/day)

Overall, to calculate the available feed quantity per animal, five important variables were considered;

1. ***Long-term DMP trend:*** This is the mean of all (2008 - 2017) data layers converted to actual DMP values. This layer was derived using simple arithmetic mean in ArcGIS and resampled to a spatial resolution of 1km.
2. ***Feed fraction:*** Fraction of total primary production that is used as feed. For cropland, we use 24%, for pastureland, we use the pasture fraction layer which shows the relative proportion of available feed on the land surface considering the land use type (Van Velthuizen et al., 2007). This variable is significant as a weighting factor to long-term DMP pixel values. It defines what proportion of DMP given the land use type is available for grazing and browsing.
3. ***Cattle density:*** This represents the number of animals per hectare. The gridded data is created through spatial disaggregation of sub-national statistical data based on empirical relationships between cattle densities and environmental variables in similar areas (Robinson et al., 2014)
4. ***Land cover****:* This is a dataset which was used to delineate rangeland and cropland land cover types.
5. ***Livestock production systems layer:*** This is the layer which was used to extract the mixed farming systems of East Africa.

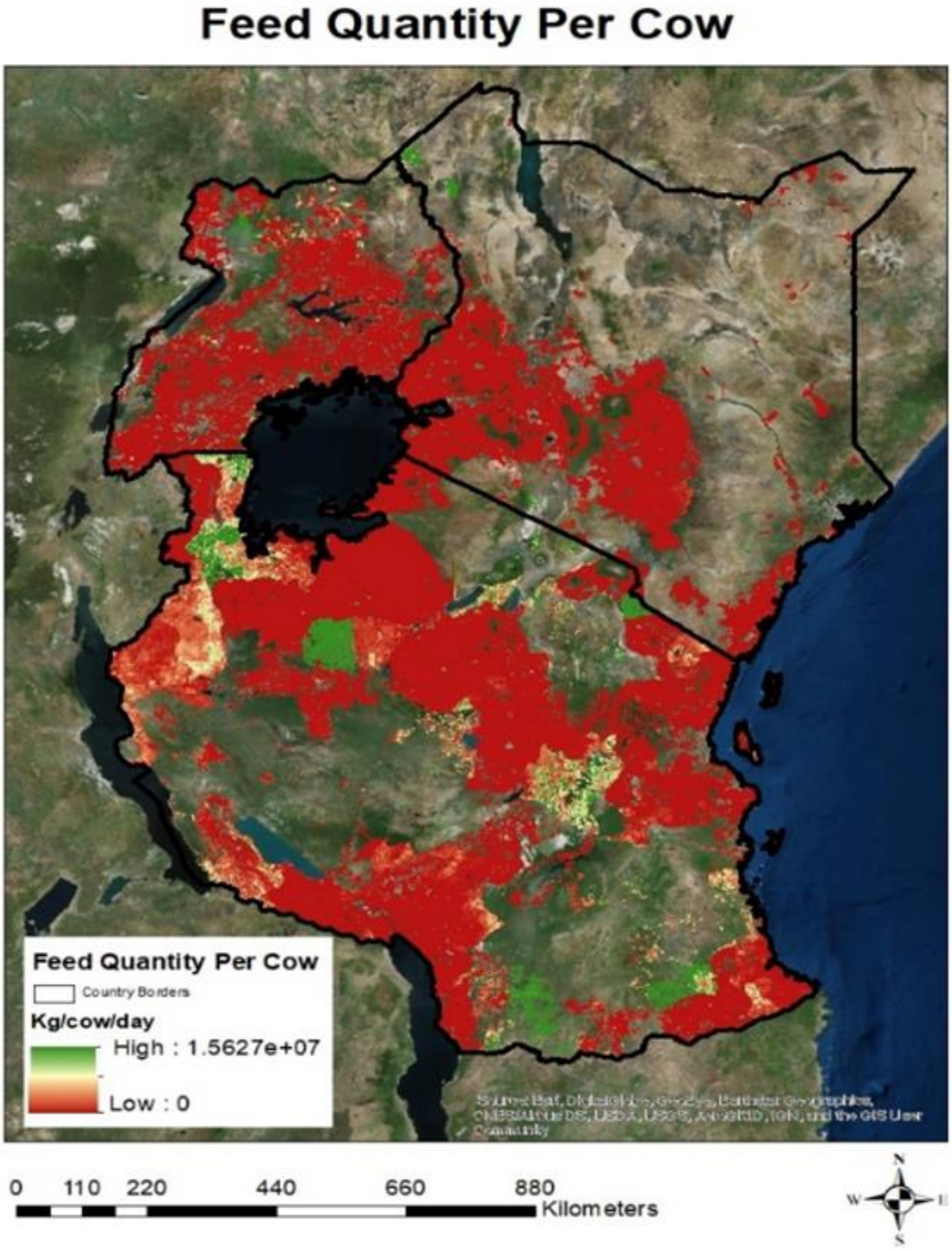

Figure 8: Feed quantity map

3.2.2. Seasonal feed scarcity

Feed scarcity was defined as the number of months with feed quantity less than the requirements of one tropical livestock unit (TLU). Feed scarcity was derived by comparing long-term (2008 - 2017) monthly DMP trend against standard feed requirement of one TLU (6.5 kg DM cow/day). To achieve this, long-term actual monthly DMP trend was first calculated through simple mean. This was done across the months (January - December) and along the years (2008 - 2017). The output of this process was 12 long-term average monthly

DMP gridded data layers. Each of these were then multiplied by pasture fraction to obtain long-term monthly pasture quantity. Feed quantity in kilograms of dry matter per cow per day (kg DM cow/day) for each of the 12 long-term months was finally derived by deriving long-term monthly pasture quantity by cattle density layer.

Data processing for the seasonal feed scarcity map

Comparison of long-term monthly pasture quantity per cow against the standard daily feed intake was done using ArcGIS Con tool. In this study, cell values of feed quantity per animal that were greater than 6.25 kg DM cow per day were assigned a value 1 and those below were assigned a value 0. This process was repeated on each long-term monthly pasture quantity per cow raster dataset while adding the output together. The result of this entire process is a single feed scarcity gridded data layer with ordinal values running from 0 to 12. Twelve (12) representing all year scarcity and zero (0) representing no scarcity *(Figure 9).*

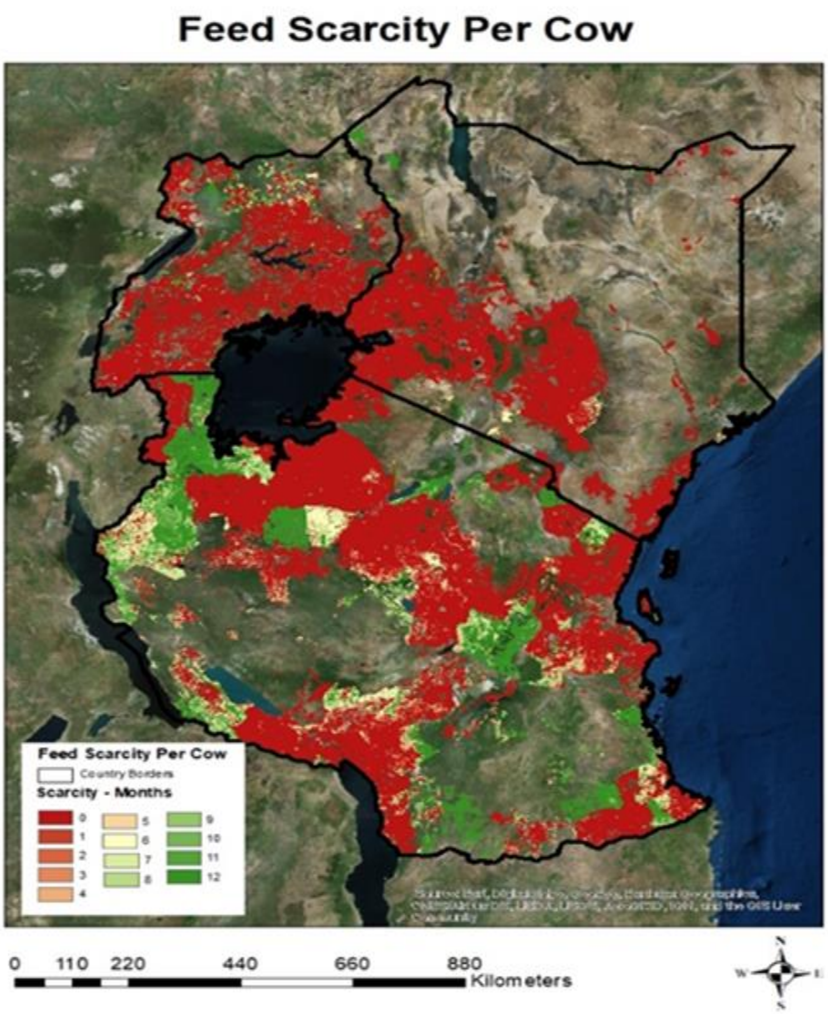

Figure 9: Seasonal feed scarcity map

3.3. Mapping of system characteristics

3.3.1. Land availability

Land availability was defined as the cropland area available per person. Population density data available from WorldPop (http://www.worldpop.org.uk/data/) and cropland data mapped by (Ramankutty et al., 2010) were used to calculate the crop area available per person.

Data processing for the land availability map

Cropland data was resampled to 0.008333333-degree pixel size for a fine spatial resolution. Thereafter, the cropland area was divided by population density using a raster calculator. The output *(Figure 10)* shows the area of cropland available per person within each pixel.

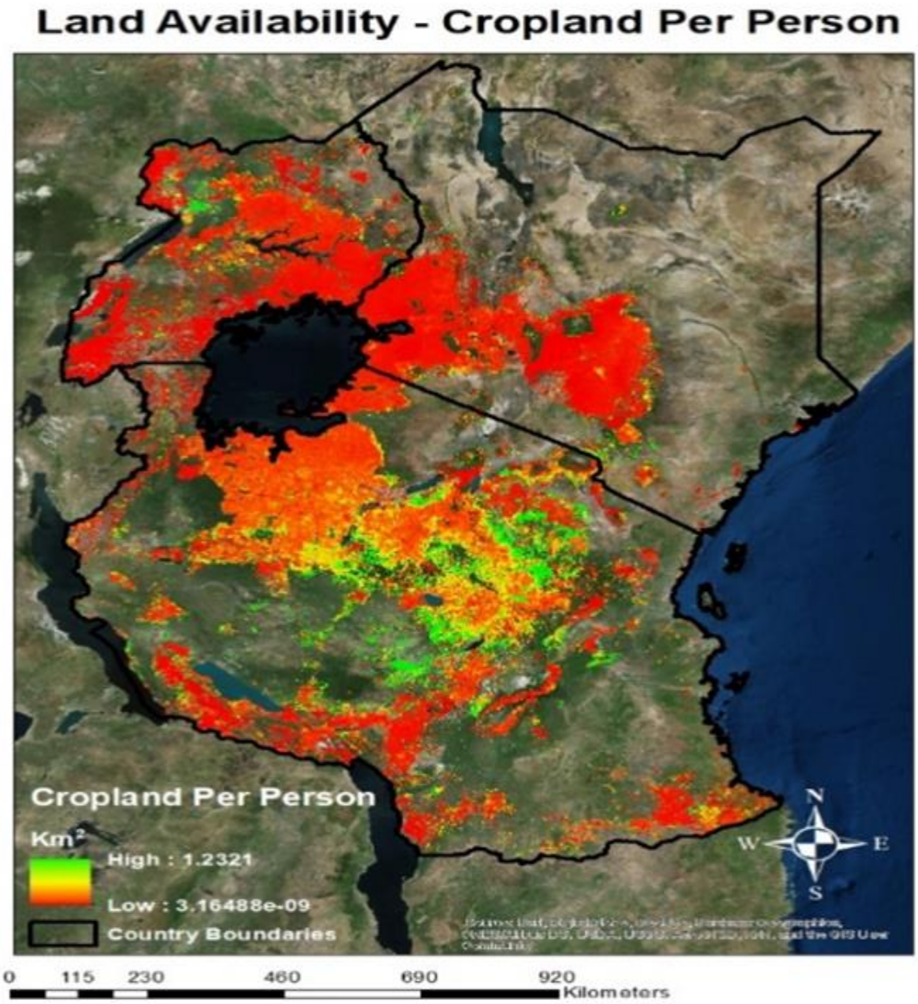

Figure 10: Land availability map

Furthermore, soil loss was calculated as a proxy indicator for risk of future land degradation which may reduce available land for forage production. The calculation was done using the standard RUSLE equation as described by (Artiola et al., 2004) where:

- **A=2.24R*K*LS*C*P**
- A = the estimated average annual soil loss (metric tons per hectare)
- R = the rainfall and runoff erosivity index, describing the intensity and duration of rainfall over the study site over a maximum 30-minute intensity rainfall event. The R factor was derived from Global R and clipped to the study area.
- K = the soil erodibility factor. K is related to soil physical and chemical properties that determine how easily soil particles can be dislodged. It is related to soil texture,

aggregate stability, and soil permeability or ability to absorb water. It ranges from 1 (very easily eroded) to 0.01 (very stable soil).

- LS = describes the length and steepness of a slope. This impacts the velocity of water runoff and therefore erosivity. For determining LS in this model Wischmeier and Smith's LS factor formula was calculated in the ArcMap 10.6 raster calculator with the following input:

  Pow(([FlowLength]/22.13),[m_factor]/10)*(((Sin([Slope_degrees]/deg)*Sin([Slope_degrees] / deg))*65.41)+(Sin([Slope_degrees] / deg)*4.56)+0.065)
- C = land cover factors that influence soil surface runoff were calculated based on the amount of protection from runoff provided by different cover classes, from bare soil (c-value of 1), to forested land (c-value of 0.001).
- P = the p-factor describes supporting practices to avoid erosion. Values range from 0-1, where 1 is the absence of any erosion control practices. Given the large area at which this study is based, erosion control factors were assumed absent. Individual case studies for smaller swaths of land can tease out individual practice benefits.

3.3.2. Water availability

Water availability was defined as the amount of rainfall and flow accumulation in each area. For rainfall distribution, precipitation data was downloaded from NOAA (http://www.cpc.ncep.noaa.gov/) giving the daily precipitation throughout East Africa (Novella and Thiaw, 2013). annual precipitation and a long-term average annual precipitation (2008-2017) was calculated using the daily precipitation estimates. For flow accumulation, flow accumulation layer with a resolution of 15 arc seconds derived from a Digital Elevation Model (DEM) was downloaded from Google Earth Engine, then an extraction was performed in ArcMap10.6 to clip the layer to East Africa. The flow accumulation layer details the amount of upstream area that drains into each cell. Drainage direction details which cells flow into the target cell. The number of accumulated cells measures the upstream catchment area.

Data processing for the water availability map

Daily precipitation data was brought into R as raster data and were clipped to the extent of the study, then averaged together in the raster calculator. Using the ArcMap10.6 model builder, iterative raster processes resampled the cell values to align, and calculated monthly averages. The output *(Figure 11)* shows a total time frame precipitation average for the years 2008 to 2017, as well as the sum of the monthly average per watershed.

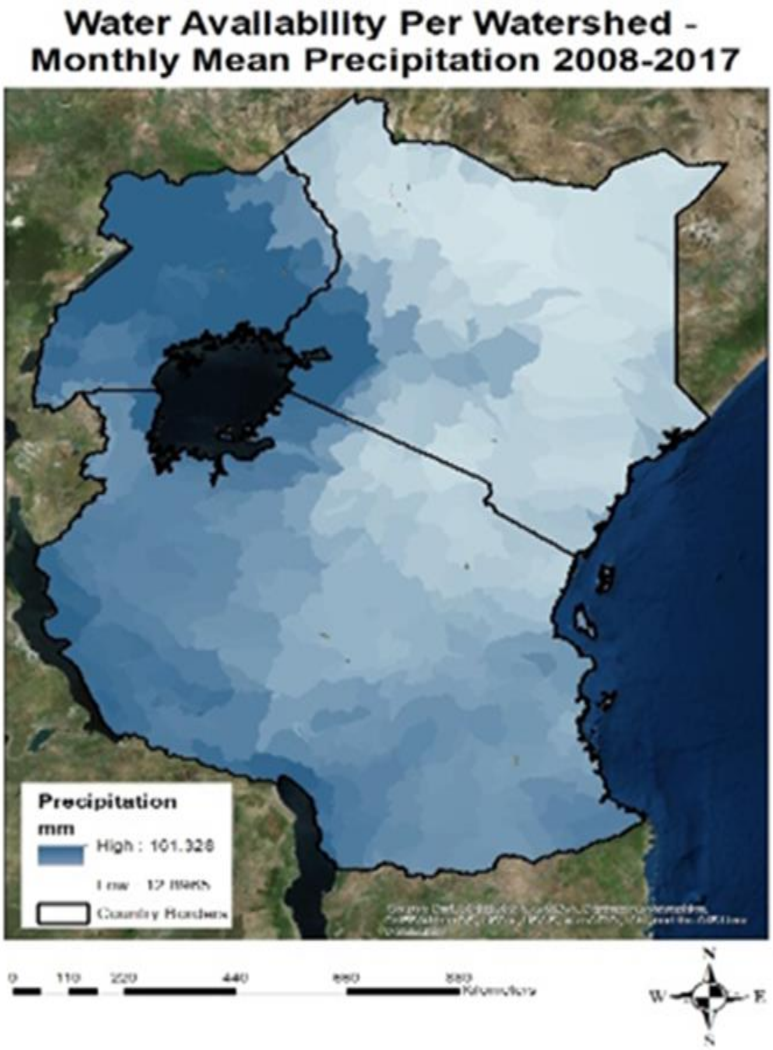

Figure 11: Water availability map

3.4. Mapping spatial domains

For this study, sixteen (16) spatial domains were mapped using R software (Team, 2017). A random Forest model was used to calculate proximity values based on raster attributes of the four variables which are feed quantity, feed scarcity, land availability and water availability, then clustered the values using k-means technique. Thereafter, clusters were used to train another random Forest model for classification. The output *(Figure 12)* was a map showing 16 clusters.

4. Results

Overlaying the four maps (feed quantity, seasonal scarcity, land availability and water availability) produced a single map showing 16 domains. The map showing the 16 domains is presented in *Figure 12*. For the purposes of this master's project, only four (4) highly contrasting domains were picked to portray availability of feed resources and predict the adoption of new climate-resilient feed interventions in the mixed farming systems of Kenya, Tanzania and Uganda. A summary of the descriptive statistics of domains is presented in *Table 2*. These statistics were extracted from the domains map and were used to interpret the domains and rank them from very low to very high.

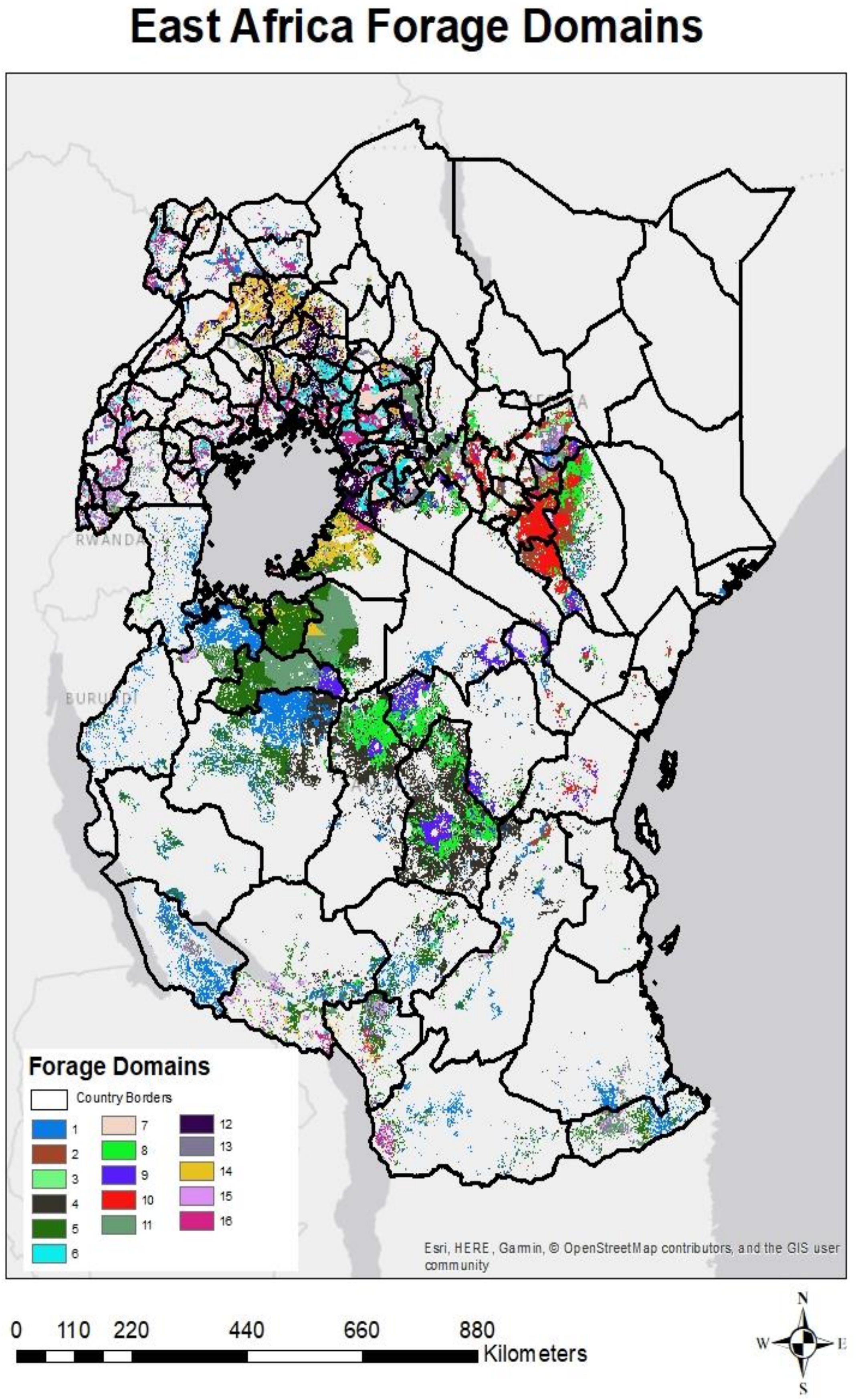

Figure 12: Map showing domains

Table 2: Summary statistics (mean) per domain

Domains	Feed quantity (kg DM/km2/cow/day)	Seasonal scarcity (months/year)	Land availability (hectares/person)	Water availability (mm)
2	5278.33	3	0.7	882
4	1351.02	6	3.6	479
7	259.15	11	0.1	1348
16	9.36	12	0.1	554

**These values were extracted from the statistics of the domains map*

4.1. Interpretations of the four (4) selected domains as shown in *Table 2*

Domain 2: Very high feed quantity

- 3 months of seasonal scarcity/ Low land availability/High water availability

Domain 4: Medium feed quantity

- 6 months of seasonal scarcity/ Very high land availability/ Medium water availability

Domain 7: Low feed quantity

- 11 months of seasonal scarcity/ Low land availability/ Very high-water availability

Domain 16: Very low feed quantity

- 12 months of seasonal scarcity/ Very low land availability/ Medium water availability

Table 3: Domains interpretations

Domains	Feed quantity	Seasonal scarcity	Land availability	Water availability	Domains abbreviations
2	Very high	3 months	Low	High	VHF
4	Medium	6 months	Very high	Medium	MF
7	Low	11 months	Very low	Very high	LF
16	Very low	12 months	Very low	Medium	VLF

**Domains rankings range from very low to very high (very low; low; medium; high; very high*

Table 4: Counties, Regions, Districts found within the four domains

Countries	Domain	Interpretation	Counties, Regions, Districts
Kenya	2	Very high feed	Kitui, Mkueni, Embu, Muranga, Kirinyaga, Meru, Nakuru
	4	Medium feed	Taita-Taveta
	7	Low feed	Bungoma, Vihiga, Kisii, Bomet
	16	Very low feed	Siaya, Kakamega, Bungoma, Homa Bay
Tanzania	2	Very high feed	Morogoro
	4	Medium feed	Dodoma, Singida, Tabora, Simuyu, Iringa, Morogoro
	7	Low feed	-
	16	Very low feed	Mara, Mbeya, Njombe, Ruvuma
Uganda	2	Very high feed	-
	4	Medium feed	-
	7	Low feed	-
	16	Very low feed	Tororo, Maguye, Jinja, Kamuli, Wakiso, Kampala, Mukono, Bushenyi, Hoima, Masindi, Pade, Gulu, Nebbi, Arua

**Kenya-counties; Tanzania-regions; Uganda-districts*

Domain 2 (Kenya, Tanzania)

Feed quantity in this domain is abundant. This domain experiences only three months of feed scarcity. This domain has enough feed resources to meet the feed requirements of one TLU for nine months in a year. In contrast, this domain recorded low land availability and also recorded high water availability. As shown in *Table 4*, In Kenya this domain was found in Kitui, Mkueni, Embu, Muranga, Kirinyaga, Meru, Nakuru. In Tanzania, this domain was found in one region which is Morogoro.

The FEAST-Techfit sheet (*Table 5*) reveals that the practice of producing irrigated fodder is a suitable feed intervention given its low land requirement and its high potential to mitigate feed quantity problems and feed scarcity during the cool or dry season. Nevertheless, irrigated fodder production *does not* mitigate feed scarcity problems during the growing season. Therefore, integrating the use of energy-rich supplements such as molasses and the use of protein by-products such as legume leaf meal with the option of irrigated fodder production is a suitable feed intervention to close the three-month feed scarcity gap.

Domain 4 (Kenya, Tanzania)

This area is characterized by adequate feed availability. In a year, this area experiences six months of feed scarcity and six months of feed abundance. This is an indication that half of the year, livestock productivity is high due to the availability of feed resources which meet animal's nutrition requirements. Furthermore, this area shows the availability of very high land which can support forage production. On average, for the past ten years there has been adequate rainfall to support forage production. Hence water availability was reported to be adequate or medium in this domain. As shown in Table 4, In Kenya this domain was found in Taita-Taveta county only where as in Tanzania the domain was found in six regions and those are Dodoma, Singida, Tabora, Simuyu, Iringa and Morogoro.

According to the FEAST Techfit sheet (*Table 5*), short-duration or annual fodder crops such as oats, maize, sorghum and vetch are suitable feed interventions for this domain considering that this domain has very high land which can be allocated to forage production and adequate water availability. However, annual fodder crops only solve problems of feed quantity and feed scarcity during the growing season, leaving a feed scarcity problem during the cool and dry season. Therefore, fodder trees and shrubs such as *Calliandra calothyrsus* and *Leucaena diversifolia* are suitable feed interventions which can be integrated with the use of annual fodder crops given the potential of fodder trees to close the feed scarcity gap during the dry season or cool season. Furthermore, the water and the land available to farmers in this domain match the requirements of fodder trees and shrubs and this will enable farmers to adopt these two feed interventions.

Domain 7 (Kenya)

This domain has low feed quantity and experiences eleven months of feed scarcity. This implies that there is only one month where feed quantity is enough to satisfy the requirements of one TLU in a year leaving a feed gap in all the other eleven months. Apart from the high feed scarcity problem, this area has no land for forage production. However, high rainfall has been experienced in the past ten years, resulting in the area having very high water to support forage production. As shown in *Table 4*, this domain was only found in Kenya where it includes counties such as Bungoma, Vihiga, Kisii and Bomet.

Feed interventions suitable for the mixed farming systems in domain 7 are those which do not require land and have a high potential to mitigate feed quantity and feed scarcity. The FEAST-Techfit (*Table 5*) reveals that the practice of supplementing feed with protein by-products such as legume leaf meal and oilseed is a suitable feed intervention for this domain given its characteristics of having no land for forage production. However, supplementing feed with protein by-products does not deal with the feed quantity constraint. Therefore, the feed quantity gap can be prevented by adopting the use of thinnings, tops and leaf strips of crops which are cultivated on-farm such as maize, sorghum, cassava, depending on the crop in season. As this domain receives very high rainfall, the practice of rainwater harvesting may be essential as it may enable farmers to adopt irrigated fodder production to close the feed quantity gap.

Domain 16 (Kenya, Tanzania, Uganda)

Table 3 indicates that the mixed farming systems located in Domain 16, are characterized by very low feed quantity and all year feed scarcity. This is an indication that livestock production is very poor in this area. Over and above the feed scarcity constrain, the area shows low land availability for forage production. However, it has recorded adequate amount of rainfall which may enable farmers to adopt other feed options which have a potential to improve livestock productivity. As shown in *Table 4*, this domain is largely found in the Ugandan districts (Tororo, Maguye, Jinja, Kamuli, Wakiso, Kampala, Mukono, Bushenyi, Hoima, Masindi, Pade, Gulu, Nebbi and Arua) compared to Kenyan counties (Kitui, Mkueni, Embu and Muranga, Kirinyaga, Meru, Nakuru) and Tanzanian regions (Mara, Mbeya, Njombe and Ruvuma).

According to the FEAST-Techfit scores shown in *Table 5*, suitable feed interventions for this domain include the practice of rehabilitation of degraded grazing land given the potential of land rehabilitation to restore land and improve forage growth for sustainable livelihoods. Supplementation of feed with energy-rich supplements such as molasses may be a suitable intervention for this domain given its nature of requiring no land and its high potential to mitigate feed scarcity during the dry or cool season and feed scarcity during the growing season. However, molasses deals well with feed scarcity and feed quality but has a low potential to solve feed quantity problems. Therefore, a suitable feed intervention to close the feed quantity gap is for farmers to adopt the use of purchased crop residues or hay given the potential of crop residues and hay to mitigate feed quantity constraints and its suitability to this domain's systems characteristics. Furthermore, the use of thinnings, tops, and leaf strips of crops such as maize, sorghum, and cassava are also a suitable option to mitigate feed quantity constraints and it is a cheap option with no requirements for more land and can be accessed on farm.

FEAST-Techfit feed interventions

Table 5 presents a summary of feed interventions with FEAST-Techfit scores. The scores show the potential of each feed intervention to prevent feed constraints and the factors which influence the uptake of each feed intervention. The Techfit module scores the candidate feed options from low to very high, depending on the intervention's potential to mitigate feed constraints. Therefore, *Table 5* was used to predict suitable interventions according to domain properties or interpretations.

Table 5: Summary of recommended feed interventions with FEAST-*Techfit scores*

Feed Interventions	**Potential to mitigate feed constraints** Scores run from 0 to 4 where 0=none; 1=low; 2=medium; 3=high; 4=very high			**Requirements of feed interventions/ Adoption factors** Scores run from 4 to 1 where 4=none; 3=medium; 2=high; 1=very high	
	Seasonal scarcity (dry/cool season)	Seasonal scarcity (growing season)	Feed quantity	Land	Water/Rainfall
Rehabilitation of communal/degraded grazing land	2	2	3	3	4
Supplementation with energy-rich supplements e.g. molasses	3	3	1	4	4
Purchase crop residues or hay	4	2	3	4	4
Thinnings, tops, leaf strips e.g. maize, sorghum, cassava etc	2	3	3	4	4
Short-duration / annual fodder crops e.g. Oats, maize, sorghum, vetch	2	4	4	2	2
Grasses (cut from cultivated fodder field under rainfed)	2	4	4	2	2
Irrigated fodder production (grasses, maize, sorghum)	4	2	4	3	1
Supplementation using protein by-products e.g. legume leaf meal	3	3	1	4	4
Silage – silage making	4	2	3	1	4
Fodder trees and shrubs	4	2	2	3	3

**Potential to mitigate score run from 0 to 4 where 0=none; 1=low; 2=medium; 3=high; 4=very high*
**Requirements of feed interventions score run from 4 to 1 where 4=none;3=medium; 2 = high; 1 = very high*

Table 6 shows suitable feed interventions based on domains feed constraints and system characteristics.

Table 6: Domains and suitable feed interventions

Domains	Feed constraints	System characteristics	Suitable feed interventions
2	Very high feed quantity/ 3 months of seasonal scarcity	Low land availability/ High water availability	-Irrigated fodder production. -Supplementation with energy-rich supplements such as molasses. -Supplementation with protein by-products such as legume leaf meal.
4	Medium feed quantity/ 6 months of seasonal scarcity	Very high land availability/ Medium water availability	-Short-duration or annual fodder crops such as oats, maize, sorghum, vetch. -Fodder trees and shrubs
7	Low feed quantity/ 11 months of seasonal scarcity	Low land availability/ Very high-water availability	-Supplementation with protein by-products such as legume leaf meal and oilseed. -Thinnings, tops and leaf strips of crops such as maize, sorghum, cassava -Irrigated fodder production
16	Very low feed quantity/ 12 months of seasonal scarcity	Very low land availability/ Medium water availability	-Rehabilitation of degraded grazing land -Supplementation with energy-rich supplements such as molasses -Purchased crop residues or hay

5. Discussion

Rapid urbanization and Improved standards of living in developing countries have resulted in a substantial shift in diets, leading to a greater demand for livestock products (Herrero et al., 2009). However, farmers are not successful in responding to the demand due to poor livestock productivity instigated by feed constraints. Therefore, due attention needs to be paid to the feed constraints faced by farmers and system characteristics which exist in the mixed farming system in order to improve livestock productivity. The main aim of producing a map showing the sixteen (16) domains, was to identify specific counties in Kenya, specific regions in Tanzania and specific districts in Uganda with feed constraints in order to predict suitable feed interventions which deal with the feed constraints thereby improving livestock productivity.

Domain 7 and 16 represents the areas in which available feed resource fail to match the daily feed requirements of one TLU all year round. This also indicates that livestock productivity in these areas is poor and farmers are not only failing to respond to the demand of livestock products, but are also failing to make enough income out this livelihood strategy (Randolph et al., 2007). These results are in line with the findings of Kavana and Msangi (2005) and Katongole et al. (2012) who reported poor livestock productivity due to feed constrains in Eastern Tanzania and Uganda (Kampala).

Considering the system characteristics of all the domains, it is evident that water availability has not been a problem in these mixed farming systems for the past ten years (2008-2017) and there has been water to support forage in the area. However, land availability for overall forage production is a significant constrain to forage availability in the study area. Therefore, the feed constraints reported in the domains may be attributed to unavailability of land, given that land plays a major role in forage production and adoption. The unavailability of land may be attributed to land degradation and soil loss caused by the increase in rainfall as predicted by climate change models in East Africa (Nearing et al., 2004) . In this study, available land was defined as productive land. Therefore, degraded land was not calculated as part of land available for forage production. As a result, the study shows low land availability and this raises a need to rehabilitate degraded land as it reduces land allocated to forage production. (Claessens et al., 2008, Taddese, 2001).

Given that all the domains show unavailability of land which might be compounded amongst other factors by land degradation, farmers need a policy intervention which promotes rehabilitation of land in order to restore degraded communal land, thereby improving forage production to meet livestock nutrition requirements. In addition, the domains show high rainfall availability, and rainfall is a significant resource which can enable farmers to harvest rainfall water to support forage production. This has an implication that farmers in this domain require policy interventions which will enable them to practice rainwater harvesting and also enable farmers to easily access irrigation systems which suit their local context.

Domain 4 was the only one which showed high land availability, thus the availability of land can enable farmers to adopt a range of feed interventions with land requirements such as short annual fodder crops (maize and sorghum) and fodder trees and shrubs. However, farmers may not be in a position to access seeds due to long distances to markets. Thus, this domain requires a policy intervention which will ease access to seeds given that the scarcity of seeds has a potential to limit the uptake of the two feed interventions. In addition, policy interventions which can play a major role in the uptake of feed interventions such as fodder trees and shrubs, are those which target extension workers to equip farmers with skills such as nursery establishment, tree pruning, and seed collection campaigns given that forage tree establishment for livestock feed is a knowledge-intensive practice (Franzel et al., 2014).

Furthermore, practices such as supplementing feed with molasses were found to be suitable for almost all the domains given the character of molasses of requiring no land. Molasses is known for its potential to increase livestock productivity (Tegegne et al., 1992). However, purchasing it adds to the production cost and this is a factor which may lead to its poor adoption by smallholder farmers. Apart from the production cost, the use of molasses requires specific knowledge for its successful use. Therefore, there is a need of a policy intervention which will enable farmers to access molasses without excessively adding to the production cost as well as policy interventions which will target extension workers to train farmers on the correct use of molasses as a supplement.

Due to time constraints this study focussed on two feed constraints and two system characteristics from the FEAST while the FEAST approach focussed on three feed constraints and six system characteristics. The three feed constraints were feed quantity, seasonal scarcity and feed quality and the six system characteristics were land, water, labour, credit, input delivery and knowledge. Therefore, the feed interventions predicted in this study were not based on all the feed constraints and system characteristics included on the FEAST approach. Thus, there is a possibility of the domains changing if all the feed constraints from FEAST can be considered in the analysis. There is also a possibility of the predicted feed interventions changing if the system characteristics such as credit and labour can be added into the analysis. Therefore, this leaves possibilities of improving this study. Furthermore, the FEAST approach defined water availability as proximity and access to standing water such as dams and boreholes. However, due to lack of spatial data which shows standing water, this study defined water availability as available water per watershed. As a result, monthly precipitation data sets were used to produce the water availability map.

To expand the findings of this study, other researchers may look into other types of livestock when mapping feed availability, as this study considered cattle density only. Accounting for the produced commodity in a certain domain can allow for more specific feed intervention recommendations, therefore, future researchers can improve the findings of this study by comparing the Techfit feed interventions to applicability to commodity (Dairy, fattening, breeding). It can also be interesting for other academics to map the same domains under a climate change context to find out how will the domains shift under future climate conditions so as to predicts feed interventions which will be suitable under projected future climate conditions.

6. Conclusion

The four selected domains were found in both Kenya and Tanzania and this indicates the variations in feed availability within different counties as some counties have high feed quantity and some have low feed quantity. However, Uganda reported the opposite given that domain 16 was the only domain found in all the mixed farming systems indicating twelve months of feed scarcity, very low feed quantity and no land for forage production. The other two domains which represent high (domain 2) medium (domain 4) feed quantity were not found in Uganda. This is an indication that livestock productivity is poor and there is an urgent need to introduce feed interventions which match Uganda's land and water availability context.

The domains' map shows that feed scarcity is one of the factors which constrain livestock productivity, thereby compromising livelihoods in the mixed farming systems of Kenya, Tanzania, and Uganda. The suitable feed interventions predicted in this study can be instrumental in closing the feed scarcity gap and improve livestock productivity for better livelihoods.

However, it is very important to understand that there is not one feed intervention which is ideal to solving all the feed scarcity issues which exist in an area but, integrating the two or three feed interventions recommended for each domain may eliminate all the feed scarcity constraints which exist within a certain domain. For instance, one feed intervention may deal with seasonality and the other may deal with quantity, thus, their combined effect can eliminate the feed constraint according to their mitigation potential.

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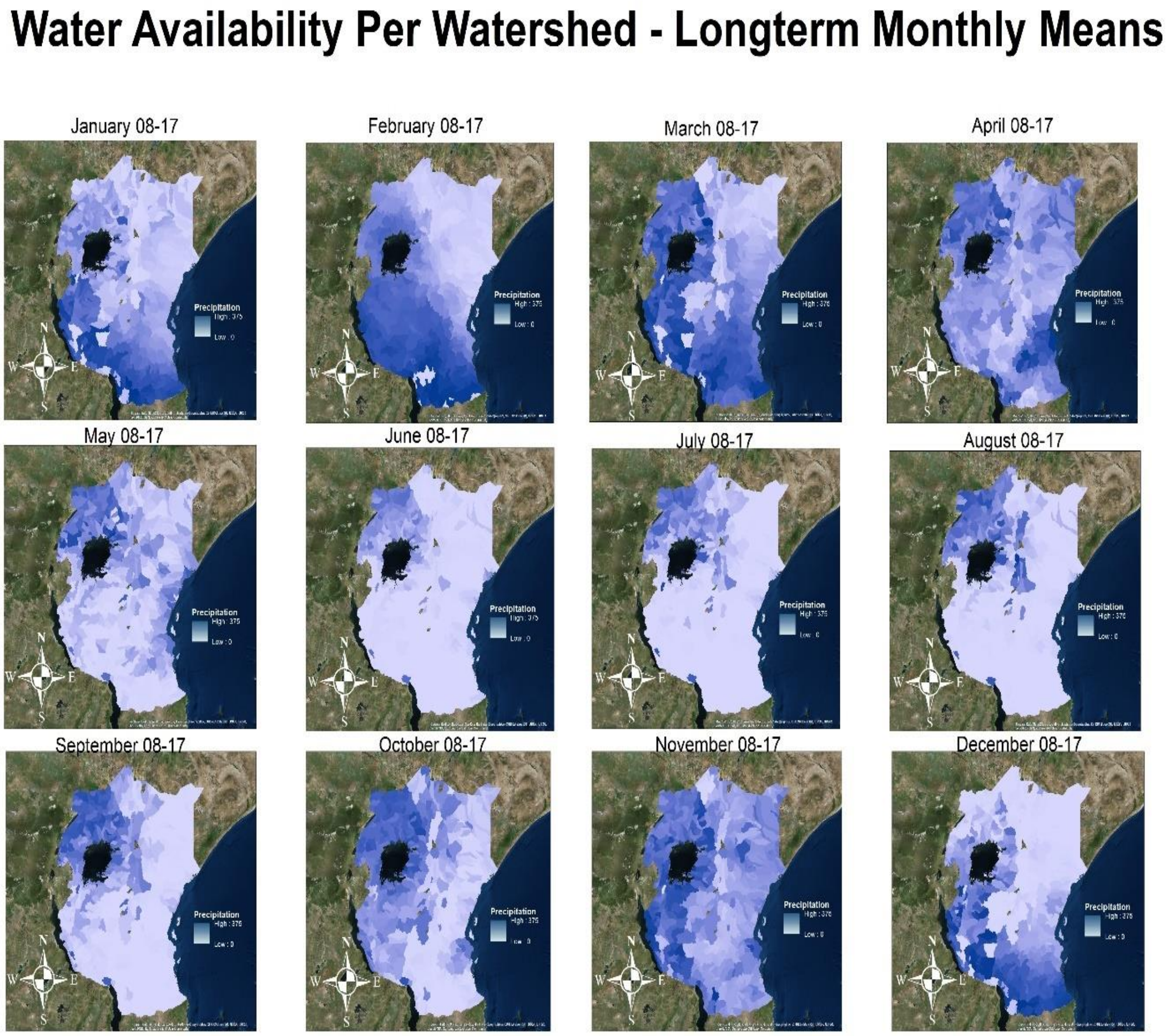
https://www.ilri.org/feast

8. Appendices

Appendix 1: Long-term monthly means of precipitation from the year 2008 to the year 2017



Appendix 2: Feed quantity domains statistics (the four domains were selected based on the mean values)

A	B	C	D	E	F	G	H	I
FEED QUANTITY	DOMAINS	COUNT	AREA	MIN	MAX	RANGE	MEAN	STD
	1	29881	2.07506944451	31.90831565860	467.25219726600	435.34388160700	127.94714885700	82.92730552080
	2	50410	3.50069444455	42.95533370970	2972313.00000000000	2972270.04467000000	5278.33042499000	18170.08037940000
	3	41422	2.87652777786	0.00000000000	36.05494689940	36.05494689940	17.17155965190	8.48855312173
	4	27751	1.92715277783	0.00000000000	183254.14062500000	183254.14062500000	1351.02893992000	4384.23610207000
	5	68639	4.76659722236	0.00000000000	55.62424850460	55.62424850460	18.60806962840	11.13919306390
	6	52166	3.62263888900	0.00000000000	34.92758560180	34.92758560180	12.19567786750	6.68817452371
	7	51113	3.54951388899	28.53589820860	648246.43750000000	648217.90160200000	259.15751588400	4144.64338757000
	8	35617	2.47340277785	30.56745529170	469.57894897500	439.01149368300	119.01854778800	83.35564591980
	9	42516	2.95250000009	0.00000000000	44.88459014890	44.88459014890	18.86340998710	9.20360662594
	10	28818	2.00125000006	0.00000000000	42.15449523930	42.15449523930	15.51065561210	8.02330109435
	11	47204	3.27805555565	0.00000000000	31.70490074160	31.70490074160	11.66507872490	5.53796115595
	12	47504	3.29888888899	31.66345405580	542.87689209000	511.21343803400	108.99022882800	74.75061019590
	13	27423	1.90437500006	31.24060249330	9820.02929688000	9788.78869438000	129.06097770800	193.44897896200
	14	51565	3.58090277788	2.85239458084	352.42144775400	349.56905317300	89.87173438470	70.09578526500
	15	50730	3.52291666677	13.32294178010	57.16909408570	43.84615230560	25.25543591930	9.91399150656
	16	54283	3.76965277789	0.00000000000	20.89627456670	20.89627456670	9.36898587488	2.86290336589

Appendix 3: Seasonal Scarcity domains statistics

A	B	C	D	E	F	G	H	I
FEED SCARCITY	DOMAIN	COUNT	AREA	MIN	MAX	RANGE	MEAN	STD
	1	29881	2.07506944451	10	12	2	11.99936414440	0.02650251709
	2	50410	3.50069444455	0	12	12	3.80716127752	3.95365036588
	3	41422	2.87652777786	12	12	0	12.00000000000	0.00000000000
	4	27751	1.92715277783	0	12	12	6.81366437246	4.92408389748
	5	68639	4.76659722236	12	12	0	12.00000000000	0.00000000000
	6	52166	3.62263888900	12	12	0	12.00000000000	0.00000000000
	7	51113	3.54951388899	0	12	12	11.32019251460	2.49955185194
	8	35617	2.47340277785	9	12	3	11.98511946540	0.18569087049
	9	42516	2.95250000009	12	12	0	12.00000000000	0.00000000000
	10	28818	2.00125000006	12	12	0	12.00000000000	0.00000000000
	11	47204	3.27805555565	12	12	0	12.00000000000	0.00000000000
	12	47504	3.29888888899	8	12	4	11.96617126980	0.27377814348
	13	27423	1.90437500006	0	12	12	11.85132917620	0.96011076307
	14	51565	3.58090277788	11	12	1	11.99992242800	0.00880715499
	15	50730	3.52291666677	12	12	0	12.00000000000	0.00000000000
	16	54283	3.76965277789	12	12	0	12.00000000000	0.00000000000

Appendix 4: Land availability domains

A	B	C	D	E	F	G	H	I
LAND AVAILABILITY	DOMAINS	COUNT	AREA	MIN	MAX	RANGE	MEAN	STD
	1	29881	2.07506944451	0.00038874536	1.09461534023	1.09422659487	0.00250931564	0.01196218881
	2	50410	3.50069444455	0.00000000494	1.09461534023	1.09461533530	0.00651363381	0.02746750214
	3	41422	2.87652777786	0.00037485160	0.13985250890	0.13947765730	0.00426851328	0.00563810388
	4	27751	1.92715277783	0.00062229385	1.05640125275	1.05577895889	0.03619826185	0.05994999573
	5	68639	4.76659722236	0.00000012964	0.00035121635	0.00035108671	0.00012194512	0.00006297047
	6	52166	3.62263888900	0.00000012150	0.00131874532	0.00131862381	0.00017888645	0.00020455091
	7	51113	3.54951388899	0.00000001279	0.98244643211	0.98244641933	0.00105610764	0.00602856114
	8	35617	2.47340277785	0.00162760180	1.11391568184	1.11228808004	0.00717962398	0.01589261434
	9	42516	2.95250000009	0.00021765487	0.14166365564	0.14144600077	0.00095989069	0.00376376405
	10	28818	2.00125000006	0.00076389802	0.33811765909	0.33735376108	0.00418206003	0.00940842902
	11	47204	3.27805555565	0.00000002093	0.00033493777	0.00033491684	0.00008192052	0.00004972962
	12	47504	3.29888888899	0.00145240768	0.03126367182	0.02981126413	0.00716196904	0.00481915976
	13	27423	1.90437500006	0.00000006814	0.00240772474	0.00240765660	0.00064638349	0.00044121244
	14	51565	3.58090277788	0.00000000166	0.00109699834	0.00109699668	0.00018931921	0.00017678586
	15	50730	3.52291666677	0.00000008044	0.00122013828	0.00122005784	0.00018772690	0.00014134077
	16	54283	3.76965277789	0.00000008390	0.00113291782	0.00113283392	0.00014094677	0.00012297566

Appendix 5: Water availability domains statistics

A	B	C	D	E	F	G	H	I
WATER AVAILABILITY	DOMAINS	COUNT	AREA	MIN	MAX	RANGE	MEAN	STD
	1	29881	2.07506944451	734.10980224600	1194.83862305000	460.72882080100	1005.79263989000	95.58441176050
	2	50410	3.50069444455	53.74269485470	2140.94360352000	2087.20090866000	882.94787848200	198.24594659200
	3	41422	2.87652777786	75.47223663330	691.30456543000	615.83232879600	464.34225450100	102.20574260600
	4	27751	1.92715277783	64.11176300050	996.99688720700	932.88512420700	479.50759654700	155.00020441000
	5	68639	4.76659722236	1081.65100098000	1978.92993164000	897.27893066400	1385.31127515000	175.22548181900
	6	52166	3.62263888900	677.41589355500	1001.44152832000	324.02563476600	758.66577810300	48.96454828080
	7	51113	3.54951388899	1058.84167480000	2224.07543945000	1165.23376465000	1348.66796973000	136.21173905900
	8	35617	2.47340277785	693.85583496100	1256.36132813000	562.50549316400	864.95454430000	77.65929485100
	9	42516	2.95250000009	869.63134765600	1914.36767578000	1044.73632813000	1263.92078139000	136.39291757000
	10	28818	2.00125000006	684.27062988300	1185.80078125000	501.53015136700	914.91580902100	125.20250168400
	11	47204	3.27805555565	825.57958984400	1161.85253906000	336.27294921900	954.12177021400	85.28469442420
	12	47504	3.29888888899	80.20389556880	714.71398925800	634.51009368900	536.32969971000	102.66301433700
	13	27423	1.90437500006	85.04782867430	797.51293945300	712.46511077900	515.43972016200	136.89783399800
	14	51565	3.58090277788	688.65521240200	1223.82934570000	535.17413330100	907.70314180600	124.17573721200
	15	50730	3.52291666677	80.20389556880	714.69177246100	634.48787689200	545.41692724100	107.56680319200
	16	54283	3.76965277789	85.04782867430	687.21160888700	602.16378021200	554.47162625400	95.86918868030